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**DEVELOPMENT OF GAS INSULATED HIGH VOLTAGE
COMPONENTS FOR NEUTRAL BEAM INJECTORS (NBI)**

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Abstract

The High Voltage Direct Current (HVDC) gas-insulated (GIS) technology will play a fundamental role for the future generation of Neutral Beam Injectors (NBI) operating at very high energy levels. As a matter of fact, the HVDC-GIS components will be used to transfer the electric power provided by the Acceleration Grid Power Supply (AGPS), to the ion acceleration grids of the NBI. The main focus of this Ph.D. thesis is to develop specialized numerical tools capable of resolving the nonlinear time-dependent behavior of the HVDC-GIS, analyze the leakage currents flowing in the gas under different conditions, the breakdown detection and the shape optimization of the components themselves. The proposed tools will allow to correctly analyze the phenomena occurring in the dielectric gas and can be used to study the dielectric behavior of the new materials used for solid insulators to increase the reliability and dielectric performances of the equipments. Although mainly focused on the design of the high voltage components for the NBI that will equip the Divertor Tokamak Test (DTT) facility, the construction of which is in the start phase in Frascati, Italy, the methodologies described in the Ph.D. thesis constitute an effective tool for analysis and design optimization of general HVDC-GIS equipments.

Abstract (Italiano)

La tecnologia dei sistemi di trasmissione di corrente continua ad alto voltaggio (HVDC) isolati in gas (GIS) giocherà un ruolo fondamentale nella futura generazione di iniettori a fasci di neutri (NBI) operanti ad alti livelli energetici. I componenti HVDC-GIS saranno infatti utilizzati per trasferire la potenza elettrica prodotta dal sistema elettrico di alimentazione delle griglie (AGPS), alle griglie dell'iniettore a fasci di neutri adibite all'accelerazione degli ioni. Lo scopo principale della tesi di dottorato consiste nello sviluppo di strumenti numerici specializzati, in grado di risolvere il comportamento non lineare dipendente dal tempo dei sistemi HVDC-GIS, analizzare le correnti di perdita che fluiscono nel gas in diverse condizioni, la possibile insorgenza di scariche elettriche nel gas e la capacità di svolgere l'ottimizzazione delle forme dei componenti stessi. Gli strumenti proposti consentiranno di analizzare correttamente i fenomeni che avvengono nel gas dielettrico e potranno essere utilizzati per studiare il comportamento dielettrico dei nuovi materiali impiegati per gli isolatori solidi al fine di aumentare l'affidabilità e la tenuta dielettrica dei componenti. Sebbene focalizzata principalmente sulla progettazione dei componenti ad alta tensione per l'NBI che equipaggerà l'esperimento Divertor Tokamak Test (DTT), la cui costruzione è in fase di avvio a Frascati in Italia, le metodologie descritte nella tesi di dottorato costituiscono un efficace strumento per l'analisi e l'ottimizzazione progettuale di generici apparati HVDC-GIS.

Abstract (Dutch)

De gasgeïsoleerde (GIS)-technologie met hoogspanningsgelijkstroom (HVDC) zal een fundamentele rol spelen voor de toekomstige generatie Neutral Beam Injectors (NBI) die op zeer hoge energieniveaus werken. In feite zullen de HVDC-GIS-componenten worden gebruikt om het elektrische vermogen van de Acceleration Grid Power Supply (AGPS) over te dragen naar ionenversnellingsroosters van het NBI. De belangrijkste focus van dit doctoraatsproefschrift is het ontwikkelen van gespecialiseerde numerieke hulpmiddelen die in staat zijn om het niet-lineaire tijdsafhankelijke gedrag van het HVDC-GIS op te lossen, de lekstromen die in het gas stromen onder verschillende omstandigheden te analyseren, de doorslagdetectie en de vormoptimalisatie van de componenten zelf. De voorgestelde tools zullen het mogelijk maken om de fenomenen die optreden in het diëlektrische gas correct te analyseren en kunnen worden gebruikt om het diëlektrische gedrag te bestuderen van de nieuwe materialen die worden gebruikt voor vaste isolatoren om de betrouwbaarheid en diëlektrische prestaties van de apparatuur te verbeteren. Hoewel voornamelijk gericht op het ontwerp van de hoogspanningscomponenten voor de NBI die de Divertor Tokamak Test (DTT)-faciliteit zal uitrusten, waarvan de bouw zich in de startfase bevindt in Frascati, Italië, zijn de methodologieën beschreven in dit doctoraatsproefschrift vormen een effectief hulpmiddel voor analyse en ontwerpoptimalisatie van algemene HVDC-GIS-apparatuur.

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Acronyms

ACA Adaptive Cross Approximation.

AG Acceleration Grid.

AGPS Acceleration Grid Power Supply.

DCG Direct Current Generator.

DE Differential Evolution.

DTT Divertor Tokamak Test.

ECRH Electron Cyclotron Resonant Heating.

EG Extraction Grid.

ELM Edge Localized Modes.

FEM Finite Element Method.

FFT Fast Fourier Transform.

FGM Functionally Grading Materials.

GCB Gas Circuit Breakers.

GG Grounded Grid.

GIL Gas Insulated Line.

GIS Gas Insulated System.

GMRES Generalized Minimal Residual.

GWP Global Warming Potential.

HDI Human Development Index.

HNB Heating Neutral Beam.

HVAC High Voltage Alternating Current.

HVB High Voltage Bushing.

HVD High Voltage Deck.

HVDC High Voltage Direct Current.

ICRH Ion Cyclotron Resonant Heating.

IEA International Energy Agency.

IEM Integral Equation Method.

ISEPS Ion Source and Extraction Power Supply.

ITER International Thermonuclear Experimental Reactor.

JET Joint European Torus.

MAMuG Multi Aperture Multi Grids.

MCF Magnetic Confinement Fusion.

MHD Magnetohydrodynamic.

MITICA Megavolt ITER Injector and Concept Advancement.

MMC Modular Multilevel Converter.

NBI Neutral Beam Injector.

NBTF Neutral Beam Test Facility.

PEEC Partial Element Equivalent Circuit.

PRIMA Padova Research on ITER Megavolt Accelerator.

PS Power Supply.

RAMI Reliability, Availability, Maintainability and Inspectability.

RF Radio Frequency.

RFP Reversed Field Pinch.

RFX Reversed Field eXperiment.

SINGAP Single-Gap Single-Aperture.

SPIDER Source for the Production of Ions of Deuterium Extracted from a
Radio frequency plasma.

TL Transmission Line.

TO Topology Optimization.

TSS Toroidal Support Structure.

VI Volume Integral.

List of Symbols

Symbol	Name	Unit
α	first Townsend ionization coefficient	m^{-1}
$\bar{\alpha}$	effective ionization coefficient	m^{-1}
i	imaginary unit	–
ε	electric permittivity	F m^{-1}
ε_0	vacuum electric permittivity	F m^{-1}
ε_r	relative electric permittivity	–
η	attachment coefficient	m^{-1}
μ	magnetic permeability	H m^{-1}
μ_0	vacuum magnetic permeability	H m^{-1}
μ_r	relative magnetic permeability	–
ρ	electric resistivity	$\Omega \text{ m}$
ϱ	free volume electric charge density	C m^{-3}
ϱ_s	free surface electric charge density	C m^{-2}
σ	electric conductivity	S m^{-1}
σ_s	surface electric conductivity	S
ϕ	electric scalar potential	V
ω	angular frequency	rad s^{-1}
A	magnetic vector potential	Wb m^{-1}
A*	modified magnetic vector potential	Wb m^{-1}
B	magnetic flux density	T
D	electric displacement	C m^{-2}
E	electric field	V m^{-1}
H	magnetic field	A m^{-1}
J	current density	A m^{-2}
n	normal unit vector	m
r	observation point	m
r'	source point	m
t	tangent unit vector	m

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Summary

THE INCREASING request for clean and environmental friendly resources to satisfy the world energy demand, has driven the search of new technologies for energy generation on the one hand, and the need for novel methods of power transmission on the other. The electric power generated for example by offshore wind turbines, cannot be transmitted over long distances with High Voltage Alternating Current (HVAC) systems without running into significant losses. The most suitable solution is to use the High Voltage Direct Current (HVDC) technology. The high electric power is transmitted through (pressurized) gas-insulated transmissions lines with a small footprint, ensuring very low power losses. The major drawback of these systems, limiting the spread of the technology, is the degradation of the dielectric performances during their operating life, highly remarkable for commercial components operating in steady state conditions. The degradation of the performances can be traced back to the intrinsic nature of the electric field distribution, which in the case of HVAC systems is only due to the electrical permittivity of the materials involved (gas and solid insulators), while for HVDC components, both permittivity and the electrical conductivity affect the final electric field map. For HVDC systems, during the transition from the initial capacitive field to the final resistive distribution, electric charge accumulates along the interfaces between gas and solid insulators. The effect of this accumulation phenomenon is the reduction of the flashover voltage of the solid insulator, with the consequence of increasing the probability of breakdown, which results in damage or complete destruction of the component.

Charge accumulation is mainly due to the discontinuity of the electric conductivities and thus of current density along the gas-solid insulator interface. The current flowing in the gas is mainly due to the movement of free ions, which results in, albeit improperly said, a non-uniform electrical conductivity which depends on several parameters like temperature, pressure and electric field. These ions are mainly generated by natural ionization and in situ sources. In this respect, the surface roughness of the high voltage elec-

trode, the residual water content and the emission of electrons from small metallic tips are key drivers. The current flowing in the gas can be seen as a leakage current (or dark current) affecting its insulation performance and in the worst cases driving to complete breakdown. An accurate design of HVDC gas-insulated equipments must account for the phenomena enhancing the leakage current, moreover, during the operational phase the gas state must be continuously monitored.

In the context of thermonuclear fusion research, the HVDC gas-insulated technology will play a fundamental role for the future generation of Neutral Beam Injectors (NBI) operating at very high energy levels. As a matter of fact, the electrostatic acceleration of the ions produced by the ion source, subsequently neutralized before entering the Magnetic Confinement Fusion (MCF) device and colliding with plasma particles, is performed through an electrostatic accelerator made up of a series of grids at different voltages up to the nominal acceleration voltage. The 1 MV AGPS (Acceleration Grid Power Supply) of ITER NBI currently is the most complex and technologically advanced application of HVDC gas-insulated systems in the context of nuclear fusion. The 1 MV voltage is provided by the Acceleration Grid Power Supply (AGPS) which include the following gas insulated high voltage components: Transmission Line (TL), the High Voltage Bushings (HVB), DC-filter and Direct Current Generators (DCG). To ensure the 1 MV voltage holding and at the same time reducing the overall footprint of the components, the natural gases such as dry air cannot be used in principle, but more complex molecules must be conceived. In view of its excellent dielectric properties, pressurized Sulfur hexafluoride is commonly adopted in the HVDC gas-insulated context and represents the baseline solution since 1960. However, its main disadvantage, which contradicts the context of ecological transition in which HVDC gas-insulated systems are located, is the significant environmental impact, orders of magnitude higher than Carbon dioxide, in case the gas is released into the atmosphere following a fault. This issue prompts the research on novel eco-compatible solutions mainly for HVDC gas insulated systems for commercial purposes, which may reflect also in the nuclear fusion field.

The improvement of the reliability of HVDC gas-insulated equipments for long-lasting operations can be done by an accurate design of the solid insulator, selecting the material able to homogenize the electric field intensity along its surface. Usually these materials are characterized by a nonlinear electric conductivity function of both electric field and temperature. Recently, the novel Functionally Grading Materials (FGM) gain great interest in the context of gas-insulated transmission lines for commercial purposes, and may represent a breakthrough for the performances of HVDC gas-insulated systems. The reliability of HVDC technology is also affected by inaccurate

design of the high voltage parts. As a matter of fact the breakdown of the gas can be triggered from regions suffering high electrical stress, but this condition is not sufficient. In most of cases the streamer inception mechanism, as a precursor of breakdown, is sufficient to give information about the critical areas which must be re-designed. The concept of shape optimization is well-suited for this purpose, by automatically defining a new shape of the component satisfying the engineering requirements.

With the previous concepts in mind, the conceptual design of HVDC gas-insulated components for the AGPS of NBIs, must be defined aiming at reducing their complexity and economic impact. However, conflicting demands must be met: reduce gas pressure, minimize mechanical stress and gas volume, minimize geometrical dimensions (for example the cross section of the TL), in order to reduce cost, weight and impact on the route footprint or building design, by guaranteeing at the same time the dielectric strength of the system avoiding breakdown events. The assessment of all the aforementioned phenomena require specialized numerical tools to be developed, capable of resolving the nonlinear time-dependent behavior of the HVDC gas-insulated systems and coping with leakage current, breakdown detection and shape optimization. In the context of industrial research, in which this thesis envisages, the goal is to embed these tools in a commercial software that can be easily shared between the engineering teams. The tool described in this work can be used for general analysis of HVDC gas-insulated equipments, however, it mainly focuses on the design of the 500 kV TL and HVB for the NBI that will equip the Divertor Tokamak Test (DTT) facility, the construction of which is in the start phase in Frascati, Italy.

Sommario

LA CRESCENTE domanda di fonti energetiche pulite e rispettose dell'ambiente per soddisfare la costante richiesta di energia a livello globale, ha indotto la ricerca di nuove tecnologie, finalizzate da un lato alla generazione di energia e dall'altro alla trasmissione della potenza elettrica. La potenza elettrica generata da impianti eolici offshore ad esempio, non può essere trasmessa in modo efficiente per lunghe distanze con la trasmissione di corrente alternata al alto voltaggio (HVAC) senza incorrere in elevate perdite. La soluzione più efficace a questo problema consiste nell'utilizzo della tecnologia di trasmissione di corrente continua ad alto voltaggio (HVDC). In tale contesto, l'elevata potenza elettrica viene trasmessa mediante linee di trasmissione coassiali, nelle quali la tenuta dielettrica è garantita dalla presenza di un gas isolante pressurizzato; ciò consente una diminuzione generale delle dimensioni dell'impianto ed notevole riduzione delle perdite di potenza. Il maggiore ostacolo di questa tecnologia, che ne limita la diffusione, riguarda la degradazione delle prestazioni dielettriche alle quali sono soggetti i componenti nel corso della loro intera vita operativa; effetto che risulta notevolmente accentuato per componenti impiegati nell'ambito commerciale ed operanti in stato stazionario. La degradazione delle prestazioni dielettriche si può ricondurre al modo in cui si distribuisce il campo elettrico nel sistema essendo, nei sistemi HVAC, guidato esclusivamente dalle rigidità dielettriche dei materiali coinvolti (gas ed isolanti solidi), mentre nei componenti HVDC, sia la rigidità dielettrica che la conducibilità elettrica influenzano la mappa di campo elettrico. Nei sistemi HVDC durante la transizione di campo elettrico dallo stato iniziale capacitivo a quello finale resistivo, carica elettrica viene depositata lungo le superfici di interfaccia tra l'isolante gassoso e l'isolante solido. Da tale accumulo di carica elettrica ne consegue una riduzione della tensione minima in grado di innescare una scarica lungo l'isolatore, pertanto un aumento della probabilità di completa rottura delle proprietà dielettriche con conseguente danneggiamento, o nel peggiore dei casi distruzione, dei componenti.

L'accumulo di carica è riconducibile alla discontinuità della conducibilità

elettrica e quindi della densità di corrente attraverso la superficie di interfaccia tra l'isolante gassoso e quello solido. La corrente che fluisce nel gas è principalmente dovuta al moto di ioni liberi che, anche se impropriamente detto, danno luogo ad una conducibilità elettrica non uniforme, funzione della temperatura, della pressione e del campo elettrico. La presenza degli ioni liberi è dovuta principalmente alla ionizzazione naturale ed a sorgenti localizzate all'interno del sistema. In questo senso, la rugosità della superficie dell'elettrodo ad alta tensione, il contenuto residuo di molecole d'acqua e l'emissione di elettroni da punte metalliche costituiscono i fattori principali. La corrente nel gas isolante può essere vista come una corrente di perdita (o corrente oscura) che ne inficia le proprietà isolanti e nel peggiore dei casi può portare alla completa rottura della tenuta dielettrica. La progettazione accurata degli apparati HVDC isolati in gas, richiede che i fenomeni menzionati siano accuratamente presi in considerazione; inoltre, durante le fasi operative, lo stato del gas deve essere continuamente monitorato.

Nell'ambito della ricerca nel campo della fusione termonucleare controllata, la tecnologia dei sistemi HVDC isolati in gas giocherà un ruolo chiave nello sviluppo della futura generazioni di iniettori a fasci di neutri (NBI) operanti ad alti livelli energetici. Infatti, l'accelerazione degli ioni prodotti dalla sorgente ionica, successivamente neutralizzati prima di essere iniettati all'interno della macchina a fusione a confinamento magnetico (MCF) nella quale trasferiscono la loro energia al plasma fusionistico tramite collisione, viene svolta mediante un acceleratore elettrostatico composto da una serie di griglie a diversi potenziali elettrici. Il sistema elettrico di alimentazione delle griglie di accelerazione (APGS) operante ad 1 MV di tensione del NBI di ITER rappresenta la più complessa e tecnologicamente avanzata applicazione dei sistemi HVDC isolati in gas nel contesto della fusione nucleare. La tensione nominale di accelerazione di 1 MV è fornita dal AGPS che include i seguenti componenti isolati in gas: la linea di trasmissione (TL), i passanti in alta tensione (HVB), il filtro in corrente continua e i generatori in corrente continua (DCG). Al fine di assicurare la tenuta in tensione a 1 MV ed allo stesso tempo ridurre le dimensioni dell'impianto, i gas naturali quali l'aria secca, non possono essere impiegati come isolanti e molecole più complesse devono essere sviluppate. Viste le sue eccellenti proprietà dielettriche l'esaffluoruro di zolfo è comunemente impiegato come gas isolante nei sistemi HVDC in gas e rappresenta la soluzione di riferimento già dal 1960. Tuttavia, lo svantaggio maggiore, che contraddice il contesto di transizione ecologica nei quali si collocano i sistemi HVDC in gas, è il notevole impatto ambientale, di ordini di grandezza superiore a quello dell'anidride carbonica, nel caso in cui il gas venga rilasciato nell'atmosfera a seguito di un guasto. Questa limitazione ha recentemente spinto alla ricerca di soluzioni più ecosostenibili

soprattutto nel campo dei sistemi HVDC in gas per impianti commerciali, che possono avere ricadute anche nelle soluzioni adottate nell'ambito della fusione nucleare.

L'incremento dell'affidabilità degli apparati HVDC isolati in gas per operazioni di lunga durata può essere ottenuta grazie ad una accurata fase di progettazione degli isolatori solidi, selezionando i materiali in grado di omogeneizzare l'intensità del campo elettrico lungo la superficie di interfaccia con il gas. Solitamente tali materiali sono caratterizzati da una conducibilità elettrica non lineare dipendente sia dal campo elettrico stesso che dalla temperatura. Recentemente, nuovi materiali quali i "Functionally Grading Materials" (FGM) stanno attirando grosso interesse nella progettazione di linee di trasmissione coassiali isolate in gas per scopi commerciali e possono rappresentare un punto di svolta per accrescere le prestazioni dei sistemi. L'affidabilità della tecnologia HVDC in gas è inoltre influenzata dal disegno delle parti ad alta tensione. Infatti, la rottura delle proprietà dielettriche del gas può essere causata dalle regioni che manifestano un elevato livello di campo elettrico, tuttavia questa conduzione non è sufficiente. Nella maggior parte dei casi il meccanismo dello "streamer inception", come precursore della rottura del dielettrico, è sufficiente per fornire informazioni sulle aree del design che richiedono di essere riprogettate. Il concetto di ottimizzazione delle forme ben si sposa con questo aspetto, e consente di ridefinire in modo automatico una nuova forma che possa soddisfare i requisiti richiesti durante la fase ingegneristica.

Tenendo in considerazione i concetti presentati, il progetto concettuale di componenti HVDC isolati in gas per l'AGPS di NBI deve essere svolto con l'obiettivo di ridurre la complessità e l'impatto economico degli impianti. Tuttavia ciò richiede la capacità di soddisfare esigenze contrastanti: ridurre la pressione del gas isolante, minimizzare lo stress meccanico ed il volume di gas impiegato, minimizzare le dimensioni (per esempio la sezione della TL) al fine di ridurre i costi, il peso e l'impatto sulla definizione degli edifici, garantendo allo stesso tempo le prestazioni dielettriche evitando l'insorgenza di fenomeni di scarica all'interno del sistema. A tale scopo si rende necessario lo sviluppo di strumenti numerici specializzati al fine di risolvere il comportamento non lineare e dipendente dal tempo dei sistemi HVDC in gas, in grado di analizzare anche le correnti di perdita, la possibile insorgenza di scariche nel gas e la capacità di svolgere l'ottimizzazione delle forme. Nel contesto di ricerca in ambito industriale nel quali si colloca il lavoro di tesi, l'obiettivo consiste nello sviluppo degli strumenti citati mediante software commerciali che possano essere facilmente condivisi tra i diversi gruppi di lavoro. Sebbene focalizzata principalmente sulla progettazione dei componenti ad alta tensione per l'iniettore a fasci di neutroni che equipaggerà l'esperimento

Divertor Tokamak Test (DTT), la cui costruzione è in fase di avvio a Frascati in Italia, le metodologie descritte nella tesi di dottorato costituiscono un efficace strumento per l'analisi e l'ottimizzazione progettuale di generici apparati HVDC isolati in gas.

Samenvatting

DE TOENEMENDE vraag naar schone en milieuvriendelijke hulpbronnen om aan de wereldwijde vraag naar energie te voldoen, heeft enerzijds geleid tot het zoeken naar nieuwe technologieën voor energieopwekking en anderzijds tot de behoefte aan nieuwe methoden voor energietransmissie. De elektrische stroom die bijvoorbeeld door offshore windturbines wordt opgewekt, kan met High Voltage Alternating Current (HVAC)-systemen niet over lange afstanden worden getransporteerd zonder aanzienlijke verliezen op te lopen. De meest geschikte oplossing is het gebruik van de High Voltage Direct Current (HVDC) technologie. Het hoge elektrische vermogen wordt overgedragen via (onder druk staande) gasgeïsoleerde transmissielijnen met een kleine voetafdruk, waardoor zeer lage vermogensverliezen worden gegarandeerd. Het grootste nadeel van deze systemen, die de verspreiding van de technologie beperken, is de verslechtering van de diëlektrische prestaties tijdens hun levensduur, die zeer aanzienlijk is voor commerciële componenten die in stabiele toestand werken. De achteruitgang van de prestaties is terug te voeren op de intrinsieke aard van de elektrische veldverdeling, die in het geval van HVAC-systemen alleen te wijten is aan de elektrische permittiviteit van de betrokken materialen (gas- en vaste isolatoren), terwijl voor HVDC-componenten beide permittiviteit en de elektrische geleidbaarheid de uiteindelijke elektrische veldkaart beïnvloeden. Voor HVDC-systemen, tijdens de overgang van het initiële capacitieve veld naar de uiteindelijke resistieve distributie, accumuleert elektrische lading langs de interfaces tussen gas en vaste isolatoren. Het effect van dit accumulatieverschijnsel is de vermindering van de overslagspanning van de vaste isolator, met als gevolg een grotere kans op doorslag, wat resulteert in schade of volledige vernietiging van het onderdeel.

Ladingsaccumulatie is voornamelijk te wijten aan de discontinuïteit van de elektrische geleidbaarheid en dus van de stroomdichtheid langs de gas-vaste isolator-interface. De stroom die in het gas vloeit, is voornamelijk het gevolg van de beweging van vrije ionen, wat resulteert in een niet-uniforme elektrische geleidbaarheid die afhangt van verschillende parameters zoals

temperatuur, druk en elektrisch veld. Deze ionen worden voornamelijk gegenereerd door natuurlijke ionisatie en in situ bronnen. In dit opzicht zijn de oppervlakteruwheid van de hoogspanningselektrode, het restwatergehalte en de emissie van elektronen uit kleine metalen punten belangrijke oorzaken. De stroom in het gas kan worden gezien als een lekstroom (of donkerstroom) die de isolatieprestaties aantast en in het ergste geval tot een volledige storing leidt. Een nauwkeurig ontwerp van HVDC-gasgeïsoleerde apparatuur moet rekening houden met de fenomenen die de lekstroom versterken, bovendien moet tijdens de operationele fase de gastoestand continu worden gecontroleerd.

In het kader van het onderzoek naar kernfusie zal de HVDC-gasgeïsoleerde technologie een fundamentele rol spelen voor de toekomstige generatie Neutral Beam Injectors (NBI) die op zeer hoge energieniveaus werken. In feite wordt de elektrostatische versnelling van de ionen geproduceerd door de ionenbron, die vervolgens worden geneutraliseerd voordat ze het Magnetic Confinement Fusion (MCF)-apparaat binnendringen en botsen met plasmadeeltjes, uitgevoerd door een elektrostatische versneller die bestaat uit een reeks roosters op verschillende spanningen tot aan de nominale versnellingsspanning. De 1 MV AGPS van ITER NBI is momenteel de meest complexe en technologisch geavanceerde toepassing van HVDC-gasgeïsoleerde systemen in de context van kernfusie. De 1 MV-spanning wordt geleverd door de Acceleration Grid Power Supply (AGPS) die de volgende gasgeïsoleerde hoogspanningscomponenten bevat: transmissielijn (TL), de hoogspanningsbussen (HVB), DC-filter en gelijkstroomgeneratoren (DCG). Om de spanning van 1 MV te behouden en tegelijkertijd de totale voetafdruk van de componenten te verminderen, kunnen de natuurlijke gassen zoals droge lucht in principe niet worden gebruikt, maar moeten er complexere moleculen worden bedacht. Gezien zijn uitstekende diëlektrische eigenschappen, wordt zwavelhexafluoride onder druk algemeen toegepast in de HVDC-gasgeïsoleerde context en vertegenwoordigt het de basisoplossing sinds 1960. Het belangrijkste nadeel, dat in tegenspraak is met de context van ecologische transitie waarin HVDC-gasgeïsoleerde systemen zijn gelegen, is de aanzienlijke milieu-impact, ordes van grootte hoger dan koolstofdioxide, voor het geval het gas na een storing in de atmosfeer vrijkomt. Dit probleem vormde de aanleiding voor het onderzoek naar nieuwe eco-compatibele oplossingen, voornamelijk voor HVDC-gasgeïsoleerde systemen voor commerciële doeleinden, die ook op het gebied van kernfusie kunnen worden toegepast.

De verbetering van de betrouwbaarheid van HVDC-gasgeïsoleerde apparatuur voor langdurige operaties kan worden gedaan door een nauwkeurig ontwerp van de vaste isolator, waarbij een materiaal wordt geselecteerd dat in staat is om de elektrische veldintensiteit langs het oppervlak te homogenis-

eren. Gewoonlijk worden deze materialen gekenmerkt door een niet-lineaire elektrische geleidbaarheidsfunctie van zowel elektrisch veld als temperatuur. Onlangs hebben de nieuwe Functionally Grading Materials (FGM) grote belangstelling gekregen in de context van gasgeïsoleerde transmissielijnen voor commerciële doeleinden, en kunnen ze een doorbraak betekenen voor de prestaties van HVDC-gasgeïsoleerde systemen. De betrouwbaarheid van HVDC-technologie wordt ook beïnvloed door een onnauwkeurig ontwerp van de hoogspanningsonderdelen. In feite kan de afbraak van het gas worden veroorzaakt door gebieden die onder hoge elektrische spanning staan, maar deze voorwaarde is niet voldoende. In de meeste gevallen is het startmechanisme van de streamer, als voorbode van storing, voldoende om informatie te geven over de kritieke gebieden die opnieuw moeten worden ontworpen. Het concept van vormoptimalisatie is hiervoor zeer geschikt, door automatisch een nieuwe vorm van het onderdeel te definiëren dat voldoet aan de technische vereisten.

Met de voorgaande concepten in gedachten, moet het conceptuele ontwerp van HVDC-gasgeïsoleerde componenten voor de AGPS van NBI's worden gedefinieerd met als doel hun complexiteit en economische impact te verminderen. Er moet echter aan tegenstrijdige eisen worden voldaan: gasdruk verlagen, mechanische belasting en gasvolume minimaliseren, geometrische afmetingen minimaliseren (bijvoorbeeld de dwarsdoorsnede van de TL), om kosten, gewicht en impact op de voetafdruk van de route of het ontwerp van het gebouw te verminderen, door tegelijkertijd de diëlektrische sterkte van het systeem te garanderen en storingen te voorkomen. De beoordeling van alle bovengenoemde verschijnselen vereist de ontwikkeling van gespecialiseerde numerieke hulpmiddelen die in staat zijn om het niet-lineaire tijdsafhankelijke gedrag van de HVDC-gasgeïsoleerde systemen op te lossen en om te gaan met lekstroom, doorslagdetectie en vormoptimalisatie. In de context van industrieel onderzoek, waarin dit proefschrift voorziet, is het doel om deze tools in te bedden in commerciële software die gemakkelijk kan worden gedeeld tussen de technische teams. Hoewel voornamelijk gericht op het ontwerp van de hoogspanningscomponenten voor de NBI die de Diverter Tokamak Test (DTT)-faciliteit zal uitrusten, waarvan de bouw zich in de startfase bevindt in Frascati, Italië, zijn de methodologieën beschreven in dit doctoraatsproefschrift vormen een effectief hulpmiddel voor analyse en ontwerpoptimalisatie van algemene HVDC-GIS-apparatuur.

1

General introduction

THIS CHAPTER introduces the basic concepts of controlled thermonuclear fusion, in view of its possible future usage to generate safe and CO₂-free electricity to meet the increasing demand for clean energy. In the first section a very brief introduction regarding the world energy problem is given, without any pretense of completeness. Then, the basic physical mechanism which are at the base of nuclear fusion reaction is described. Differently from the core of the stars, where fusion reactions take place due to the intense gravitational force, on earth, specialized machines must be used to trigger and control this phenomenon. The so-called Magnetic Confinement Fusion (MCF) devices are thus briefly introduced. Lastly, a dedicated section about the Neutral Beam Injector (NBI) is provided with the purpose of giving the minimum background to one of the possible auxiliary heating methods to start and control the fusion process. The electric power supply of this component will be the main subject of the Ph.D. thesis and is discussed in the remainder chapters.

1.1 World energy problem

Since the very beginning the human society has increased its energy consumption towards a more comfortable way of life. Starting from the industrial period towards the modern technological one with the development of internal combustion engines, the fossile fuels (at the beginning coal and later oil) pushed a rapid growth of both the human population and technology, allowing for a higher standard of living compared to previous centuries.

1.2. CONTROLLED THERMONUCLEAR FUSION

The level of human development and the amount of energy consumption per capita are strictly correlated. As a matter of fact the increasing number of people accessing new technologies drives to an increase of energy demand, conversely, the capability of developing new efficient technologies is limited by the amount of available energy. The correlation between human well-being and energy consumption per capita is described by the Human Development Index (HDI), annually updated by the United Nations. Strictly speaking, a highly developed society with a high per capita energy consumption, has a high HDI. The influence of human activities with the consequent release of CO₂ in the atmosphere is co-responsible for climate change since the mid-20th century [1]. As illustrated in Fig. 1.1 nowadays the most of energy consumption can be traced back to oil (30%), natural gas (24%) and coal (27%) resources. However, the supply of fossil fuels cannot continue indefinitely given their limited availability and high impact on the global warming. In addition, as evidenced by the recent crisis between Russia and Ukraine, the geopolitical aspect plays a fundamental role in the shifting of economic, social and energy policies. It is a well-known fact that renewable sources like solar or wind are strictly related to environmental conditions which cannot be controlled by humans. The world energy demand cannot be entirely satisfied by these resources, however their contribution will be of fundamental importance for the definition of an energy mix capable of zeroing the CO₂ emission by 2050 according to International Energy Agency (IEA) scenarios. The goal of carbon-free energy resources by the middle of the current century must be achieved with the technologies currently available, which also include nuclear energy, referring only to the conventional nuclear fission power plants. In this regard not only the environmental and economical sustainability are fundamental, but also the socio-cultural acceptance of CO₂-free technologies is of central importance. This is one of the aspects that limits the worldwide use of nuclear fission, particularly following the Chernobyl and Fukushima accidents. In summary, the challenge of electrification and the gradual reduction of fossile fuels usage requires huge effort in finding environmental friendly, safe, long lasting economically and socially accepted solutions. In this context, nuclear fusion is presented as one of the possible candidate.

1.2 Controlled thermonuclear fusion

Nuclear fusion is the power lighting up the sun and the other stars. As opposed to nuclear fission reactions, for which an heavy atom splits into small nuclei producing energy, nuclear fusion deals with light nuclei joining together with a subsequent substantial release of energy. To trigger the

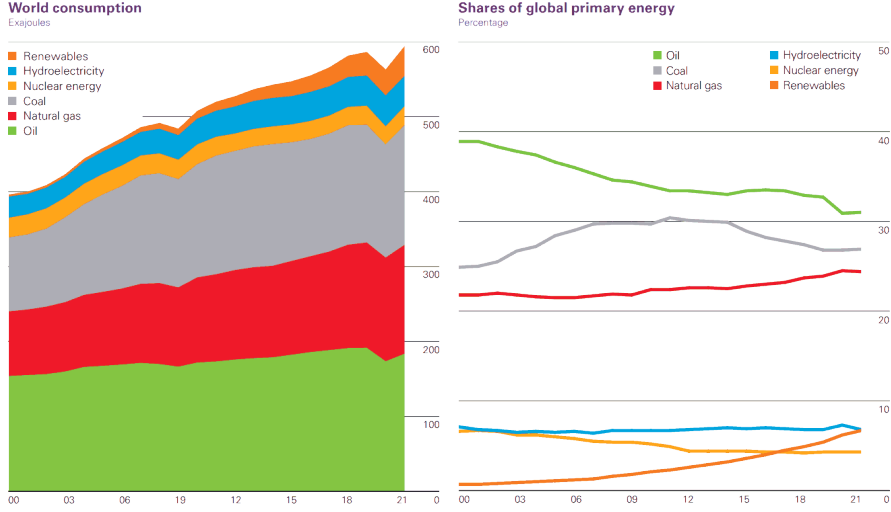
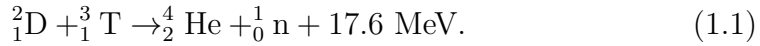


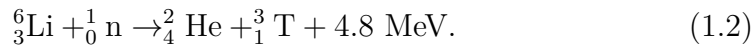
Figure 1.1: World energy consumption rates in the last twenty years from [2]. The temporal trend of reduction in energy demand in 2019-2020 following the COVID-19 pandemic was reversed again in 2021, with an increase of about 5.8%.

fusion reactions the potential barrier due to the Coulomb repulsion of the two reacting nuclei has to be crossed for sufficiently long times. The nuclear fusion rates are mainly described by their cross section $\langle \sigma v \rangle$ [cm^3/s] as a function of the energy of the reaction, in which σ [cm^2] is a measure for a particular process to takes place. Among all the possible reactions, due to its higher cross section at low energies, the most promising channel to get energy from a fusion power plant is by reacting Deuterium (D) and Tritium (T) nuclei, producing Helium (He), a neutron (n) and energy as:



The 17.6 MeV produced by reaction (1.1), shared between Helium (3.5 MeV) and neutron (14.1 MeV) is due to the mass defect of the reactants, following the Einstein relation. Strictly speaking, the fusion reactions are possible until the mass excess of the products is higher than that of reactants, that is until the binding energy reaches its maximum in the correspondence of iron (${}^5_6\text{Fe}$).

Deuterium and Tritium are two isotopes of Hydrogen. Deuterium can be extracted from seawater, while the Tritium amount in nature is limited to its decaying process. To conceive a D-T based fusion power plant, a way to obtain the Tritium nuclei in situ is mandatory. For example, Tritium can be obtained as a by-product of the Lithium-neutron reaction involving the rare isotope ${}^6_3\text{Li}$:



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In stars the fusion process is due to the gravitational force which tends to compress the matter driving to an increase of its temperature and density, triggering the fusion reactions which in turns ensure the force equilibrium. On planet the fusion reactions cannot be traced back to gravitational forces, thus the increase in temperature and the binding time of the reactants plays a fundamental role to allow fusion reactions to occur. For such high temperatures the matter is in the plasma state, the fourth state of matter, in which the gas is fully ionized into electrons and ions resulting in a quasi-neutral ensemble. Apart from the inertial fusion confinement [3], the magnetic confinement approach, based on the concept of Lorentz force experienced by a charged particle moving in an electromagnetic field, is the current path followed by the thermonuclear fusion community for the realization of a power plant. There, the plasma is confined inside a vacuum vessel by means of strong magnetic fields keeping it far away from the walls. Since the Tritium cannot be extracted directly from nature, on the basis of reaction (1.2) a blanked, attached to the vacuum vessel containing a certain amount of Lithium and Beryllium be conceived for the generation of the Tritium in situ to sustain the fusion chain. Beryllium, a toxic and carcinogenic material, is used as neutron multiplier. The blanked has two main tasks:

- The production of Tritium to sustain the fusion chain,
- Transfer the energy of the neutrons exiting the plasma, to a steam boiler which in turns is converted to electricity.

The scheme of electricity production by a fusion power plant is depicted in Fig. 1.2.

The research on controlled thermonuclear fusion started in 1950 with the first linear devices and is still ongoing to this date. Presently, three main configurations are considered as magnetic confinement devices: the Stellarator, the Tokamak acronym of “toroidal chamber with magnetic coils”, and the Reverse Field Pinch (RFP).

In Tokamak and RFP devices the confinement is achieved by inducing a toroidal current in the plasma as it is the secondary of a transformer, whose primary is the so-called central solenoid. An helical shape of the magnetic field lines, necessary to reduce particle losses, is achieved by superimposing a toroidal B_t and a poloidal B_p field, where the former ensures the plasma motion around the symmetry axis of the torus and the latter is for plasma shape and control. The schematic representation of the magnet system of a Tokamak is shown in Fig. 1.3. The main difference between Tokamak and RFP is the intensity of the toroidal component of the magnetic field with respect to the poloidal one. In RFP B_t is about 10 times lower than that of

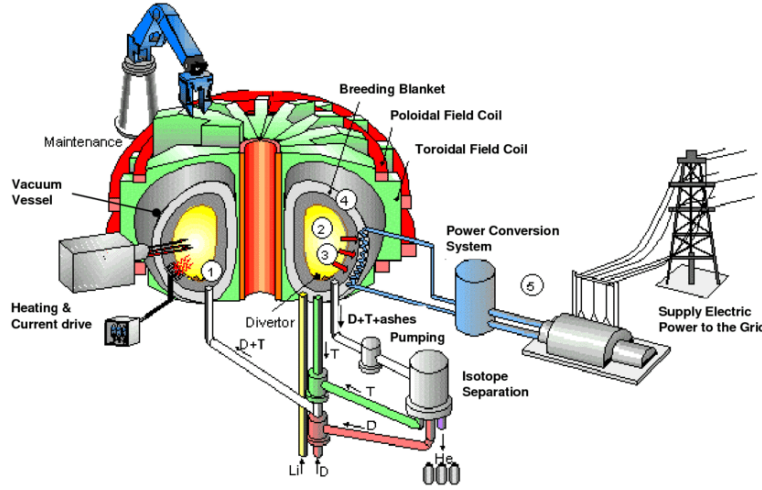


Figure 1.2: Sketch of electricity production scheme in a fusion power plant from [4].

Tokamaks and is comparable with the intensity of B_p . In addition, for RFP plasmas, the radial component of the toroidal field changes sign moving from the symmetry axis towards the plasma edge. To date, a variety of Tokamaks were realized around the world, for example the Joint European Torus (JET) in UK and the JT-60SA in Japan. In Italy at Consorzio RFX, Padova, the largest RFP machine, called RFX, is hosted. RFX-mod is a toroidal device with major radius $R = 2$ m and minor radius $a = 0.459$ m equipped with a set of 192 (48×4) saddle coils to control the Magnetohydrodynamic (MHD) instabilities. Recently RFX-mod is undergoing a major upgrade called RFX-mod2 [5].

The stellarators, for example the Wendelstein 7-X (W-7X), are very complex systems from the magnetic point of view. They does not make use of any induced plasma current, which is reached in steady state conditions, but require a very complex set of planar and non-planar magnet systems.

Currently the Tokamak is the most viable solution towards the realization of a commercial fusion power plant. The International Thermonuclear Experimental Reactor (ITER) under construction in Cadarache (FR) by an international joint cooperation between China, European Union, India, Japan, Korea, Russia and United States will be the most advanced Tokamak ever built. ITER has been designed in order to demonstrate the feasibility of long-lasting plasmas with better confinement, to test several technologies for the development of future fusion power plants and to show the safety characteristics of a fusion machine. Moreover ITER will be the the first fusion

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device with an effective energy gain, measured as the ratio between the fusion power P_{fus} and power supplied in input to the plasma P_{aux} :

$$Q = \frac{P_{fus}}{P_{aux}}, \quad (1.3)$$

greater than 10 ($Q \geq 10$) [6]. It is important to emphasize that P_{aux} is not the power absorbed by the grid, which actually is much higher. ITER will not supply electricity to the grid, a task that will be performed by the machines that will follow in order to demonstrate the feasibility of a fusion power plant. In this respect the DEMOnstration power plant DEMO, following ITER, requires the development of technologies which are beyond the current technological limit which must also comply with the RAMI (Reliability, Availability, Maintainability and Inspectability) concept. To produce energy with high efficiency, a much higher Q value is needed, therefore there is also a need for further developments in plasma physics, in particular the confinement of alpha particles (which are not produced in current reactors), plasma MHD stability (absolutely avoiding violent unstable modes such as Edge Localized Modes (ELMs) or disruption, which would destroy the machine) and plasma control with minimal additional power. Furthermore, to have a good efficiency but manageable power densities in the machine, DEMO must be much larger than ITER, which also poses enormous cost and logistics problems, as well as technological ones. Among the various engineering problems to be solved, the correct *divertor* concept, is one of the most challenging. The divertor is the exhaust of a fusion machine where the particles escaping the magnetic confinement are directed, depositing a huge amount of power.

To test different divertor configurations in conditions similar to that of ITER and the conceptual DEMO, a specific facility was proposed in the context of European program on fusion research, called Divertor Tokamak Test (DTT) facility. DTT is under construction at the ENEA research center in Frascati, Italy [7].

1.3 Neutral beam injector

In order to fusion reactions to occur the temperature of the plasma has to be increased above a certain limit. Despite the fact that the plasma is a conductor characterized by the electrical resistivity η , thus producing Joule heating as $Q_J = \eta J^2$, where J is the plasma current density, the *Ohmic heating* is inefficient to heat the plasma at high temperatures T because the plasma resistivity exhibits a decreasing trend with T according to the Spitzer law: $\eta \propto T^{-3/2}$. Usually the Ohmic heating alone is able to increase

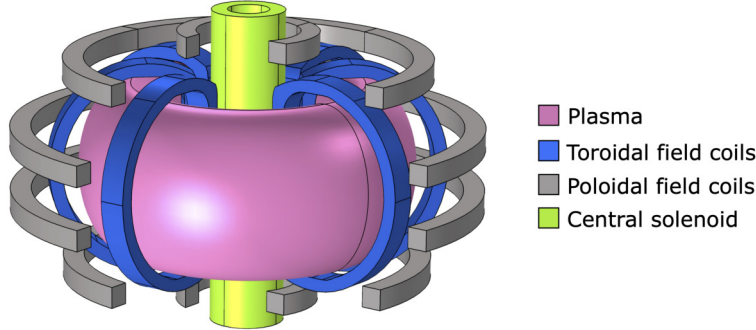


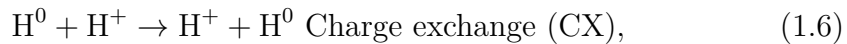
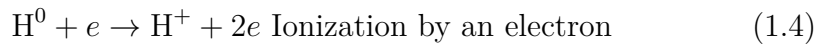
Figure 1.3: Schematic representation of a Tokamak.

the plasma temperature up to ≈ 3 keV (where $1 \text{ eV} \approx 11604 \text{ K}$), thus the gap to the relevant fusion temperatures, of about $5 \div 7$ keV, must be closed by exploiting additional (external) heating methods [8]. The so-called Heating & Current Drive (H&CD) systems not only are useful to increase the plasma temperature but also to drive plasma current, plasma fluid rotation and for other purposes, for example the plasma control.

Nowadays a variety of H&CD methods are proposed, generally subdivided in two categories. The first are electromagnetic waves, which heat the plasma through (electron and/or ion) resonances. This category includes the Ion and Electron Cyclotron Resonance Heating, respectively ICRH ($30 \div 50 \text{ MHz}$) and ECRH ($100 \div 200 \text{ GHz}$), and the Lower Hybrid Current Drive (LHCD) heating.

The Neutral Beam Injector (NBI) is an H&CD method based on energy transfer due to particle collisions. The NBI heating [9] is a well known technology already installed in most of fusion machines such as the Large Helical Device (LHD) [10], W7-X [11] stellarators and the JET [12], ASDEX Upgrade [13], DIII-D [14], EAST [15], KSTAR [16], JT-60SA [17] Tokamaks. Moreover, NBI is planned to be installed also in ITER [18] and DTT [19].

The NBI heating process starts with the generation of ions of a given species in the so-called ion source, which are then accelerated by means of an electrostatic accelerator and subsequently neutralized to enter the fusion machine. The neutrals reaching plasma core collide with plasma particles transferring their energy. In the case of Hydrogen (H) plasma, the main three process by which this can happen are [20]:



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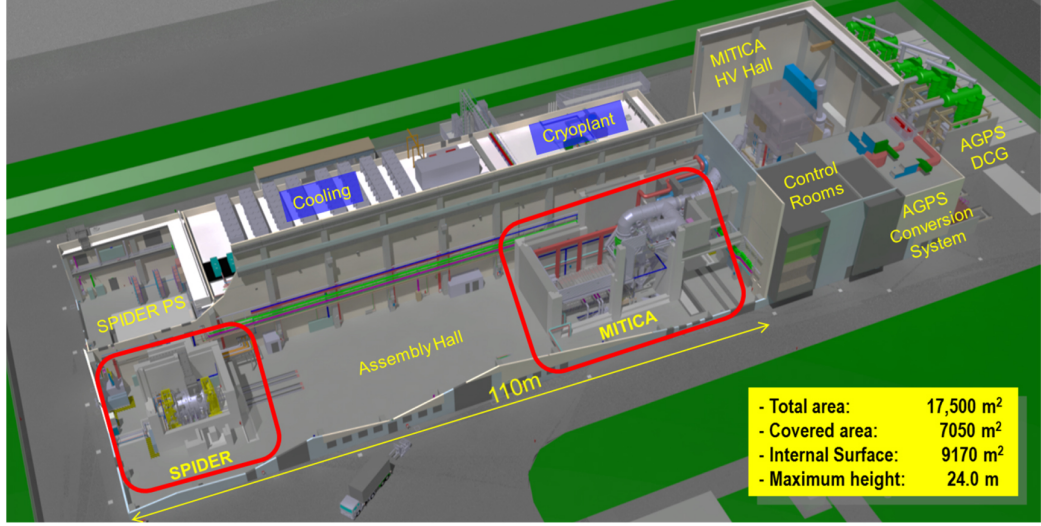


Figure 1.4: 3D CAD view of the PRIMA test facility, Padova, Italy. Figure taken from [23].

A more detailed explanation of the NBI-to-plasma interaction can be found, for example, in the books of fusion science [20, 21]. In the following, the engineering aspects of the beam generation process are discussed referring to the most advanced and powerful NBI that will equip the ITER machine.

Two Heating Neutral Beam Injectors (HNB) will be installed in ITER, each one delivering about 17 MW to the fusion plasma by means of neutral Deuterium atoms accelerated up to an energy of 1 MeV with a maximum beam pulse length of 3600 s [22]. With the purpose of constructing, testing and optimizing the full-scale prototype of the ITER HNB, the MITICA (Megavolt ITER Injector and Concept Advancement) experiment is begin build as a part of the PRIMA (Padova Research on ITER Megavolt Accelerator) test facility hosted at Consorzio RFX in Padova, Italy [23]. A 3D CAD illustration of the facility is reported in Fig. 1.4.

1.3.1 Beam generation

In this section the fundamental processes of beam generation, namely the *ion production*, the *beam acceleration* and the neutralization phase, are briefly discussed. The aforementioned processes cause consistent power losses, that is the fraction of power effectively coupled to the fusion plasma is only a fraction of that provided by the power supplies. For ITER NBI only 17 MW out of 59 MW of input power are effectively delivered to the plasma.

The following discussion does not claim any completeness about the de-

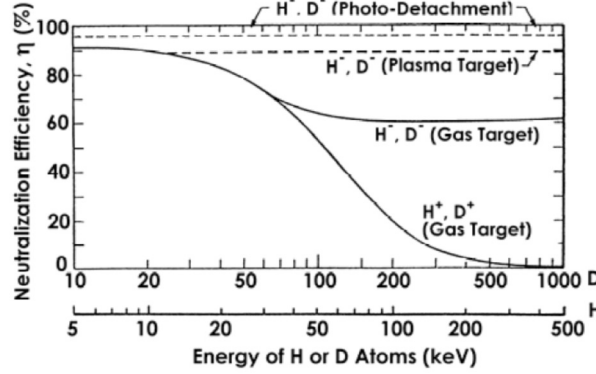


Figure 1.5: Neutralization efficiency of positive and negative Deuterium and Hydrogen ions as a function of beam energy. Figure taken from [21].

tailed physics behind the generation and optimization of ion source and beam neutralization, which is beyond the scope of the thesis.

Beam source

The ion source may be conceived for the generation of either positive or negative ions, however the choice strictly depends on the desired energy of the neutral beam penetrating the fusion plasma. Most of the NBIs currently installed in experimental magnetic confinement fusion devices are low energy, thus, positive ions can be efficiently used. However, as depicted in Fig. 1.5 when dealing with high energetic beams, such as the one conceived for ITER NBI, the use of negative ion sources is mandatory due to the rapid decrease of the neutralization efficiency of the positive ions when using the concept of gas neutralization. From now on the positive and negative NBIs are termed as P-NBI and N-NBI respectively. N-NBIs were successfully installed and operated both in stellarators and Tokamaks such as the LHD and JT-60U, where the latter is equipped with a 500 keV N-NBI [24]. However, the construction and operation of NBIs with high energy levels equipping future machines like ITER requires further research activities.

In the context of the PRIMA test facility, the investigation of the negative ion source for ITER N-NBI is of central importance [23]. In this respect the SPIDER experiment, acronym for Source for Productions of Ions of Deuterium Extracted from a Radio-frequency plasma, was conceived. SPIDER experiment aims at testing and optimizing the full-scale ion source in terms of magnetic and electrostatic configurations, uniformity and optics of the beam and beam current and duration up to $t = 3600$ s [25]. On SPIDER the beam generated by a Radio Frequency (RF) ion source is accelerated up

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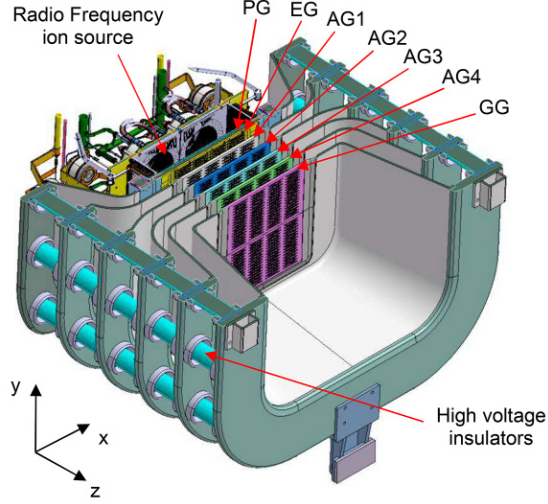


Figure 1.6: 3D CAD section of the MITICA beam source and acceleration grids from [28].

to an energy of 96 keV. This low voltage level allows the use of air-insulated components for the transmission of electric power supplying the RF drivers and the electrostatic accelerator. Specifically, the electric power devoted to supply the ion source components (such as RF drivers, plasma grid, ...) is procured by the Ion Source and Extraction Power Supply (ISEPS). All these power supplies are referred to the ion source voltage which is polarized at -96 kV with respect to ground.

Beam acceleration

The negative ions extracted by the Extraction Grid (EG) at the highest electric potential, are successively accelerated by using an high-energy electrostatic accelerator made of Acceleration Grids (AGs) characterized by many apertures through which the beam can pass. Two acceleration concepts were considered for the ITER N-NBI accelerator: the Multi-Aperture Multi-Grid (MAMuG) [26] composed by many AGs, and the Single-Gap Single-Aperture (SINGAP) solution which provides only one acceleration stage [27]. The MAMuG represent the reference solution for the 1 MeV ITER N-NBI and is composed by five AGs labelled AG1, ..., AG4, each having 1280 apertures and a voltage difference between two consecutive grids of 200 kV. The last Grounded Grid (GG) is referred to ground potential. Fig. 1.6 gives a section of the MITICA beam source and the five acceleration grids.

To accelerate negative ions the Power Supply (PS) has to provide negative voltages to the grids that is, the five grids are polarized at -1 MV, -800 kV, -600 kV, -400 kV and -200 kV with respect to ground. Compared to the NBIs realized so far, the insulating structure to guarantee the dielectric strength for such high voltages requires a considerable industrial research effort. The complex PS layout of MITICA shown in Fig. 1.7 was developed by the Japanese and European Domestic Agencies (JADA, Fusion for Energy–F4E). In particular, the High Voltage (HV) components coloured in blue are provided by JADA and include the Acceleration Grid Power Supply (AGPS) Direct Current Generators (DCGs) feeding the five electrostatic grids, the DC-filter, the gas-insulated Transmission Line (TL) and the 1 MV insulating transformer feeding the ISEPS. While the AGPS Conversion System (CS) is furnished by European Domestic Agency. As previously stated, ISEPS are referred to the voltage of the ion source, which in this case is -1MV, thus are hosted in the High Voltage Deck (HVD1) which is a unique component in terms of size and complexity. It is a Faraday cage of dimension 12 m (L) $\times$ 8 m (W) $\times$ 10 m (H) subdivided into two floors insulated from ground for 1 MV.

The whole electrical scheme of MITICA/ITER AGPS is given in Fig. 1.8. The AGPS is composed by two main subsystems: The AGPS-CS responsible for the static conversion, and the AGPS-DC generators, or briefly DCGs, each composed by a step-up transformer and the gas-insulated diode rectifier. The AGPS-CS foresees two step-down oil transformers fed by the medium voltage grid. These transformers feeds the AC/DC converter, which in turn is connected at the output side to a DC-link capacitor bank and to five Neutral Point Clamped (NPC) three phase inverters, based on IGBTs [29]. Each output of the three phase inverter is connected to the step-up transformer, which in turn feeds a SF₆-insulated diode rectifier. The -1 MV output of the series-connection of the five DCGs and the other intermediate voltages of -800 kV, -600 kV, -400 kV and -200 kV are filtered by the gas-insulated DC-filter. The DC-filter contains a set of resistors and capacitors to limit the ripple and the overshoots in case of loss of load. Then the voltages are transmitted to the ion source through the TL, which is approximately ≈ 100 m long. In order to keep the dimensions of the HV gas-insulated components compact at the same time ensuring high levels of insulation performances pressurized Sulphur hexafluoride (SF₆) is used [30]. The development of such components, for example the DC-filter [31] and the SF₆ diode rectifier [32], require a lot of effort to ensure the 1-h continuous operation at -1 MV. Moreover, the design of the insulation structure of the TL require deep investigation to mitigate possible insulation faults due to inaccurate design [33, 34, 35].

1.3. NEUTRAL BEAM INJECTOR

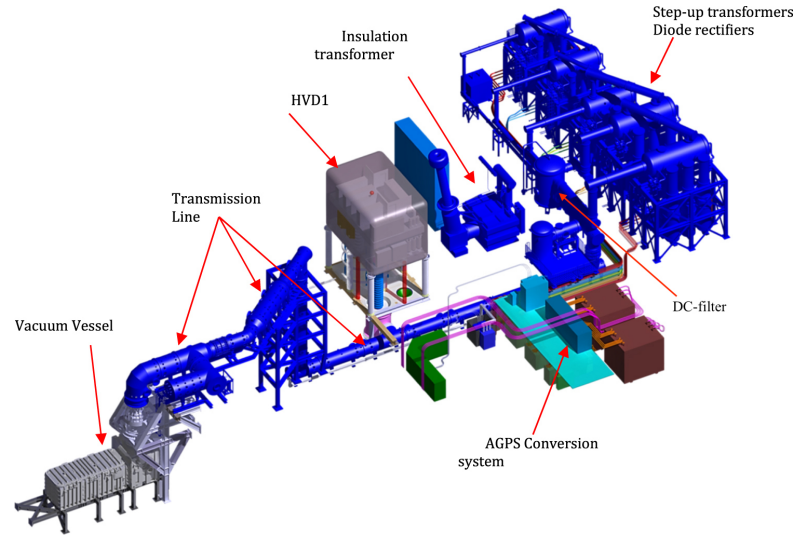


Figure 1.7: 3D CAD view of the 1 MV MITICA power supply [23].

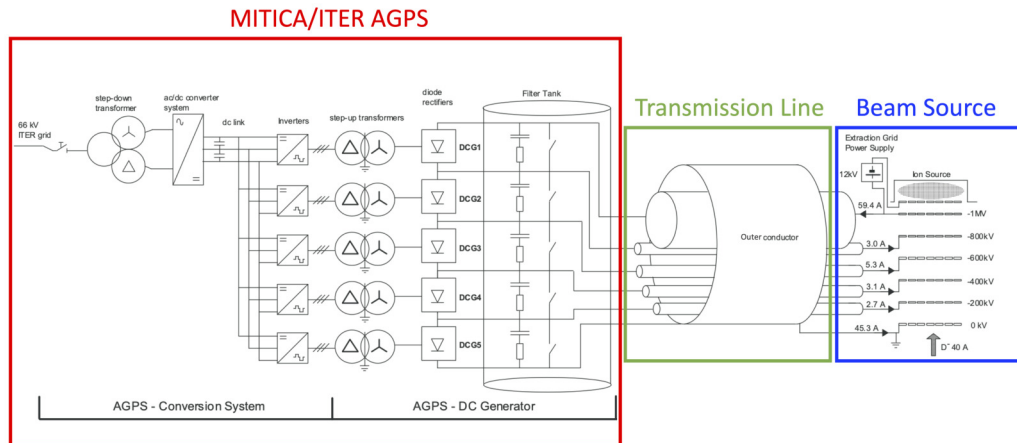


Figure 1.8: Scheme of the MITICA (ITER) AGPS [29].

Beam line

The negative ions accelerated to the nominal energy by the acceleration grids must be neutralized before entering the magnetic confinement fusion device. This task is performed by the *neutralizer* where a neutral gas made of, for example, Deuterium, neutralizes the energetic ions with charge exchange process. The loss of efficiency of the NBI systems is mainly due to this process, in which only $\approx 40\%$ of ions are effectively neutralized. The remaining ions are removed by a Residual Ion Dump (RID), installed downstream and deflecting the residual charged particles using electrostatic field.

1.4 Aim of the thesis

The main focus of the work is to investigate the mathematical and numerical modeling techniques of HVDC (High Voltage Direct Current) gas-insulated systems and the issues related with their operation. The ultimate goal of the thesis is to embed the developed numerical models into a unified tool based on commercial software, which can be used in the context of industrial research regarding HVDC gas-insulated apparatus for nuclear fusion applications.

In view of the need to replace the Sulphur hexafluoride with more eco-friendly alternatives and the solid insulating materials with solutions capable of reducing the degradation of dielectric performances during the operation, a survey on the current research trends is given.

The state-of-art mathematical approaches for the electric field modeling adopted within the HVDC world are described in the thesis, examining their strengths and weaknesses.

From the engineering point of view, the possibility of evaluating the probabilities of electrical discharges within the gas, caused by an inaccurate design of the high voltage parts is extremely important. In this respect a wide range of mathematical approaches exist, with different levels of complexity for the numerical assessment. Keeping in mind the industrial application of this work, a simple but already useful method for the gas breakdown detection is analyzed in the thesis.

The very important aspect of leakage currents (or dark currents) flowing in the gas is also examined. The leakage currents enhancement driven by external ionization fields is well-known in the context of HVDC gas-insulated equipments for NBIs, however external ionization is not the only source of leakage currents, which can emerge even from field enhancement phenomena inside the apparatus. In this work the leakage current regimes are mathematically and numerically analyzed.

1.4. AIM OF THE THESIS

In order to support the engineering phase of the HVDC gas-insulated systems, the numerical aspects developed along the thesis converge into an automatic optimization tool which can be used for the definition of an electrode configuration which reduce the inset of possible streamer inception channels or to perform a capacitive field grading, homogenizing the electric field intensity on prescribed geometrical entities.

At the end, the tools described will be used for the conceptual design of the HVDC gas-insulated components for the AGPS (Acceleration Grid Power Supply) of DTT (Divertor Tokamak Test) N-NBI. Hopefully, the results reported here may be useful to sustain other experimental campaigns involving HVDC gas-insulated equipments, for example that of MITICA test facility.

The rest of the work is organized as follows. In Chapter 2, the DTT NBI is described and possible CAD layouts of the AGPS in the DTT site are discussed. Two successive solutions are investigated: 1) the *double N-NBI solution* which foresees two N-NBI each of 400 keV, and 2) the *single N-NBI solution* based on a unique N-NBI of 500 keV. Although this chapter presents aspects closer to the field of civil engineering, it plays a key role in the body of the thesis and in the activities carried out during the Ph.D. program. In fact, the numerical study of the HVDC gas-insulated components was firstly motivated by the need to estimate their footprint in the site that will host DTT and to sustain the conceptual design phase of the equipments itself. The topics dealt with in Chapter 2, such as the definition and CAD design of the AGPS layouts, directly involved the author of the thesis in close collaboration with the buildings team of DTT.

Mathematical and numerical modeling of gas-insulated high voltage components starts from the description of the dielectric materials usually adopted. In this respect, chapter 3 focuses on dielectric gases and solid insulating materials. In particular, the properties of the extensively-used SF_6 gas are summarized together with an insight in alternative eco-friendly solutions. Moreover, the novel *field grading materials* for the solid insulators, which recently gained great interest in the community, will be presented. The aim of this chapter is twofold: from one side it gives a survey of the current state-of-art solutions, the other side it gives an overview on possibile alternative solutions which can be considered for the development of future gas-insulated high voltage components.

Chapter 4 concerns the mathematical and numerical formulation underlying the modeling of HVDC gas-insulated systems. After the description and comparison of the different electric field modeling methods, the issues related with the *streamer inception* and *leakage currents* phenomena are investigated. The correct modeling of discharge precursors in the gas and that

of leakage currents, namely the currents flowing in the insulating gas which can drastically reduce the voltage holding, is of great interest for general gas-insulated systems. At the end of chapter, a series of numerical examples are collected. These examples are mostly academic, not directly related with the HVDC gas-insulated components for the AGPS of DTT NBI, but are necessary to gain confidence with the described numerical approaches.

The deep investigation of the contents of chapters 3 and 4, which represent the core of the thesis, is fundamental to gain knowledge about the complex task of modeling the HVDC gas-insulated components and to understand the strengths and weaknesses of the mathematical and numerical approaches. In fact, the purpose of these chapters is to provide a unified literature review, not directly related to the subject of the AGPS of DTT NBI. The intense research activity in the modeling of gas HVDC systems was pursued by the author after the limited knowledge that did not allow to provide a conceptual design of gas-insulated components for the AGPS of DTT N-NBI. However the correct mathematical and numerical analysis, through academic examples it is necessary in order to become familiar with the phenomena from a numerical point of view, and to provide the basis for future experimental verification.

In Chapter 5, the concept of *numerical optimization* applied to HVDC gas-insulated systems is described. The numerical optimization with single and many objectives can be very useful in defining a design that meets specific engineering needs, for example reduction of streamer inception and the surface charge accumulation. The aim of this chapter is to “close the circle” around the numerical modeling of gas-insulated components, since the numerical optimization is based on the concepts described in the previous chapters. The methodologies described in this chapter will be of particular interest to fine designing gas-insulated components and eventually correct parts of the design which may cause a reduction of the voltage holding.

With the concepts described in the previous chapters in mind, the design of the gas-insulated high voltage components that will be used for the AGPS of DTT N-NBI, based on the 500 kV solution, is conceived in Chapter 6. Although the solutions that will be given in this chapter are not the final one, they represent the first step towards the conceptual design of the real components. These components include the HVD hall, the gas-insulated TL and the SF₆-air bushing. In addition to the mentioned components, the chapter describes also the numerical investigation of the small-scale test bed that will be realized in this context to sustain the research of HVDC gas-insulated systems. The experimental test bed will be of fundamental importance for the future activities to compare the numerical results with the measurements, with the purpose of fine tuning the parameters of the model, test different gas and insulating materials and check the correctness

1.4. AIM OF THE THESIS

of the numerical methods used to describe the phenomena occurring in the gas, for example the leakage (dark) currents.

Finally in Chapter 7 conclusions and future perspectives are drawn.

In Appendix A the complementary activities carried out during the PhD program are described. These activities include the numerical modeling of *eddy current* problems, the *low-rank approximation* methods, the *Partial Element Equivalent Circuit* (PEEC) method and the *topology optimization* for electromagnetics.

2

DTT neutral beam injector

IN THE CONTEXT of the European roadmap of thermonuclear fusion research, the challenging task of exploring alternative divertor configurations to tackle the power exhaust issue for the fusion machines that will follow ITER (International Thermonuclear Experimental Reactor), such as the European Demonstration Fusion Power Plant (DEMO), need to be resolved [36]. This fundamental problem will be investigated by the Divertor Tokamak Test facility (DTT), the construction of which is in the start phase in the ENEA center located in Frascati, Italy, currently headquartered of the Frascati Tokamak (FTU) [7].

The DTT machine, whose schematic representation is given in Fig. 2.1, is a Tokamak characterized by a major radius R of 2.19 m and a minor radius a of 0.7 m, with a relatively high toroidal field B_t of 6 T and a plasma current of 5.5 MA. DTT was conceived to reach DEMO-relevant power fluxes on the divertor in order to comply with the material problem. In this respect a value of the parameter $P_{sep}/R \geq 15$ MW/m is required, where P_{sep} indicates the power through the last closed magnetic surface [36]. A summary of the main DTT parameters in comparison to that of ITER and the European DEMO is reported in Table 2.1.

To test different divertor configurations, DTT will be equipped with a significant amount of external heating power P_{tot} . At the beginning of the operational phase the DTT plasma will be coupled with additional 14.5 MW from ECRH (Electron Cyclotron Resonant Heating) [37] and 3 MW provided by ICRH [38]. In the later operational stage the ECRH power is planned to 29 MW, and ICRH (Ion Cyclotron Resonant Heating) to 6 MW, in addition

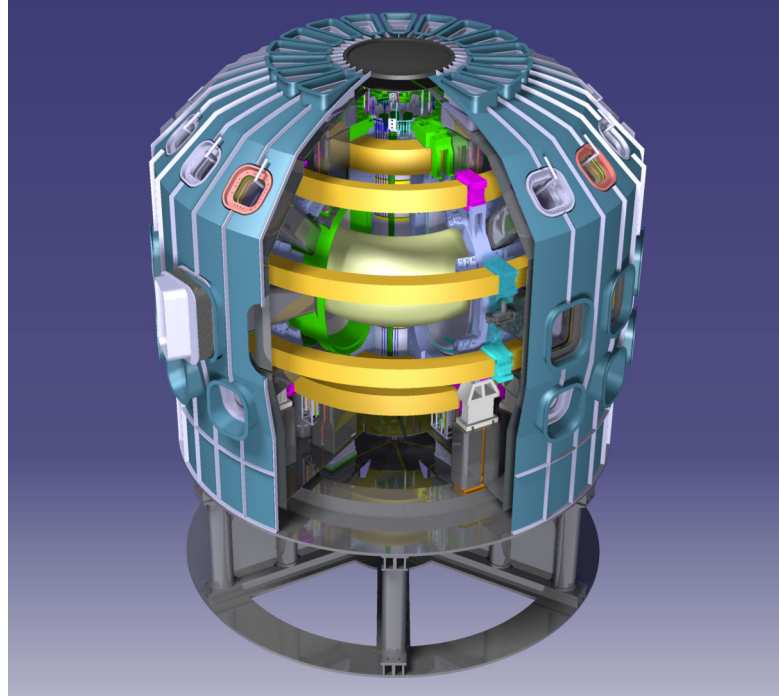


Figure 2.1: Schematic representation of the DTT Tokamak ©ENEA.

to 10 MW of power provided by N-NBI (Negative-Neutral Beam Injector) accelerating negative Deuterium ions [39]. Different proposals were considered in the past for the N-NBI heating, in particular the first one foresees two N-NBI of 400 keV energy, with an output power of 7.5 MW each [19]. Recently, a single N-NBI rated for an energy of 500 keV and 10 MW coupled to the plasma, was conceived [39], allowing for significant advantages regarding plasma energy transport and particles dynamic.

Differently from MITICA/ITER N-NBI whose ion source operates in vacuum, the DTT N-NBI uses the same concepts of the 500 keV N-NBI installed in JT-60SA which has an air-insulated ion source. However, a common aspect with the MITICA/ITER N-NBI is the choice of the ion source, since in both cases is based on radio frequency [40]. The first design solution for the DTT N-NBI ion source, both for 400 keV and 500 keV, was the so-called *double-source* approach. This solution, whose overall 3D CAD view is given in Fig. 2.2(a), is characterized by two sub-beams each with an angle of 0.0925 rad with the equatorial plane [40]. The need to use the N-NBI also for diagnostic purposes led to the definition of a new solution characterized by a single beam in the equatorial plane, to this aim the *single-source* design approach was proposed [41]. This solution shows many advantages with respect

Parameter	DTT	ITER	DEMO
R [m]	2.19	6.2	9.1
a [m]	0.70	2	2.93
A	3.1	3.1	3.1
I_p [MA]	5.5	15	19.6
B_t [T]	6	5.3	5.7
Additional heating power P_{tot} [MW]	45	120	TBD
P_{sep}/R [MW/m]	15	14	17
λ_q [mm]	0.7	0.9	1.0
Pulse length [s]	100	400	7600

Table 2.1: Comparison of main parameters of DTT, ITER and DEMO [36].

the previous one, both from construction, operational and maintenance point of views, for example:

- Possibility to use the heating NBI also as a diagnostic NBI because the beam is on the equatorial plane,
- The correction coils, are more effective in protecting the beam from the detrimental effect of the stray magnetic field from the tokamak. In fact, the beam is located in the middle between the two sets of correction coils (located above and below the vessel, as given in Fig. 2.2),
- More clearance around the beam in the duct region, with a reduction of the heat loads generated by the beam halo on the duct,
- Less components and less electrical and cooling connections, implying a better RAMI score and a lower cost,
- Faster alignment procedure because the components to be aligned (accelerator grids, neutralizer, Residual Ion Dump (RID), and calorimeter) are fewer,
- The research and development from ITER NBI would constitute a much better reference because the ion source can be almost identical to the MITICA one, with only some minor adaptations,
- The maintenance of Non-evaporable getter (NEG) pumps is improved because there is space for dedicated ports above and below the beam source.

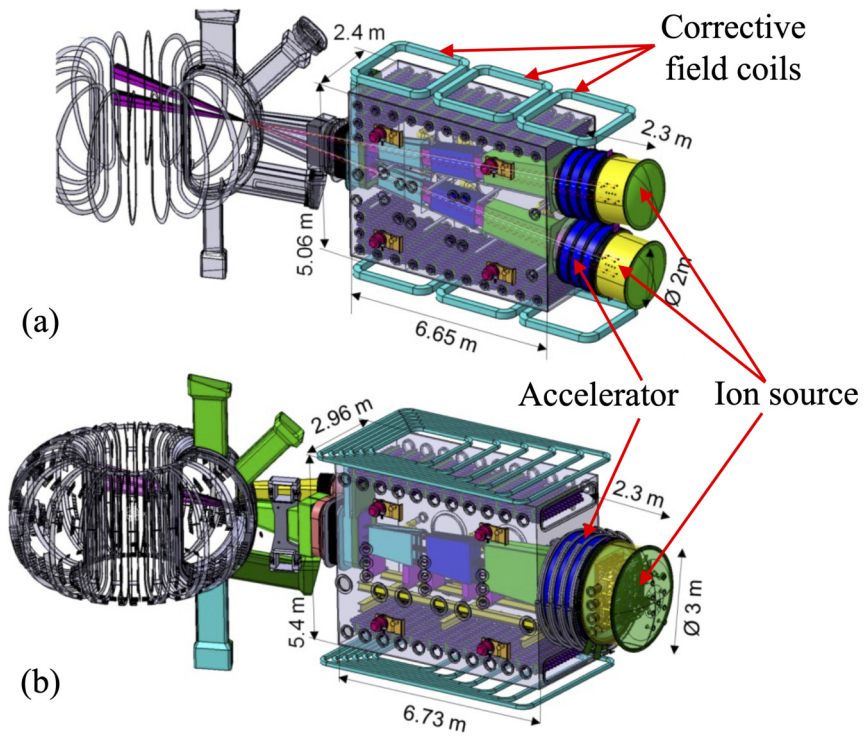


Figure 2.2: Overall view of the 500 keV DTT NBI: *double-source* (a) [40] and *single-source* solution (b) [41].

The overall 3D CAD view of the *single-source* solution is shown in Fig. 2.2(b).

The AGPS (Acceleration Grid Power Supply) is the core system providing the acceleration voltage of the acceleration grids. In this chapter the conceptualization of the AGPS system for the DTT N-NBI is described. Particular emphasis will be placed on the arrangement of the AGPS components into the current site of the ENEA Frascati Research center, starting from the double 400 keV N-NBI solution firstly proposed in [7]. In the following, the MITICA/ITER (or MITICA-like) AGPS briefly described in Section 1.3.1 is considered as reference solution also for the AGPS of DTT N-NBI.

The site constraints and engineering requirements, both from electrical and structural point of view led to the investigation of many layouts for the AGPS system, detailed in Section 2.1. Looking at the MITICA/ITER scheme, the geometrical dimensions of AGPS-CS and AGPS-DC generators, are extrapolated to perform a first estimation of the footprint of the high voltage components in the DTT site. Due to the recent improvement of the N-NBI system, from the double 400 keV to the single 500 keV solution, new layouts were investigated together with the feasibility of alternative HVDC concepts. The 500 keV solution based on the MITICA/ITER N-NBI scheme and the Modular Multilevel Converter (MMC)-based AGPS is depicted in Section 2.1.2. During the early construction phase and for maintenance reasons, the insulating gas used in the HVDC gas-insulated components must be removed and stored in pressurized tanks. An estimation of the whole amount of gas to be used in the system is mandatory to determine the impact of the storage area on the site. This is made in Section 2.1.3 for the 500 keV MITICA-like solution.

2.1 AGPS layout in the DTT site

In this section, the CAD drawings for the deployment of the AGPS components in the current site of the DTT experiment in Frascati, are reported. Referring to the CAD of the DTT site map shown in Fig. 2.3, the ISEPS (Ion Source and Extraction Power Supply) and the AGPS components are planned to be distributed in buildings 87 and 90. Photographs of parts of buildings 87 and 90 taken from the positions marked with  symbol in Fig. 2.3 are given in Fig. 2.4. The main issue of this engineering phase is the integration of the components accounting for both the site constraints and other engineering requirements. The most stringent constraints that guided the arrangement of the NBI power supply were:

- Guarantee access to building 89 through the ramp,

2.1. AGPS LAYOUT IN THE DTT SITE

- Guarantee the transit of vehicles along the new route highlighted in red in the site CAD Fig. 2.3,
- Consider possible needs coming from other system plants, for example ICRH power supply.

This Section is organized as follows: in 2.1.1, following the MITICA-like concept, the layout of the double 400 keV NBI solution is investigated. In 2.1.2 the single 500 keV NBI with two alternative approaches, namely the MITICA-like and the MMC-based are analyzed.

2.1.1 Double 400 keV solution

At the beginning of the engineering phase the DTT machine was planned to be equipped with two NBIs each one rated for an energy of 400 keV. This value represented a good compromise between dimensions, costs and performances [7]. In view of this the AGPS systems of 400 kV composed by two acceleration stages for the acceleration grids, each one of 200 kV, has to be defined. The power supply scheme for the 400 kV DTT N-NBI, based on the MITICA-like solution, is shown in Fig. 2.5. The electrical distribution of the power supply from the AGPS to the ion source inside the Tokamak hall is performed by the gas-insulated TL (Transmission Line). The TL of each NBI can be subdivided in three main sections:

- TL1: from the output of the DC-filter to a T-junction entering the HVD (High Voltage Deck) building,
- TL2: from the High Voltage Bushing (HVB) of the HVD to the Tokamak hall,
- TL3: the last part of the TL which terminates on the HVB inside the Tokamak hall, eventually equipped with a core snubber.

As can be guessed from the DTT map, the selection of the path to be followed by the TL has a lot of impact on the arrangement of the NBI power supply components, thus must be carefully addressed. For the sake of clarity, from now on, the new building hosting the DTT N-NBI AGPS is termed as building 190 (B190) to be built in place of the existing B90.

The first solutions proposed for the DTT N-NBI AGPS, also reported in [7], had to be reviewed since it presented several criticalities. Looking Fig. 2.6, a major problem arises from the path of the two gas-insulated TL. In the former solution, the TL2 originating from the HVB inside building 87 (B87) were supposed to underpass the concrete wall of the building. This

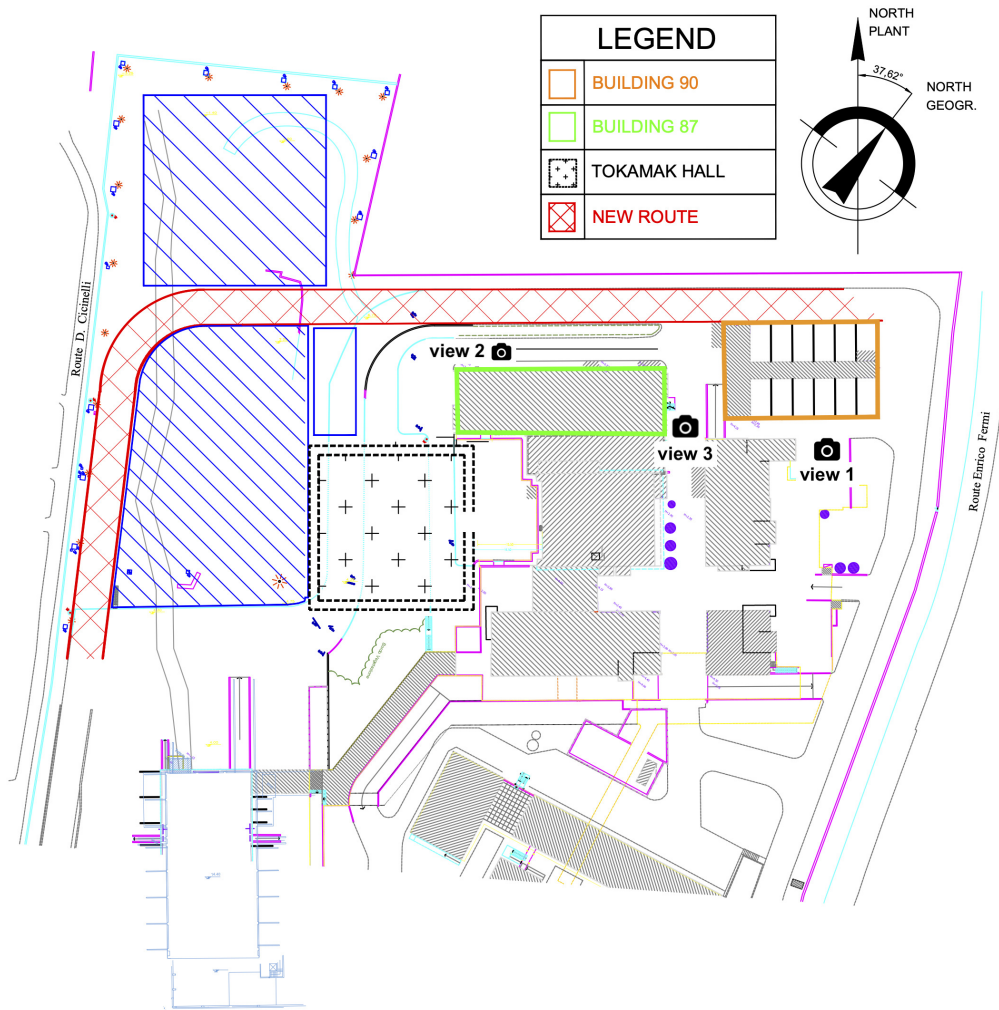


Figure 2.3: Overview of the DTT site map (scale 1:500). The legend highlights the position of buildings 87, 90 and the Tokamak hall.

2.1. AGPS LAYOUT IN THE DTT SITE



(a) View of building 90 from 📷 labeled “view 1” in Fig. 2.3.



(b) View of building 87 from 📷 labeled “view 2” in Fig. 2.3.



(c) View of ramp between building 87 and building 90 from 📷 labeled “view 3” in Fig. 2.3.

Figure 2.4: Photographs of parts of buildings 87 and 90 in the current DTT site.

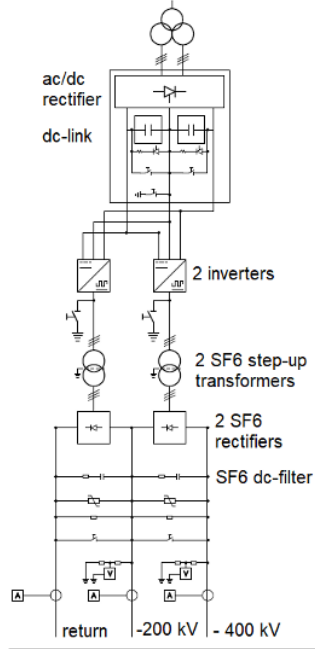


Figure 2.5: Electrical scheme of the 400 kV DTT N-NBI AGPS based on the MITICA-like solution from [7].

solution carries two main criticalities: firstly from the economical point of view, secondly, the structural modifications, for example for the excavation of the trenches below B87, may impact the structural and seismic stability of the building and thus should be avoided. All these problems prompted the need to define a new layout for the AGPS of DTT N-NBI.

The first alternative solution examined the feasibility of a completely external (to building 87) TL for each NBI, at the beginning excluding the constraint about the access to building 89 through the ramp. In this respect also the positioning of AGPS-CS and AGPS-DC generator components to be placed in B190 are redefined. In this solution, here termed as *solution 1*, whose CAD is shown in Fig. 2.7, the building 190 was slightly modified to comply with the space requirements of the AGPS systems, assuming as baseline design the same spatial dimensions of the components adopted in the MITICA test facility.

The two TL1 originating from the output of the DC-filters had to be buried to reduce the general impact, however, as given in Fig. 2.8 this solution reduced the usability of the road on the north of B87. For these reasons the alternative *solution 2*, for which the two TL1 would lay at the beginning on a bridge and then on a rack along B87, has been proposed. A photograph of the road and the north wall of B87 in which the rack is planned to be

2.1. AGPS LAYOUT IN THE DTT SITE

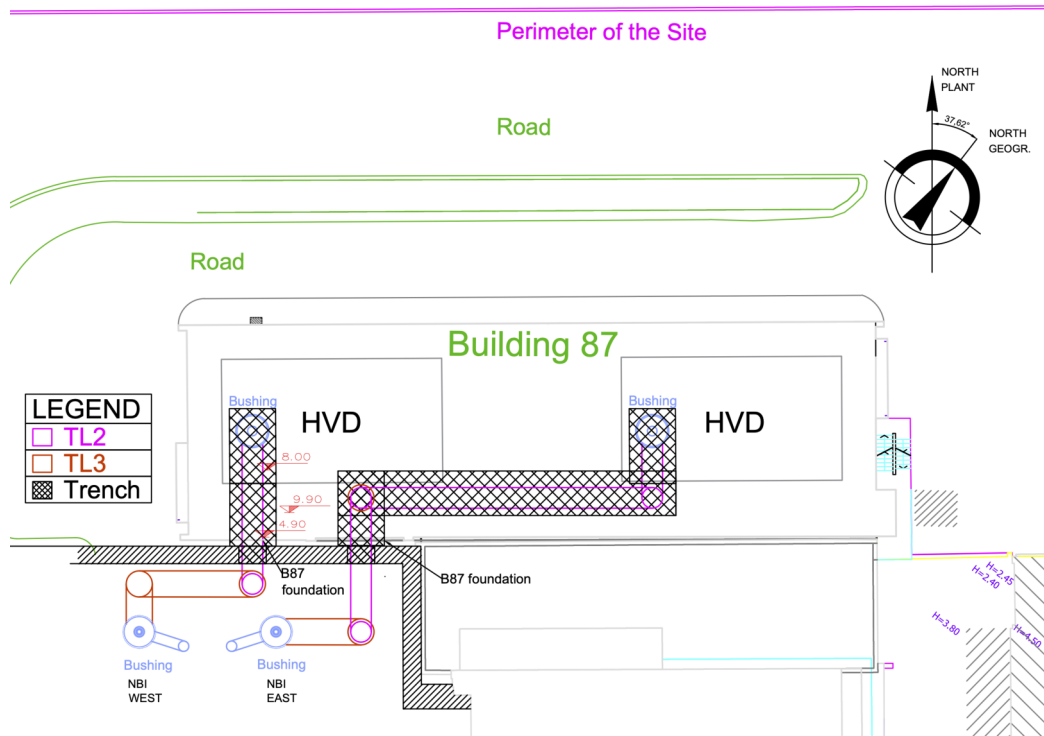


Figure 2.6: TL path for the first solution of DTT NBI AGPS. The need of realizing deep trenches going towards the Tokamak hall from below the foundations of B87, represented one of the major criticalities. The insulating transformers, not reported in the CAD, are placed on the north of B87, invading the road.

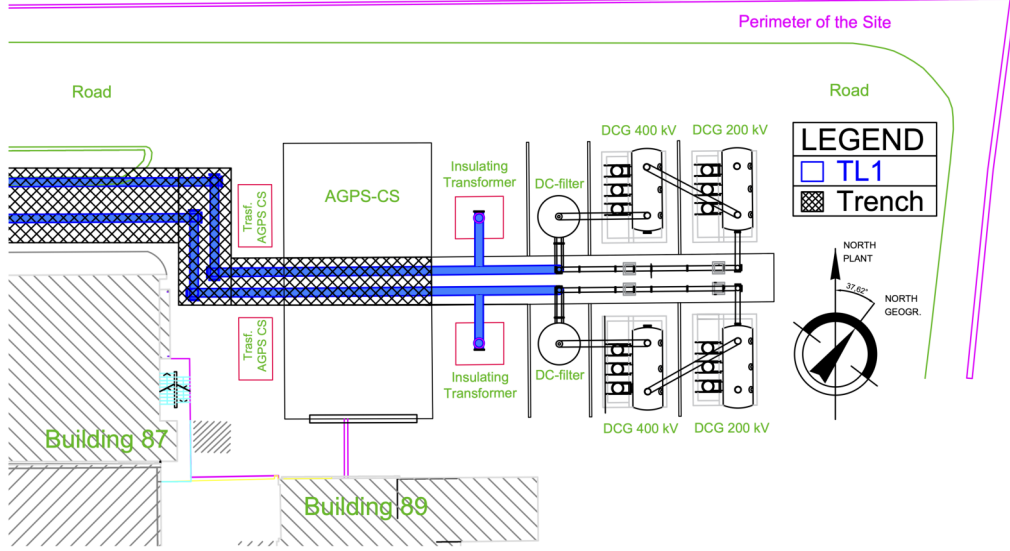


Figure 2.7: Mirror configuration of AGPS components in B190 for the *solution 1*. The trench where TL1 and TL2 run is also highlighted and, as can be seen, completely invades the road on the north of B87.

realized is given in Fig. 2.9. In this solution only the last part of TL2 and TL3 are placed in trench. The layout can be seen in Fig. 2.10, while the new disposal of the components in B190 is illustrated in Fig. 2.11. The trench is mandatory since the Tokamak hall basement is 5.6 m underground [39]. Both for *solution 1* and *solution 2*, the connection of the TL3 to the NBI is performed through an HVB which in addition to the main -400 kV output carrying all the ISEPS conductors, includes also the smaller bushing rated for -200 kV.

2.1.2 Single 500 keV solution

Even if the final mix is still under definition, the last proposal for the DTT N-NBI evaluates the possibility of realizing only one N-NBI, accelerating negative Deuterium ions with an energy of 500 keV. The increase in energy with respect to the 400 keV solution reported in [7], was conceived to achieve a suitable fast particle population in the Tokamak plasma. The realization of a single N-NBI opens up the possibility to investigative alternative solutions for the AGPS design, in particular, the feasibility of the Modular Multilevel Converter (MMC)-based technology is investigated as a possible alternative to the MITICA-like configuration. Moreover, the reduced space requirements of AGPS-CS and AGPS-DC generators in B190 and the free space left by the

2.1. AGPS LAYOUT IN THE DTT SITE

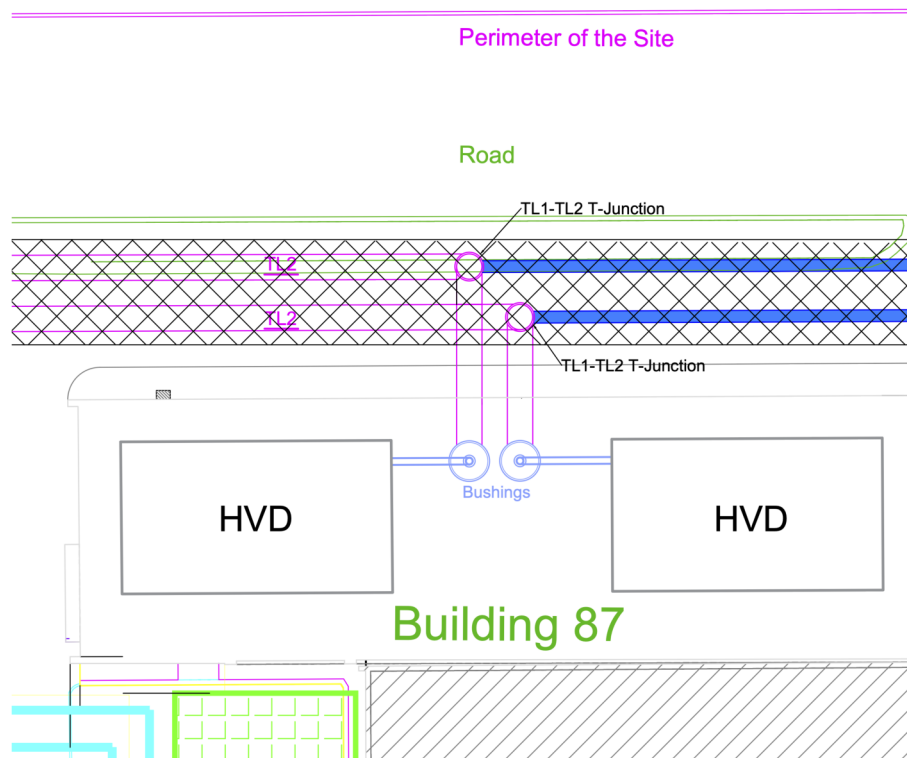


Figure 2.8: Overview of the T-junction between TL1 and TL2 in the North of B87. The TL2 originates from the HVB inside building 87.



Figure 2.9: Photograph of part of wall of building 87 in which the construction of the rack is planned.

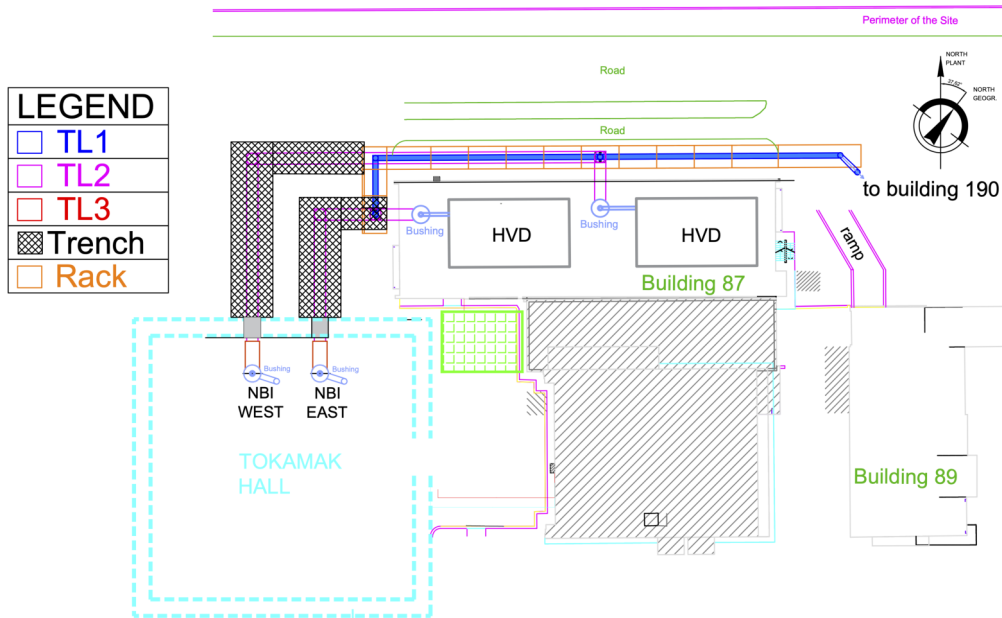


Figure 2.10: Overview of the rack along North wall of B87 for the *solution 2* and the path of TL1-TL2-TL3 sections.

2.1. AGPS LAYOUT IN THE DTT SITE

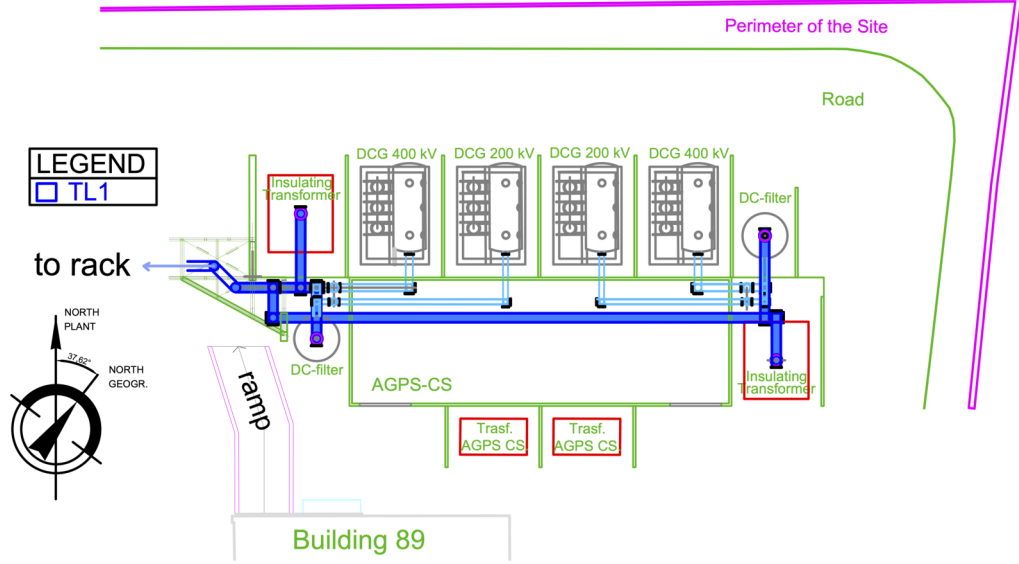


Figure 2.11: Top view of B190 for the *solution 2*. The TL1 originating from the North-East DC-filter runs on the roof of the AGPS-CS building, then the two TL1 are stacked one over each other over the rack.

second HVD in B87, opens up the possibility of placing therein the power supply of the ICRH system. In what follows, the 500 keV solution based on the previously discussed MITICA-like technology and the alternative MMC scheme, is described. The tentative ratings for the 500 kV AGPS solution for the DTT N-NBI are listed in Table 2.2 [39].

MITICA-like

In the same fashion of the previously discussed 400 keV solution based on the MITICA-like design, the AGPS for the 500 kV N-NBI can be conceived. The electrical scheme of the DTT N-NBI AGPS based on the MITICA-like solution is shown in Fig. 2.12. In this case, the N-NBI is equipped with three acceleration grids, each of 167 kV, thus the AGPS-DC generator system is composed by three DCGs (Direct Current Generators) connected in series, fed by the AGPS-CS system. The three electric potentials of -167 kV, -334 kV and -500 kV produced by the AGPS system are transferred to the accelerator inside the Tokamak hall by the multi-conductor TL which must be redesigned to account for the augmented operational voltage and conductors number. By looking at the layout illustrated in Fig. 2.13, a clear advantage of the single 500 keV solution is the less impact of the DCGs compartment, allowing the inclusion of ICRH power supply in the free space available in

Parameter	Value
Rated voltage	-500 kV
Number of acceleration stages	3 (-167 kV -167 kV -167 kV)
Voltage accuracy, referred to full voltage	$\pm 2\%$
Max voltage ripple, referred to set voltage	$\pm 5\%$, synchronous among stages
Max rise time of the output voltage	80 ms (to reach 90%)
Max voltage undershoot at beam on	15% (with 20 ms current ramp-up)
Voltage regulation range	$\sim 20\% \div 100\%$
Rated current	60 $\div$ 70 A
Duty cycle	50 s every hour
Switch-off delay in case of grid breakdown	$\sim$ tens of μ s
Maximum charge transferred to the arc	250 mC
Maximum number of breakdowns in a pulse	50, also consecutive
Time to be ready for restart after a breakdown	20 ms
Input voltage	20 kV $\pm 10\%$, 50 Hz

Table 2.2: Tentative ratings for the 500 kV AGPS of DTT NBI [39].

B190.

MMC-based

The Modular Multilevel Converter (MMC) technology has attracted attention due to its intrinsic properties of modularity, scalability and controllability. Despite this technology is more and more widely used for commercial HVDC systems, has been never considered for the realization of the AGPS for NBIs. The scheme of MMC-based AGPS for DTT N-NBI, shown in Fig. 2.14, foresees three Insulating Transformers connected to the medium voltage grid and feeding a 3-phase HV rectifier each, arranged in air-insulated towers. Each rectifier supplies an acceleration step through the TL and HVB. The arm of each MMC rectifier is formed by tens of Sub-Modules (SM) connected in series to an inductor to smooth the AC current ripple and to limit the overcurrent at grid breakdown [39].

Looking at the preliminary layout of Fig. 2.15, a major advantage of this solution is the short length of the gas-insulated TL (about 20 m), since it is formed only by TL2 and TL3 sections, with the TL2 originating near the Tokamak hall as output of the HV Bushing placed next to the B87. The reduction of the length reflects in less use of SF₆ insulating gas, thus reducing the potential environmental risk. However, a major drawback of MMC technology is the larger volume occupied by the high voltage components, since most of them are air-insulated. Investigations on the applicability of MMC-based solution for the AGPS of DTT are ongoing, possibly by using

2.1. AGPS LAYOUT IN THE DTT SITE

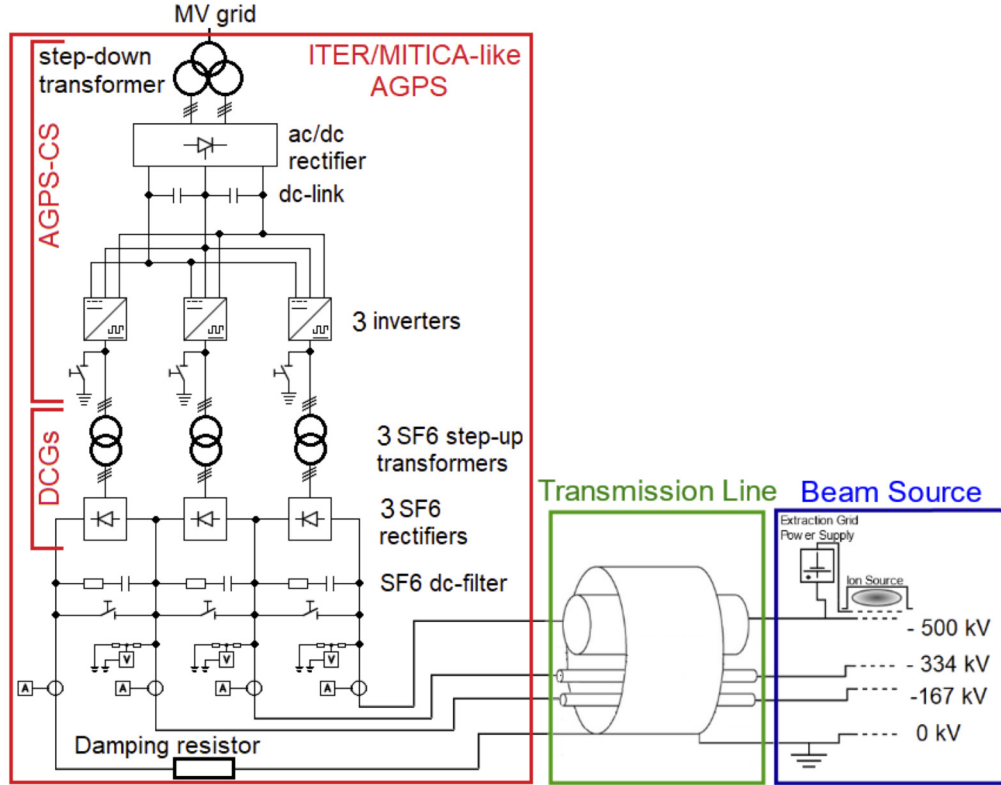


Figure 2.12: MITICA-like electrical scheme for the 500 kV AGPS of DTT NBI.

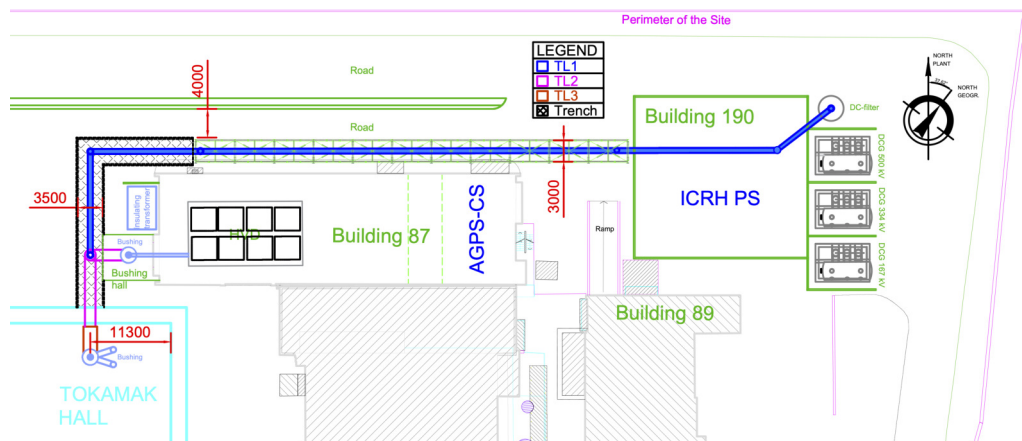


Figure 2.13: Preliminary layout of the DTT AGPS based on the MITICA-like solution.

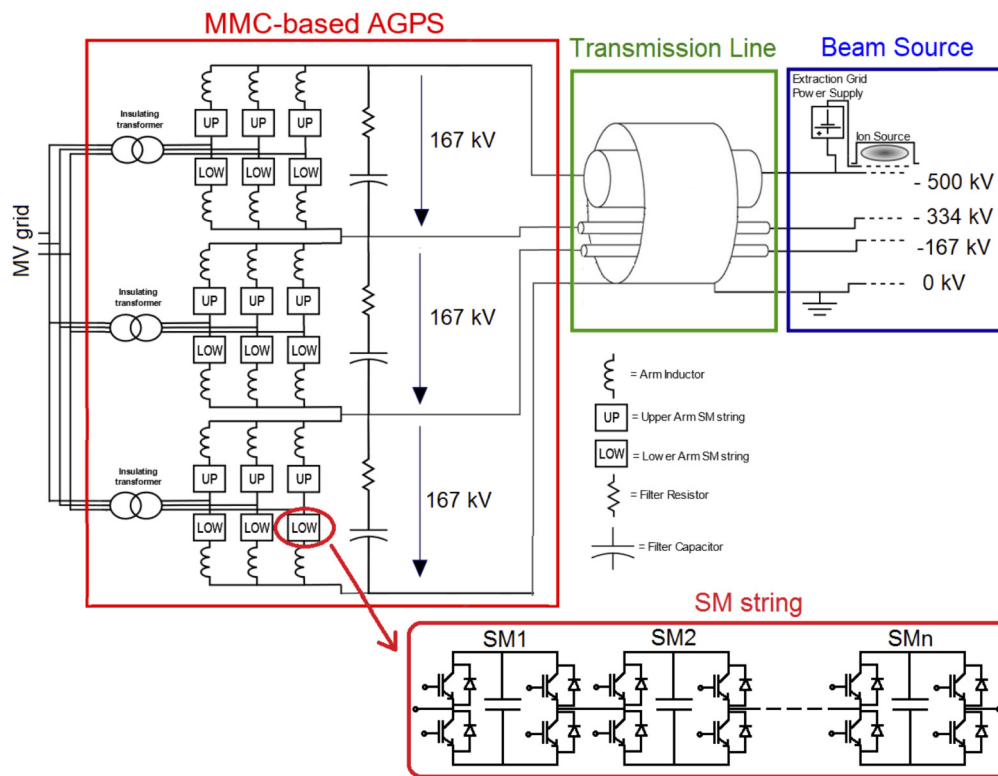


Figure 2.14: MMC-based electrical scheme for the 500 kV AGPS of DTT NBI.

2.1. AGPS LAYOUT IN THE DTT SITE

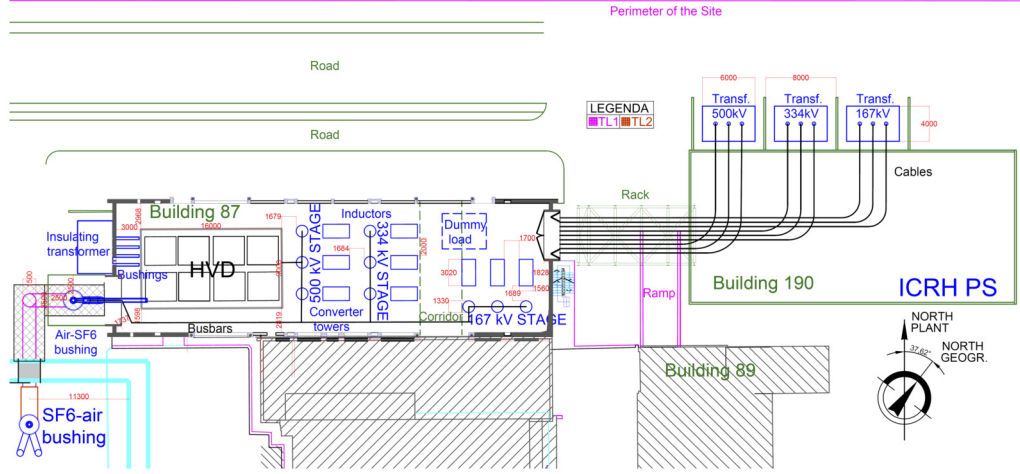


Figure 2.15: Preliminary layout of the DTT AGPS based on the MMC technology. The three Insulating Transformers feeding the MMC conversion towers placed inside building 87, by using HV cables, are located in the new B190. The acceleration voltages and the ISEPS are transferred from the HVB inside B87 to the Tokamak hall by the TL, which in this case is composed only by TL1 (from the air-SF₆ bushing hall) and TL2 (inside the Tokamak hall) sections.

the Hybrid Symmetric (HS)-MMC configuration [42].

Recently the possibility of placing the air-insulated MMC converters in a new building far away from the Tokamak hall is under evaluation [43]. To this aim, the connection from the AGPS to the loads will be performed with HVDC cables. This possibility is taken into account as the layout presented in Fig. 2.15 underestimates by a factor of about 3 the footprint required by the MMC converters (including electrostatic screens, maintenance constraints and so on), thus resulting unfeasible.

For the conceptual design of the AGPS of DEMO however, this technology is of particular interest and further investigations are underway [44, 45].

2.1.3 Gas handling and storage plant

During the early operational phases and plant maintenance the insulating gas employed in the HVDC gas-insulated components of the AGPS needs to be removed and stored in pressurized tanks in liquid form. The movement and storage of the gas is provided by the so-called *Gas Handling and Storage Plant*. In this section the dimensioning of the storage tanks is inves-

tigated referring to the MITICA-like 500 keV N-NBI solution described in Section 2.1.2. The gas system is generally subdivided in many compartments between which the gas can flow freely under normal operating conditions. For the 500 kV MITICA-like solution the following gas compartments are defined:

1. 500 kV DCG,
2. 334 kV DCG,
3. 167 kV DCG,
4. DC-filter,
5. TL1,
6. TL2,
7. TL3,
8. HVB inside B87,
9. HVB inside Tokamak hall.

For the TL1 originating from the DC-filter, a radius of 350 mm is used, while for TL2 and TL3 parts the radius is 650 mm. These value were scaled from that of MITICA 1 MV transmission line. The length of TL1, TL2 and TL3 are respectively 130 m, 13.6 m and 4.6 m. The high voltage bushings inside Tokamak hall and HVD hall are assumed equal for simplicity with a volume of $\approx 11 \text{ m}^3$. Assuming the SF_6 gas at a pressure of 0.5 MPa absolute and extrapolating the geometrical dimensions of the components from the CAD of Fig. 2.13, the volume $[\text{m}^3]$ and mass [tons] of gas for each compartment can be estimated. Here the pressure of 0.5 MPa, lower than that of 0.6 MPa used in MITICA HVDC gas-insulated components is chosen in view of the reduced voltage level of the power rating for DTT NBI. The results are reported in Table 2.3, from which by summing up each value, a total of $\approx 255 \text{ m}^3$ and 8.18 tons of gas are used in the investigated solution. The storage system consisting of pressurized tanks, an high pressure pipeline and the monitoring systems must be able to store the entire amount of gas at the same time. To do so, the gas pressure is increased until a phase change to the fluid state occur. By considering a pressure of 30 bar at 298.15 K the density is about $\rho_l = 1.42 \cdot 10^3 \text{ kg/m}^3$ ¹, thus the liquid volume of SF_6 can be retrieved:

$$v_{\text{SF}_6 \text{ liquid}} = \frac{m}{\rho_l} = \frac{9.25 \cdot 10^3}{1.42 \cdot 10^3} = 5.7 \cdot 10^3 \text{ l.} \quad (2.1)$$

¹The value can be retrieved by looking at the data reported in <https://webbook.nist.gov/cgi/cbook.cgi?ID=C2551624&Mask=4>.

2.2. CONCLUSIONS

Compartment	Volume [m ³]	Mass [tons]
1	34	1.08
2	34	1.08
3	34	1.08
4	56	1.86
5	50	1.60
6	18	0.57
7	5.7	0.18
8	11	0.35
9	11	0.35

Table 2.3: Volume and mass of SF₆ gas @ 0.5 MPa, to be used in the 500 kV MITICA-like solution for the DTT AGPS. The HVB inside B87 and Tokamak hall are assumed equal in this analysis.

By using the same tanks employed in the MITICA test facility, rated for 50 bar and 5840 l of storage capacity, an equivalent number of tanks can be estimated for the DTT case. Assuming to fill the tanks at 85% capacity, the number of tank are:

$$N_{tanks} = \left\lceil \frac{v_{SF_6 liquid}}{0.85 \times 5840} \right\rceil = 2, \quad (2.2)$$

moreover for safety reasons an empty tank must always be ensured, that is, the number of tanks is increased by one unity. Thus a total of 3 tanks must be placed in the DTT site if the MITICA-like solution is followed. Referring again to the tanks used in MITICA, their external dimensions are 4.52 m (L) $\times$ 1.4 m (W) $\times$ 2.135 m (H), thus the storage area reported in Fig. 2.16 can be conceived.

2.2 Conclusions

In this chapter the preliminary activities for the definition of the AGPS footprint in the ENEA research center that will host the DTT experiment were described. Throughout the chapter different CAD solutions proposed by the RFX team, of which the author of the thesis is part, in collaboration with the buildings team of DTT, were analyzed. The outcomes of that activity is of fundamental importance for the definition of the buildings layout. Despite the contents of the chapter are manly related to civil engineering tasks, it acts as a trigger to the topics that will be described in the remainder of the

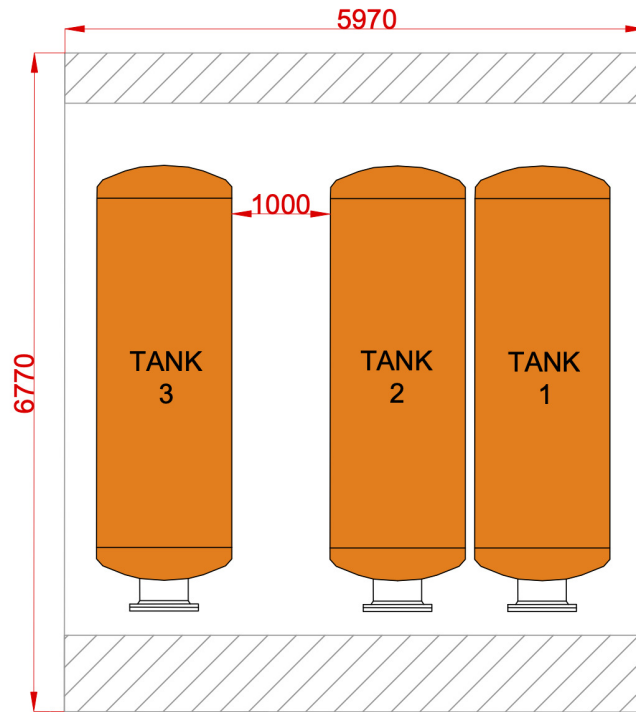


Figure 2.16: Gas storage area conceived for the 500 kV MITICA-like solution. The tanks dimensions are retrieved from the MITICA experiment.

2.2. CONCLUSIONS

thesis. Indeed a realistic definition of the footprint of gas-insulated components, such as the TL and the SF₆-air bushing must follow an electromagnetic analysis, whose purpose is to verify the voltage holding capability of a proposed solution. The tools that will be used to perform such analysis will be described in the next chapters, required a lot of effort and research during the Ph.D. course, and represent the core of the thesis.

3

Insulating gases and solid materials

IN THIS CHAPTER the dielectric materials used in the HVDC (High Voltage Direct Current) gas-insulated equipments are described. In gas-insulated high voltage components two types of dielectrics are used, namely the gases and materials. Referring to the standard HVDC Gas Insulated Line (GIL) illustrated in Fig. 3.1, the solid insulating materials are usually subdivided in post-insulators and disk-shaped insulators. The post-insulators are used for structural reasons, to support the central conductor along the gas-insulated line, while the disk-shaped insulators, typically with a conical shape, can be gas tight or non-gas tight, where the former are used to separate gas compartments [46].

In HVDC gas-insulated system, the volume between the inner high voltage conductor and the outer grounded shell, is filled with pressurized gas. The pressurized gas has the task of ensuring high dielectric strength of the systems possibly avoiding partial discharges. The choice of gas type and its operational pressure has great impact in the overall layout of the HVDC gas-insulated system. Referring again to the gas-insulated line of Fig. 3.1, this reflects in an increased (decreased) distance between central conductor and grounded shell, thus an augmented (reduced) cross section of the line. As stated in Chapter 2, the deployment of HVDC components, such as the -500 kV TL (Transmission Line), has great impact in the site. Moreover, this impact has to be measured starting from a rough estimation of the dimensions. In addition to manufacturing constraints, the dimensioning of HVDC gas-

3.1. DIELECTRIC GASES

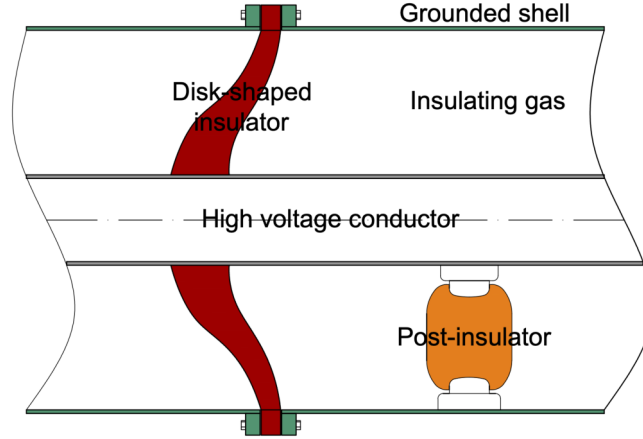


Figure 3.1: 2D view of coaxial gas-insulated line with post-insulator and gas tight disk-shaped (conical) insulator.

insulated systems depends on the dielectric materials selected. As explained in what follows, the latter aspect has enormous impact on the reliability and durability of the plants.

In Section 3.1 the common dielectric gases used in HVDC gas-insulated equipments are summarized, together with a brief discussion regarding the future trends. In Section 3.2 the dielectric materials for the solid insulating parts are described, with a particular focus on the mathematical modeling of their electromagnetic properties.

3.1 Dielectric gases

At the beginning of the applications in the context of high voltage gas-insulated systems, air was used as dielectric gas. This choice represented the cheapest and most eco-sustainable solution. However, the increase in voltages and the possibility of making systems more compact has pushed research towards more complex but more efficient insulating gases. The task of ensuring high dielectric capabilities and at the same time reducing the overall space impact of the HVDC gas-insulated equipments, was efficiently solved since the 1960s by using pressurized Sulfur hexafluoride (SF_6). Due to its high Global Warming Potential (GWP), in the 1997 SF_6 became part of the Kyoto Protocol as one of the greenhouse gases, which requires that its usage is restricted in the coming years. This need pushed towards the research of alternative eco-friendly solutions, which are currently under evaluation.

Different metrics can be used to compare the performances of insulating

gases. Among all of them in the context of the electromagnetic modeling of HVDC gas-insulated equipments, the dielectric performances of the gas and its environmental impact are considered. The former is usually described using the so-called *effective ionization coefficient* $\bar{\alpha} = \bar{\alpha}(E/P)$ [1/m], difference between the ionization and attachment coefficients, which is a function of the ratio between the electric field strength E and the gas pressure P . The critical field strength driving to gas breakdown is denoted with $(E/P)_0$ and correspond to the value for which $\bar{\alpha} = 0$. A detailed explanation of the evaluation of $\bar{\alpha}$ for a given gas is reported in Section 4.4.

The environmental impact does not affect the electromagnetic analysis but is a fundamental aspect to be considered for the future development of the gas-insulated systems. In this respect, the definition of the GWP for a given gas or mixture of gases is outlined. The GWP as stated in the USA Environmental Protection Agency, is defined as: “*a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO₂)*”. A mathematical definition of GWP can be found in the report of the Intergovernmental Panel on Climate Change (IPCC), by time-integrating the Radiative Forcing (RF) over an Integration Time Horizon (ITH) of 100 years [47]:

$$GWP_i = \frac{\int_0^{ITH} RF_i(t)dt}{\int_0^{ITH} RF_{CO_2}(t)dt}, \quad (3.1)$$

where RF_i is the radiative forcing of the compound and RF_{CO_2} the one relative to CO₂. Regarding the gas mixtures, the GWP of the ensemble is calculated directly by the GWP of its compounds as [48]:

$$GWP_{mix} = \sum_i x_i GWP_i, \quad (3.2)$$

in which x_i is the fraction of i th compound and GWP_i its global warming potential. In the subsequent discussion the GWP is used as a metric to compare the environmental impact of the different insulating gases.

During standard operational conditions of an HVDC gas-insulated system, positive and negative ions can be generate in the gas, for example due to natural ionization. These ionized molecules moves under the electric force in the system and in turn modify the electric field map. Therefore, when operating a gas-insulated system the knowledge of the gas parameters as a function of the operational settings is of key importance. Thus, for a complete description of the gas from the electrical point of view, the knowledge of mobility, recombination, ion-pair generation and diffusion coefficients is required.

3.1.1 Sulphur hexafluoride

The Sulphur hexafluoride molecule, whose chemical formula is SF_6 , was designed in 1920s for chemical purposes and due to its excellent dielectric, chemical and physical properties was extensively used since 1960 as insulating gas in many HVDC systems, such as: Gas Insulated Switchgear (GIS) [49], Gas Circuit Breakers (GCB) [50] and Gas Insulated Transmission Lines (GIL) [51]. SF_6 gas represent the state-of-art for the design of nuclear fusion HVDC gas-insulated components such as TL, DC-filter and SF_6 -insulated diodes [31, 32, 52].

The high dielectric capabilities of SF_6 molecule, about 2.5 times higher than air, is due to its high electron affinity (electronegativity) χ . The electronegativity is the capability of the gas to capturing free moving electrons and forming heavy negative ions with low mobility, thus reducing the probability of gas discharge [53]. Sulphur hexafluoride behaves as a perfect gas following the Beattie-Bridgman equation of state [54]:

$$P = 56.2 \cdot 10^{-6} \rho T (1 + B) - \rho^2 A, \quad (3.3)$$

with:

$$A = 7.49 \cdot 10^{-5} (1 - 0.727 \cdot 10^{-3} \rho), \quad (3.4)$$

$$B = 2.51 \cdot 10^{-3} \rho (1 - 0.846 \cdot 10^{-3} \rho), \quad (3.5)$$

where P is the pressure, T the temperature and ρ the gas density [kg/m^3]. As an example, from the expression (3.3) the density at $P = 0.5$ MPa and $T = 293.15$ K is $32.4 \text{ kg}/\text{m}^3$ ¹.

The numerical investigation of the insulating gas for electromagnetic purposes, requires the specification of the electrical conductivity σ_G [S/m] and eventually the transport parameters such as the ion mobilities μ^+, μ^- if a charge-oriented approach is used. Historically, the SF_6 electrical conductivity ranging between $10^{-16} - 10^{-20} \text{ S}/\text{m}$, neglecting any pressure, temperature and electric field dependence, was adopted [35]. Recently, attempts were made in finding an analytical expression for the electrical conductivity in pressurized SF_6 , with the capability of accounting both for the temperature T and pressure P [kPa] effects in low electric field (less than $\approx 12 \text{ kV}/\text{mm}$) conditions [55]:

$$\sigma_{G,\text{SF}_6}(T, P) = \sigma_{G0,\text{SF}_6} \exp\left(-\frac{W_a}{k_B T}\right) \frac{P_0}{P}, \quad (3.6)$$

¹Some SF_6 parameters can be retrieved from the online APP provided by DILO® at <https://dilo.eu/en/sf6-gas/dilo-sf6-apps>.

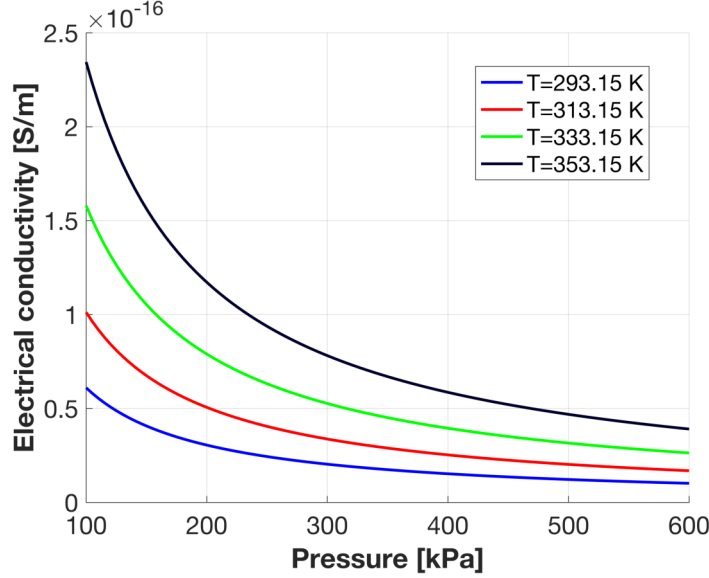


Figure 3.2: Electrical conductivity of SF_6 with pressures ranging from 100 kPa to 600 kPa and varying temperature values, using expression (3.6).

where $\sigma_{G0, \text{SF}_6} = 1.658 \cdot 10^{-13} \text{ S/m}$, $W_a = 0.2 \text{ eV}$ and $P_0 = 101.325 \text{ kPa}$. With this expression the electrical conductivity values for SF_6 pressures ranging from 100 kPa to 600 kPa and $T \in [293.15, 313.15, 333.15, 353.15] \text{ K}$ are depicted in Fig. 3.2.

Due to the presence of both positive and negative free ions in normal operational conditions, and negligible free electrons because of the high SF_6 electronegativity, the mobilities $\mu^+, \mu^- [\text{m}^2/(\text{V}\cdot\text{s})]$ have to be specified. Usually these quantities are function of pressure, temperature and electric field [56]. In [56] the ion mobilities μ^+ and μ^- are given as a function of the reduced electric field E/N in Townsend units [Td], where $N [1/\text{m}^3]$ is the gas number density. Their functional dependence is expressed as:

$$\mu^\pm(P, T, E/N) = \mu_0^\pm(E/N) \frac{P_0}{P} \frac{T}{T_0}, \quad (3.7)$$

where $T_0 = 273.16 \text{ K}$ with:

$$\mu_0^+(E/N) = \begin{cases} 6 \cdot 10^{-5} & \frac{E}{N} < 120 \text{ Td} \\ 1.216 \cdot 10^{-5} \ln(E/N) + 5.89 \cdot 10^{-5} & 120 \leq \frac{E}{N} < 350 \text{ Td} \\ -1.897 \cdot 10^{-5} \ln(E/N) - 7.346 \cdot 10^{-4} & \frac{E}{N} \geq 350 \text{ Td} \end{cases} \quad (3.8)$$

and

$$\mu_0^-(E/N) = 1.69 \cdot 10^{32} (E/N)^2 + 5.3 \cdot 10^{-5} \quad \frac{E}{N} < 500 \text{ Td} . \quad (3.9)$$

3.1. DIELECTRIC GASES

Parameter	0.1 MPa	0.5 MPa
μ^+, μ^- [$\text{m}^2/(\text{V}\cdot\text{s})$]	$3.6\cdot 10^{-5}$	$4.8\cdot 10^{-6}$
R [m^3/s]	$2.27\cdot 10^{-13}$	$1.7\cdot 10^{-12}$
S [$1/(\text{m}^3\cdot\text{s})$]	$1\cdot 10^7$	$2.9\cdot 10^7$

Table 3.1: Summary of SF_6 ion transport coefficients for 0.1 MPa and 0.5 MPa.

By assuming equal mobility for positive and negative ions, the functional dependence with respect to the operating pressure P is usually expressed as [57]:

$$\mu^\pm \propto P^{-1.25}. \quad (3.10)$$

The free moving ions can join together with a specific rate given by the recombination coefficient R [m^3/s]. As suggested in [57], the recombination rate can be derived from the mobilities by using the Langevin formula:

$$R = \frac{e}{\varepsilon_0 \varepsilon_r} (\mu^+ + \mu^-), \quad (3.11)$$

where ε_0 is the vacuum permittivity and ε_r the relative permittivity of the gas, equal to 1.002 for SF_6 . Alternative expressions for the recombination coefficient accounting for the temperature variation are listed in literature [56] and a comparison between them is reported in Fig. 3.3. Newly free gas ions are generated with a rate given by the ion-pair generation rate S [$1/(\text{m}^3\cdot\text{s})$] (or $\partial n_{IP}/\partial t$). As will be explained in Section 4.5 the generation rate depends on the environmental conditions, such as the location where the HVDC gas-insulated systems is planned to be placed. In standard conditions an expression accounting for the gas pressure effect can be expressed using an approximation function, for example following the measurements reported in [58]. The trend of $S = S(P)$ for such conditions is given in Fig. 3.4 together with standard values usually adopted for $P = 0.1$ MPa and $P = 0.5$ MPa. For the positive and negative ions diffusion coefficients D^+ and D^- [m^2/s], the Einstein relation is usually adopted [59]:

$$D^\pm = \mu^\pm \frac{k_B T}{e}, \quad (3.12)$$

where k_B is the Boltzmann constant. A summary of SF_6 ion parameters for $P = 0.1$ MPa and $P = 0.5$ MPa are listed in Table 3.1.

When dealing with thermal analysis of HVDC gas-insulated equipments, the temperature dependence of the parameters has to be specified. Expression (3.3) relates the gas density ρ with temperature and pressure in the

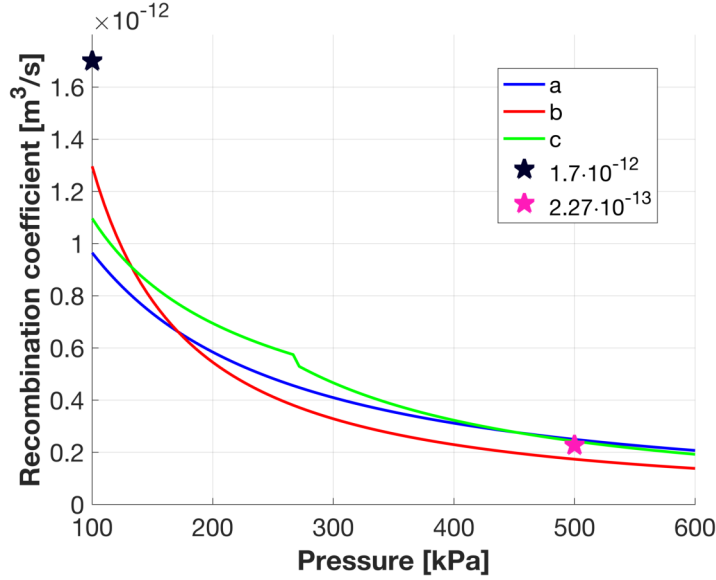


Figure 3.3: Recombination coefficient R as a function of gas pressure P using an approximation function (a), [57] (b), [56] (c), together with its typical value at 100 kPa [58] and 500 kPa [60].

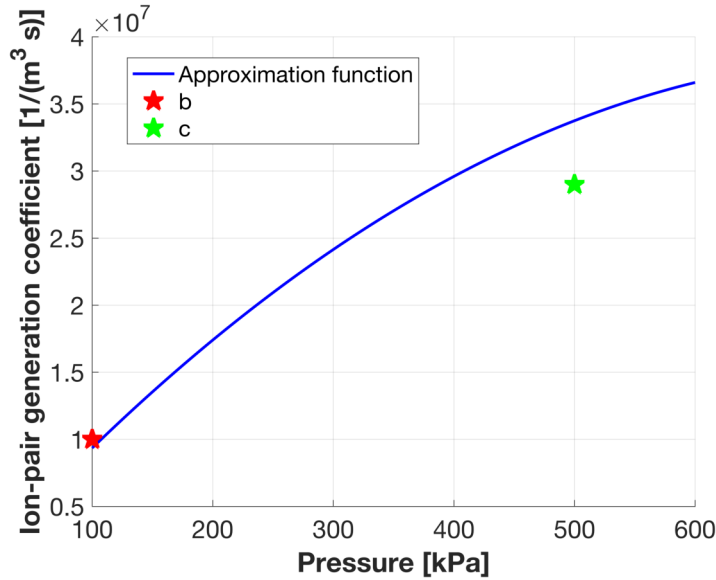


Figure 3.4: Ion-pair generation coefficient S as a function of gas pressure P using an approximation function, together with its typical value at 100 kPa [58] and 500 kPa [60].

3.1. DIELECTRIC GASES

general case, however, in literature, SF₆ density is usually retrieved from the classical ideal gas law [61, 62]:

$$\rho = \frac{PM_{SF_6}}{RT} \quad (3.13)$$

where $R_{gas} = 8.314 \text{ J}/(\text{mol}\cdot\text{K})$ is the gas constant. Using this expression at $P = 0.5 \text{ MPa}$ and $T = 293.15 \text{ K}$, $\rho = 29.96 \text{ kg}/\text{m}^3$, with a relative error of $\approx 7.5\%$ with respect to the value predicted by Eq. (3.3), which is in most cases acceptable. The thermal conductivity of the gas $k \text{ [W}/(\text{m}\cdot\text{K})]$ usually is a function of the temperature itself and can be described, for example, by means of the Sutherland's law [61]:

$$k(T) = k_0 \left(\frac{T}{T_0} \right)^{1.5} \frac{T_0 + S_c}{T + S_c}, \quad (3.14)$$

where k_0 is the reference value for the thermal conductivity at the reference temperature T_0 and $S_c = 110.56 \text{ K}$ the Sutherland constant. By the way, in literature alternative expressions are proposed, for example in [55] the polynomial expression:

$$k(T) = A + BT + CT^2, \quad (3.15)$$

is used, with the values of the constants A, B and C respectively of $-9.51 \cdot 10^{-3} \text{ W}/(\text{m}\cdot\text{K})$, $0.08657 \cdot 10^{-3} \text{ W}/(\text{m}\cdot\text{K}^2)$ and $-0.03186 \cdot 10^{-6} \text{ W}/(\text{m}\cdot\text{K}^3)$. A graphical comparison of expression (3.14) and (3.15) for SF₆ gas is given in Fig. 3.5.

Even the dynamic viscosity of the gas $\eta \text{ [Pa}\cdot\text{s]}$, required for fluid-dynamics investigations, can be expressed using the Sutherland's law:

$$\eta(T) = \eta_0 \left(\frac{T}{T_0} \right)^{1.5} \frac{T_0 + S_c}{T + S_c}, \quad (3.16)$$

where $\eta_0 = 1.42 \cdot 10^{-5} \text{ Pa}\cdot\text{s}$. The heat capacity at constant pressure $C_p \text{ [J}/(\text{kg}\cdot\text{K})]$ of SF₆ is usually kept constant and equal to $C_{p,SF_6} = 665.18 \text{ J}/(\text{kg}\cdot\text{K})$, or given as a function of T as [63]:

$$C_{p,SF_6}(T) = 0.02065 + 1.9 \cdot 10^{-7}T^2 - 9.05 \cdot 10^{-5}T^5. \quad (3.17)$$

A summary of the properties of SF₆ gas for the purposes of the present work are reported in Table 3.2.

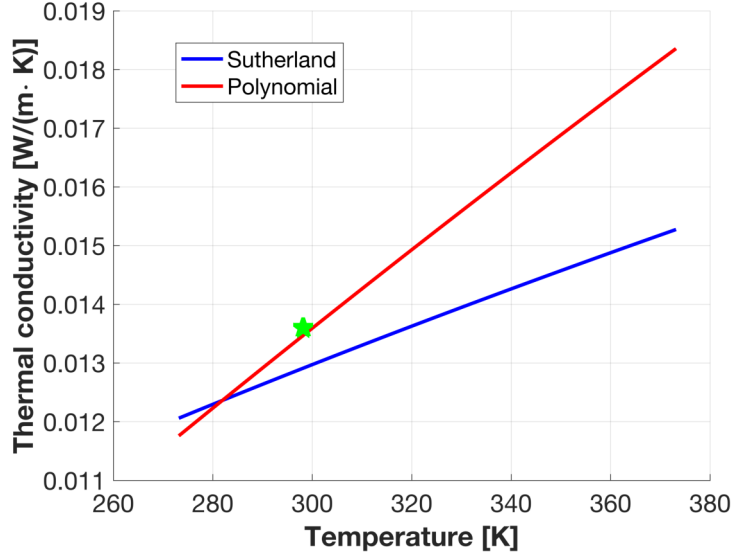


Figure 3.5: Thermal conductivity of SF_6 from Sutherland law (3.14) and expression (3.15). For the Sutherland law $k_0 = 0.01206 \text{ W/(m}\cdot\text{K)}$ at $T_0 = 273.15 \text{ K}$ and 1 atm [61]. The green star denotes the standard value $k = 0.0136 \text{ W/(m}\cdot\text{K)}$ usually adopted at $T = 298.15 \text{ K}$ and 1 atm [53].

3.1.2 Alternative insulating gases

Despite its excellent dielectric properties SF_6 is listed in the Kyoto protocol because of its high GWP, about 23000 among the dangerous greenhouse gases CO_2 at ITH=100 years. The need to replace SF_6 gas for the future development of HVDC-GIS equipments, has prompted the search for alternative eco-friendly solutions.

The simple solution fall on natural gases, for example dry air, N_2 and CO_2 which have relative dielectric strength with respect to SF_6 respectively of $0.37 \div 0.40$, $0.34 \div 0.43$ and $0.32 \div 0.37$ [64]. Despite these gases are easily to handle, to achieve the same performances of SF_6 , they require a higher operational pressure or the size of components to be increased, according to Paschen's law [65]. For example for pure CO_2 gas, breakdown properties comparable to that of SF_6 are achieved for pressures of $1 \div 1.5 \text{ MPa}$, thus suggesting that CO_2 is better suited for medium voltage equipments [66].

Starting from 1970s, firstly for economical reason, research activities in mixing SF_6 with N_2 were initiated in the context of GILs [51, 67]. This solution not only reduce the economical impact of the system, but even the environmental one due to the reduced amount of SF_6 introduced in the line. Usually, mixtures of 80% N_2 and 20% SF_6 are considered [68]. The amount

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Parameter	Value
Molar mass M_{SF_6}	146.06 g/mol
Density (@ 298.15 K, 1 atm)	6.04 kg/m ³
Thermal conductivity (@ 298.15 K, 1 atm)	0.0136 W/(m·K)
Heat capacity	665.18 J/(kg·K)
Dynamic viscosity (@ 298.15 K, 1 atm)	1.42·10 ⁻⁵ Pa·s
Boiling point (sublimation point)	-63.9°C
Vapor pressure	2372 kPa
Critical electric field $(E/P)_0$	89 kV/(mm·MPa)

Table 3.2: Summary of SF₆ gas properties.

SF ₆ (%)	$(E/P)_0$ [kV/(mm·MPa)]
100	88.6
73.1	85.1
50	79
25	68.1
20	65.2
15	61.5
10	57
5	50.6

Table 3.3: Critical field $(E/P)_0$ function of the SF₆ percentage in the SF₆/N₂ mix [68].

of SF₆ to be used in the mix is a compromise solution between economical, environmental and dielectric capabilities. In fact, the critical field $(E/P)_0$ is lowered by reducing the SF₆ percentage content, as reported in Table 3.3 [68]. By using only 20% of SF₆ the dielectric properties are 70% of that of pure SF₆, therefore, the pressure has to be increased up to 0.7 MPa to reach the same performance of the pure SF₆ gas [67]. Clearly, SF₆/N₂ mixtures does not completely resolve the environmental issue due to the SF₆ content.

Experiments were made in comparing the performances of SF₆/N₂ mixtures to that of N₂/O₂ mixtures by changing the ratio of O₂ content for example to 20%, 40% and 60% [69]. From the measurements, good agreements between dielectric performances are achieved between N₂(60%)/O₂(40%) and SF₆(10%)/N₂(90%) [69].

In searching alternative insulating gases, some fundamental features have to be satisfied by the compound [64]:

CHAPTER 3. INSULATING GASES AND SOLID MATERIALS

Gas	(E/N) ₀ [Td]	GWP	Boiling point [°C]	Molar mass [g/mol]
SF ₆	360 [73]	23900	-63.9	146.06
N ₂	60 [73]	0	-195.8	28.02
CO ₂	86 [73]	1	-78.5	44.01
N ₂ (60%)/O ₂ (40%)	136.7 [74]	0.4	–	–
SF ₆ (20%)/N ₂ (80%)	260	4780	–	–
NOVEC TM 4710	981 [75]	2100	-4.7	195
NOVEC TM 4710(20%)/CO ₂ (80%)	362.81 [75]	421	–	–
CF ₃ I	437 [64]	0.45 [76]	-22.5	195.91

Table 3.4: Properties of dielectric gases for HVDC gas-insulated equipments.

- Capability of capturing free electrons, thus high electronegativity χ ,
- High thermal conductivity and specific heat,
- High vapour pressure (low boiling point),
- Compatibility with conductive and insulating materials [70].

Besides all the possible solutions it is commonly accepted that fluorinated gases have best insulation performances [64]. The novel fluorinated nitriles ($C_nF_{2n+1}CN$), trifluoriodomethane (CF_3I) and fluoroketones ($C_nF_{2n}O$ for $n = 3, 4, 5, 6, 7, 8$), appear as promising substitutes to pure SF₆. The fluorinated nitriles C₃F₇CN and (CF₃)₂CFC(O)CF₃ were synthesized by the 3MTM company under the names NOVECTM 4710 and NOVECTM 5110 [48]. These insulating solutions are characterized by low GPW (2100 for NOVECTM 4710 and < 1 for NOVECTM 5110) and dielectric capabilities even higher than pure SF₆ [48]. Despite their excellent dielectric properties, the major drawback of the NOVECTM compounds and the trifluoriodomethane, is their high boiling point, respectively of -4,7°C, 26.9°C, -22.5°C, for NOVECTM 4710, NOVECTM 5110 and CF₃I. Because of this, usually these gases are mixed with other species such as CO₂ or N₂ as show in [71, 72].

About the electrical parameters of the alternative gases, for example the electrical conductivities, from the author knowledge, up to now few data are available in the literature. For the SF₆/N₂ mixtures for example the SF₆(20%)/N₂(80%) and SF₆(10%)/N₂(90%), the reported electrical conductivities are $\sigma = 3.83 \cdot 10^{-25}$ S/m and $\sigma = 4.31 \cdot 10^{-25}$ S/m respectively, while for CF₃I/N₂ mixtures as CF₃I(20%)/N₂(80%) and CF₃I(10%)/N₂(90%) the values $\sigma = 3.87 \cdot 10^{-25}$ S/m and $\sigma = 4.33 \cdot 10^{-25}$ S/m can be used [77]. For the NOVECTM 4710 gas, positive and negative ions mobilities useful for charge-oriented analysis, are reported in [78].

3.1. DIELECTRIC GASES

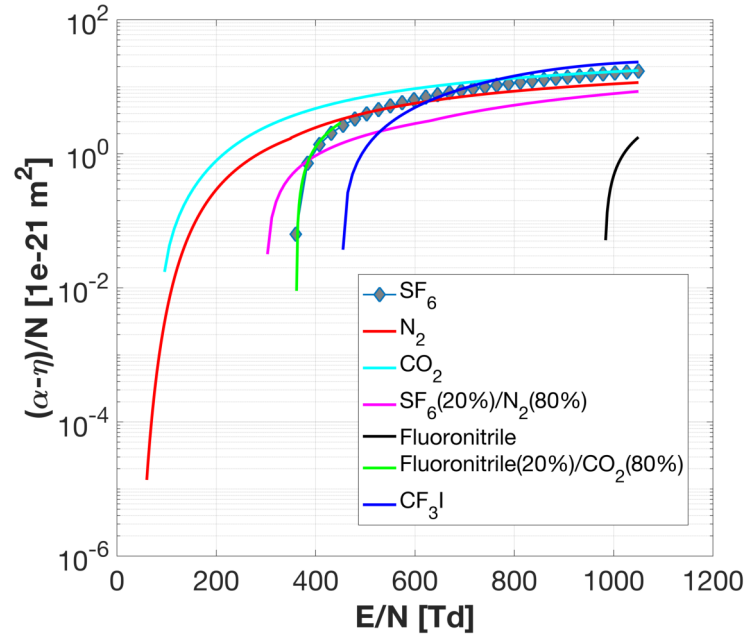


Figure 3.6: Reduced effective ionisation coefficient $\bar{\alpha}/N$ function of the reduced electric field E/N for different insulating gases. The critical electric field for breakdown $(E/N)_0$ correspond to $\bar{\alpha} = 0$.

A comparison between the dielectric performances of different insulating gases, through the effective ionization trend is reported in Fig. 3.6, while a summary of gas properties is reported in Table 3.4. To date, the applicability of the novel fluorinated alternative solutions appears to be limited by the following aspects [79]:

- High production costs,
- More stringent mechanical requirements due to the increased operational pressure,
- Low knowledge of the compatibility of the gas with solid insulating materials.

For these reasons in the remainder SF_6 will be considered as reference gas for the design of HVDC gas-insulated components for nuclear fusion applications.

3.2 Solid insulator materials

In this section the description of the electrical properties characterizing the solid materials used for the post-insulators and the conical insulators is provided. The mathematical description passes through the definition of the electrical conductivity σ_I [S/m] and relative permittivity ε_r of the medium. Usually ε_r is homogeneous in the whole solid insulator and in the simplest case also the electric conductivity σ_I which can be taken as constant. However, since most of the materials used for HVDC apparatus exhibits a nonlinear dependence both from electric field strength and temperature, more complicated expressions for $\sigma_I = \sigma_I(E, T)$ must be adopted. In addition, when the surfaces of the insulators are covered with thin films with different electrical properties, a possibly nonlinear surface conductivity has to be prescribed. Recently, the desire to expand the use of HVDC equipments has prompted the search of new solid insulating material with the capability of homogenizing the electric field intensity, allowing for more durable component performance over time. These are the so-called Functionally Grading Material (FGM).

3.2.1 Bulk conductivity

In the simplest case, the electrical description of the bulk material foresees a constant electrical conductivity over the whole insulator domain. Usually

3.2. SOLID INSULATOR MATERIALS

cast epoxy resin is considered in such case with electrical conductivities σ_I ranging from 10^{-12} to $10^{-15}/10^{-16}$ S/m [35]. The characterization of the solid insulator with a constant conductivity value is extremely rough for realistic material for which both electric field intensity E and temperature field T affect the electrical conductivity trend. The correct modeling of the E, T dependence allows to consider intrinsically the presence of volumetric charge inside the material, associated with the conductivity gradient [80]. This trend can be observed experimentally by analyzing the electrical behavior of epoxy resin composites, for example the conventional epoxy resin filled with micro-sized alumina particles forming the Al_2O_3 -filled epoxy materials commonly used for HVDC insulation. The nonlinear trend of electrical conductivity can be observed also for the so-called *resistive field grading materials* described later in the chapter.

The alumina-filled epoxy materials are widely used for high voltage gas-insulated systems, both in AC and in DC, in combination with SF_6 dielectric gas due to their resistance against SF_6 decomposition byproducts [46]. In literature different electrical conductivity trends for σ_I can be found [35, 81, 82]:

$$\sigma_I(E) = \sigma_{I,0} \exp(\alpha_V E) \quad (3.18)$$

$$\sigma_I(E, T) = \sigma_{I,0} \exp(\alpha_V E + \beta_V T) \quad (3.19)$$

$$\sigma_I(E, T) = \sigma_{I,0} \exp\left(\alpha_V E - \frac{W_a}{k_B T}\right) \quad (3.20)$$

which may take into account only the electric field dependence or the combined effect with the temperature distribution. The parameters α_V [m/V] and β_V [1/K] in the exponential function, can be extrapolated from experimental measurements and depend on the resin type. Expression (3.20) exhibits an Arrhenius-like dependence of the electrical conductivity with respect to the temperature, through the term $\exp[-W_a/(k_B T)]$, where W_a [eV] is the activation energy [83].

As already did for the dielectric gas, when analyzing the thermal behaviour of the solid insulator materials, the thermal conductivity, the heat capacity and the density must be specified. For the Al_2O_3 -filled epoxy solid insulators the constant values $k_{Epoxy} = 0.25$ W/(m·K), $C_{p,Epoxy} = 1500$ J/(kg·K) and $\rho_{Epoxy} = 2200$ kg/m³ are commonly used in literature.

3.2.2 Surface conductivity

The gas-solid interface layer plays a fundamental role in determining the charge accumulation phenomenon. In fact, the electrical charge depositing

therein is highly influenced by the surface condition of the solid insulator, and the charging can be also traced back to the electrical conductivity of the gas-solid interface layer [84]. Accounting for such aspect requires the definition of an equivalent surface electrical conductivity, which in the simplest case can be taken as a constant value σ_S [S]. From experimental measurements under DC fields in pressurized SF₆ gas, it can be observed that a more realistic conductivity trend for the surface layer follows a nonlinear behavior similar to (3.18) in dependence on the electric field intensity [85]:

$$\sigma_S(E_t) = \sigma_{S,0} \exp(\alpha_S E_t), \quad (3.21)$$

where $\sigma_{S,0}$ [S] the basic conductivity, α_S [m/V] is the sensitivity to the field stress, and E_t is the electric field component tangential to the surface layer [81].

3.2.3 Field grading materials

The capability of reducing the local electric field enhancement within gas-insulated components, is of great interest to reduce the probability of HVDC insulation faults. The electric field grading is the set of techniques aiming at homogenizing the electric field distribution in the critical locations of high voltage apparatus which may include the triple-junctions and the locations next to the grounded ring electrode inside the bushings [86, 87].

A measure usually adopted to quantify the degree of non-homogeneity of the electric field in the system is the Field Enhancement Factor (FEF) denoted with η and defined as:

$$\eta := \frac{E_{avg}}{E_{max}}, \quad (3.22)$$

corresponding to the ratio between the average E_{avg} and the maximum E_{max} values of electric field strength. Usually, values of $\eta \sim 0.01$ correspond to a highly non-homogeneous electrode configuration. In general, the field grading techniques are subdivided in two classes [86]:

- Capacitive field grading, for example by appropriate design of electrodes,
- Resistive field grading acting on the material of the insulator by combining dielectric (ϵ_r) and conductive (σ) properties [88].

The resistive field grading materials are usually polymers, such as the epoxy resin filled with particles, of $50 \dots 100 \mu\text{m}$ diameter [89], for example the Silicon Carbide (SiC) or the Zinc Oxide (ZnO) microvaristor, whose microstructures are reported in Fig. 3.7. These particles fillers transfer their properties

3.2. SOLID INSULATOR MATERIALS

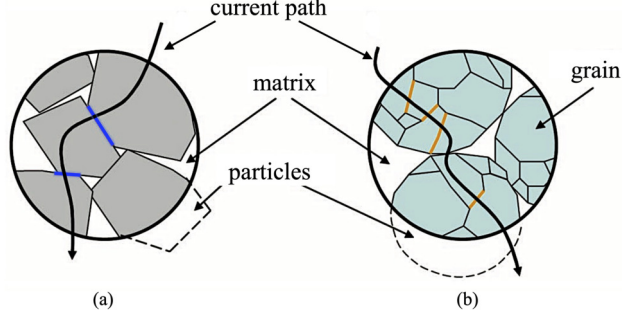


Figure 3.7: Field grading material microstructure: SiC based (a) and ZnO microvaristor (b) from [88].

to the composite material [90] resulting in a nonlinear trend in the $J - E$ plane and a relatively high permittivity ϵ_r . The origin of the nonlinearity can be traced back to the microscopic properties of the particles [88]:

- For SiC based field grading materials, the nonlinearity is due to the interface zone between the particles,
- In ZnO microvaristors, the nonlinearity is an intrinsic property of the particle.

The use of SiC coating on epoxy and Al_2O_3 -filled epoxy insulators has been shown to be effective in reducing the accumulation of surface charge density, if sufficient SiC particle content is present [91, 92]. The electrical conductivity of SiC/epoxy compounds exhibits a nonlinear dependence with respect to the electric field, which can be written as [93]:

$$\sigma(E) = 1.8 \cdot 10^{-12} \exp(2 \cdot 10^{-6} E), \quad (3.23)$$

for a SiC content of 33%. The resistive field grading materials composed by microvaristor particles has been applied to increase the performances of high voltage components [89, 94, 95]. From the mathematical viewpoint, a nonlinear field-dependent electrical conductivity for such materials can be expressed as [96]:

$$\sigma(E) = \sigma_0 \left[1 + \left(\frac{E}{E_1} \right)^\alpha \right], \quad (3.24)$$

where σ_0 [S/m] is the basic electrical conductivity, α the degree of nonlinearity and E_1 [V/m] the threshold electric field. The material shows a very low conductivity value for low electric field intensities and increases for field strengths above the threshold level E_1 . Typically, for microvaristor-filled

epoxy compounds the current-field characteristics can be subdivided into three regimes as shown in Fig. 3.8a. The electrical conductivity of such material exhibits a highly nonlinear behavior in the so-called *breakdown region*. The current conduction depend on the capability of the applied voltage to overcome the potential barrier established in the grain boundaries [97]. That is, for high electric field stresses, all potential barriers are overcome and the material become conductive. This means that the field grading materials, such as the microvaristor-filled epoxy compound, exhibits an electrical state transition from dielectric to conductive thus producing Joule heating [94]. To reproduce the $J - E$ curve of Fig. 3.8a an expression for the nonlinear electrical conductivity accounting also for the saturation trend for high fields, must be defined. One of the possibilities is [97]:

$$\sigma(E) = \sigma_0 \frac{N_1 \sqrt{1 + X^{N_1(E-E_1)/E_1}}}{N_2 \sqrt{1 + X^{N_2(E-E_2)/E_1}}}, \quad (3.25)$$

where E_2 is the saturation field, X the indicator of nonlinearity and N_1 , N_2 are two smoothing parameters. The resulting $\sigma(E)$ trend is given in Fig. 3.8b. A more general expression for the field grading material conductivity, accounting for the temperature distribution with an Arrhenius-like form is reported in [82]:

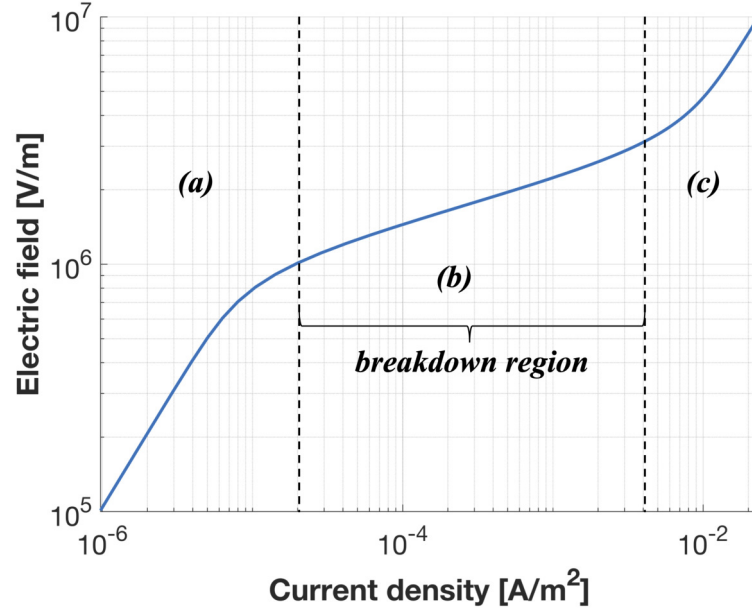
$$\sigma(E, T) = \sigma_{0,T} \exp\left(-\frac{W_a}{k_B T}\right) \frac{1 + \left(\frac{E}{E_1}\right)^{\alpha-1}}{1 + \left(\frac{E}{E_2}\right)^{\alpha-1}}, \quad (3.26)$$

where $\sigma_{0,T}$ is the specific conductivity at the reference temperature T_0 . A graphical comparison between the bulk electrical conductivities trends of equations (3.20) and (3.26) for $T \in [293.15, 313.15, 333.15, 353.15]$ K is depicted in Fig. 3.9.

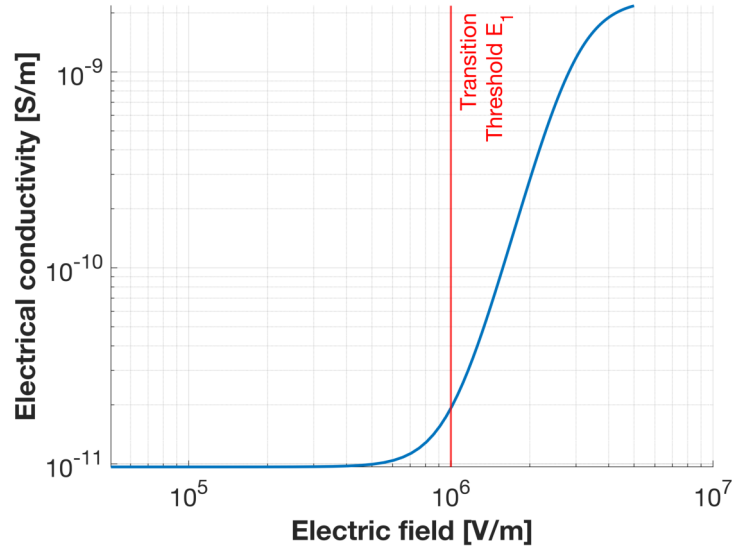
Recently, the so-called Functionally Grading Materials (FGM) has been proposed for the compact design of gas insulated substations and gas insulated lines. The goal of FGM materials is to modify the spatial distribution of bulk and or/surface electrical properties, for example the surface electrical conductivity and the bulk relative permittivity, to homogenize the electric field distribution [98]. Those FGM which act only on the electrical conductivity distribution are commonly denoted with σ -FGM, while the ones characterized by spatial variation of the electrical permittivity are the so-called ε -FGM. Both the effects can be combined in designing a solid insulator, in that case the functionally grading material is termed as σ/ε -FGM [99].

Of particular interest are the Surface FGM (SFGM) controlling the electrical conductivity along the gas-solid interface. Numerical optimization

3.2. SOLID INSULATOR MATERIALS



(a) Typical $J - E$ characteristic for the microvaristor-filled epoxy resin. The non-linear breakdown region is highlighted.



(b) $\sigma - E$ characteristic for the microvaristor-filled epoxy resin from equation (3.26) with $E_1 = 1$ kV/mm, $E_2 = 3$ kV/mm, $\alpha = 6$, $\sigma_{0,T} = 3.83 \cdot 10^{-3}$ S/m and $W_a = 0.5$.

Figure 3.8: Microvaristor-filled epoxy resin characteristics.

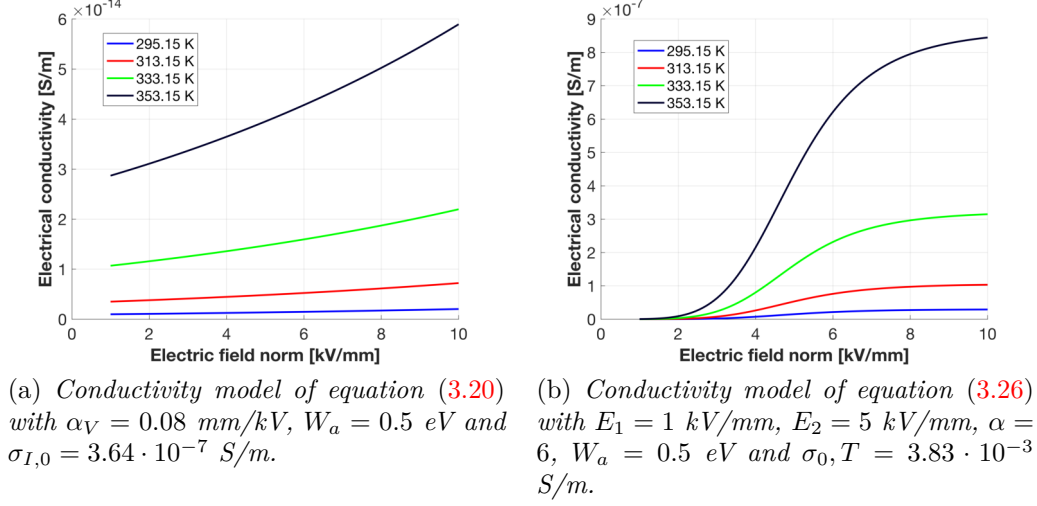


Figure 3.9: Conductivity trends for solid insulator materials.

methods can be used to determine the thickness of the surface layer; in this situation the grading is due to geometrical considerations at fixed electrical properties [100]. Conversely, the grading can be traced back to the spatial distribution of the surface electrical conductivity σ_S [101]. From the manufacturing point of view the surface conductivity gradient can be obtained by stratified ZnO controlling the sputtering time [102].

Usually the grading of the electrical permittivity ε -FGM is of volumetric nature, meaning that the bulk solid insulator can be ideally subdivided into a number of layers with different relative permittivities ε_r . This, for an axisymmetric configuration, means splitting along the r -plane ($\varepsilon_r(r)$) or the z -plane ($\varepsilon_r(z)$) [98]. This is also valid for σ -FGM solid insulators, for which, in the case of spatial variation along r direction, can be described by the electrical conductivity trend [55]:

$$\sigma_I(E, T, r) = \sigma_I(E, T) f(r) \quad (3.27)$$

with:

$$f(r) = 1 + (\sigma_{HV} - 1) \exp\left(-\frac{r - r_i}{\zeta_{HV}}\right) + (\sigma_{LV} - 1) \exp\left(\frac{r - r_o}{\zeta_{LV}}\right), \quad (3.28)$$

where σ_{HV} and σ_{LV} are the increasing factors at the high voltage electrode at radius $r = r_i$ and at low voltage electrode at $r = r_o$ respectively, and ζ_{HV}, ζ_{LV} are related to the gradient of $f(r)$ near the electrodes. From the manufacturing point of view the FGM solid insulators can be realized by

3.2. SOLID INSULATOR MATERIALS

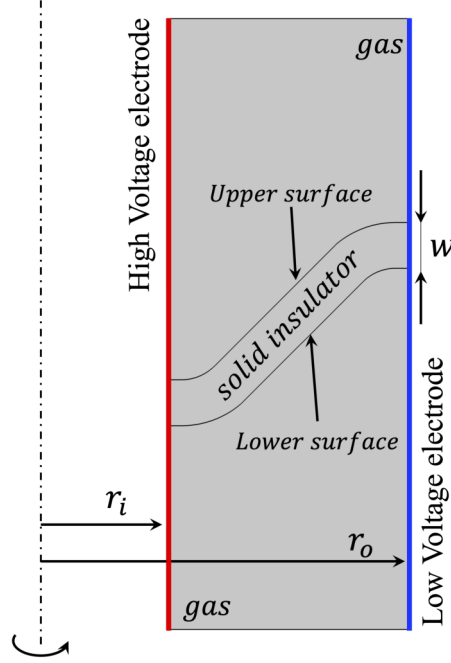


Figure 3.10: 2D axisymmetric conical insulator model. Inner and outer radius are $r_i = 90$ mm and $r_o = 250$ mm, while the solid insulator thickness is $w = 30$ mm.

applying a centrifugal force to the bulk epoxy resin filled with particles of different electric properties [103, 104].

3.2.4 Numerical examples

The conductivity trends both for the bulk and the surface layer domains are analyzed from the numerical point of view for the design of a 2D axisymmetric conical insulator with $\varepsilon_r = 4.5$, whose geometry is depicted in Fig. 3.10. The insulator is embedded in an air-insulated chamber and the applied voltage on the high voltage electrode is $U_{DC} = -500$ kV, while the low voltage electrode is grounded. The first example compares three different bulk conductivity models, while the second example aims at describing the effect of the surface conductivity.

Comparison of bulk conductivity models

The electric field characterization of three conductivity models, namely the constant conductivity, the alumina-filled epoxy (3.20) and the resistive field grading (3.26) is compared. As usually done when analyzing conventional

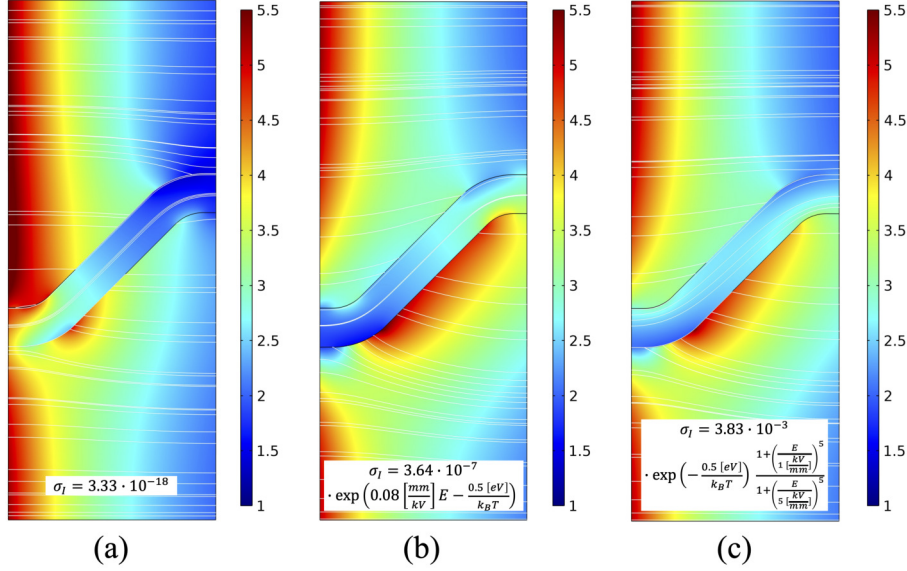
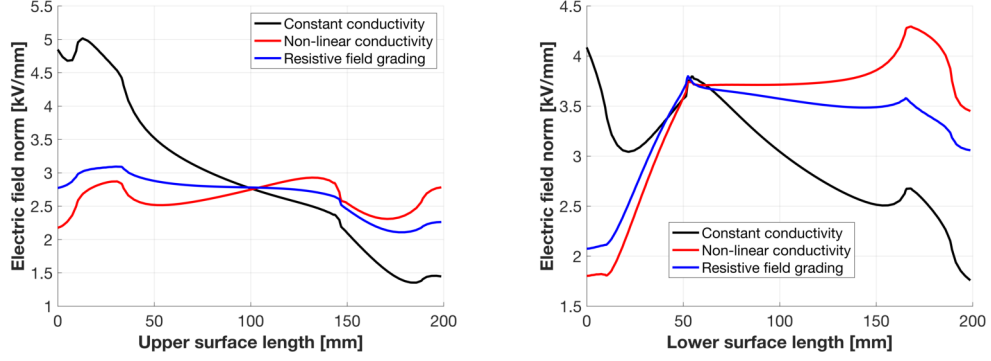


Figure 3.11: Comparison of electric field distribution in the computational domain: (a) constant conductivity, (b) non-linear conductivity and (c) resistive field grading material. Colorbar unit in kV/mm.

gas-insulated transmission line components for which the heating effect of the central conductor is notable, a temperature gradient is applied between high voltage and grounded shell by fixing their temperatures to $T_{HV} = 378.15$ K and $T_{LV} = 343.15$ K respectively [55]. The constant conductivity analysis is performed with $\sigma_I = 3.33 \cdot 10^{-18}$ S/m, while the parameters of the nonlinear relation (3.20) are: $\sigma_{I,0} = 3.64 \cdot 10^{-7}$ S/m, $W_a = 0.5$ eV and $\alpha_V = 0.08$ mm/kV. The resistive field grading material is characterized by a switching field $E_1 = 1$ kV/mm and a saturation field of $E_2 = 5$ kV/mm, moreover $\alpha = 6$ and $\sigma_{0,T} = 3.83 \cdot 10^{-3}$ S/m. Fig. 3.11 shows the electric field map in the whole computational domain for the three cases, while Fig. 3.12 illustrates the electric field intensity along the creepage length on the upper and lower surfaces of the conical insulator. The resistive field grading material is able to increase the degree of homogeneity to $\eta = 0.54$, with respect to the constant conductivity model, which has $\eta = 0.49$. The homogenization of the electric field is more evident looking at the intensity trend along the solid insulator surfaces.

3.3. CONCLUSIONS



(a) Electric field norm along upper surface. (b) Electric field norm along lower surface.

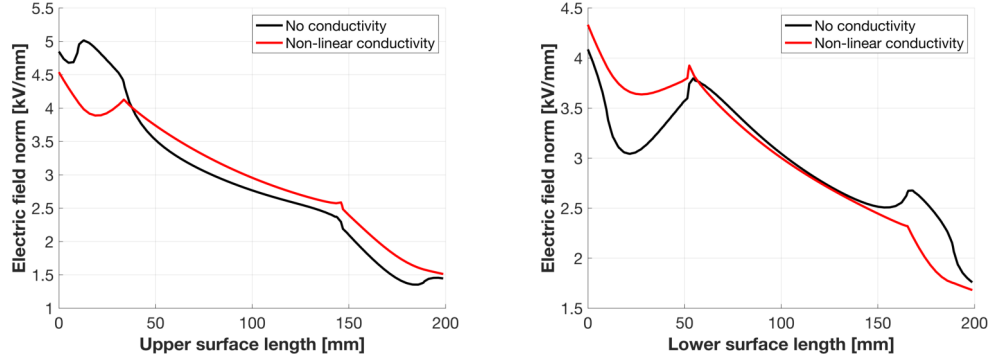
Figure 3.12: Electric field norm on upper and lower surfaces of the conical insulator of Fig. 3.10.

Comparison of surface conductivity models

The effect of using a surface conductivity layer of thickness $d_L = 320 \mu\text{m}$ is examined in this example. The absence of a conductivity layer is compared with the nonlinear field dependent relation (3.21) with the following parameters: $\sigma_{S,0} = 4 \cdot 10^{-18} \text{ S}$ and $\alpha_S = 1.22 \cdot 10^{-18} \text{ m/V}$. The bulk conductivity of the solid insulator is characterized by a constant value $\sigma_I = 3.33 \cdot 10^{-18} \text{ S/m}$. The numerical results reported in Fig. 3.13 shows the electric field strength along the upper and lower gas-solid interfaces. As can be seen, the inclusion of a nonlinear model for the surface conductivity drastically modifies the surface distribution of the electric field intensity in proximity of the electrodes which in turn affect the charge accumulation.

3.3 Conclusions

In this chapter the gaseous and solid insulating materials usually adopted for the gas-insulated high voltage technology were described. For the development of HVDC gas-insulated components that will be used in the nuclear fusion field, for example for the Acceleration Grid Power Supply (AGPS) of the Neutral Beam Injector (NBI) of the Divertor Tokamak Test (DTT) facility, SF_6 will be considered as reference gas, as its usage is well established. For the solid insulating materials both the constant conductivity model, the nonlinear Alumina-filled epoxy equation (3.20) and the resistive field grading defined by equation (3.26) will be used. The latter material will be used to



(a) *Electric field norm along upper surface.* (b) *Electric field norm along lower surface.*

Figure 3.13: Electric field norm on upper and lower conical insulator surfaces for different surface conductivity models.

reduce the electric field stress along a critical location of the SF₆-air bushing for the AGPS of DTT NBI, however the field grading materials (FGM) will be of particular interest for the development of future gas-insulated components, and the experimental phases following the thesis.

3.3. CONCLUSIONS

4

HVDC gas-insulated systems modeling

THIS CHAPTER explains the mathematical formulations at the basis of HVDC (High Voltage Direct Current) gas-insulated systems modeling. After a brief introduction on the general formulation of the electromagnetic problem, the electric field formulations of HVDC systems, including the standard Electro-quasistatic (EQS) approach and the charge-oriented approach are provided. The chapter then continues with the mathematical formulation of streamer breakdown inception and leakage current phenomena in the dielectric gas. Then, a brief description of the coupled electro-thermal-fluid analysis is given. The chapter concludes with a description of the peculiarities of the methods used for the numerical solution and a series of selected test cases covering the topic described.

4.1 Introduction

The electromagnetic (EM) field for every point $\mathbf{r}$ within a domain $\Omega \subset \mathbb{R}^d$, where generally $d = 2, 3$ in this context, is determined by the well-known

4.2. MAGNETIC FORMULATION

Maxwell equations [105]:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (4.1)$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (4.2)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (4.3)$$

$$\nabla \cdot \mathbf{D} = \varrho, \quad (4.4)$$

where $\mathbf{E}$, $\mathbf{H}$, $\mathbf{B}$ and $\mathbf{D}$ are the electric field, the magnetic field, the magnetic flux density and the electric displacement. The vector field $\mathbf{J}$ and the scalar quantity ϱ represent the current density and the free volumetric charge density inside Ω . The electromagnetic description is completed using the constitutive relations:

$$\mathbf{D} = \varepsilon \mathbf{E} \quad (4.5)$$

$$\mathbf{B} = \mu \mathbf{H}, \quad (4.6)$$

where $\varepsilon = \varepsilon_r \varepsilon_0$ and $\mu = \mu_r \mu_0$ are the electrical permittivity and magnetic permeability of the medium, with ε_r, μ_r its relative permittivity and permeability values and ε_0, μ_0 the ones of vacuum. The link between the electric field and the current density is given by the Ohm's law:

$$\mathbf{E} = \rho \mathbf{J} = \sigma^{-1} \mathbf{J} \quad (4.7)$$

with ρ the electrical resistivity and σ the electrical conductivity. The charge continuity equation, is derived directly from Ampère-Maxwell law (4.2) and reads:

$$\nabla \cdot \mathbf{J} = -\frac{\partial \varrho}{\partial t}. \quad (4.8)$$

4.2 Magnetic formulation

In this section the magnetic field formulations commonly adopted in the context of mathematical modeling of high voltage apparatus are briefly recalled. The magnetostatic form of Maxwell equations is described in 4.2.1, while the magneto-quasistatic one in 4.2.2.

4.2.1 Magnetostatic formulation

Starting from the Ampère-Maxwell law (4.2) and introducing the magnetic vector potential $\mathbf{A}$ such that:

$$\mathbf{B} = \nabla \times \mathbf{A}, \quad (4.9)$$

the magnetostatic $\mathbf{A}$ -formulation can be conceived by neglecting the time varying displacement field $\mathbf{D}$:

$$\nabla \times (\mu^{-1} \nabla \times \mathbf{A}) = \mathbf{J} \quad (4.10)$$

where $\mathbf{J}$ must satisfy the condition $\nabla \cdot \mathbf{J} = 0$, which follows by taking the divergence of both sides of equation (4.10) and by exploiting the vectorial identity $\nabla \cdot \nabla \times (\bullet) \equiv 0$. The non uniqueness of $\mathbf{A}$ is resolved by adding an additional gauge condition, for example the Coulomb gauge $\nabla \cdot \mathbf{A} = 0$ [106].

4.2.2 Magneto-quasistatic formulation

By using the magnetic vector potential as in equation (4.9), the Faraday law (4.1) is rewritten as:

$$\nabla \times \left(\mathbf{E} + \frac{\partial \mathbf{A}}{\partial t} \right) = 0. \quad (4.11)$$

or, by introducing the scalar electric potential φ , as:

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla \varphi. \quad (4.12)$$

Neglecting the time varying displacement field $\mathbf{D}$ in Ampère-Maxwell law (4.2), and expanding the current density $\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_s$ where $\mathbf{J}_s$ correspond to the source term, (4.2) is rewritten as:

$$\nabla \times (\mu^{-1} \nabla \times \mathbf{A}) = -\sigma \frac{\partial \mathbf{A}}{\partial t} - \sigma \nabla \varphi + \mathbf{J}_s. \quad (4.13)$$

From this, the $\mathbf{A}^*$ -formulation can be defined by using the Coulomb gauge for $\mathbf{A}$ and assuming the electrical conductivity within the conductive domain is uniform, i.e., $\nabla \sigma = 0$, resulting in [107, 108]:

$$\nabla \times (\mu^{-1} \nabla \times \mathbf{A}^*) = -\sigma \frac{\partial \mathbf{A}^*}{\partial t} + \mathbf{J}_s \quad (4.14)$$

where $\mathbf{A}^*$ is the modified magnetic vector potential. The electric field in the computational domain is given by:

$$\mathbf{E} = -\frac{\partial \mathbf{A}^*}{\partial t}. \quad (4.15)$$

4.3 Electric formulation

In this section the electric field formulations used for the mathematical modeling of gas-insulated component in transient DC conditions are described. Differently from capacitive fields, whose electric field can be well described by an electrostatic analysis for which the electrical properties are governed solely by the relative permittivity (ϵ_r) of the mediums, the transient DC distribution depends on both the relative permittivity and the electrical conductivity (σ). In fact, after the application of DC voltage, the field changes from the initial (capacitive) one, to the final (resistive) distribution governed by the electrical conductivities of the mediums. The transition time depends on the time constant of the system, given by the ratio of the relative permittivity and the electrical conductivity [35]. After several time constants the DC field distribution is governed solely by electrical conductivity. During the capacitive-resistive transition under transient DC fields, surface charge density accumulates on solid-gas interfaces due to the discontinuity of the ratio between permittivity and conductivity in the two sides. In literature, the surface charge accumulation is known to be driven by three main channels [109]

- Conduction through the volume (bulk) of the insulator,
- Electrical conduction within the gas volume,
- Conduction along the gas-solid insulator interface.

In the HVDC gas-insulated systems the accumulated surface charge density expressed by ϱ_s , may drastically lower the flashover voltage of the solid insulators, thus leading to premature breakdown [110]. The decrease of breakdown voltage $U_b(t)$ can be described by the following empirical formula proposed in [111]:

$$U_b(t) = U_b(t_0) \left(\frac{t}{t_0} \right)^{-1/m}, \quad (4.16)$$

where m is an empirical coefficient retrieved from experimental measurements. The decrease of flashover voltage is more pronounced for DC fields [112], however, different factors affect the flashover voltage under different voltage conditions [113]. An additional factor that can drastically reduce the dielectric capabilities of HVDC gas-insulated systems, is the pollution caused by conducting metal particle formed during manufacturing and operation. When the force equilibrium on the particle is broken, it starts to move freely in the system with a random motion. Among the several motions depicted in Fig. 4.1, two of them are particularly dangerous, that are [114]:

- The deposition of charged metal particle on solid insulator surfaces,
- The “firefly” phenomenon.

Metal particles accumulated on dielectric surfaces drastically modify the electric field distribution and may lower the flashover voltage triggering the breakdown [115, 116, 117]. The so-called “firefly” mechanism is characteristic of HVDC gas-insulated systems operating in negative polarity; for example, this is the case of the AGPS gas-insulated components for negative ion driver NBIs (N-NBIs). For a coaxial transmission line, the firefly can be described by looking at the motion of a positive charged particle with a radial elongation (see Fig. 4.1) moving towards the inner electrode negative polarized. When the particle reaches the electrode it becomes negatively charged attracting a positive ion cloud. The small metal particle tip enhances the electric field strength, which in turn reflects into emission of electrons and consequent formation of gas anions which move towards the outer conductor. The current traced back to this phenomenon can be measured and result in a leakage current flowing into the gas, as described in Section 4.5. If the electric force acting on the metal particle is sufficient to detach it, the positive ion cloud in front of it neutralize the free conductive particle charging it positively. The entire cycle can now be restarted, giving rise to the trajectory given in Fig. 4.1 [118].

The field enhancement in the particle tip may drive to complete breakdown of the gas gap, which can be described by the streamer inception mechanism explained in Section 4.4. The phenomenon of firefly particles was examined in the context of the 1 MV HVDC gas-insulated TL for ITER N-NBI [33], suggesting a threshold field of 1.8 kV/mm for 5 mm particles. To stop the motion of free conductive particles, the so-called electrostatic traps can be conceived. Looking at the simple expression of momentum equation:

$$m\mathbf{a} = \mathbf{F}_{ele} + \mathbf{F}_{grav} + \mathbf{F}_{drag}, \quad (4.17)$$

where $\mathbf{F}_{ele}$ is the electric force, $\mathbf{F}_{grav}$ the gravitational force, $\mathbf{F}_{drag}$ the friction force and m the mass, the goal of the particle trap is to counteract $\mathbf{F}_{ele}$ thus stopping the undesired motion. As stated in [119], the efficiency of the particle traps depend on the groove thickness and the trap width itself. Another possibility to prevent particle levitation is through the electrode coating. This solution increases the levitation electric field strength as shown in Fig. 4.2 [120].

To summarize, Table 4.1 lists the major macroscopic differences between pure capacitive and transient DC fields in high voltage apparatus. As will be discussed in the following sections, the modeling of HVDC gas-insulated

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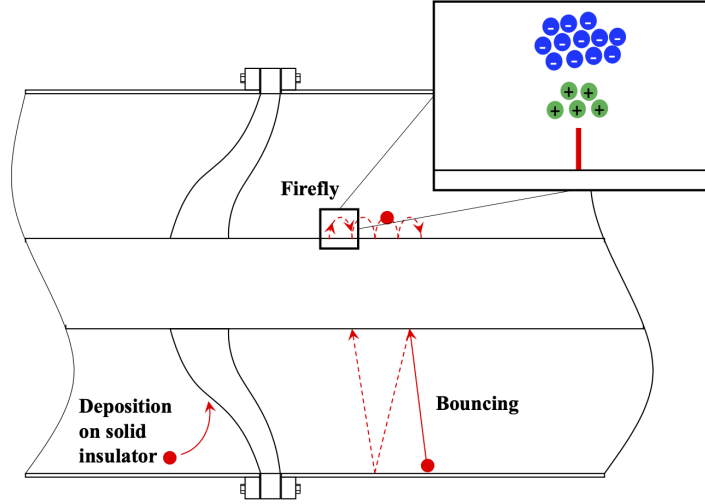


Figure 4.1: Particle motions in a HVDC gas-insulated system.

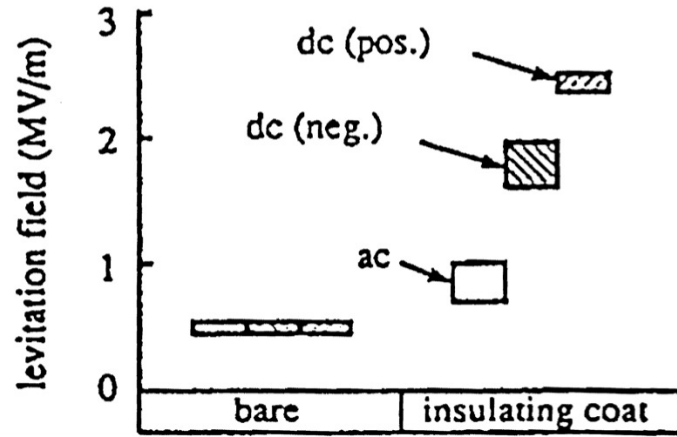


Figure 4.2: Effect of electrode coating with thickness $20 \div 40 \mu\text{m}$ and relative permittivity $\epsilon_r = 4$ on particle levitation field, for 10 mm long particles with 0.2 mm diameter. Figure taken from [121].

–	Capacitive	DC
Capacitive field distribution	✓	✓
Resistive field distribution	✗	✓
Transient calculation	✗	✓
Surface charge accumulation	✗	✓
Temperature dependence	✗	✓
Charge emission	✗	✓

Table 4.1: Characteristics of capacitive and transient DC fields distributions [122].

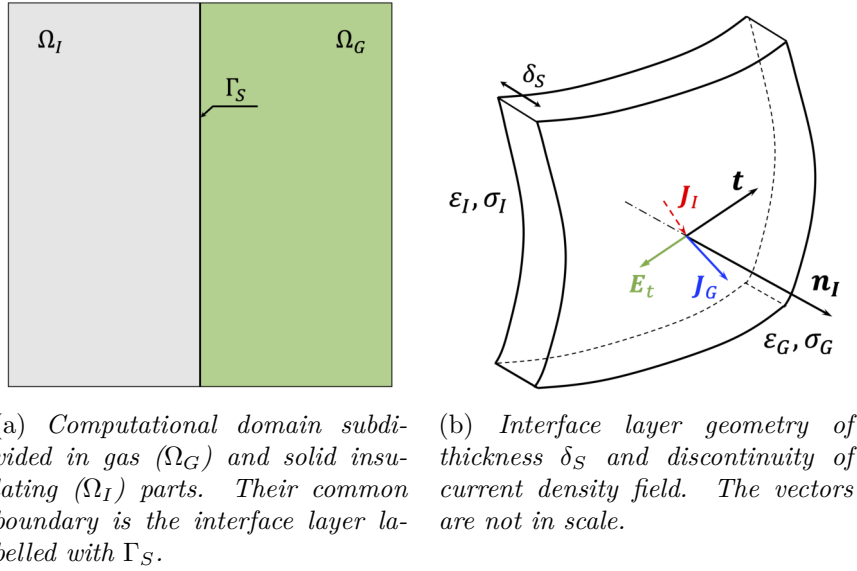


Figure 4.3: Computational domain.

components generally does not require the solution of the full set of Maxwell equations, but is based on some simplifying assumptions.

When dealing with gas-insulated systems the computational domain is generally subdivided in two subsets Ω_I and Ω_G as shown in Fig. 4.3a, such that $\Omega = \Omega_I \cup \Omega_G$, where the subscripts I and G refer to solid and gas insulating media respectively. The interface between these two domains is denoted with Γ_S .

Due to the discontinuity of material properties at the interface between Ω_I and Ω_G the surface charge density accumulation takes place, given by the discontinuity of the electrical conductivity, which results in a discontinuity

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of the electric displacement field:

$$\varrho_s = \mathbf{n}_1 \cdot (\mathbf{D}_I - \mathbf{D}_G), \quad (4.18)$$

moreover, as depicted in Fig. 4.3b, the conservation law of charge at the interface layer drives the time evolution of the surface charge density ϱ_s :

$$\frac{\partial \varrho_s}{\partial t} = \mathbf{n}_1 \cdot (\mathbf{J}_I - \mathbf{J}_G) - \nabla_t \cdot (\sigma_S E_t) \quad (4.19)$$

where the last term depend on the electrical conductivity σ_S of the interface layer and E_t is the tangential component of the electric field. As already stated, the surface charge density accumulating during the capacitive-resistive transient behavior is the major drawback of HVDC gas-insulated systems, contrary to HVAC ones, and is one of the aspects that must be solved to spread the applicability of such transmission technology for commercial purposes.

4.3.1 Electro-quasistatic formulation

The electro-quasistatic (EQS) φ -formulation of Maxwell equations is derived by assuming $\partial \mathbf{B} / \partial t = 0$ in the Faraday law (4.1) and by using the vectorial identity $\nabla \cdot \nabla \times (\bullet) \equiv 0$ on the Ampère-Maxwell equation (4.2):

$$0 \equiv \nabla \cdot (\nabla \times \mathbf{H}) = \nabla \cdot \left(\mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \right) = \nabla \cdot \mathbf{J} + \nabla \cdot \left(\frac{\partial \mathbf{D}}{\partial t} \right). \quad (4.20)$$

Using Ohm's law (4.7) and the constitutive relation (4.5), the previous expression can be rewritten as:

$$\nabla \cdot (\sigma \mathbf{E}) + \nabla \cdot \left(\frac{\partial (\varepsilon \mathbf{E})}{\partial t} \right) = 0, \quad (4.21)$$

moreover, for simply connected domains $\nabla \times \mathbf{E} = 0$ implies:

$$\mathbf{E} = -\nabla \varphi, \quad (4.22)$$

where φ defines the scalar electric potential. Combining equation (4.21) with (4.22) the law for the temporal variation of the scalar electric potential can be derived:

$$\nabla \cdot (\sigma_e \nabla \varphi) + \nabla \cdot \left(\varepsilon \nabla \left(\frac{\partial \varphi}{\partial t} \right) \right) = 0. \quad (4.23)$$

Such formulation was applied over a wide range of HVDC electric field simulations, such as HVDC cables [123, 124] and HVDC insulators [89, 125].

Moreover, EQS was historically used for the modeling of HVDC gas-insulated components employed in nuclear fusion [34, 35, 126].

Application of EQS model for the electric field analysis in HVDC-GIS systems requires the specification of the electromagnetic properties for each domain Ω_I and Ω_G , in addition to the surface properties of Γ_S . Strictly speaking this reflects in the assignment of the electrical conductivity and the relative permittivity for each subdomain. As depicted in Section 3.2, often σ_I for the solid insulating parts is a non-linear function of electric field strength and temperature, the same also for the interface layer conductivity. For the gas domain Ω_G , usually σ_G is kept constant over a wide range of electric field values.

4.3.2 Drift-diffusion-reaction model

In this section a charge-oriented approach accounting for the movement of free ions in the gas generated by an external radiation field, is presented. The model treats the gas and solid domains using different approaches and the coupling between the parts is established in their interface layer, which correspond to the region of charge accumulation.

Gas domain

Due to the presence of free ions in the insulating gas in normal operational conditions, the electrical conductivity is not uniform neither constant and a gas model is required for the correct analysis of electric fields under transient DC voltages in a self-consistent way. Such model takes into account all the physical mechanism affecting the electrical conduction in the gas, described in Section 3.1, that are: generation (S) recombination (R), motion (μ) and diffusion (D) of charge carriers [46]. In electronegative gases, as for example the SF_6 , a negligible amount of free electrons is present, and therefore the electrical behavior of the gas can be ascribed to the only motion of positive and negative ions, always present due to the natural ionization described by the S quantity. Positive and negative ion densities are governed by a set of drift-diffusion-reaction Partial Differential Equations (PDE) [81]:

$$\frac{\partial n^+}{\partial t} = S - Rn^+n^- - \nabla \cdot (n^+\mu^+\mathbf{E}) + D^+\Delta n^+, \quad (4.24)$$

$$\frac{\partial n^-}{\partial t} = S - Rn^+n^- + \nabla \cdot (n^-\mu^-\mathbf{E}) + D^-\Delta n^-, \quad (4.25)$$

where Δ is the Laplace operator, n^+ , n^- [$1/\text{m}^3$] are the positive and negative ion number densities respectively.

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The ion densities contribute to the volumetric charge density appearing in the right and side of Gauss equation 4.4:

$$\nabla \cdot \mathbf{D} = e(n^+ - n^-), \quad (4.26)$$

where e is the elementary charge. The equivalent conduction current density in the gas domain Ω_G follows from equations (4.24) and (4.25), multiplying both of them for the elementary charge e and subtracting equation (4.25) from equation (4.24):

$$e \frac{\partial(n^+ - n^-)}{\partial t} = -e \nabla \cdot [(n^+ \mu^+ + n^- \mu^-) \mathbf{E} - D^+ \nabla n^+ + D^- \nabla n^-]. \quad (4.27)$$

This expression correspond to the law of conservation of charge and the vector field on the right hand side corresponds to the conduction current density in the gas, defined as:

$$\mathbf{J}_{Gc} := e[(n^+ \mu^+ + n^- \mu^-) \mathbf{E} - D^+ \nabla n^+ + D^- \nabla n^-]. \quad (4.28)$$

The total current density in Ω_G is given by the sum of conduction and displacement current densities as:

$$\mathbf{J}_G = \mathbf{J}_{Gc} + \frac{\partial \mathbf{D}}{\partial t}. \quad (4.29)$$

From Eq. (4.28), it can be seen that the conduction current density is not uniform neither constant and depend on the spatial distribution of positive and negative charge carriers. Formally, the equivalent electrical conductivity of the gas can be retrieved from equation (4.29) as:

$$\sigma_G = \frac{\|\mathbf{J}_{Gc}\|}{\|\mathbf{E}\|}. \quad (4.30)$$

Solid domain

In the solid insulating parts, in the general case of transient phenomena, the Gauss law (4.4), the continuity equation (4.8), and Ohm's law (4.7) hold. The transient equation for the space charge density ϱ in solid insulator is derived from the combination of the aforementioned laws assuming a homogeneous permittivity ε :

$$\frac{\partial \varrho}{\partial t} = -\frac{\sigma_I}{\varepsilon} \varrho - \mathbf{E} \cdot \nabla \sigma_I. \quad (4.31)$$

The hypotheses of constant permittivity can be stated with confidence since it is only slightly affected by temperature and electric field intensity. On the contrary, the solid insulator electrical conductivity is considerably affected by electric field and temperature distributions, as reported in Section 3.2.2.

Gas-solid interface

The gas-solid interface is described by means of charge accumulation process due to the discontinuity of normal current densities and the current conduction along the layer. That is, equation (4.19) is assigned to such parts.

Boundary and initial conditions

The solution of the non-linear time dependent model described in this section requires the specification of boundary and initial conditions. For the High Voltage (HV) and Low Voltage (LV) electrodes, Dirichlet boundary conditions are required to specify the electric potential φ . On gas-solid interfaces, the continuity of electric potential is imposed:

$$\varphi_G = \varphi_I. \quad (4.32)$$

Regarding the reaction-diffusion equations (4.24) and (4.25) governing the ion densities, the Dirichlet boundary conditions are specified looking at the sign of the quantity $\mathbf{n} \cdot \mathbf{E}$, where $\mathbf{n}$ denotes the outward normal vector along gas domain boundary and $\mathbf{E}$ the electric field. The following boundary conditions, usually termed as *open boundary conditions*, are assigned [127]:

- No positive ions are emitted from surfaces where $\mathbf{n} \cdot \mathbf{E} < 0$, i.e., $n^+ = 0$ and no diffusion of negative ions occurs from these surfaces, i.e., $-\mathbf{n} \cdot D^- \nabla n^- = 0$.
- No negative ions are emitted from surfaces where $\mathbf{n} \cdot \mathbf{E} > 0$, i.e., $n^- = 0$ and no diffusion of positive ions occurs from these surfaces, i.e., $-\mathbf{n} \cdot D^+ \nabla n^+ = 0$.

As an example, along the high voltage electrode with $U_{DC} > 0$, $\mathbf{n} \cdot \mathbf{E} < 0$ and a Dirichlet condition for equation (4.24) is $n^+ = 0$. Conversely, along the low voltage electrode, $\mathbf{n} \cdot \mathbf{E} > 0$ and the density of negative ions is zero, that is $n^- = 0$, corresponding to a Dirichlet condition for Eq. (4.25).

The time dependent problem also needs initial conditions for the ion densities at $t = t_0$. In literature, zero initial densities [128] or an equilibrium state [129]:

$$n^+(t_0) = n^-(t_0) = \sqrt{\frac{S}{R}}, \quad (4.33)$$

are usually assumed.

4.3.3 Volpov transient field model

Since the surface charge accumulation in gas-insulated high voltage direct current systems during the field transition is a key issue of such systems, fundamental is the capability of the mathematical model to correctly capture the phenomenons occurring at the gas-solid interface layer.

The model proposed in [130] is here described assuming the computational domain Ω subdivided into two dielectric subdomains Ω_I and Ω_G , each characterized by homogeneous media with specified material properties. The electric field distribution is obtained from the Gauss law (4.4) and the continuity equation (4.8), by assuming zero volumetric charge density inside each subdomain. Mathematically, the following boundary value problem is defined for each subdomain:

$$\nabla \cdot \mathbf{D} = 0, \quad (4.34)$$

with interface conditions:

$$\varrho_s = \mathbf{n}_I \cdot (\mathbf{D}_I - \mathbf{D}_G), \quad (4.35)$$

$$\frac{\partial \varrho_s}{\partial t} = \mathbf{n}_I \cdot (\mathbf{J}_I - \mathbf{J}_G) - \nabla_t \cdot (\sigma_S E_t) \quad (4.36)$$

at the gas-solid insulator interface, by adopting the references of Fig. 4.3b. The model is closed by appropriate initial and boundary conditions for the electric potential φ . The current densities on both sides of the interface layer are retrieved from the Ohm's law (4.7) using the electrical conductivities σ_I and σ_G specified a priori. Strictly speaking this model consists in solving a series of electrostatic problems together with a boundary Ordinary Differential Equation (ODE) (4.36) to update the surface charge density at the interface layer. However this makes sense only to consider the electrical conduction along the gas-solid interface layer, otherwise ϱ_s is obtained automatically with equation (4.35).

If Ω_2 correspond to the gas domain the assumption of zero volumetric charge density is not valid, thus the Gauss equation (4.26) with n^+ and n^- retrieved from equations (4.24) and (4.25), has to be used as suggested in [81].

4.4 Streamer breakdown

The reduction of the geometrical dimensions of HVDC gas-insulated equipments, such as the cross section of gas-insulated transmission line feeding the 500 keV N-NBI of DTT, is of great interest both to decrease the footprint of the components and the amount of gas, which reflects to a reduction of the

plant costs. However, as stated in Chapter 3, to ensure high dielectric capabilities the sizing of the components cannot be reduced arbitrarily. Moreover, particular attention must be paid to highlight the areas of the components that suffer from excessive electrical stresses and preventing them with an accurate design. Sharp edges, tips and metal particle contamination can drastically reduce the insulation reliability of the system due to the local electric field enhancement. Moreover, the pollution layer along the solid insulators can trigger surface flashover [131]. Usually for SF₆ gas, an empirical formula is suggested in literature to estimate the breakdown electric field as a function of the pressure [32]:

$$E_{th} = (E/P)_0 P^{0.88}, \quad (4.37)$$

where E_{th} refers to the electric field value corresponding to a 50% flashover probability. However different factors affect the breakdown voltage for SF₆ insulation, for example the voltage polarity [132] and the surface area of the high voltage electrode [133]. Indeed as can be seen in Fig. 4.4 the measured breakdown voltage for negative DC supplies can be lower than half of the theoretical value.

Knowledge of the electric field distribution alone, thus considering the areas where the field exceed a critical value, can be misleading. As design criterion, the breakdown in gas requires the fulfillment of particular conditions along the whole distance from cathode to anode in order to take place.

In principle the breakdown of the insulating medium can be traced back to the presence of free electrons in the gas triggering an avalanche phenomenon. The free electrons accelerated within the gas under the effect of the electric force, may collide with neutral gas molecules. If the energy gained by electrons is sufficiently high, after the collision with the gas molecule, the ionization of such molecule takes place eventually conducting to an avalanche phenomenon which proceeds in form of streamers. The streamers are filaments of plasma propagating into non-ionized gas which, in the worst case, can result in complete breakdown of the gas gap in dependence of the electric field intensity and gas pressure [134].

The type of chemical reaction resulting from the electron-molecule collision depends on the energy of the electron itself. For SF₆ gas, if the electron energy is sufficiently high, the ionization channel:



may takes place. Conversely, for low energetic electrons, the direct attachment



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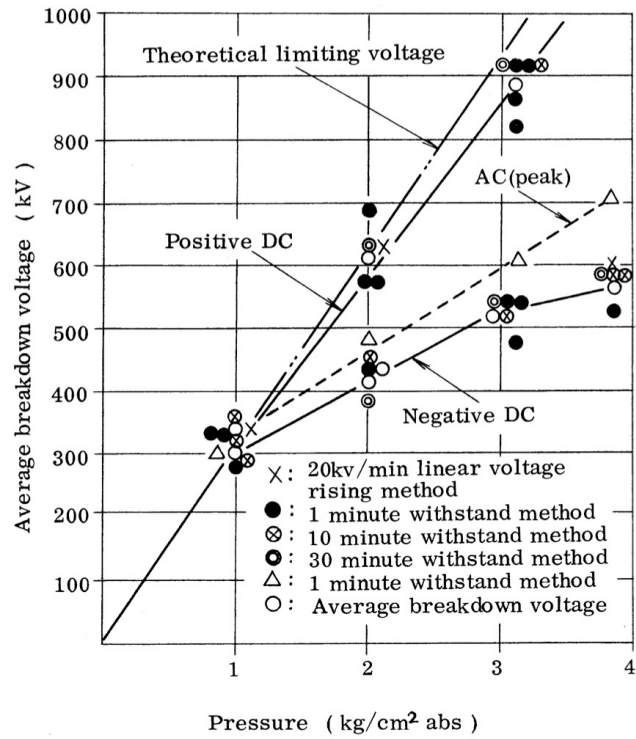


Figure 4.4: Breakdown voltage for a coaxial cylinder gap with 80 mm of inner diameter and 200 mm of outer diameter. Figure taken from [132].

is able to produce a negative ion. The direct attachment is not the only attachment channel, in fact, the so-called dissociation attachment reactions can occur. For example via:



The ionization process is described by means of the first Townsend ionization coefficient α [1/m] and the attachment channel is described by attachment coefficient η [1/m]. Both coefficients in general depend on the electric field strength E and the gas parameters, such as its pressure P . From the knowledge of α and η , the increase dN_e in the number of electrons N_e along the path Γ , described by the metric ds , tangent to the electric field lines is given by [135]:

$$\frac{dN_e}{ds} = N_e(\alpha - \eta), \quad (4.41)$$

which predicts an exponential growth of the electron number until $\alpha > \eta$. Unlike Townsend's breakdown mechanism, the streamer breakdown is based on a single electron avalanche. That is, when the amount of electrons in the avalanche head reaches the critical size N_{cr} , the streamers can result into a partial or complete breakdown of insulating gas. The typical value of N_{cr} is about 10^8 electrons [134]. According to [136], the streamer inception criterion can be formulated as:

$$\int_{\Gamma} (\alpha - \eta) ds = K \geq \ln(N_{cr}) = K_{cr}. \quad (4.42)$$

The integrand $(\alpha - \eta)$ can be incorporated into a single quantity termed *effective ionization coefficient* [137]:

$$\bar{\alpha}(E, P) := \alpha(E, P) - \eta(E, P). \quad (4.43)$$

In literature the pressure-normalized effective ionization coefficient, termed as *reduced effective ionization* $\bar{\alpha}/P = f(E/P)$, is usually reported. In some cases, $\bar{\alpha}$ is normalized by the gas number density N [1/m³], resulting in a reduced effective ionization coefficient written in the form $\bar{\alpha}/N = f(E/N)$. The gas number density N and the pressure P are related via the gas law.

From the previous discussion it is clear that a key task for analyzing the gas breakdown by means of the streamer criterion, is the knowledge of the ionization and attachment coefficient, or more generally, the effective ionization coefficient as a function of electric field and pressure (or number density).

For common insulating gases like air, N₂, CO₂ and SF₆, empirical relations for $\bar{\alpha}/N$ well-fitting the experimental measurements over a wide range of

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E/N , are reported in literature [73]. As an example, for the cases of air and SF_6 the following expressions may be used:

$$(\bar{\alpha}/N)_{\text{air}} = -4 \cdot 10^{-20} \exp(-985/(E/N + 43)) - 30 \cdot 10^{-24} \quad (4.44)$$

$$(\bar{\alpha}/N)_{\text{SF}_6} = -9.06 \cdot 10^{-20} \exp(-(E/N)/2875) + 8 \cdot 10^{-20}, \quad (4.45)$$

where the former relation is valid for $94 < E/N < 1500$ Townsend [Td] and the latter for $360 < E/N < 5000$ Townsend [Td]. For SF_6 the simple and common expression reported in [137] reads:

$$(\bar{\alpha}/P)_{\text{SF}_6} = k(E/P - (E/P)_0), \quad (4.46)$$

with $k = 28 \text{ kV}^{-1}$ and $(E/P)_0 = 89 \text{ kV}/(\text{mm} \cdot \text{MPa})$. While in [56] the following expression for the ionization coefficient:

$$(\alpha/N)_{\text{SF}_6} = \begin{cases} 3.4473 \cdot 10^{34} (E/N)^{2.985} & E/N < 4.6 \cdot 10^{-19} \text{ V} \cdot \text{m}^2 \\ 11.269 (E/N)^{1.159} & E/N > 4.6 \cdot 10^{-19} \text{ V} \cdot \text{m}^2 \end{cases}, \quad (4.47)$$

and the attachment coefficient:

$$(\eta/N)_{\text{SF}_6} = 2.0463 \cdot 10^{-20} - 0.25379(E/N) + 1.4705 \cdot 10^{18}(E/N)^2 - 3.0078 \cdot 10^{36}(E/N)^3 \quad (4.48)$$

for $5 \cdot 10^{-20} < E/N < 2 \cdot 10^{-19} \text{ V} \cdot \text{m}^2$ and:

$$(\eta/N)_{\text{SF}_6} = 7 \cdot 10^{-21} \exp(-2.25 \cdot 10^{18}(E/N)) \quad (4.49)$$

for $E/N > 2 \cdot 10^{-19} \text{ V} \cdot \text{m}^2$, are given. Expressions (4.46), (4.47), (4.48) and (4.49) for SF_6 and relation (4.44) are here reported only for completeness and to give a literature survey, however are not used in the remainder of the thesis.

An alternative way of obtaining the reduced effective ionization coefficient without using empirical experimental fittings, is based on the numerical solution of the collisional Boltzmann equation for a specified set of electron-molecule collisional reactions [138]. The numerical approach requires the definition of a set of reactions, R_i , each one characterized by its scattering cross section $\sigma_i(\epsilon)$, function of the incident electron energy ϵ . The Electron Energy Distribution Function (EEDF) $f(\epsilon)$, according to the kinetic theory of plasmas, satisfies the Boltzmann equation describing its evolution in the six-dimensional phase space described by particle position $\mathbf{r}$ and momentum $\mathbf{p} = m_e \mathbf{v}$ [139]:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f - \frac{e}{m_e} (\mathbf{E} \cdot \nabla_{\mathbf{v}}(f)) = C[f], \quad (4.50)$$

where $C[f]$ is the collisional term, m_e the electron mass, $\mathbf{v}$ the particle velocity and $\nabla_{\mathbf{v}}(\bullet)$ is the gradient operator with respect to velocity variable. From the EEDF the rate coefficient for the electron collision reaction R_i can be evaluated as [140]:

$$k_i = \gamma \int_0^\infty \epsilon \sigma_i(\epsilon) f(\epsilon) d\epsilon, \quad (4.51)$$

where $\gamma = \sqrt{2e/m_e}$. The swarm coefficient α_i/N , corresponding to the collisional reaction with cross section $\sigma_i(\epsilon)$, is directly computed from the i th rate coefficient k_i by using the relation [140]:

$$\alpha_i/N = k_i/W, \quad (4.52)$$

where W is the drift velocity of the electron.

In principle the streamer inception criterion does not provide any information about the propagation of the streamer. A streamer generated from one electrode can propagate towards the counter electrode only if the applied voltage is sufficiently high to sustain the propagation phenomenon [141]. As an example, in air under positive polarity U_0 , the lowest voltage value U_w enabling the streamer propagation, can be derived from the relation:

$$\int_0^{d_s} E(s) ds \approx E_{BD} d_s, \quad (4.53)$$

that is:

$$U_w = U_0 + E_{BD} d_s, \quad (4.54)$$

where d_s is the distance between the two counter electrodes and E_{BD} the constant field in the streamer channel, which is $E_{BD} \approx 0.5$ kV/mm in the assumed conditions. In general, a complete mathematical model for the analysis of the streamer propagation phenomenon requires the description of the complete set of physical phenomena occurring in the gas, which include recombination, ionization, attachment and diffusion of charge carriers. A self-consistent drift-diffusion-reaction model governing the time and space behavior of positive (n_p), negative (n_n) ions and electron (n_e) number densities in the gas can be conceived similarly to that of Eq. (4.24)-(4.25) [142]:

$$\frac{\partial n_p}{\partial t} = S + \alpha n_e \mu_e E - \beta_{ep} n_e n_p - \beta_{np} n_n n_p - \nabla \cdot (\mu_p n_p E), \quad (4.55)$$

$$\frac{\partial n_n}{\partial t} = S + \eta n_e \mu_e E - \beta_{np} n_n n_p - \nabla \cdot (-\mu_n n_n E), \quad (4.56)$$

$$\frac{\partial n_e}{\partial t} = S + (\alpha - \eta) n_e \mu_e E - \beta_{ep} n_e n_p - \nabla \cdot (-D_e \nabla n_e - \mu_e n_e E). \quad (4.57)$$

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This model was applied to analyze the streamer propagation both in pure SF₆ [142] gas and SF₆/N₂ [143] mixtures in standard needle-to-plate geometries. Due to the high computational effort required to solve the described model for general electrode configurations, the streamer propagation is not investigated in this work, which focuses on the stream inception condition alone.

4.5 Leakage current modeling

During normal operational conditions of HVDC gas-insulated equipments the current flowing through the dielectric gas originating from the movement of free ions, can be conceived as a leakage current or *dark current*. The term dark current can be traced back to those currents which are not correlated to any emission of light [144]. From experimental observations, as shown in Fig. 4.5, the leakage current trend can be generally subdivided into two macro-regions in dependence of the applied voltage [60]:

- *The ionization region* (a)-(b). For low voltage levels the leakage current is mainly controlled by external ionization fields, which generate ion-pairs in the gas. This generation term can be modified in the drift-diffusion equations (4.24)-(4.25) by varying the source term S . The ionization region extends from very low electric fields intensities to several kV/mm, up to the so-called transition field $E_{transition}$,
- *The injection region*. For electric field approximately above $E_{transition}$ the leakage current flowing therein increases by several order of magnitudes because of the injected charges. Generally, the mechanism controlling such transition is connected to the surface roughness of the high voltage electrode and the field emission phenomenon, which are sources of new ions.

In this section the main phenomena characterizing the ionization region 4.5.1 and the injection region 4.5.2 are described with the support of numerical examples.

4.5.1 Ionization region

At the beginning of the conceptual design of 1 MV ITER N-NBI pressurized SF₆ was considered as insulating gas not only for the high voltage systems as the TL, DCGs and high voltage bushings, but also for the beam source components [145]. Highly energetic neutrons, X and gamma (γ) rays produced by

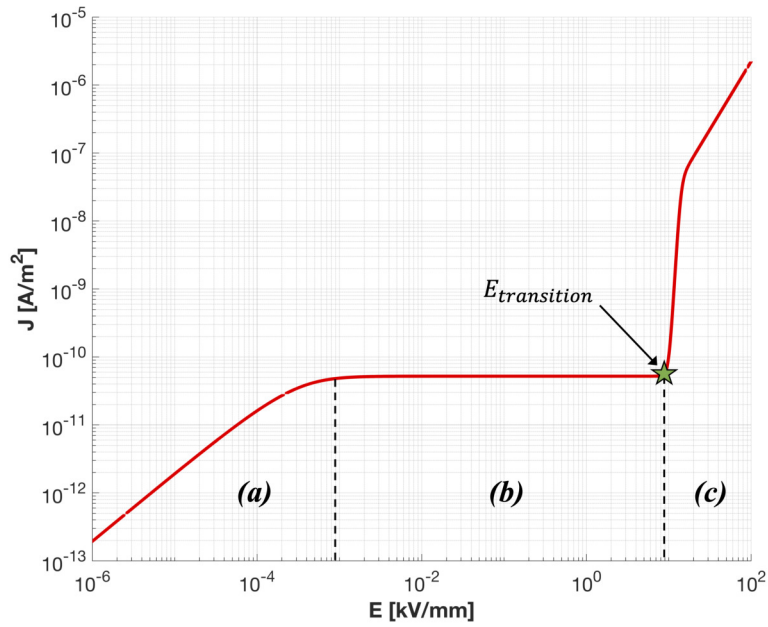


Figure 4.5: Example of leakage current trend in SF₆ as a function of the electric field. Regimes (a)-(b) below the transition field $E_{transition}$, characterize the ionization region. Above $E_{transition}$, in part (c), the current increases rapidly with the field as new ions are formed in the gas.

4.5. LEAKAGE CURRENT MODELING

the fusion machine causes ionization and dissociation of gas molecules, drastically modifying the electrical conductivity of SF₆ if the HVDC gas-insulated components are placed on the critical path. In literature this phenomenon is termed as Radiation Induced Conductivity (RIC). The evaluation of leakage currents under radiation field ϕ [Gy/s] is of central importance to estimate the power losses in the gas and determine the feasibility of using gas-insulated components in these conditions.

A first estimation of the leakage current flowing in the gas in the saturation conditions, that is, in the high voltage/field intensity situation, can be obtained by the formula [146]:

$$I_{sat} = F_{gas} V P \phi, \quad (4.58)$$

where F_{gas} is a parameter specific for the type of insulating gas ($F_{gas} = 2.06$ for SF₆), V [m³] the volume of gas and P its pressure. For an absorbed dose rate of $\phi = 0.1$ Gy/s, as in the case of ITER N-NBI, the ionization current estimated by equation (4.58) is about 4.6 A, thus resulting in power losses in the order of $\sim$ MW for 1 MV of applied voltage [146]. This value was considered unacceptable both from the capacity of power supply and cooling systems, thus for the volume surrounding the beam source of ITER N-NBI the vacuum insulation is used instead the gas insulation. This decision entailed the complex task of carrying out the SF₆-to-vacuum High Voltage Bushing (HVB) which is a unique component beyond the present industrial standard for insulation voltage level, linking the 1 MV SF₆ insulated line with the beam source components in the vacuum vessel [26, 30, 147].

In this section the RIC phenomenon is investigated from the numerical point of view by analyzing the effect of ion-pair generation rate S variation in the drift-diffusion model (4.24)-(4.25). Historically, a mathematical model for the leakage current in the ionization region was proposed by E.R. Hodgson [148] to overcome the complex task of obtaining experimental results for large gas volumes, pressures and high applied voltages [149]. The following analytical expression for the leakage current flowing in the gas was proposed [148]:

$$I = \frac{N Z_m \phi^{0.5} \sigma \tau_0 \mu_m U A}{P^{1.5} L} \left[1 - \exp \left(- \frac{L^2 \phi^{0.5} P^{1.5}}{\tau_0 \mu_m U} \right) \right], \quad (4.59)$$

where the electrode separation distance is L and A the electrode area. U is the applied voltage, N the number of gas molecules proportional to the pressure P , Z_m the atomic number and μ_m the ion mobility proportional to the mass m , that is $\mu_m \propto 1/m$, σ is the ionization cross-section and $\tau_0 = \tau \sqrt{P \phi}$ where τ is the lifetime of an electron-ion pair [148]. From equation (4.59) two general trends can be extrapolated [148]:

- $I \propto (Z_m A \phi^{0.5} \sigma \tau_0 \mu_m U) / (P^{0.5} L)$ at large volumes/electrode separation ($L \gg (\tau \mu_m) E / P$),
- $I \propto Z_m \sigma A L P \phi$ at high voltages/field saturation conditions ($L \ll (\tau \mu_m) E / P$). This expression coincides with the formula (4.58).

To show the capability of the drift-diffusion model in treating external ionization fields, a plate-parallel electrode configuration is analyzed, whose geometry is reported in Fig. 4.6a. For this simple electrode configuration, the drift-diffusion model (4.24)-(4.25) has an analytical solution for the current density field in the gas as a function of electric field intensity E , which is expressed as [150]:

$$J(E) = \frac{e(\mu^+ + \mu^-)^2 E^2}{2RL} \left[\sqrt{1 + \frac{4RL^2 S}{(\mu^+ + \mu^-)^2 E^2}} - 1 \right]. \quad (4.60)$$

Its trend, shown in Fig. 4.6b with the continuous blue curve, tends towards a saturation value for high electric fields. This saturation value can be determined by the previous expression (4.60) for high electric field values and is controlled by the ion-pair generation rate S [151]:

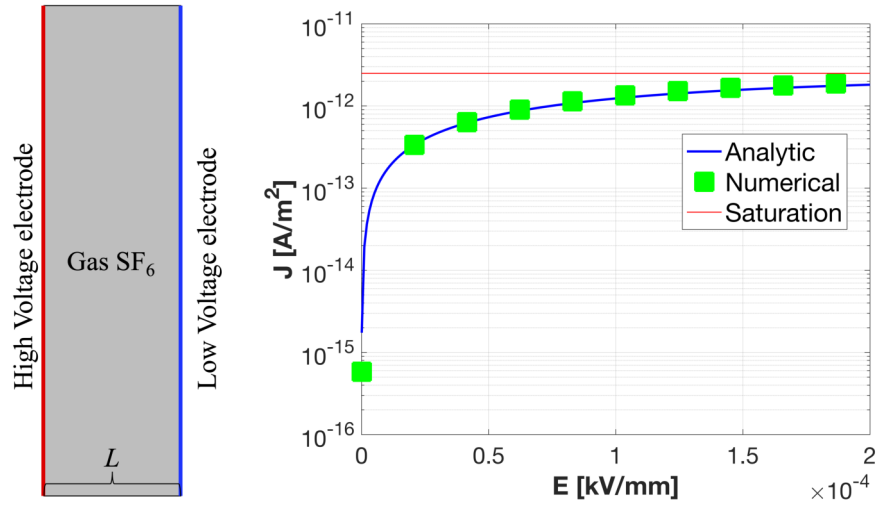
$$J_{sat} = eSL. \quad (4.61)$$

This line is shown in red in Fig. 4.6b. It is clear that increasing the amount of external radiation the ion-pair generation rate S increases, consequently the saturation current density, following Eq. (4.61). The trend predicted by Eq. (4.60) can be equivalently obtained from the numerical solution of the drift-diffusion model in the proposed geometry by sweeping the applied voltage in the high voltage electrode. The simulation results are given in Fig. 4.6b using green squares, and agree very well with the analytical trend.

To account for the RIC phenomenon in standard EQS electric field analysis, an expression for the equivalent electrical conductivity of the gas as a function of the source parameter S must be given in the form $\sigma_G = \sigma_G(S)$. As explained in [34], the orders of magnitude of $\sigma_G(S)$ can be extrapolated from the expression of the saturation current (4.58). In the same way, the expression (4.61) can be adopted, once the relation between the dose rate ϕ and the ion-pair generation rate S is introduced [152]:

$$S = \frac{\phi \rho}{eW}, \quad (4.62)$$

4.5. LEAKAGE CURRENT MODELING



(a) 2D plate-parallel geometry used in the analysis. The gap distance is $L = 50$ cm, while SF_6 @ 0.5 MPa is used as insulating gas.

(b) Leakage current density for the ionization region at relatively low field strengths.

Figure 4.6: 2D electrode layout setup and ionization region curve.

where ρ [m³/kg] is the gas density and W [eV] is the energy required for generating one ion-pair (≈ 34 eV for SF₆). Combining Eq. (4.61) and Eq. (4.62) the orders of magnitude of the equivalent conductivity of gas are given by:

$$\sigma_{G,RIC} = \frac{J}{E} = \frac{eSL^2}{U}. \quad (4.63)$$

4.5.2 Injection region

The saturation condition predicted by Eq. (4.61) for high electric field intensities is denied by experimental evidence. That is, the measured leakage currents flowing, for example in SF₆, at fields of several kV/mm are much larger than those predicted by the saturation condition alone. In principle the experimental observations can be related to the influence of the surface roughness of the electrode: *for high field stresses at the cathode, electrons are emitted due to the rough surface field enhancement. If the insulating gas is highly electronegative these electrons attached to gas molecules leading to negative ions.* This means that, in the case of electronegative gases and neglecting the free electron content, the process reflects to negative ion injection. Originally the injection of negative ions from the cathode to the gas volume, was modeled with Schottky or Fowler-Nordheim (FN) theories, such as [129]:

$$-\mathbf{n} \cdot \Phi_{n^-} = \alpha_{FN} \lambda_{FN} a_{FN} \frac{(\beta_{FN} E)^2}{e W_W} \exp \left(-\frac{v_{FN}(y_{FN}) b_{FN} W_W^{3/2}}{\beta_{FN} E} \right), \quad (4.64)$$

where Φ_{n^-} [1/(m² · s)] is the flux of negative ions, a_{FN} [ÅeV/V²] and b_{FN} [V/(eV^{3/2} · m)] are the Fowler-Nordheim constants, α_{FN} is the ratio of an effective emitting area to the whole electrode area, λ_{FN} is a correction factor, β_{FN} is the field enhancement factor due to surface roughness, W_W [eV] the metal work function and $v_{FN}(y_{FN})$ a function accounting for the deformation of potential barrier, which can be simplified by the following relation [144]:

$$v_{FN}(y_{FN}) \sim 0.956 - 1.062 y_{FN}^2 \quad (4.65)$$

with:

$$y_{FN} = \frac{3.795 \cdot 10^{-5} \sqrt{E}}{W_W}. \quad (4.66)$$

However, as highlighted in [153] in the specific case of pressurized SF₆ gas, the measured leakage current for high field stresses both for positive and negative electrode polarities exhibit different trends. The leakage current for negative voltages shows a steep increase, while the one for positive polarities

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remain unchanged. This observation suggested that the Fowler-Nordheim theory is not able to correctly reproduce the leakage current increase which therefore must be traced back to different causes [154]. From experimental observations, the leakage current injection in SF₆ can be traced back to surface roughness and the residual relative humidity content (%RH) in the gas, in addition, the effect of the pressure level seems to be irrelevant for high electric field values. This trend is not exclusive of SF₆ gas-insulated systems; as a matter of fact the same trend is observed for the novel Fluoronitrile/CO₂ mixtures [155].

With the purpose of characterizing the negative ion injection behaviour from the numerical viewpoint within the drift-diffusion model, a numerical flux along the emitting boundary $-\mathbf{n} \cdot \Phi_{n-}$ must be defined, possibly starting from the experimental data [156]. As suggested in [154], the negative ion injection due to the rough surface electrode and relative humidity content, can be interpreted as a Neumann-type boundary condition for Eq. (4.25):

$$-\mathbf{n} \cdot \Phi_{n-} = g(E, P, RH), \quad (4.67)$$

where $g(E, P, RH)$ is function of the electric field strength E , gas pressure P and the percentage of relative humidity content RH . For example, in [154] the exponential fitting is proposed:

$$-\mathbf{n} \cdot \Phi_{n-} = \frac{\sum_i j_i \exp(a_i E^{b_i})}{e}, \quad (4.68)$$

where the pressure and relative humidity dependence are embedded in the exponential equation parameters j_i , a_i and b_i . These parameters are selected in such a way that the cathode regions satisfying $E > E_{transition}$ exhibits injection of negative ions, driving to a steep increase in the electric conductivity of the gas. To inspect this topic from the numerical point of view, the already described plate-parallel geometry of Fig. 4.6a is again used. The function $g(E, P, RH)$ is retrieved from the experimental results in [156] with $RH = 1\%$ following the exponential trend (4.68). The equivalent leakage current density is illustrated in Fig. 4.7. As expected, the numerical solution well agree with the experimental one from which the flux of negative ions is constructed. It is important to highlight that the transition field $E_{transition}$ which generates new negative ions in the systems, is not uniquely determined, in fact under the same experimental conditions the transition is poorly reproducible and varies for each measurement [153].

To analyze the leakage current regime in SF₆ a Graphical User Interface (GUI) in MATLAB® is developed and its layout is given in Fig. 4.8. The GUI is able to capture different trends for the function $g(E, P, RH)$ by

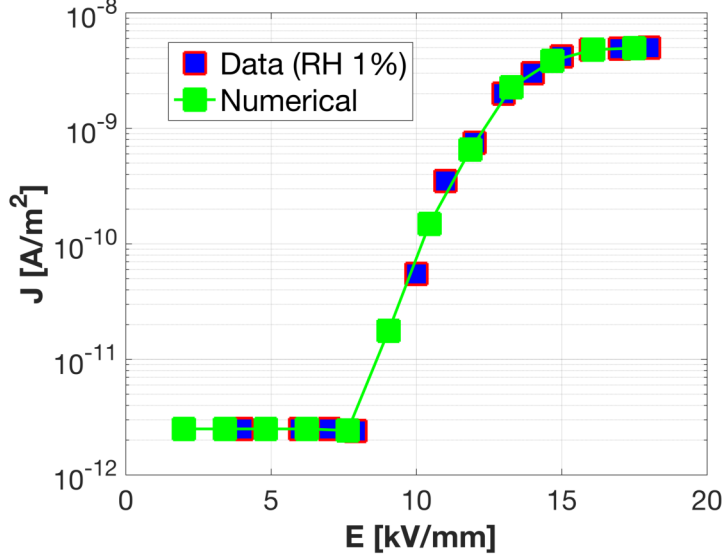


Figure 4.7: Leakage current density for the injection region at high field strengths. The experimental data for a relative humidity of RH=1% are retrieved from [156] and the injected current density constructed accordingly.

choosing the gas pressure and the relative humidity parameter. Then the underlying MATLAB® scripts combined with the FEM solver of COMSOL® Multiphysics, produce the whole trend of the leakage current density for the selected geometry by sweeping the applied voltage.

As explained in the introduction of this chapter the firefly motion of conducting metal particles eventually attaching to the high voltage electrode, can be seen as a source of new negative ions in the gas due to the electric field enhancement in the very small tip of the particle. The flux of injected ions due to local field enhancement can be modeled with the micro-discharge flux which accounts only for the electric field effect [115]:

$$-\mathbf{n} \cdot \Phi_{n^-} = \tilde{k} \beta_{eff} E \left(\beta_{eff} E - \left(\frac{E}{P} \right)_0 \right) \quad (4.69)$$

where β_{eff} is the field enhancement factor and $\tilde{k}$ [1/(V² · s)] a correction coefficient. In [115] the flux expression (4.69) is also used to analyze the emission due to rough surfaces, by properly setting the enhancement factor β_{eff} . It is important to emphasize that the effect of metal particles not only causes an emission of ions in the gas, but can also lead to streamer inception due to the highly inhomogeneous electric field in the system, measured with expression (3.22).

4.6. THERMAL-FLUID MODELING

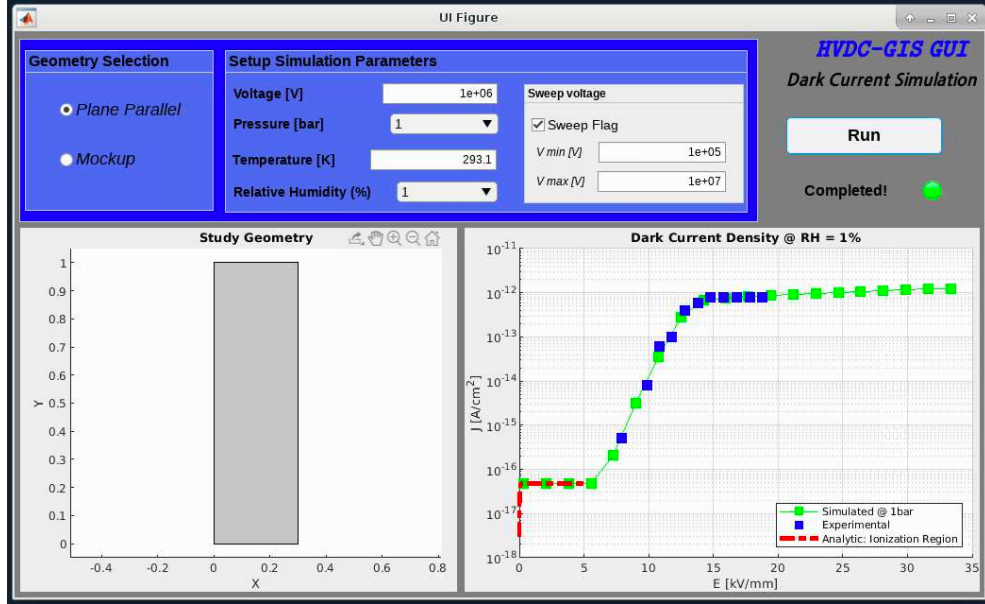


Figure 4.8: COMSOL[®] with MATLAB[®] GUI developed for the leakage current modelling in SF₆.

In view of the described phenomena, when operating HVDC gas-insulated systems, particular attention must be made in analyzing the environment where the components are placed. For example, the components located in the proximity of radiation sources, as those facing the Tokamak hall of a nuclear fusion device, must account for the RIC phenomenon which can drastically reduce the electrical resistivity of the insulating gas up to a saturation level. Numerically, this aspect can be analyzed by changing the ion-pair generation rate S in the drift-diffusion model. In addition, if the electric field stresses in the system are above a certain threshold, for example due to small metallic defects or rough surfaces, the leakage current can exhibit a step transition which may completely destroy the dielectric performances of the system.

4.6 Thermal-fluid modeling

As stated at the beginning of this chapter the accumulation of surface charge along the gas-solid interfaces is driven by the discontinuity of current density fields and the surface conductivity of the interface layer. As stated in Section 3.2, the electrical conductivity of the solid insulator material is affected by the temperature field in the system, and in general this should be true

even for the insulating gas.

For commercial gas-insulated transmission lines carrying conduction currents of thousands of Ampere, the Joule heating produced by the central conductor may drastically affect the temperature distribution both in the solid and gas parts. The temperature field induces a motion of the gas, treated as a fluid domain, under the effect of buoyancy force. In fact, the gas heated by the central conductor tends towards the upwards and, when cooled down by the external shell of the transmission line, goes downwards transferring the heat in a cyclical way [157].

Due to the fluid behaviour of the insulating gas, the mathematical description of the temperature field in the transmission line, or in general HVDC gas-insulated systems, has to be treated as a coupled electro-thermal-fluid problem, which drastically increases the computational burden for its numerical solution. In addition, if the flow outside the system, for example the surrounding air, has to be analyzed, the computational domain has to be extended to impose the reference temperature at the (far away) boundaries.

The coupling between the thermal-fluid and the electromagnetic field is performed through the Joule heating effect, which is a heat source term for the thermal analysis:

$$Q_J = \mathbf{J} \cdot \mathbf{E} = \frac{||\mathbf{J}||^2}{\sigma}, \quad (4.70)$$

where σ is the electrical conductivity of the central conductor. A major difference between HVAC and HVDC gas-insulated systems is the induction of eddy currents in the enclosure. In transient DC no eddy currents are induced in the enclosure, this means that the $\mathbf{E}$ and $\mathbf{J}$ fields can be described by decoupled equations, for example using separated electric and magnetic analyses. In principle the magnetostatic assumption is sufficient for the thermal analysis, however, when the solid insulator is characterized by temperature and electric field dependency, the electric analysis is mandatory. The simpler way to do so is to solve at the same time electrostatic, or stationary current conduction, and magnetostatic as in [158]. The heat source Q_J to be imposed in the thermal analysis correspond to the volumetric power losses calculated from the magnetic problem. In [62, 159] the thermal analysis is coupled with the drift-diffusion model 4.3.2 for the gas domain, and the heat source Q_J specified manually for a given current flowing in the inner conductor.

The thermal analysis can be neglected when the power losses P_R of the high voltage conductor are negligible or for short operational times t_{op} . As a matter of fact a rough estimation of the temperature increase of the dielectric gas, can be determined under adiabatic conditions as:

$$\Delta T = \frac{P_R \times t_{op}}{m \times C_p}, \quad (4.71)$$

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where m is the mass of gas and C_p [J/(kg K)] the heat capacity.

Aim of this section is to briefly recall the mathematical background for the description of the aforementioned multiphysics problem.

4.6.1 Thermal modeling

This section briefly describes the mathematical foundations for the thermal field modeling. The general problem of heat conduction, convection and radiation is described by the following PDE:

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = \nabla \cdot (k \nabla T) + Q, \quad (4.72)$$

ρ is the density, $\mathbf{u}$ is the convective field, C_p the heat capacity, k [W/(m·K)] the thermal conductivity and Q [W/m³] the heat source. In solids, as the insulator, inner conductor and enclosure, heat conduction is the main process of heat exchange where $\mathbf{u} = 0$. In addition, the thermal radiation emitted by solid bodies at a certain temperature can be included in the heat transfer equation (4.72) with the additional term [160]:

$$Q_{rad} = \epsilon [G - n_R^2 \sigma_{SB} T^4] \quad (4.73)$$

where ϵ is the surface emissivity, G the irradiation [W/m²], n_R the refractive index and σ_{SB} constant of Stefan-Boltzmann.

Moreover, looking for example at the simple ideal gas law, the gas density can be express as a function of the temperature:

$$\rho(T) = \frac{PM}{RT}, \quad (4.74)$$

where P is the pressure, M is the molar mass and R is the gas constant. It is a well known fact that the metallic conductive parts, such as the grounded enclosure or the inner conductor, have an electrical conductivity σ which exhibits a dependence with respect to the temperature field. This functional dependence can be expressed as [158]:

$$\sigma(T) = \frac{\sigma_0}{1 + \alpha_t(T - T_0)}, \quad (4.75)$$

where α_t is the temperature coefficient of conductivity and σ_0 the reference value of the electrical conductivity.

4.6.2 Fluid dynamics modeling

The buoyancy force acting on the the gas, drives the exchange of heat with the solid parts. This process is the convective heat transfer, also known as natural convection, which determines the convective velocity $\mathbf{u}$ to be used in Eq. (4.72) for the fluid domain. The motion of a compressible gas is described by the well-known Navier-Stokes (NS) equations [160]:

$$\nabla \cdot (\rho \mathbf{u}) = -\frac{\partial \rho}{\partial t}, \quad (4.76)$$

$$\rho \frac{d\mathbf{u}}{dt} = \nabla \cdot \left[-P + \eta(\nabla \mathbf{u} + (\nabla \mathbf{u})^\top) - \frac{2}{3}\eta(\nabla \cdot \mathbf{u}) \right] + \rho \mathbf{g}, \quad (4.77)$$

where equation (4.76) is the law of conservation of mass and equation (4.77) the momentum conservation. The parameter η models the dynamic viscosity. It is a well known fact the the solution of equation (4.77) is highly involving in the case of compressible ($\nabla \cdot \mathbf{u} \neq 0$) turbulent flows. In natural convection dynamics, the flow may be categorized by looking at the dimensionless Rayleigh R_a and Grashof G_a numbers [160]:

$$R_a = \frac{\rho g \beta (T_c - T_e) L_c^3}{\eta \alpha}, \quad (4.78)$$

$$G_a = \frac{\rho^2 \beta g (T_c - T_e) L_c^3}{\eta^2} \quad (4.79)$$

where T_c and T_e are the conductor and enclosure temperatures, $\alpha = k/(\rho C_p)$ [m²/s] the thermal diffusivity, L_c [m] the characteristic length and β [1/K] the thermal expansion coefficient, evaluated as:

$$\beta = -\frac{1}{\rho} \frac{\partial \rho}{\partial T}, \quad (4.80)$$

which reduces to $\beta = 1/T$ for an ideal gas. A Grashof number in the order of $\sim 10^9$ is considered as a threshold between laminar and turbulence flows [158].

4.7 Numerical methods

In this section the numerical methods adopted for the modeling of HVDC gas-insulates systems are depicted. After a brief introduction concerning the common numerical approaches used for EM simulations, the numerical issues arising when solving nonlinear time dependent PDE, as the drift-diffusion equations (4.24)-(4.25), are examined.

4.7. NUMERICAL METHODS

In the context of electromagnetic modeling, the so-called Finite Element Method (FEM), is a common and widely used approach to tackle the numerical solution of the Partial Differential Equations (PDE). Such technique, historically developed in the context of structural engineering problems, represent the state-of-art approach used by the majority of commercial software. The FEM is based on discretization (or meshing) of the computational domain Ω into finite elements, typically of triangular or quadrilateral shape in 2D and tetrahedral or hexahedral shape for 3D problems. Such partition is denoted with $\mathcal{K}$ and each of its elements with v_k in such a way that:

$$\Omega = \bigcup_{v_k \in \mathcal{K}} v_k, \quad (4.81)$$

moreover the number of mesh nodes, for example coincident with the vertices of triangular elements, is denoted with N_n . The discretized form of the PDE is achieved by exploiting the variational formulation and using, for example, the Galerkin method by expanding the unknown quantity by means of appropriate basis functions [161]. As an example, consider the EQS equation for the electric potential φ (4.23). Associating φ to the nodes of the mesh thus expanding it with nodal basis functions:

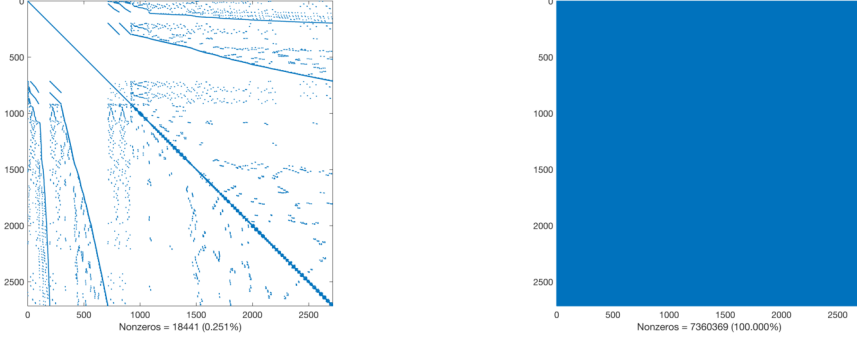
$$\varphi(\mathbf{r}) = \sum_{k=1}^{N_n} \Phi_k w_k^n(\mathbf{r}), \quad (4.82)$$

where $w_k^n(\mathbf{r})$ can be taken as the classical Lagrange basis function, the FEM discretization result in the following Differential Algebraic Equation (DAE) system:

$$\mathbf{K}_\varepsilon \frac{d\Phi}{dt} + \mathbf{K}_\sigma \Phi = \mathbf{0} \quad (4.83)$$

where $\mathbf{K}_\varepsilon$ and $\mathbf{K}_\sigma$ are the so-called mass and stiffness matrices and the array Φ contains the (unknown) nodal values of the electric potential.

The main advantage of FEM relies in the fact that the arising matrices are very *sparse*, thus most of their elements are zero and therefore do not need to be stored in memory. An example of FEM matrix pattern is shown in Fig. 4.9a. Alternatively, the so-called Integral Equation Methods (IEMs) can be adopted. These methods avoid the meshing of non-conducting parts, such as the air domain surrounding the object, thus in principle reducing the number of unknowns n . However, their major drawback is the generation of *dense* matrices, as highlighted in Fig. 4.9b, which may rapidly saturate the RAM memory for realistic EM models due to their $\mathcal{O}(n^2)$ storage cost. To circumvent this issue specialized numerical techniques were developed to reduce the computational burden. For the numerical treatment of HVDC


 (a) *FEM matrix sparsity pattern.*

 (b) *IEM matrix dense pattern.*

Figure 4.9: Pattern of system matrices.

gas-insulated components, since the electric field lines are mostly confined inside the system, the FEM approach is conveniently adopted and is used for analysis that will follow.

When solving drift-diffusion-reaction models such as the one of equations (4.24)-(4.25), care must be given in avoiding numerical instabilities. Defining the local (elemental) Peclet number as a measure of how much the convective term dominates the diffusion one [161]:

$$\mathbb{P}_e := \frac{\|\mathbf{u}\| h}{2D}, \quad (4.84)$$

where h is the mesh size, D the diffusion coefficient and $\mathbf{u}$ the convective field, numerical instabilities may arise when $\mathbb{P}_e > 1$. To address this issue, artificial numerical diffusion must be added to the original PDE. Usually we are referring to *streamline diffusion*. The additional stabilization term modifies the original PDE, therefore the amount of numerical diffusion to be added is a compromise solution.

Alternative to standard FEM approaches, the local Discontinuous Galerkin FEM (DGFEM) allows discontinuous functions to be used and the coupling between the mesh elements is performed using a numerical flux through the boundaries of the elements. One of the main advantage of this approach relies in its general efficiency in treating conservation laws.

In order to achieve accurate results, a high level of mesh refinement in specific areas of the domain such as the triple points and sharp edges, is required. Particularly in case of time dependent 3D analyses, a uniform refinement all along the domain is wasteful in terms of computation time and resources. Local refinement is of course convenient and a so-called goal-oriented adaptivity based on a quantity of interest which is function of the solution, as

4.7. NUMERICAL METHODS

described in [162], is of particular interest in this case. The adaptation of the mesh is particularly important when solving the streamer propagation model described by equations (4.55)-(4.56)-(4.57), to follow the propagation and to efficiently resolve the areas with large charge density gradients. This is one of the major efforts required for the numerical implementation of the streamer propagation model.

By exploiting the drift-diffusion model, the imposition of Dirichlet boundary conditions for the ion densities as explained in 4.3.2, may be challenging from the computational point of view. In fact, in a discrete setting, the discriminating sign of $\mathbf{n} \cdot \mathbf{E}$ must be checked for all the boundaries of the gas domain Ω_G , and the condition of the ions densities imposed accordingly. A way of imposing the Dirichlet conditions is by means of a penalization method characterized by the penalization constant Λ and, for example, rewriting the Neumann condition of n^+ as:

$$\mathbf{n} \cdot D^+ \nabla n^+ = 0 - \Lambda \Theta(-\mathbf{n} \cdot \mathbf{E}) n^+, \quad (4.85)$$

where $\Theta(\cdot)$ is the Heaviside step function. In this way, when $\mathbf{n} \cdot \mathbf{E} > 0$, $\Theta(\cdot) = 0$ and the boundary is equipped with a Neumann type condition, conversely if $\mathbf{n} \cdot \mathbf{E} < 0$, $\Theta(\cdot) = 1$ thus $n^+ \approx 0$ if Λ is sufficiently high.

When dealing with nonlinear time dependent problems, such as for the time integration of the drift-diffusion model, the choice of the time integration scheme is of key importance. By using commercial FEM software, this task is usually resolved with Backward Differentiation Formula (BDF) with an adaptive order selection between 1 (backward Euler method) and 5. The selection of the order is a trade-off between the computational burden and the stability of the method. Since the stability region of BDF becomes poorer increasing the order [163], setting a maximum order of 3 usually lead to satisfactory results.

A note on cell method

The cell method, historically used for the analysis of HVDC gas-insulated components in nuclear fusion [34, 126] is briefly described here, as a possible technique for solving the EQS model described in 4.3.1. The analysis starts with the discretization of the computational domain Ω by finite elements collected in $\mathcal{K}$, made up of N_n nodes, N_e edges, N_f faces and N_v volumes. A dual tessellation $\tilde{\mathcal{K}}$ obtained from $\mathcal{K}$ using a barycentric subdivision, is defined. The geometric entities associated with $\mathcal{K}$ are called *primal*, while those ones associated with $\tilde{\mathcal{K}}$ are the *dual*. The relation between primal elements are provided by the $N_n \times N_e$ node-to-edge incidence matrix $\mathbf{G}$, the

$N_f \times N_e$ face-to-edge incidence matrix $\mathbf{C}$ and the $N_v \times N_f$ volume-to-face incidence matrix $\mathbf{D}$ [164]. The following relations hold for the dual grid:

$$\tilde{\mathbf{G}} = \mathbf{D}^\top \quad (4.86)$$

$$\tilde{\mathbf{C}} = \mathbf{C}^\top \quad (4.87)$$

$$\tilde{\mathbf{D}} = -\mathbf{G}^\top. \quad (4.88)$$

These matrices are the discrete counterpart of the gradient $\mathbf{G}$, divergence $\mathbf{D}$ and rotor $\mathbf{C}$ operators, for which the discrete counterparts of the vector calculus identities $\nabla \cdot \nabla \times (\bullet) \equiv 0$ and $\nabla \times \nabla (\bullet) \equiv 0$ are still valid, even in the dual grid [165]. According to the classification provided by Tonti's scheme, the physical variables, thus the degrees of freedom (DoFs), are associated with specific geometric entities of the primal and dual grids [166].

As explanatory case, the cell method is applied for the derivation of EQS DAE (4.83), as reported in [126]. The starting point is the Tonti's diagram given in Fig. 4.10. The following array of DoFs living on the primal and dual entities are introduced:

- $\Phi = \{\Phi_k\}$ electric potential on primal nodes n_k ,
- $\mathbf{u} = \{u_k\}$ on primal edges e_k , $u_k = \int_{e_k} \mathbf{E} \cdot d\mathbf{l}$,
- $\mathbf{d} = \{d_k\}$ on dual faces $\tilde{f}_k$, $d_k = \int_{\tilde{f}_k} \mathbf{D} \cdot d\mathbf{s}$,
- $\mathbf{j} = \{j_k\}$ on dual faces $\tilde{f}_k$, $j_k = \int_{\tilde{f}_k} \mathbf{J} \cdot d\mathbf{s}$,
- $\mathbf{q} = \{q_k\}$ on dual volumes $\tilde{v}_k$, $q_k = \int_{\tilde{v}_k} \rho dv$.

The two constitutive matrices $\mathbf{M}_\varepsilon$ and $\mathbf{M}_\sigma$ can be computed exploiting Whitney interpolation schemes, by expanding the electric and displacement fields in terms of edge basis functions $\mathbf{w}_j^e$ [165]. The coefficient of the permittivity matrix $M_{\varepsilon,ij}^k$ relative to mesh element v_k can be expressed as:

$$M_{\varepsilon,ij}^k = \int_{v_h} \varepsilon(\mathbf{r}) \mathbf{w}_j^e(\mathbf{r}) \cdot \mathbf{w}_i^e(\mathbf{r}) dv_k. \quad (4.89)$$

The same is valid for the conductivity matrix $\mathbf{M}_\sigma$ changing $\varepsilon(\mathbf{r})$ with $\sigma(\mathbf{r})$.

A note on gas-insulated systems modeling using commercial FEM software

The solution of HVDC electric field in gas-insulated systems may be addressed with commercial FEM software, with different pros and cons. The

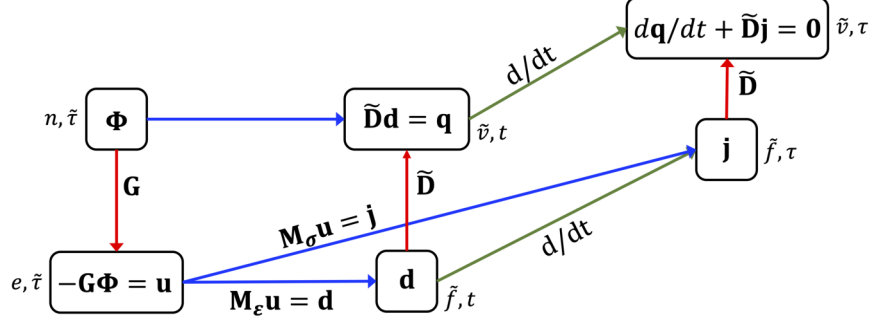


Figure 4.10: The Tonti's diagram for the EQS system.

possibility of using commercial software is of great interest from the industrial point of view, in particular to simplify the dialogue between different partners of a project. However, unlike proprietary codes, the user is not allowed to fully control the numerical technicalities and this can be a limitation. Also, not all numerical problems can be solved efficiently with commercial code, this is for example the case of eddy currents problems, as will be explained in Section A.1.

As an example of commercial FEM software, COMSOL[®] Multiphysics is here considered for the solution of HVDC fields. The EQS formulation for the electric potential described in Section 4.3.1 can be realized in COMSOL[®] under the time-dependent *Electric Currents* module specifying the electrical conductivities, even through nonlinear relations, for each domain and the boundary/initial conditions for the electric potential.

For the solution of the drift-diffusion-reaction model of Section 4.3.2, the method proposed in [167] can be adopted. Since the final goal of the simulation is the correct modeling of the phenomena occurring at the gas-solid interfaces, the correct modeling of the volumetric charge density distribution in the gas domain is not really of interest, thus an *Electric Currents* physics can be solved for the whole computational domain, assigning $\sigma_G \approx 0$. To account for the free charge distribution effect driven by equations (4.24) and (4.25) the *Transport of Diluted Species* physics is solved in the gas domain only and a *boundary current source*, based on the calculated fluxes, is implemented in the electric currents analysis.

For the solution of the electrostatic transient field model of Section 4.3.3, an *Electrostatics* physics can be used, adding the appropriate Dirichlet boundary conditions on the electrodes. For the solid parts no volumetric charge density is present, however for the gas parts the expression (4.26) has to be realized using a *space charge density* node. The field in the gas domain is solved again by the transport of diluted species physics. The charge ac-

cumulation process is incorporated with a *surface charge density* given by equation (4.35), retrieved from the solution of a *Boundary ODEs and DAEs* physics solving equation (4.36).

4.8 Case studies and numerical examples

In this section, a number of selected academic examples are resolved, covering the topics described throughout the chapter. The given numerical examples are not directly correlated with the development of gas-insulated high voltage components for the AGPS of DTT NBI, however they are fundamental in the learning process to become familiar with the modeling aspects. In 4.8.1 the explanation of the drift-diffusion PDE stabilization is given. Then, the penalization method for the Dirichlet condition of the ion densities in the drift-diffusion model is analyzed in example 4.8.2. These first examples are done only for academic purposes as they treat common numerical issues when solving drift-diffusion equations. The Maxwell capacitor benchmark 4.8.3 is used as HVDC gas-insulated system to compare the drift-diffusion and EQS models. The field transition from the initial capacitive to the final restive distribution is figured out in the example 4.8.4, which examines an air-insulated post-insulator. In 4.8.5 the streamer inception in pressurized SF₆ is examined, while the leakage current behavior for 2D axisymmetric HVDC gas-insulated systems is studied in 4.8.6. The coupled electro-thermal analysis over a 2D cross section of a gas insulated transmission line is evaluated in 4.8.7.

4.8.1 Drift diffusion equation

This first explanatory example is addressed to show the numerical issues arising in solving the drift-diffusion equation for a convection dominated problem when $\|\mathbf{u}\| \gg D$. To simplify the analysis, the general time dependent drift-diffusion-reaction is reduced to the following stationary case in $\Omega = [0, 1] \times [0, 1]$:

$$-D\Delta f + \nabla \cdot (f\mathbf{u}) = 0, \quad (4.90)$$

where $\mathbf{u} = [3, 3]^\top$ is the solenoidal convective field and $D = 0.01$ the diffusion coefficient. The boundary value problem is completed with the following Dirichlet boundary conditions:

$$\begin{aligned} f(x, y) &= 1 && \text{on } \Gamma_1 \\ f(x, y) &= 0 && \text{on } \Gamma_2 \end{aligned} \quad (4.91)$$

where:

$$\begin{aligned}\Gamma_1 &= \{(x, y) \text{ s.t. } [x = 0, 0 \leq y \leq 1] \cup [0 \leq x \leq 0.5, y = 0]\} \\ \Gamma_2 &= \{(x, y) \text{ s.t. } [x = 1, 0 \leq y \leq 1] \cup [0 \leq x \leq 1, y = 1] \cup [0.5 \leq x \leq 1, y = 0]\}.\end{aligned}$$

The numerical solution of Eq. (4.90) is tackled with the following methods:

- Discontinuous Galerkin FEM (DGFEM),
- Standard FEM,
- Stabilized FEM with added streamline diffusion coefficient.

The proposed approaches are realized within the commercial FEM software COMSOL® Multiphysics, using both *Weak Form PDE* and pre-existing physics, in particular the *Stabilized Convection-Diffusion equation* module. The latter automatically sets the amount of streamline diffusion to be added in the problem. From the graphical solutions reported in Fig. 4.11, it is clear that the numerical instabilities appearing in the domain boundaries leading to a non-physical solution are noticeably suppressed with the added numerical diffusion term.

4.8.2 Penalization of Dirichlet boundary conditions

The penalization method described at the end of Section 4.7 to impose the Dirichlet boundary conditions for the ions densities at the gas-solid insulator interface, is here analyzed for academic purposes. In this example the geometry given in Fig. 4.12 is used. The chamber is filled with SF₆ at 0.5 MPa and the high voltage electrode supplied with $U_{DC} = 250$ kV. The solid insulator material is characterized by a constant electrical conductivity of $\sigma_I = 3.33 \cdot 10^{-18}$ S/m and $\varepsilon_r = 4.5$. The ion densities and a scaled $\mathbf{n} \cdot \mathbf{E}$ along the creepage length of the gas-solid interface, are reported in Fig. 4.13 after $t = 3600$ s of time integration. As shown in Fig. 4.13 the penalization method with $\Lambda = 10^2$ is capable of correctly capturing the trend for n^+ and n^- . The effect of using a lower penalization parameter is also given in Fig. 4.13, for $\Lambda = 10$. As an example, for $\mathbf{n} \cdot \mathbf{E} < 0$ $n^+ = 0$ as stated in Section 4.3.2. This condition is better reproduced with $\Lambda = 10^2$, indeed with the lower Λ , the transition is less sharp.

4.8.3 Maxwell capacitor benchmark

With the aim of comparing the modeling approaches described in section 4.3.1 and in section 4.3.2, the axisymmetric Maxwell capacitor illustrated in

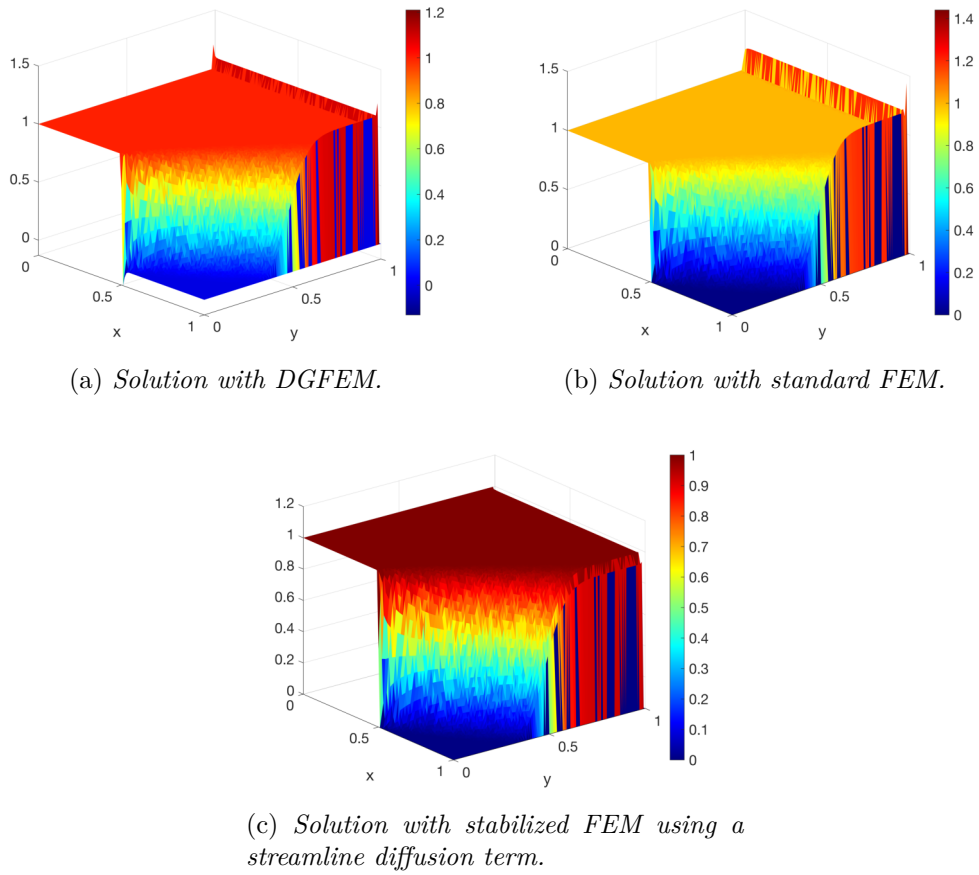


Figure 4.11: Numerical solution of convection diffusion equation. Figures (a) and (b) correspond to non-stabilized numerical solutions, for which non-physical oscillations appear in the domain boundary. The stabilized solution is shown in (c), where greatly reduction of instabilities is achieved.

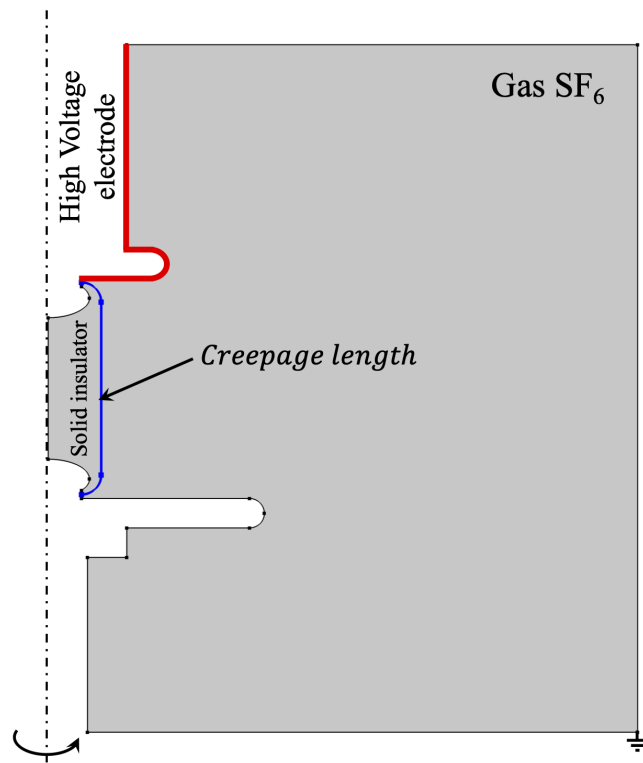


Figure 4.12: 2D axial-symmetric model of the gas-insulated chamber.

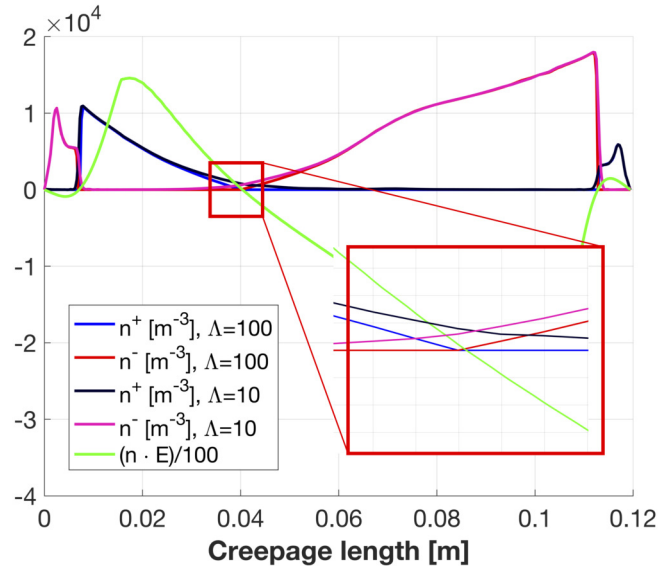


Figure 4.13: Investigation of Dirichlet condition for n^+ and n^- along the gas-solid interface together with the $\mathbf{n} \cdot \mathbf{E}$ trend on the gas-solid interface. The effect of using two different penalization parameters, namely $\Lambda = 10$ and $\Lambda = 10^2$ is shown. A lower penalization parameter reflects in a less sharp transition of ion densities at the boundary.

4.8. CASE STUDIES AND NUMERICAL EXAMPLES

Fig. 4.14a is used as test-case. The inner cylindrical surface of radius $r_i = 4$ m is connected to the high voltage (HV) electrode, while the outer surface at $r_o = 10$ m is grounded. The two dielectric slabs of thickness $\Delta r_1 = 2$ m and $\Delta r_2 = 4$ m refer to solid Ω_I and gas Ω_G domains, for which their interface is denoted with Γ . The HV electrode is supplied with the following transient excitation:

$$U(t) = U_{max} f \min(t, 1/f) \sin(2\pi f t), \quad (4.92)$$

where $f = 10^5$ Hz is the frequency and $U_{max} = 12$ V the peak value. For the solid domain $\varepsilon_r = 4$ and $\sigma_I = 10^{-16}$ S/m are used, while the gas domain, with $\varepsilon_r = 1.002$, is filled with SF₆ pressurized at 0.5 MPa, and the corresponding transport parameters of equations (4.24) and (4.25) are listed in Table 3.1. To compare the drift-diffusion model with the EQS one, an equivalent conductivity in Ω_G has to be assigned. To do so, here, the drift-diffusion model is firstly solved and the mean value of σ_G extrapolated using equation (4.30). The corresponding scalar value is then used for the solution of the classical EQS model of equation (4.23). For the solution of the drift-diffusion-reaction and EQS models COMSOL[®] Multiphysics is used, together with an in-house EQS solver based on cell method (or Discrete Geometric Approach, DGA). To address the numerical instabilities arising in the drift-diffusion model, a streamline stabilization term is added to the original equations. The simulation runs for $t = 4 \cdot 10^{-5}$ s and the results reported in Fig. 4.14, showing great accordance between the results.

4.8.4 Post-insulator in air

To illustrate the different pattern of the initial capacitive field and the final resistive distribution after long-time operation of an HVDC gas-insulated system, the post-type insulator embedded in an air-insulated chamber proposed in [59] is realized. The system is energized by a high voltage electrode entering from the top of the chamber with $U_{DC} = 15$ kV while the walls of the chamber are referred to ground potential. The drift-diffusion equations (4.24)-(4.25) are solved with the *Transport of Diluted Species* module of COMSOL[®] with the following gas parameters: $\mu^+ = 1.36 \cdot 10^{-4}$ m²/(V·s), $\mu^- = 1.87 \cdot 10^{-4}$ m²/(V·s), $R = 1.4 \cdot 10^{-12}$ m³/s and $S = 7 \cdot 10^6$ 1/(m³·s). The simulation runs for $t = 730$ h (approximately corresponding to 1 month) and the results are extrapolated. Specifically, Fig. 4.15a reports the electric potential along the creepage length of the solid insulator at the beginning ($t = 0$) and at the end of the time integration, while the accumulate charge density at $t = 24$ h, $t = 168$ h and $t = 730$ h is given in Fig. 4.15b. In Fig. 4.16 the initial capacitive and final resistive field distribution after $t = 730$ h are

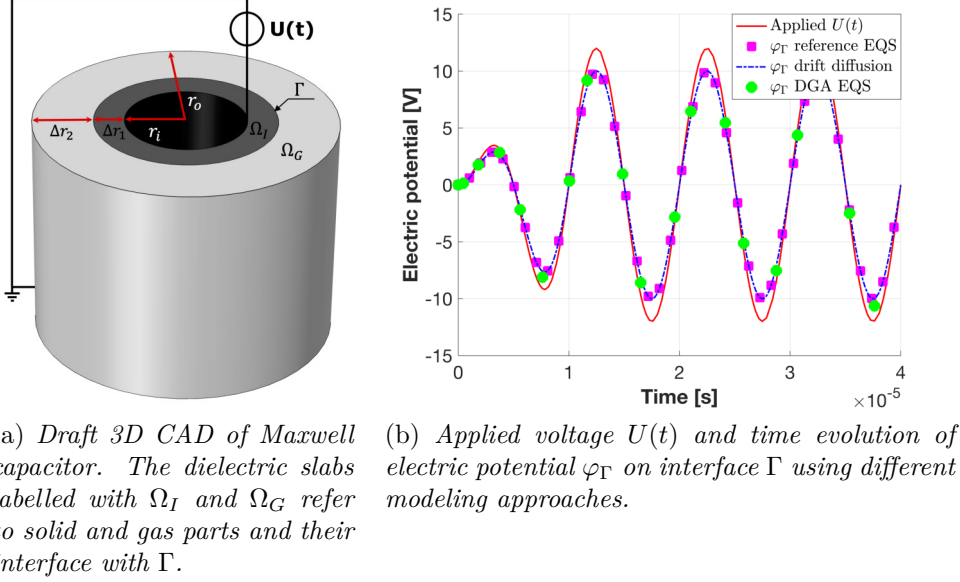


Figure 4.14: Maxwell capacitor benchmark.

illustrated.

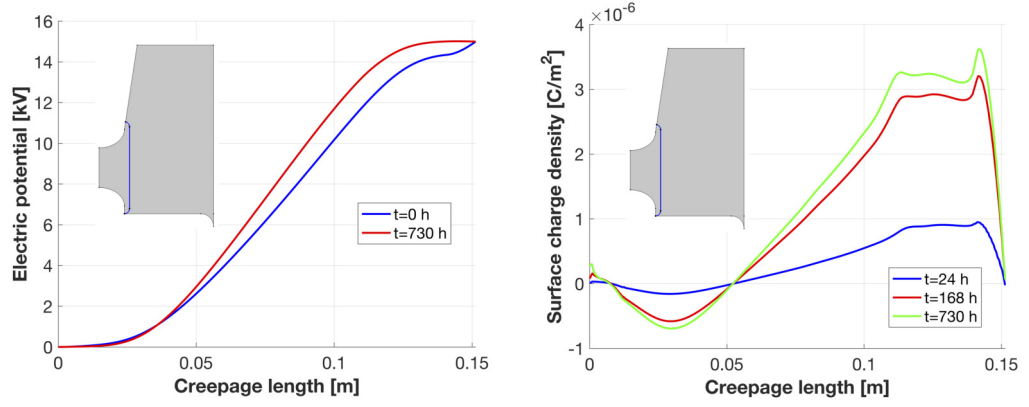
4.8.5 Streamer inception in SF_6

In this example the streamer inception mechanism for SF_6 -gas insulated equipments is analyzed. In principle, the capability of COMSOL[®] *Plasma* module in solving the collisional Boltzmann equation to obtain the effective ionization coefficient $\bar{\alpha}$ is verified. Next, the streamer inception for a 2D axisymmetric electrode configuration is examined.

Effective ionization coefficient of SF_6

With the purpose of comparing the capability of the collisional Boltzmann equation described in 4.4 with the empirical formula expressed by Eq. (4.45), Eq. (4.50) is solved by means of the commercial software COMSOL[®] Multiphysics using the *Plasma* module. The set of electron-molecule collisional reactions used in this example are reported in Table 4.2. Using COMSOL[®] the reduced Townsend coefficient α/N and the reduced attachment coefficient η/N are automatically obtained in the post processing analysis. The resulting trend of $\bar{\alpha}/N$ is then compared with the empirical one defined by equation (4.45), and looking at Fig. 4.17, the results are in good agreement. Both expressions predict a critical reduced field $(E/N)_0$ of about 360 Td and

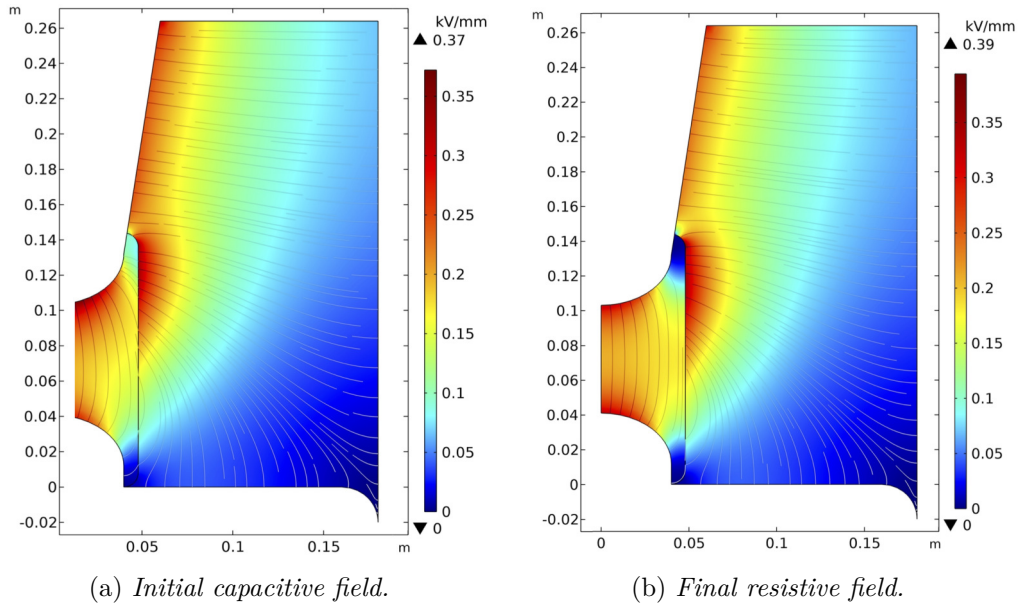
4.8. CASE STUDIES AND NUMERICAL EXAMPLES



(a) Electric potential at the beginning and at the end of simulation. The inset shows the geometric model and the where the creepage length is highlighted in blue.

(b) Accumulated charge density for three selected time instants. The inset shows the geometric model and the where the creepage length is highlighted in blue.

Figure 4.15: Electric potential and charge density accumulation trend along the creepage length of the air-insulated post-type insulator test case for an applied voltage of 15 kV for $t = 730$ h.



(a) Initial capacitive field.

(b) Final resistive field.

Figure 4.16: Electric field intensity for the air-insulated post-type insulator test case for an applied voltage of 15 kV for $t = 730$ h.

Sequence	Reaction	Type
R ₁	$e + \text{SF}_6 \rightarrow e + \text{SF}_6$	Elastic collision
R ₂	$e + \text{SF}_6 \rightarrow e + \text{SF}_6^*$	Excitation ($\Delta\epsilon = 10$ V)
R ₃	$e + \text{SF}_6 \rightarrow e + \text{SF}_6^{**}$	Excitation ($\Delta\epsilon = 11.7$ V)
R ₄	$e + \text{SF}_6 \rightarrow e + \text{SF}_6^{***}$	Excitation ($\Delta\epsilon = 15$ V)
R ₅	$e + \text{SF}_6 \rightarrow 2e + \text{SF}_6^+$	Ionization
R ₆	$e + \text{SF}_6 \rightarrow \text{SF}_5 + \text{F}^-$	Attachment
R ₇	$e + \text{SF}_6 \rightarrow \text{SF}_4 + \text{F}_2^-$	Attachment

Table 4.2: Electron-collisional reactions for pure SF₆. The asterisk in the excitation type reactions, refers to the three different channels.

by using the ideal gas law $P = Nk_B T$ assuming $T = 293.15$ K, the usual value of the critical breakdown field $(E/P)_0 = 89$ kV/mm/MPa commonly reported in literature [53], is retrieved.

Prediction of streamer inception in SF₆-gas insulated chamber

In this example the prediction of streamer inception for the electrode configuration shown in Fig. 4.12 is analyzed. In this case the chamber is filled with pressurized SF₆ at 0.1 MPa, while the high voltage electrode is supplied with $U_{DC} = 250$ kV. The proposed electrode-insulator system differs from GIL configurations, but corresponds to typical experimental arrangements adopted for investigations on GIS applications. For the electric field calculation, stationary-resistive conditions are taken and the drift-diffusion model of equations (4.24)-(4.25) solved in the gas domain. The values of $\mu^\pm = 3.6 \cdot 10^{-5}$ m²/(V·s) are taken, while the recombination coefficient and ion-pair generation rate are $R = 1.7 \cdot 10^{-12}$ m³/s and $S = 1 \cdot 10^7$ 1/(m³s). Once the electric field is computed, the streamer criterion can be verified. Streamer integrals (4.42) are calculated with COMSOL® by using the *Charge Particle Tracing* (CPT) module, integrating along particle trajectories and using a massless formulation [168, 169]. The results are shown in Fig. 4.18. It can be observed that, for the assigned operational parameters, the streamer breakdown inception occurs: there exist field lines, originating from the high voltage electrode, for which $K > K_{cr}$.

4.8.6 Leakage current in SF₆

The injection of negative ions from the cathode and the consequent rise in the leakage current flowing in the gas is examined. The first example deals with the effect of a small metal defect attached to the electrode, while the

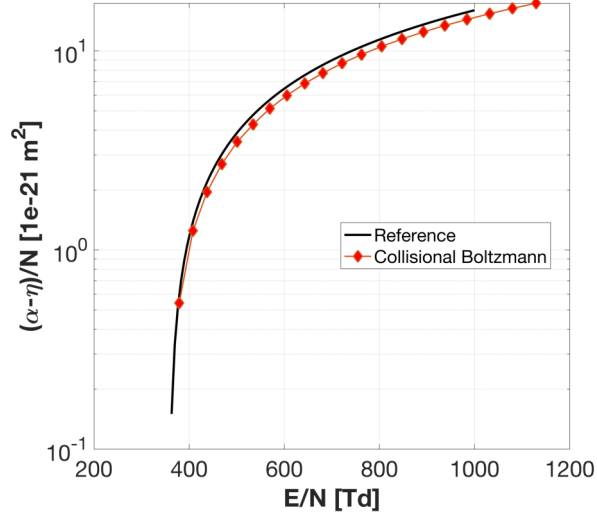


Figure 4.17: Reduced effective ionization coefficient $\bar{\alpha}/N$ in logarithmic scale for pure SF_6 , evaluate with the reference equation (4.45) and by solving the collisional Boltzmann equation (4.50) with COMSOL®.

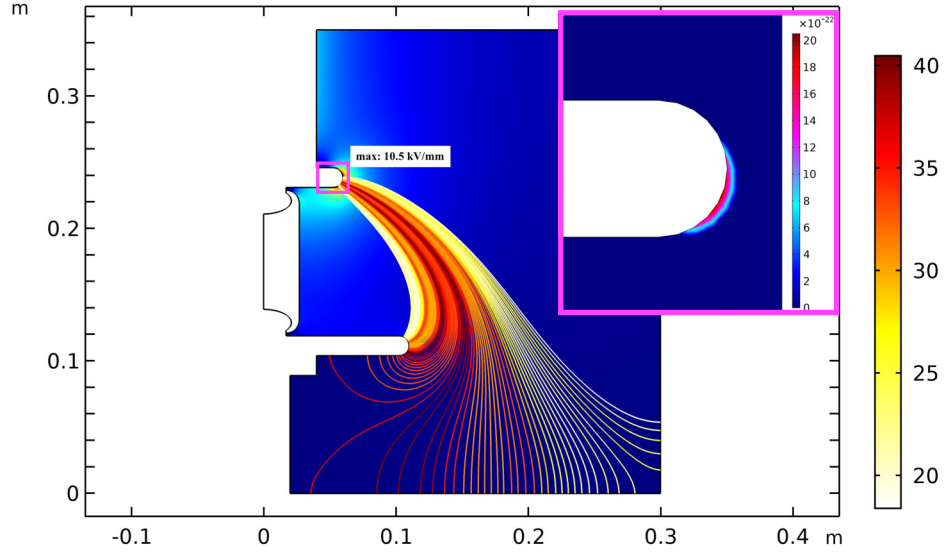


Figure 4.18: Streamer integrals of equation (4.42) satisfying streamer criterion for discharges originating from high voltage electrode. The peak value of simulated electric field is above the breakdown electric field of SF_6 of 8.9 kV/mm at 0.1 MPa. The inset detail shows the region where $\bar{\alpha} > 0$ in proximity of the high voltage electrode.

second example compare the equivalent current density in the gas under ideal operational conditions and with charge injection.

Leakage current induced by small metal particle

As stated in the introduction of the chapter, the firefly of metal particles moving around negative polarized transmission lines, may result in gas breakdown if the electric field strength is sufficiently high in the particle tip. Moreover, the emitted ions enhance the leakage current in the gas, which can be measured by external probes.

In this example, the effect of a small defect with a thickness of 0.25 mm, attached to the negative polarized electrode is analyzed. The geometry consists in a 2D axisymmetric conical spacer already used for numerical investigations of the 1 MV HVDC TL for ITER NBI [35], characterized by $\sigma_I = 3.5 \cdot 10^{-15}$ S/m, $\sigma_S = 0$ S and $\varepsilon_r = 4$. The insulator is embedded in a chamber with pressurized SF₆ at 0.5 MPa with $\varepsilon_r = 1.002$ and the applied voltage to the high voltage electrode is $U_{DC} = -550$ kV. The electric field is evaluated with the drift-diffusion model with the SF₆ parameters listed in Table 3.1, up to $t = 3600$ s. The negative ions injected from the metal particle tip follow equation (4.69) with $\beta_{eff} = 4$ and $k = 1.56 \cdot 10^{-3}$ 1/(V² · s). The enhanced leakage current is given in 4.19a. Moreover, due to the high electric field stress in the tip, streamers can originate following Eq. (4.42). To consider the non-uniformity of the field, the critical electric field $(E/P)_0$ of SF₆ is reduced by the field utilization factor expressed by relation (3.22) which is equal to $\eta = 0.08$ for this geometry. The streamer integrals are shown in Fig. 4.19b, from which a streamer inception channel satisfying $K \geq K_{cr} = 18.4$ is deduced.

Leakage current induced by rough cathode electrode

The effect of negative ions emitted from a rough electrode against the surface charge accumulating on the solid insulator, is investigated for the geometry reported in Fig. 4.20. For simplicity, a constant electrical conductivity $\sigma_I = 3.33 \cdot 10^{-18}$ S/m is used for the solid insulator, characterized by $\varepsilon_r = 4.5$, while SF₆ gas at $P = 0.5$ MPa and $T = 293.15$ K is used as dielectric medium in the chamber. The high voltage conductor at $U_{DC} = -500$ kV is the cathode region from which negative ions are emitted quasi-uniformly following expression (4.69) with $\beta_{eff} = 4$ and $\tilde{k} = 1.56 \cdot 10^{-3}$ 1/(V² · s). The numerical simulation lasts for $t = 3600$ s. The equivalent current density in the gas in ideal and rough cathode conditions, that is, without and with charge injection are shown in Fig. 4.21. The effect of newly negative ions

4.8. CASE STUDIES AND NUMERICAL EXAMPLES

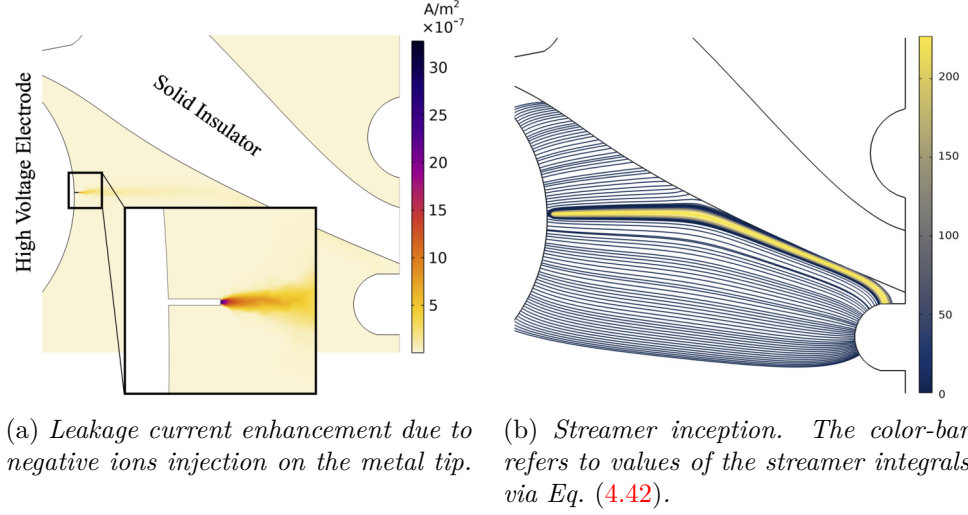


Figure 4.19: Effect of small metallic defect attached to the negative polarized high voltage electrode.

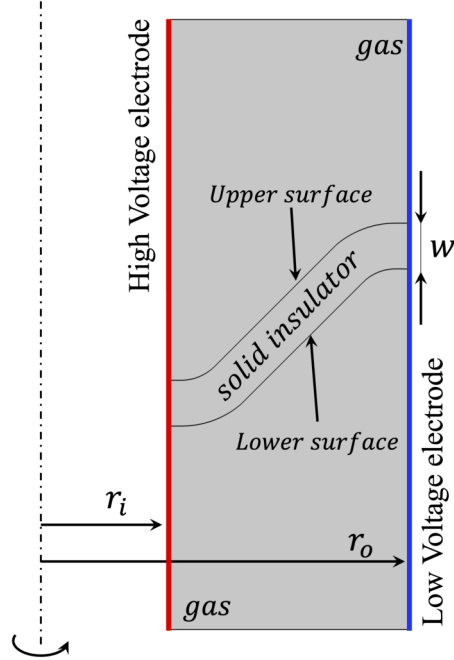


Figure 4.20: 2D axisymmetric conical insulator model. Inner and outer radius are $r_i = 90$ mm and $r_o = 250$ mm, while the solid insulator thickness is $w = 30$ mm.

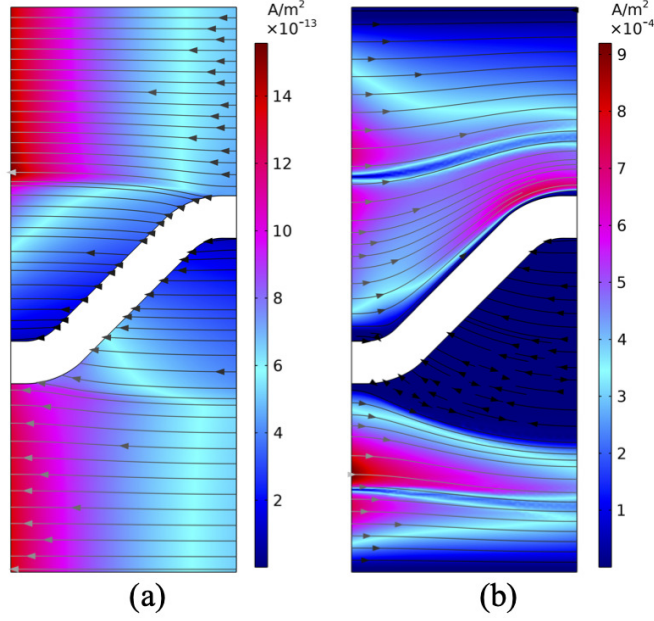


Figure 4.21: Leakage current density in SF_6 : with (a) and without (b) cathode emission.

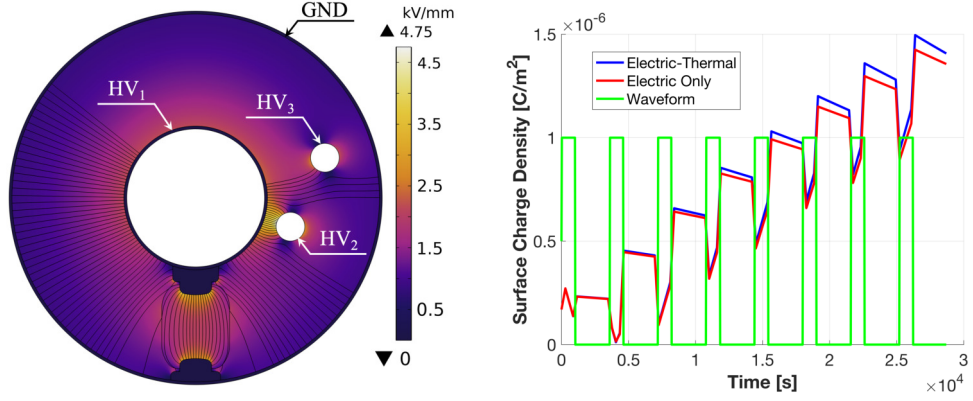
moving in the chamber remarkably affects the behavior of the leakage current flowing in the gas and must be considered in the operational phase.

4.8.7 Coupled electro-thermal analysis of gas insulated line

The electro-thermal model described in Section 4.6 is applied to study the effect of the thermal field on the charge accumulation behavior. The model is applied to a 2D cross section of a multi-conductor TL filled with SF_6 at 0.5 MPa. The solid insulator is characterized by the temperature-dependent electrical conductivity expressed by Eq. (3.20), while for SF_6 the conductivity law of Eq. (3.6) is used together with Eq. (3.15) for thermal conductivity.

Referring to Fig. 4.22a, the voltages HV_1 , HV_2 and HV_3 are -510 kV, -334 kV and -167 kV respectively, and the enclosure is grounded. The electric current flowing in the central and intermediate conductors is $I_1 = 3150$ A, $I_2 = I_3 = 1$ A. The value of I_1 follows from typical values given in literature, in the context of electro-thermal analysis of gas-insulated transmission lines [159]. The imposed voltages and currents have a square waveform of period $T = 3600$ s and duty-cycle $\delta = 0.28$ as given in Fig. 4.22b. The transmission line is embedded in an air environment whose temperature at

4.8. CASE STUDIES AND NUMERICAL EXAMPLES



(a) Voltage labels and electric field map after $t = 25500$ s of time simulation.

(b) Normalized waveform of imposed currents and voltages together with the absolute value of surface charge density accumulation trend in coupled electric-thermal and electric only analysis. The time integration runs for $t = 28800$ s after which no steady station condition is reached.

Figure 4.22: Simulation results for coupled electro-thermal field analysis.

infinity is fixed at 293.15 K, while the surface emissivities of outer enclosure, inner enclosure, conductors and solid insulator are taken as $\epsilon = 0.92, 0.93, 0.2$ and 0.93 [160].

The electric field is evaluated with the EQS model 4.3.1 with a time horizon of $t = 28800$ s (8 hours). The resulting electric field map for the coupled electro-thermal field problem is shown in Fig. 4.22a while the comparison of the trend of charge density accumulation $|\rho_s|$, along the gas-solid interface is shown in Fig. 4.22b. The difference is not that significant in the specific case, however the contribution of a precise modeling of thermal effects in charge accumulation is evident.

It is worth noting that in the specific case of the TL for the NBI of DTT the thermal effects are negligible, given the low value of the transmitted current (of the order of 50 A) and the short pulse duration. We wanted to quote this paragraph for the sake of completeness, as it is considered useful for a comprehensive description of the phenomena at play and the related modeling to take it into account.

4.9 Conclusions

In this chapter, the mathematical and numerical tools currently used in the electromagnetic community for the analysis of gas-insulated high voltage components were described. The EQS model with prescribed electrical conductivities, described in section 4.3.1, extensively investigated in literature due to its simplicity, also from the numerical implementation point of view, can be conveniently used for HVDC gas-insulated systems modeling. This model is useful to obtain preliminary information on electric field levels in the HVDC-GIS system. However, the specification of the electric conductivity of the gas a priori represents its major limitation, since the gas is characterized by drift-diffusion-reaction phenomena which give rise to a non uniform conductivity. To account for all the phenomena occurring in the gas, the drift-diffusion model described in section 4.3.2 is required. By using this model, the ion densities, the effect of external radiation sources and the leakage currents in the gas can be correctly analyzed. The major drawback of the drift-diffusion model is its numerical solution, which may result in numerical instabilities due to the nature of the equations as explained in section 4.7. For completeness, the chapter explains also the coupled electro-thermal model, which is of fundamental importance for the analysis of commercial gas-insulated high voltage components for which the effect of the heating of the central conductor, carrying thousand of Ampère of current, is considerable. In fact, as explained in section 3.2, the electric conductivity of the solid insulator usually exhibits an exponential dependance on the temperature field which may result in a different electric behavior. The numerical examples given at the end of the chapter were selected for academic purposes to cover all the topics described in the chapter, which are general and not directly related with the high voltage gas-insulated components to be developed for the AGPS of DTT NBI.

4.9. CONCLUSIONS

5

Shape optimization

THE KNOWLEDGE of powerful methods for the numerical modeling of electromagnetic devices and the increased performances of the modern computers opens up the possibility of exploiting automatic optimization tools. When facing engineering problems this possibility is of great interest to improve the performances of the components under design possibly reducing their overall cost. Formally, the optimization problem can be formulated as a minimization problem for a given Objective Function (OF) $f(\mathbf{x})$ under D design variables collected in the array $\mathbf{x}$, written as: find $\mathbf{x}^*$ such that:

$$f^* = f(\mathbf{x}^*) = \min_{\mathbf{x}} f(\mathbf{x}). \quad (5.1)$$

One class of optimization problems of particular interest are those involving *shape optimization*. The shape optimization of a device is a parametric optimization in which the design variables (parameters) collected in the array $\mathbf{x}$, defines the shape of the object. For example, in the TEAM problem 25 illustrated in [170], the goal of the optimization is to identify the shape ($\mathbf{x}$) of nonlinear die molds such that the magnetic flux density equals desired values along a specific line (OF). Clearly this optimization task may be solved by “trial and error”, however, in most cases the number of parameters is relatively high and the functional dependence $f(\mathbf{x})$ cannot be argued a priori, thus the solution retrieved by the trial and error procedure is often sub-optimal.

When designing HVDC (High Voltage Direct Current) gas-insulated systems different tasks must be resolved. For example, the engineer may ask which is the shape of a post-insulator that helps homogenize the field in-

tensity along its surface (capacity field grading) or what is the shape of the electrode that minimizes the occurrence of streamers, which in the worst cases can lead to the complete breakdown of the gas with consequent damage or complete destruction of the components. In most practical cases the answer to these questions is a complex task, therefore an automatic procedure able to sustain the engineering phase is of great importance.

Starting from the parametrized geometry, that is, the geometrical description of the domain under optimization by means of a finite number of parameters $\mathbf{x}$, an optimization tool can be conceived by appropriately combining the following numerical ingredients:

- A method to solve the minimization problem stated by Eq. (5.1),
- A technique for solving the underlying Partial Differential Equation (PDE) governing the physics, from which the objective function is determined.

The solution of the PDE can be carried out by means of an in-house numerical solver or by using commercial software. The task of solving the minimization problem can be tackled by different techniques as stated in literature, generally following two main approaches [171]: gradient-based and gradient-free techniques, each one characterized by pros and cons. Gradient-based methods, requiring the sensitivity (derivative) of the objective function with respect to the design variables, usually not easy to compute:

$$\text{Sensitivity} := \frac{df}{d\mathbf{x}}, \quad (5.2)$$

typically exhibit a higher rate of convergence, but suffer from local optimal trapping. Usually the objective function f is not an explicit function of the parameters $\mathbf{x}$, thus the evaluation of the derivative may not be easy and specialized numerical techniques, such as the Adjoint Variable Method (AVM), must be used to this purpose [172]. Gradient-free methods, on the other hand, are more flexible since they do not require the knowledge of the sensitivity but generally require a higher computational effort. Alternative to these methods, deterministic gradient-free ones, such as the simplex gradient method or the simplex-base simplicial Nelder-Mead method, can be adopted [173].

In this chapter an automatic shape optimization tool is conceived. As described in [138] the tool combines a commercial software for the solution of the electric field distribution, based on the electromagnetic modeling of HVDC gas-insulated systems described in Chapter 4, and an in-house gradient-free method for the solution of the minimization problem of equation (5.1). The

flowchart of the optimization tool is summarized in Fig. 5.1 and foresees the following steps performed in an iterative manner:

1. The initial parametrized model is generated, by describing the geometrical part under optimization with parameters x_i collected in the array $\mathbf{x} \in \mathbb{R}^D$, specifying for each parameter, its lower and upper bounds, that is $x_i^{low} \leq x_i \leq x_i^{upp}$,
2. The computational domain based on the current parametrization $\mathbf{x}$ is partitioned into finite elements (mesh) and the objective function evaluated from the solution of the PDE,
3. The gradient-free optimization algorithm, based on stochastic arguments, generate new candidate parameters within the bounds,
4. The new parameter array $\mathbf{x}$ implicitly defines a new geometry for the problem.

The steps 2–4 are performed iteratively until an exit condition is satisfied. The fundamental steps performed by the iterative procedure are describe in the subsequent section. In particular, in Section 5.1 the issues of geometry parametrization is addressed, while in Section 5.2 a gradient free method based on evolutionary concepts is described. The chapter is closed with a series of selected numerical examples in Section 5.3.

5.1 Geometry parametrization

The first task to be faced in performing a shape optimization is the parameterization of the geometric part to be optimized. In general this is the most difficult task a user faces when defining an optimization problem, especially the definition of lower and upper bounds x_i^{low} , x_i^{upp} of the design variables. In principle, one can use non-physical bounds and discard any geometry consisting of unreasonable shapes, however, in this way a lot of computational time is wasted. Beyond the choice of parameters bounds, which depends on the problem in question, the corresponding geometry can be defined by using, for example, *spline* or *Bézier* interpolation here described.

Restricting the analysis to the one dimensional domain $I = [a, b]$ subdivided into $n - 1$ intervals $[x_i, x_{i+1}]$ for $i = 1, \dots, n - 1$, the function $S(x)$ is

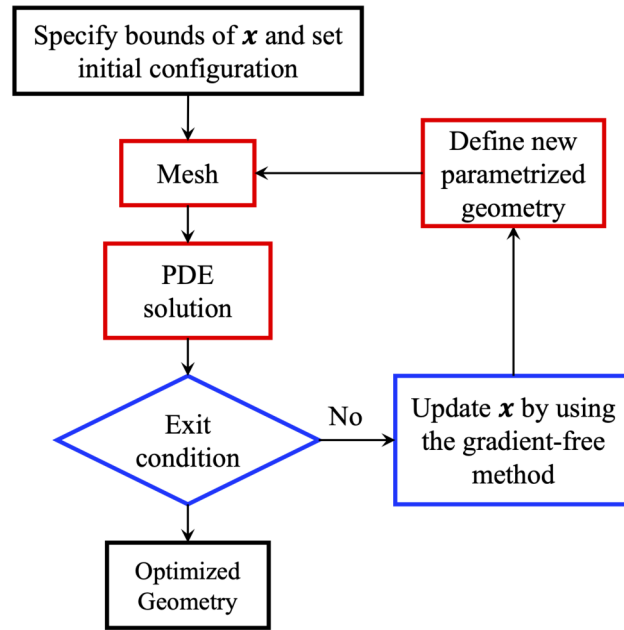


Figure 5.1: Flowchart of the shape optimization tool. The tasks of the blue boxes are up to the gradient-free optimizer, while the ones in the red boxes are performed by the PDE solver.

a spline of degree k in I if $S \in C^{k-1}(I)$ and for each interval:

$$S(x) = \begin{cases} s_1(x) & x_1 \leq x \leq x_2 \\ s_2(x) & x_2 \leq x \leq x_3 \\ \vdots & \\ s_{n-1}(x) & x_{n-1} \leq x \leq x_n \end{cases} \quad (5.3)$$

with $s_i(x)$ a polynomial of degree $k \forall i = 1, \dots, n-1$. Given data y_i and control points x_i for $i = 1, \dots, n$, the spline is interpolant, that is $S(x_i) = y_i$. A particular class of splines are the natural cubic splines, characterized by polynomials $s_i(x)$ of order $k = 3$ with zero second derivative at the endpoints x_1, x_n [174]. The cubic spline interpolation were used for the geometrical parametrization of HVAC SF₆-insulated bushings [175] and disk-shaped spacers for HVDC gas-insulated transmission lines [35].

Alternative to splines, the Bézier interpolation can be used. The Bézier curve can be conveniently adopted when smooth contours are needed, in fact, the Bézier curve will not in general pass through the vertices other than the two endpoints x_1, x_n . The shape of the curve can be modified varying the intermediate points $x_2, \dots, x_{n-1}$ which become the control points of the curve [176]. The general Bézier function of order k can be expressed as:

$$B(t) = \sum_{i=1}^k b_{i,k}(t)x_i, \quad \text{for } 0 \leq t \leq 1 \quad (5.4)$$

where $b_{i,k}(t)$ is k order of Bernstein multinomial and x_i for $i = 1, \dots, n$ a set of points, with x_1, x_n the two endpoints. A graphical comparison between the cubic spline and Bézier curve for $n = 4$ points is given in Fig. 5.2.

5.2 Differential evolution scheme

The task performed by the optimizer is to evolve the D -dimensional design vector $\mathbf{x}$ in such a way the minimization problem is satisfied. The so-called stochastic approaches, are gradient-free methods avoiding the computationally expensive calculation of the objective function sensitivity. A wide class of stochastic approaches, such as the Genetic Algorithm (GA), Differential Evolution (DE), Particle Swarm Optimization (PSO), Simulated Annealing (SA) and Bat algorithm, were extensively applied in literature for the optimization of a wide class of electromagnetic components [170, 177, 178]. The Differential Evolution (DE) algorithm is one of the most popular methods to solve numerical optimization problem and was firstly presented by K. Prince and R. Storn in 1997 [179]. DE is based on typical evolutionary schemes involving mutation, cross over and selection and its basic scheme is shown in

5.2. DIFFERENTIAL EVOLUTION SCHEME

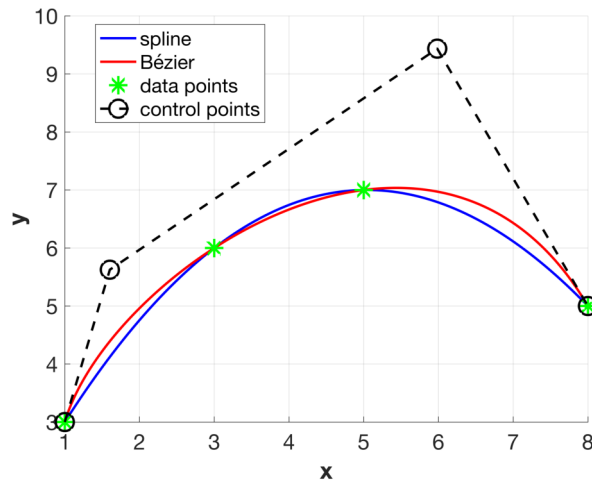


Figure 5.2: Comparison of cubic $k = 3$ spline and Bézier interpolation.

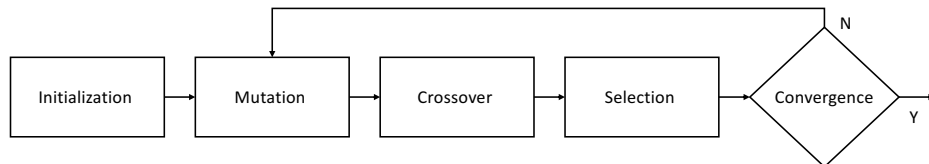


Figure 5.3: Differential evolution basic flowchart.

Fig. 5.3. In this section the principles of DE algorithm are described. The initialization procedure creates a random population of N_p individuals in a D -dimensional parameter space, within specified boundary bounds. Each generation k deals with:

$$\mathbf{x}_i^k = \{x_{i,j}\} \quad i = 1, \dots, N_p \quad j = 1, \dots, D, \quad (5.5)$$

parameter vectors. The mutation operation expands the search space adding difference vectors (donors) to a base individual, for example by using the following scheme, labelled as *DE/rnd/1*:

$$\mathbf{v}_i = \mathbf{x}_{r1} + F(\mathbf{x}_{r2} - \mathbf{x}_{r3}), \quad (5.6)$$

where $\mathbf{v}_i$ $i \in \{1, \dots, N_p\}$ is called the donor vector, while the first $\mathbf{x}$ on the right-hand side is the target. F represents the mutation probability factor. The indexes $r_1, r_2, r_3 \in \{1, \dots, N_p\}$ have to be chosen mutually different and also different from the index i [179]. Usually, best performances are obtained by selecting $\mathbf{x}_{r1} = \mathbf{x}_{best}$ [177], where $\mathbf{x}_{best}$ is the array of parameters which gives a best solution for the minimization problem stated by expression (5.1) at the previous iteration step. In this case the DE scheme is classified as *DE/best/1*. In the recombination phase, parameters from the target and donor individuals are mixed in order to form the so-called trial individuals:

$$u_{i,j} = \begin{cases} v_{i,j} & \text{if } rand_{i,j} \leq CR \text{ or } j = irand \\ x_{i,j} & \text{else} \end{cases}, \quad (5.7)$$

where CR is the crossover ratio, $rand_{i,j}$ random numbers and $irand$ a random integer. Vectors $\mathbf{u}_i = \{u_{i,j}\}$ with $j = 1, \dots, D$, are called trial vectors. The last block of Fig. 5.3 is the selection. Here, a greedy scheme is applied in order to select the next generation:

$$\mathbf{x}_i^{k+1} = \begin{cases} \mathbf{u}_i^k & \text{if } f(\mathbf{u}_i^k) \leq f(\mathbf{x}_i^k) \\ \mathbf{x}_i^k & \text{else} \end{cases}, \quad (5.8)$$

In the selection phase the objective function for each parameters vector $\mathbf{x}_i^k$ is evaluated. If this is obtained from an electromagnetic problem this step correspond to the solution of the systems of equations with the PDE solver, which in general requires a lot of computational effort. The described procedure is repeated iteratively until the termination criterion is reached, usually prescribing the maximum number of DE algorithm iterations it_{max} .

The differential evolution is a heuristic scheme in the sense that the population numerosity N_p , the mutation probability factor F and the crossover ratio CR are selected by the user without no prior information. Parameter

5.3. NUMERICAL EXAMPLES

selection affects how the DE algorithm evolves. As a matter of fact increasing the population size N_p helps in finding better solutions, however, the computational burden increases since the number of objective function evaluations grows as $it_{max} \times N_p$. This issue may be partially solved by exploiting novel deep learning techniques, which recently gained great interest for the optimization of electromagnetic devices [180]. By using these approaches the number of objective functions, thus PDE solutions, can be reduced by constructing surrogate models.

When facing engineering optimization problems, the design of components often requires conflicting demands to be satisfied for their best functionality [178, 181]. This reflects into the need of solving multi-objective optimization problems, where the scalar objective functions $f_i(\mathbf{x})$ are formally collected in vector form [182]:

$$\mathbf{f}(\mathbf{x}) = [f_1(\mathbf{x}), \dots, f_n(\mathbf{x})]^\top \quad (5.9)$$

and the optimal solutions lie on the so-called *Pareto optimal front* [177]. Consider a feasible solution vectors $\mathbf{x}_P$, it is said that $\mathbf{x}_P$ *dominates* a candidate vector $\mathbf{x}_Q$ if the following statement is verified [182]:

$$f_i(\mathbf{x}_P) \leq f_i(\mathbf{x}_Q) \quad \forall i = 1, \dots, n \quad (5.10)$$

and if exist at least one objective f_i ($i = 1, \dots, n$) for which:

$$f_i(\mathbf{x}_P) < f_i(\mathbf{x}_Q). \quad (5.11)$$

The vector $\mathbf{x}_P$ so defined, is a Pareto optimal solution and the collection of all the Pareto optimal objective vectors is the so-called Pareto optimal front.

When only two conflicting objectives are considered it may be convenient to rewrite the vectorial multi-objective optimization problem into a scalar one through the convex combination

$$f(\mathbf{x}) = \alpha_1 f_1(\mathbf{x}) + \alpha_2 f_2(\mathbf{x}), \quad (5.12)$$

where $\alpha_i \in \mathbb{R}$ are weights in $[0,1]$. These weights can be retrieved using the Adaptive Weighted Sum (AWS) scheme, which for some problems complies also with non-convex Pareto optimal fronts [183].

5.3 Numerical examples

In this section the optimization tool is applied for the shape optimization of HVDC gas-insulated components. By looking at the optimization flowchart

of Fig. 5.1 the optimization is performed with the differential evolution scheme written in MATLAB[®], while the meshing of the domain, the numerical solution of the PDE and consequently the objective function evaluation are made in the commercial FEM software COMSOL[®] Multiphysics. The two environments are combined into a COMSOL[®] plus MATLAB[®] code by using the LiveLink[™].

Scalar optimization of high voltage electrode

In this test case the tool is used to define a new shape for the high voltage electrode of the gas-insulated system illustrated in Fig. 4.12 to avoid the streamer inception depicted in Fig. 4.18. To this aim the following scalar optimization problem is defined: find $\mathbf{x}^*$ such that:

$$f^* = f(\mathbf{x}^*) = \min_{\mathbf{x}} f(\mathbf{x}) = \min_{\mathbf{x}} (\max \bar{\alpha}), \quad (5.13)$$

where $\bar{\alpha}$ is the effective ionization coefficient of SF₆ gas. In particular we are searching for a new shape of the high voltage electrode for which the streamer criterion predicted by Eq. (4.42) is not satisfied. The array of design parameters $\mathbf{x}$, as illustrated in Fig. 5.4 (dashed blue), define a new contour of the high voltage electrode through a cubic Bézier curve defined in the COMSOL model geometry, and characterized by four control points. More specifically the $D = 4$ design variables are the (r,z) coordinates of control points P2 and P3, that is:

$$\mathbf{x} = [r_{P2}, r_{P3}, z_{P2}, z_{P3}]^T. \quad (5.14)$$

The heuristic parameters of the differential evolution algorithm are selected as:

- it_{max} (number of iterations): 30
- N_p (number of chromosomes for each population): 20
- F (mutation probability): 0.8
- CR (crossover probability): 0.5

Starting from the peak value of 10.5 kV/mm, the optimization procedure reduces the maximum value electric field strength to about 8.5 kV/mm, below the critical value for streamer inception, as it can be seen in Fig. 5.5 where all calculated trajectories are associated to a zero value for the streamer integrals.

5.3. NUMERICAL EXAMPLES

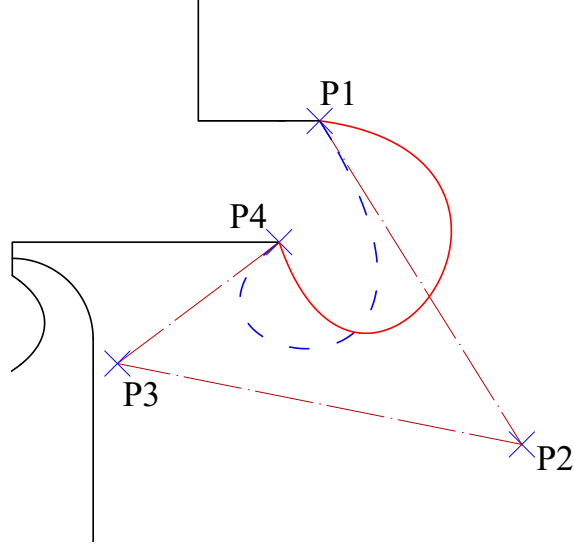


Figure 5.4: Detail of high voltage electrode contour. Initial (dashed blue) and optimized (solid red). Points P1,...,P4 with $\times$ symbol, are the control points of the cubic Bézier curve.

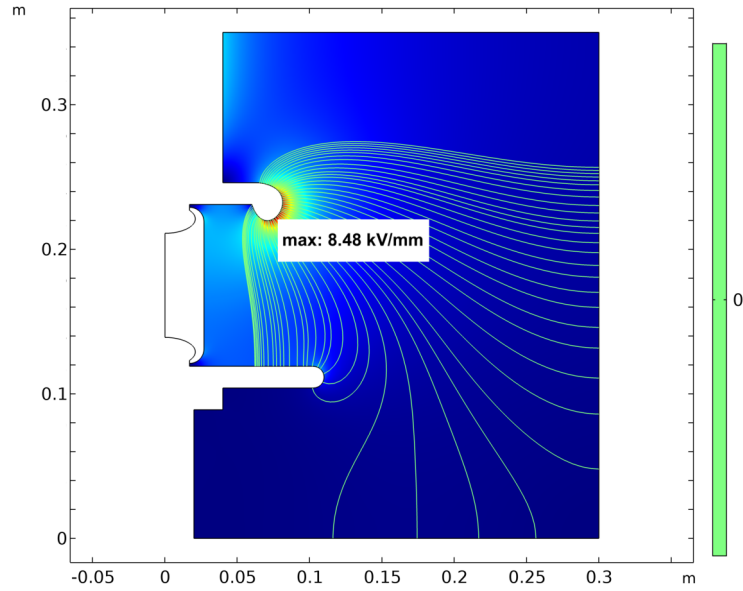


Figure 5.5: Streamer integrals and electric field map for the optimized electrode shape. The peak value of the electric field is reduced to about 8.5 kV/mm and the streamer criterion is not exceeded for any of the calculated trajectories for which the integral is always zero.

Multi-objective optimization of post-type insulator

The multi-objective optimization tool is applied in this example to mitigate the surface charge accumulation on the gas-solid insulator interface. As reported in [111], the surface charging is generally driven by the normal and tangential components of the electric field on the solid insulator at the initial capacitive state [34]. With the purpose of reducing the charge accumulation and mitigate the probability of surface flashover, these field components can be minimized through a shape optimization of the insulator [82]. This geometric approach can be seen as a capacitive field grading method. Differently from the method proposed in [34] here the optimization is treated as a multi-objective optimization problem where the objective function becomes a vector constituted by the normal E_n and the gradient $\nabla_t E_t$ component of the electric field along the solid insulator, that is:

$$\mathbf{f}(\mathbf{x}) = [f_1(\mathbf{x}), f_2(\mathbf{x})]^\top = [\nabla_t E_t(\mathbf{x}), E_n(\mathbf{x})]^\top. \quad (5.15)$$

To avoid the onset of numerical issues that could alter the solution in specific points, it is preferable to control integral rather than local quantities, that is the optimization acts on the quantities:

$$\frac{1}{L_0} \int_L \nabla_t E_t(\mathbf{x}) dl, \quad \frac{1}{L_0} \int_L E_n(\mathbf{x}) dl, \quad (5.16)$$

where the integral is performed along the parametrized boundary and L_0 is a normalization parameter. The design variables define the shape of the insulator surface by using a Bézier curve as shown in Fig. 5.8 (dashed blue). The Bézier curve have seven control points, of which only P3 and P4 are used as design variables, due to the symmetry of the system, i.e., the parameter vector became:

$$\mathbf{x} = [r_{P3}, r_{P4}, z_{P3}]^\top \quad (5.17)$$

and points P2 (and P6) are kept fixed in order to obtain reasonable shapes. The multi-objective optimization is performed with a modified differential evolution algorithm to comply with the Pareto optimal solutions. $N_p = 30$ chromosomes for each population are used in the differential evolution scheme with $it_{max} = 200$ maximum iterations. The mutation and crossover probability are selected as $F = 0.4$ and $CR = 0.8$. The optimization runs for approximately $t = 4$ hours and the Pareto front in the normalized objective function space (f_1, f_2) after 200 iterations is shown in Fig. 5.6. The theoretical convergence of the multi-objective optimization with DE can be analyzed with probability tools [184], however by looking at the Pareto plot at different iterations, the convergence can be argued. As an example, the convex Pareto plot given in Fig. 5.6 after 200 iterations has similar trend already

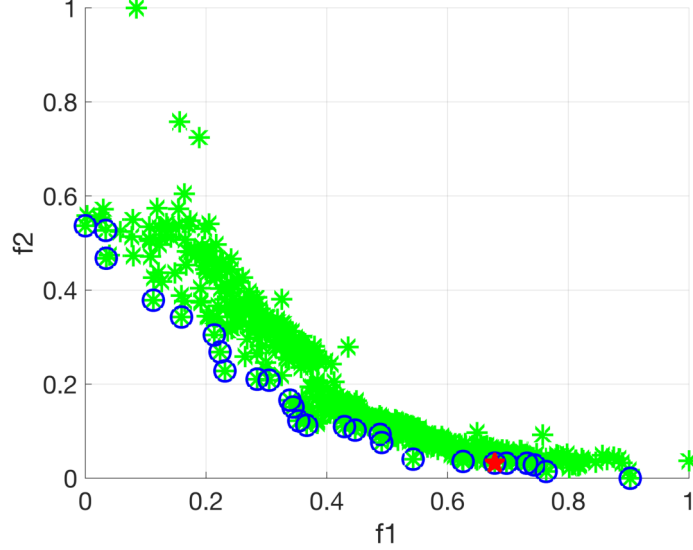


Figure 5.6: Pareto front in objective function space after 200 iterations. The objective functions f_1 and f_2 are normalized to their maximum value stored in the story archive of the optimization. The blue circles highlight the current Pareto solutions, while the green asterisks are the dominated solutions. Among all the equally valid Pareto solutions, the red star marker shows the selected one.

at 100 iterations, as shown in Fig. 5.7. Conversely, the Pareto front after 10 iterations of DE it is very different. Considering the heuristic logic of the optimizer, the maximum number of iterations must be chosen considering a compromise between computational cost and reasonableness of the results. The cross-section profile for the optimized geometry is shown with solid red line in Fig. 5.8; the considered solution is shown with the red star marker in Fig. 5.6. The electric field components E_n , E_t of the reference and optimized configurations are compared in Fig. 5.9. From the figure it is understood the effective capacity of the optimization in reducing the normal and tangential components along the insulator.

Multi-objective optimization of high voltage bushing

The detailed design of the high voltage bushing (HVB) insulated with pressurized gas, for example SF_6 , requires particular attention to avoid possible discharge paths. In an HVB three main discharge paths can emerge due to inappropriate design of the component [175]:

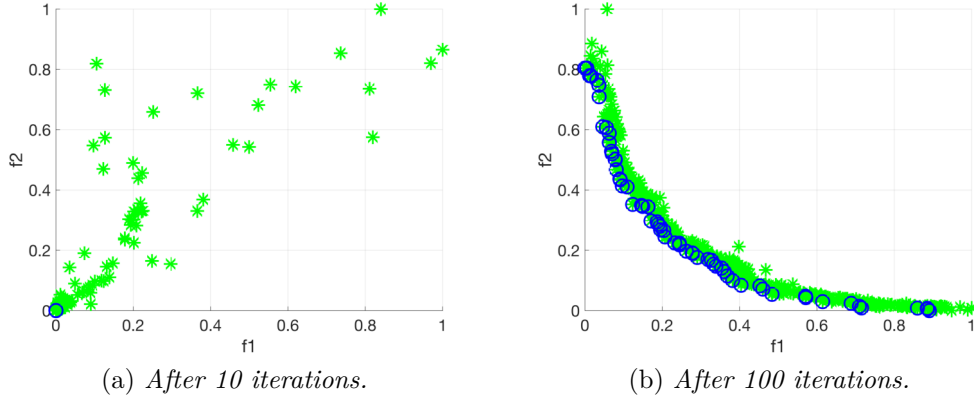


Figure 5.7: Pareto front in normalized objective function space at 10 and 100 iterations of multi-objective DE.

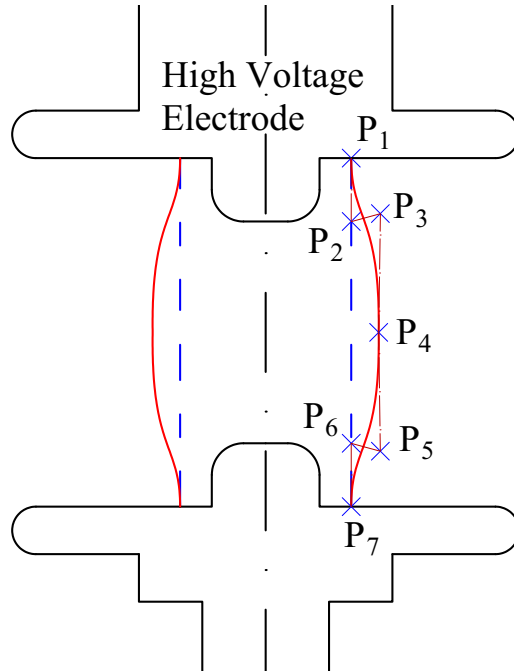


Figure 5.8: Contours of the insulator cross-section: reference (dashed blue) and optimized (solid red). Points P3 and P4 with $\times$ symbol, are the control points of the cubic Bézier curve.

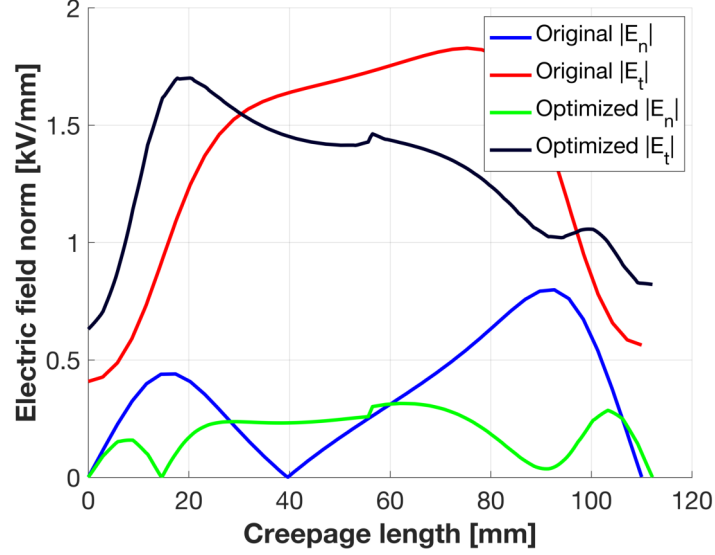


Figure 5.9: Electric field components $|E_n|$ and $|E_t|$ on the insulator surface for the reference and optimized configurations.

1. Breakdown between the central high voltage conductor and the grounded electrode, which can be examined using the streamer criterion of Section 4.4,
2. Partial discharge at the triple point located at the top-flange, silicone rubber sheds and surrounding air intersection,
3. Flashover in air along the silicone rubber sheds.

As stated in Section 3.2.3 a way to reduce the peak of electric field intensity along the the silicone rubber sheds, involve the application of resistive field grading materials [94]. Even the shape of the silicone rubber sheds may affect the field distribution and different solutions can be conceived in dependence on the location where the bushing will be placed (e.g., outdoor or indoor bushing) [185]. As shown in [186, 187] the screening of the field near the triple point in the top-flange can be achieved by using grading rings, which are polarized at the same voltage of the central conductor. This is a common (and simple) practice when designing high voltage components. Following [188, 189], the present analysis focuses on the three critical regions shown in Fig. 5.10:

1. Position A: the surface of the central conductor,
2. Position B: the surface of the grounded ring electrode,

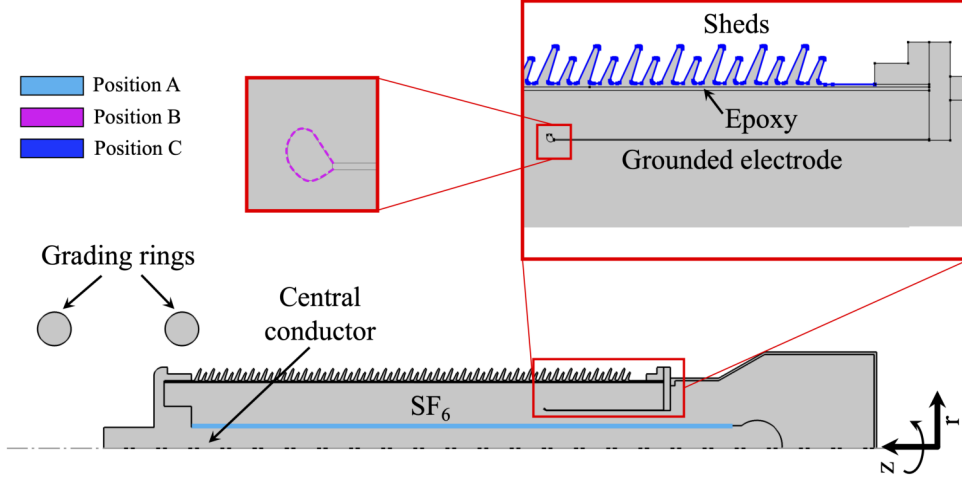


Figure 5.10: 2D axial-symmetric model of the bushing examined in this example. The three critical paths where the electric field stress must be reduced are colored in cyan, blue and magenta.

3. Position C: the surface of the sheds.

There, the electric field strength must be decreased to reduce the probability of partial discharges or complete breakdown of the insulating gas. In this example, the capability of an optimized shape for the grounded ring electrode to reduce the electric field strengths in positions A (E_1), B (E_2) and C (E_3) is demonstrated. The following multi-objective optimization problem is formulated: find $\mathbf{x}^*$ such that:

$$\mathbf{f}^* = \mathbf{f}(\mathbf{x}^*) = \min_{\mathbf{x}} \mathbf{f}(\mathbf{x}) = \min_{\mathbf{x}} [E_1, E_2, E_3]^\top, \quad (5.18)$$

where the design variables $\mathbf{x}$ describe the shape of the grounded electrode whose detail is shown in Fig. 5.11b. The design array is composed by the following five control variables:

$$\mathbf{x} = [H, d, r_{P2}, r_{P3}, r_{P4}, z_{P4}]^\top. \quad (5.19)$$

The electric field is retrieved from a stationary current conduction analysis. The bushing is filled with SF_6 at 0.5 MPa and Al_2O_3 -filled epoxy is used for the solid insulator, while the sheds are made in silicone rubber. A summary of the parameters used in the analysis is given in Table 5.1. A population of $N_p = 30$ individuals is selected for the differential evolution with a maximum algorithm iterations of $it_{max} = 200$ together with a mutation probability factor $F = 0.4$ and a crossover constant of $CR = 0.8$. The contour of the

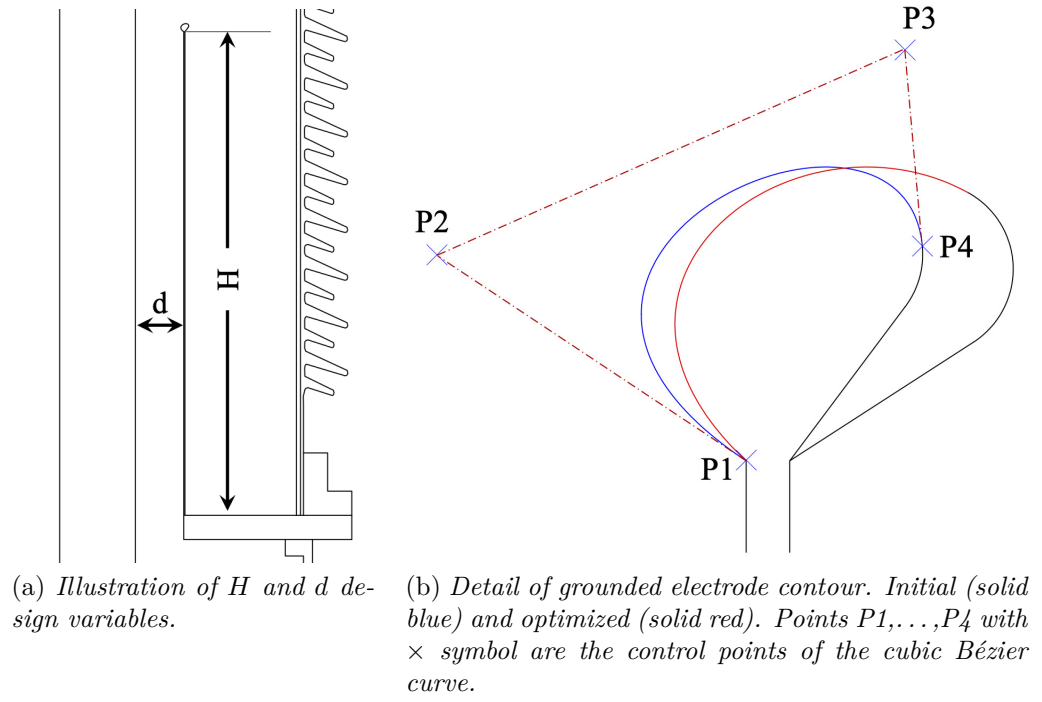


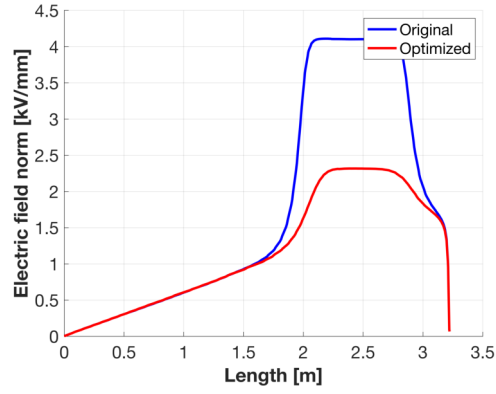
Figure 5.11: Grounded electrode parametrization.

Material	ε_r	σ [S/m]
SF ₆	1.002	$2 \cdot 10^{-18}$
Epoxy	4	$3.64 \times 10^{-7} \times$ $\exp[0.08E - 0.5/(k_B T)]$
Silicone rubber	3	$2.51 \cdot 10^{-15}$
Air	1	0

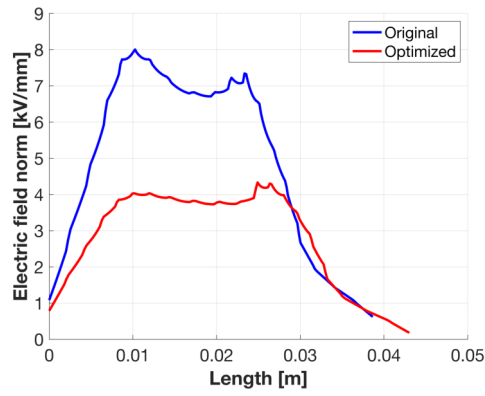
Table 5.1: Material parameters for the electric field calculation.

optimized grounded electrode is shown in Fig. 5.11b with $H = 0.71$ and $d = 0.17$. A comparison between the initial distribution of electric field norm along positions A, B and C is shown in Fig. 5.12 from which it can be seen that the shape variation of the grounded electrode has minor impact on the electric field norm along the silicone rubber sheds.

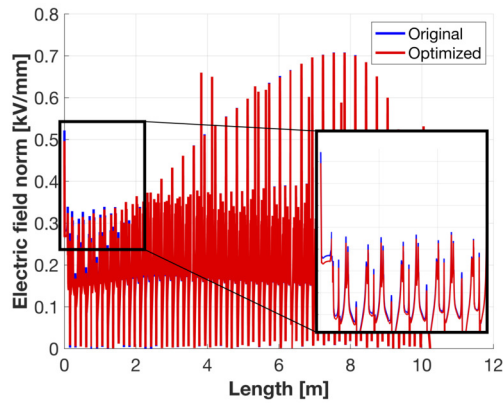
5.3. NUMERICAL EXAMPLES



(a) *Electric field norm along position A (inner conductor).*



(b) *Electric field norm along position B (grounded electrode).*



(c) *Electric field norm along position C (sheds).*

Figure 5.12: Comparison of electric field strength along positions A, B and C at the beginning of optimization problem and for the optimized configuration.

6

High voltage components for the AGPS of DTT NBI

ON THE BASIS of the concepts described previously, this chapter is devoted to the numerical investigation of the HVDC (High Voltage Direct Current) gas-insulated components for the AGPS (Acceleration Grid Power Supply) of the DTT (Divertor Tokamak Test) N-NBI (Negative-Neutral Beam Injector). As stated in Chapter 2, the AGPS of DTT N-NBI foresees many HVDC gas-insulated system, such as the transmission line (TL), the SF₆-air high voltage bushings (HVB), the DC-filter and the gas-insulated diode rectifiers. Among them, the subsequent analysis are focused on the conceptual design of the gas insulated TL and the SF₆-air HVB, due to their major impact in the Frascati site. The reference solution for the DTT N-NBI here considered is the single 500 keV MITICA-like, described in Section 2.1.2, which foresees three DC acceleration voltages. Despite alternative dielectric gases can be conceived in this preliminary study, by appropriately specifying the electrical conductivity, in the electromagnetic analysis that follow, the SF₆ is considered as reference insulating medium. This choice is made for two main reasons:

- The SF₆ represents the state-of-art for the design and operation of HVDC gas-insulated components for the AGPS,
- Currently, the manufacturability of HVDC gas-insulated systems with alternative insulating gases is still under study.

The chapter is organized as follows: Section 6.1 examines the electric

field map of the high components to be placed inside building 87 for the 500 kV MITICA-like solution, namely the high voltage bushing and the high voltage deck. In 6.2 the multi-conductor 500 kV TL is conceptualized. In particular, the analysis is focused on the TL2 part, originating from the SF₆ bushing of the HVD (High Voltage Deck). In Section 6.3 a detailed 3D model of the bushing hall attached to building 87 and the SF₆-air bushing placed inside, is developed. The model of the bushing includes small geometrical features like the silicone rubber-sheds, which increase the computational effort both for the mesh and FEM solution. The possibility of using a non-linear resistive field grading material to homogenize the field intensity along the sheds, which in turn reduces the probability of discharges in air, is also investigated. Lastly, Section 6.4 describes the test bed that will be realized for the experimental investigation of HVDC gas-insulated systems, with the purpose of validating the numerical tools described in the present work. The solutions that will be presented in this chapter, concerning the AGPS components of DTT NBI, are not the final one, and may be subjected to variations in the future. However the layouts here proposed represent a step towards the conceptual design of real components.

6.1 Electric analysis HVD building

Looking at the draft layout of the 500 kV MITICA-like solution given in Fig. 2.13, the high voltage deck and the SF₆-air high voltage bushing rated for -510 kV are placed in closed buildings, respectively building 87 and the bushing hall, where the latter is a completely new structure that will be realized in the west side of B87. The ISEPS (Ion Source and Extraction Power Supply) hosted in the HVD, are connected to the HVB (High Voltage Bushing) by a ≈ 8.5 m long conductor, which passes through the door in the west side of B87 and connects to the bushing terminal. A photograph of the door of building 87 through which the connection will pass is shown in Fig. 6.1.

A conceptual design of the HVD can be derived from the one used in SPIDER (Source for the Production of Ions of Deuterium Extracted from a Radio frequency plasma) experiment, in the PRIMA (Padova Research on ITER Megavolt Accelerator) test facility. The HVD of SPIDER is a one-floor Faraday cage rated for 100 kV whose external dimension are 13 m (L) $\times$ 11 m (W) $\times$ 5 m (H) [190]. Considering the limited height of building 87 (about 13 meters), combined with the minimum clearance distance required for the installation of high-voltage components in closed buildings, a single-floor HVD with external dimensions of 16 m (L) $\times$ 9 m (W) $\times$ 5 m (H), is



Figure 6.1: Photograph of the west door of building 87 through which the HDV-HVB connection will pass.

conceived. The HVD is built with AlMg_3 panels accurately jointed together to form the electrostatic screen. The 2D CAD drawing of the proposed solution is given in Fig. 6.2.

From the electrical point of view, it is of fundamental importance the evaluation of the electric field map of the air-insulated high voltage components to be placed in the buildings. In fact, the electric field strength in air must be kept below the critical breakdown field to reduce the probability of electrical discharges towards the walls of the building. Following the guidelines used for MITICA (Megavolt ITER Injector and Concept Advancement) HVD [191], the environmental parameters to be considered inside B87 and the bushing hall are reported in Table 6.1. The theoretical critical breakdown field of dry air at atmospheric pressure is about 3 kV/mm, which is reduced to 1 kV/mm accounting for a safety factor [192]. To keep the electric field below the maximum allowed value the HVD and the HVB cannot be placed arbitrarily inside the buildings, however, their distance from the grounded walls must be sufficiently high. A rough estimation of the minimum distance is retrieved looking at the tip-to-plane discharge characteristic curves reported in Fig. 6.4. For negative voltage polarity the slope of the curve is constant and equal to 1.2 kV/mm. Therefore assuming $\Delta V = 510$ kV the

6.1. ELECTRIC ANALYSIS HVD BUILDING

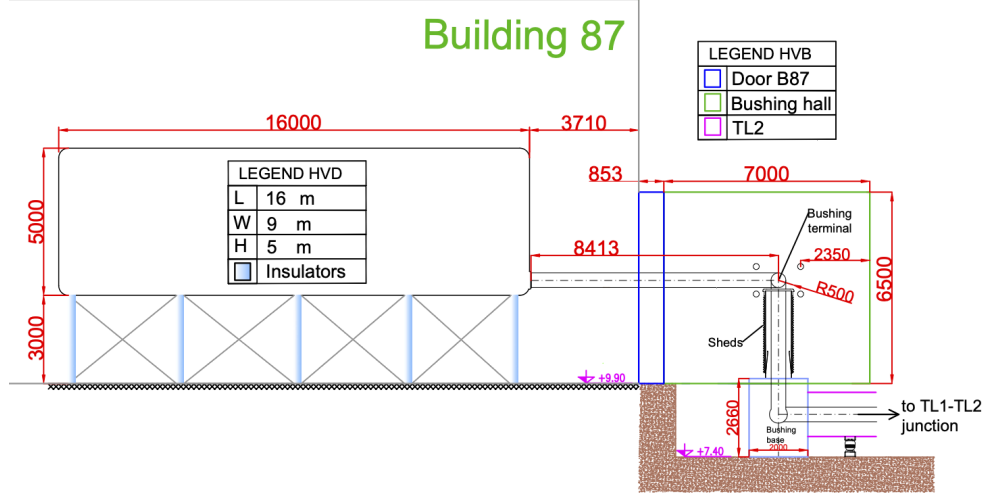


Figure 6.2: 2D CAD drawing of building 87 and bushing hall including the HVD and the HVB. The base of the bushing is located in trench at the same level of the TL1-TL2 junction. Dimensions in mm.

minimum distance in ideal conditions is:

$$d_{min} = \frac{\Delta V}{1.2} = \frac{510}{1.2} \approx 425 \text{ mm.} \quad (6.1)$$

The actual distance between the top of the HVD is more than 3 meters, therefore sufficient to ensure the voltage holding in air. As a matter of fact the electric field can be enhanced by several geometrical features, as:

- Sharp edges and tips,
- Surface irregularities in AlMg₃ panels [193].

To verify the feasibility of the proposed solution from the electrical point of view, a 3D model of building 87 plus the bushing hall with the mentioned HVD and HVB concepts is realized in COMSOL® and is given in Fig. 6.3 [194]. For simplicity the HVD insulators are neglected in the subsequent analysis. Moreover, the HVB model is further simplified by excluding the connection with the transmission line and small geometrical detail like the silicone rubber sheds and the grading rings, with the latter substituted with a uniform sphere.

The electric field is calculated under electrostatic hypothesis by supplying the high voltage parts with $U_{DC} = -510 \text{ kV}$ and assuming electrostatic conditions. The output 3D electric field map is shown in Fig. 6.5. As expected

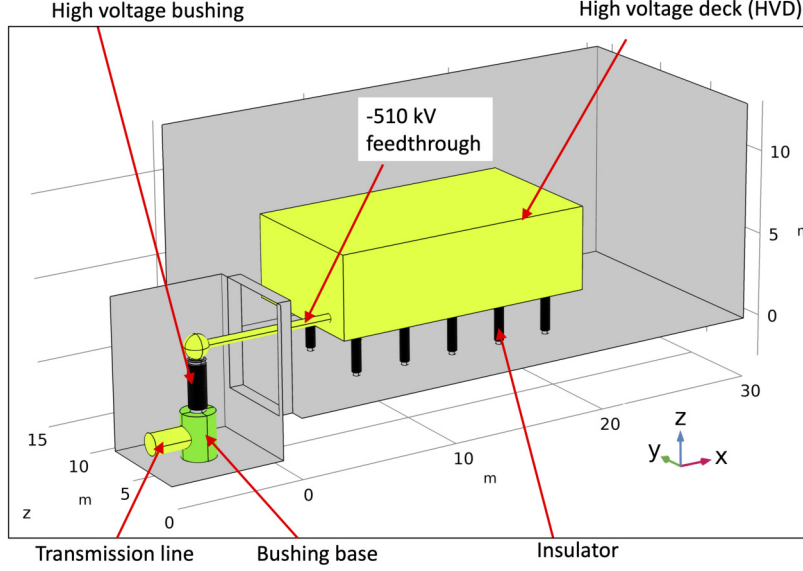


Figure 6.3: Draft 3D CAD of HVD and bushing buildings for the AGPS of DTT NBI.

Parameter	Value
Temperature (min ÷ max)	18° C ÷ 35°C
Air humidity (min ÷ max)	40% ÷ 60%
Dust class	100.000 P/ft ³
Maximum allowed electric field in air	1 kV/mm

Table 6.1: Environmental conditions and parameters inside B87 hosting the HVD in accordance to the ones of MITICA HVD hall [191].

it can be seen that the peak value of the electric field is located inside the SF₆-air bushing, in the vicinity of the grounded ring electrode. The electric field map in air can be examined in Fig. 6.6 where a 2D slice plot parallel to XZ-plane is given. Values of $E > 1$ kV/mm are excluded.

6.2 Gas insulated transmission line

The gas insulated transmission line (TL) is a multi-conductor line carrying the HVDC for the acceleration grids and the auxiliary DC and radio frequency voltages for the ion source, provided by the Ion Source and Extraction Grid Power Supply (ISEPS). As stated in the introductory part of this chapter, the TL for the 500 keV N-NBI solution is here considered, that

6.2. GAS INSULATED TRANSMISSION LINE

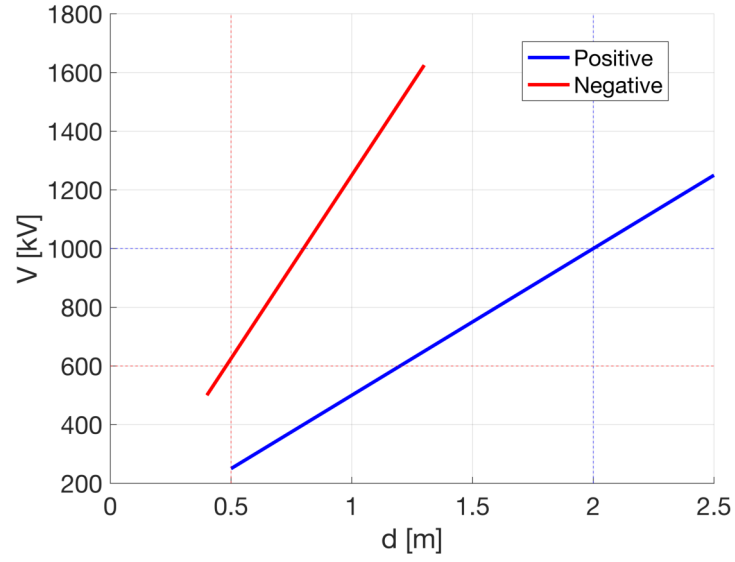


Figure 6.4: DC discharge voltages for tip-to-plane geometry for negative and positive polarity [195].

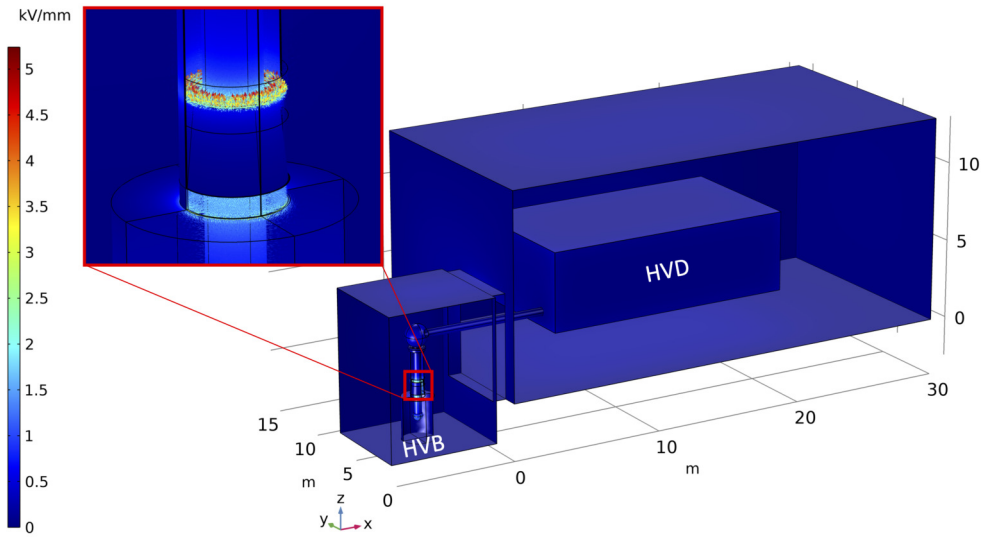


Figure 6.5: Electric field map of the HVD located inside building 87 plus the HVB hosted in the bushing hall. The peak value of the electric field is located near the grounded ring inside the SF₆-insulated HVB.

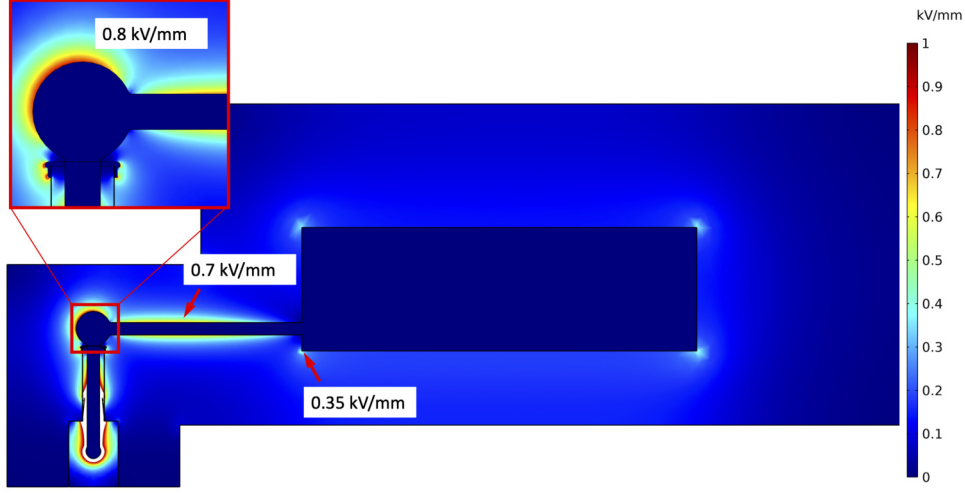


Figure 6.6: Electric field map on 2D plane along XZ axes. The electric field strength in air is below the critical value of 1 kV/mm.

is, the three AGPS voltages carried by the TL are -510 kV, -334 kV and -167 kV, termed HV_1 , HV_2 and HV_3 respectively. For the TL2 and TL3 sections, the HV_1 conductor has to be large enough to host the ISEPS lines, therefore without loss of generality the conceptual design of TL2 is considered in this example. As general guideline, the conceptual design of TL2 must be addressed considering these conflicting demands:

- Guarantee high dielectric capabilities,
- Ensure access to the system by maintenance personnel during the assembly and maintenance phases,
- Reduce the cross section to limit the volume of insulating gas to be used, which in turn reflects also in costs reduction.

The TL2 section given in the reference layout of Fig. 2.13 is located in trench and as an external diameter of $d_E = 1300$ mm. This value is selected considering a trade-off between space footprint, dielectric capabilities and maintenance constraints. The inner conductor diameter is retrieved from that of MITICA 1 MV TL as $d_1 = 500$ mm (since similar volume for ISEPS auxiliaries is expected), while the diameters of the intermediate acceleration voltages are $d_2 = d_3 = 100$ mm. A draft 2D CAD of the proposed layout is shown in Fig. 6.7a.

The first step for the design of the TL2 concerns the spatial positioning of the intermediate conductors assuming the inner one to be placed along

6.2. GAS INSULATED TRANSMISSION LINE

the central axis of the line. Ideally, the intermediate conductors have to be placed in the correspondence of -334 kV and -167 kV equipotential lines in order to minimize the distortion of the electric field map caused by their presence. The equipotential lines around the central conductor were retrieved with an electrostatic analysis of a 2D cross section of the TL where only the central conductor is present. Then, the intermediate conductors are placed in a suited position of the corresponding equipotential lines, resulting in the geometry illustrated in Fig. 6.7. There are degrees of freedom in the position of the conductors along the corresponding lines, here both conductors are placed in the right part of the TL2 leaving free the space to the left. The electric field norm for the assumed placement was evaluated in the absence of the solid insulator. The results are given in Fig. 6.8. From the analysis it follows that the electric field intensity is everywhere less than 5 kV/mm and the value along the grounded enclosure is approximately 1 kV/mm, lower than the metal particle levitation field for coated electrode.

A 3D model of 1 meter long section of TL is implemented on the basis of the previous considerations within COMSOL® CAD module [194]. The central conductor is suspended by a solid (post-type) insulator while the intermediate conductors are free. This simplification is made to facilitate the numerical analysis. Moreover, the effect of DC field and the charge accumulation phenomena is still present and can be examined on the solid insulator surface.

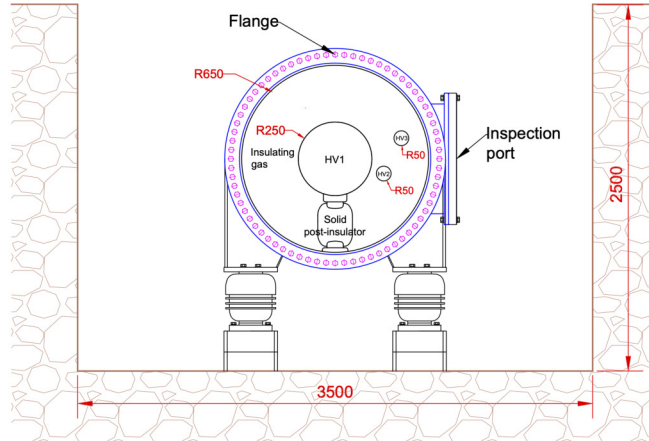
The electric field analysis of the line and the subsequent evaluation of discharge phenomena, requires the specification of the material properties which in general may depend both on the electric and temperature field. The temperature dependence can be neglected if the Joule power losses and the operational time are relatively low. Assuming the 1 meter long conductors made in Aluminium with conductivity of $\sigma_{alu} = 3.774 \cdot 10^7$ S/m and a thickness of 10 mm, the resistive power losses due to a current of $I = 60$ A flowing in the conductors can be expressed as:

$$P_R = RI^2 = 1.7 \cdot 10^{-6} \times 60^2 \approx 6.2 \cdot 10^{-3} \text{ W.} \quad (6.2)$$

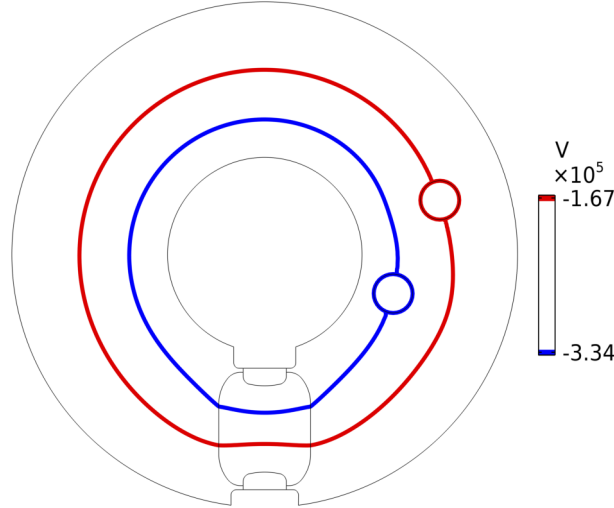
For a 1 meter long TL section, filled with pressurized SF₆ at $P = 0.5$ MPa at 293.15 K, the mass of gas is approximately $m \approx 43$ kg. Subsequently, an estimation of the temperature rise of the gas after $t = 50$ s of operation is determined under adiabatic conditions, resulting in:

$$\Delta T = \frac{6.2 \cdot 10^{-3} \times 50}{43 \times 665.18} = 1.1 \cdot 10^{-5} \text{ K.} \quad (6.3)$$

For such low ΔT , the thermal problem is neglected in the current analysis and the temperature fixed to $T = 293.15$ K.



(a) Draft 2D CAD of TL2 section in trench. Dimensions in mm.



(b) Equipotential lines of -334 kV and -167 kV evaluated with an electrostatic analysis.

Figure 6.7: 2D TL2 conceptual design.

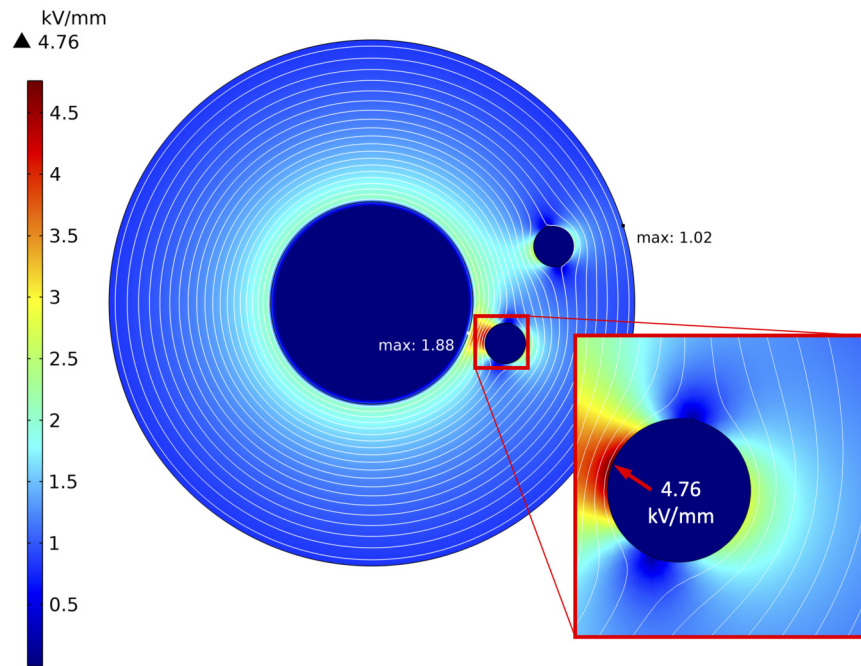


Figure 6.8: Electrostatic field map of 2D TL2 without solid insulator. The peak value is lower than 5 kV/mm and attains its maximum in the vicinity of the intermediate conductor of -334 kV as depicted in the inset. The maximum electric field in the central conductor and grounded enclosure is ≈ 1.9 kV/mm and ≈ 1 kV/mm respectively.

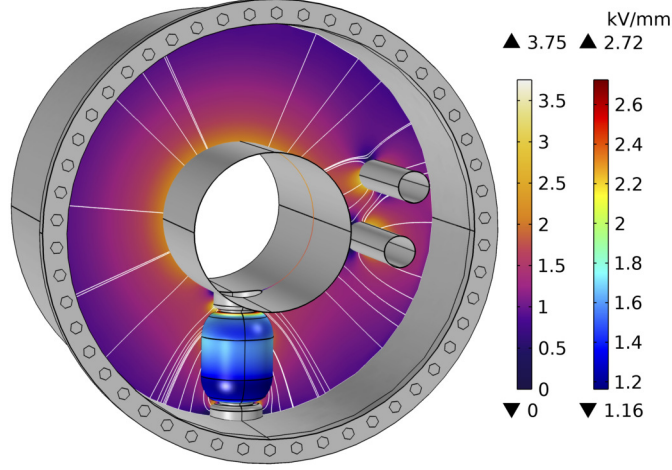
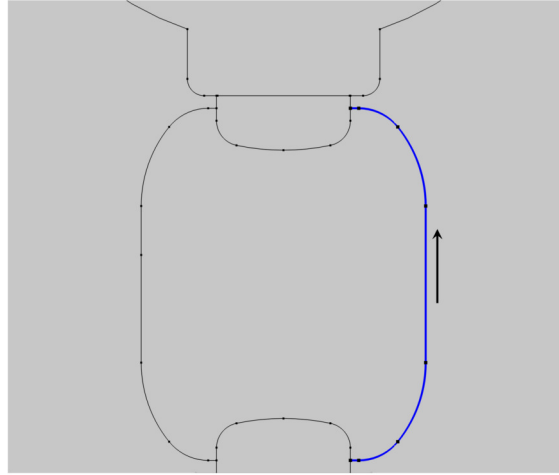


Figure 6.9: Electric field intensity evaluated with the drift-diffusion model after $t = 50$ s. The color bar on the left refers to electric field values in the gas, while that on right is related to the solid insulator.

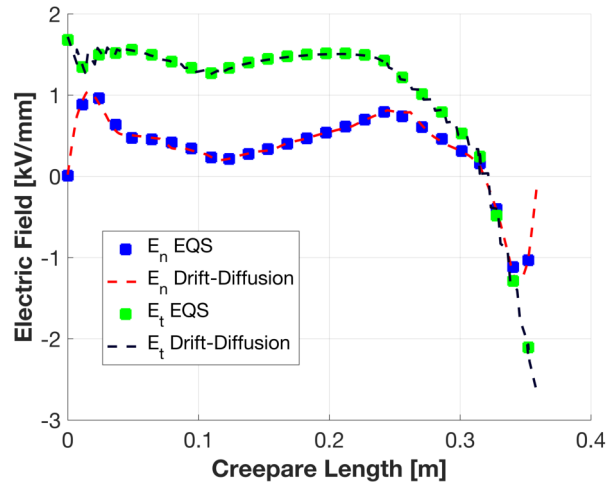
The post-type insulator is made of epoxy resin with $\sigma_I = 1.6 \cdot 10^{-16}$ S/m and $\varepsilon_r = 5$. The electric field is evaluated with two different approaches, namely the standard EQS model 4.3.1 and the drift-diffusion model 4.3.2, with the purpose of analyzing the electric field components along the creepage length of the insulator after a short time of DC voltage application. For the EQS analysis the non-linear conductivity of SF_6 expressed by (3.6) is used, while for the drift-diffusion, the transport parameters for $P = 0.5$ MPa are listed in Table 3.1. The time integration of both models runs for $t = 50$ s. The electric field map of the 3D model is shown in Fig. 6.9, while the electric field components along the creepage length of the post-insulator in Fig. 6.10. From this figure it can be seen that the two approaches agree very well.

6.3 SF_6 -air bushing

The 500 kV MITICA-like solution for the AGPS of DTT N-NBI foresees two high voltage bushing SF_6 -air, bridging the gas-insulated TL with air insulated components. The first is located in the bushing hall on the west side of building 87 and is used to connect the HVD hosting ISEPS with the TL2 in trench. The other is installed inside the Tokamak hall and bring the power out of TL3 to the ion source. The latter bushing is characterized by three outputs, namely the -510 kV, -334 kV and -167 kV feeding the corresponding accelerations grids.



(a) Creepage length of the solid insulator in blue. The length is measured in the direction given by the arrow.



(b) Electric field components, normal E_n and tangent E_t along the creepage length of the post-insulator after $t = 50$ s.

Figure 6.10: Results for 3D model of TL2.

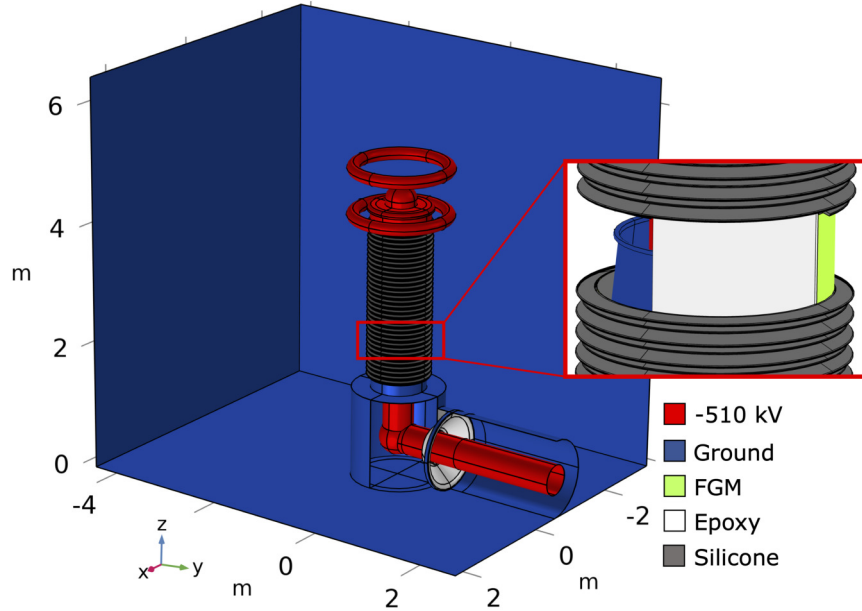


Figure 6.11: 3D CAD of the -510 kV SF₆-air bushing used for the TL2-HVD connection. Dimensions in meters.

In this example the -510 kV SF₆-air bushing located in the bushing hall used for the TL2-HVD connection is conceived [194]. This bushing characterized by the single output at -510 kV is selected due to its simpler layout and is used to:

- Characterize the general geometrical dimensions considering also small design features, for example the silicone rubber sheds,
- Determine the electric field intensities ranges,
- Test different material properties, for example the possibility of using a resistive field grading material to homogenize the intensity along the sheds.

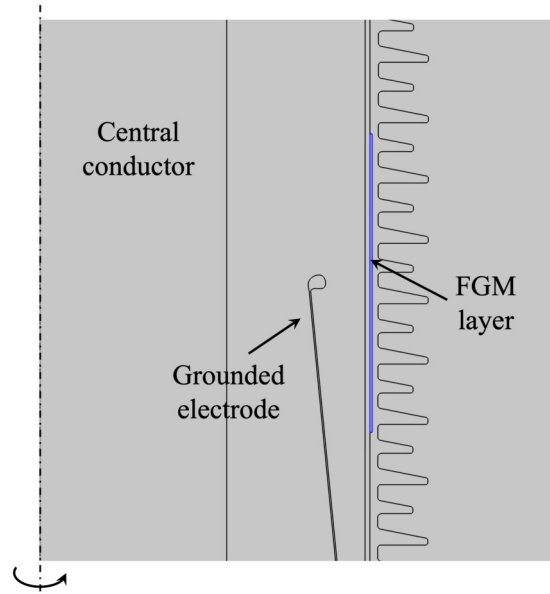
The 3D CAD realized in COMSOL® given in Fig. 6.11 includes also a section of the TL connected to the bushing base, whose central conductor is suspended by a solid insulator of conical shape. As stated in Section 5.3, the conceptual design of the bushing requires particular effort to avoid possible breakdown channels, both in SF₆ and air. With the purpose of limiting the probability of flashover along the silicone rubber sheds in air, a thin layer of 5 mm of field grading material is placed within the silicone rubber domain next to the grounded electrode of the bushing, as shown in Fig. 6.12a. The

effect of using the resistive field grading material characterized by the electrical conductivity of Eq. (3.26) with $\sigma_{0,T} = 10^{-3}$ S/m, $E_1 = 0.7$ kV/mm, $E_2 = 2.23$ kV/mm, $\alpha = 8$, $W_a = 0.5$ eV and $\varepsilon_r = 12$ is examined for a 2D axisymmetric model of the bushing and the results reported in Fig. 6.12b, where the electric field intensity after $t = 50$ s of EQS analysis is evaluated along the bushing sheds with and without the presence of the resistive field grading material. From that figure it can be seen that the layer is capable to damp the electric field intensity along the silicone rubber sheds. For the EQS electric field analysis of the 3D bushing the silicone rubber sheds are characterized by $\sigma_{SiR} = 5 \cdot 10^{-16}$ S/m and $\varepsilon_r = 2.8$, while for the epoxy parts $\sigma_I = 1.6 \cdot 10^{-16}$ S/m and $\varepsilon_r = 4.5$. The electrical conductivity of SF₆ is kept constant and equal to $\sigma_G = 10^{-18}$ S/m. The electric field intensity after $t = 50$ s on a YZ cut-plane is shown in Fig. 6.13.

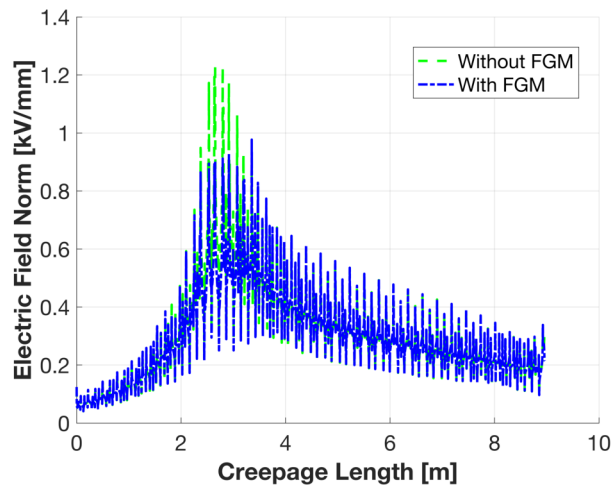
For the bushing located inside the Tokamak hall, the evaluation of the leakage current flowing in SF₆ due to the radiation field coming from the fusion machine is mandatory. In fact, the RIC effect can drastically modify the insulating behavior of the components thus an estimation of the power losses is mandatory to understand the need of radiation screens or insulating techniques different from pressurized SF₆. The maximum absorbed dose rate is SF₆ calculated by the DTT neutronics team with MCNP5 Monte Carlo code [196] is $\phi = 2.6$ mGy/s. Assuming a volume $V \approx 11$ m³ of SF₆ at the pressure of $P = 0.5$ MPa and using $F_{gas} = 2.06$, formula (4.58) gives $I_{sat} \approx 29$ mA, which for a polarization of 510 kV results in $P_{loss,RIC} \approx 15$ kW. These power losses seems to be acceptable also considering the short duration of the DTT NBI pulses, therefore no further actions are currently planned. It is worth nothing that by using the EQS model the analysis of leakage currents induced by external ionization sources cannot be performed easily, unless an equivalent electric conductivity of the gas is given.

6.4 Experimental test-bed

With the purpose of validating the numerical models described in the previous chapters a test-bed with low supplied voltages is designed. The test bed depicted in Fig. 6.14 consists in a cylindrical chamber with two portholes in the central part at 90 degrees one to the other. One port, called inspection port, mounts a window to observe inside the chamber, the other mounts a movable handle, supporting an electrostatic probe able to pass through the port flange keeping the vacuum/pressure tightness. This handle allows the horizontal movement of the probe. The chamber is rated for a maximum gas pressure of 10 bar and is fed from the top by the high voltage feedthrough,



(a) Location of FGM layer (in blue) next to the grounded ring electrode of the bushing.



(b) Electric field norm along bushing sheds in air after $t = 50$ s of EQS analysis. Using the resistive field grading material (FGM) the peak value is of about 20%. The creepage length is measured from the bottom to top of the bushing.

Figure 6.12: Results for 2D axisymmetric bushing model.

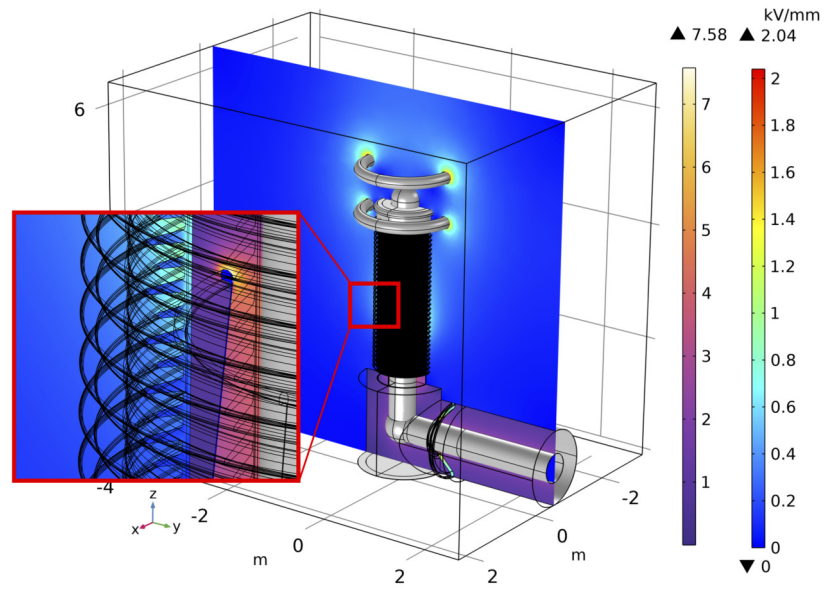


Figure 6.13: Electric field map on YZ cut-plane. The inset shows the electric field intensity next to the grounded ring electrode where the resistive field grading material layer is placed. The color bar on the left refers to electric field values in the SF_6 gas, while that on right is referred to solid insulating domains (i.e., epoxy parts, silicone rubber sheds, FGM material) and the surrounding air.

while the body of the camber is referred to ground potential. The described geometry can be considered as a reference mockup in the context on the research activities for the HVDC gas-insulated components of the DTT N-NBI AGPS.

The electromagnetic analysis is performed on a simplified version of the chamber by considering the 2D axisymmetric geometry without portholes shown in Fig. 6.15, realized in the commercial FEM software COMSOL® Multiphysics. This simplification was carried out for two reasons: firstly, due to the intrinsically axisymmetric nature of the model, secondly to study in a simplified way the numerical tools that will be validated experimentally. A transient analysis is performed by energizing the system at with $U_{DC} = -150$ kV at the HV electrode for $t = 28800$ s (8 hours). The gas injected in the chamber is pressurized SF_6 at 0.5 MPa, whose ion parameters are: $\mu^+ = \mu^- = 4.80 \cdot 10^{-6} \text{ m}^2/(\text{V} \cdot \text{s})$, $R = 2.27 \cdot 10^{-13} \text{ m}^3/\text{s}$. Since the experiment is placed in a controlled environment the ion-pair generation term can be traced back to the natural ionization, corresponding to $S = 2.90 \cdot 10^7 \text{ 1}/(\text{m}^3 \cdot \text{s})$. The solid insulator in this first configuration is made in epoxy resin with constant electrical conductivity $\sigma_I = 1.19 \cdot 10^{-18} \text{ S/m}$ and $\varepsilon_r = 5$.

The electric field in the systems is evaluated with the drift-diffusion-reaction model 4.3.2 realized in COMSOL® within the Transport of Diluted Species (TDS) physics. Fig. 6.16a depicts the equivalent current density in the gas.

A key aspect of the experimental campaign is the measurement of leakage currents flowing in the gas towards the grounded chamber and from the high voltage to the low voltage electrode through the solid insulator. The measurement of such currents is usually performed equipping the experiment with picoampere meter. By computing the current density flux towards the aforementioned boundaries, the current is obtained and the results reported in Table 6.2. As stated in Section 4.5, the leakage current flowing in the gas can be greatly elevated if emission from rough cathode surface is considered. To account for this phenomenon the injection of negative ions from the grounded chamber, using Equation (4.69) is added in the simulation, by using $\beta_{eff} = 40$ and $k = 1.56 \cdot 10^{-3} \text{ 1}/(\text{V}^2 \cdot \text{s})$. This flux can be added to the COMSOL® model by using a *flux* boundary node in the TDS physics referred to negative ions. The computed current density given in Fig. 6.16b is extremely different with respect to the one obtained without ion injection. Moreover, the measured current through the vessel and LV electrode is increased, as reported in Table 6.2.

From the experimental point of view the capability of measuring the electrical potential along the creepage length of the solid insulator is of great

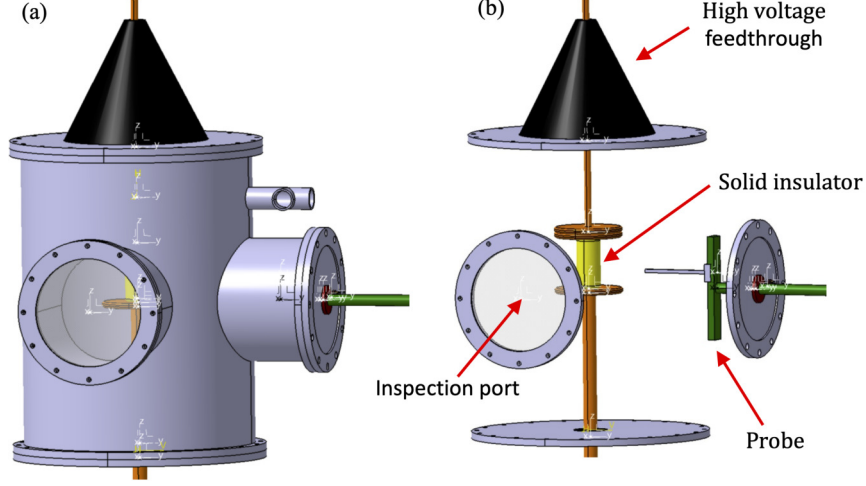


Figure 6.14: Draft 3D CAD representation of the test bed. Whole chamber (a), the system without the chamber with the electrostatic probe in retracted position (b).

–	Vessel [A]	LV electrode (gas side) [A]	LV electrode (solid side) [A]
Without ion injection	$7.09 \cdot 10^{-13}$	$5.90 \cdot 10^{-14}$	$3.33 \cdot 10^{-15}$
With ion injection	$5.88 \cdot 10^{-6}$	$1.92 \cdot 10^{-6}$	$3.39 \cdot 10^{-15}$

Table 6.2: Simulated current values.

interest since the surface charge density can be recovered from the measured voltages by using for example the *Charge Inversion Algorithm*, firstly introduced by Ootera [197] and described in Section A.2.2. Usually electrostatic probes, for example the Kelvin probes, are used to perform the voltage measurements [60, 198]. This probing method does not require the physical contact with the measured surface and the potential distribution is based on the compensation principle [198]. The probe acts as an electrode in front of the surface, with an electric potential which ideally equals the one of the measured point. A non-contact Kelvin probe with an aperture diameter of 1.59 mm placed at a distance of 3 ± 1 mm in front of the target surface, is adopted in this example. The distortion effect of the probe on the measured electric potential in the central point of the creepage length is here examined for the 3D model of the test bed using the same procedure explained in [59]. The model under examination and the measured voltage are reported in Fig. 6.17. The relative error (%) on the simulated voltage with ($V_{S,probe}$)

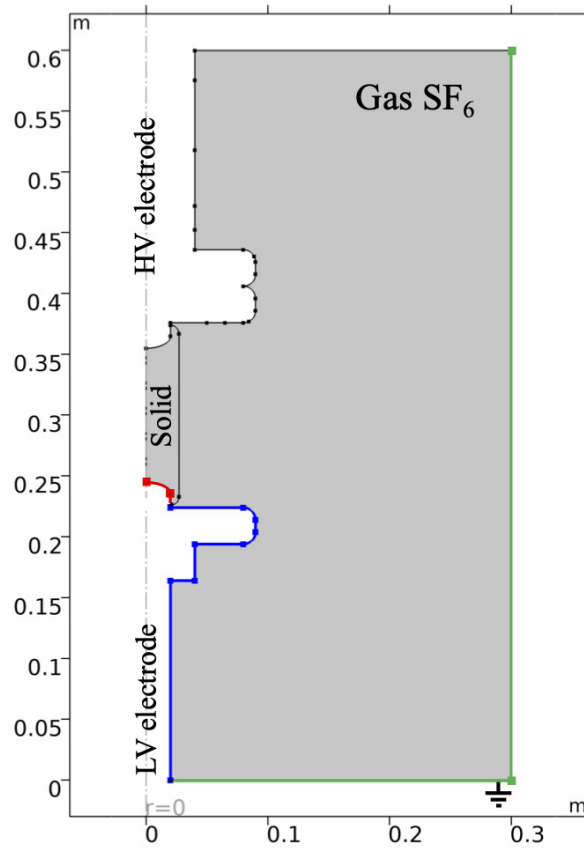


Figure 6.15: 2D axial-symmetric representation of the experimental mockup realized in COMSOL®. The current measurements are taken out of the green boundary (vessel), the LV electrode solid side (red) and the LV electrode gas side (blue). The normal vector of these surfaces is outgoing.

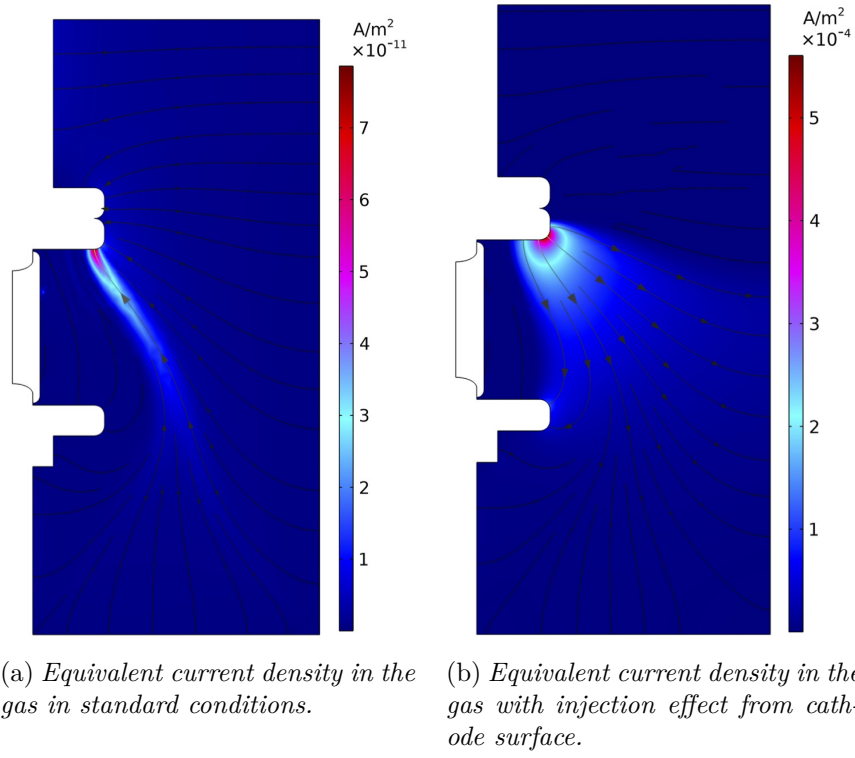


Figure 6.16: Equivalent gas current density under different conditions.

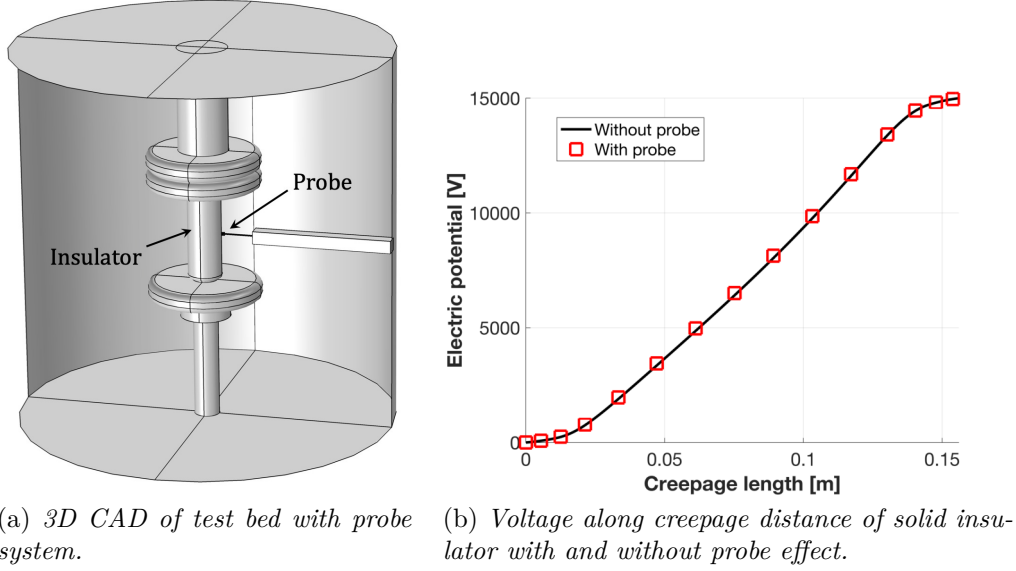


Figure 6.17: Arrangement of probe system in the simplified 3D CAD of the mockup and simulations results.

and without (V_S) the probe effect is:

$$\text{Relative Error} = \max 100 \times \frac{|V_{S,probe} - V_S|}{|V_S|} = 6.7\%. \quad (6.4)$$

6.5 Conclusions

In this chapter the modeling activities around the high voltage components that will be used for the AGPS of DTT NBI were described. This chapters allows to close the circle around the needs triggered by chapter 2, indeed it applied the tools described in the core of the thesis for the investigation of “real” components. However, the proposed layouts of the HVD, the TL and the SF₆-air bushing are not the final ones. Nevertheless, some useful informations can be extrapolated from the given results, indeed, the calculated electric field levels seems to be acceptable for the proposed solutions, that is, the first estimations given in chapter 2 seems to be reasonable. At the end of this chapter a test bed was analyzed. This mockup, that will be realized in the context of the research of gas-insulated components, will be of fundamental importance to gain confidence with the experimental phase

6.5. CONCLUSIONS

and to verify the correctness of the proposed numerical tools. In particular, the mockup will be realized with the purpose of fine tuning the model parameters, possibly testing different insulating gases and solid insulator materials, and analyze the phenomena which can lower the voltage holding of the system (for example the leakage currents).

7

Conclusions and future activities

THIS DOCTORAL thesis was aimed at the mathematical and numerical investigation of High Voltage Direct Current (HVDC) gas-insulated (GIS) technology with the main purpose of supporting the conceptual design and operational phase of the Acceleration Grid Power Supply (AGPS) of Neutral Beam Injectors (NBI).

HVDC-GIS technology plays a key role not only in the field of nuclear fusion, but also for the transmission of high power generated by new renewable energy sources, such as offshore wind turbines. For this purpose, the models developed in this thesis consider the gaseous and solid dielectric materials used in HVDC gas-insulated systems and all the phenomena involved in a general way (for example the thermal effects). In view of the stringent rules imposed by the Kyoto protocol, an important issue for the commercial diffusion of HVDC gas-insulated technology is the research of environmental friendly gases with the purpose of replacing the commonly adopted Sulphur hexafluoride, characterized by an high value of Global Warming Potential (GWP). The very stringent directives related to leakages for this gas are certainly an important limiting factor for the exploitation of GIS technology. Moreover, for the development of future HVDC components, capable of guaranteeing high dielectric performance along the entire operating cycle, the use of solid insulator materials capable of homogenize the electric field stress thus reducing the charge accumulation phenomenon is mandatory. In this context, the Functionally Grading Materials (FGM) may represent a

breakthrough for the reliability of HVDC gas-insulated systems.

The key parameters for the electromagnetic modeling of HVDC components, such as the electric conductivities of the dielectric materials were investigated in the thesis. Different mathematical models can be defined on the basis of the physical phenomena that characterize the electrical conduction in the gas. In this work two common approaches were described: the electro-quasistatic (EQS) and the drift-diffusion-reaction models. The pros and cons of the two modeling techniques were depicted. The main limitation of the standard EQS approach is the specification of the electrical conductivities a priori, while it is a well-known fact that the electric conduction in the gas is due to the motion of free ions under the effect of the electric field, which must be evaluated in a self-consistent way. The drift-diffusion-reaction model is well suited for this purpose, but requires more computational effort for the numerical solution in terms of dimension of the numerical problem, convergence and stability issues.

Research in the field of nuclear fusion can both take advantage of and provide indications in the context of HVDC gas-insulated systems. As a matter of fact some of the HVDC equipments used for the power supply of the acceleration grids of the most powerful and advanced NBIs, for example the last section of transmission line and the high voltage bushing, must satisfy very stringent electric requirements and has to be installed in locations in which the environmental radiation extremely affect the electric conduction within the gas. This phenomenon known as Radiation Induced Conductivity (RIC) is only one part of the leakage current flowing in the gas, which can be affected by different aspects, such as the field emission from small metallic tips and the residual water content in the gas. These aspects were analyzed in the thesis both from mathematical and numerical viewpoint, showing how they can be treated within the drift-diffusion-reaction model.

Differently from commercial HVDC gas-insulated transmission lines, the Transmission Line (TL) for the AGPS is not coaxial. In fact the TL carries all the acceleration voltages of the grids, that is the TL is a multi-conductor line. Furthermore, the Ion Source and Extraction Power Supply (ISEPS) conductors are placed inside the center conductor of the TL, which is at the highest voltage level and has a larger outer diameter than the others. The placement of the conductors and the shape of the high voltage parts influence the map of the electric field which in the worst cases can lead to gas breakdown. A numerical way to extract the breakdown inception parameters for a given insulating gas was described in the thesis. The modeling techniques described along the PhD work constitute the basic ingredients for the shape optimization tool based on an in-house Differential Evolution (DE) algorithm written in MATLAB®. This tool has been developed in order to

support the engineering phase of HVDC-GIS parts, in particular to find an optimal design of components that have inhomogeneities in the electric field and peaks that can induce discharges in the gas.

The developed numerical tools for the analysis of HVDC-GIS components can be used not only in the context of the nuclear fusion research, but also for the investigation of commercial HVDC-GIS equipments. All the features described above, namely the electric field modeling with the drift-diffusion-reaction equations, the phenomena that occur in the gas and affecting its voltage holding capabilities (e.g., the leakage currents) and the gas breakdown modeling by using the streamer inception criterion, are embedded in a single model developed within the commercial software COMSOL® Multiphysics. Although this implies some limitations in the control of the detailed numerical aspects, the usage of commercial software makes it easier to share the models with different users. The model can be used to analyze novel solid insulating materials and dielectric gases, once the functional dependence of the electrical conductivity for the solid and the gas parameters for the drift-diffusion model are specified.

The conceptual design of HVDC technology for the AGPS of the Divertor Tokamak Test (DTT) facility, the construction of which is in the start phase in Frascati, Italy, was based on the modeling techniques developed in the body of the thesis. The estimation of the footprint of the TL and the High Voltage Bushings (HVB) are of key importance to verify the impact on site buildings. In this respect, the developed tools were used for the electromagnetic analysis of almost realistic three dimensional models for the 500 kV TL and the SF₆-air bushing. Despite the proposed layouts may be subjected to variations before their practical realization, the numerical analyses confirm the voltage holding capabilities of the proposed solutions, which can be taken as reference.

From a research perspective, the experimental validation of the described numerical tools is crucial to proceed towards a correct modeling of the HVDC gas-insulated technology. This for different reasons, first of all to gain confidence with the underlying physical phenomena mainly arising from the motion of free ions, such as the leakage currents, and also for the fine tuning of the parameters describing the gas. For this purpose, a small-scale test-bed has been designed and will be implemented in the near future. The experiments that will be carried out in the test bed will make it possible to test different materials for the solid insulator and different types of gas, at different pressures. Of particular interest will be the experimental investigation of the FGMs and the novel eco-friendly dielectric gases. The results of these analyses will be of general interest not only for HVDC-GIS systems in the nuclear fusion field and also for the development of commercial systems.

The numerical tools developed during the doctorate, on the one hand, provide support in the design phase of AGPS for NBIs, as in the case of DTT, on the other hand they can also be used to support the experimental phase of the high voltage plants hosted at the Consorzio RFX, Padova, such as the 1 MV MITICA HVDC gas insulated systems at the ITER Neutral Beam Test Facility (NBTF), and the activities on RFX-mod2 Reversed Field Pinch (RFP).



Other topics during the PhD

THIS CHAPTER gives an overview about other research activities carried out during the Ph.D. The first sections presents two Integral Equation Methods (IEMs) for the solution of eddy current problems, which are the $\mathbf{J} - \varphi$ and loop-currents formulations. A way to efficiently handle the full (dense) matrices arising from IEMs discretization, is described in [A.2](#). Next, in [A.3](#) the IEM known as Partial Element Equivalent Circuit (PEEC) exploiting the Fast Fourier Transform and a voxelized mesh, is used to model conductive, dielectric and magnetic domains. In the end, a brief overview on the topology optimization methods for electromagnetics is given. The topology optimization, dealing with optimal material placement in a domain, recently gained great interest also in the electromagnetic community due to the development of additive manufacturing techniques.

A.1 Integral formulation of eddy currents

When analyzing the scattered field of an high-frequency antenna an *open boundary* problem has to be solved, which by using Finite Element Method (FEM), translates into embedding the radiating device into a sufficiently large vacuum sphere where artificial boundary conditions are applied. Despite the final system matrices are very sparse, by doing this, the number of degrees of freedom grows fast and the majority of mesh elements are non-electromagnetically active. Moreover, if very small geometrical features have to be resolved, the mesh generation from tiny to large scales requires huge effort (see Fig. [A.1](#)). IEMs are a suitable alternative to FEM to solve the

A.1. INTEGRAL FORMULATION OF EDDY CURRENTS

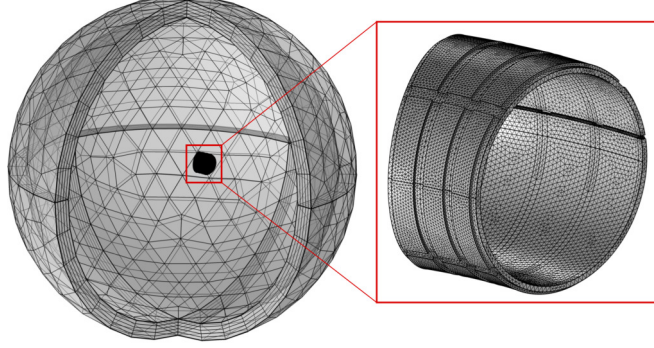


Figure A.1: 3D FEM mesh to study the eddy currents induced in a conductive section of a magnetic confinement fusion device embedded in a large vacuum sphere.

electromagnetic problem in unbounded domains since only the active (e.g., conductive) domains are discretized. The magneto-quasistatic, or eddy current approximation of the Maxwell equations, expressed by equation (4.12), is here rewritten in the time-harmonic domain with $\partial/\partial t \rightarrow i\omega$:

$$\mathbf{E} + i\omega\mathbf{A} = -\nabla\varphi_e, \quad (\text{A.1})$$

where ω is the angular frequency. The Volume Integral (VI) formulation of eddy currents problems can be conceived by expressing the magnetic vector potential $\mathbf{A}$ by means of Biot-Savart law [164]:

$$\mathbf{A}(\mathbf{r}) = \mu_0 \int_{\Omega} \mathbf{J}(\mathbf{r}') G(\mathbf{r}, \mathbf{r}') d\Omega, \quad (\text{A.2})$$

where $\mathbf{J}$ is the current density, $\mathbf{r}$ and $\mathbf{r}'$ are respectively the observation and source points and $G(\mathbf{r}, \mathbf{r}')$ is the Green's function kernel, which for low frequencies is:

$$G(\mathbf{r}, \mathbf{r}') = \frac{1}{4\pi\|\mathbf{r} - \mathbf{r}'\|}, \quad (\text{A.3})$$

exhibiting a singularity for $\mathbf{r} \rightarrow \mathbf{r}'$. Using Ohm's law, $\mathbf{E} = \rho_e \mathbf{J}$ and splitting the total electric field $\mathbf{E}$ into the sum of external $\mathbf{E}_{ext}$ and scattered $\mathbf{E}_{sca}$ parts, the integral form of equation (A.1) is written as:

$$\rho_e \mathbf{J} + i\omega\mu_0 \int_{\Omega} \mathbf{J}(\mathbf{r}') G(\mathbf{r}, \mathbf{r}') d\Omega + \nabla\varphi_e = \mathbf{E}_{ext}, \quad (\text{A.4})$$

which contains two unknowns, namely $\mathbf{J}$ and φ_e . The system is closed by exploiting the continuity equation in magneto-quasistatic assumptions:

$$\nabla \cdot \mathbf{J} = 0. \quad (\text{A.5})$$

The numerical solution of equations (A.4) and (A.5) starts from the discretization of the electromagnetically-active domain Ω into a collection of finite elements $\mathcal{K}$ made up by N_v volumes and N_f faces. For each volume v_k the unknown current density field $\mathbf{J}^k$ can be interpolated by means of vector facet basis functions $\mathbf{w}$ [199, 200] as:

$$\mathbf{J}^k(\mathbf{r}) = \sum_{i=1}^{N_f^k} \mathbf{w}_i^k(\mathbf{r}) j_{f_i}^k, \quad (\text{A.6})$$

where $j_{f_i}^k$ is the flux of $\mathbf{J}^k(\mathbf{r})$ through the i th face of the volume v_k . The unknowns j_k , with $k = 1, \dots, N_f$, are stored in the array $\mathbf{j}$. The DoFs related to the scalar electric potential are collected in the array Φ of size N_v . By exploiting the cell method of Section 4.7, the discretized form of the eddy currents problem in frequency domain become:

$$(\mathbf{R} + i\omega\mathbf{L})\mathbf{j} + \mathbf{G}\Phi = \mathbf{e}_{\text{ext}}, \quad (\text{A.7})$$

$$\mathbf{G}^\top \mathbf{j} = \mathbf{0}, \quad (\text{A.8})$$

where $\mathbf{R}$ and $\mathbf{L}$ are respectively the equivalent (sparse) resistance and (dense) inductance matrices [201] of dimension $N_f \times N_f$, and $\mathbf{G}$ is the volumes–faces incidence matrix [202] of dimension $N_f \times N_v$. For the sake of conciseness the coefficient L_{ij}^{hk} relative to mesh elements v_h and v_k is given by [200]:

$$L_{ij}^{hk} = \mu_0 \int_{v_h} \mathbf{w}_i^h(\mathbf{r}) \cdot \int_{v_k} \frac{\mathbf{w}_j^k(\mathbf{r}')}{4\pi \|\mathbf{r} - \mathbf{r}'\|} dv_k dv_h, \quad (\text{A.9})$$

whose values can be computed exploiting semi-analytical integration formulas [203].

A.1.1 J- φ formulation

Starting from equations (A.7) and (A.8) a system of equations in the unknowns $\mathbf{j}$ and Φ , can be directly set up:

$$\begin{bmatrix} \mathbf{R} + i\omega\mathbf{L} & \mathbf{G} \\ \mathbf{G}^\top & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{j} \\ \Phi \end{bmatrix} = \begin{bmatrix} \mathbf{e}_{\text{ext}} \\ \mathbf{j}_{\text{inj}} \end{bmatrix}, \quad (\text{A.10})$$

where $\mathbf{j}_{\text{inj}}$ is the array corresponding to possible injected currents which can be easily considered in the proposed formulation. It is worth noting that an electric potential for each separated domain must be set to zero in order to give a reference to the electric scalar potential.

A.1.2 Loop-currents formulation

The loop-currents formulation [204, 200] termed as **C**-formulations [205], strongly enforces the divergence-free condition (A.5) introducing the vector potential **T** in such a way:

$$\mathbf{J} = \nabla \times \mathbf{T}. \quad (\text{A.11})$$

In the discrete setting the current density is written as the curl of an electric vector potential, i.e., in terms of array of unknowns,

$$\mathbf{j} = \mathbf{C}\mathbf{t} + \mathbf{H}\mathbf{i}, \quad (\text{A.12})$$

where **t** is the array related to the electric vector potential **T**, such as $\mathbf{J} = \nabla \times \mathbf{T}$, and **C** is the curl faces-edges incidence matrix (where, according to [206], a set of edges forming a tree has been removed in order to impose a gauge on **T**).

In equation (A.12), **H** is a proper change of basis matrix which maps the extra global unknowns **i** into **j** for multiply-connected domains [207]. Actually, **i** is an array storing unknowns related to loop currents around holes of the multiply-connected domains [205]. By inserting (A.12) into (A.7) and projecting the resulting equations by using $\mathbf{C}^\top$ and $\mathbf{H}^\top$, one finally obtains [208]:

$$\begin{bmatrix} \mathbf{R}_{cc} + i\omega\mathbf{L}_{cc} & \mathbf{R}_{ch} + i\omega\mathbf{L}_{ch} \\ \mathbf{R}_{hc} + i\omega\mathbf{L}_{hc} & \mathbf{R}_{hh} + i\omega\mathbf{L}_{hh} \end{bmatrix} \begin{bmatrix} \mathbf{t} \\ \mathbf{i} \end{bmatrix} = \begin{bmatrix} \mathbf{C}^\top \mathbf{e}_{\text{ext}} \\ \mathbf{H}^\top \mathbf{e}_{\text{ext}} \end{bmatrix}, \quad (\text{A.13})$$

where

$$\mathbf{R}_{cc} = \mathbf{C}^\top \mathbf{R} \mathbf{C}, \quad \mathbf{R}_{ch} = \mathbf{C}^\top \mathbf{R} \mathbf{H}, \quad \mathbf{R}_{hc} = \mathbf{H}^\top \mathbf{R} \mathbf{C}, \quad \mathbf{R}_{hh} = \mathbf{H}^\top \mathbf{R} \mathbf{H},$$

$$\mathbf{L}_{cc} = \mathbf{C}^\top \mathbf{L} \mathbf{C}, \quad \mathbf{L}_{ch} = \mathbf{C}^\top \mathbf{L} \mathbf{H}, \quad \mathbf{L}_{hc} = \mathbf{H}^\top \mathbf{L} \mathbf{C}, \quad \mathbf{L}_{hh} = \mathbf{H}^\top \mathbf{L} \mathbf{H}.$$

Matrices $\mathbf{R}_{cc}$ and $\mathbf{L}_{cc}$ are the resistance and inductance matrices related to **t** (i.e., local loop-currents) and they can be constructed as shown in [209] without actually passing through **R** and **L**. Instead, $\mathbf{R}_{hh}$ and $\mathbf{L}_{hh}$ are matrices related to **i**, i.e., loops around holes in multiply-connected domains. The remaining matrices represent mutual resistive and inductive coupling between **t** and **i**.

Numerical example: TEAM Workshop Problem 7

In this section, the performances of the $\mathbf{J}$ - φ and the loop-currents formulations are compared for the solution of the Testing Electromagnetic Analysis

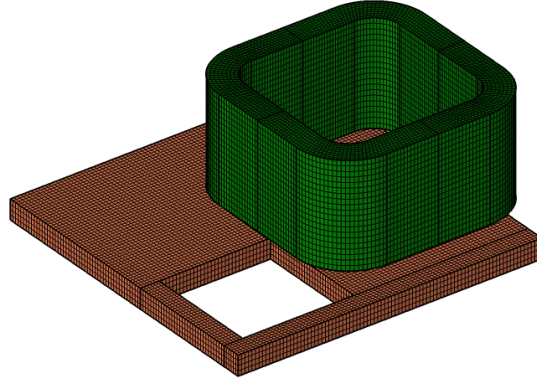


Figure A.2: 3D CAD view of TEAM Workshop Problem 7. The exciting coil is colored in green, while the asymmetrical conductor in brown.

Method (TEAM) Workshop Problem 7 [210] which consists of an asymmetrical conductor of electrical resistivity $\rho_e = 0.028 \mu\Omega \text{ m}$ with a hole, excited by a coil with 2742 At, at 50 Hz (see Fig. A.2). The discretized model of the conductor consists of 26250 hexahedral elements, resulting into 48376 unknowns for the loop-currents formulation and 97293 unknowns (71043 face currents and 26250 potentials) for the $\mathbf{J}$ - φ formulation. The computed values of the magnetic field along a reference line described in TEAM Workshop Problem 7 are compared with the ones provided by the TEAM Workshop Problem 7. This comparison is shown in Fig. A.3. The computed values are in excellent agreement and they also agree with the trend of experimental points of the TEAM Workshop Problem 7 [211].

A.2 Low-rank approximation

As briefly discusses in Section 4.7, the numerical solution of EM problem generally relies in two kinds of approaches i.e., the Finite Element (FEM) and Integral Equation (IEM) methods. The main advantage of the former is the generation of sparse matrices arising from the discretization of the underlying PDE problem. This aspect has favored the development and integration of the FEM in most commercial software. The IEM instead, which does not require the discretization of non-conductive domains, deal with fully populated (dense) matrices due to the fact that the kernel of the integral equations,

A.2. LOW-RANK APPROXIMATION

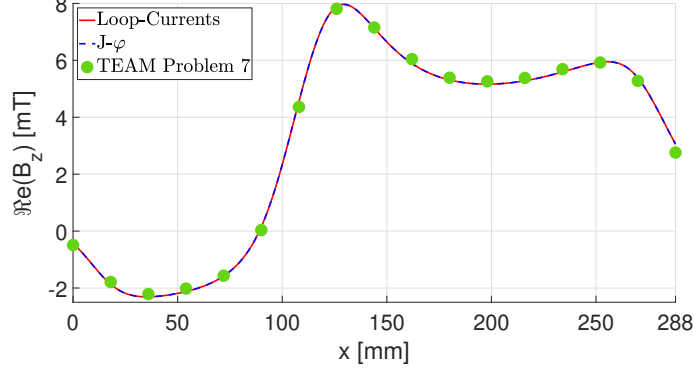


Figure A.3: Comparison of the real part of B_z -component evaluated with the two IEMs A.1.1, A.1.2 and the results of TEAM Workshop Problem 7, along a reference line.

namely the Green's function (A.3), is a non-local operator accounting for the mutual interaction between all the points $\mathbf{r}, \mathbf{r}'$ in the computational domain $\Omega \subset \mathbb{R}^d$. Using this approach all the matrix elements composing e.g., the inductance matrix $\mathbf{L}$ in (A.7) are different from zero, and, therefore the arising matrix is dense. Denoting with N the number of rows and columns of such matrix, the computational cost for the storage and assembly scales as $\mathcal{O}(N^2)$, rapidly saturating the computer memory for realistic 3D problems. In principle, this aspect limits the applicability of IEM to small problems however, due to the smoothness of the Green's function (A.3) when $\mathbf{r}$ and $\mathbf{r}'$ are far apart, the matrix contains low-rank blocks which can be stored with less computational cost. This aspect highlights the low-rank properties of the dense matrix and opens up the possibility of using data-sparse representations.

A.2.1 Data-sparse representations

As stated in the introductory part of this section, the dense matrices arising from IEM methods exhibit low-rank blocks when the observation $\mathbf{r}$ and source $\mathbf{r}'$ points are far apart.

Consider for example a tessellation of the computational domain Ω made by triangular elements, whose barycenters are identified by position vectors $\mathbf{r}_k$. Denoted with $I = 1, \dots, N$ the index set of the barycenters, if the geometric elements are reordered (e.g., following a geometric bisection criterion) in such a way that $\mathbf{r}_i$ is geometrically far away from $\mathbf{r}_j$, the matrix entry L_{ij} of has indices i and j that correspond to far positions in I . This means that off-

diagonal matrix blocks representing interaction between far-field points, can be represented with low-rank approximation making $\mathbf{L}$ compressible [212].

There exists a variety of data-sparse representations [213]: Hierarchical Off Diagonal Low Rank (HODLR) [214], Hierarchical Semi Separable (HSS) [215], Hierarchical Adaptive Low Rank (HALR) [216], and $\mathcal{H}^2$ matrices [217]. Both based on the hierarchical subdivision of index sets I and J representing row and column indices of the matrix. After proper reordering of such index sets, for example as shown in Fig. A.4, the procedure of hierarchical partitioning is performed as:

1. A bisection of each set is generated, e.g., I is partitioned into two clusters:

$$\begin{array}{ccc}
 I = \{1, \dots, N\} & & \\
 \swarrow \quad \searrow & & \\
 \tau_I = \{1, \dots, \lfloor N/2 \rfloor\} & & \sigma_I = \{\lfloor N/2 \rfloor + 1, \dots, N\}.
 \end{array} \tag{A.14}$$

The same operation for J , leading to clusters τ_J and σ_J ,

2. Each of the four cluster pairs representing the matrix blocks $\mathbf{L}_{(\tau_I, \tau_J)}$, $\mathbf{L}_{(\tau_I, \sigma_J)}$, $\mathbf{L}_{(\sigma_I, \tau_J)}$, $\mathbf{L}_{(\sigma_I, \sigma_J)}$ are tested against an admissibility criterion which identifies if the cluster is a good candidate for applying low-rank approximation or if it must be further partitioned:

$$\min\{diam(\tau), diam(\sigma)\} \leq \eta \, dist(\tau, \sigma), \tag{A.15}$$

where $\eta > 0$ is the admissibility parameter, $diam$ is the cluster diameter and $dist$ is the distance function between clusters [205],

3. Admissible cluster pairs, whose corresponding matrix block belongs to the far-field interaction, are stored efficiently with low-rank techniques, otherwise, the clusters are halved and the procedure is applied recursively from step 1, until the admissibility check is satisfied or the number of elements (i.e., unknowns) related to the matrix block reaches a specified minimum threshold ($blocksize^2$) [218].

For the sake of completeness, we briefly describe the low-rank approximation of admissible off-diagonal blocks. Consider a matrix block $\mathbf{A} \in \mathbb{R}^{m \times n}$, related to far-field interactions of elements in τ and σ . Matrix $\mathbf{A}$ has a low-rank representation if exists matrices $\mathbf{U} \in \mathbb{R}^{m \times k}$ and $\mathbf{V} \in \mathbb{R}^{n \times k}$ such that:

$$\mathbf{A} = \mathbf{U}\mathbf{V}^T, \tag{A.16}$$

A.2. LOW-RANK APPROXIMATION

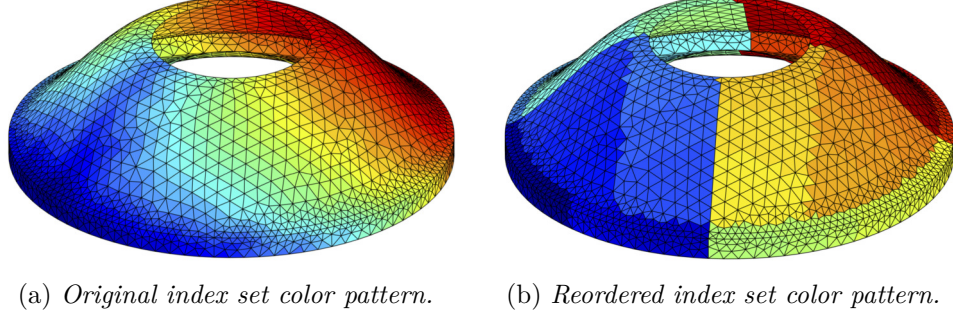


Figure A.4: Example of reordering of index sets with the geometric bisection algorithm, for triangular elements discretizing a conical spacer surface. In Fig. A.4b, triangles $\{1, \dots, N\}$ were reordered so that near ones have approximately the same colour.

with $k(m + n) < mn$, where k is the effective rank. Since this is not known a priori, the rank-revealing factorization (A.16) is computed within a prescribed tolerance ε :

$$\frac{\|\mathbf{A} - \mathbf{U}_{k'} \mathbf{V}_{k'}^T\|_F}{\|\mathbf{A}\|_F} < \varepsilon. \quad (\text{A.17})$$

where $k' < k$ is the numerical rank. The decomposition (A.17) can be obtained by using e.g., the Adaptive Cross Approximation (ACA) algorithm [219], which is a completely *matrix-free* approach which computes the columns of $\mathbf{U}_{k'}$ and $\mathbf{V}_{k'}$, without previously storing the entire matrix $\mathbf{A}$. The algorithm requires only the capability of computing the generic entry of the full matrix for $i \in \tau$ and $j \in \sigma$. Since only few entries of the original matrix must be computed, it can be proven that the computational cost required by the ACA approximation have a linear-logarithmic complexity [218].

A.2.2 Numerical examples

In this section, two numerical examples are used to show the performances of the low-rank approximation methods for the solution of IEMs. The first example deals with the acceleration of the charge inversion algorithm for HVDC-GIS systems, while the second test case investigates the applicability of data-sparse representation for the eddy current problems described in Section A.1 for a D shaped vacuum vessel employed in thermonuclear fusion devices.

Charge inversion algorithm for HVDC gas-insulated systems

As stated in Chapter 4 a relevant aspect specific of HVDC gas-insulated systems, is the surface charge accumulating on gas-solid interfaces during the transition from the initial (capacitive) to the final (resistive) field distribution. Experimentally, the quantification of this charge density is based on the measured surface potential distribution. To do so the charge inversion algorithm introduced by Ootera [197], is usually adopted.

The main drawback of this method is the computational effort required for the storage and the inversion of the dense matrix which maps potentials to surface charges [220, 221], therefore exploiting the low-rank approximation techniques these limitations can be overcome, as shown in this example.

The charge inversion algorithm is based on the integral solution of the Poisson equation $-\Delta\varphi = \varrho_{app}/\varepsilon_0$ for an apparent surface charge density distribution $\varrho_{s,app}$, sum of free and bound charge densities:

$$\varphi(\mathbf{r}) = \int_{\Gamma} \frac{\varrho_{s,app}(\mathbf{r}')}{4\pi\varepsilon_0\|\mathbf{r} - \mathbf{r}'\|} d\Gamma. \quad (\text{A.18})$$

Expanding the unknown $\varrho_{s,app}(\mathbf{r})$ in terms of DoFs by using piece-wise uniform bases function $w_k = 1/|S_k|$, where $|S_k|$ is the area of the k th triangular element [202] and exploiting a Galerkin scheme, equation (A.18) becomes:

$$\phi_i = \int_{\Gamma} w_i(\mathbf{r}) \left(\sum_{j=1}^N \int_{\Gamma} \frac{w_j(\mathbf{r}') q_{app,j}}{4\pi\varepsilon_0\|\mathbf{r}_i - \mathbf{r}'_j\|} d\Gamma \right) d\Gamma, \quad (\text{A.19})$$

where ϕ_i is the average electric potential in the i th triangle and $q_{app,k}$ is the apparent charge on the k th one [202]. Equation (A.19) can be recasted in matrix form:

$$\Phi = \mathbf{P} \mathbf{q}_{app}, \quad (\text{A.20})$$

where the coefficients of matrix $\mathbf{P} \in \mathbb{R}^{N \times N}$ are given by:

$$P_{ij} = \frac{1}{|S_j||S_i|} \int_{S_i} \int_{S_j} \frac{1}{4\pi\varepsilon\|\mathbf{r}_i - \mathbf{r}_j\|} d\Gamma' d\Gamma. \quad (\text{A.21})$$

The free charge density is obtained from the apparent one by solving the system (A.20) and applying an integral matrix operator, whose coefficients depends on the relative permittivity discontinuities [197, 221]. Nevertheless, the bottleneck is the computational effort required for the solution of (A.20), for which data-sparse techniques can be applied.

In particular, here two alternative approaches are proposed to reduce the computational burden:

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1. If the storage of the full matrix $\mathbf{P}$ is not the main problem, its data-sparse representation (HODLR, HALR or HSS), $\mathcal{H}\text{-}\mathbf{P}$, can be performed directly using the entire matrix. Thanks to the algebra of $\mathcal{H}$ -matrices, a data-sparse $\mathcal{H}$ -LU factorization of $\mathcal{H}\text{-}\mathbf{P}$ is efficiently computed and the solution of the linear system (A.20) is performed with the GMRES iterative solver using the $\mathcal{H}$ -LU of $\mathcal{H}\text{-}\mathbf{P}$ as preconditioner. Since the $\mathcal{H}$ -LU is a very good preconditioner, GMRES will require only a few iterations to converge, and no factorization of the full matrix $\mathbf{P}$ is performed.
2. If the storage of the full matrix $\mathbf{P}$ is an issue due to $\mathcal{O}(N^2)$ scaling, its data-spare representation (HODLR, HALR or HSS) can be generated by using a matrix-free approach. In this case, only an operator which evaluates the coefficients of $\mathbf{P}$ for a generic set of indices is required. As in previous approach the GMRES solver can be adopted to solve the problem by using $\mathcal{H}\text{-}\mathbf{P}$ as system matrix and the $\mathcal{H}$ -LU as preconditioner.

The accuracy analysis of the charge reconstruction in a conical spacer was taken as test case to show the performances of the data-sparse method. As shown in Fig. A.5, a charge density $\varrho_{s,imposed} = 1 \text{ C/m}^2$ was deposited on an annular area of the upper surface of the insulator and the corresponding electric potential Φ was calculated with equation (A.20). The computational domain was discretized with $N = 129384$ triangular elements. For the block cluster tree construction, $blocksize = 64$ was adopted. The numerical experiments are performed in MATLAB[®] by using parallel MEX-FORTRAN functions based on OpenMP libraries for the computation of the matrix coefficients. The low-rank approximation of the dense matrix was realized with the MATLAB[®] library hm-toolbox [222] which allows for using different techniques for the data-sparse representation of $\mathbf{P}$ and the solution of the inverse problem.

A summary of the computational performances are listed in Tables A.1 and A.2, including the following data:

- Memory Ratio: data-sparse compression percentage, defined as:

$$\text{Memory Ratio} = 100 \cdot \frac{\text{MemorySize}(\mathcal{H} - \mathbf{P})}{\text{MemorySize}(\mathbf{P})}, \quad (\text{A.22})$$

where $\text{MemorySize}(o)$ gives the computer memory required by the object o ,

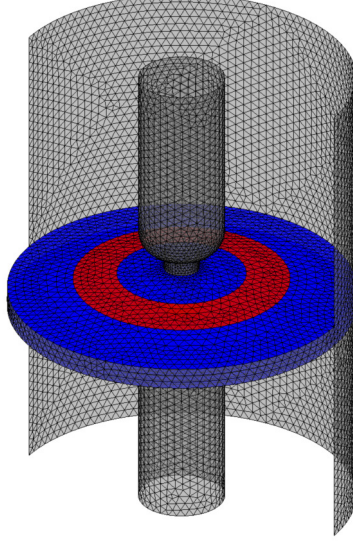


Figure A.5: 3D view of the HVDC-GIS conical insulator spacer in blue with deposited annular surface charge density in red.

- Relative Error: relative percentage error as:

$$\text{Relative Error} = 100 \cdot \frac{\|\boldsymbol{q}_s - \boldsymbol{q}_{s,imposed}\|}{\|\boldsymbol{q}_{s,imposed}\|}, \quad (\text{A.23})$$

where $\boldsymbol{q}_s$ is the array of surface charge densities reconstructed from the solution of (A.20),

- Construction: time spent to assemble data-sparse format,
- LU: time spent to compute the $\mathcal{H}$ -LU factorization,
- Solving: time spent to solve the linear system with GMRES (tol = 10^{-6}).

D-shaped vacuum vessel

The second test case is retrieved from the numerical modelling of magnetic confinement fusion (MCF) devices. The frequency response of the conductive structure of a typical D-shaped Vacuum Vessel (VV) used in thermonuclear fusion machines, is investigated. The stainless steel structure, shown in Fig. A.6, is subjected to an external vertical field of $B_z = 1$ T at 50 Hz, reproducing the magnetizing field of the machine magnet system. A tetrahedral mesh made 240 426 tetrahedral elements is used for the discretization,

A.2. LOW-RANK APPROXIMATION

Method	Memory Ratio [%]	Relative Error [%]	Construction [s]	Generating $\mathcal{H}$ -LU [s]	Solution [s]
HODLR	4.5	$8 \cdot 10^{-5}$	114	197	41
HSS	0.2	$1.7 \cdot 10^{-4}$	1798	—	109
HALR	4.3	$5 \cdot 10^{-5}$	80	123	43
Dense	100.0	0.0	889	—	1941

Table A.1: Results for $N = 129384$ triangular elements following approach (1). The low-rank accuracy ε was set to 10^{-2} to lower the computational effort for $\mathcal{H}$ -LU computation.

Method	Memory Ratio [%]	Relative Error [%]	Construction [s]	Generating $\mathcal{H}$ -LU [s]	Solution [s]
HODLR	7.8	0.5	210	492	4
HSS	1.4	1.2	9423	—	25
HALR	6.3	0.3	142	281	5
Dense	100.0	0.0	889	—	1941

Table A.2: Results for $N = 129384$ triangular elements following approach (2). The low-rank accuracy ε was set to 10^{-4} .

resulting into 152 748 unknowns for the loop-current formulation, and 224 319 current unknowns and 240 426 scalar potential unknowns for the $\mathbf{J}$ - φ formulation.

A reference solution has been obtained by solving the dense problem arising from the loop-currents formulation with a direct solver based on LU decomposition and using a Linux machine equipped with 16-core/32-thread processor (Intel Xeon Gold 6130 @2.10 GHz), for a total of 256 cores and 3 TB of RAM. The dense system required 373 GB of RAM. Low-rank approximation techniques based on $\mathcal{H}$ -matrices and ACA implemented in the highly optimized $\mathcal{H}$ LibPro library [223] were applied to both the loop-currents and the $\mathbf{J}$ - φ formulations.

The computational performances of the two methods are listed in table A.3. As can be seen, for this large-scale problem the two formulations show comparable results, with the main difference that the loop-currents formulation require a non-negligible computation time to construct matrix $\mathbf{H}$. Indeed, although the systems arising from the two formulations have different number of unknowns, the bigger one obtained from the $\mathbf{J}$ - φ formulation can be efficiently compressed by using $\mathcal{H}$ -matrices and ACA. This because the system of equations arising from the loop-current formulation has an heterogeneous structure due to the presence of the global unknowns $\mathbf{i}$. Moreover, by imposing the same accuracy for the ACA, the mutual inductance coefficients between loop-currents (i.e., $\mathbf{t}$) are less compressible with respect to

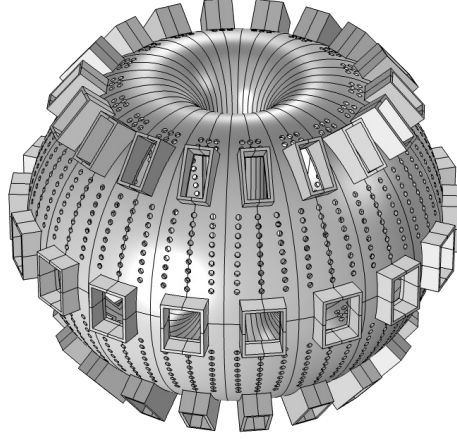


Figure A.6: 3D CAD view of a D-shaped vacuum vessel of a thermonuclear fusion devices.

Method	Memory [GB]	Assembling [s]	Generating $\mathbf{H}$ [s]	Solution [s]
Loop-Currents	34	7426	9726	3316
$\mathbf{J}\text{-}\varphi$	38	6812	—	3596

Table A.3: Computational performances of the loop-currents and $\mathbf{J}\text{-}\varphi$ formulations for the case of the D-shaped vacuum vessel.

ones corresponding to face currents (i.e., $\mathbf{j}$) because of the different support and orientation of the shape functions. The accuracy of the two formulations with respect to the dense case taken as reference was very good, i.e., errors are below 1% in the system solution were obtained from both the formulations.

A.3 Fast Fourier Transform - Partial Element Equivalent Circuit method

Among all IEMs the Partial Element Equivalent Circuit (PEEC) [224], has captured the interest of the scientific community for its versatility and its useful and natural circuit interpretation of the electromagnetic problem. In this section the way that the PEEC system can be efficiently solved by exploiting a voxelization approach to generate the mesh and the Fast Fourier Transform (FFT) to speed up the matrix-vector products opening up the possibility of using iterative solution schemes, as the GMRES. The resulting

A.3. FAST FOURIER TRANSFORM - PARTIAL ELEMENT EQUIVALENT CIRCUIT METHOD

method is called FFT-PEEC [225].

The starting point to derive the traditional PEEC system of equations of the full-Maxwell problem are the Electric Field Integral Equation (EFIE) and the Magnetic Field Integral Equation (MFIE), common to all classical volume integral equation methods [202]:

$$\mathbf{E}(\mathbf{r}) = -i\omega\mathbf{A}_e(\mathbf{r}) - \nabla\varphi_e(\mathbf{r}) - \frac{1}{\varepsilon_0}\nabla \times \mathbf{A}_m(\mathbf{r}) + \mathbf{E}_{ext}(\mathbf{r}), \quad (\text{A.24})$$

$$\mathbf{H}(\mathbf{r}) = -i\omega\mathbf{A}_m(\mathbf{r}) - \nabla\varphi_m(\mathbf{r}) + \frac{1}{\mu_0}\nabla \times \mathbf{A}_e(\mathbf{r}) + \mathbf{H}_{ext}(\mathbf{r}), \quad (\text{A.25})$$

where $\mathbf{A}_e$ and $\mathbf{A}_m$ are the electric and magnetic vector potentials and φ_e , φ_m the scalar electric and magnetic potentials. Both vectorial and scalar potential are given by integral expressions. The former, from the electric $\mathbf{J}_e$ and magnetic $\mathbf{J}_m$ current densities, the latter in terms of volumetric electric ρ_e and (bound) magnetic ρ_m charges [164]. By using the cell method and expanding the unknowns $\mathbf{J}_e$, $\mathbf{J}_m$, φ_e and φ_m in terms of degrees of freedom associated to geometric entities related by the Tonti diagram, and projecting the resulting equations with a Galerkin scheme, the following system of equations is derived [164]:

$$\begin{bmatrix} \mathbf{R}_e + i\omega\mathbf{L}_e & \mathbf{K} & \mathbf{G}_e^T & \mathbf{0} \\ -\mathbf{K}^T & \mathbf{R}_m + i\omega\mathbf{L}_m & \mathbf{0} & \mathbf{G}_m^T \\ \mathbf{P}_e\mathbf{G}_e & \mathbf{0} & -i\omega\mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}_m\mathbf{G}_m & \mathbf{0} & -i\omega\mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{j}_e \\ \mathbf{j}_m \\ \phi_e \\ \phi_m \end{bmatrix} = \begin{bmatrix} \mathbf{e}_0 \\ \mathbf{h}_0 \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix}. \quad (\text{A.26})$$

As usual in IEM, the arising system contains fully-populated (dense) matrices, such as $\mathbf{L}$, $\mathbf{P}$ and $\mathbf{K}$. The idea of using a voxelized mesh (i.e., a mesh made of regular hexahedra) in combination with the FFT [226, 227] is based on the translational invariance property of the Green's kernel which allows to embed the matrices into Block Toeplitz matrices with Toeplitz Blocks (BTTB). The BTTB matrices can be represented by means of circulant tensors reducing the memory requirement to $\mathcal{O}(N)$ and for the matrix-vector products to $\mathcal{O}(N\log(N))$ by using the FFT and its inverse (IFFT) [228]. In this way the computational burden is drastically reduced without using any data-sparse representation A.2. Obviously, when a voxelization method is adopted, the price to pay is that the original geometry is not perfectly represented by the voxelized structure. However, thanks to the $\mathcal{O}(N)$ scaling, a huge number of voxels can be adopted. Moreover, the voxelization process can be directly performed from common CAD filed (e.g., *.stl*), by automatic procedures, reducing human effort [225].

The proposed FFT-PEEC method was used to characterize the L-C-T component used in power electronics applications, for which no magneto-

quasistatic approximation is possible [225] and for the extraction of equivalent inductance of a magnetic non-linear device [229].

Sample MATLAB® implementations of the FFT-PEEC method are available at <https://github.com/UniPD-DII-ETCOMP/FFT-PEEC>.

A.3.1 Numerical example: frequency response of vacuum vessel of thermonuclear fusion devices

In the context of magnetic confinement fusion devices modeling, the frequency response of two complex toroidal stainless steel structures: an ITER-like Vacuum Vessel (VV) and the RFX-mod2 Toroidal Support Structure (TSS), are analyzed with the FFT-PEEC method.

The aim of analysis is to obtain informations about the distribution of the magnetic field in some target points and the value of the equivalent impedance of an excitation coil, which depends on the effect of eddy currents in passive conductive structures. Where the latter is a key parameter in the design of active feedback control systems for example to control RWMs or ELMs. The EM problem to be solved is the eddy current system (A.10) following the FFT-PEEC method, with the $\mathbf{L}$ matrix rewritten as BTB circulant tensor [230].

The reduced memory footprint of the FFT-PEEC method allows to use a fine voxelized mesh directly from the CAD file of the structure. The voxelization process applied to a sector of the ITER-like D-shaped vacuum vessel is illustrated in Fig. A.7. For the ITER-like VV, whose external dimensions are approximately 16 m (L) $\times$ 16 m (W) $\times$ 10 m (H), a mesh with $800 \times 800 \times 500$ voxels for each spatial dimension is generated. The effective radial component of the field B_r penetrating plasma boundary due to the reaction of the conductive VV is analyzed [230]. Fig. A.8 shows the set of active ELM coils (3 $\times$ 9), and the radial component of the perturbation field B_r , produced by an almost $m = 1, n = 1$ current pattern on a toroidal surface simulating a typical diverted plasma boundary of ITER.

A comparison between the scattered field due to the TSS of RFX-mod2, computed with the FFT-PEEC method and the Volume Integral (VI) formulation [205] is performed. The perturbation field B_r on a toroidal surface simulating the plasma boundary, due to an $m = 1, n = 1$ current pattern at 50 Hz, applied to the RFX-mod2 active coils as:

$$i_h = I_M \cos(m\theta_h + n\phi_h + \omega) \quad h = 1, \dots, 192, \quad (\text{A.27})$$

is studied. The radial component of the perturbation field $\Re B_r$ produced by the eddy currents in the TSS computed with the FFT-PEEC and the VI

A.3. FAST FOURIER TRANSFORM - PARTIAL ELEMENT EQUIVALENT CIRCUIT METHOD

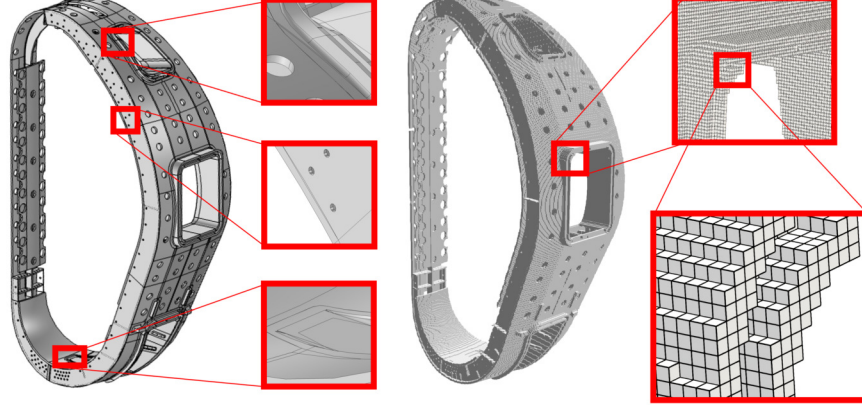


Figure A.7: Voxelization process: CAD of D-shaped vacuum vessel sector (left). Voxelized mesh (right).

Mesh	DoFs	Memory [Gb]	Assembling [s]	Solving [s]
$550 \times 550 \times 500$ (voxels)	22 895 047 (currents) 8 337 160 (potentials)	55.88	1633	2247
598 453 (tetrahedra)	479 946	294	19 612	5191
1 028 112 (tetrahedra)	840 655	598	41 253	14 235

Table A.4: Summary of computational performances of FFT-PEEC code and $\mathcal{H}$ -VI code for solving the RFX-mod2 TSS eddy current problem.

methods, is illustrated in Fig. A.9 together with the error map evaluated as:

$$\epsilon(\theta, \phi) = \Re B_r^{FFT-PEEC}(\theta, \phi) - \Re B_r^{VI}(\theta, \phi), \quad (\text{A.28})$$

resulting in a good matching of the two approaches. The preconditioner of the linear system used in the GMRES solver, is based on LU decomposition for both methods, however, the memory requirements of FFT-PEEC, can be reduced by using the Algebraic Multigrid (AMG) solver [230].

The main advantage of the FFT-PEEC approach relies in its performances, both for the computational time and the RAM usage, as compared to fast VI code based on data-sparse representations ($\mathcal{H}$ -matrices). For the RFX-mod2 TSS test case, the performances of FFT-PEEC approach and the $\mathcal{H}$ -VI are compared using two different mesh for the latter. The computational performances are listed in Table A.4

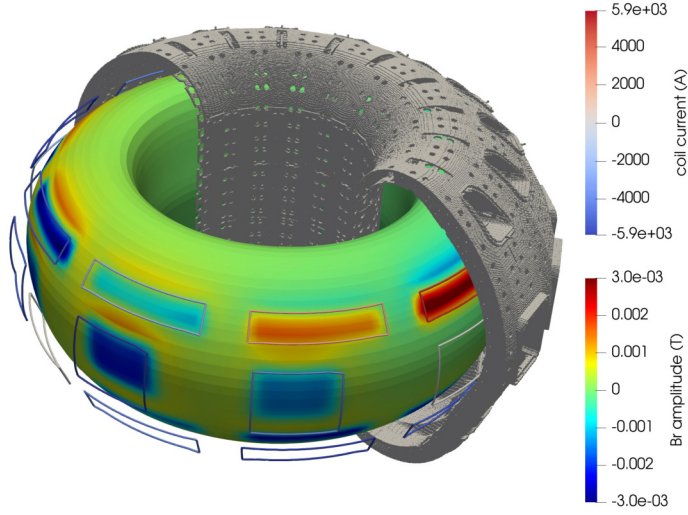


Figure A.8: Three sets of ELM-control coils and the perturbation field B_r produced by an almost $(m = 1, n = 1)$ current pattern on a toroidal surface simulating a typical diverted plasma boundary.

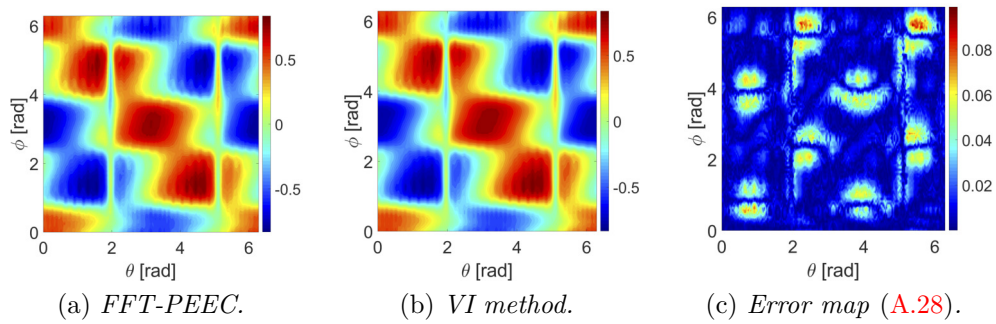


Figure A.9: Comparison of $\Re B_r$ produced by eddy currents due to the TSS.

A.4 Topology optimization

The development of technologies for the additive manufacturing [231] in particular of metallic materials, is offering the possibility of producing parts with very complex geometries. This opens up to the possibility of using topology optimization methods for the design of electromagnetic devices.

From a mathematical viewpoint the topology optimization (TO) concerns with the possibility of creating or collapsing holes in the design domain D . Nowadays the term topology optimization has a more general meaning, referring also to those techniques capable of changing the material distribution inside a domain, but not necessarily changing its *topology*. This is the major difference with respect to the parameterized shape optimization described in Chapter 5, which in general acts only on the design domain boundaries. The TO approach can be clarified referring to the simple magnetostatic example of Fig. A.10: *which is the best ferrite distribution in the design domain D , surrounding the square current-carrying coil, which maximizes the magnetic energy?* The answer is trivial, that is, if D is initially filled with air the TO proceeds until D is fully filled with ferrite. However the answer becomes more difficult if the amount of ferrite must be kept below a specific value, e.g., due to economical reasons or if particular objectives are needed. In this case additional constraints must be added to the TO problem.

Defined with $\rho(\mathbf{x})$ the material distribution at any point $\mathbf{x}$ of the design domain $D \subset \mathbb{R}^d$, the TO problem can be formally written as a minimization problem in the same way of equation (5.1):

$$\begin{aligned} & \min_{\rho} f(\mathbf{u}(\rho), \rho) \\ & \text{under given constraints} \end{aligned} \quad , \quad (\text{A.29})$$

where f is the objective function depending on the solution $\mathbf{u}(\rho)$ of an electromagnetic problem and $\rho(\mathbf{x})$ plays the role of design variable. The constraints can of equality and/or inequality type, for example, the inequality constraint on the final amount of volume can be written as:

$$G(\rho) = \int_D \rho(\mathbf{x}) d\mathbf{x} - V_{trg} \leq 0, \quad (\text{A.30})$$

where V_{trg} is the desired maximal volume. Since the objective function depends on the solution of an electromagnetic problem, (A.29) is a PDE-constrained optimization, i.e., an optimization where at least one of the constraints is expressed as a partial differential equation:

$$\mathcal{L}(\mathbf{u}(\rho), \rho) = 0. \quad (\text{A.31})$$

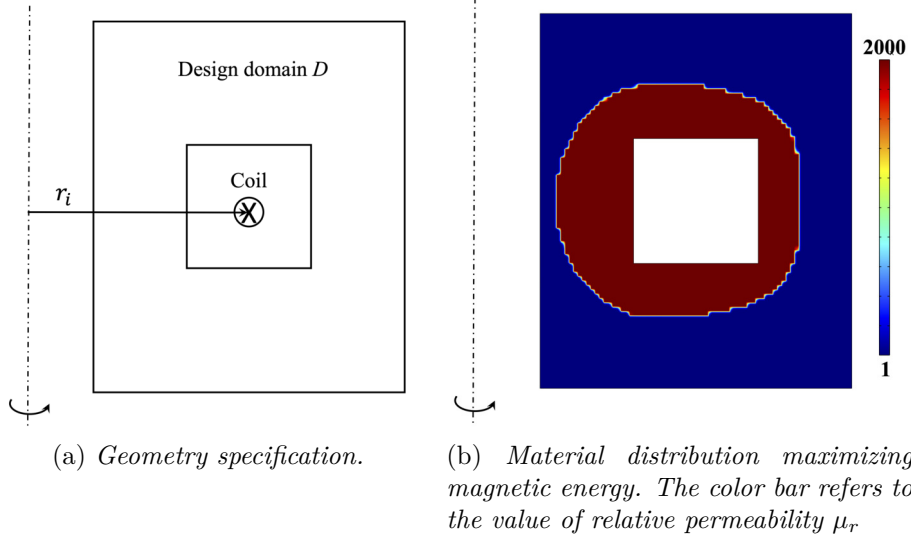


Figure A.10: Topology optimization concept applied to a 2D domain D surrounding a square coil with prescribed current. The final distribution of ferrite must be kept below a fraction 0.3 of the area of the design domain.

The design variable $\rho(\mathbf{x})$ maps the material property g in $\mathbf{x}$ which, in a discrete setting means that g is specified for each mesh element using a material interpolation scheme (MIS):

$$\mathbb{S} \rightarrow \mathbb{R} \quad (\text{A.32})$$

$$\rho_i \mapsto g(\rho_i), \quad (\text{A.33})$$

where ρ_i is the design variable related to i th mesh element. A general distinction between topology optimization approaches, concerns in the space $\mathbb{S}$ where the design variable is defined, that can be continuous or binary, i.e.,:

$$\text{if } \begin{cases} 0 \leq \rho_i \leq 1 & \rightarrow \text{continuous} \\ \rho_i = \{0, 1\} & \rightarrow \text{binary} \end{cases} . \quad (\text{A.34})$$

The discrete problem is the most common approach for topology optimization and the most natural one since it naturally distinguish between materials *with* (1) and *without* (0) property g . Instead, when the design variable lies in the continuous space the intermediate values (0,1) are the so-called “gray scales”, which have no clear material specification. A common expression for the MIS in the continuous setting is the power-law [232]:

$$g(\rho) = p_{mat1} + (p_{mat2} - p_{mat1})\rho^\alpha, \quad (\text{A.35})$$

A.4. TOPOLOGY OPTIMIZATION

where p_{mat1} and p_{mat2} are the two possibilities for the property g and $\alpha > 1$ is a penalization parameter which can be increased up to a certain value to avoid the generation of “gray scale” regions. Referring again to the academic example given in Fig. A.10, p_{mat1} and p_{mat2} match with $\mu_{r,air} = 1$ and $\mu_{r,ferrite} = 2000$.

The advantage of using continuous design variables instead of discrete ones, lies in the possibility of computing the derivatives for sensitivity analysis. Although it would be better if the optimization problem was binary, it is in any case convenient to work continuously with the drawback of having to manage the gray scale issue.

The wide spectrum of TO applications, from the structural mechanics framework, where it finds its roots [233], to the fluid dynamics problems and so on, may lead to the erroneous conclusion that the methods there proposed can be used “as is” also in electromagnetics [234]. In fact each physical problem has specific requirements to be satisfied. For instance, when dealing with solid mechanics the optimized topology has to comply with structural connectivity properties. In this class of problems, for which the compliance is the objective function, the structural robustness from the mechanical point of view is guaranteed by the TO problem itself. In designing electromagnetic devices the concept of structural connection, is sometimes misleading because the connectivity between the different parts may or may not be wanted. Mostly of the TO algorithms developed in the solid mechanics are not general purpose and sometimes intrusive modifications are required to use them for electromagnetic problems. In principle, the TO can be based both on FEM and IEM approaches for the solution of the PDE governing the physics, however, the general performances may be remarkably different. Looking at example of Fig. A.10, if a FEM approach is used the whole domain (air plus magnetic) has to be discretized, however by using an IEM the air part is discarded, thus the degrees of freedom of the problem are restricted to the magnetic domain and can be augmented or reduced during the TO algorithm (since ferrite material is added or removed). An additional peculiarity of electromagnetics is that several sub-classes of problems can be defined: electrostatic, magnetostatic, electro- and magneto-quasistatic, full-wave with and without propagation. The solution of the electromagnetic field for each sub-class can be tackled by different techniques requiring different computational effort. In particular, the objective function derived from the solution of a full wave propagation problem, is highly demanding from the computational point of view. Since the TO algorithm requires the objective function to be evaluated many times, it is clear that the reduction of the number of evaluations is mandatory to reduce the computational burden. As already stated for the shape optimization problems, the mini-

APPENDIX A. OTHER TOPICS DURING THE PHD

Method	References	Characteristics
Homogenization	[235]	first TO approach, continuous ρ
Density-based	[236]	simple concept, used in many physical fields, continuous ρ , suited for multi-material TO, built in commercial software
Level-Set	[237]	evolve boundary of design domain, hole seeding for topology change, used for multi-material TO
BESO with Sensitivity	[238]	binary ρ , heuristic search algorithm,
TOBS	[239]	combines continuous and binary logic, binary ρ , integer search algorithm,
Two-Step	[240]	sensitivity information used to increase performance of stochastic algorithms

Table A.5: List of gradient-based methods.

mization problem (A.29) can be tackled with gradient-based or gradient-free approaches, where the former requires the (usually computationally costly) derivative of objective function and constraints. The major drawback of the latter approaches particularly highlighted in the case of stochastic methods is the difficulty to ensure domain connectivity. Moreover they require a higher number of objective function evaluations which can be reduced using novel deep learning techniques [180]. A summary of the common gradient-based and gradient-free approaches used in electromagnetic topology optimization are listed in Table A.5 and Table A.6.

A.4.1 Numerical example: WPT device

The wireless power transfer device WPT1-Z1, according to the SAE international standard is considered as 3D test case. Referring to Fig. A.11, the design domain D lies below the Ground Assembly (GA) coil. There, the relative magnetic permittivity is the subject of topology optimization, that is μ_r can be changed from $\mu_{r,air} = 1$ to $\mu_{r,ferrite} = 3300$ and vice-versa, where $\mu_{r,ferrite}$ is the relative permittivity of ferrite material. The geometrical parameters of the device are reported in Table A.7. The topology optimization

A.4. TOPOLOGY OPTIMIZATION

Method	Reference	Characteristics
Boolean	[241]	simple logic, uses logical operators ($\otimes, \oplus, \odot, \dots$)
Binary	[242]	same algorithmic structure of standard evolutionary convert continuous $\boldsymbol{\rho}$ to binary using e.g., a sigmoid function
μ GA	[243]	based on genetic approach of GA, uses small population number w.r.t. GA
Immune Algorithm (IA)	[244]	combines local and global search
NGnet	[245]	smooth design using Gaussian basis, used in combination with GA
Nelder-Mead	[246]	deterministic approach used as local search in combination with global stochastic
Deep Learning	[180]	reduced number of function evaluations create surrogate model suitable for large-scale optimization

Table A.6: List of gradient-free methods.

Parameter	Value
Air-gap	100 mm
Ferrite width	440 mm
Ferrite length	600 mm
Ferrite $\mu_{r,ferrite}$	3300
Ferrite σ	0.16667 S/m
Turns GA coil	15
Turns VA coil	8 (upper layer), 9 (lower layer)

Table A.7: WPT1-Z1 device parameters.

aims at maximizing the coupling coefficient k , while keeping the amount of ferrite below half of the volume of the design domain, i.e.,

$$\begin{aligned}
 \text{find } k^* = \max k &:= \frac{M}{\sqrt{L_{GA}L_{VA}}} \\
 \frac{V_{ferrite}}{V_D} &\leq V_{frac} = 0.5,
 \end{aligned} \tag{A.36}$$

where M is the mutual inductance between GA and VA coils and L_{GA} , L_{VA} their self-inductances.

Two gradient-based methods are compared, namely the TOBS using combined COMSOL[®] plus MATLAB[®] algorithms and the SIMP method fully developed within COMSOL[®]. In both cases the initial design domain is fully-filled with ferrite and $k = 0.3619$. The TOBS approach increases the

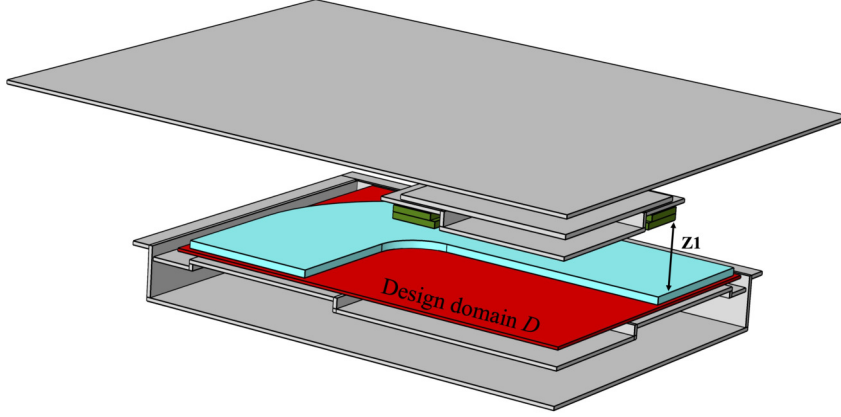
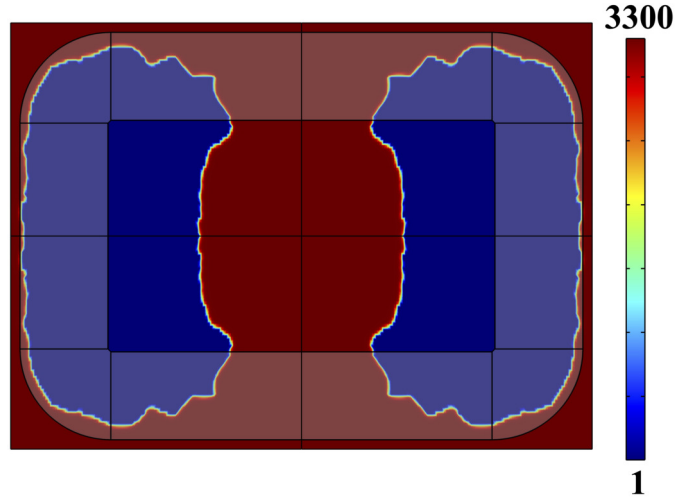
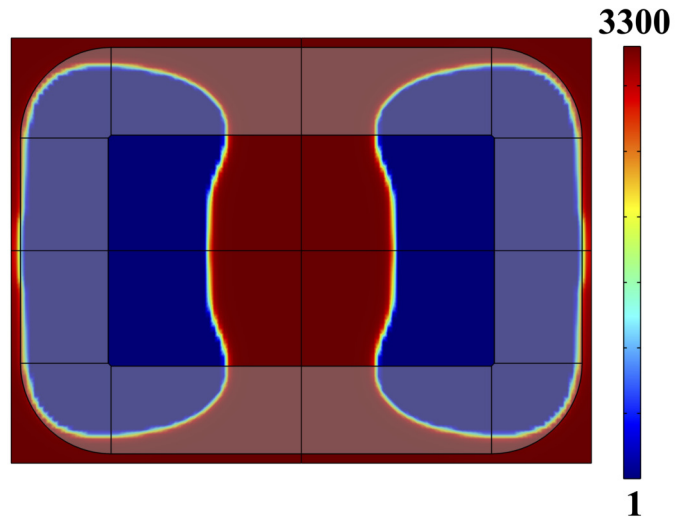


Figure A.11: Cutaway of WP1-Z1 device. Due to symmetry, only a quarter of the design is shown. The design domain D highlighted in red, correspond to the ferrite in the Ground Assembly (GA). GA and Vehicle Assembly (VA) coils are colored in cyan and green, respectively, while gray parts are aluminum shielding.

objective function to $k^* = 0.4071$ after 18 iterations, while SIMP results in $k^* = 0.4123$ after 18 iterations. In the latter case, due to the continuous nature of the design variables, the value of the relative permittivity is intrinsically spread over the interval $[1, \mu_{FE}]$ and post-processing is required to cut the final layout. The final material distribution in the design domain is reported in Fig. A.12.



(a) *TOBS solution.*



(b) *SIMP solution.*

Figure A.12: Top view of final ferrite topology of WPT1-Z1 device. Light blue area represents GA coil. The color bar refers to the value of the relative permeability.

B

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