Thermal Analysis of a Five–Phase Motor Under Faulty Operations

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This presentation refers to the paper

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8th **IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED 2011)**

held in Bologna, Italy, September 5-8 2011

Outline

Aim of this work

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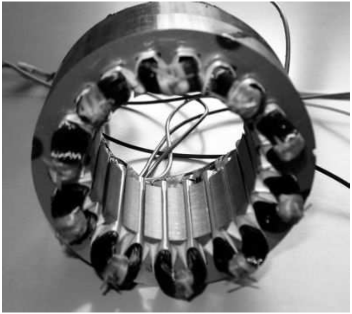
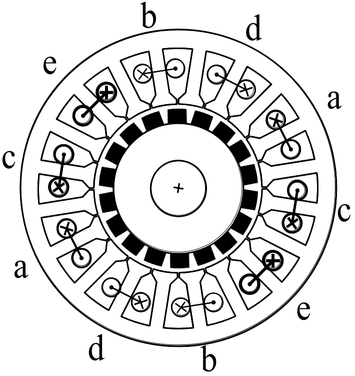
- **thermal behaviour** of a five–phase permanent magnet motor during the post–fault control strategy,
- **open circuit fault** of both one and two phases
- **current** of the healthy phases is **increased** to get a higher average torque $\Longrightarrow$ **same Joule losses** of the healthy case
- The aim is to verify the motor can continue to operate, even if the current in the operating phases is increased $\Longrightarrow$ **maximum temperature rise** in the winding **lower than 115 K** (thermal limit for F insulation class)

The Five–phase motor

The 5–phase motor

- **high fault–tolerance capability** (physical and thermal separation among the phases, a very low mutual inductance, etc.)

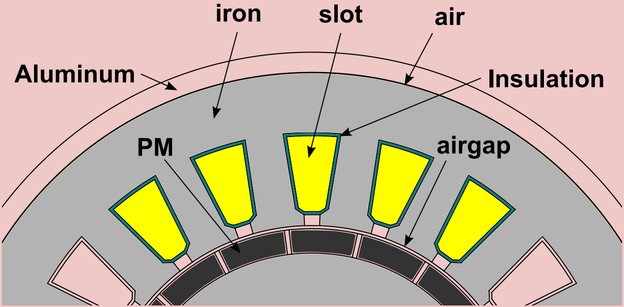




The Finite–Element model

Finite Elements modeling

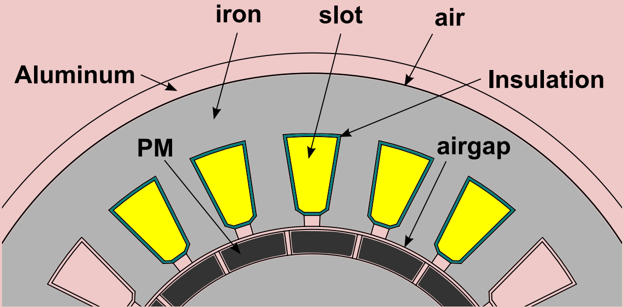
FE model



- aluminum covering on the stator external surface, with the function of heat sink

Finite Elements modeling

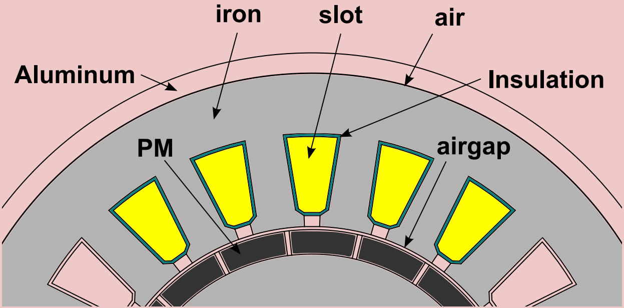
FE model



- boundary conditions at the outer surface of the aluminum: a convection factor of 18 $W/(m^2K)$ (surface increase of a factor 3 due to the presence of fins)

Finite Elements modeling

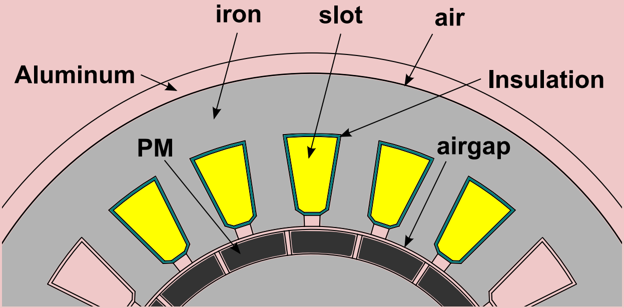
FE model



- a thin layer of air has been added, which thickness is 0.05 *mm* to take into account the imperfect contact with the external aluminum covering

Finite Elements modeling

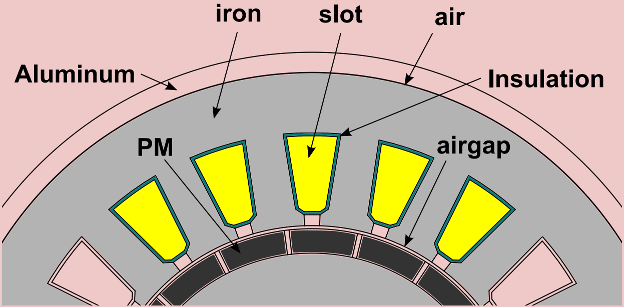
FE model



- The inner surface of the motor (motor shaft) presents an insulated condition, i.e. no heat flux across the boundary

Finite Elements modeling

FE model



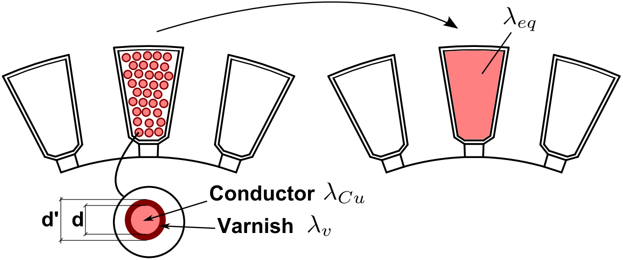
- thermal conductivity of the air–gap: it refers to a fluido–dynamic calculation, using the rotation speed of the motor

Thermal conductivity

Material	Thermal conductivity $W/(m \cdot K)$
Iron	40
Aluminum	100
Slot insulation	0.15
Slot	0.783
Air–gap	0.013
Air	0.026
PMs	9

Slot thermal model

The real slot is constituted by conductors, insulated each other by means of varnish ⇒ The slot is simulated using an **equivalent thermal conductivity**



The slot thermal model is derived from: **[W. Schuisky, *Berechnung Elektrischer Maschinen*. Springer Verlag, Wien, 1967]**

Four configurations are analyzed:

- the healthy motor
- one phase open circuited
- two non–adjacent phases open circuited
- two adjacent phases open circuited

Chosen control strategy

According to each fault case, solution that yields the best result in terms of:

- **high average torque**
- **low torque ripple**

The resulting losses are imposed in the thermal model.

References

[N. Bianchi, S. Bolognani, M. Dai Prè, and E. Fornasiero, *"Post-fault operations of Five–phase motor using a full–bridge inverter"* in Power Electronics Specialists Conference, 2008. PESC 2008. IEEE, Rhodes, Jun. 15–19, 2008, pp. 2528–2534.]

[N. Bianchi, E. Fornasiero, and S. Bolognani, *"Performance of Five–phase motor drive under post-fault operations"* Electric Power Components and Systems, vol. 39, no. 12, pp. 1302–1314, 2011. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/15325008.2011.567221]

To increase the average torque

Currents are increased to reach the **same Joule losses of the healthy case.**

- One phase open–circuited: current increased of a factor $\sqrt{5/4} \simeq 1.12$
- Two phases open–circuited: current increased of a factor $\sqrt{5/3} \simeq 1.29$

Source of losses

- **Heat generation in each slot**, equivalent to the Joule losses in each slot
- **Heat generation on the iron**, taking into account both the *hysteresis* and *eddy current* iron losses. (calculated for a speed of $n = 300\ rpm$, $f = 45 Hz$)

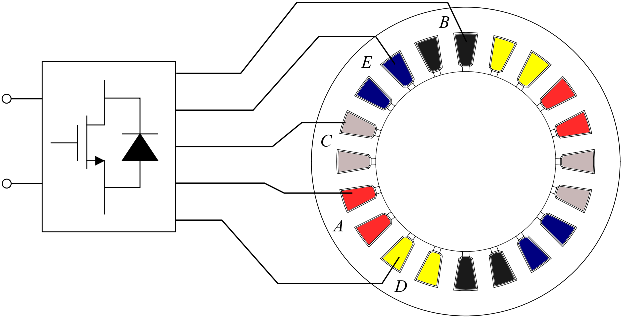
Result of the simulations

- Temperature rise of the copper in the slots,
- Temperature rise of the stator iron and,
- Temperature rise of the PMs

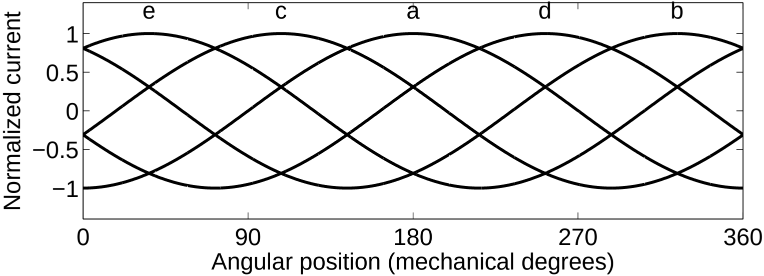
with respect to the environment temperature, $T_{env} = 0\ K$

Healthy mode

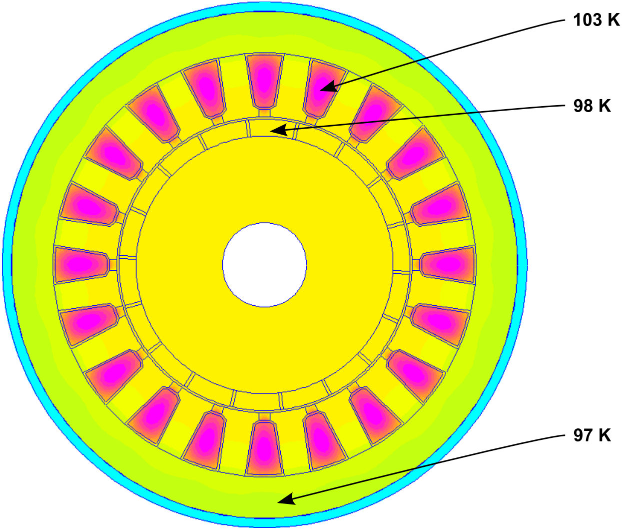
- In healthy mode operation all the five phases are fed by a 5 phase inverter



Healthy mode



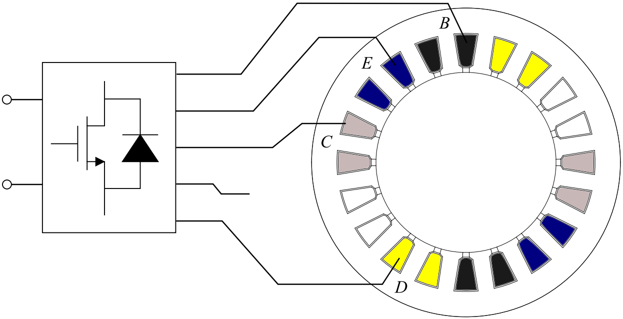
- The phase currents are sinusoidal
- The rms current is $I_{rms} = \hat{I}/\sqrt{2}$



- The higher temperature is reached in the slots (103 K)
- The average temperature in the slots is about 101 K

Open circuit fault of one phase

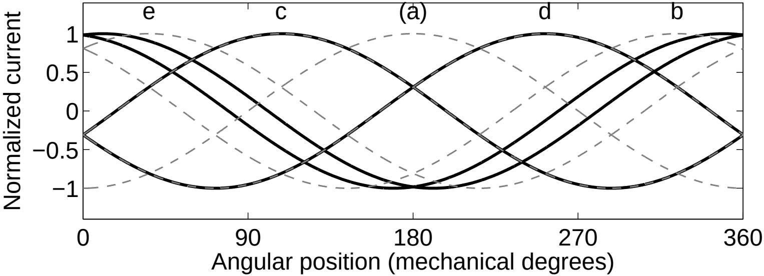
- The *a*–phase is open circuited so that $i_a = 0$



Before the control strategy

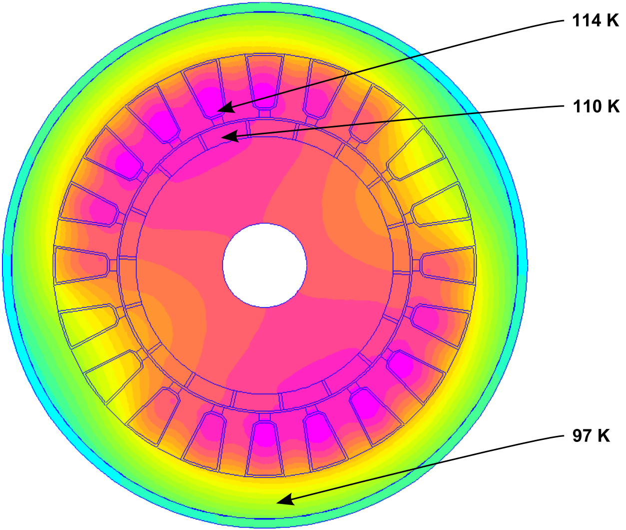
- reduction of the average torque of about 20 %
- peak–to–peak ripple of 50 %

Best control strategy

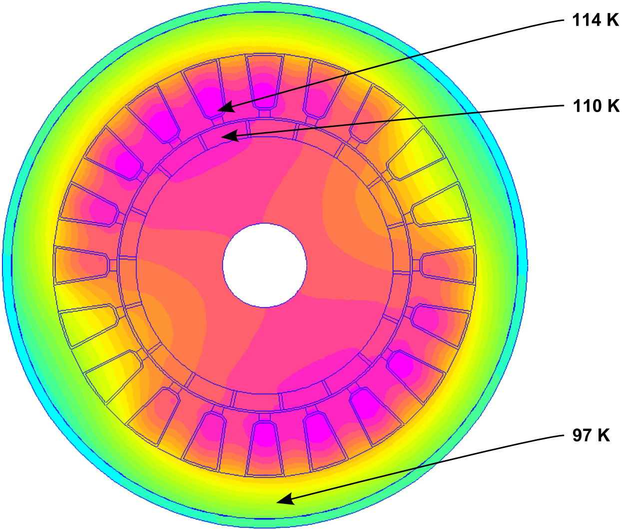


After the control strategy

- resulting average torque higher than 76% of nominal torque
- torque ripple equal to that measured under healthy operation



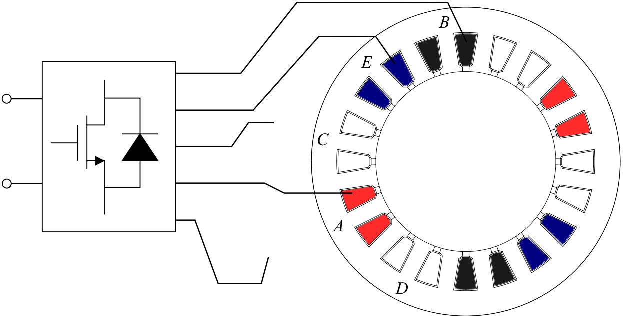
- current of the four healthy phases increased of 1.12
- losses concentrated around the supplied phases (4)



- maximum temperature rise in the slots: 114 K
- average temperature rise in the slots is 104.6 K

Open circuit fault of two non–adjacent phases

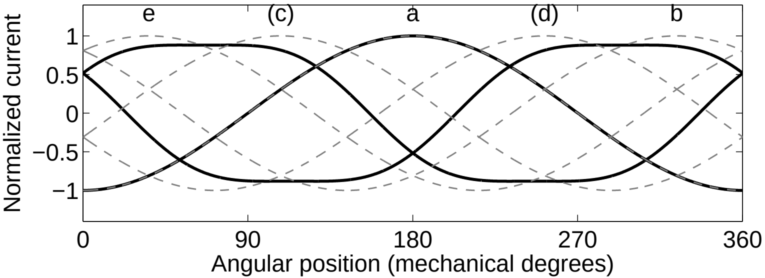
- Phases *c* and *d* are considered to be open circuited



Before the control strategy

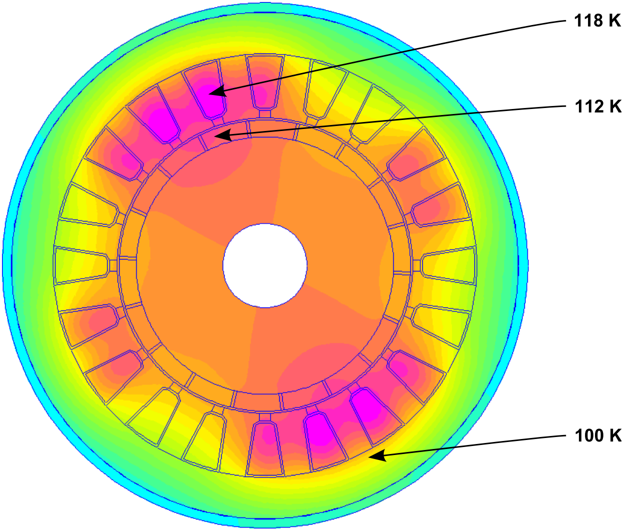
- average torque about 40 % less of the nominal torque
- torque ripple about 90 % without any change in healthy current waveforms

Best control strategy

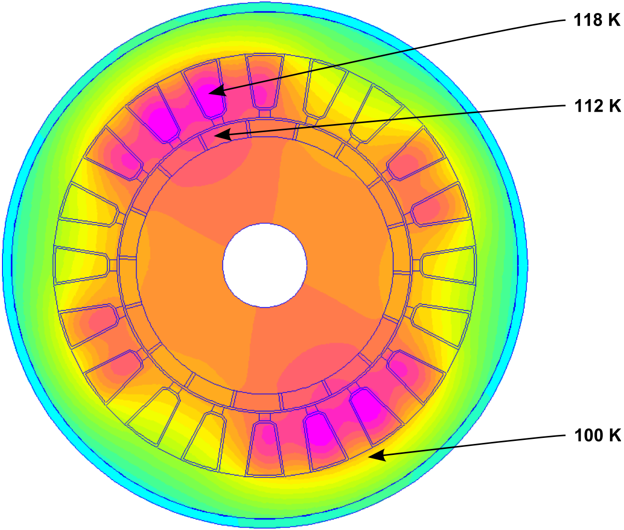


After the control strategy

- A good torque behaviour is achieved by injecting current harmonic of third order



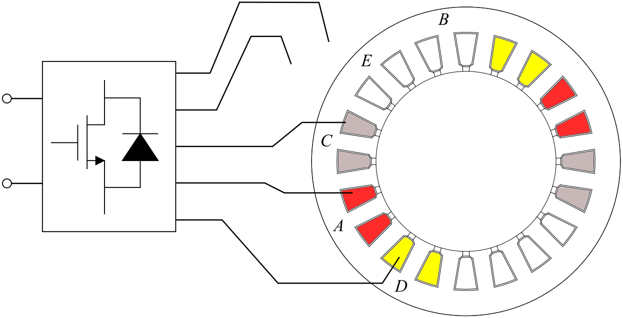
- three phases with an internal heat generation.
- current of the three healthy phases is increased of 1.29



- maximum temperature rise in the slots is 118 K
- the average temperature rise is 104.6 K

Open circuit fault of two adjacent phases

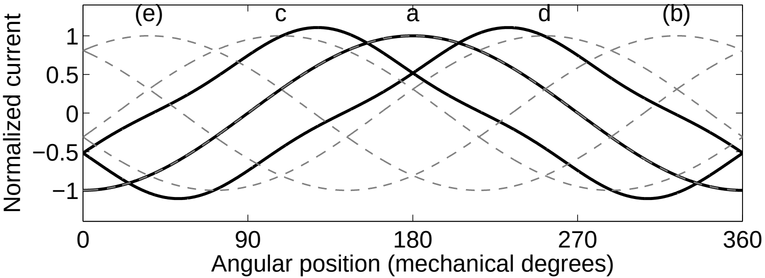
- The faulty phases are chosen to be the phases *b* and *e*



Before the control strategy

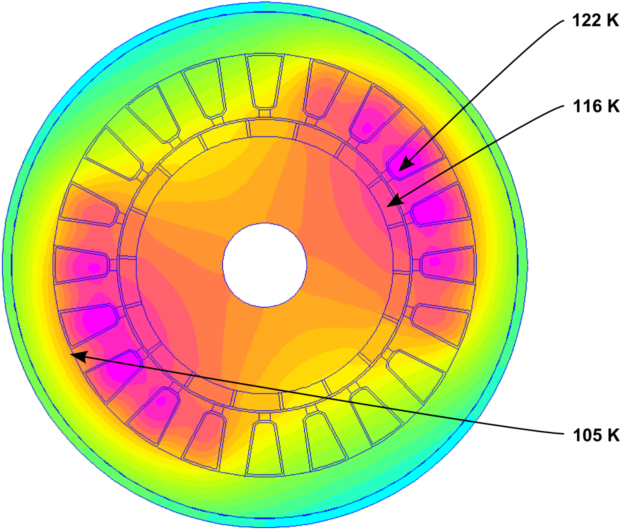
- According to the loss of two phases, the average torque decreases to 60 % of the nominal value
- The torque ripple is about 46 %

Best control strategy

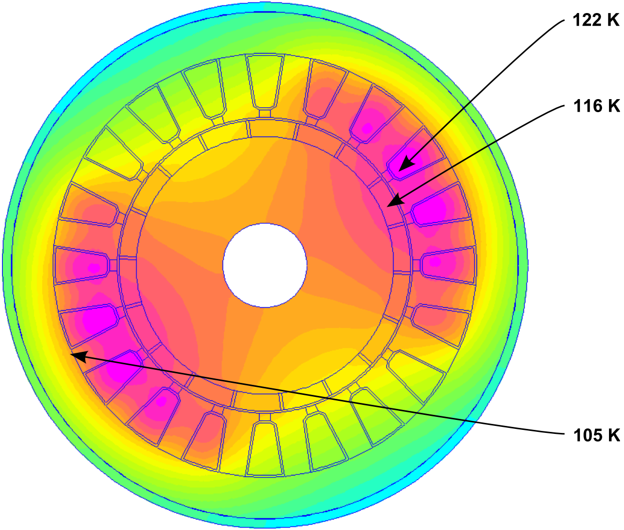


After the control strategy

- Best behaviour injecting current harmonics of third order only on phases *c* and *d*



- three phases with an internal heat generation.
- current increased of a factor 1.29



- maximum temperature rise in the slot is 122 K
- average temperature rise is 104.8 K

Conclusions

- The open circuit faults of one and two phases (either adjacent or non–adjacent) of a five–phase PM motor have been studied, focusing on the thermal behaviour during faulty operating conditions.
- The best current control for each fault case have been considered.
- A finite element thermal analysis has been carried out both in healthy mode and in the event of the open circuit faults.

- In order to get a higher average torque in healthy and in faulty operating conditions, the phase current is increased, adopting proper increasing factors but maintaining the same Joule losses
- It is shown that the temperature distribution is changed when an open circuit fault occurs, but the maximum temperature rise is limited, and the motor can continue to operate indefinitely.

Related Papers by the Authors

N. Bianchi, S. Bolognani, and M. D. Pré, "Design and tests of a fault–tolerant five–phase permanent magnet motor," in *Proc. of IEEE Power Electronics Specialist Conference, PESC'06*, Jeju, Korea, 18–22 June 2006, pp. 2540–2547.

N. Bianchi, S. Bolognani, M. Dai Pré, and G. Grezzani, "Design considerations for fractional-slot winding configurations of synchronous machines," *IEEE Transactions on Industry Applications*, vol. 42, no. 4, pp. 997–1006, Jul./Aug. 2006.

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- N. Bianchi, S.Bolognani, and G. Grezzani, "Fractional-slot IPM servomotors: analysis and performance comparisons," in *Proc. of International Conference on Electrical Machines, ICEM'04*, vol. CD Rom, paper no. 507, Cracow, Poland, 5–8 Sept. 2004, pp. 1–6.
- N. Bianchi, E. Fornasiero, and S. Bolognani, "Performance of five-phase motor drive under post-fault operations," *Accepted for Publication in Electric Power Components and Systems, Paper no. UEMP-2010-0601*, 2010.

Thank you for the attention