# Design Procedure of IPM Motor Drive for Railway Traction


Massimo Barcaro   Emanuele Fornasiero
Nicola Bianchi   Silverio Bolognani

Electric Drives Laboratory
Department of Electrical Engineering
University of Padova



IEEE - IEMDC 2011
International Electric Machines and Drives Conference
Niagara Falls, 15-18 May 2011

This presentation refers to the paper

Massimo Barcaro, Emanuele Fornasiero, Nicola Bianchi and Silverio Bolognani

**“Design Procedure of IPM Motor Drive for Railway Traction”**

**International Electric Machines and Drives Conference (IEMDC 2011)**

held in Niagara Falls, CA, May 15-18, 2011

## Outline

# Aim of this work

## Aim of this work

### The aim

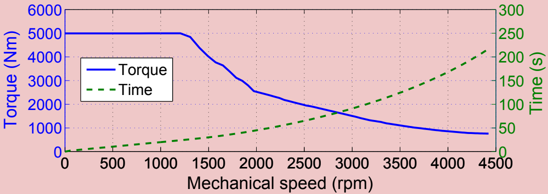
of this work is to investigate how the design choices of both the machine and the power converter affect the total performance of the traction drive.

- **Railway application**
  1. Italian system,
  2. Commuter train.
- **Adoption of a permanent magnet machine**
  1. High efficiency
  2. High power density
  3. Lower maintenance
  4. Sensorless control capability
  5. Flux–weakening capability (Interior Permanent Magnet)

## Requirements

- **Maximum motor size**
  1. Frame length: 800mm,
  2. Frame diameter: 500mm.

- **Torque–to–speed curve**
  1. Base operating point: 5000Nm @ 1200 r/min,
  2. Max speed: 4500 r/min.



## Requirements

- **Voltage**
  1. Nominal dc bus: 3000V (min. 80%),
  2. Uncontrolled Generator Operation (UGO) voltage lower than nominal voltage at maximum speed.
- **IGBT Volt–Ampere rating**
  1. Series and parallel IGBT connections are avoided

# PM machine design and analysis

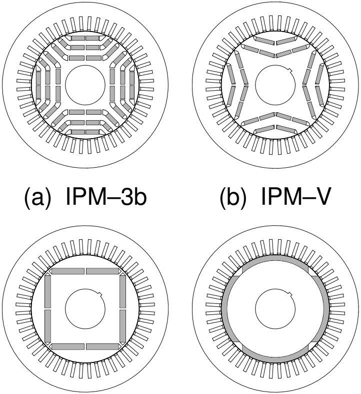
## Geometries

Different rotor geometries are investigated:



### Main parameters

- 48 slots,
- 4 poles,
- SmCo magnets,
- Different PM volume,
- $L_{stk} = 500mm$,



(a) IPM–3b (b) IPM–V (c) IPM–SQ (d) SPM

## Winding design with different PM contribution

Changing the PM volume, the number of series conductors per slot, $n_{cs}$, can be changed

### Variation of $n_{cs}$

The variation of series conductors per slot does not affects the electromechanical torque for given slot current $\hat{I}_S$.

### If $n_{cs}$ increases:

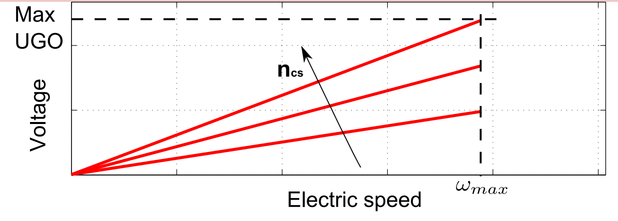
- the phase current decreases
- the nominal flux–linkage increases
- the base speed $\omega_B$ decreases

## Winding design with different PM contribution

### Uncontrolled Generator Operation

The flux–linkage due to the PM has to be limited so as to satisfy the UGO requirement at the el. maximum speed:

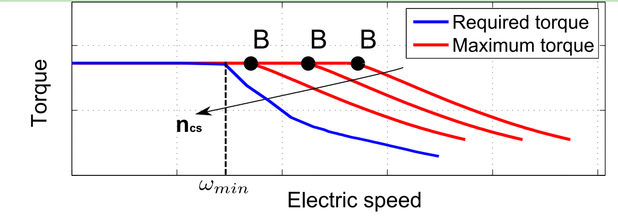
$$\omega_{max} n_{cs} \lambda_m \leq \frac{V_{dc,n}}{\sqrt{3}}$$



## Base speed

$$\left(\frac{V_n}{\omega_B}\right)^2 \simeq \Lambda^2 = n_{cs}^2 \left[\left(\lambda_m + I_d \hat{I}_{S,d}\right)^2 + \left(I_q \hat{I}_{S,q}\right)^2\right]$$

For a given nominal voltage $V_n$ the increase of $n_{cs}$ yields an increase of the nominal flux–linkage and a reduction of the base speed $\omega_B$.




Once the $n_{cs}$ is defined, the nominal current of the machine $I_{n,mot}$ is selected to satisfy the requirements.

## Summary of the motor designs parameters

| Motor | $V_{pm}$ (%) | $\xi_B$ | $n_{cs}$ | $\hat{I}_{n,mot}$ $(A)$ | $\Lambda_m$ $(Vs)$ | $\omega_{B,max}$ $(el.rad/s)$ |
|---|---|---|---|---|---|---|
| IPM–3b | 100% | 3.34 | 6.0 | 512 | 1.93 | 448 |
| IPM–3b | 90% | 3.35 | 7.0 | 458 | 1.95 | 382 |
| IPM–3b | 80% | 3.34 | 8.0 | 422 | 1.88 | 332 |
| IPM–3b | 70% | 3.12 | 9.5 | 379 | 1.82 | 272 |
| IPM–3b | 60% | 3.02 | 8.5 | 458 | 1.26 | 299 |
| IPM–3b | 40% | 2.84 | 7.0 | 667 | 0.47 | 351 |

- $n_{cs}$ is due to UGO requirement ($\Lambda_m < 2$Vs). It increases with the PM volume reduction (IPM–3b).
  $n_{cs} = 9.5 \Rightarrow$ limit value: the minimum $\omega_B$ is reached
- IPM–3b with 60% and 40% $V_{pm} \Rightarrow$ UGO satisfaction is not sufficient. $n_{cs}$ reduced, with a corresponding increase of the current to provide suitable FW torque.

| Motor | $V_{pm}$ (%) | $\xi_B$ | $n_{cs}$ | $\hat{I}_{n,mot}$ $(A)$ | $\Lambda_m$ $(Vs)$ | $\omega_{B,max}$ $(el.rad/s)$ |
|---|---|---|---|---|---|---|
| IPM–3b | 100% | 3.34 | 6.0 | 512 | 1.93 | 448 |
| IPM–3b | 90% | 3.35 | 7.0 | 458 | 1.95 | 382 |
| IPM–3b | 80% | 3.34 | 8.0 | 422 | 1.88 | 332 |
| IPM–3b | 70% | 3.12 | 9.5 | 379 | 1.82 | 272 |
| IPM–3b | 60% | 3.02 | 8.5 | 458 | 1.26 | 299 |
| IPM–3b | 40% | 2.84 | 7.0 | 667 | 0.47 | 351 |
| IPM–V | - | 2.38 | 5.0 | 650 | 1.83 | 522 |
| IPM–SQ | - | 1.41 | 5.0 | 750 | 2.08 | 509 |
| SPM | - | 0.81 | 3.5 | 1006 | 1.83 | 794 |

- $\xi_B$ is almost equal to 3 for all the IPM–3b machines. The IPM–V and the IPM–SQ machine has lower saliency.

| Motor | $V_{pm}$ (%) | $\xi_B$ | $n_{cs}$ | $\hat{I}_{n,mot}$ $(A)$ | $\Lambda_m$ $(Vs)$ | $\omega_{B,max}$ $(el.rad/s)$ |
|---|---|---|---|---|---|---|
| IPM–3b | 100% | 3.34 | 6.0 | 512 | 1.93 | 448 |
| IPM–V | - | 2.38 | 5.0 | 650 | 1.83 | 522 |
| IPM–SQ | - | 1.41 | 5.0 | 750 | 2.08 | 509 |
| SPM | - | 0.81 | 3.5 | 1006 | 1.83 | 794 |

- The IPM–V machine requires lower current than the IPM–SQ machine thanks to the higher saliency ratio.
- The SPM machine requires an excessive current and the base speed is about 3 times higher than the required.

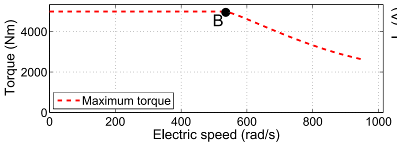
# Procedure to compute machine performance

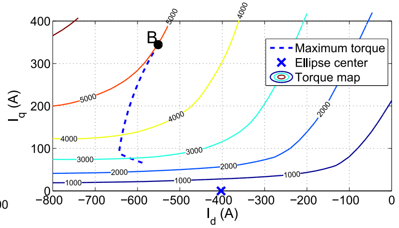
## Finite element simulations

- Torque, Flux linkages, Flux densities

## Maximum machine performance

- MTPA trajectory is followed up to the voltage limit: from zero up to the base speed $\omega_B$, **B** base point.
- At higher speed the flux–weakening control is adopted.



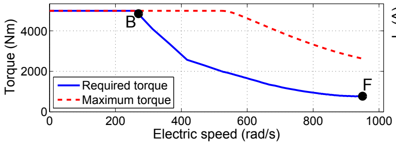



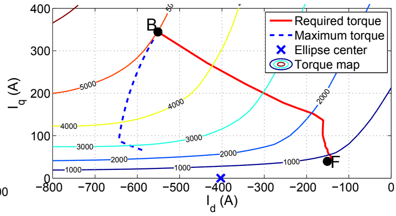
## Procedure to compute machine performance



### Fitting of the required torque–to–speed

- The current vector trajectory is modified,
- The lowest current that satisfies both the voltage limit and torque requirement is selected.

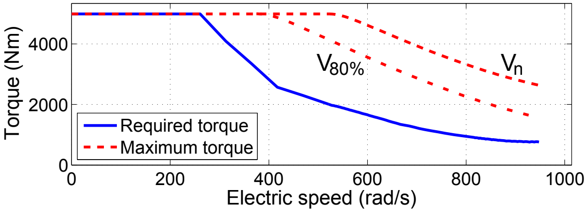


## Procedure to compute machine performance

### Operations with reduced voltage

The required torque has to be satisfied also considering the variation of the grid voltage, e.g. according to the 80% of the rated voltage. A decrease of $V_{dc}$ implies a shift of the torque characteristic due to the reduction of speed $\omega$ associated to each vector position.

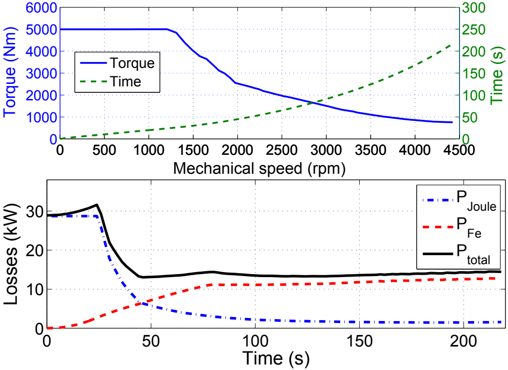


# Procedure to compute machine performance



## Machine losses

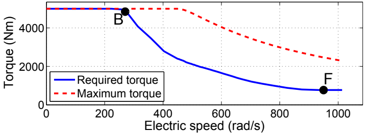
- The machine losses are computed considering the standard traction cycle,

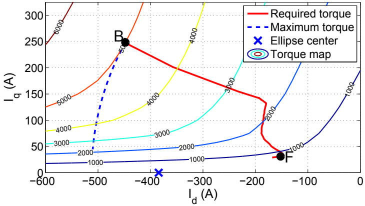


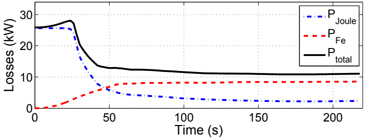
# Predicted machine performance

# IPM 3b

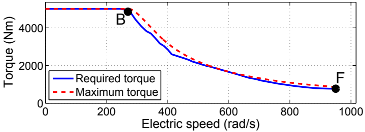
## IPM 3b - 100% $V_{pm}$

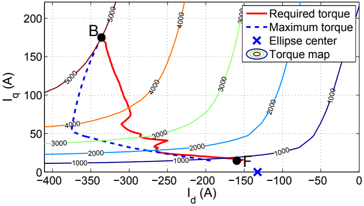


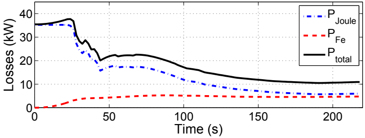




## IPM 3b - 70% $V_{pm}$



## Summary of motor performance

| Motor | $V_{pm}$ (%) | Voltage 80% | $P_{mot_{avg}}$ $(kW)$ | $P_{Cu}$ (%) | $P_{Fe}$ (%) |
|---|---|---|---|---|---|
| IPM–3b | 100% | ✓ | 13.86 | 48.0 | 50.5 |
| IPM–3b | 90% | ✓ | 13.34 | 58.0 | 40.5 |
| IPM–3b | 80% | ✓ | 14.21 | 65.0 | 33.6 |
| IPM–3b | 70% | - | 18.68 | 76.3 | 22.6 |
| IPM–3b | 60% | - | 18.87 | 73.1 | 25.9 |
| IPM–3b | 40% | - | 22.05 | 69.7 | 29.4 |
| IPM–V | - | ✓ | 16.13 | 40.3 | 58.5 |
| IPM–SQ | - | ✓ | 20.20 | 39.7 | 59.3 |
| SPM | - | ✓ | 20.00 | 35.4 | 63.6 |

- Only the IPM–3b configurations with $V_{pm}$ from 70% to 40% are not able to provide the required torque versus speed characteristic at a reduced voltage (80%).

| Motor | $V_{pm}$ (%) | Voltage 80% | $P_{mot_{avg}}$ ($kW$) | $P_{Cu}$ (%) | $P_{Fe}$ (%) |
|---|---|---|---|---|---|
| IPM–3b | 100% | ✓ | 13.86 | 48.0 | 50.5 |
| IPM–3b | 90% | ✓ | 13.34 | 58.0 | 40.5 |
| IPM–3b | 80% | ✓ | 14.21 | 65.0 | 33.6 |
| IPM–3b | 70% | - | 18.68 | 76.3 | 22.6 |
| IPM–3b | 60% | - | 18.87 | 73.1 | 25.9 |
| IPM–3b | 40% | - | 22.05 | 69.7 | 29.4 |
| IPM–V | - | ✓ | 16.13 | 40.3 | 58.5 |
| IPM–SQ | - | ✓ | 20.20 | 39.7 | 59.3 |
| SPM | - | ✓ | 20.00 | 35.4 | 63.6 |

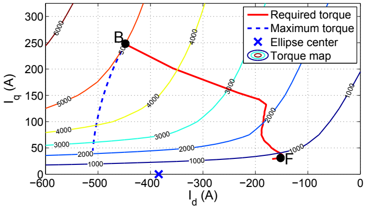
- The IPM–3b motors with a $V_{pm} > 80\%$ exhibit lower average losses during the standard cycle.

| Motor | $V_{pm}$ (%) | Voltage 80% | $P_{mot_{avg}}$ $(kW)$ | $P_{Cu}$ (%) | $P_{Fe}$ (%) |
|---|---|---|---|---|---|
| IPM–3b | 100% | ✓ | 13.86 | 48.0 | 50.5 |
| IPM–3b | 90% | ✓ | 13.34 | 58.0 | 40.5 |
| IPM–3b | 80% | ✓ | 14.21 | 65.0 | 33.6 |
| IPM–3b | 70% | - | 18.68 | 76.3 | 22.6 |
| IPM–3b | 60% | - | 18.87 | 73.1 | 25.9 |
| IPM–3b | 40% | - | 22.05 | 69.7 | 29.4 |
| IPM–V | - | ✓ | 16.13 | 40.3 | 58.5 |
| IPM–SQ | - | ✓ | 20.20 | 39.7 | 59.3 |
| SPM | - | ✓ | 20.00 | 35.4 | 63.6 |

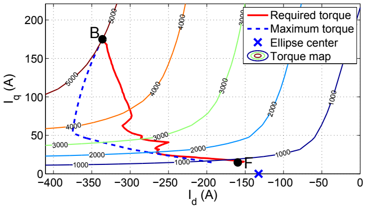
- With IPM–3b machines the $V_{pm}$ reduction leads to a shift of the losses from iron to copper, due to the higher average phase current.

This behaviour is reasonable, since the current of the IPM–3b with 100% $V_{pm}$ decreases significantly from the nominal value $\hat{I}_{n,mot}$ at the base point B.

## IPM 3b - 100% $V_{pm}$




## IPM 3b - 70% $V_{pm}$



# Power converter

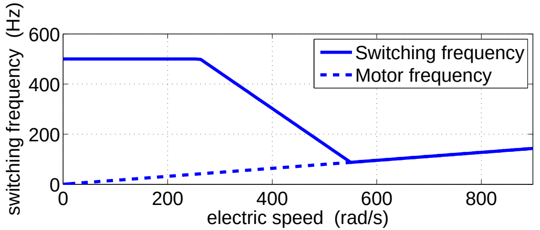
## IGBT choice

- Use of a single power switch for each inverter leg. $\Rightarrow$ power switch must be chosen with a reverse voltage of 6500 $V$, to sustain voltage peaks due to the commutations.
- Referring to the values of the machine phase current $\hat{I}_{n,mot}$, an IGBT with nominal current equal to 750$A$ is adopted in the computation of the power converter losses.

## IGBT parameters, $V_n = 3600\,V$

| $I_c$ $A$ | $V_{ce,on}$ $V$ | $R_{on}$ $m\Omega$ | $V_{d,on}$ $V$ | $R_{d,on}$ $m\Omega$ | $E_{on}$ $J$ | $E_{off}$ $J$ | $E_d$ $J$ |
|---|---|---|---|---|---|---|---|
| 400 | 2.8 | 6.2 | 2.1 | 4 | 4 | 2.3 | 1.05 |
| 600 | 2.9 | 4 | 2.3 | 2.7 | 5.9 | 3.5 | 1.6 |
| 750 | 2.2 | 2 | 1.7 | 1.38 | 6.5 | 4.2 | 3 |

## Switching frequency profile




- The switching frequency is kept constant ($f_{sw} = 500\ Hz$) up to the electrical base speed $\omega_B = 251\ el.rad/s$.
- Then, it decreases linearly until about two times the base speed.
- Finally, the switching frequency is kept equal to the main frequency of the drive, so that the motor is practically supplied with a square wave voltage.

## IGBT losses computation

$$P_{IGBT} = \underbrace{P_{cd}}_{\text{conduction losses}} + \underbrace{P_{sw}}_{\text{switching losses}}$$

## Conduction losses

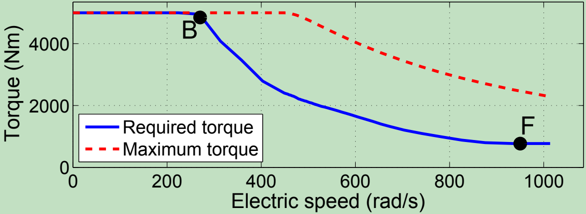
$$P_{cd} = \underbrace{V_{ce,on} I_{avg} + R_{on} I_{rms}^2}_{\text{IGBT losses}} + \underbrace{V_{d,on} I_{d,avg} + R_d I_{d,rms}^2}_{\text{diode losses}}$$

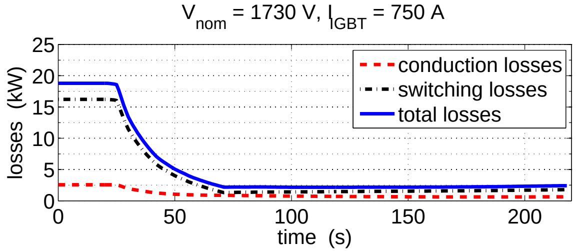
## Switching losses

$$P_{sw} = (E_{on} + E_{off} + E_{rec}) f_{sw} \frac{V_{dc}}{V_{IGBT}}$$

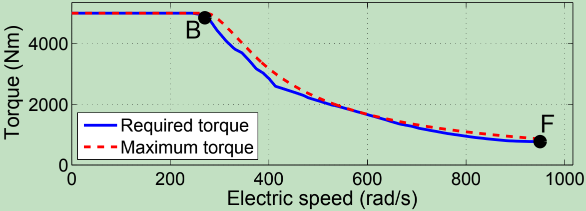
- Losses scaled with the supply voltage ($V_{dc}$), since the datasheet refers to a supply voltage $V_{IGBT} = 3600\ V$.
- The energies are computed from the component datasheet, according to its actual current.

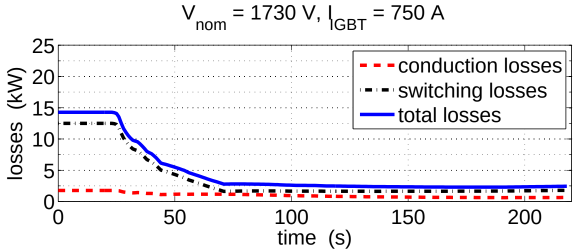
## IPM 3b machine with 100% $V_{pm}$



## IPM 3b machine with 70% $V_{pm}$



## Results of the losses computation

| Motor | $V_{pm}$ (%) | Voltage 80% | $P_{mot_{avg}}$ $(kW)$ | $P_{Cu}$ (%) | $P_{Fe}$ (%) | $P_{IGBT,avg}$ $(kW)$ |
|---|---|---|---|---|---|---|
| IPM–3b | 100% | ✓ | 13.86 | 48.0 | 50.5 | 5.17 |
| IPM–3b | 90% | ✓ | 13.34 | 58.0 | 40.5 | 4.81 |
| IPM–3b | 80% | ✓ | 14.21 | 65.0 | 33.6 | 4.61 |
| IPM–3b | 70% | - | 18.68 | 76.3 | 22.6 | 4.71 |
| IPM–3b | 60% | - | 18.87 | 73.1 | 25.9 | 5.18 |
| IPM–3b | 40% | - | 22.05 | 69.7 | 29.4 | 6.56 |
| IPM–V | - | ✓ | 16.13 | 40.3 | 58.5 | 6.00 |
| IPM–SQ | - | ✓ | 20.20 | 39.7 | 59.3 | 6.57 |
| SPM | - | ✓ | 20.00 | 35.4 | 63.6 | - |

**SPM not considered**

SPM nominal current $I_{n,mot} = 1006A > 750A$

## Results of the losses computation

| Motor | $V_{pm}$ (%) | Voltage 80% | $P_{mot_{avg}}$ $(kW)$ | $P_{Cu}$ (%) | $P_{Fe}$ (%) | $P_{IGBT,avg}$ $(kW)$ |
|---|---|---|---|---|---|---|
| IPM–3b | 100% | ✓ | 13.86 | 48.0 | 50.5 | 5.17 |
| IPM–3b | 90% | ✓ | 13.34 | 58.0 | 40.5 | 4.81 |
| IPM–3b | 80% | ✓ | 14.21 | 65.0 | 33.6 | 4.61 |
| IPM–3b | 70% | - | 18.68 | 76.3 | 22.6 | 4.71 |
| IPM–3b | 60% | - | 18.87 | 73.1 | 25.9 | 5.18 |
| IPM–3b | 40% | - | 22.05 | 69.7 | 29.4 | 6.56 |
| IPM–V | - | ✓ | 16.13 | 40.3 | 58.5 | 6.00 |
| IPM–SQ | - | ✓ | 20.20 | 39.7 | 59.3 | 6.57 |
| SPM | - | ✓ | 20.00 | 35.4 | 63.6 | - |

**Best converter performance**

IPM–3b with 80% PM volume

## Results of the losses computation

| Motor | $V_{pm}$ (%) | Voltage 80% | $P_{mot_{avg}}$ $(kW)$ | $P_{Cu}$ (%) | $P_{Fe}$ (%) | $P_{IGBT,avg}$ $(kW)$ |
|---|---|---|---|---|---|---|
| IPM–3b | 100% | ✓ | 13.86 | 48.0 | 50.5 | 5.17 |
| IPM–3b | 90% | ✓ | 13.34 | 58.0 | 40.5 | 4.81 |
| IPM–3b | 80% | ✓ | 14.21 | 65.0 | 33.6 | 4.61 |
| IPM–3b | 70% | - | 18.68 | 76.3 | 22.6 | 4.71 |
| IPM–3b | 60% | - | 18.87 | 73.1 | 25.9 | 5.18 |
| IPM–3b | 40% | - | 22.05 | 69.7 | 29.4 | 6.56 |
| IPM–V | - | ✓ | 16.13 | 40.3 | 58.5 | 6.00 |
| IPM–SQ | - | ✓ | 20.20 | 39.7 | 59.3 | 6.57 |
| SPM | - | ✓ | 20.00 | 35.4 | 63.6 | - |

**Best drive performance**

IPM–3b with 90% PM volume

## Conclusions

- A railway application has been considered; in particular:
  - a torque/speed characteristic was given
  - different motors topologies have been compared
  - the motors are different in terms of the amount of flux given from the magnets and rotor saliency.
  - the number of turns per phase $n_{cs}$ is computed during the design process in order to avoid a too high UGO voltage and to satisfy the required torque versus speed characteristic.
  - the same IGBT component have been used for all the motor drives
- All motors satisfy the requirements of the traction application

## Conclusions

- The SPM motor is not suitable for the application, since it has a limited flux weakening capability and presents a too high current
- Motors with low volume of permanent magnet does not have an adequate Torque/Volume ratio
- Motors characterized by higher saliency exhibit better performance.
- In addition, the fulfillment of the different requirements leads to configurations with also high PM flux
- The IPM–3b 90% machine is characterized by a high saliency and high PM volume (90%), that leads to current and losses reduced. It results to be the more suitable candidate for the commuter train considered in this study.

# Thank you for the attention