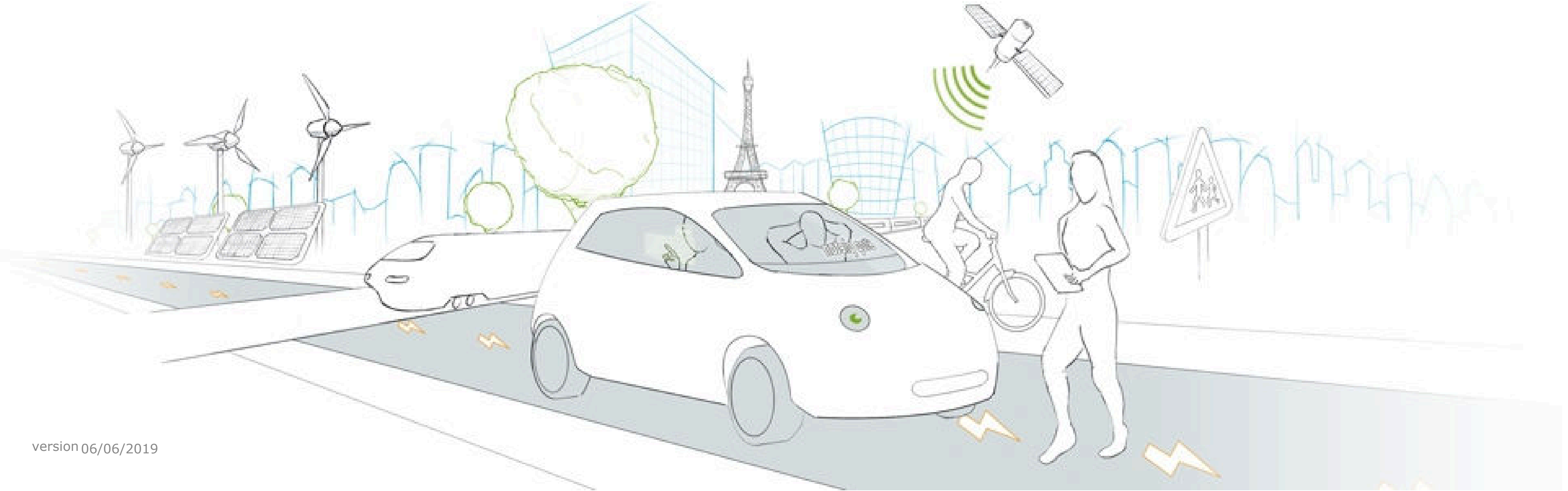
# Performance Analysis of Hybrid Excitation Flux Switching Permanent Magnet Motor PHEV Application

EVS 32 – Lyon – 20/05/2019

Sid Ali RANDI

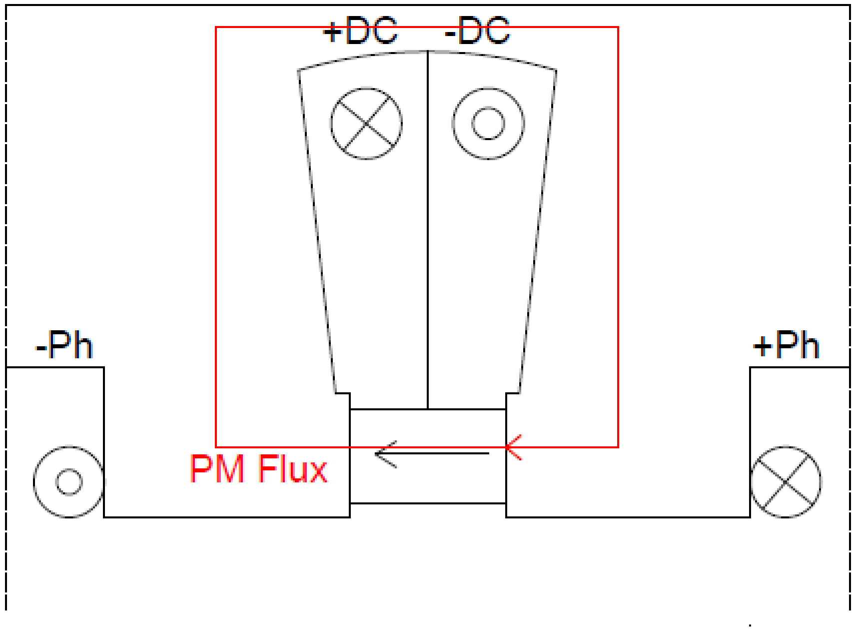


version 06/06/2019

# SUMMARY

# WHY HYBRID EXCITATION FLUX SWITCHING PERMANENT MAGNET MOTOR FOR PHEV APPLICATION ?

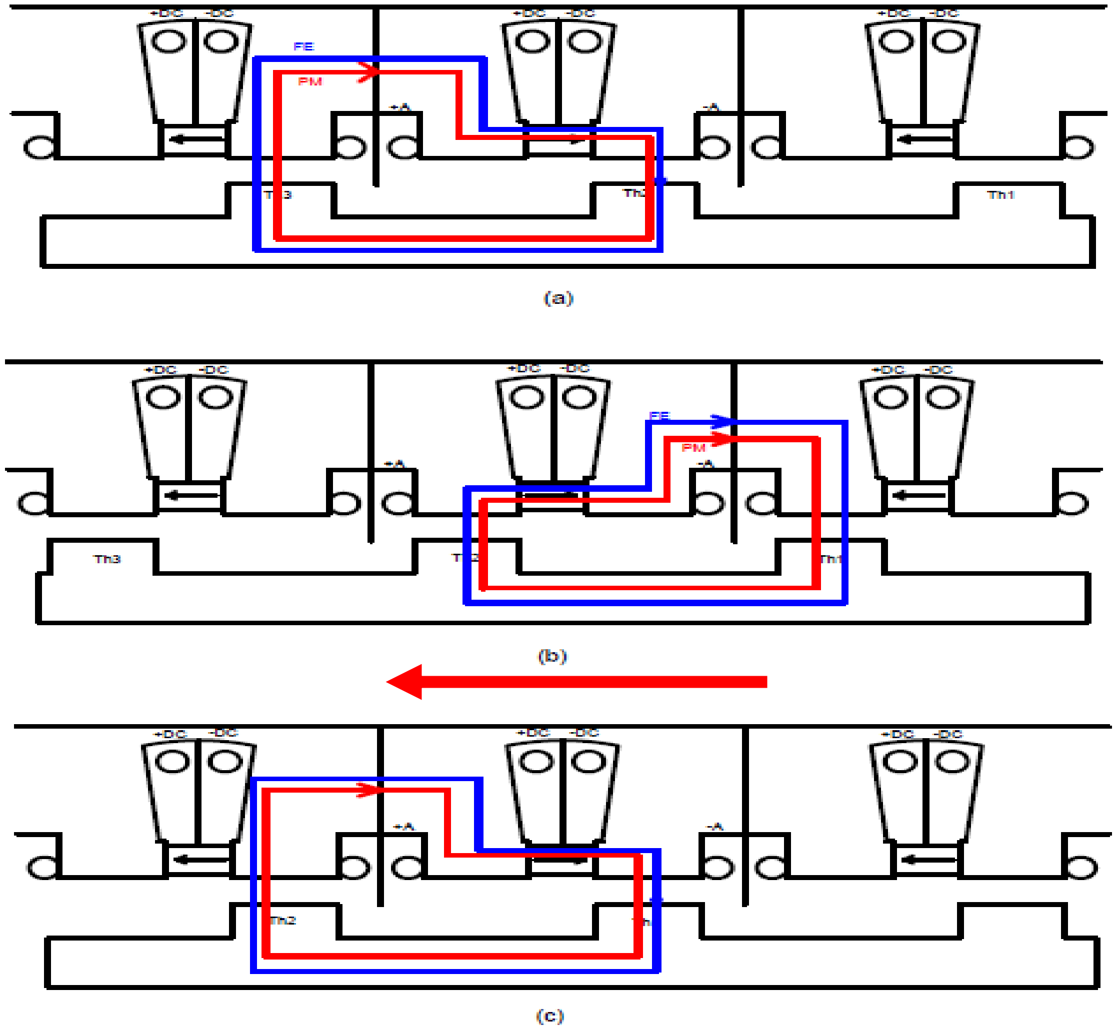
# OPERATING PRINCIPLE OF HEFSPM - EMC

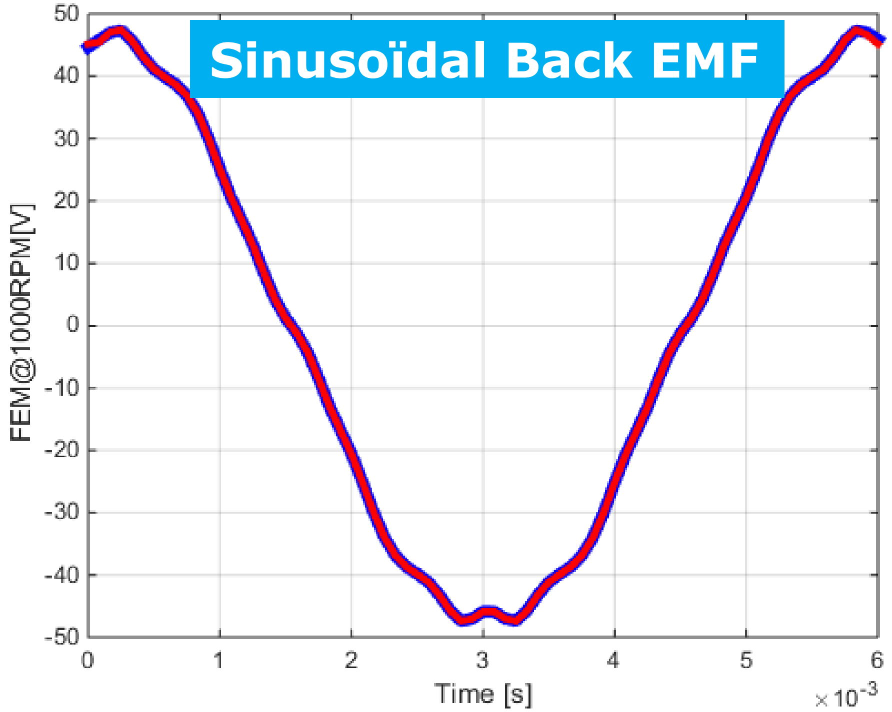



**EMC: Elementary Magnetic Circuit**

# OPERATING PRINCIPLE OF HEFSPM

## No-Load Characteristics




| Rang de l'harmonique | Valeur Max [V] | % / H1 |
|---|---|---|
| H1 | 47 V | 100 % |
| H5 | 1,15 V | 2,4% |
| H7 | 0,85 V | 1,8 % |

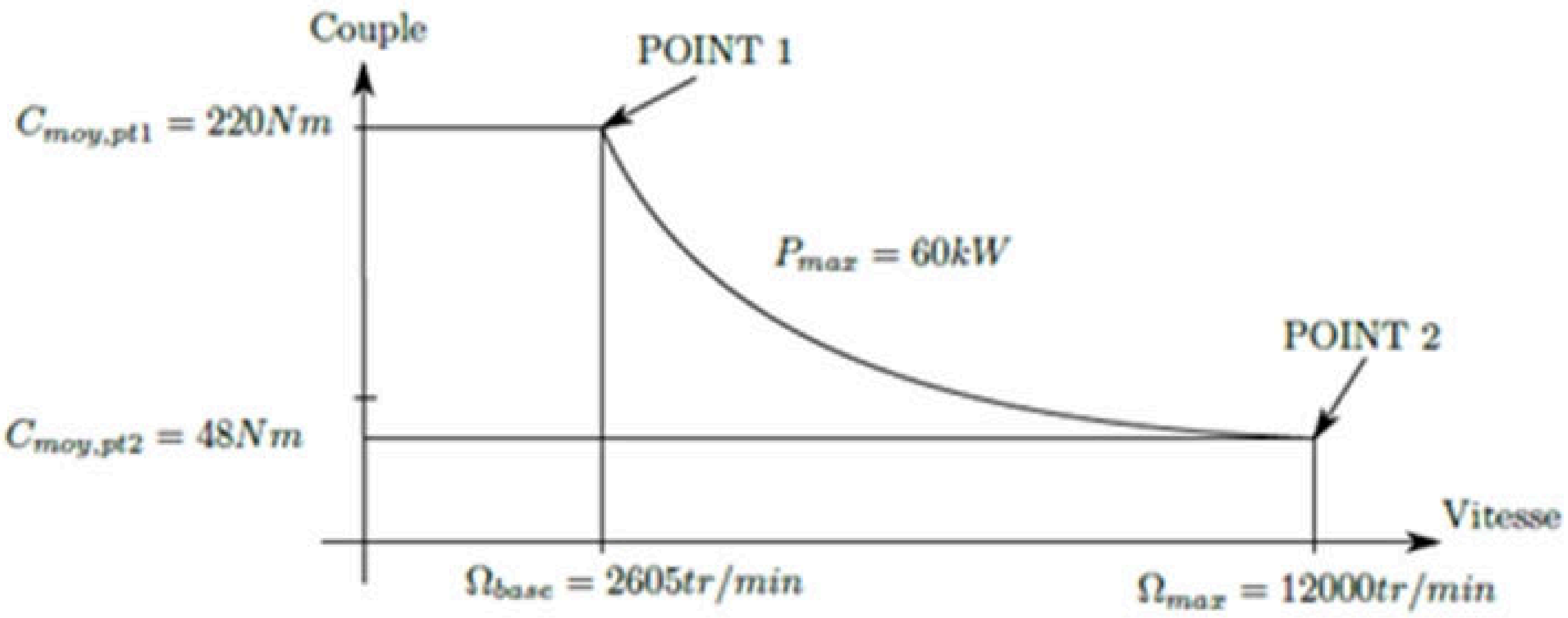
# PHEV APPLICATION REQUIREMENT

## Supply Voltage & Current - Geometry



| SUPPLY | | | |
|---|---|---|---|
| DC Supply Voltage | Rated | 285 | Vdc |
| | maxi | 400 | Vdc |
| | mini perfo max | 270 | Vdc |
| | mini perfo min | 200 | Vdc |
| Drop Voltage DC/AC Inverter | | 10% | |
| Phase Voltage – RMS Value | Rated | 115 | Vrms |
| | Mini perfo max | 109 | Vrms |
| Phase Current – RMS Value | Maxi | 261,7 | Arms |
| DC Excitation Voltage | | 400 | Vdc |
| DC Excitation Current | | 50 | Adc |
| **GEOMETRY** | | | |
| Active Length | | 110 | mm |
| Stator Outer Diameter | | 260 | mm |

# PHEV APPLICATION REQUIREMENT
## Performances

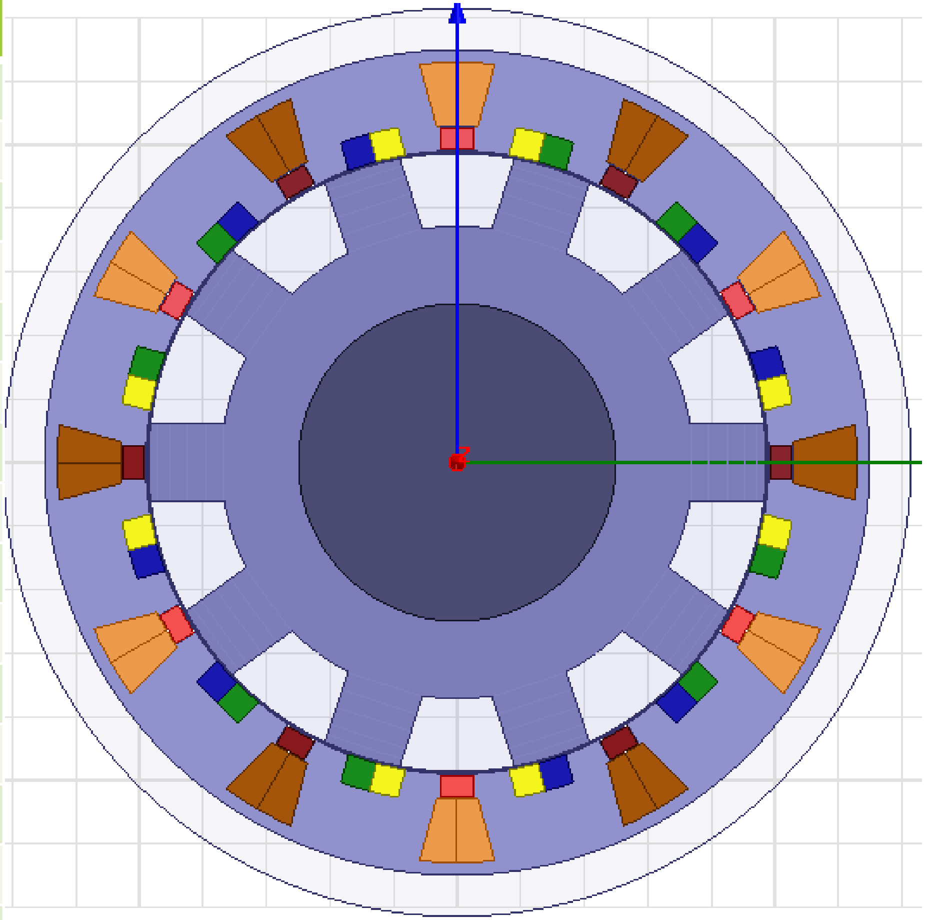



| PERFORMANCES | | | |
|---|---|---|---|
| Maximum Torque | For 20 s | 220 | N.m |
| Base Speed | @ Base | 2605 | tr/min |
| Maximum Speed | max | 12000 | tr/min |
| Continuons Power | continuous | 21 | kW |
| Maximum Power | For  20 s | 60 | kW |

# TECHNICAL DEFINITION OF THE MOTOR

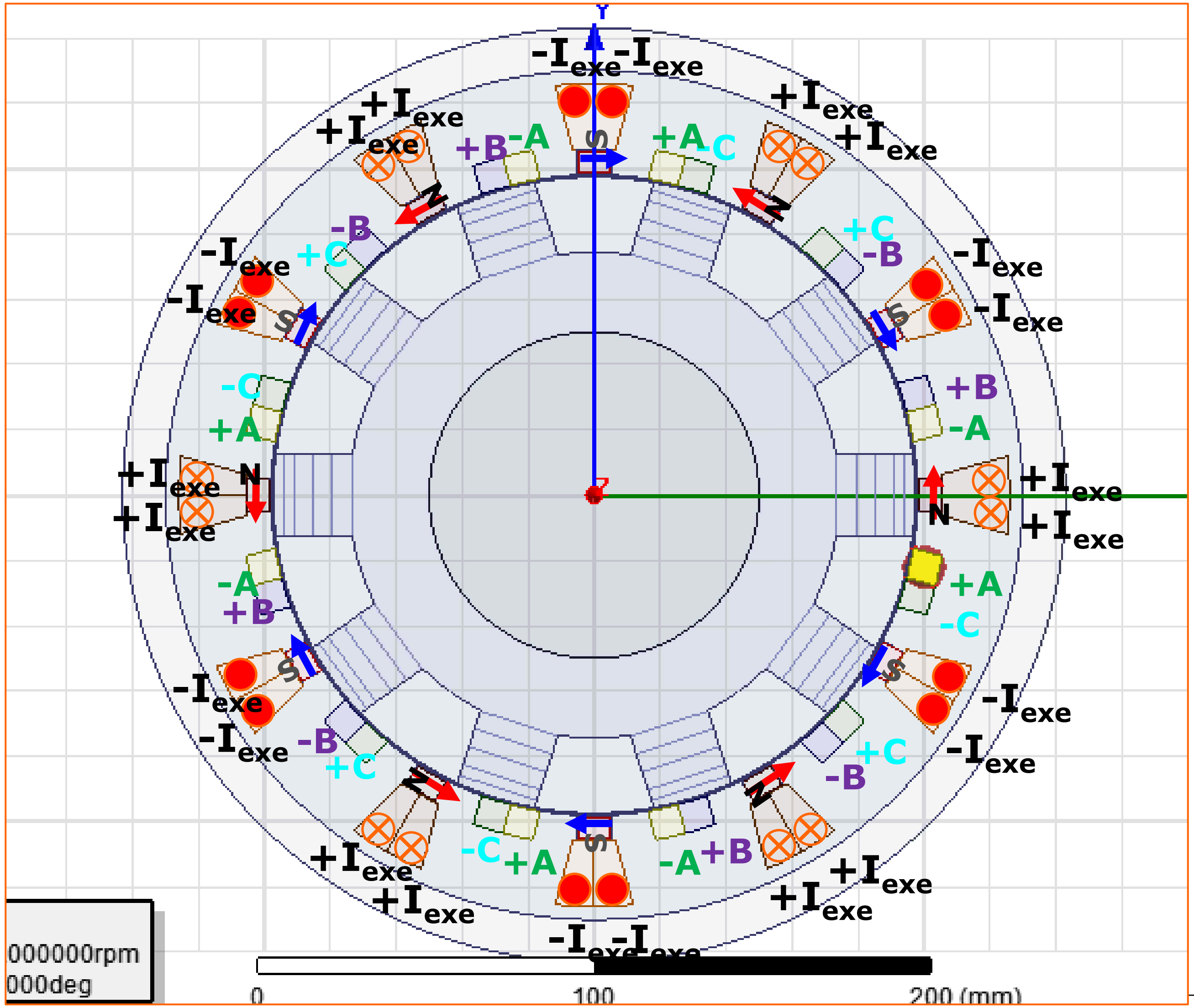
## HEFSPM – Prototype version

| Symbol | Value | Description |
|---|---|---|
| Ns | 12 | Number of Stator Slots |
| Nr | 10 | Number of Rotor Slots |
| $D_{s\_ext}$ | 260 mm | Outer Stator Diameter |
| $L_f$ | 110 mm | Active Length |
| $D_{al}$ | 196,3 mm | Bore Diameter |
| $L_{enc\_s}$ | 18,54 mm | Width of Phase Slot |
| $H_{enc\_s}$ | 9 mm | High of phase Slot |
| $L_{enc\_exe\_s}$ | 12,88 mm | Width of Excitation Slot |
| $H_{enc\_exe\_s}$ | 20,24 mm | High of Excitation Slot |
| $L_a$ | 10 mm | Width of Magnet |
| $H_a$ | 6,56 mm | High of Magnet |
| e | 0,8 mm | Airgap Length |
| $D_{rot}$ | 194,7 mm | Rotor Diameter |
| $L_{dr}$ | 24,7 mm | Width of Rotor Teeth |
| $H_{dr}$ | 23 mm | High of Rotor Teeth |
| $D_{ar}$ | 50 mm | Shaft Diameter |



# TECHNICAL DEFINITION OF THE HEFSPM

## Winding Characteristics

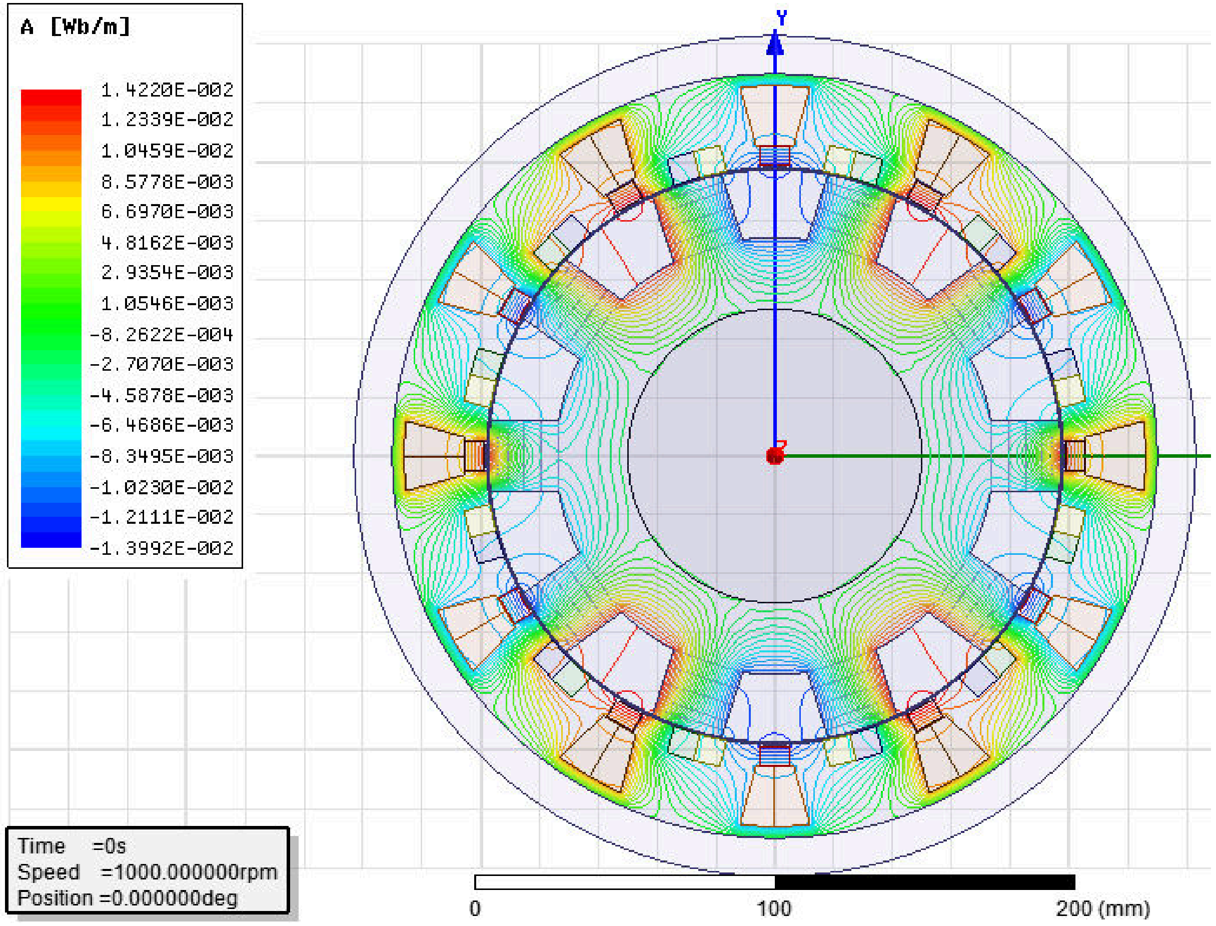


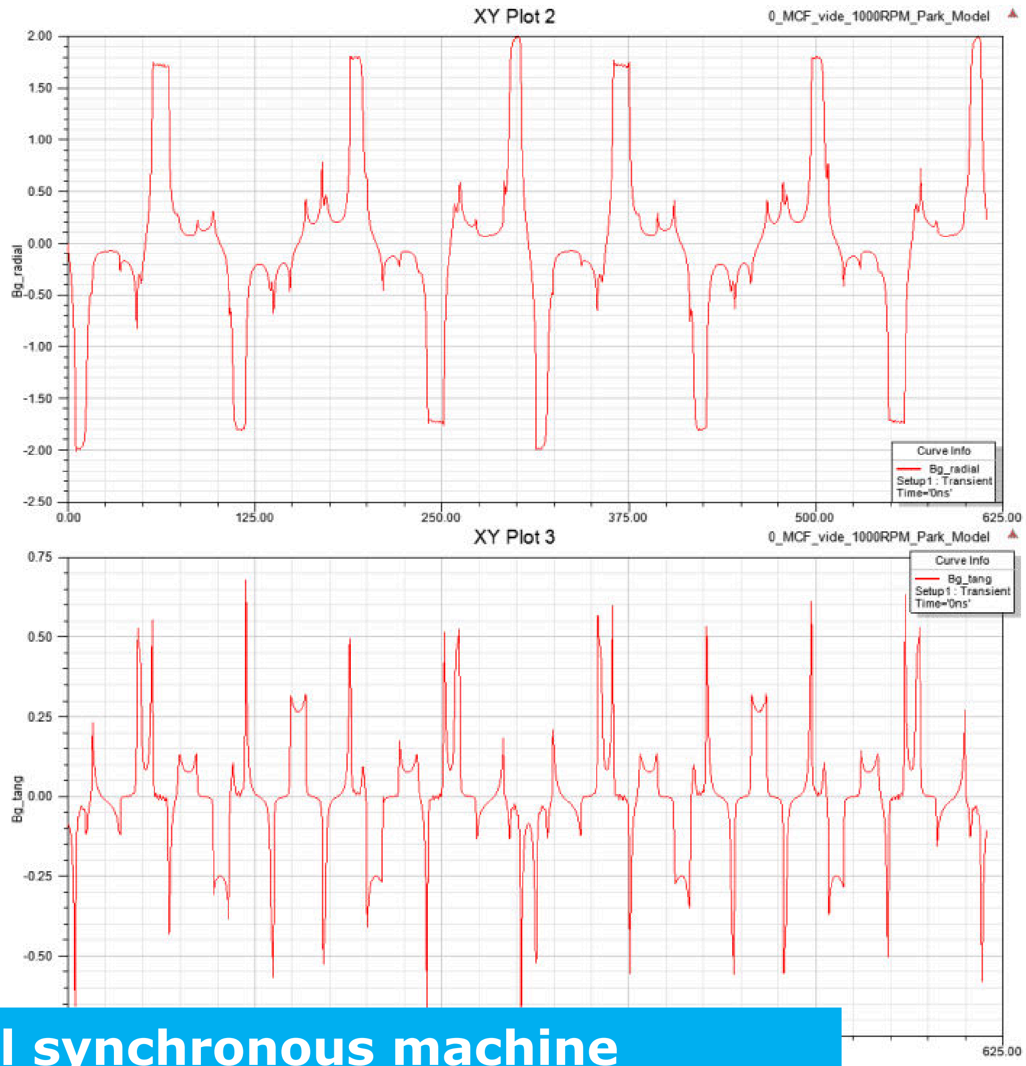

| PHASE WINDING | |
|---|---|
| Number of // wires | 6 |
| Number of turns / Coils | 5 |
| Wire Diameter [mm] | 1,25 |
| Number Coils in Series / Phase | 4 |
| Phase Resistance @ 20°C [mΩ] | 22.35 |
| Current Density @ Max. Current [A/mm²] | 35,53 |

| EXCITATION WINDING | |
|---|---|
| Number of // wires | 4 |
| Number of turns / Coils | 50 |
| Wire Diameter [mm] | 0.75 |
| Number Coils in Series | 12 |
| Phase Resistance @ 20°C [Ω] | 2.4 |
| Current Density @ Max. Current [A/mm²] | 28.3 |

# MATHEMATICAL MODEL

## Why Park Approach is Still Valid ?




**Not obvious to consider the machine as classical synchronous machine**

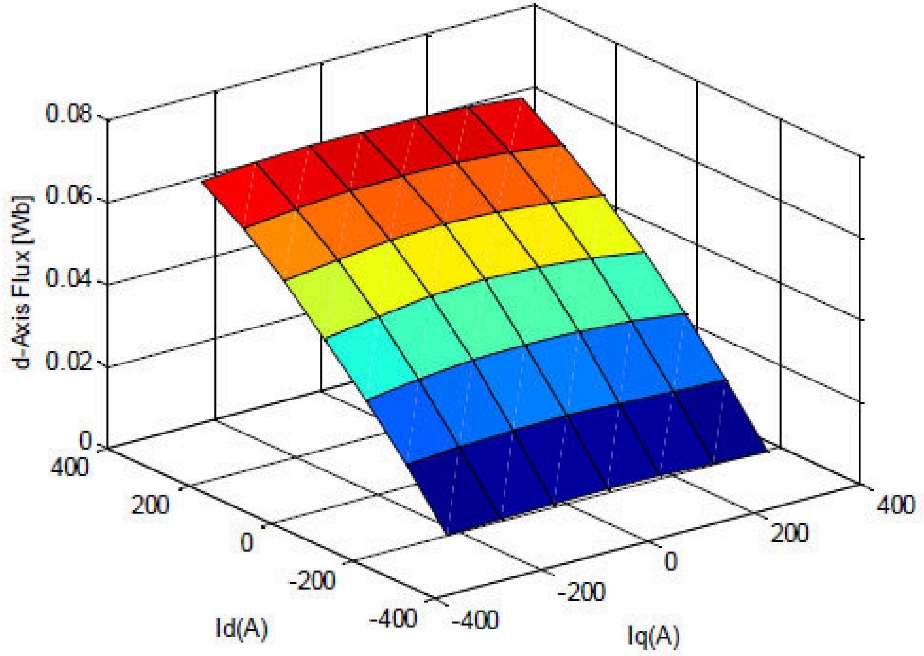
# MATHEMATICAL MODEL

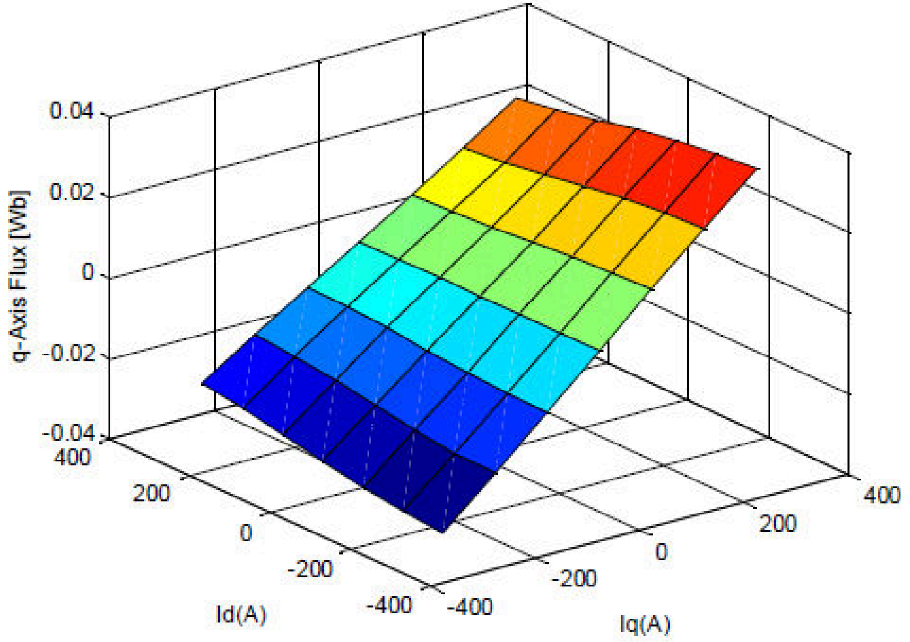
## Flux Mapping

$$\Phi_d = \Phi_d(I_d, I_q, I_f)$$
$$\Phi_q = \Phi_q(I_d, I_q, I_f)$$

→ $I_d \in [-400{,}400]Amps$ ; $I_q \in [-400, 400]Amps$; $I_f \in [-50, 50]Amps$

- ➔ MAXWELL 2D® FEA Computation 405 computation over 2 electrical period
- ➔ 9 points for Id, 9 points for Iq , 5 points for If.
- ➔ FEA @ 1000 RPM : Torque , Fluxes, Iron Losses, Magnet Losses, Induced Voltage

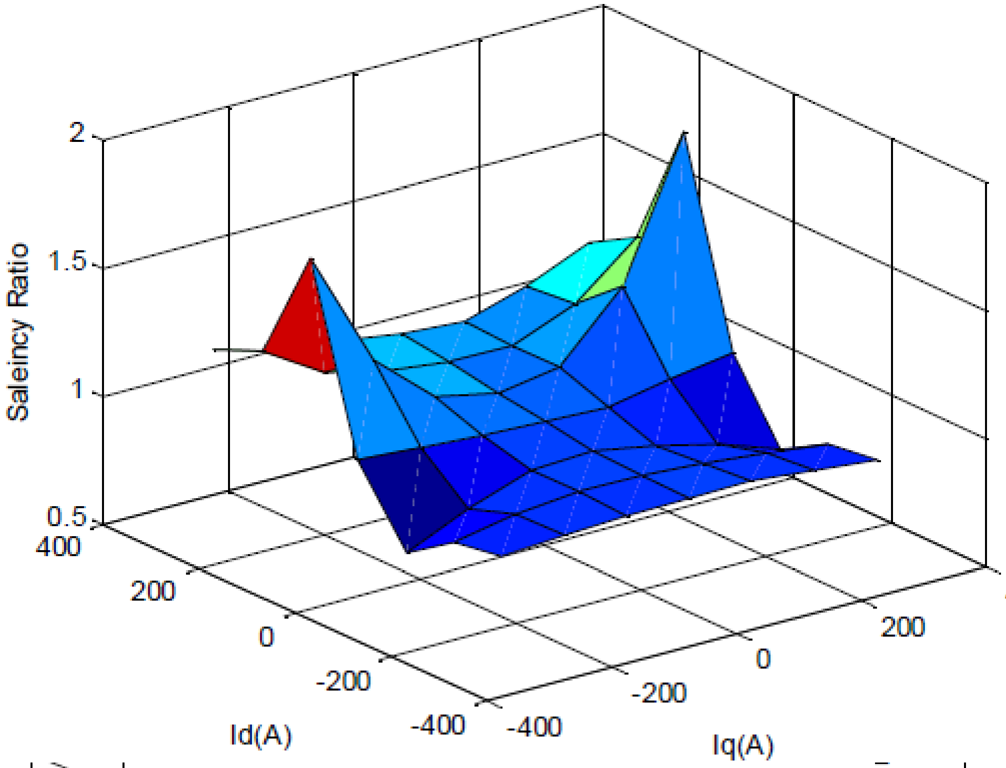


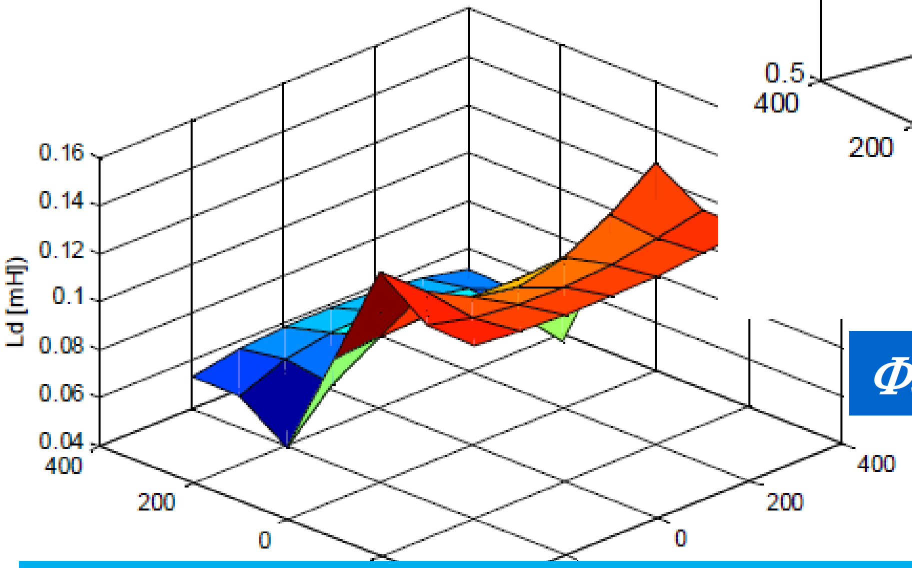



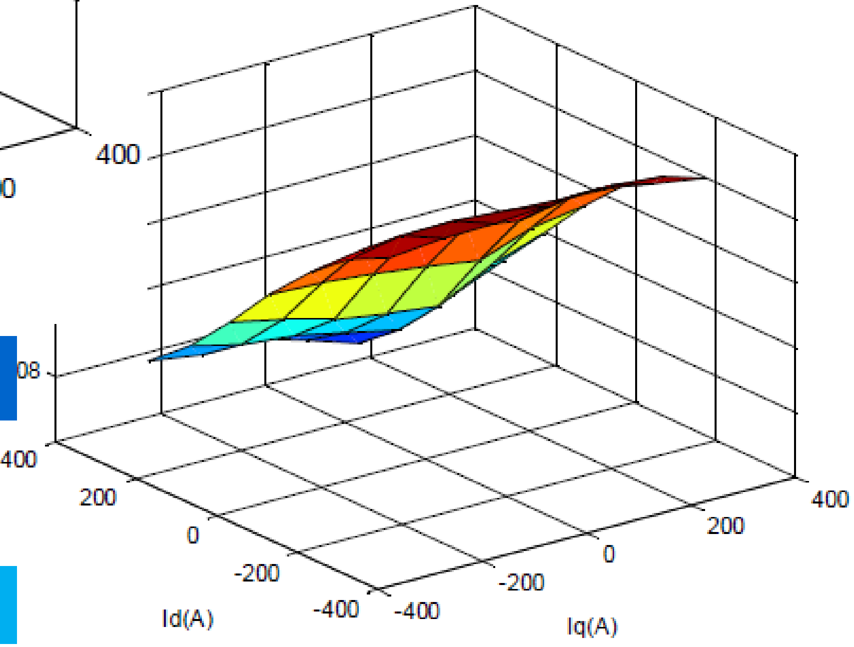

VEDECOM

# MATHEMATICAL MODEL
## Inductance and Motor behavior

$$\begin{cases} \Phi_d = \Phi_v + L_d\, I_d \\ \Phi_d = L_q I_q \end{cases}$$

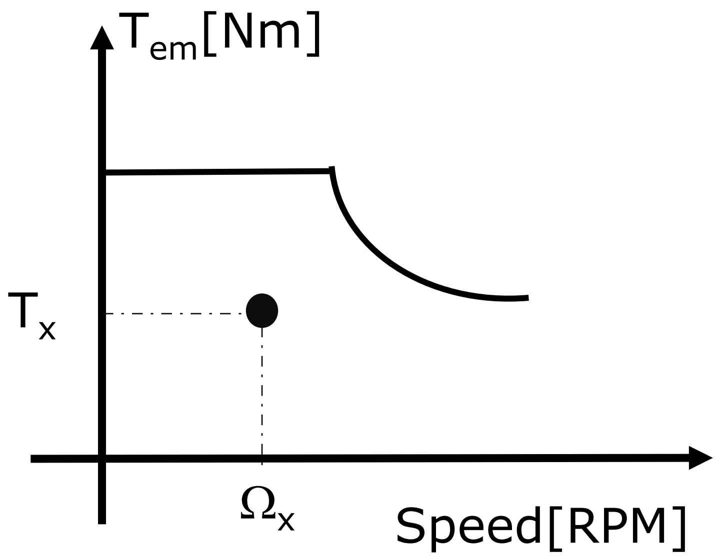



**$\Phi_v$=45,43mWb @ $I_f$= 50A**

**Motor exhibit the behavior of Surface Mounted PM Motor**




$(I_{dx}, I_{qx}, I_{fx})$ ?

$$Vs = \sqrt{Vd^2 + Vq^2} \leq 0.9\frac{Vdc}{\sqrt{3}}$$

$$Is = \sqrt{Id^2 + Iq^2} \leq I_{smax}$$

$$\begin{cases} V_d = \frac{d\Phi_d}{dt} - \omega_e \Phi_q + R_s I_d \\ V_q = \frac{d\Phi_q}{dt} + \omega_e \Phi_d + R_s I_q \end{cases}$$

$$T_{em} = \frac{3}{2} P\left[\phi_v I_q + (L_d - L_q) I_d I_q\right]$$

➔ *fminimax* function of MATLAB® to solve the following optimization problem :

Find $(I_{dx}, I_{qx}, I_{fx})$ that allow losses minimization

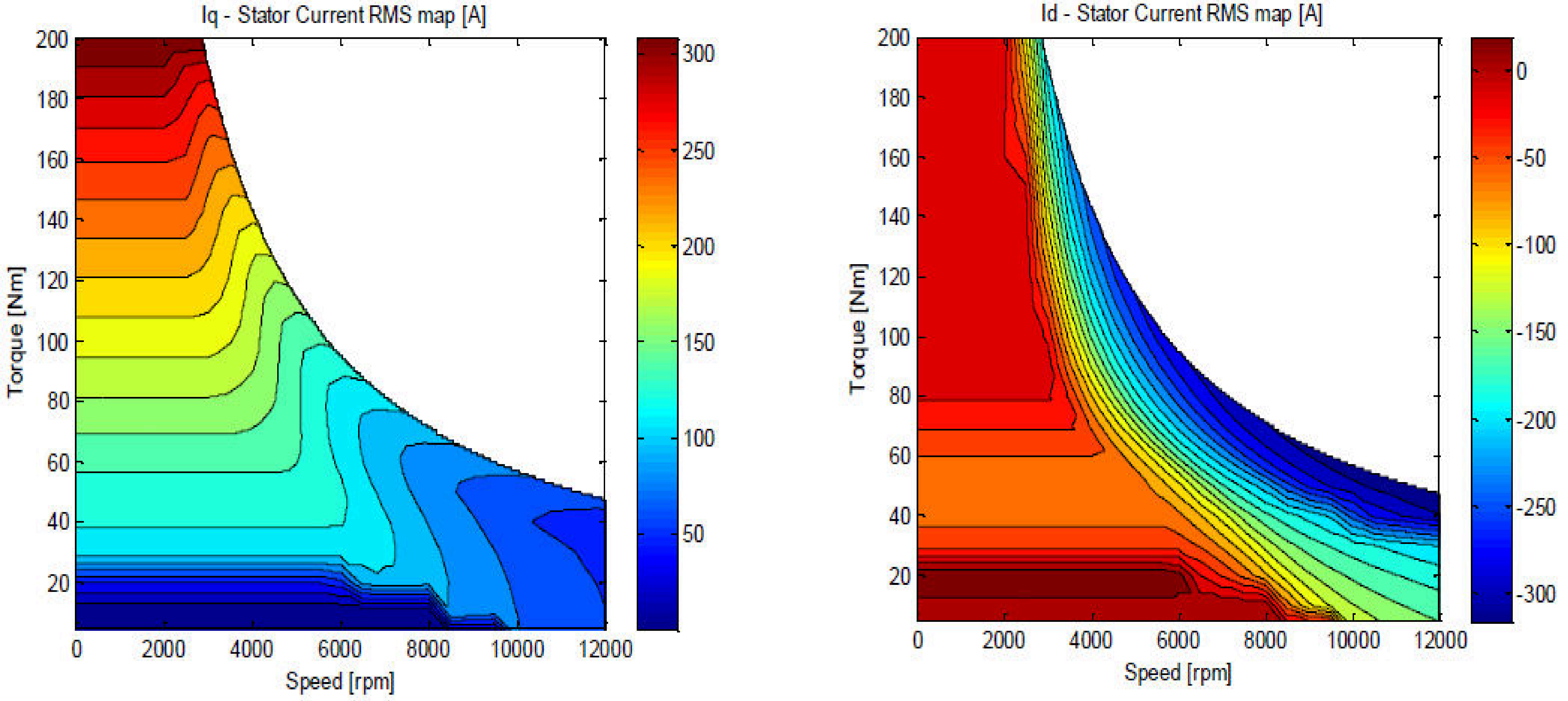
$$Vs = \sqrt{Vd^2 + Vq^2} \leq 0.9\frac{Vdc}{\sqrt{3}}$$

$$Is = \sqrt{Id^2 + Iq^2} \leq I_{smax}$$

$$T_{em} = T_x \ @ \ \Omega = \Omega_x$$

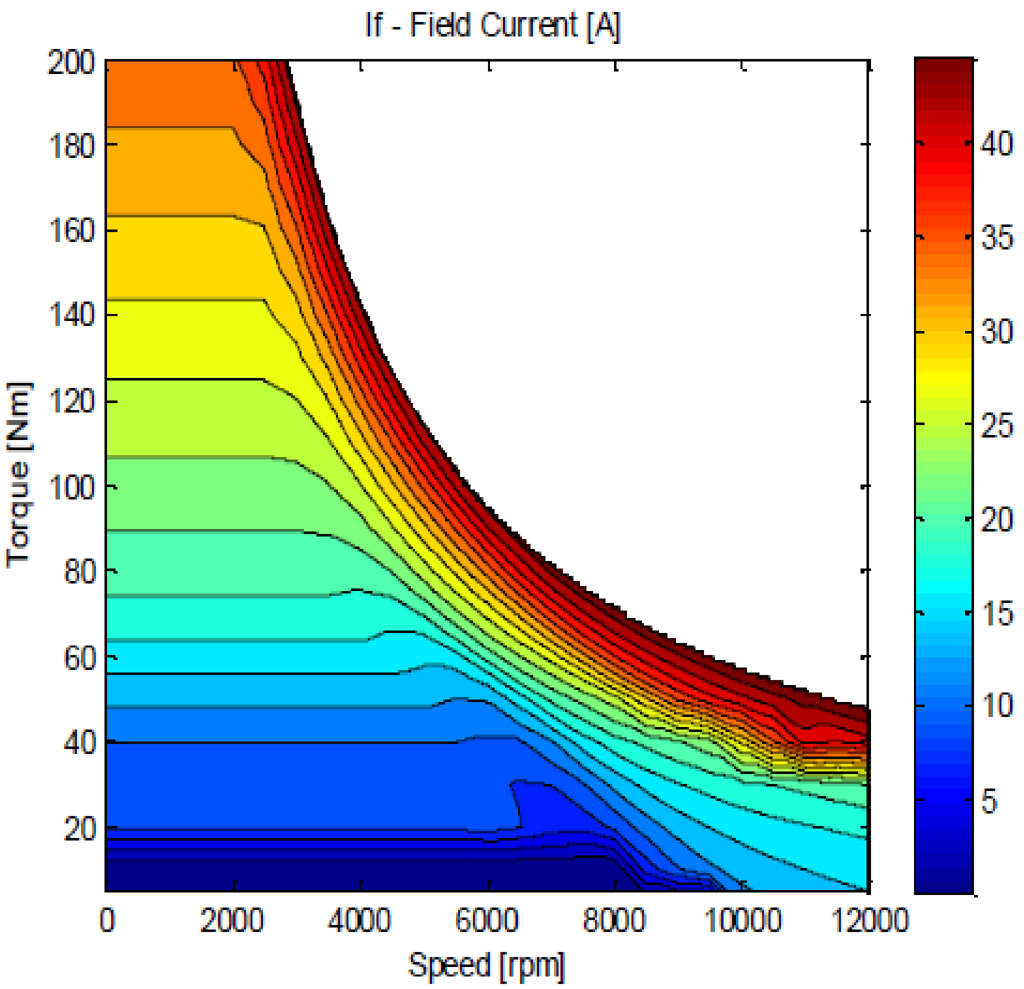
# OPTIMAL CONTROL STRATEGY

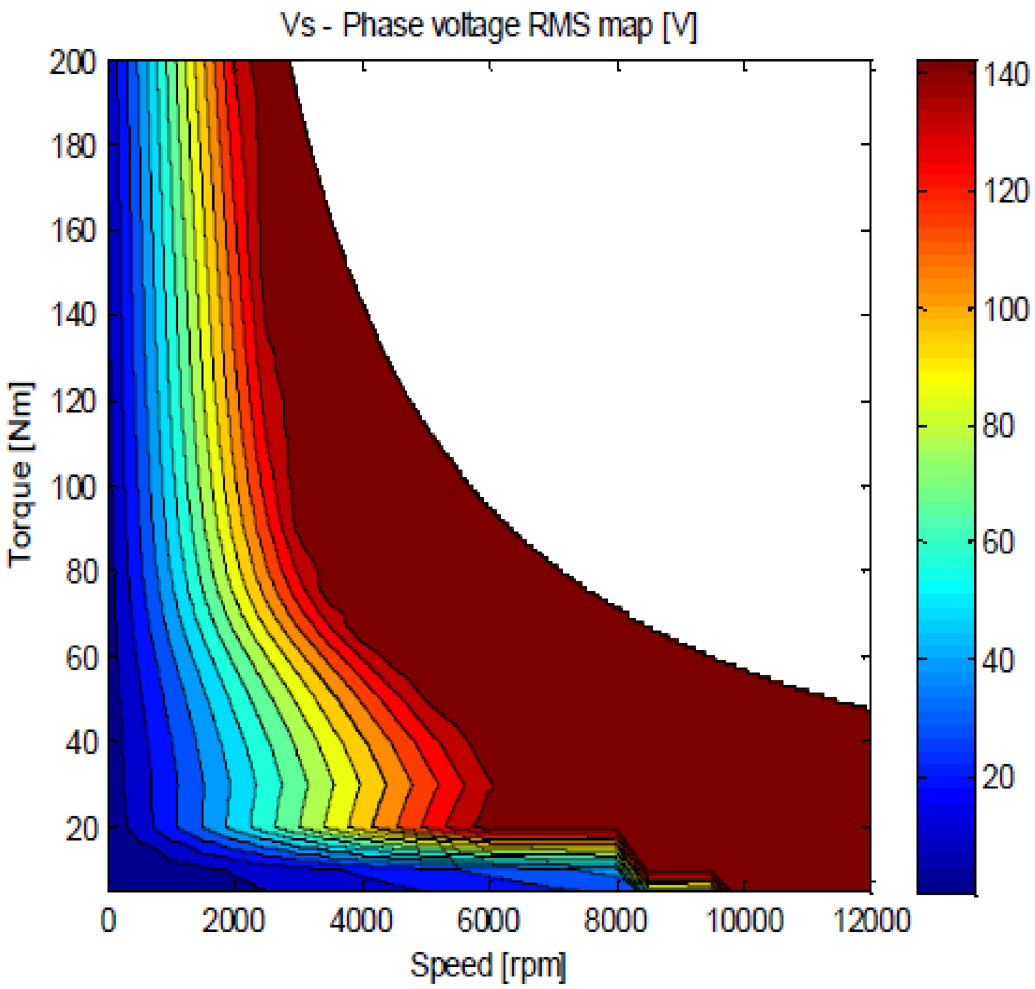
## Results of Optimization problem



# OPTIMAL CONTROL STRATEGY

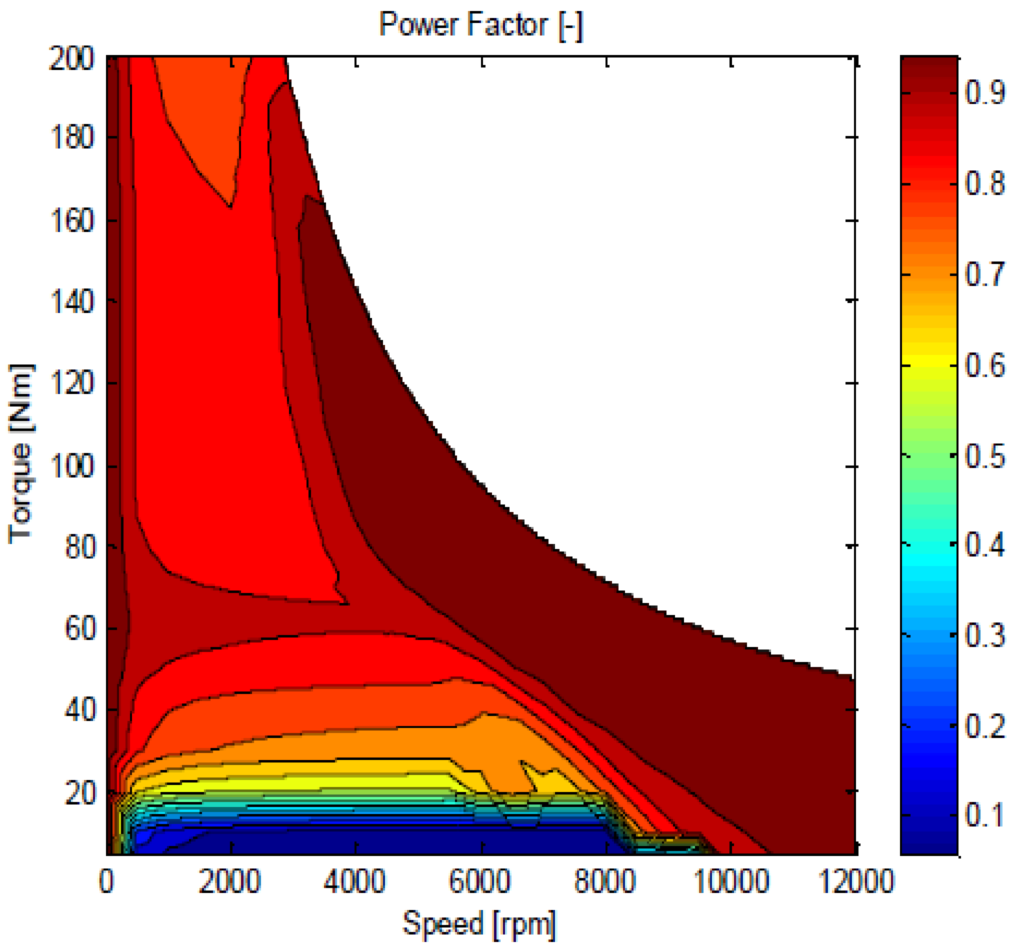
## Results of Optimization problem

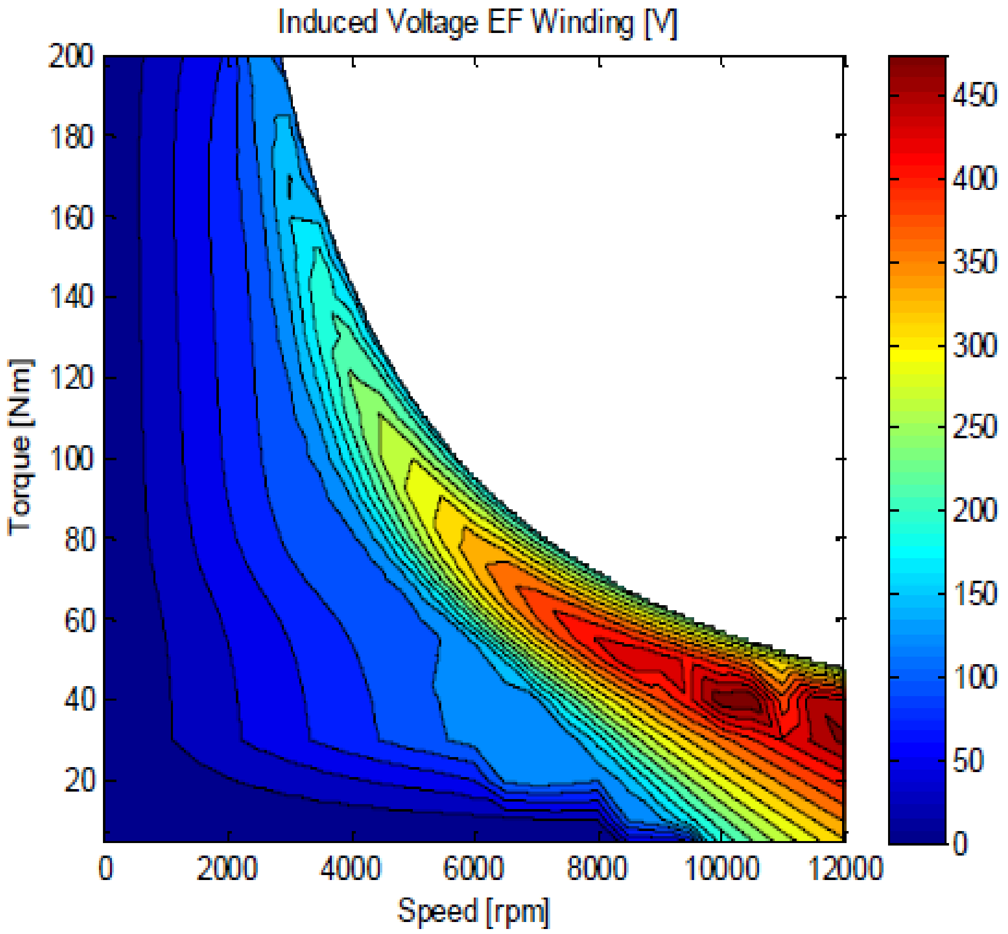


# RESULTS & ANALYSIS

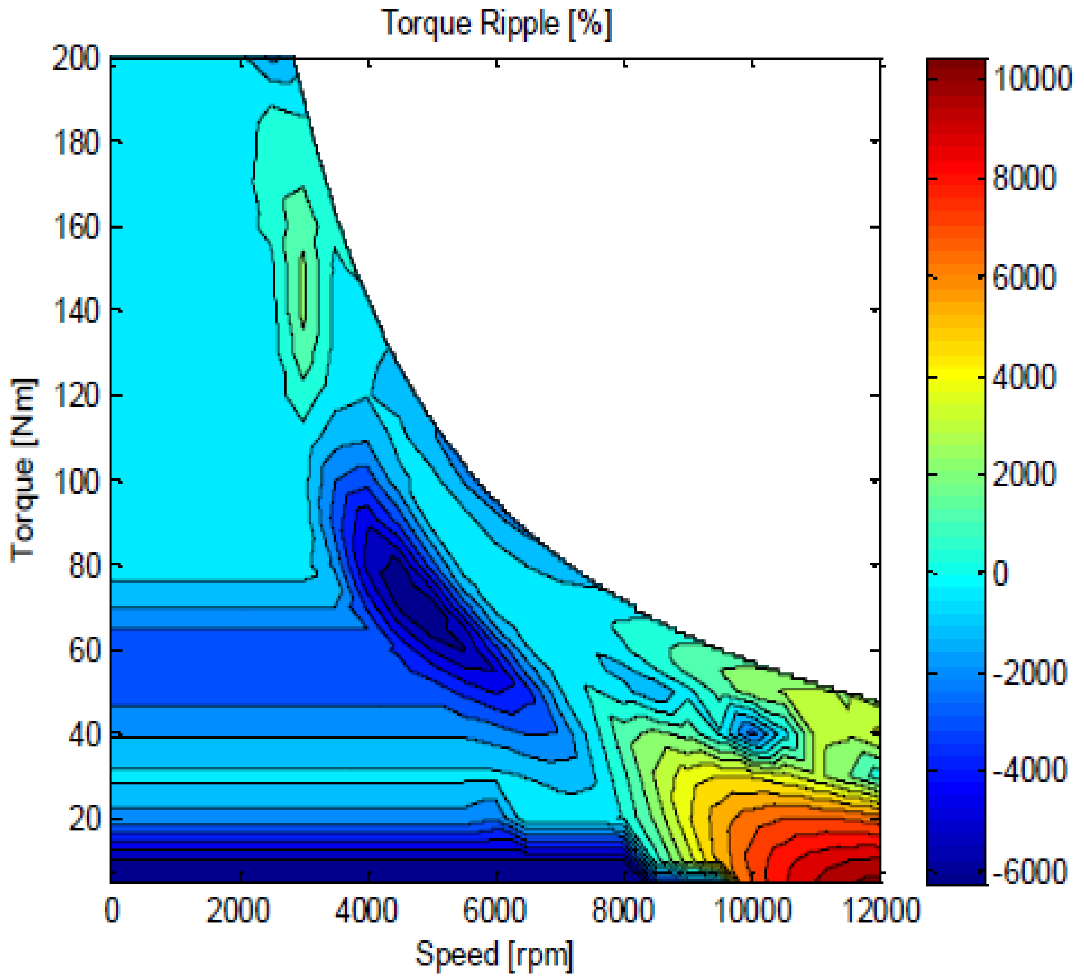
## Power Factor and EF Induced Voltage

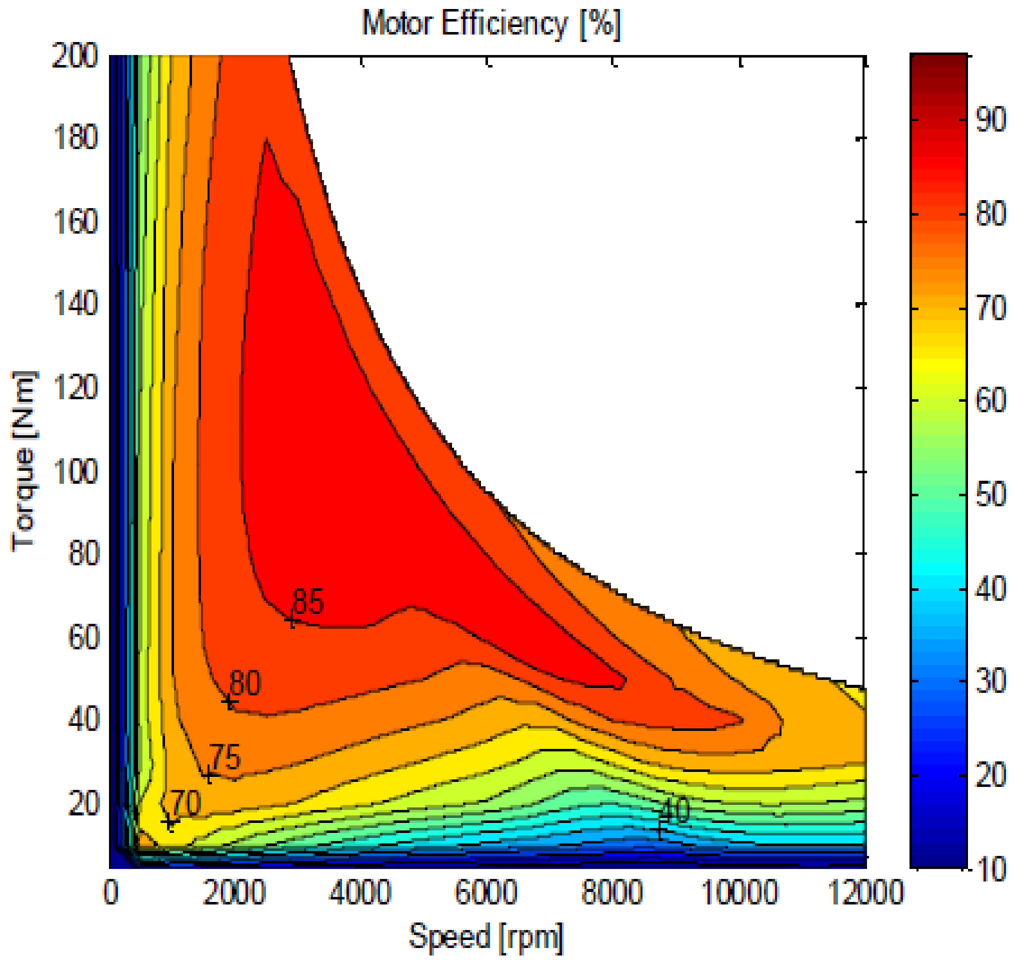


# RESULTS & ANALYSIS

## Torque Ripple and Efficiency



# PROTOTYPE BUILDING



Masse production cost in 2020 # 300€

| Items | Values |
| --- | --- |
| Rotor Iron Weight [kg] | 12,8 |
| Stator Iron Weight [kg] | 15,7 |
| Magnets Weight [kg] | 0,684 |
| FE Cooper Weight [kg] | 3,33 |
| Phase Cooper Weight [kg] | 1,3 |
| Total Machine Weight [kg] | 33,8 |
| Torque Density [Nm/kg] | 6,5 |

INSTITUT VEDECOM

# CONCLUSIONS & FUTUR WORKS