Ph.D Dissertation Summary
Multiphase Electrical Machines for Vehicular Traction

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Biography and Context

M. F. Troncoso C. born in Chile in 1988, received the MSc in electrical engineering from Politecnico di Torino, Turin, Italy in 2013 in a double degree with Pontificia Universidad Catolica de Chile (PUC). He is currently performing an industrial PhD at the Power Electronics Interdepartmental Laboratory (PEIC) at Politecnico di Torino within a collaboration with Ferrari. He currently works at Ferrari as Manager of Hybrid Components Testing Department.

Contents and Motivation

This thesis focus in two multiphase cases of study for the automotive industry. Both are fractional slot permanent magnet motors for high power density and high-speed application, and the objective is maximizing performance and minimize noise emissions.

Fractional slot multiphase applications are not much studied, and there are becoming popular in racing or very high-density applications like automotive.

1. 12 slot 10 pole asymmetrical six phase permanent magnet machine
2. 20 slot 10 pole two phase machine

Content N° 1: 12 slot 10 pole 6ph vs 3ph

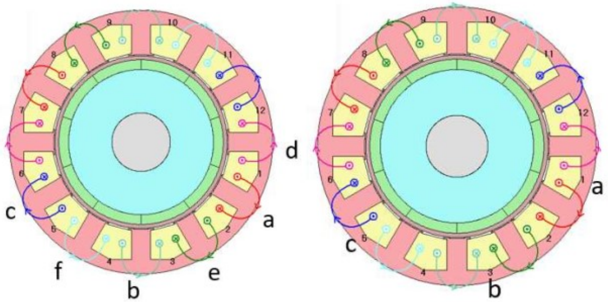


Fig.1

Starting from a 12s10p 3ph machine, a 6ph winding as Fig. 1 is proposed.

The main theorical findings are:

1. Increased by 3.5% of winding factor and thus peak torque. Fig. 2 shows the consequent increase on back-EMF.
2. Reduction of solid rotor losses through the elimination of MMF 1st subharmonic, as per Fig. 3.

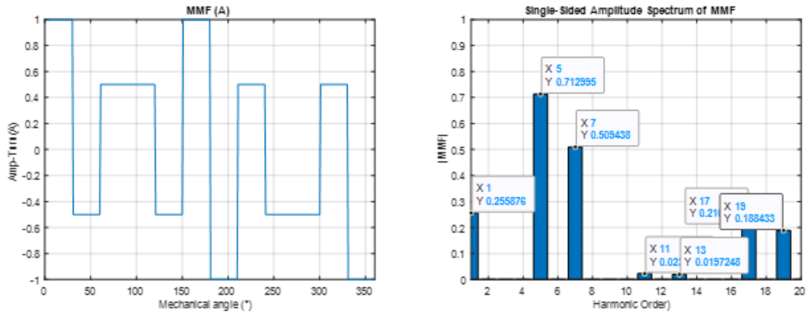


Figure 8: Normalized spatial 3ph MMF and its FFT for 12/10

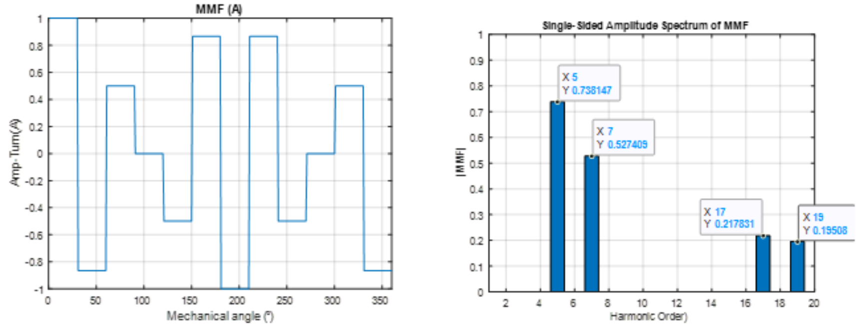


Figure 9: Normalized spatial 6ph MMF and its FFT for 12/10

Fig.3

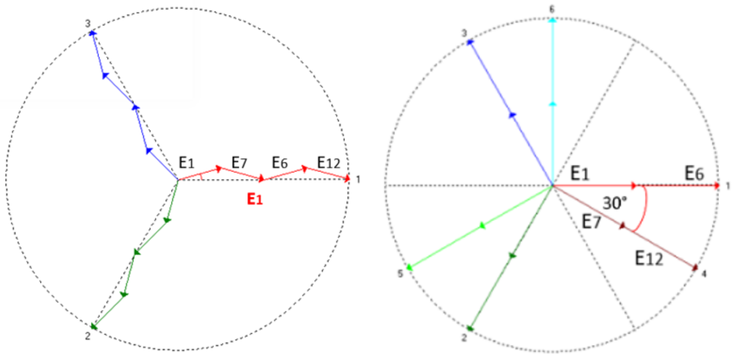


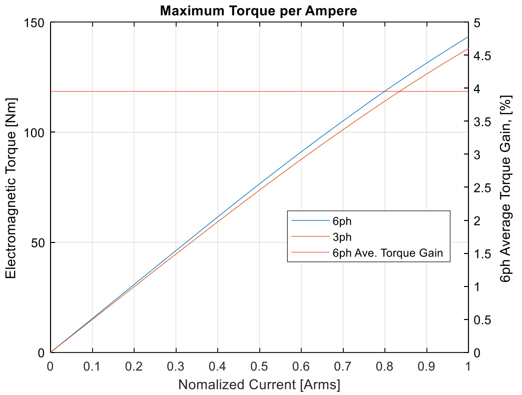
Fig.2

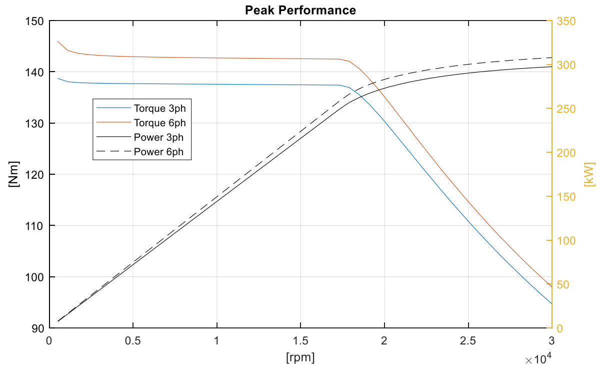
FEM Simulation

The 6ph machine was thoroughly simulated with a 2D and 3D Altair Flux Model, to quantify the effect on performance of the solid rotor losses.

Peak performance Comparison:

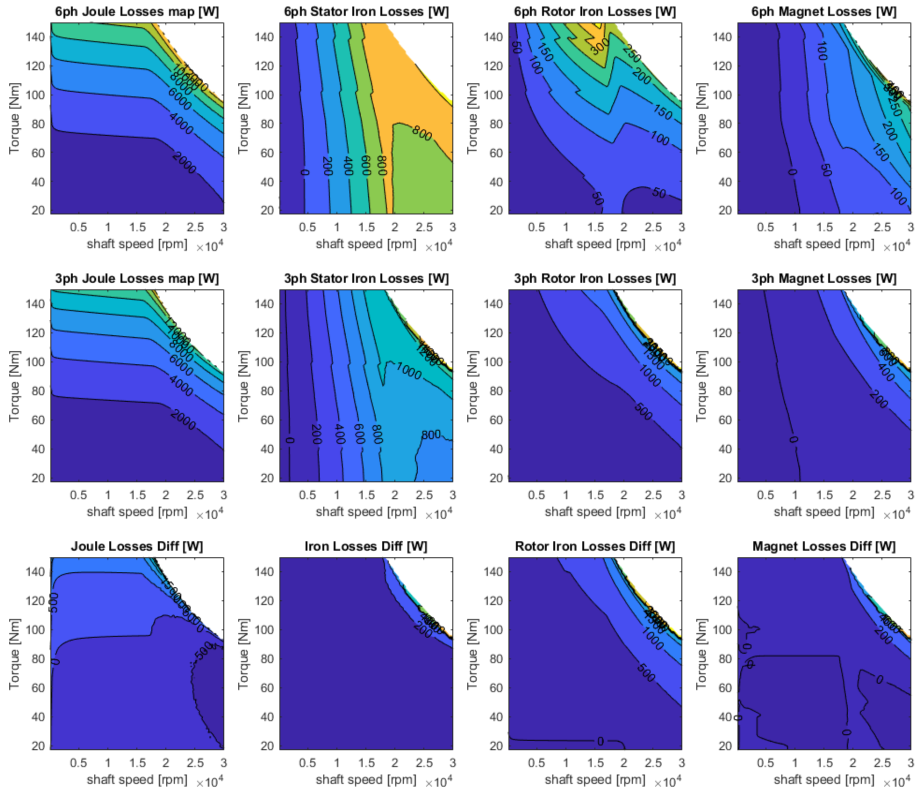
- 6ph incraesed torque >3%





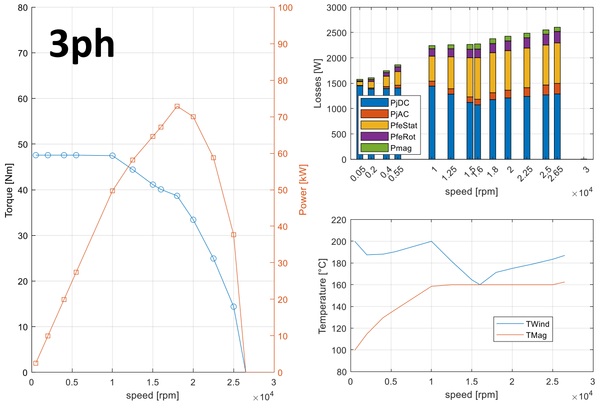
Losses Comparison

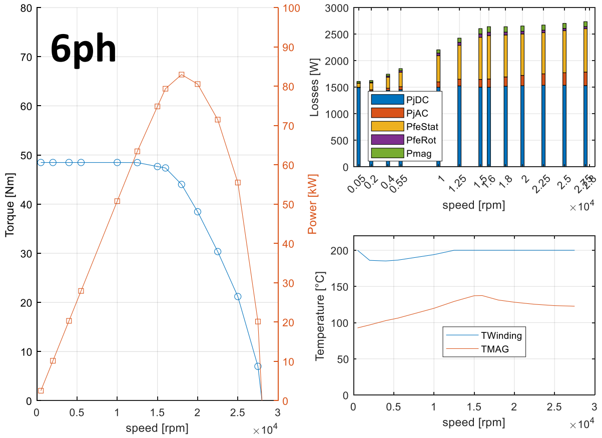
- 6ph solid rotor losses < 50%



Cont. Performance Comparison

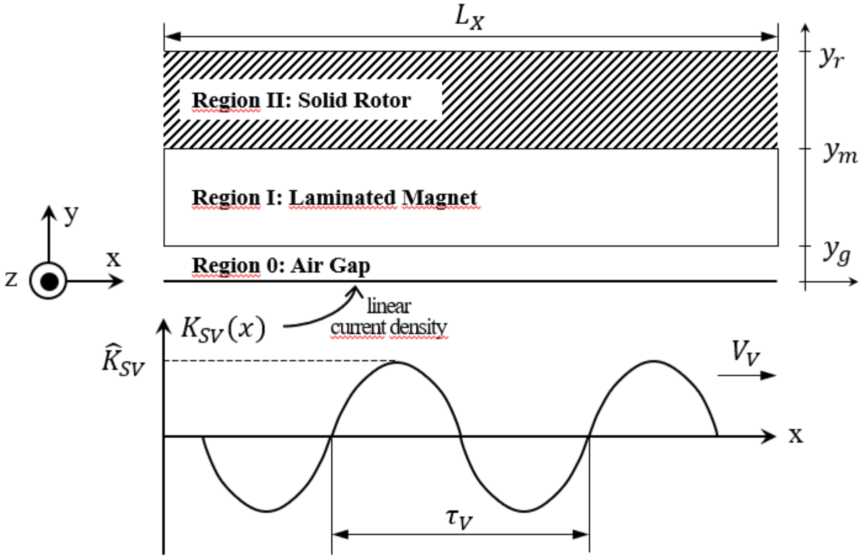
- Cont. Power increase up to 15%





Analytical Model

To further study the phenomenon an analytical model was developed, which rendered evident the effect of the first harmonic of the MMF on solid rotor losses.

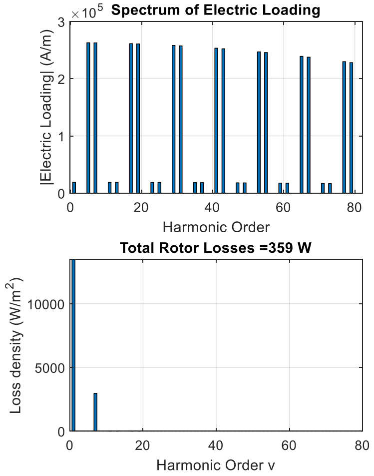


$$q = \frac{(2\pi f_{rv})^2 \sigma^{II} \left|c_4^{II}\right|^2}{4\cdot Re(d^{II})} \cdot \left(e^{-2Re(d^{II})y_m} - e^{-2Re(d^{II})y_r}\right)$$

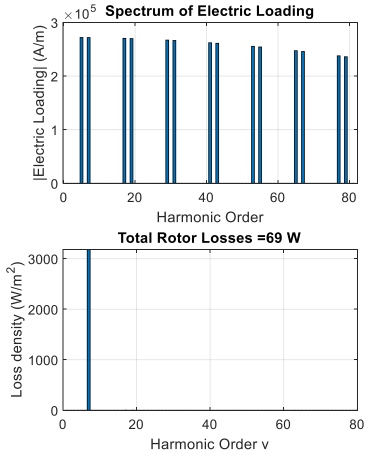
$$d^{II} = \sqrt{\left(\frac{\pi}{\tau_v}\right)^2 - j\omega\mu^{II}\sigma^{II}}.$$

2

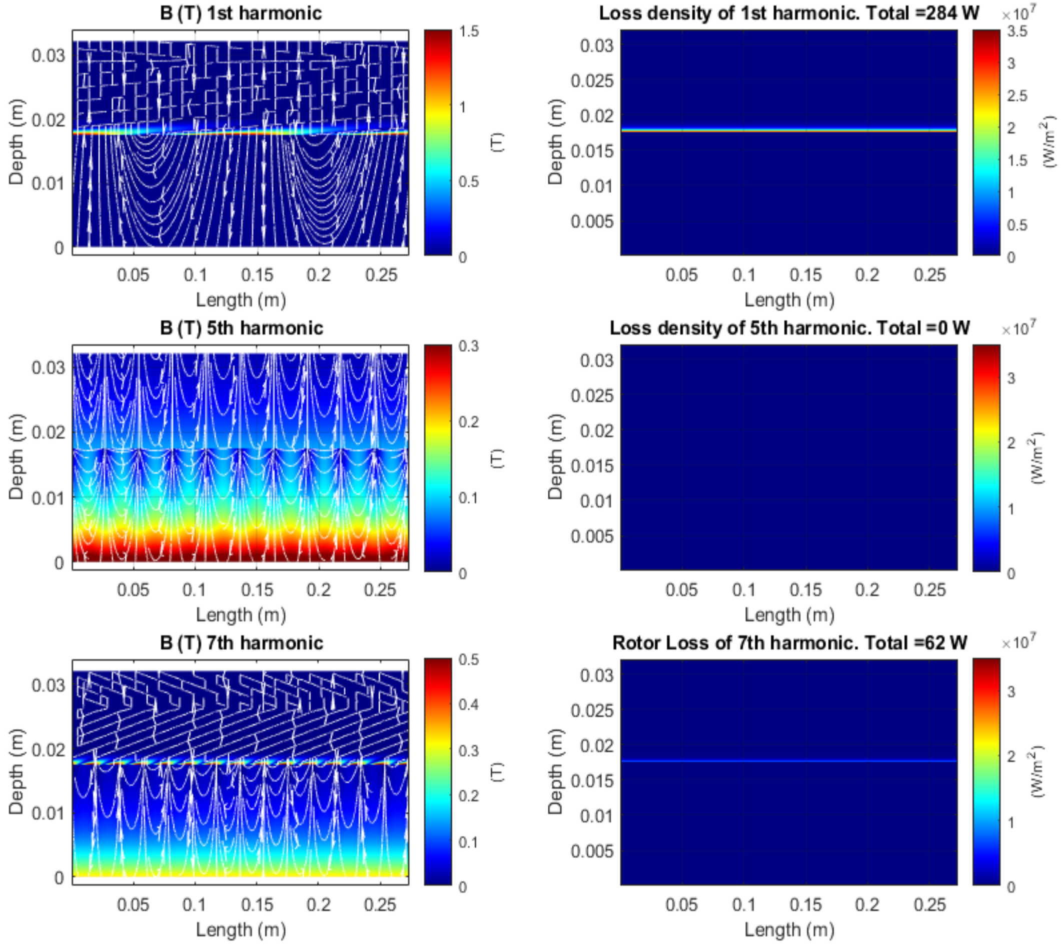
3ph Model Outcome



6ph Model Outcome



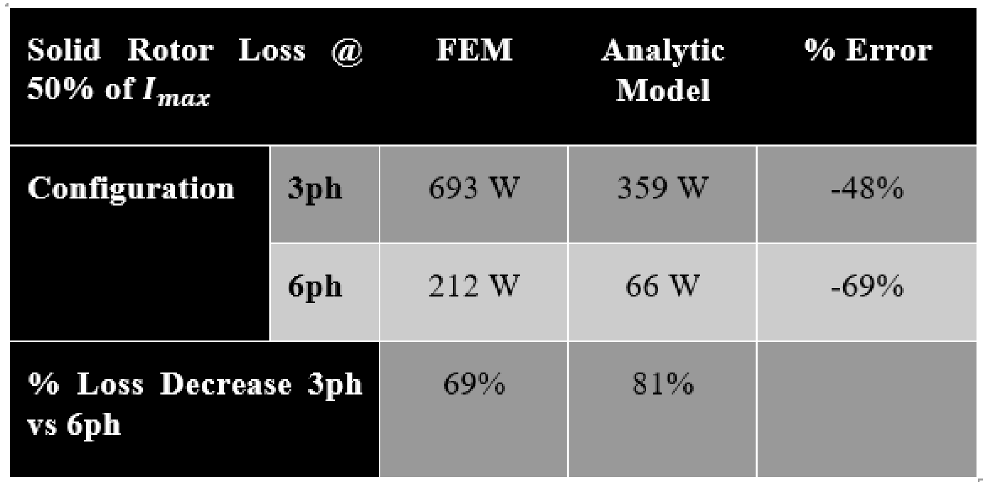
3ph Model Outcome



Rotor Losses Comparison

Below is presented the different results from FEM and analytical model. Both models show that 6-ph configuration has an advantage due to milder MMF harmonics. Also, analytical model tends to underestimate rotor losses with respect to FEM model, however, shows a similar reduction trend.

FEM Solid Rotor Loss – [W]		I_{rms} (% of I_{max})				
		10%	30%	50%	80%	100%
Configuration	**3ph**	92 W	299 W	693 W	1239	1582
	6ph	77 W	112 W	212 W	441	783
% Loss Decrease 3ph vs 6ph		16%	63%	69%	64%	51%

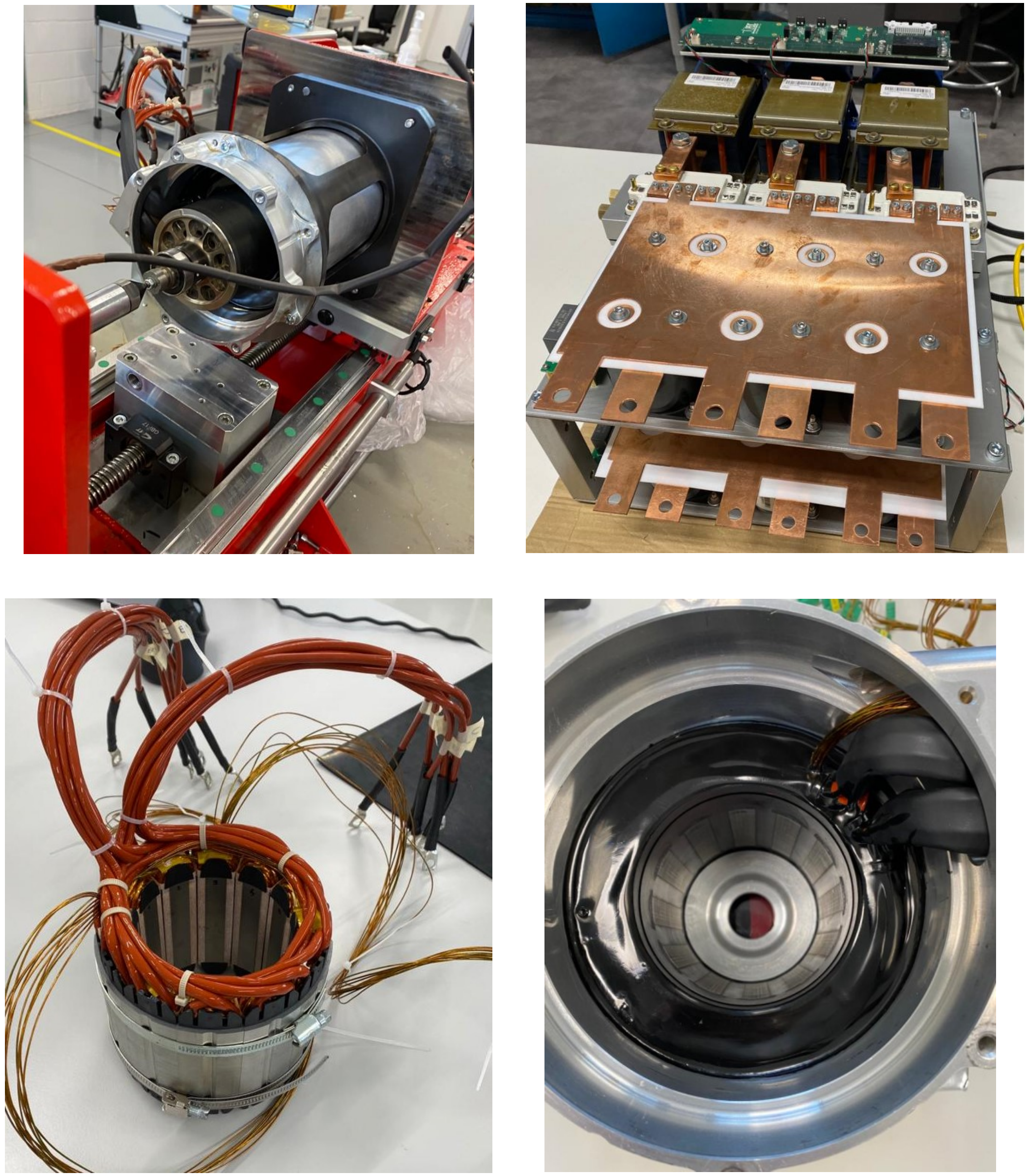


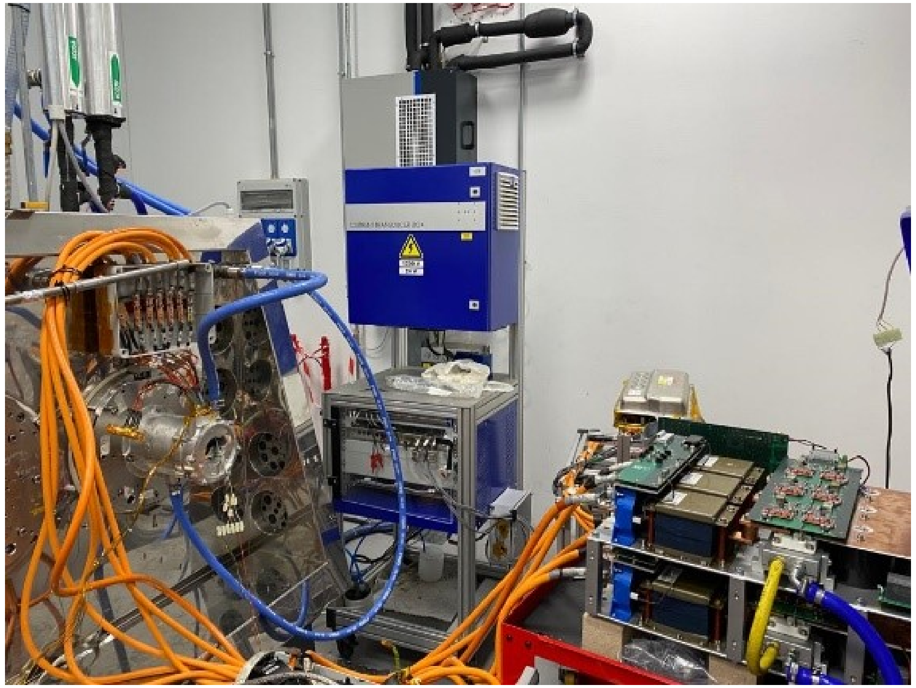
Solid Rotor Loss @ 50% of I_{max}		**FEM**	**Analytic Model**	**% Error**
Configuration	**3ph**	693 W	359 W	-48%
	6ph	212 W	66 W	-69%
% Loss Decrease 3ph vs 6ph		69%	81%	

Construction and Testing

The 6ph motor was constructed, together with a 6ph inverter to validate the hypothesis.

Due to components shortage the assembly of the inverter went very long and testing occurred during all 2023.

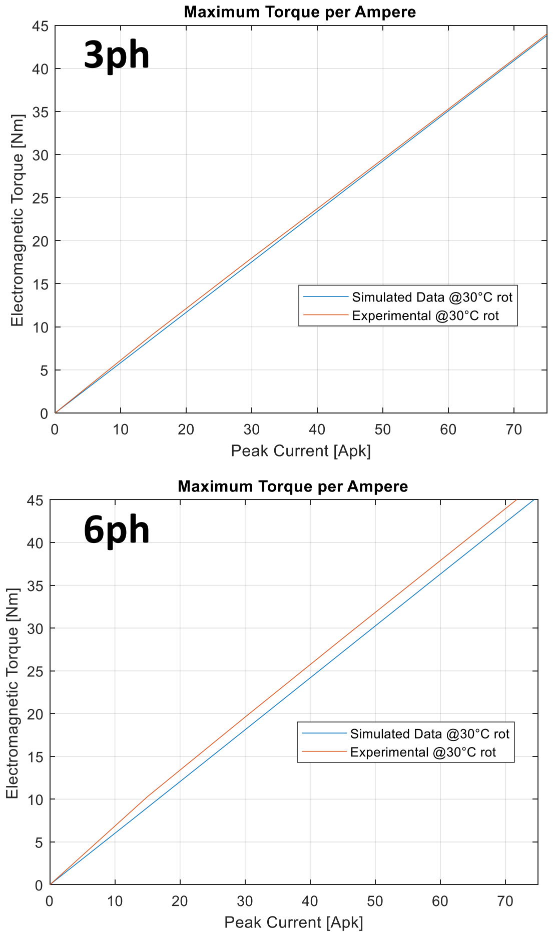




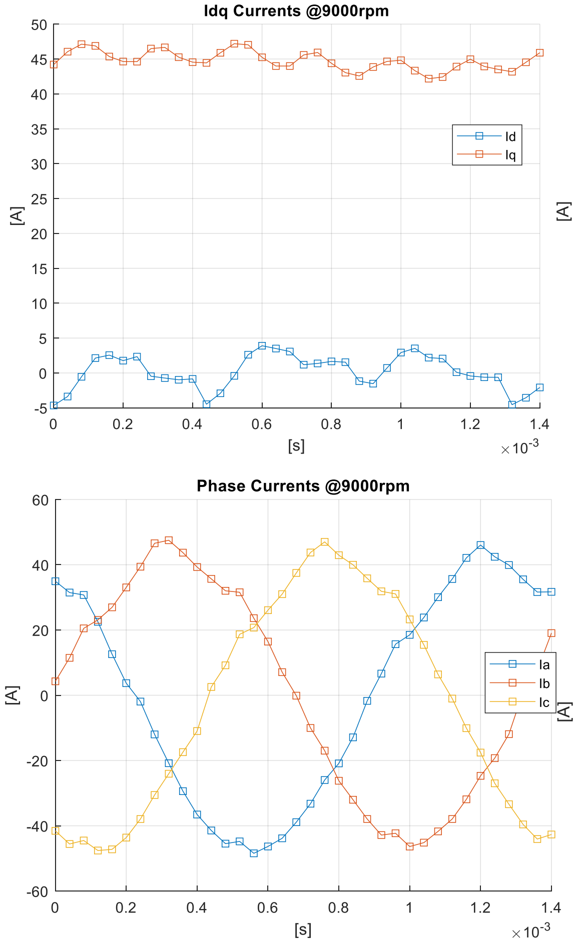
Performance Testing

Good correlation was seen for 3ph and 6ph peak performance at lower speeds.

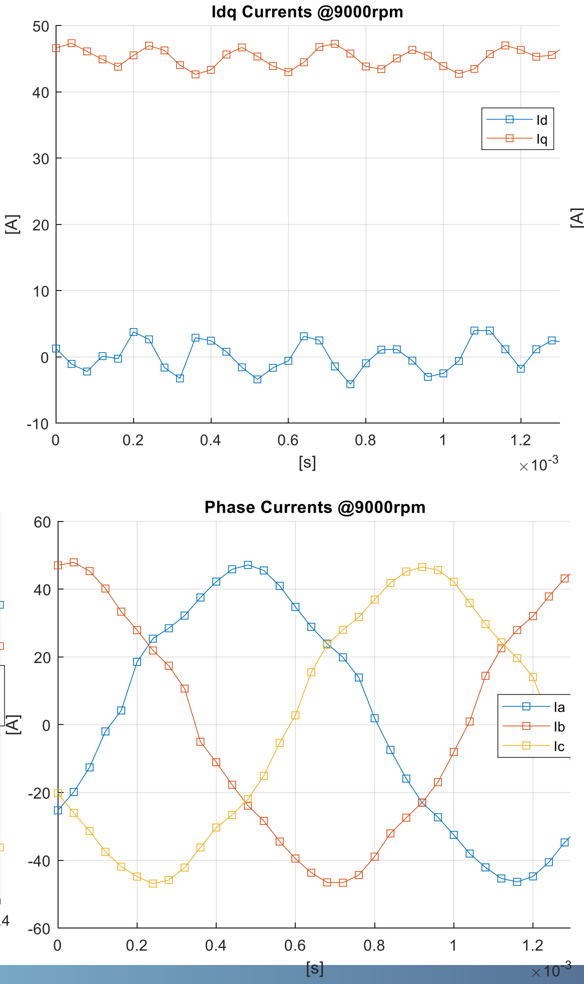
At higher speeds (9krpm), a 5th current harmonic (@3.5kHz) appeared when commanding the machine, which was detrimental to rotor losses. This harmonic was not controllable for the available control bandwidth (25kHz).



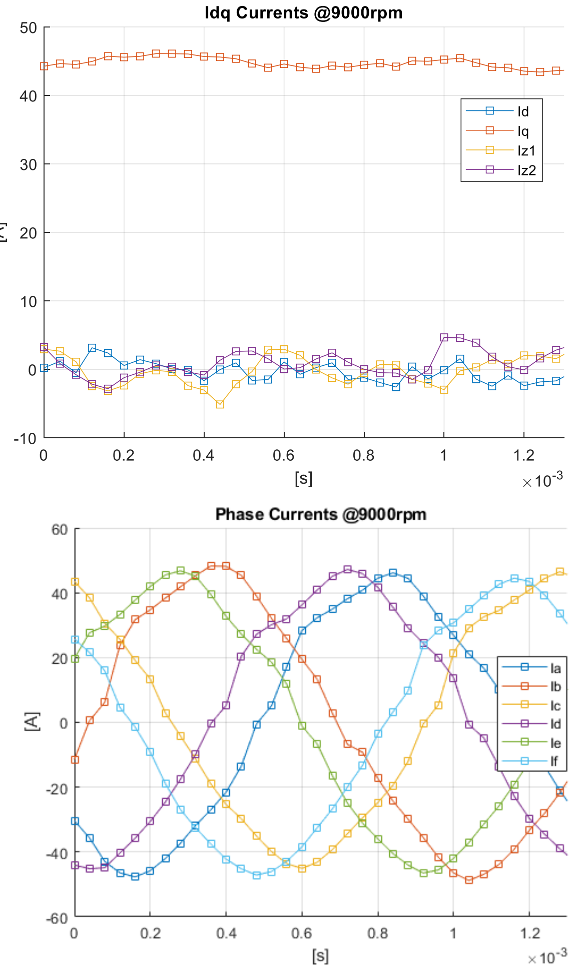
3ph FOC



6ph 1 inverter ("abc" only)



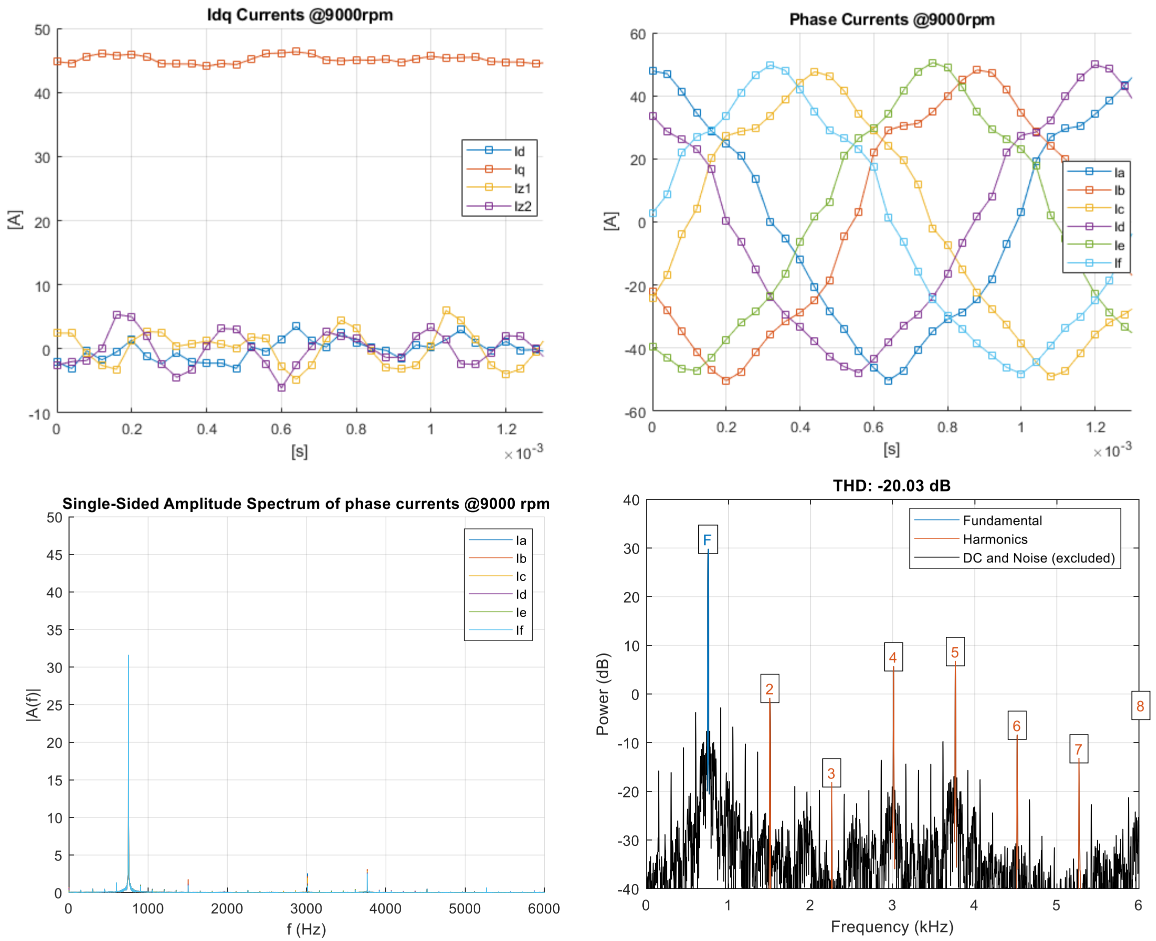
6ph VSD with resonant control



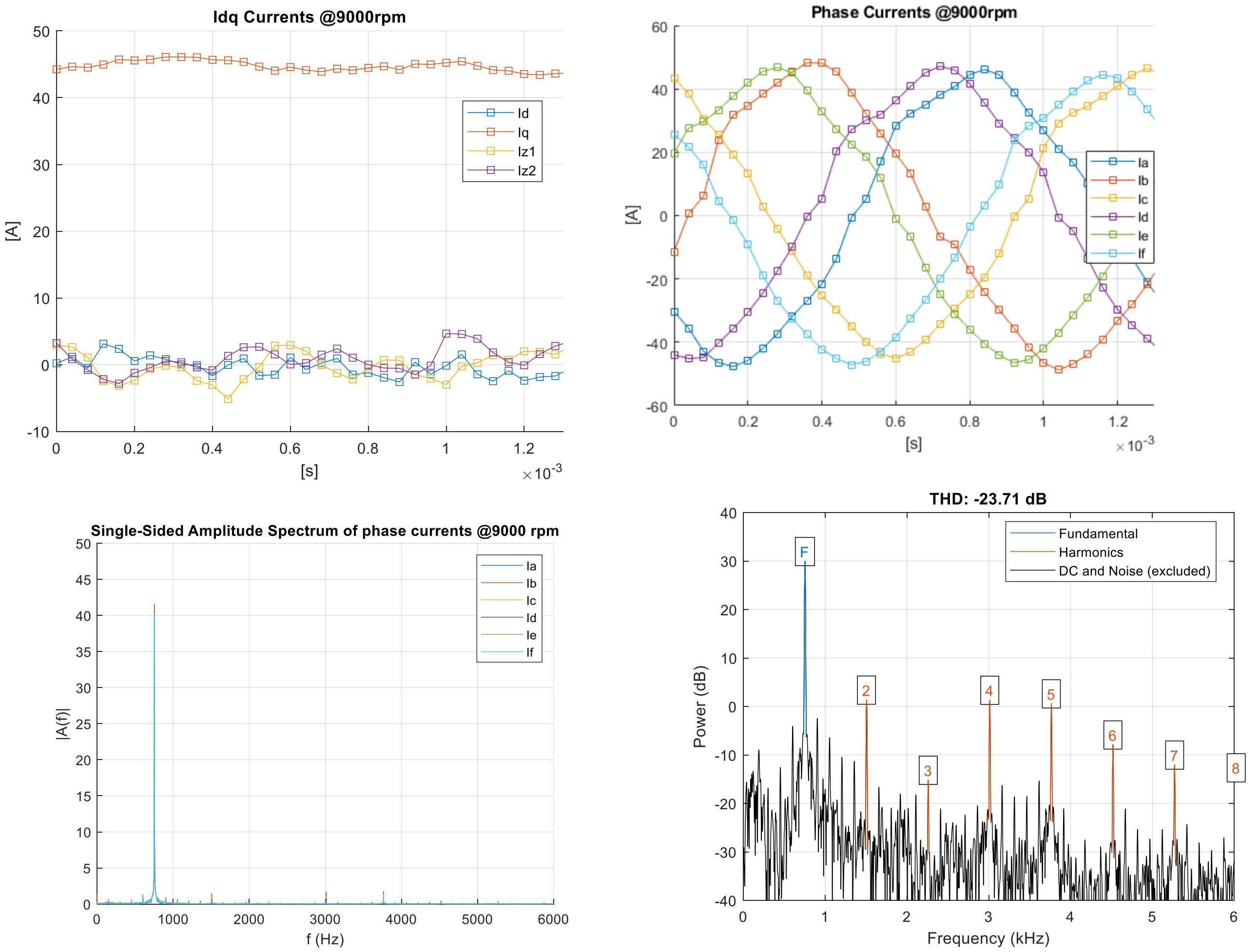
Testing – VSD Resonant Control

Resonant control at the z1z2 axis was implemented, having an important reduction in THD but still high level of harmonics are present.

VSD



VSD with Resonant z1z2



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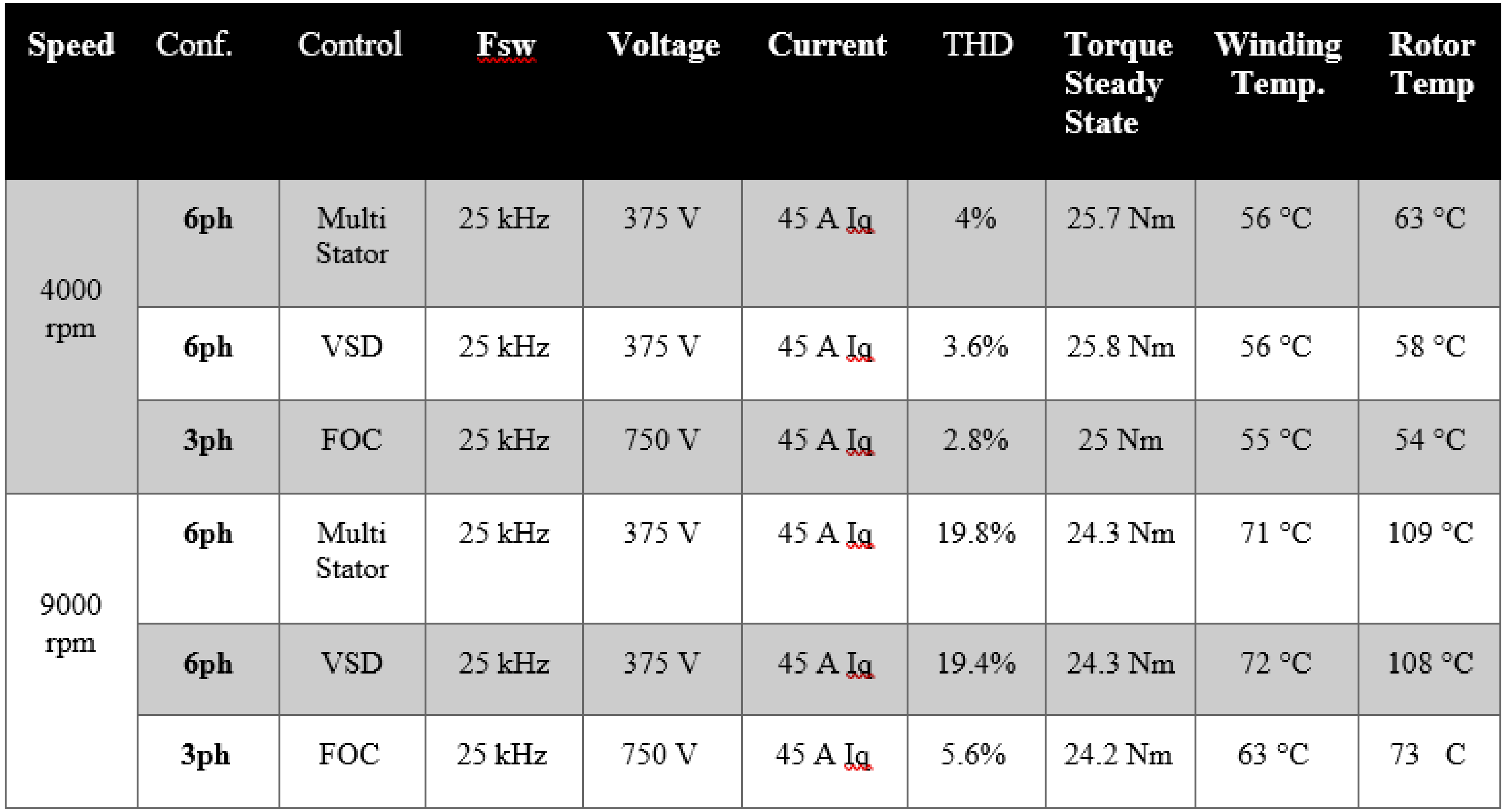
Experimental Control Performance

Below a summary of different control performance with respect to THD. In all control configurations, high harmonic content remained at 9krpm.

Speed	Configuration	Control Type	Distortion Attenuation $\boldsymbol{a_k}$	Distortion Factor THD
1000 rpm	**6ph**	Multi Stator	-33.5 dB	2.1%
4000 rpm	**6ph**	Multi Stator	-27.9 dB	4%
	6ph	VSD	-29.6 dB	3.3%
	6ph – 1 set	FOC	-36.4 dB	1.5%
	3ph	FOC	-32 dB	2.5%
9000 rpm	**6ph**	Multi Stator	-17.5 dB	13.3%
	6ph	VSD	-20 dB	10%
	6ph	VSD – z1z2 PIR	-23.7 dB	6.5%
	6ph – 1 set	FOC	-26.6 dB	4.7%
	3ph	FOC	-25 dB	5.6%

Continuous Performance Testing

The effect of the controllability influenced rotor losses making the 6ph configuration even worst than the 3ph for the rotor temperature, the opposite as expected from simulations (with perfect sine currents).

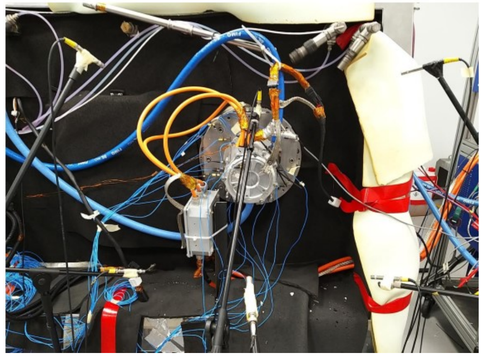


Speed	Conf.	Control	Fsw	Voltage	Current	THD	Torque Steady State	Winding Temp.	Rotor Temp
4000 rpm	**6ph**	Multi Stator	25 kHz	375 V	45 A Iq	4%	25.7 Nm	56 °C	63 °C
	6ph	VSD	25 kHz	375 V	45 A Iq	3.6%	25.8 Nm	56 °C	58 °C
	3ph	FOC	25 kHz	750 V	45 A Iq	2.8%	25 Nm	55 °C	54 °C
9000 rpm	**6ph**	Multi Stator	25 kHz	375 V	45 A Iq	19.8%	24.3 Nm	71 °C	109 °C
	6ph	VSD	25 kHz	375 V	45 A Iq	19.4%	24.3 Nm	72 °C	108 °C
	3ph	FOC	25 kHz	750 V	45 A Iq	5.6%	24.2 Nm	63 °C	73 C

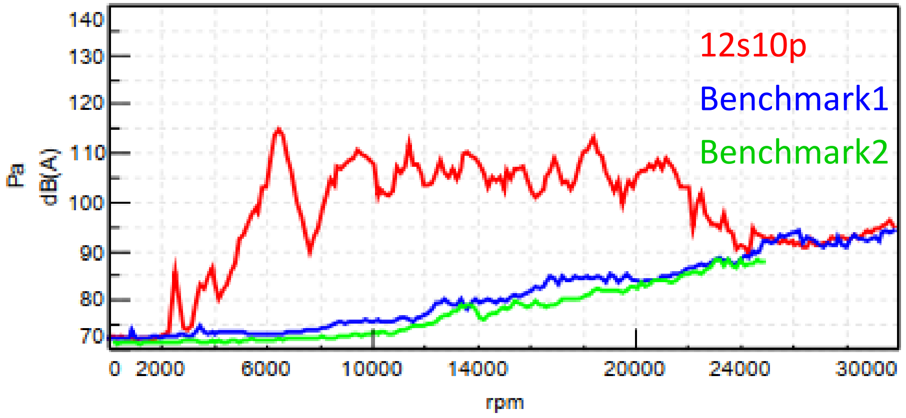
NVH Testing

The 12s10p machine was tested with an array of microphones to determine the Sound Power Level according to ISO 3741. As it can be seen below, SWL achieved 106 dB(A) at no load, which is not compatible with a commercial application.

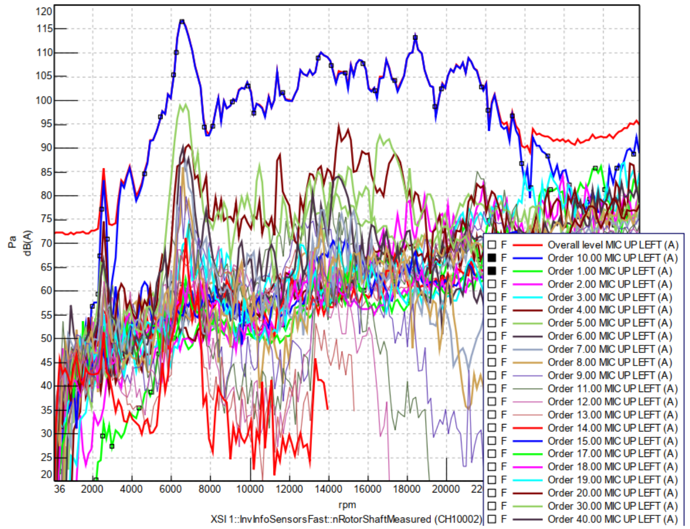
Testing Setup



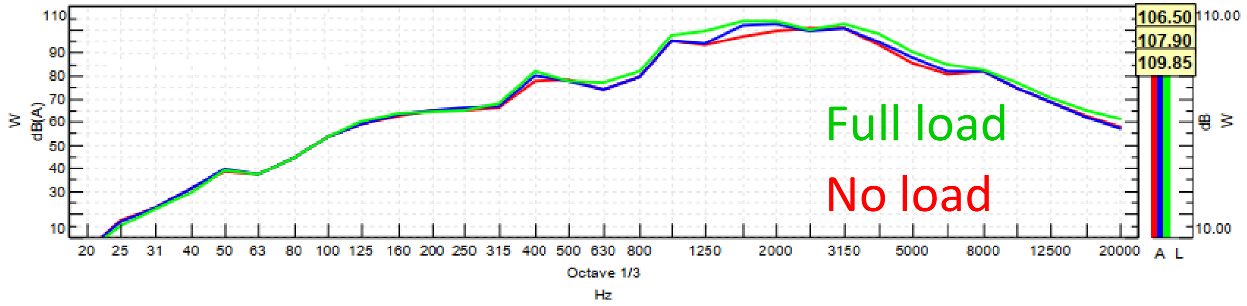
Nearfield Microphone Measurement



Order Analysis



Sound Power Level (SWL)



Content N° 2: 20 slot 10 pole two phase machine

A two phase winding is proposed for high power density automotive applications. The following assumptions are taken

1. Same external diameter and same rotor for all the machines.
2. The DC bus voltage is 650Vdc and inverter phase current rating is 370Arms.
3. Wire fill factor of 65% (copper + insulation) (strong assumption for 20s10p).
4. Windings sized for the same Joule loss at peak current.
5. 2ph machine is operated in open winding configuration with 1 additional inverter leg.

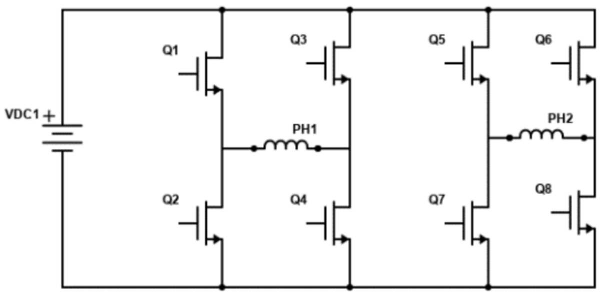
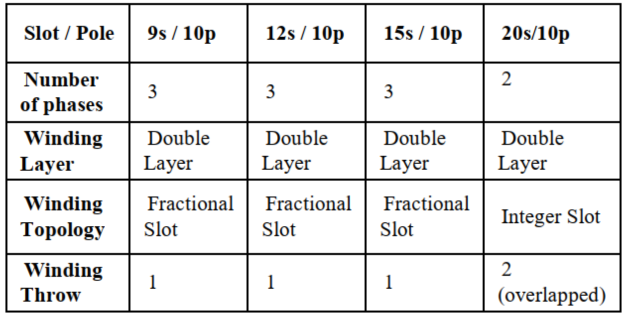


Figure 2. 4-leg inverter for the 20s10p electric machine.

Table I – Motor topologies under comparison



Slot / Pole	9s / 10p	12s / 10p	15s / 10p	20s/10p
Number of phases	3	3	3	2
Winding Layer	Double Layer	Double Layer	Double Layer	Double Layer
Winding Topology	Fractional Slot	Fractional Slot	Fractional Slot	Integer Slot
Winding Throw	1	1	1	2 (overlapped)

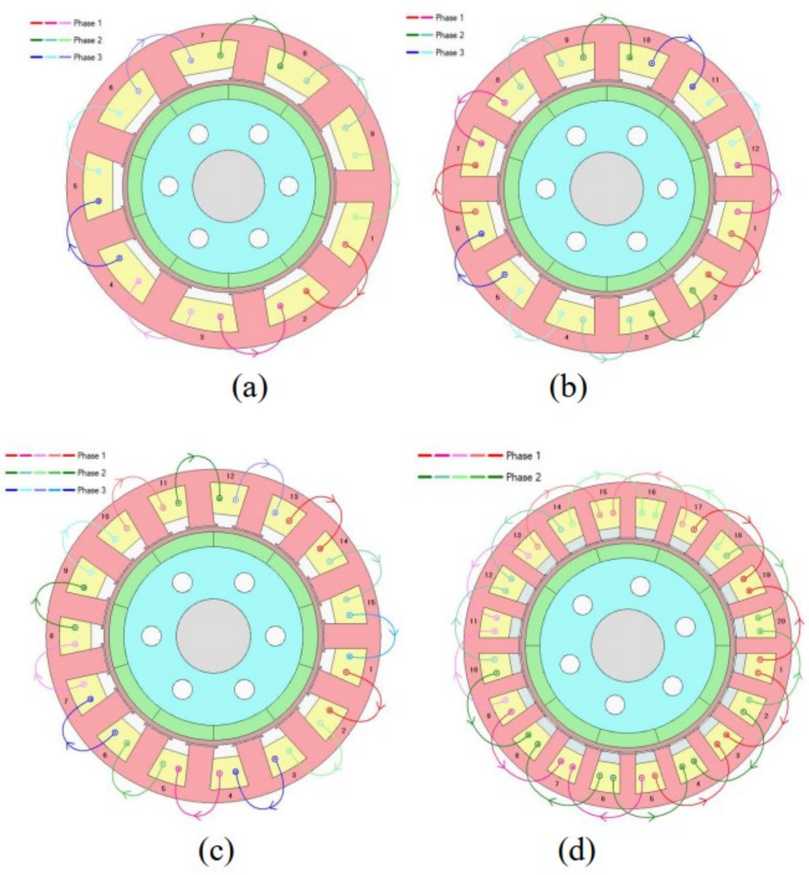


Figure 1. Cross section of the motors under comparison. (a): 9slot – 10 pole. (b) 12 slot – 10 pole. (c) 15 slot – 10 pole. (d) 20 slot – 10 pole.

2-ph Peak Performance

Peak power performance is increased by 28% with respect to the 12s10p, and 6% of peak torque because of higher winding factor. On the other side torque ripple is increased 12X.

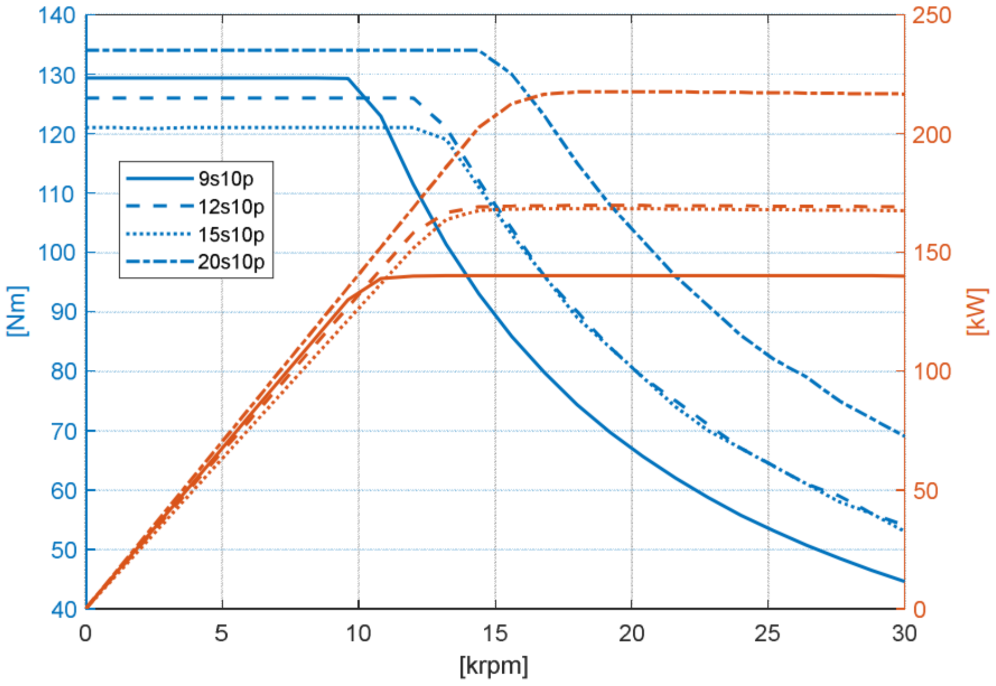
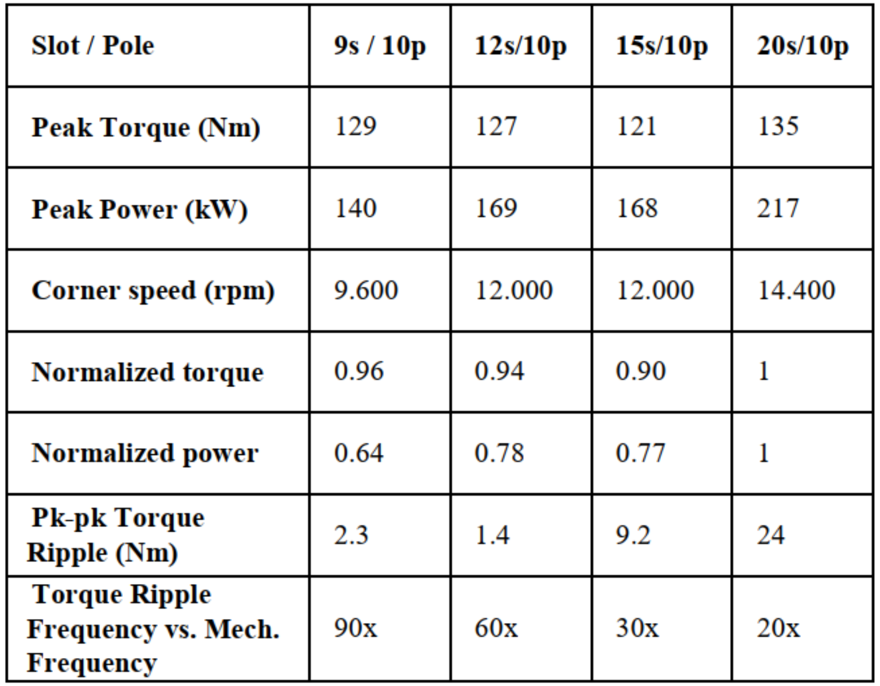


Figure 4. Peak performance results at 650Vdc for all configurations.

Table III – Peak performance summary



Slot / Pole	9s / 10p	12s/10p	15s/10p	20s/10p
Peak Torque (Nm)	129	127	121	135
Peak Power (kW)	140	169	168	217
Corner speed (rpm)	9.600	12.000	12.000	14.400
Normalized torque	0.96	0.94	0.90	1
Normalized power	0.64	0.78	0.77	1
Pk-pk Torque Ripple (Nm)	2.3	1.4	9.2	24
Torque Ripple Frequency vs. Mech. Frequency	90x	60x	30x	20x

NVH Performance

An analytical NVH model was developed to estimate noise emission from the 2ph machine. This model shows that for the 12s10p up to 106dB are expected from the 2nd mechanical order, while the 20s10p only delivers 58dB of noise as the lowest radial force order is much higher.

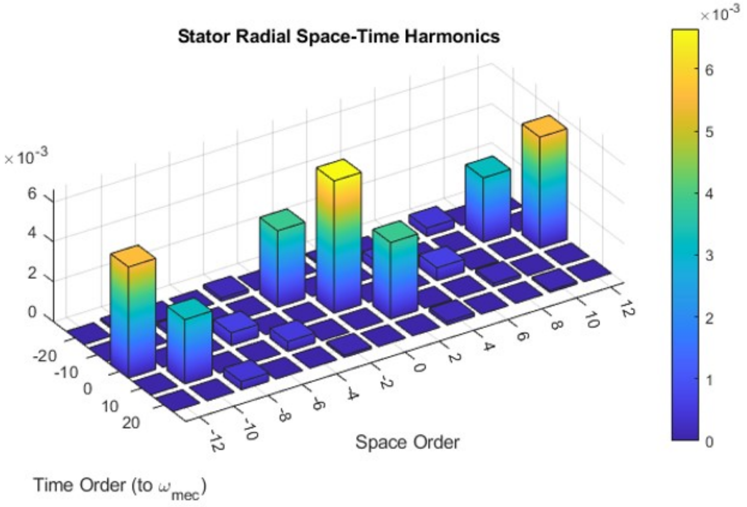


Figure 10. Space and time order (time with respect to mechanical frequency) radial force harmonics

Table IV – Lowest radial force order for studied machines

Slot / Pole Combination	9s / 10p	12s / 10p	15s / 10p	20s/10p
Lowest spatial radial force order	1	2	5	10

Table V – Sound Power Level

Slot / Pole	9s / 10p	12s / 10p	15s / 10p	20s/10p
Open Circuit RMS sound power. 8000 rpm	63 dB	100 dB	45 dB	< 20 dB
On Load RMS sound power level at 8000 rpm	89 dB	106 dB	58 dB	58 dB

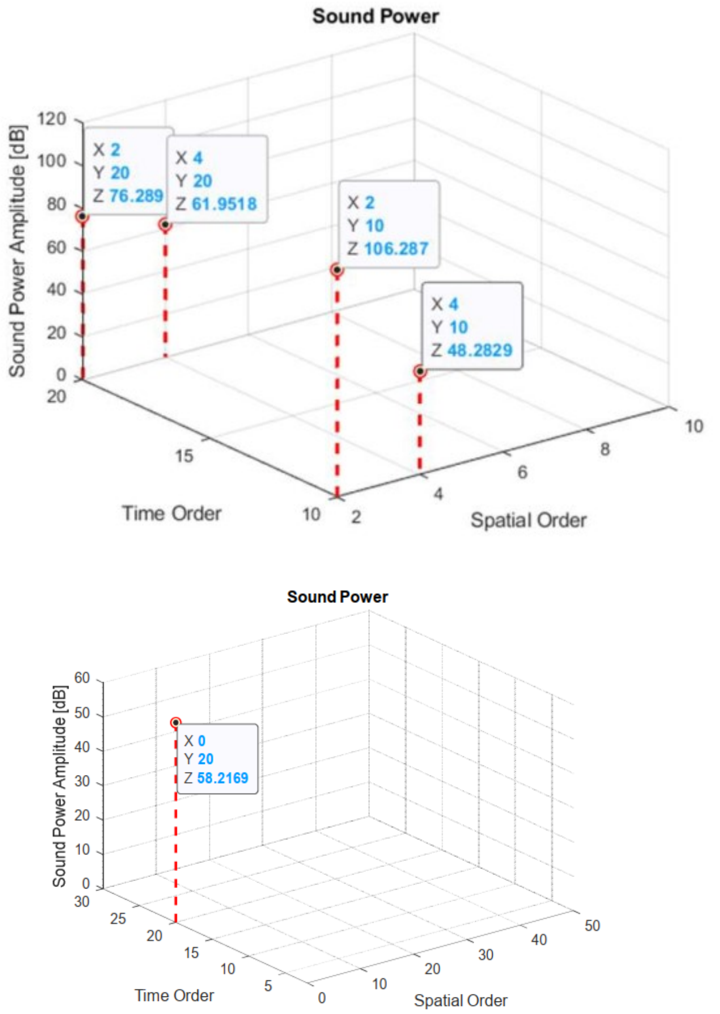


Figure 12. Simulation output for 20s10p configuration. Up: Radial Pressure Input. Down: Sound Power Amplitude. (X axis: Spatial Order. Y axis: Time Order w.r.t mech. frequency. Z axis: Sound Power Amplitude)

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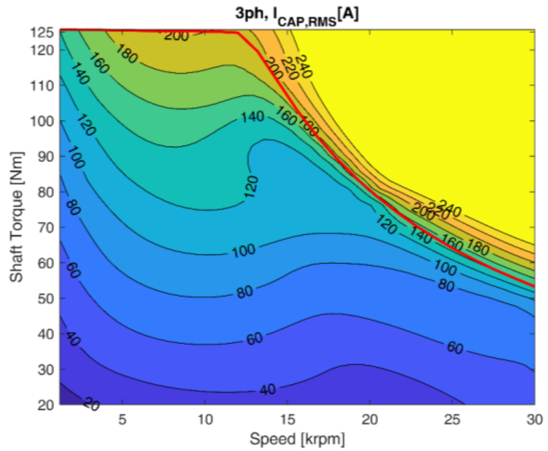
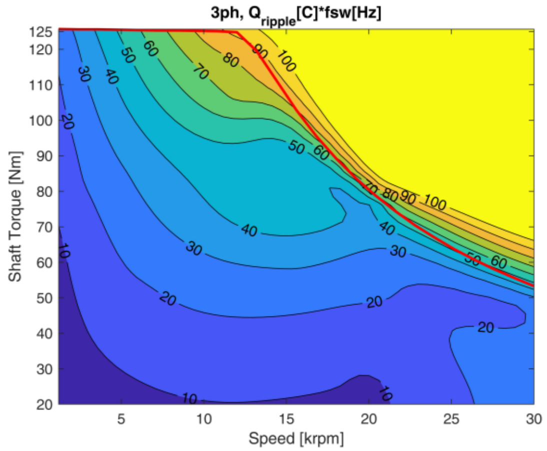
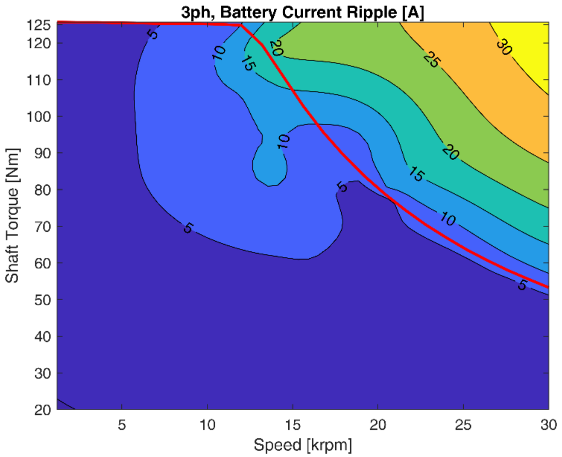
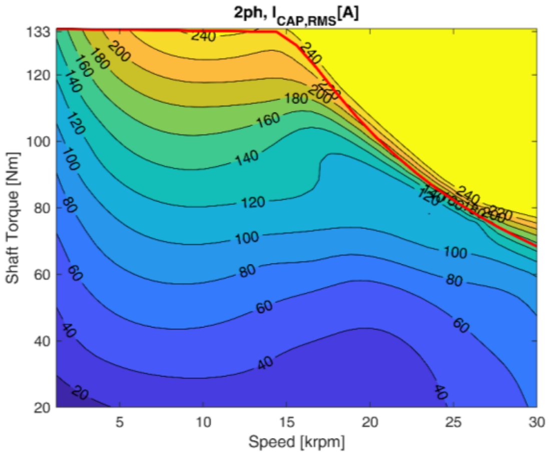
DC-link stress comparison

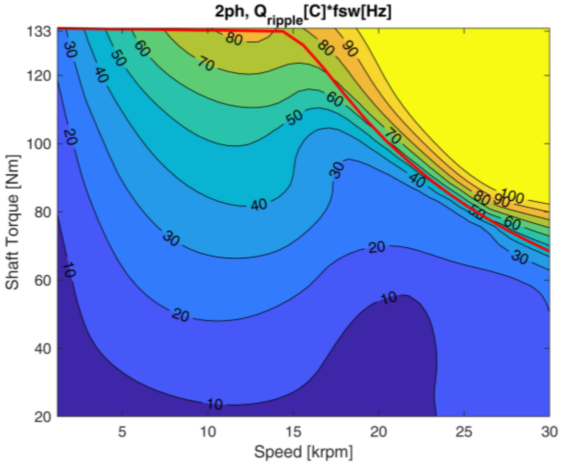
A numerical analysis was conducted to compare DC link capacitor RMS current and voltage ripple for 3ph 12s10p and 2ph 20s10p. Below is possible to see that RMS current and ripple charge does not change significatively between 3ph and 2ph machines. However, battery current ripple is much higher mainly due to the high torque ripple of the machine, which can be detrimental for battery aging.

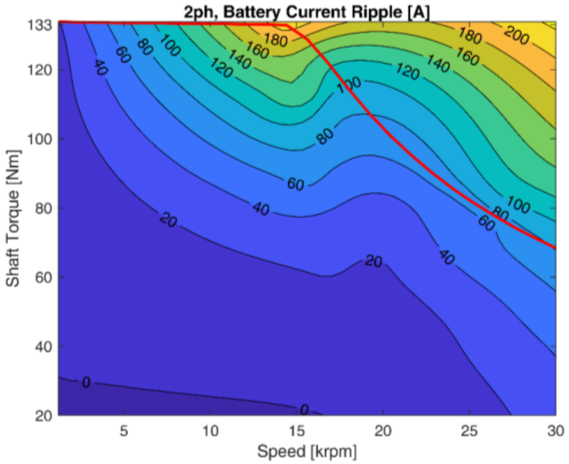

3ph, $I_{CAP,RMS}$[A]


3ph, Q_{ripple}[C]*fsw[Hz]


3ph, Battery Current Ripple [A]


2ph, $I_{CAP,RMS}$[A]


2ph, Q_{ripple}[C]*fsw[Hz]


2ph, Battery Current Ripple [A]

Conclusions I: 6ph vs 3ph 12s10p

In this part of the study, we can extract the following conclusions:

- The 6ph asymmetrical 12/10 machine presents >3% of peak performance due to a higher winding factor and back-emf. This assumption was verified experimentally for 3ph and 6ph windings.
- In principle, 6ph asymmetrical 12/10 machine has a better continuous performance due to a milder MMF harmonics spectrum. This was verified from an analytical model and through FEM simulations. This finding could not be successfully tested so far due to the incapability of controlling to zero current harmonics which are detrimental to rotor losses.
- The 6-ph asymmetrical 12s10p machine requires a higher control bandwidth with either DMS and VSD control approaches, in order to control 6th harmonics on *d-q* axis (which translates in a 5th harmonic at phase current level). For the tested setup, limited to 25 kHz, the 5th current harmonic generated high rotor losses which risk to demagnetize the machine already at 9krpm. Introducing a resonant control in z1z2 space of VSD helps reducing the 5th current harmonic, but still remains higher than a 3-ph configuration of the same machine.
- 12s10p machine suffers from high noise emissions for the selected geometry, as the 2nd spatial mode is excited with the 10th time order. This high noise emission reaches >100dB values already at no-load, which means that they are independent on the winding configuration. From simplified analytical model, is possible to see that 6-ph configuration on-load has not any relevant influence as well.

Conclusions II: 2ph 20s10p

Due to high NVH harmonics in the 12/10 machine, a 2ph 20s/10p winding is proposed with the following main benefits.

- The inverter has 4 legs instead of 3, with open end motor windings. Each phase is allowed full V_{dc} peak voltage instead of $\frac{V_{dc}}{\sqrt{3}}$. This translated into a 15% increase in peak power for the same dc voltage and maximum phase current. In turn, the inverter cost and complexity increases.
- Due to the high order of the lowest spatial mode (10 for the 20s/10p instead of 2 for the 12s/10p), reduced noise emissions are expected from this machine.
- The winding factor is improved to unity, as the machine is an integer slot instead of fractional. This is a +7% improvement with respect to 0.933 of the 12s/10p.
- Higher torque ripple is expected with respect to the 12s/10p case.
- No impact on DC Link capacitor (sized for high frequency PWM current), however high content of AC current drawn from battery.

Future work shall be devoted to review the electromagnetic design of the two-phase machine to reduce harmonic contents of voltage and torque ripple, and thus the AC current from the battery, but maintaining its clear advantages in high power density and low noise emissions

Thank you!

QUESTIONS?

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