

#### ICEM2022 VALENCIA

#### XXV International Conference on Electrical Machines

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# Design, Identification and Simulation of PM Synchronous Machines for Traction

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#### About the speakers



**Gianmario Pellegrino** (F' 22, SM '13, M'06) is Professor of Power Converters, Electrical Machines and Drives at Politecnico di Torino. Dr. Pellegrino is constantly engaged in research projects with the industry, and the co-founder of the open-source project SyR-e. He was a visiting fellow at Aalborg University, the University of Nottingham, and the University of Wisconsin-Madison. He has 60 IEEE journal papers, five patents and nine Best Paper Awards. He is an IEEE Fellow and the recipient of the 8<sup>th</sup> Grand Nagamori Award in 2022.



**Simone Ferrari** (S'17-M'20) received the Ph.D. degree "cum laude" in 2020 from Politecnico di Torino, where he is currently a Research Fellow. He was a Visiting Scholar at the NC State University in Raleigh, NC, USA. He leads the team of developers of the open-source project SyR-e. Since 2021 he is also the responsible of the testing infrastructure TEST-eDRIVE of the Energy Department and the Power Electronics Innovation Center of Politecnico di Torino.





Gratitude goes to the **SyR-e team** of the PEIC at PoliTO, as per the papers cited throughout the presentation

Mr. Gaetano Dilevrano and Mr. Paolo Ragazzo, PhD students, helped preparing the material presented today, besides their direct contributions to SyR-e



G. Dilevrano, PhD candidate



P. Ragazzo, PhD candidate





### Today's Content

#### Introduction (20 min)

- Politecnico di Torino and the Power Electronics Innovation Center (PEIC)
- Permanent magnet machines used in traction

#### Overview of SyR-e (40 min)

- SyR-e geography
- Main tools for design and modelling
- Magnetics
- Thermal
- Structural
- PWM waveforms and loss

#### Design of the IPM machine (60 min)

- Case study: Tesla Model 3 rear axle IPM machine
- FEAfix-corrected (x,b) design plane
- Design procedure
- Number of turns determination
- Stack length minimization
- Structural and Thermal aspects
- syreDrive: Control simulation

#### Conclusion





## Politecnico di Torino

Technical School for Engineers founded in 1959, Politecnico di Torino since 1906

Home to Galileo Ferraris, pioneer of electrical engineering

35000 BSc and MSc, 800 PhD students

1000 Faculty members900 Administrative and Technical staff

Budget (2020): 263 M€ (62% State, 12% student fees, 26% projects)

Tuition fee: 0 - 2600€, depending on family income and merit





#### Research Revenues of PoliTO in FY 2020



## Departments of PoliTO

**INDUSTRIAL** ENGINEERING



#### DENERG Energy

DIMEAS

Mechanical and Aerospace Engineering

#### DISAT

Politecnico Torino

Applied Science and Technology

DAUIN **Control and Computer** Engineering

INFORMATION

**TECHNOLOGIES** 

DET Electronics and DIGEP Management and Production Engineering

AND MANAGEMENT AND

MATHEMATICS FOR ENG.

**Mathematical Sciences** 



**ENG., ARCHITECTURE AND** 

DAD Architecture and Design

DIATI Environment, Land and Infrastructure Engineering

#### DISEG

INDUSTRIAL ENGINEERING CIVIL AND ENVIRONMENTAL

Structural, Geotechnical and Building Engineering

#### DIST

Regional and Urban Studies and Planning



**Telecommunications** 

DISMA



## Interdepartmental Centers of PoliTO



#### CARS@PoliTO

Center for Automotive Research and Sustainable mobility



TECH @PoliTO

CLEAN CWC CleanWater Center@PoliTO





Energy Center Lab

FULL Future Urban Legacy The Future Urban Legacy Lab Lab

> IAM@PoliTO Integrated Additive Manufacturing

> > J-Tech@PoliTO

Advanced Joining Technology



SISCON Safety of Infrastructures and Constructions

Responsible Risk Resilience Centre



**SmartData@PoliTO** Big Data and Data Science Laboratory





PEIC Power Electronics Innovation Center

**PHOTONEXT** PhotoNext

R<sub>3</sub>C

PIC4SeR

PIC4SeR | PoliTO Interdepartmental Centre for Service Robotics



BO PoliTo<sup>BIO</sup>Med Lab **Biomedical Engineering Lab** 

# PEIC: the Power Electronics Innovation Center

The Inter-Departmental Center dedicated to Power Electronics, from the Si-SiC-GaN device to the final application, established in 2017

- 20+ faculty, 2 technicians, 25 PhD students
- Main fields of application: Transportation, Energy, Industry and Home App.
- TRL4 demonstrators, support to higher-TRL prototypes

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• E-motor drive tests up to 20.000 rpm, 500 kW pk





#### http://www.peic.polito.it/



# PEIC: the Power Electronics Innovation Center

#### Since 2017

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- 2 new IEEE Fellows, 2 Nagamori-award awardees
- Several best paper awards
- 10 patent applications

Opportunities of collaboration

- Funded and co-funder PhD grants
- Research contracts
- EU funded projects: Horizon Europe. MSCA, Clean Aviation





#### http://www.peic.polito.it/



### eDrives testing



#### Test -eDrive facility (video)

- Experimental flux maps, cold and hot motor operating conditions (PoliTo benchmark methods)
- Efficiency maps
- HBM Data recorders and torque sensor T12HP
- Automotive test rig: 150 kW, 200Nm, 20,000 rpm, controlled cooling conditions (0-85 °C)









Overview of e-Motors for traction



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### PM and Reluctance torque tradeoff

PMSMs with increasing rate of Reluctance torque

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- $^{\circ}$  peak of rare-earth (RE) metals in 2011  $\rightarrow$  RE-free trend
- Reluctance torque maximization reduces the RE-PM content



[1] A. Krings and C. Monissen, "Review and Trends in Electric Traction Motors for Battery Electric and Hybrid Vehicles," in 2020 International Conference on Electrical Machines (ICEM), 2020

## Hairpin windings

# Reluctance torque maximization needs distributed windings

Hairpin windings are today's standard for distributed winding-interior PM machines

Pressed-wire solutions exist, both for distributed- and concentrated-winding motors, but tend to show a worse tradeoff between loss minimization and heat extraction

Manufacturability of hairpin on large volumes seems to be established





Fill factor 85% (source: Mitsubishi)



Fill factor 40% (source: Brusa)



### Concentrated windings

**Concentrated-winding** motors cannot minimize the RE-PM content via reluctance torque [2]

They remain competitive in axial-flux PMSM solutions and high-end radial-flux applications

# We focus today on the design of radial-flux, distributed-winding IPM machines for traction

[2] M. Gamba, G. Pellegrino and A. Vagati, "A new PM-assisted Synchronous Reluctance machine with a nonconventional fractional slot per pole combination," 2014 OPTIM, Brasov, Romania









### Torque and power density targets

# Torque and power density targets are steadily increasing

#### Torque density requires

- strong magnets
- high current density, thus advanced cooling

# Power density increase is pursued via higher speed

[3] Electric Machines Roadmap 2020 – Advanced Propulsion Center UK www.apcuk.co.uk/app/uploads/2021/09/https\_\_\_www.apcuk\_.co\_.uk\_app\_uploads\_2021\_02\_Ex ec-summary-Technology-Roadmap-Electric-Machines-final.pdf

	2020	2025	2035
Cost (\$/kW)	6	4.8	3.3
Volumetric Power Density (kW/l)	8	25	30
Gravimetric Power Density (kW/kg)	4	8	10
WLTP Average Efficiency	93%	95%	97%

## Higher speed trend

Speed increase is the most direct measure for increasing peak power density

Operating speeds are currently in the 20.000 rpm range, **30.000 rpm is the new target** 

The carbon-sleeved rotor of the Tesla Model S Plaid can sustain the maximum speed of 23.300 rpm (source <u>insideevs</u>)

Increasing importance of structural optimization

[1] A. Krings and C. Monissen, "Review and Trends in Electric Traction Motors for Battery Electric and Hybrid Vehicles," in 2020 International Conference on Electrical Machines (ICEM), 2020

Max Speed (rpm) — Max Surface Velocity (m/s) 20.000 160(m/s) 18.000 140 16.000 Maximum Surface Velocity 120 14.000 12.000 10.000 80 8.000 60 6.000 40 4.000 20 2.000 0

Carbon-sleeved rotor of Tesla Model S Plaid e-motors

Maximum Speed (rpm)



### Advanced cooling

[4] K. Bennion, G. Moreno, "Convective Heat Transfer Coefficients of Automatic Transmission Fluid Jets with implications for Electric Machine Thermal Management", International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems, San Francisco, 2015

Oil cooling tends to replace water cooling

The standard water-glycol cooling jacket, with potted windings is being replaced by advanced solutions such as:

- End-winding oil spray cooling
- Direct stator cooling
- Rotor cooling

Yet, today we refer to standard backiron, as per a water-glycol cooling jacket The focus today is magnetic design



Oil spray cooling principle [4]



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#### https://github.com/SyR-e



SyR-e Geography

#### GUI\_Syre Motor design and simulation





🕼 GU	I_Syre_MMM							
Main	Scaling & Skewing	Torque-Speed	syreDrive	Waveform	Thermal			
Mode	Is Loaded					Sy Magnetic Mad	R-e	latio
$\checkmark$	dq Flux Map	Load	Plot	Save	Print		erivianipu	auc
	dqt Flux Məp	Load	Plot	Save		Load	ave FileC	heck
	dq Iron Loss Map	Load	Plot	Save		New Sa	ve As Clos	e all
	AC Loss Model	Load	Plot	Save				
						Motor Ratings		
Contr	ol Trajectories					Motor name	TeslaModel3_c	ustom
	Control Trajectories	Load	Plot	Save	Print	Pathname	D:\syre working	g copy
	Method:				Evaluate	Motor type	PM	
						Rated power [W]	523370.0995	
Induc	tance and Anisotropy Maj	ps				Rated speed [rpm]	10835.6046	N
	dq Inductance Map	Eval	Plot	Save		Rated current [Apk]	1403.75	
						DC link voltage [V]	231	Ph
Curre	nt Angle Curves			Steady-S	State Short Circuit	PM temperature	80 🔻	
	Current levels	1	Plot		Evaluate	Stack length [mm]	134	End
Invers	se Model					Turns in series per phase	12	N
	Inverse dg Flux Mep	Eval	Plot	Save		inertia [kg m^2]	0.041435	



GUI\_Syre\_MMM



#### Phase currents with PWM ripple



Ô.

syre

461.2402

18100

1414.2136 0.0054794

120

126.7903

Axis type SR

End winding length [mm]

hname D:/svre working copy/motorExamples



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# GUI\_SyRe: initial GUI for design and FEA simulation

Main Data	Geometry	Options	Windings	Materials	Optimization	Simulation	Motor-CAD	Utilities		
Main Motor	Parameters				Preliminary Desig	IN			Load Machine	
١	lumber of pole	pairs	3						Save machine	
Number of	of slots/(pole*ph	ase)	3		syrr	nDesign(x,b)		FEAfix		
Ai	rgap thickness [	mm]	0.7						Close all Clear \tmp	
Stat	or outer radius [	mm]	112.5	Scale	Ra	nge of x (rotor/s	ator split)	[0.5 0.7]	Current mot file is:	
	Airgap radius [	mm]	74.95		Ra	nge of b (airgap	/iron split)	[0.4 0.6]	TeslaModel3_custom.mat	ver. 3.4
	Shaft radius [	mm]	34.75			Iron Lo	bading [T]	1.5		
	Stack length [	mm]	134		Th	ermal Loading k	j [W/m^2]	196000		
	Type of	rotor Seg	▼		Cu	rrent Density [A	ms/mm2]	39.31		$\frown$
						Tooth size fa	ctor [p.u.]	1		$\land$
						Stator yoke fa	ctor [p.u.]	1		$\sim$
						Rotor yoke fa	ctor [p.u.]	1		
						PM filling fa	ctor [p.u.]	1		$\sim$
Custom Co.	motri					# of FEAfix si	mulations 1	▼		
	Jineuy				Constant flux b	arrier permeanc	e			
		Import from			Constant flux c	arrier thickness		▼		
		Clea	ar		Compute satura	ation factor		▼		
					Constant therm	al loading kj		▼		
					Current angle in	mposed		▼		

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## syrmDesign and FEAfix

Main Data	Geometry	Options	Windings	Materials	Optimization	Simulation N	Motor-CAD	Utilities			Air
Main Motor	Parameters				Preliminary Desig	n			Load	Machine	
١	Number of pole p	airs	3		sym	nDesign(x,b)		FEAfix	Save		
Number o	of slots/(pole*pha	se)	3						Close all	Clear \tmp	p
Stat	or outer radius [r	nm]	112.5	Scale	Rai	nge of x (rotor/stato	r split)	[0.5 0.7]	Curren	t mot file is:	
	Airgap radius [r	nm]	74.95		Ra	nge of b (airgap/iror	n split)	[0.4 0.6]	TeslaMode	l3_custom.mat	ver. 3.4
	Shaft radius [r	nm]	34.75			Iron Loadi	ing [T]	1.5			
	Stack length [r	nm]	134		Th	ermal Loading kj [W	//m^2]	196000			
	Type of r	otor Seg	•		Cu	rrent Density [Arms/	/mm2]	39.31			$\sim$
						Tooth size factor	r [p.u.]	1		RID	
						Rotor yoke factor	r [p.u.]	1			$\langle \lambda \rangle$
						PM filling factor	r [p.u.]	1		HY	D/
						# of FEAfix simula	ations 1	▼			
Custom Ge	ometry	Import fro	m EEMM		Constant flux ba	arrier permeance		▼	$\boldsymbol{\lambda}$		
		Cle	ar		Constant flux carrier thickness				 /		
		UIE.			Compute satura	ation factor		▼	/ \		VE
					Constant therm	al loading kj		▼			
					Current angle ir	nposed		•			
	DLIC										

### FEAfix Motor Design

[5] S. Ferrari and G. Pellegrino, "FEAfix: FEA Refinement of Design Equations for Synchronous Reluctance Machines," in *IEEE Transactions on Industry Applications*, vol. 56, no. 1, pp. 256-266, Jan.-Feb. 2020.
[6] P. Ragazzo, G. Dilevrano, S. Ferrari and G. Pellegrino, «Design of IPM Synchronous Machines Using Fast-FEA Corrected Design Equations," presented at *2022 XXV International Conference on Electrical Machines (ICEM)*, Valencia, Spain, 2022

Parametric design plane

Torque and PF curves function of the crosssectional geometry are pre-calculated via equations

The **16 FEAfix simulated designs** calibrate the results of the equations and make the contour curves **exact in the entire design space** 

The FEAfix plane is the design tool presented at ICEM'22





## Optimization tab

	I GUI_Syre			- 🗆 X
	Main Data         Geometry         Options         Windings         Materials         Optimization	Simulation Motor-CAD Utilities		A.S.
MODE	Optimization Parameters Time stepping during MODE	Time stepping for Paretofront reevaluation	Load Machine	
settings	# of generations 60 Rotor angular excursion 30	Rotor angular excursion 60	Save machine	
566661185	Population size 60 # of rotor positions 5	# of rotor positions 20		
	Variables and Bounds		Close all Clear \tmp	SVIC
	Airgap radius [mm]         [52 78]         1st barrier pos. [p.u.]         [0.25 0.5]	Radial ribs [mm] [0 0]	Current mot file is:	
	Tooth width [mm]     [3.8 6.3]     Barriers positions [p.u.]     [0.17 0.5]	Tangential ribs [mm] [0 0]		ver. 3.4
	Tooth lenght [mm]         [15 22.5]         Barrier width [p.u.]         [0.2 1]	Fillet Rad ribs in [mm] [0.4 0.8]		
Input	Stator slot open [p.u.]         [0.2 0.3]         Barrier offset [p.u.]         [-0.75 0.75]	Fillet Rad ribs out [mm]       [0.4 0.8]		
	Tooth tan. depth [mm]         [0.8 1.2]         Barriers shrink [p.u.]         [0 0]	Fillet Tan ribs in [mm]     [0.4 0.8]		$\boldsymbol{\lambda}$
	Airgap thickness [mm]       [0.4 0.8]       Barrier shift [mm]       [0 0]	Fillet Tan ribs out [mm]       [0.4 0.8]		$\lambda$
	Theta FBS [mech °]         [0 15]         PM dimension [p.u.]         [0 1]	PM shape factor [p.u.] [10 89]		$\langle \lambda \rangle$
	Gamma [°]         [40 75]         PM remanence [T]         [0.3 0.38]			$2 \lambda$
	Objectives and Penalization Limits	Optimization inputs		
	Torque [Nm]         -10         Power factor         0	Current overload [p.u.] 2		
Goals	Torque ripple (pp) [Nm]     8     No load flux [Vs]     0	Optimization type Design		
	Copper mass [kg]         0         PM mass [kg]         1.58	Mechanical Stress Control		
		Optimize		
di Torino	P Prover Electronics Innovation Center	Ιζεν 2022 τι ιτοριδι		

## Design Optimization

[7] G. Pellegrino, F. Cupertino and C. Gerada, "Automatic Design of Synchronous Reluctance Motors Focusing on Barrier Shape Optimization," in IEEE Transactions on Industry Applications, vol. 51, no. 2.
[8] F. Cupertino, G. Pellegrino and C. Gerada, "Design of Synchronous Reluctance Motors With Multiobjective Optimization Algorithms," in IEEE Transactions on Industry Applications, vol. 50, no. 6

MODE (Multi-Objective Differential Evolution) is usable in SyR-e to optimize motor cross-section

#### Selectable optimization goals are

- Torque and torque ripple
- PM and copper mass
- Power Factor
- Open-circuit flux linkage

Optimization was used for design from scratch of Synchronous Reluctance motors

Use for design refinement is recommended for IPM machines





# Structural co-design

Mesh for structural FEA, PDE Toolbox

The overspeed (rpm) input field determines the size of the additional internal rib

#### Analytical

 Center post evaluated automatically according to max speed

#### FEA

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 Centrifugal stress analysis included, using the PDE Toolbox of Matlab



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Slot model for AC loss

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[9] S. Ferrari, P. Ragazzo, G. Dilevrano and G. Pellegrino, "Flux-Map Based FEA Evaluation of Synchronous Machine Efficiency Maps," 2021 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), 2021



# Hairpin Windings

The case of bar conductors is covered, relevant for traction motors

Effects of **frequency** (fundamental and PWM spectrum) and **temperature** are accounted for

End-turns contribute to DC resistance



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(source: BMW)

### FEA Simulation tab

	SUI_Syre												_	
	Main Data	Geometry	Options	Windings	Materials	Optimization	Simulation	Motor-CAD	Utilities				a t -	
	Simulation	Setup					Custom C	urrent			Load Machine			é
		Rotor angular	excursion [elt	°]	60		Off	On			Save machine			
		Number	of rotor positio	ns	1			Load Custom Cu	irrent					
		Current pl	nase angle [elt	°]	55			Custom Current f	ile is:	Close	e all Clea	SV/re	ć	
		С	urrent load [p.	u.] Single F	Point			-			Current mot file is:		Oyre	<b></b>
		F	hase current [	[A] Flux Ma	р						TeslaModel3.mat		ver. 3.4	
	-	PI	/I remanence	[T] HWC SI	eristic Current hort-Circuit Cu	rent								
		PM	temperature [°	C] Demagr	netization Curv	e						$\wedge$		
Type of		Number of p	oints in [0, Ima	ax] Demagr	netization Analy	/sis								
simulation	ulation Number of map quadrants			Flux De Current	nsity Analysis Offset					-	D		$\land$	
		R	otor speed [rp	m] Airgap F	orce							$\mathcal{O}_{\mathcal{A}}$	$\wedge$	
		Act	ive 3-phase se	ets Iron Los	s - Single Poir	t						1 \}/ <i> </i>	$\langle \rangle$	
			Axis ty	pe Structur	s - Flux Map al Analysis						/ 11	<b>V</b>		
			Evaluation ty	pe Single P	Point	▼					/	K	6-	$\lambda$
												¥		
Simulator								Start						
Simulator							MAG	NET	ANSYS			$\sim$		$\neg$
							MAG		Alloro					
Politecnice	> \	PFIC												
1859	Power Electronic	s Innovation Center					ICI	EM 2022 TUTOR	IAL					

[10] S. Ferrari, G. Dilevrano, P. Ragazzo and G. Pellegrino, "The dq-theta Flux Map Model of Synchronous Machines," *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*, Vancouver, BC, Canada, 2021

### Flux maps

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The flux maps are calculated with magnetostatic FEMM runs\*

 $\lambda_d = \Lambda_d(i_d, i_q) \qquad \lambda_q = \Lambda_q(i_d, i_q)$ 

Torque and torque ripple maps come as a result from the same FEA simulations

The torque map is also the external product of the flux and current maps

 $T(i_d, i_q) = \frac{3}{2}p(\Lambda_d \odot I_q - \Lambda_q \odot I_d)$ 

 $I_d(i_d, i_q)$  and  $I_q(i_d, i_q)$  are the current maps

\* Red dots are the 15 x 15 grid. Each is 60° rotor excursion on 15 positions Simulation time ~30 min (14-core workstation)



# GUI\_SyRe\_MMM: magnetic model manipulation

	💿 GUI	_Syre_MMM						- 🗆 X		
	Main	Scaling & Skewing	Torque-Speed	syreDrive	Waveform	Thermal				
	Mode	ls Loaded					SyR-e			
		dq Flux Map	Load	Plot	Save	Print	Magnetic Model Manipulation			
		dqt Flux Map	Load	Plot	Save		Load Save FileCheck			
		dq Iron Loss Map	Load	Plot	Save		New Save As Close all			
		AC Loss Model	Load	Plot	Save			Syle		
				Motor Ratings						
	Contr	ol Trajectories				Motor name TeslaModel3				
MTPA - MTPV		Control Trajectories	Load	Plot	Save	Pathname C:\syre\motorExamples\				
		Method:	LUT <b>V</b>			Evaluate	Pathname       C:\syre\motorExamples\         Motor type       PM         Axis type       SR         Rated power [W]       203483.0982         Rated torque [Nm]       NaN	Axis type SR		
						Rated power [W]   203483.0982   Rated torque [Nm]   NaN				
Inductance	Induc	tance and Anisotropy Ma	)S				Rated speed [rpm] 4390.4933 Maximu	Im speed [rpm] 18100		
mans		dq Inductance Map	Eval	Plot	Save		Rated current [Apk] 1414 Ma	x current [Apk] 1360		
maps							DC link voltage [V] 231 Phase read	sistance [Ohm] 0.0049574		
	Curre	nt Angle Curves			Steady-S	tate Short Circuit	PM temperature 80 Vindia	ng temperature 20		
		Current levels	1	Plot		Evaluate	Stack length [mm] 134 End windi	ng length [mm] 126.7903		
	Invers	se Model					Turns in series per phase 12 Number	of 3phase sets 1		
	$\checkmark$	Inverse dq Flux Map	Eval	Plot	Save		Inertia [kg m^2] 0.039653			
		Inverse dqt Flux Map	Eval	Plot	Save					
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### Flux maps manipulation

[11] Pellegrino, G., Jahns, T.M., Bianchi, N., Soong, W. and Cupertino, F., The Rediscovery of Synchronous Reluctance and Ferrite Permanent Magnet Motors Tutorial Course Notes.

Flux maps manipulation is used for deriving the inductance maps, where needed (e.g. for Simulink and PLECS models)

Apparent inductance maps, Vs/A division

$$L_d = \frac{\Lambda_d(i_d, i_q)}{i_d}, L_q = \frac{\Lambda_q(i_d, i_q)}{i_q}$$

**Incremental** inductance maps, differentiation



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## Manipulation for MTPA

Torque and current magnitude contours are defined on the  $i_d$ ,  $i_q$  domain

$$T(i_d, i_q) = \frac{3}{2}p(\Lambda_d \odot I_q - \Lambda_q \odot I_d)$$
$$I(i_d, i_q) = |I_d + j \cdot I_q|$$

The MTPA is evaluated by searching the minimum current magnitude for each torque contour

The MTPV (Max Torque per Volt) is retrieved in similar manner

MTPA curve in the dq current plane







# Torque-speed tab

	💿 GUI_	Syre_MMM							- 🗆	×	
	Main	Scaling & Skewing	Torque-Speed	syreDrive Waveform	Thermal						
	Operat	ting Limits			SyF	R-e			-		
Power curve		Current levels	1	Evaluate	Magnetic Model Manipulation						
					Load Sa	Load Save FileCheck					
	Efficier	псу Мар									
			Min	Max	# of points	New	Close		syre		
		Speed limits [rpm]	0	18100	25						
		Torque limits [Nm]	0	450	30	Motor Ratings					
	Wir	nding temperature [°C]	20	Mech. loss poly	0	Motor name	TeslaModel3				
		Iron loss	Yes •	Iron loss factor	1.5	Pathname	C:\syre\motorE	torExamples\			
	1	PM loss	No <b>v</b>	PM loss factor	1	Motor type	PM	Axis typ	e SR		
Effy man		Skin effect	No V	Method	LUT V	Rated power [W]	203483.0982	Rated torque [Nr	n] NaN		
Enymap		Control strategy	Maximum efficiency	▼]	Evaluate	Rated speed [rpm]	4390.4933	Maximum speed [rpr	n] 18100	2	
			T-n fea	sible points		Rated current [Apk]	1414	Max current [Ap	k] 1360		
	40	00			· · · · · · · · · · · · · · · · · · ·	DC link voltage [V]	231	Phase resistance [Ohr	n] 0.00495	574	
	30	00 -				PM temperature	80 🔻	Winding temperatu	re 20		
	[mN] - 20	20 -				Stack length [mm]	134	End winding length [mr	n] 126.790	03	
						Turns in series per phase	12	Number of 3phase se	ts 1		
	10					Inertia [kg m^2]	0.039653				
		0 2000 400	00 6000 8000	10000 12000 14	000 16000 18000						
<ul> <li>(6)</li> </ul>			r	[rpm]							
Politecnico		11									
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#### Power vs Speed Curve

Torque and Power versus Speed curves at peak current and maximum voltage conditions

#### Speed regions:

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- MTPA at max current (0 rpm − A)
- Flux weakening at max current (A − B)
- Flux weakening under MTPV limit (B  $n_{max}$ )









### FEA Iron Loss Map

The 2-term Steinmetz electric steel loss model is adopted

$$p_{Fe} = k_h f^{\alpha} B^{\beta} + k_e B^2 f^2 \left(\frac{W}{kg}\right)$$

The iron loss map is FEA simulated with FEMM (or Magnet, or Maxwell) at a single speed value  $n_0$ , with breakdown of hysteresis and eddy-current loss terms

$$P_{Fe,n0}(i_d, i_q) = \underbrace{P_{hs} + P_{es}}_{\text{stator}} + \underbrace{P_{hr} + P_{er}}_{\text{rotor}}$$

(\*) Red dots: 9 x 9 grid, 180° of rotor excursion, 90 positions, simulation time ~2 hours (14-core workstation)

olitecnico Torino [9] S. Ferrari, P. Ragazzo, G. Dilevrano and G. Pellegrino, "Flux-Map Based FEA Evaluation of Synchronous Machine Efficiency Maps," 2021 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), 2021, pp. 76-81




### Speed Dependency

[9] S. Ferrari, P. Ragazzo, G. Dilevrano and G. Pellegrino, "Flux-Map Based FEA Evaluation of Synchronous Machine Efficiency Maps," 2021 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), 2021, pp. 76-81

The loss map is scaled speed-wise using the Steinmetz law

$$P_{Fe}(i_d, i_q, n) = (P_{sh} + P_{rh})_{n0} \cdot \left(\frac{n}{n_0}\right)^{\alpha} + (P_{se} + P_{re})_{n0} \cdot \left(\frac{n}{n_0}\right)^2 \stackrel{\simeq}{\underset{\scriptstyle alphi}{\cong}}$$

FEA calculated PM loss is speed-scaled as the eddy-current loss term, in conservative manner

$$P_{PM}(i_d, i_q, n) = P_{PM, n0} \cdot \left(\frac{n}{n_0}\right)^2$$

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2000 5000 $P_{PM} \left[ W \right]$ 1000 0 2000 20000 1000 1000 0 -1000 -1000 -2000 0 -2000  $i_q [A]$  $i_q \ [A]$  $i_d [A]$  $i_d [A]$  $n = 2000 \, rpm$  $n = 2000 \, rpm$  $n = 4000 \, rpm$  $n = 4000 \, rpm$  $n = 8000 \, rpm$  $n = 8000 \, rpm$ 

Iron and PM loss maps function of speed

37

# Efficiency Map

The efficiency map is calculated from the flux and loss maps, accounting for the inverter limits

- A regular (T, n) grid is considered
- For each point, the minimum loss  $(i_d, i_q)$  condition is computed, considered the current and voltage limits

Simulation conditions

- Temperature values (Cu and PM) are imposed
- DC and AC copper losses are included
- Sinusoidal supply (no PWM), for now

[9] S. Ferrari, P. Ragazzo, G. Dilevrano and G. Pellegrino, "Flux-Map Based FEA Evaluation of Synchronous Machine Efficiency Maps," 2021 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), 2021, pp. 76-81





# Structural Validation

### Integrated method: PDE Toolbox

- 2D linear problem
- Approximated periodic boundary condition (pole sides fixed)
- Single-body model with individual material properties for iron and PM
- Benchmark: SolidWorks and Comsol
- SyR-e export to dxf
- 1-pole simulation (periodic boundary)
- Centrifugal force only
- Fine mesh, with finer mesh around the ribs

### **Comparable results**

**Conservative linear simulation** ( $\sigma_{VM} < \sigma_y$ )



SolidWorks Linear Simulation





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### Motor-CAD interface

					Electromagnetic I	Module				Load M	achine	
	Mo	del export			EMag	Sim	Export flu	x maps		Save m	achine	
					Build Thermal Mo	odel			Clos	se all	Clear \tmp	SVIE
						Housing Type	Axial fins (Ser	vo) 🔻		Current m	not file is:	
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	Trar	sient period [	s] 60		Fluid	d flow rate [l/min]	6					
	N	umber of point	ts1				]					$\searrow$
	Initial te	emperature [°C	6] 45		Build T	hermal			-			$\mathbf{\lambda}$
	Ambient te	emperature [°C	50									
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	Ro	tor speed [rpn	n] 4000	)								
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					Calculat	e Sleauy	Na	N				
	The sume Ois	_				<b>T</b>	Outpu	it [A]				
	i nerm Sir	11			Calculate	iransient	Na	N				

### Export to Motor-CAD

[12] P. Ragazzo, S. Ferrari, N. Riviere, M. Popescu, and G. Pellegrino, "Efficient Multiphysics Design Workflow of Synchronous Reluctance Motors," in *2020 International Conference on Electrical Machines (ICEM)*, Gothenburg, Sweden, Aug. 2020



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# Thermal Limit

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This is the continuous curve obtained iterating Motor-CAD under assumptions of 10 liters/min water-glycol, <u>45°C inlet temperature</u>, full potting 1.9 W/°C/m (end-winding and stack)

Temperature limits: copper 180°C, PM 160°C

This shows the co-simulation capability

Transient thermal simulations can be launched directly from SyR-e or in Motor-CAD



# syreDrive tab for control simulation

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lain	Scaling & Skewing	Torque-Speed	syreDrive	Waveform	Thermal							
Model Setup Converter data					SyR-e Magnetic Model Manipulation							
	Model type A	q Model	Inte	ON threasho rnal resistance   Dead tim	id [V]	0		Load Save Save Save Save Save Save Save Save	ave FileC re As Clos	heck e all	Syre	
Sensor	less control						M	lotor Ratings				
O	ff On	Low speed region (HF Voltage Injection)						Motor name TeslaModel3_custom				
		I	Sinusoidal	dal 🔻			Pathname	C:\syre\motorExamples\				
			Demodulation	odulation Current				Motor type	PM	Axis typ	e SR	
								Rated power [W]	523370.0995	Rated torque [Nm	n] 461.	24(
		High speed region						Rated speed [rpm]	10835.6046	Maximum speed [rpm	n] 18 <sup>-</sup>	100
		Position er	ror estimation	r estimation APP		▼		Rated current [Apk]	1403.75	Max current [Apl	(] 1414	.21
								DC link voltage [V]	231	Phase resistance [Ohm	n] 0.005	47
								PM temperature	80 🔻	Winding temperatur	e 12	20
								Stack length [mm]	134	End winding length [mm	n] 126.	790
						DUN		Turns in series per phase	12	Number of 3phase set	s	1
						RUN		Inertia [kg m^2]	0.041435			

# PWM Current Waveforms

[13] S. Ferrari, P. Ragazzo, G. Dilevrano and G. Pellegrino, "Flux and Loss Map Based Evaluation of the Efficiency Map of Synchronous Machines," under review.

PWM loss is calculated in selected points for the sake of time efficiency:

- FEA re-evaluated under PWM current waveforms
- Copper loss corrected via AC loss factor

At 100 Nm, 5.000 rpm:

- +110 W in Cu and Fe
- PM loss explodes





#### Selected point for PWM loss evaluation

# New Public Release

### v3.4 on GitHub, September 2022

New SyR-e release with ICEM'22 updates

- Improved (x,b) design plane (ICEM22 pape
- Improved scaling rules (ECCE22 paper)
- New demo TeslaModel3\_custom
- 3<sup>rd</sup> GUI syrmDesignExplorer
- syreDrive improved

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- Improved structural simulation
- Preliminaries of Induction Motor

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# Today's Content

#### Introduction (20 min)

- Politecnico di Torino and the Power Electronics Innovation Center (PEIC)
- Permanent magnet machines used in traction

#### Overview of SyR-e (40 min)

- SyR-e geography
- Main tools for design and modelling
- Magnetics
- Thermal
- Structural
- PWM waveforms and loss

#### Design of the IPM machine (60 min)

- Case study: Tesla Model 3 rear axle IPM machine
- FEAfix-corrected (x,b) design plane
- Design procedure
- Number of turns determination
- Stack length minimization
- Structural and Thermal aspects
- syreDrive: Control simulation

#### Conclusion





# Demo model of SyR-e

Custom version of Model3 rear axle e-motor

TeslaModel3\_custom.fem, TeslaModel3\_custom.mat

Main reference is [14], the custom cross-section is derived from pictures available on the internet

Assumptions when data incomplete:

- Slot fill factor:  $k_{Cu}$  = 0,38 (net copper/slot area)
- Fe-Si grade: M270-35A
- PM grade: N52UH

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• PM temperature: 80°C (avg.)

# No direct oil cooling, we focus mostly on magnetic design

Thermal validation refers to water jacket



[14] MotorXP, Performance Analysis of the Tesla Model 3 Electric Motor using MotorXP-PM. VEPCO, Jun. 2020, <u>https://motorxp.com/wp-content/uploads/mxp analysis TeslaModel3.pdf</u>

# Case Study Specs

2-V IPM rotor type instead of 1-V

The torque and power factor vs (x,b) design plane refers to **a single operating point** per machine, **at MTPA conditions** 

Target torque and PF, at MTPA:

- $T_{max} \ge$  430 Nm
- $\cos(\varphi_{base}) \ge$  **0.71** (estimated efficiency 95% )

The **PF at MTPA and base speed** replaces the **peak power requirement** in the plane



[6] P. Ragazzo, G. Dilevrano, S. Ferrari and G. Pellegrino, "Design of IPM Synchronous Machines Using Fast-FEA Corrected Design Equations," presented at *ICEM 2022*, Valencia

Case stu	dy specs	
Peak torque	[Nm]	430
Peak power	[kW]	192
Maximum speed	[rpm]	18100
Peak phase current	[Arms]	1000
DC link voltage (min)	[V]	231
Peak current density	[Arms/mm2]	36
Stator outer diameter	[mm]	225
Stack length	[mm]	134
Base speed	[rpm]	4200
Target power factor		0.71
Number of pole pairs		3
Number of slots		54
PM mass	[kg]	1,8
Cu mass	[kg]	4,7



Model3 custom



# Peak Torque and Power specs

The magnetic design refers to the indicated point, where the specified **peak torque and power**  $T_{max}$ ,  $P_{max}$  ideally meet

The base speed value  $n_{base}$  is defined, referring to the ideal case

$$n_{base} = \frac{P_{max}}{T_{max}} \cdot \frac{30}{\pi}$$

It is assumed that

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- $T_{max}$  is at  $\leq I_{max}$  in MTPA conditions
- $T_{max}$  reaches the voltage limit  $V_{dc}$  at  $\geq n_{base}$



# PF in place of Pmax

Considered the inverter limits  $V_{dc}$  and  $I_{max}$ , and estimated the efficiency at base speed  $\eta_{base}$ , the active power balance at the reference  $T_{max}$ ,  $n_{base}$  point is:

$$\frac{\sqrt{3}}{2} \cdot V_{dc} \cdot I_{max} \cdot \cos(\varphi_{base}) \ge \frac{P_{max}}{\eta_{base}}$$

Therefore

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$$\cos(\varphi_{base}) \ge \frac{P_{max}}{\eta_{base} \cdot \frac{\sqrt{3}}{2} \cdot V_{dc}I_{max}}$$

### The PF constraint represents $P_{max}$ , given the kVA rating



### and reference design point at base speed

Torque and power specs

# Significance of PF

Considered the inverter limits  $V_{dc}$  and  $I_{max}$ , and estimated the efficiency at base speed  $\eta_{base}$ , the active power balance at the reference  $T_{max}$ ,  $n_{base}$  point is:

$$\frac{\sqrt{3}}{2} \cdot V_{dc} \cdot I_{max} \cdot \cos(\varphi_{base}) \ge \frac{P_{max}}{\eta_{base}}$$

Therefore

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$$\cos(\varphi_{base}) \ge \frac{P_{max}}{\eta_{base} \cdot \frac{\sqrt{3}}{2} \cdot V_{dc}I_{max}}$$

# The PF constraint represents $P_{max}$ , given the kVA rating

### This is a conservative assumption

Case study specs								
Peak torque	[Nm]	430						
Peak power	[kW]	192						
Maximum speed	[rpm]	18100						
Peak phase current	[Arms]	1000						
DC link voltage (min)	[V]	231						
Peak current density	[Arms/mm2]	36						
Stator outer diameter	[mm]	225						
Stack length	[mm]	134						
Base speed	[rpm]	4200						
Target power factor		0.71						
Number of pole pairs		3						
Number of slots		54						
PM mass	[kg]	1,8						
Cu mass	[kg]	4,7						

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# Realistic flux weakening behavior

#### **Conservative assumption**

The PF target guarantees meeting the peak power spec with margin

 $\cos(\varphi_{base}) \ge 0.71 \rightarrow P_{max} > 192 \text{ kW}$ 

Real-world curves of IPM machines with flux weakening properties have a power increase at early FW stages

#### Moreover

The higher the PF, the higher the peak power, fixed all other quantities





# T(x,b) and PF(x,b) design plane

Each point of the plane is one cross-section

The coordinates are:

- Rotor/Stator split ratio  $x = \frac{d}{D}$
- Airgap/iron flux density ratio  $b = \frac{B_g}{B_{Fe}}$

Common to all designs

- Stack size D = 225 mm, L = 134 mm
- pk current density  $J_s$  = 36 A/mm<sup>2</sup> rms

The design equations used to obtain the contours are briefly reviewed





### Core dimensions

[6] P. Ragazzo, G. Dilevrano, S. Ferrari and G. Pellegrino, "Design of IPM Synchronous Machines Using Fast-FEA Corrected Design Equations," presented at ICEM 2022, Valencia
[5] S. Ferrari and G. Pellegrino, "FEAfix: FEA Refinement of Design Equations for Synchronous Reluctance Machines," in *IEEE Transactions on Industry Applications*, vol. 56, no. 1, pp. 256-266, Jan.-Feb. 2020.

### Core dimensions are function of $x \cdot b$

Stator

#### Rotor

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• 
$$\boldsymbol{l}_{\boldsymbol{y},\boldsymbol{r}} = \sum h_{Fe} = k_{Fe,r} \cdot l_{\boldsymbol{y}}$$





# Core dimensions coefficients

Core dimensions are function of  $x \cdot b$ 

### Stator

• 
$$l_y = \frac{D}{2p} \cdot \mathbf{k}_y \cdot xb$$
  
•  $w_t = \frac{\pi D}{6pq} \cdot \mathbf{k}_t \cdot xb$ 

Rotor

• 
$$l_{y,r} = \sum h_{Fe} = \mathbf{k}_{Fe,r} \cdot l_y$$

Dedicated coefficients further define the stator and rotor iron dimensions

#### Example

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•  $k_t = 1$  is equal pk flux density in yoke and tooth •  $k_t < 1$  is a smaller and more saturated tooth





### Ampere-turns

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The total slot cross-sectional area  $A_{slots}$  is function of the coordinates x, b

Fixed the current density  $J_s$  (A/mm<sup>2</sup>)  $J_s = \frac{6 N_s I_0}{k_{Cu} A_{slots}}$ 

the corresponding phase Ampere-turn value  $N_s I_0$  is determined, also function of the coordinates

$$N_s I_0 = \frac{J_s k_{Cu}}{6} A_{slots}(x, b)$$

Each design has a determined  $N_s I_0$ 

The number of turns is not yet defined



# Pole Magnetic Flux

In similar way, the <u>base</u> flux linkage  $\lambda_0$  at fixed current density is defined throughout the x, bplane

This is roughly proportional to b, except for the effects of non-idealities such as core saturation, structural ribs, etc ..

The base flux linkage is normalized to the number of turns

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Each design has a determined  $\frac{\lambda_0}{N_s}$ 

(Number of turns not yet defined)



### **Design Equations Summary**

The flux linkages are normalized by the number of turns and defined as:

$$\begin{cases} \frac{\lambda_d}{N_s} = \frac{(L_{md} + L_{\sigma})}{N_s^2} \cdot N_s i_d + \frac{\lambda_m}{N_s} \\ \frac{\lambda_q}{N_s} = \frac{(L_{mq} + L_{\sigma})}{N_s^2} \cdot N_s i_q \end{cases}$$

The normalized inductance components  $L/N_s^2$ and the PM flux term  $\frac{\lambda_m}{N_s}$  are calculated via dedicated lumped-parameter networks

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 $L_{md}$ ,  $L_{mq}$  are magnetizing inductance  $L_{\sigma}$  is leakage inductance  $\lambda_m$  is the PM flux linkage



[5] S. Ferrari and G. Pellegrino, "FEAfix: FEA Refinement of Design Equations for Synchronous Reluctance Machines," in *IEEE Transactions on Industry Applications*, vol. 56, no. 1, pp. 256-266, Jan.-Feb. 2020.

# q axis model

The q inductance is estimated from the solid rotor assumption, considered the **saturation coefficient**  $k_{sat}$ 

$$\frac{L_{mq}}{N_s^2} = \frac{3}{\pi} \cdot \mu_0 \cdot \left(\frac{k_w}{p}\right)^2 \cdot \frac{DL}{k_c g} \cdot \frac{1}{k_{sat}} \cdot \boldsymbol{x}$$

The reference paper [5] covers the SyR machine, and the same equations are used also for the IPM machine.







# d axis model

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[6] P. Ragazzo, G. Dilevrano, S. Ferrari and G. Pellegrino, "Design of IPM Synchronous Machines Using Fast-FEA Corrected Design Equations," presented at ICEM 2022, Valencia

The PM flux linkage is computed with the magnetic equivalent circuit of the pole

The node potentials  $r_k$  are solved from the linear system

For example, the PM flux linkage is computed

$$\frac{\lambda_m}{N_s} = 2 \cdot k_w \cdot k_f \cdot \sum_{k=1}^{n_{lay}} \frac{r_k}{R_{g,k}}$$





### Torque equation and current components

(electromagnetic) Torque equation:

$$T_e = \frac{3}{2}p \cdot \left(\lambda_d \cdot \mathbf{i_q} - \lambda_q \cdot \mathbf{i_d}\right)$$

The q-axis MMF is determined so that the peak flux density at the airgap is  $b \cdot B_{Fe}$ 

$$N_s i_q = \frac{\pi}{3} \frac{k_c g}{\mu_0} \frac{p}{k_w} \cdot B_{Fe} \cdot \boldsymbol{b} \qquad \begin{array}{l} k_c \text{ is the Carter coefficient} \\ g \text{ (mm) is the airgap length} \end{array}$$

The d-axis MMF is derived from  $N_s I_0$  (current density input)

$$N_s i_d = \sqrt{(N_s I_0)^2 - (N_s i_q)^2}$$

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### Power Factor equation

The current angle is defined after the q and d current components

$$\gamma = \operatorname{atan}\left(\frac{-N_s i_d}{N_s i_q}\right)$$

The flux linkage components and angle follows from the lumped-parameter model

$$\delta = \operatorname{atan}\left(\frac{\lambda_q/N_s}{\lambda_d/N_s}\right)$$

This is NOT YET the MPTA condition, to be found at FEAfix stage

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Neglecting the resistance voltage, the PF is calculated, independently of speed  $\cos \varphi \cong \cos(\gamma - \delta)$ 

# FEAfix correction of the contours

### Selected FEA simulations (16 dots):

- To estimate MTPA angle correctly
- To correct the T and PF estimates

For each green dot:

- MTPA is searched iteratively with FEA
- Correction factors are computed

The correction factors are retrieved, to correct:

• q flux linkage

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• *d* flux linkage divided into PM and armature components

[5] S. Ferrari and G. Pellegrino, "FEAfix: FEA Refinement of Design Equations for Synchronous Reluctance Machines," in *IEEE Transactions on Industry Applications*, vol. 56, no. 1, pp. 256-266, Jan.-Feb. 2020.



# Mechanical integrity

The inner posts of each design of the plane is estimated with a simplified analytical model

Tangential ribs are constant for all the designs

# Radial ribs are calculated to sustain rotating mass with no help from the tangential ribs

This is conservative, provided that the tangential ribs are reasonably set

[15] M. Palmieri, M. Perta, F. Cupertino and G. Pellegrino, "High-speed scalability of synchronous reluctance machines considering different lamination materials," *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society*, Dallas, TX, 2014.
[16] G. Dilevrano, P. Ragazzo, S. Ferrari, G. Pellegrino and T. Burress, "Magnetic, Thermal and Structural Scaling of Synchronous Machines,", to be presented at *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, 2022

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### Design Flowchart

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# Feasible designs

The area of feasible designs is evidenced T>430~Nm $\cos \varphi>0{,}71$ 

Opposite trends:

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- Torque decreases towards the up-right corner
- PF decreases towards the down-left corner

How to pick up the optimal design?



# Guidelines

#### The closer to the up-right corner, the better

- Smaller slots → better heat rejection, less copper cross-section and thus electric loading, lower copper mass
- $\circ$  Higher power factor  $\rightarrow$  flatter power curve

Other quantities will be considered to drive the selection of the optimal design

• PM mass

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- Copper mass
- Feasible number of turns



### PM mass

The PM mass of the demo model is used as boundary

 $m_{PM} < 1,8 \ kg$ 

The PM mass contours are evidenced, and the are of feasible designs is correspondingly limited





### Copper mass

Similarly, the copper mass is evaluated on the plane, and the value of the demo model is used as a reference

 $m_{Cu} < 4,74 \ kg$ 

This further restricts the area of feasible designs





# Number of turns according to the current limit

Designs respect the current limit when

 $N_s I_0 \leq N_s I_{max}$ 

The inverter current limit  $I_{max} = 1414$  Apk is associated to feasible numbers of turns  $N_s = 9,12,15,18$  ...

The example shows the area of respect of the current limit with  $N_s = 9$ 

### The valid area is above the limit line

The larger  $N_s$ , the larger the area

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Number of turns according to current

# Number of turns according to the voltage limit

 $N_s = 9$ 

Simplified voltage equation at base speed

$$p\frac{\pi}{30} \cdot n_{base} \cdot \lambda_0 \le \frac{V_{dc}}{\sqrt{3}}$$

It defines the base flux linkage limit

$$\lambda_0 \le \frac{V_{dc}}{\sqrt{3} \cdot p \frac{\pi}{30} \cdot n_{base}} = 996 \text{ mVs}$$

The  $\lambda_0/N_s$  contours are reported for feasible values of  $N_s$ , the area of respect of the voltage limit for  $N_s = 12$  is highlighted

The valid area is the below the line

The smaller  $N_s$ , the larger the area

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# Feasible numbers of turns

The current and voltage constraints are crossed for the feasible numbers of turns

Feasible solutions are  $N_s = 9$  and  $N_s = 12$ 

• The area of respect of  $N_s = 9$  is in light blue

• The area of respect of  $N_s = 12$  is in magenta





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### Number of turns selection

Intersecting the feasibility area of each number of turns with the sweet spot previously defined:

- $\circ N_s = 9$  can fulfill all constraints
- $\circ N_s = 12$  is **outside the sweet spot** because it cannot beat the PM mass limit





### Design#1

x = 0.668 / b = 0.663

 $N_s = 9$ 

The motor is selected at the crossing of the torque and PM mass limits

A little margin is noticed w.r.t. the current limit

Copper mass way lower than the limit



0.7



### Motor Analysis – Operating Limits

The flux maps of Design#1 are FEMM evaluated and manipulated

The operating limits for this inverter tell

• Peak torque is ok

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- Peak power is unnecessarily high, because
  - $\circ N_s = 9$  has large margin w.r.t. the voltage spec
  - The curves refer to a lossless situation
  - The PF @ nbase criterion is pessimistic
  - The PF on the plane is circa 0.9 >> 0.71

### Actions: Reduce A/mm<sup>2</sup>? Reduce the stack length L?



### Remember the flowchart

### Here we **reduce the stack length** and restart

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### Stack length reduction

What is unchanged

- PF contour
- Ampere-turns

### What has changed

- Torque contour shrinks
- PM mass and Cu mass shrink
- Voltage-driven
   N<sub>s</sub> contours go up

The plane is length-adjusted, not FEA recalculated (!!)

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## Design plane for L = 114 mm

The green area moves downwards and leftwards in the plane

Downwards means less iron

Leftwards means **smaller rotor, longer slots** 

W.r.t. the number of turns:

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★  $N_s = 9$  is not feasible current wise
✓  $N_s = 12$  intersects the green area
★  $N_s = 15$  is not feasible voltage wise



### Selected 114mm motors

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### Focus on Design#3

This is considered the best candidate

The plane tells that

- $\circ$  450 Nm are expected at  $I_{max}$  (> 430 Nm)
- A PF of 0,83 (> 0.71)
- PM mass 1,55 kg (< 1.8 kg)
- Cu mass 4 kg (< 4.74 kg) x = 0

**Design #3** x = 0.639 / b = 0.640







### Power curves comparison

The operating limits of the three motors are compared, with the same inverter

All comply with the torque and power specs

Design#3 has minimized stack volume AND minimized PM mass

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## Flux Maps of Design#3

The flux map curves highlight :

- saturation of q-axis occurs
- cross-saturation more evident on d axis

### Effect of PM temperature:

- d-axis flux linkage shift
  - $^\circ~$  -8% for 60°C variation (-1.3% /°C)
- Little effect on q-axis

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#### Flux linkage curves at 80°C (blue and green) and 20°C (red)

### Temperature effect on torque

Torque capability under MTPA is mildly affected by temperature:

• -3% for 60°C variation (-0.5% /°C)

The effect on power curve at high speed is more evident





### Comparison with the benchmark

Torque capability of Design#3 compared to the custom Model3:

Comparable torque vs current curves

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- Design #3 has higher peak torque and a better power curve
- Stack volume 4,5 liters vs 5,3 liters (-15%)





### Torque ripple comparison

Design #3 is not optimized for torque ripple

Yet, the peak-peak torque envelope is under control (65 Nm pk-pk at 450 Nm) and can be further optimized

Comparison of torque waveforms shows the effect of dedicated torque ripple optimization (notches at optimal positions)



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### Demagnetization Limit

Demagnetization current function of PM temperature is retrieved with SyR-e automation • Max 1% PM volume is tolerated

The demagnetization limit of Design #3 is slightly lower compared to the benchmark below 140°C of PM temperature

This relates to the smaller PM dimensions

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Yet, the crossing with the maximum inverter current occurs at 140°C in both cases



## Efficiency map

Efficiency map is computed at reference temperature values PM 80°C and Cu 100°C

- DC, AC and iron loss considered
- maximum efficiency control implemented
- Sinusoidal currents (no PWM)

High-efficiency area between 3000 and 7000rpm, partial load

The maps are very similar, despite the smaller stack volume of Design#3



3000

6000

12000

15000

9000

 $n \, [rpm]$ 



18000

## Thermal limit

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Steady-state thermal limit curve computed with the same cooling system of the benchmark (10 liters/min, 45°C inlet, full potting) • Higher loss density leads to a lower thermal limit • Hotspot found in the inner end-winding







## Thermal limit

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Steady-state thermal limit curve computed with the same cooling system of the benchmark (10 liters/min, 45°C inlet, full potting) • Higher loss density leads to a lower thermal limit • Hotspot found in the inner end-winding



Design#3

#### Hotspot temperature according to MotorCAD



### PWM waveforms and additional loss

PWM loss computed at 100Nm, 5000rpm

- Additional loss 172W (+14%)
- Mostly on the stator (eddy current term)

### PM loss explodes due to PWM:

- Fine segmentation mandatory
- Refinement with transient FEA

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Loss breakdown

### syreDrive: Control Simulation

The Simulink (and soon PLECS) model of the e-drive is automatically generated, along with floating ANSI-C control code

Different options are possible

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For e-motor design, we mostly use PWM current calculation for FEM re-evaluation



[17] A. Varatharajan, D. Brunelli, S. Ferrari, P. Pescetto and G. Pellegrino, "syreDrive: Automated Sensorless Control Code Generation for Synchronous Reluctance Motor Drives," 2021 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), Modena, Italy, 2021, pp. 192-197.



### syreDrive tab

### Main features

- Circuital motor model
- Flux-map based
  - 2D (dq) or 3D (dq-theta) maps
  - time-average or instantaneous PWM
- Discrete-time control
- Source code in ANSI-C
  - Torque control, speed control, current control
  - Sensorless control

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💿 GUI_	Syre_MMM					-	- 🗆	×			
Main     Scaling & Skewing     Torque       Model Setup     Model type     Istantaneou       Flux maps model     dq Model       Control type     Torque con		Istantaneous (dq Model Torque control	syreDrive Waveform Thermal Converter data ON threashold [V] Internal resistance [Ohm] Dead time [us] 1		0	Sy Magnetic Mod Load S New Sa	heck e all	Syre			
Sensorless control							Motor Ratings				
o	Off On	Low speed region (HF Ir	on) Sinusoidal ▼ Current ▼			Motor name Pathname Motor type Rated power [W]	Design3_PMax G:\Shared drive PM 224558.128	@ PEIC\2022 PM 437.2354	2		
		High speed region					Rated speed [rpm]	4904.3885	Maximum speed [rpm]	18100	
		Position en	APP V		Rated current [Apk] DC link voltage [V]	231	Max current [Apk] Phase resistance [Ohm]	0.0036398	; ; ;		
							PM temperature	80 🔻	Winding temperature	20	
							Stack length [mm]	114	End winding length [mm]	129.9672	
						RUN	Turns in series per phase Inertia [kg m^2]	12 0.028914	Number of 3phase sets	1	

#### syreDrive tab of GUI\_Syre\_MMM

### Simulink Model Overview

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## Control Subsystem

Triggered sub-system executed at sampling time Ts

C-MEX S-Function with user defined library calls

C source code

- automatically generated and calibrated using the machine params
- Accessible

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The control code is portable to dSPACE and STM32 ARM based MCUs



### Inverter Subsystem



Based on Simscape 3-ph circuital Converter

- Instantaneous or time-averaged switches
- Dead-time effect considered
- $\circ$  Forward voltage and  $R_{ON}$  of semiconductors

The circuital model is compatible with fault conditions

#### Content of the Inverter subsystem



[18] A. Bojoi, "Advanced Dynamic Model of E-motor for Control Rapid Prototyping [MSc Thesis]", Politecnico di Torino, 2022, <u>https://webthesis.biblio.polito.it/22088/1/tesi.pdf</u>



### Motor Subsystem

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Controlled current generators approach

Phase currents are calculated by manipulation of current generators' voltages, using the motor parameters and flux maps

Inverse flux maps (flux input, current output)

 $i_d = f(\lambda_d, \lambda_q)$  $i_q = g(\lambda_d, \lambda_q)$  Content of the Motor subsystem





### Motor Subsystem

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SIMULINK® Electrical Directing Directing

Controlled current generators approach

Phase currents are calculated by manipulation of current generators' voltages, using the motor parameters and flux maps

Inverse flux maps (flux input, current output)

$$i_d = f(\lambda_d, \lambda_q)$$
  
$$i_q = g(\lambda_d, \lambda_q)$$

Controlled current generators approach







### Results: torque reversal

500(Nm)Torque reversal, **dq** model -500 0.790.7950.80.805 0.81t(s)2000 (Indu) 1000  $\omega_r$ 0.7950.790.80.8050.81t(s)2000  $(\mathbf{A})$ 0  $i_B$ -2000 0.80.790.7950.805 0.81t(s)(in.d) 0.5  $d_B$  $d_C$ 0.8 0.790.805 0.810.795

t(s)

Peak torque reversal is shown at 2000 rpm

- FOC control with MTPA id, iq references is used
- PWM time averaged model

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This example uses the standard dq model of the machine (no ripple effect), based on inverse dq flux maps

Under proper current control, currents are sinusoidal, and torque is smooth

98

## dq-theta model

Torque reversal, **dq-theta** model

Peak torque reversal is shown at 2000 rpmFOC control with MTPA id, iq references is used

• PWM time averaged model

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The **dq-theta model** of the machine is used this time, including the flux linkage and torque harmonic effects

Currents no longer sinusoidal, torque ripple is evident

High-fidelity model for better control development and better modelling overall (model-based control design, digital twin, ..)



### Results: PWM ripple

Steady-state current waveforms at 4000 rpm and 2000 rpm, under load

The PWM frequency is 10 kHz

Pk-pk current ripple is mild at all operating conditions, as its secondary effects (loss)

The worst-case dc-link voltage of 231V is bestcase in this sense

Yet, 10 kHz is lower than real

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### Conclusion

The SyR-e approach to the design of IPM machines for traction was presented, using Tesla Model3 as reference

The FEAfix design plane covers many aspects of the design, and permits to cross design goals and constraints in graphic and insightful manner

In the example, PM and copper mass were considered as additional constraints, and the stack length was reduced with respect to the initial machine

Other aspects such as loss evaluation, thermal and structural simulation, control simulation were touched in the presentation

SyR-e is evolving under the push of the industry and the dedication of talented researchers

We invite you to try SyR-e and collaborate with us!



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# Thank you!

Questions are very welcome

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