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Efficient Multiphysics Design Workflow of Synchronous Reluctance Motors

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***Abstract*—This paper proposes a new design strategy for Synchronous Reluctance machines, with cooperative design in the two environments SyR-e and Motor-CAD. The paper proposes to use the open-source SyR-e for initial, equation based design of the machine. Then, the design is validated and refined in Motor-CAD, in multiple physical domains. This synergy complements both design environments and turns into a comprehensive design package, not yet available in the literature, assembling accessible design equations, magnetic and mechanical FEA and drive operating profiles evaluation to the trademark thermal analysis of Motor-CAD. The cooperative design strategy is described in the paper with reference to the case of a Pure Synchronous Reluctance motor prototype for vehicular traction.**

***Index Terms*—Electric Machines, Motor Design, Finite Element Analysis, Design Software, Synchronous Reluctance**

I. Introduction

A. Background

Nowadays, several electric motors typologies are available and largely employed in numerous fields of application; among these, one of growing interest is the automotive sector. Indeed, the diffusion of Electric Vehicles (EV) and Hybrid Electric Vehicle (HEV) is still partial, but also growing at increasing pace, as pointed out in [1] [2]. Currently, the EVs and HEVs drive trains are equipped with different motor types [3]. Among others, the Internal Permanent Magnet (IPM) motors have been widely used in several EVs and HEVs [4] [5], like Audi e-tron, Chevrolet Bolt, Mercedes EQC, Tesla 3 and Nissan Leaf; although, Jaguar I-Pace Jaguar I-Pace and BMW i3 use IPM machines designed for higher reluctance torque components, based on Synchronous Reluctance (SyR) rotor types; while the Tesla S and X adopted Induction Motors (IMs).

The high efficiency SyR machines led them to be a valid alternative to induction motors in variable speed industry applications as the automotive field. Nevertheless, their design procedures are not extensively known, particularly for the rotor design, whereas the stator is similar to that of IMs. Also, the rare-earth magnet price volatility obstacles the PM motor drives spread, in fact the neodymium and dysprosium price has been unstable and led to an energetic search for alternative machine types, such as PMSMs with smaller amounts of PM [6], with alternative magnets as ferrite [7] or without any PM (SyR motors) [8]. Over the last years, several design procedures have been proposed as in [9] [10], providing a defined guideline in the design algorithm, but not a comprehensive procedure. Most of the design procedures rely on Finite Element Analysis (FEA), which reliability and precision is assessed to be valuable in [11].

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B. Paper scope and organization

The design of an electric motor for traction is a complex, multi-objective problem involving multiple physical domains. Concerning the SyR machines, one of the most critical conflict is between electromagnetic torque and structural integrity, since it can compromise the overall performance [12]. In fact, the rotor integrity is strictly dependent on the iron ribs dimension and position, that are widened to improve the structural properties, at the cost of torque and power factor detriment [13].

This paper proposes a design procedure for SyR machines contemplating the challenge to make the design process a multi-physics problem but maintaining the algorithm straightforward and quick. Such task is executed employing SyR-e, an open-source software, and Motor-CAD [14], a commercial software leader in the field of electric machines design, both aided by FEA solvers. Motor-CAD is an advanced software design tool, that grants the capability to quickly and easily perform electromagnetic, thermal and mechanical performance tests on different electric machine designs. Whereas, Synchronous Reluctance evolution (SyR-e) [15] is an open-source code developed in Matlab or Octave and FEMM [16], aimed to design synchronous reluctance machines using analytical models coordinated with fast FEA and optimization algorithms.

II. Proposed design methodology

Firstly, a design process was formulated made upon the strengths of both environments evaluated in Tab I, then the optimal combination of the two tools is shown in Fig. 1.

SyR-e is used for preliminary magnetic design of the stator and the rotor, using design equations corrected by FEA. This feature is not present in Motor-CAD, where the SyR machine rotor geometry is also described by a higher number of variables, making preliminary design even more complex. On the contrary, Motor-CAD is very powerful in evaluating the machine output in the different domains of interest: mechanical and thermal, besides magnetic, and it is used for mechanical optimization and performance evaluation.

TABLE I
SOFTWARE COMPARISON FOR SYR MACHINE DESIGN

	Pros	Cons
SyR-e	- Smooth barrier shape - Rotor pre-design - Low number of DOFs	- No thermal analysis - Limited mechanical validation - No duty/drive-cycle analysis
MCAD	- Multiphysics analysis, incl. mechanical FEA - Duty/drive-cycle analysis evaluation	- Complex rotor parametrization - High number of DOFs - No rotor pre-design

The preliminary design is thus executed in SyR-e. Starting from the main design specifications and constraints of Tab. III, different solutions can be quickly verified, having different pole pairs, stator slot and rotor barrier numbers, and so on. The parametric design plane and FEAfix approaches permit to determine the torque and power factor figures of the initial design accurately and quickly [17].
The preliminary geometry is then exported to Motor-CAD via new dedicated Matlab ActiveX automation scripts for further magnetic, mechanical and thermal studies, and for a comprehensive evaluation of the motor performance. Exporting the model to Motor-CAD is one of the new functionality of SyR software. Last, one of the most critical path is the mechanical validation process, depicted in Fig. 2.

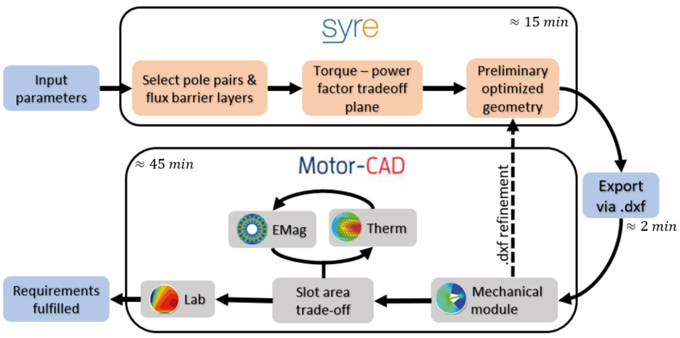

Fig. 1. Joint comprehensive design methodology for SyR machines with SyR-e and Motor-CAD. Computational times obtained with a quad-core i7-1065g7 up to 3.9 GHz and 16 GB RAM.

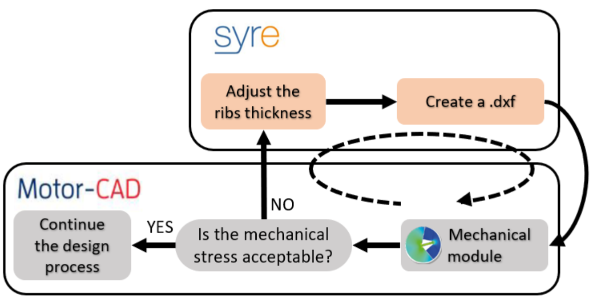

Fig. 2. Loop for mechanical sizing of SyR machine.

III. SYR-E DESIGN PROCEDURE

The procedure to design a SyR machine entirely in SyR-e is represented in Fig. 3 and begins with the definition of the active parts envelope and the feasible Joule loss per outer surface, which is strictly related to the maximum winding temperature.
Then, a trade-off between power factor and torque is selected through the design plane, as the one reported in Fig. 4 and built by the buttons $'syrmdesign'$ and $'FEAfix'$, described in [17]. The torque versus power factor plane is function of the two geometric parameters, x and b, defined in (1) and (2), respectively the rotor/stator split ratio and the airgap/iron flux density ratio. Once the x and b values are selected, SyR-e quickly provides a preliminary optimized geometry.

$$x = \frac{r}{R} \quad (1) \qquad\qquad b = \frac{B_g}{B_{Fe}} \quad (2)$$

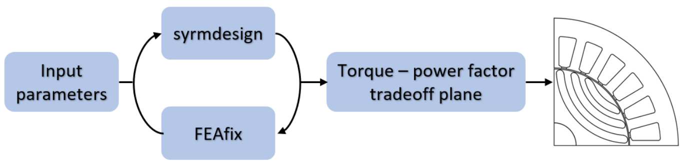

Fig. 3. SyR-e design procedure

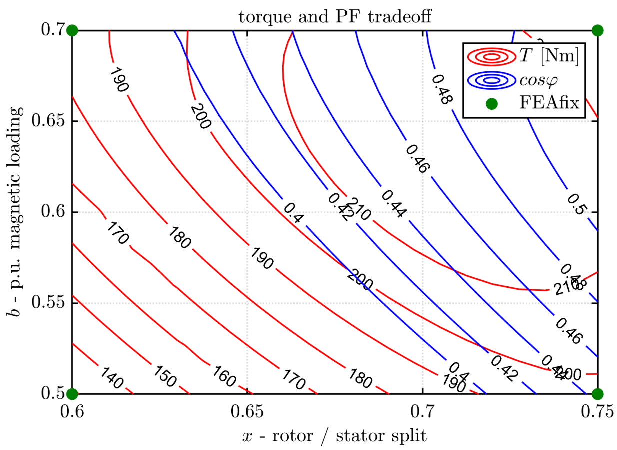

Fig. 4. Example of a torque and power factor trade-off plane.

At this point, the design constraints are met and the SyR machine design in SyR-e is finished. Once the motor is designed, several evaluations may be executed and the data collected by means of Matlab scripts, as displayed in Fig. 5. Here, SyR-e is supported by Mentor - MagNet [18] and FEMM [16]; the first is mainly employed for loss evaluations and to compute the iron losses map, the latter is used for magnetostatic simulations and to obtain the flux maps. These results are the inputs of Matlab scripts aimed to obtain the listed outputs in Fig. 5.
In order to extend the evaluations available in SyR-e and to allow a joint design procedure with Motor-CAD, a bridge between the two software environments has been created by means of Matlab and ActiveX scripting. In turn, for the time

being, SyR-e lacks of mechanical and thermal validation. In fact, the software adapts the radial ribs thickness according to maximum speed using a 1D analytical approximation, but does neglect the contribution and maximum stress in the tangential ribs. Whereas, Motor-CAD allows centrifugal stress evaluation, based on 2D mechanical FEA.

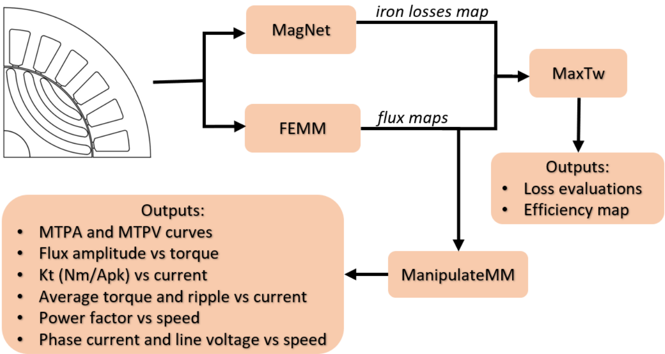

Fig. 5. SyR-e analysis procedure with the support of FEMM and MagNet.

IV. Export from SyR-e to Motor-CAD

This task, disclosed in Fig. 6, is broken up into two main steps: the model export from SyR to Motor-CAD, making sure parameters match up on both sides, and the simulation of the exported model into Motor-CAD environment.

1) Model export ($'draw\_motor\_in\_MCAD'$)
   a) geometric parameters export
   b) winding setup export to Motor-CAD ($'windingSyreToMCAD'$)
   c) $.dxf$ creation and import to Motor-CAD ($'syreToDxfMCAD'$)
2) simulation of the exported design in Motor-CAD ($'MCADfitness'$)

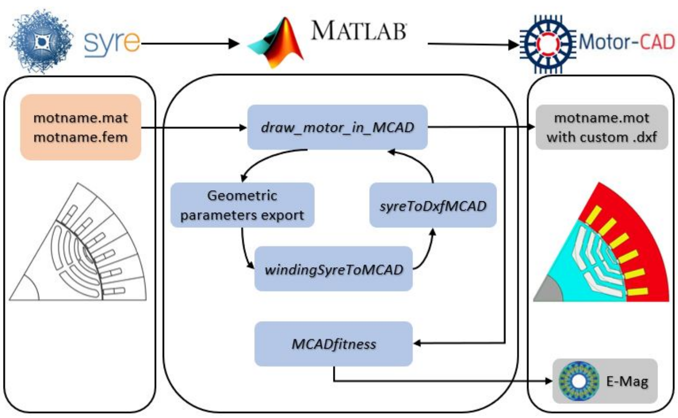

Fig. 6. Export path from SyR-e to Motor-CAD by means of Matlab.

A. Geometry export

For the time being, Motor-CAD does not include the circular flux barrier geometry. Therefore, the available 'SynCRel' model of Motor-CAD having segment flux barriers was used in the first place, with the rotor geometry custom defined according to a $.dxf$ drawing exported from SyR-e. In comparison to Motor-CAD, SyR-e reduces the number of geometric parameters (reported in Fig. 7) by taking some assumptions first, and simplifying the way to parameterize the geometry.

The export is divided into two steps. First, a geometry similar to the target one must be created into Motor-CAD, then the $.dxf$ file of the rotor is imported, to model the actual geometry. The first step is automatically performed by a Matlab script, written after establishing the relationship between SyR-e and Motor-CAD parametrizations. Then, the $.dxf$ of the rotor is automatically built from SyR-e and loaded in Motor-CAD, as shown in Fig. 9. The E-Magnetic and Mechanical modules are capable to utilize the imported $.dxf$ drawing, whereas the Thermal module uses the Motor-CAD sketch. However, the template based geometry for the thermal analysis can be used, since Motor-CAD's thermal model is based on an equivalent resistance network. Thus tiny changes in the rotor flux barriers will still give accurate and correct results.

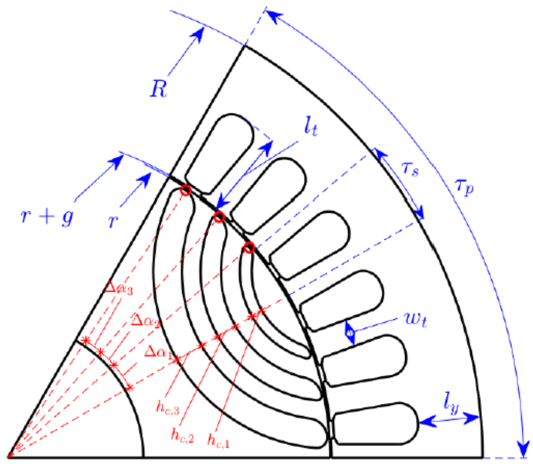

Fig. 7. Geometry parameterization of a general SyR-e machine [17]

B. Winding export

The winding setup is comprehensively exported from SyR-e to Motor-CAD. A double layer winding is considered, arranged as reported in Tab. II. The Matlab function $'windingSyreToMCAD'$ creates the winding setup in Motor-CAD displayed in Fig. 8, perfectly duplicating the SyR-e winding.

TABLE II
WINDING SETUP IN SYR-E

Slot number	1^{st}	2^{nd}	3^{rd}	4^{th}	5^{th}	6^{th}
Layer 1	1	1	-3	-3	2	2
Layer 2	1	1	-3	-3	2	2

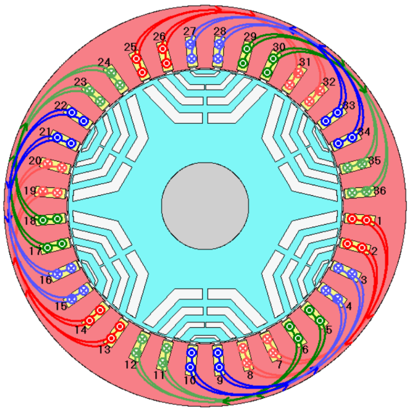

Fig. 8. Exported winding from SyR-e to Motor-CAD.

C. .dxf creation

The rotor geometry is exported via a $.dxf$ file, superimposed to the standard rotor geometry of Motor-CAD, as said. At this stage the final Motor-CAD file, in Fig. 9, is built, resulting entirely equivalent to the SyR-e model.

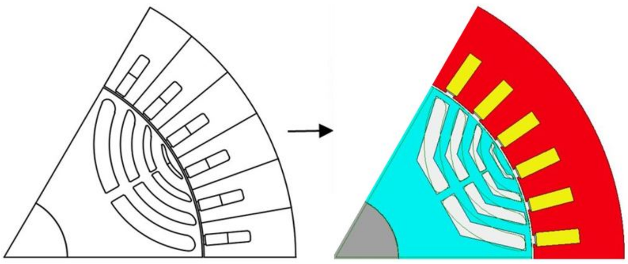

Fig. 9. Geometry model export from SyR-e to Motor-CAD

D. New Motor-CAD window in SyR-e

The new export functionalities are embedded in the new tab of SyR-e. The available options are listed below.

- 'Export .mot' button: it allows to create a $.mot$ Motor-CAD model as a copy of a circular flux barriers synchronous reluctance machine model realized in SyR-e.
- 'EMag sim' button: it runs a single point simulation in the Motor-CAD E-Magnetic FEA solver and saves the results in Matlab.
- 'Export maps' button: it exports flux maps to the Motor-CAD Lab, allowing to perform analysis using custom flux maps.
- 'Therm Export' button: it exports thermal parameters to the Thermal module in Motor-CAD.
- 'Therm Sim' button: it runs a thermal simulation in Motor-CAD and collects the results in Matlab.

V. Design of a 200kW pk SyR Motor for Traction

The proposed design procedure is tested by re-designing a demanding SyR motor for automotive, presented in [19] and its main data are reported in Tab III and Fig. 10. The design and optimization procedure executed in [19] led to a rotor layout with multiple ribs and fluid flux barriers, clearly unusual compared to those typically reported in literature. However, it represented the best design solution achieved by means of a topology optimization made in Ansys Mechanical [19]. Whereas, the present design procedure adopts a standard simplified geometry with circular flux barriers, tangential and radial ribs.

TABLE III
Motor Requirements [19]

Outer Stator diameter	[mm]	230
Stack length	[mm]	200
Airgap length	[mm]	0.7
Iron material		M235-35A
Motor stack mass	[kg]	≤ 48
Maximum speed	[rpm]	18000
DC Voltage	[V]	800
Specific Peak Power	[kW/kg]	≥ 4.0
Specific Peak Torque	[kW/kg]	≥ 8.0
Peak Power @5 krpm	[kW]	≥ 200
Peak Torque @5 krpm	[Nm]	≥ 380
Peak efficiency	[%]	≥ 95
Power @ max speed	[kW]	≥ 50

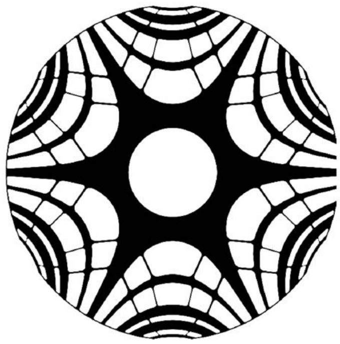

Fig. 10. Benchmark fluid shaped rotor geometry [19]

A. Initial Design

Fixed the input constraints, the design procedure described in Fig. 1 can be applied. Firstly, it is interesting to point out that a lower number of pole pairs favors high power factor and ultimately high torque, at the cost of higher iron and copper mass, fixed the outer stack dimensions and the airgap length (see Fig. 4 and Fig. 12 for comparison of p = 4 and p = 3 respectively). A higher number of poles also increases frequency related loss, i.e. iron and skin-effect loss. Conversely, heat extraction is easier with higher numbers of poles, i.e. smaller slots and stator back iron, when an outer cooling jacket is considered. For these reasons, the numbers of pole pairs p considered suitable for the given application are 3 and 4. Expectedly, with 8 poles the i_d current component is larger in p.u. than with 6 poles, due to a larger p.u. airgap. Therefore, fixed to $0.7\,mm$ the airgap, $p = 4$ is not a competitive option. Thus, the design procedures continued with a new constrained parameter: $p = 3$ (3 pole pairs).

Then, the number of flux barriers per pole and stator slots were selected in accordance with the guidelines reported in [20]: all the designs considered, both with 72 and 36 slots, have 4 rotor layers in order to minimize the harmonic content. Therefore, several design options were evaluated as displayed in Fig. 11. All the design options have in common the same x and b values, chosen through the design plane in Fig. 12. The specific plane reported is referred to the Option 1; however, the others design options have similar characteristics, thus the same trade-off point was assumed optimal for all of them. At this stage, two options, underlined in Fig. 11 as Option 1 and Option 2, are selected among the others by means of the quick performance evaluations embedded in SyR-e. Therefore, they are further analysed as explained in the following, leading to the final design in Figs. 14 and 13.

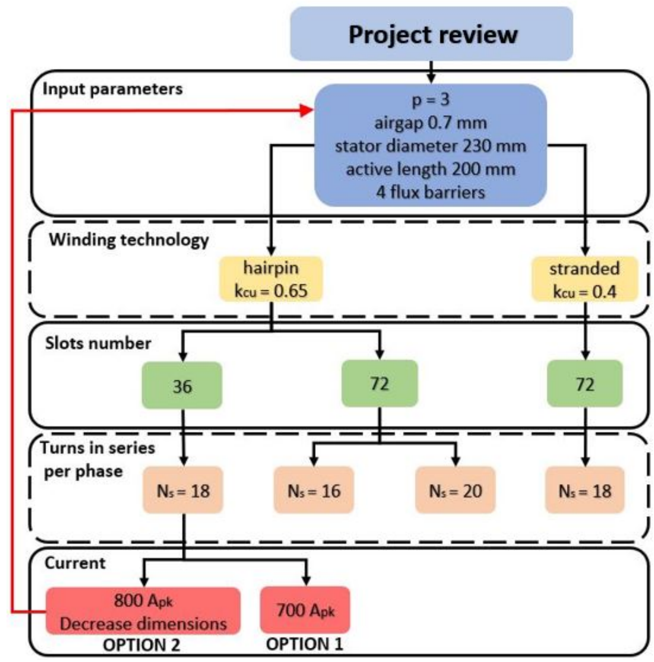

Fig. 11. Analysed design options with different winding technology, slots number, turns in series per phase and maximum peak current.

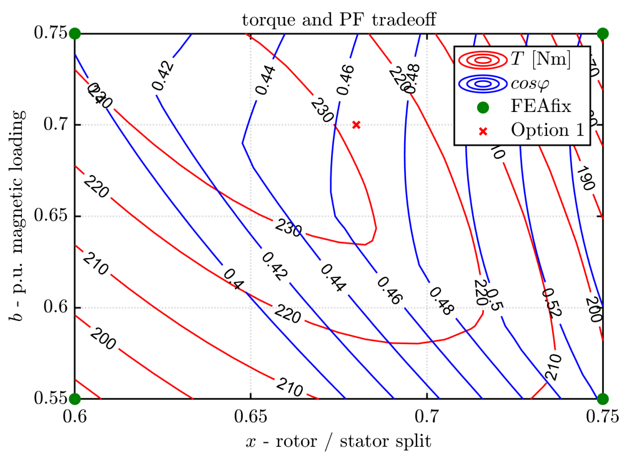

Fig. 12. Option 1 - Torque and power factor trade-off plane.

B. Mechanical Refinement

To size the maximum mechanical stress, the loop in Fig. 2 was applied to both design options, executing a refinement on the radial and tangential ribs. Each rib was gradually thickened or thinned in order to meet the maximum Von Mises stress, evaluated by means of the mechanical FEA embedded in Motor-CAD. In addition, the flux barriers internal sides were rounded to minimize the mechanical stress.

C. E-Magnetic and Thermal modules

Thereafter, the design process went through the E-Magnetic and Thermal Motor-CAD modules. The first allows magnetic insight evaluations; the latter permits a comprehensive definition of the cooling system. For the cases taken into account, a standard cooling system for automotive application was adopted: a spiral jacket system with 50%/50% water and glycol and a fluid flow rate of $6.5\,l/min$.

D. Performance Curves Evaluation

At this stage, the two design options are deeply analyzed using Motor-CAD Lab module. Firstly, Option 2 is rewinded obtaining 20 turns in series per phase. In addition, it is characterized by a smaller volume thanks to an higher peak current than the Option 1. These factors increase the peak torque and power density of the motor and improve the structural safety factor, thanks to the lower volumes. Conversely, Option 1 is characterized by a higher efficiency (as shown in Figs.16-17) and a longer admitted overload. Torque ripple is low for both motors (below 10%), even if the geometry is not optimized for that. If lower torque ripple is pursued, additional refinements can be adopted, as skewing or asymmetric rotor poles, implemented in SyR-e but not yet included in the SyR-e/Motor-CAD interface. The Tab. IV underlines the effectiveness of the built design procedure; indeed, with a simplified rotor geometry and concise computational time, the performance are similar to the benchmark with non conventional and optimized rotor geometry. This thanks to the preliminary sizing equations embedded in SyR-e and to the mechanical refinement applied. The efficiency maps in Figs.16-17 are computed at 100 $°C$ and they point out that, overall, the Option 1 has slightly higher efficiency.

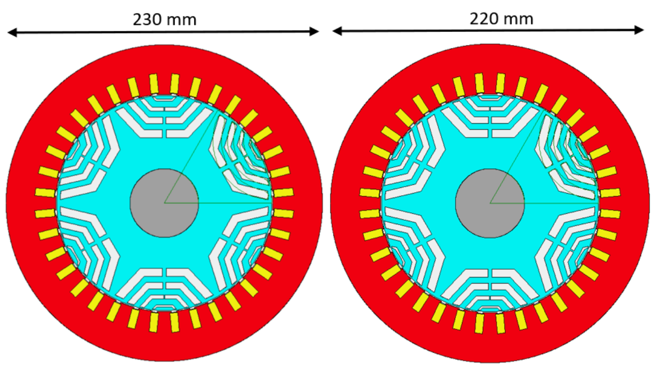

Fig. 13. Radial view - Option 1 (left), Option 2 (right)

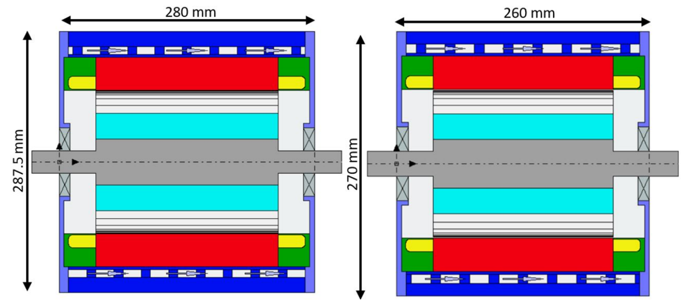

Fig. 14. Axial view - Option 1 (left), Option 2 (right)

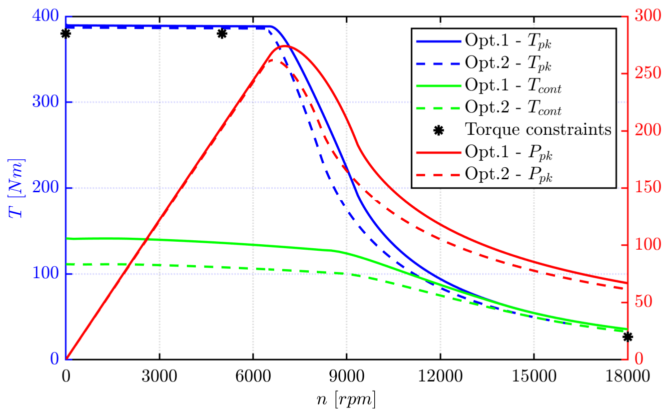

Fig. 15. Power and torque vs speed graph for Option 1 and 2

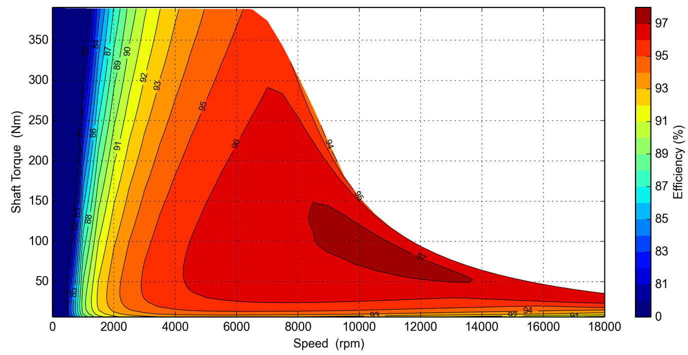

Fig. 16. Option 1 - Efficiency map @ 100 $^{\circ}C$

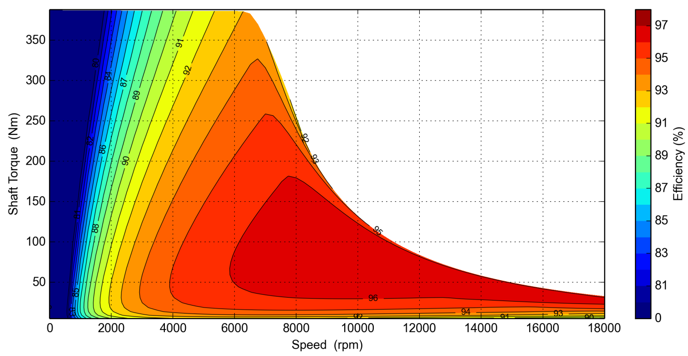

Fig. 17. Option 2 - Efficiency map @ 100 $^{\circ}C$

TABLE IV
PERFORMANCE COMPARISON

	Option 1	Option 2	Benchmark
Stator outer diameter [mm]	230	220	230
Rotor diameter [mm]	156.4	151	-
Stack length [mm]	200	185	200
Stack mass [kg]	57	48	48
Maximum current [A_{pk}]	700	720	700
DC voltage [V]	800	800	800
Torque at max current @ 5 krpm [Nm]	392	390	384
Peak power [kW]	270	262	250
Corresponding corner speed [rpm]	6500	6500	6100
Power @ max speed [kW]	67	63	58.5
Continuous torque @ low speed [Nm]	140	110	-
Continuous power @ max speed [kW]	67	63	-
Max time @ peak torque 5 krpm [s]	72	30	-
Specific power, peak [kW/kg]	4.8	5.5	5.2
Specific torque, peak [Nm/kg]	7	8.12	8
Torque ripple at max torque	8.6 %	9.3%	-
with stator skewing	1.8 %	1.9 %	-
Torque ripple at max speed and torque	10 %	10.8%	-
with stator skewing	3 %	3.5%	-
Max mechanical stress [MPa]	430	340	361
Safety factor @ max speed	1.1	1.37	1.28

VI. CONCLUSION

This paper investigates the SyR motor design, proposing an innovative comprehensive procedure. The key contributions are:

- A new SyR-e version is released with a section entirely dedicated to Motor-CAD: this allows exporting a motor design as well as single-point magnetic and thermal simulation.
- An original design procedure for SyR machines is proposed: the new synergy turns into the most complete design package available in the literature for this type of machine, including accessible design equations, magnetic and mechanical FEA validation, trademark thermal analysis and drive operating profiles evaluation.
- The procedure is validated by designing an automotive high performance electric machine: a high-speed 200 kW SyR motor was designed taking as reference a machine prototype for rare-earth free traction application.

In conclusion, the proposed design procedure furnished a SyR motor with comparable if not better performance than the benchmark, with less computational effort and time. It must be reminded that no optimization algorithm was used here, neither for magnetic nor mechanical design. The proposed procedure is thus straightforward and quick in tackling the multi-physics design problem, in accordance with nowadays challenges in the automotive field.

VII. ACKNOWLEDGMENT

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VIII. Biographies

Paolo Ragazzo is currently pursuing the Ph.D. degree at Politecnico di Torino, Turin, Italy. He received the B.S. and M.Sc. degrees in electrical engineering from Politecnico di Torino in 2017 and 2020, respectively. In 2018, he was an Exchange Student at Norwegian University of Science and Technology (NTNU), Norway. In 2019, he developed his Master’s Thesis at Motor Design Ltd, Wrexham, United Kingdom, focused on synchronous reluctance machine design procedures. His research activities are concentrated on the design and analysis of electrical machines for automotive applications.

Simone Ferrari (S’17-M’20) received the Ph.D. degree “cum laude” in 2020 from Politecnico di Torino, Turin, Italy, where he is currently a Research Fellow. From July to December 2018, he was a Visiting Scholar with North Carolina State University, Raleigh, NC, USA. He is one of the authors of SyR-e, an open-source design tool for synchronous reluctance and permanent magnet machines. His research interests include electrical machine design and multiphysical evaluation of electrical machines, with a focus on synchronous reluctance and permanent magnet machines.

Nicolas Rivière is a Senior Engineer at Motor Design Ltd where he mainly involves in consultancy projects, UK and European funded projects. He received the Master Engineering degree in electrical engineering from Toulouse University (France) in 2014 where he specialised in electromechanical energy conversion and advanced mechatronics. He worked three years in the LAPLACE Lab. (Laboratory on Plasmas and Energy Conversion) in Toulouse on the design of a high speed permanent magnet synchronous machine for an automotive application.

Mircea Popescu (M’98–SM’04–F’15) received the M.Eng. and Ph.D. degrees from the University “Politehnica” Bucharest, Bucharest, Romania, in 1984 and 1999, respectively, and the D.Sc. degree from the Helsinki University of Technology, Espoo, Finland, in 2004, all in electrical engineering. He was with the Research Institute for Electrical Machines, Bucharest, the Helsinki University of Technology, and the SPEED Laboratory, Glasgow University, Glasgow, U.K. In 2008, he joined Motor Design Ltd., Ellesmere, U.K., as an Engineering Manager. He has more than 25 years of experience in electrical motor design and analysis. He has authored or coauthored more than 100 papers in conference proceedings and peer-reviewed journals. Dr. Popescu was a recipient of the First Prize of Best Paper Award from the IEEE Industry Applications Society (IAS) Electric Machines Committee (EMC) in 2002, 2006, and 2008. He acted as officer of IEEE IAS EMC between 2010 - 2017, and prominent lecturer IAS, Region 8, 2014 - 2016.

Gianmario Pellegrino (M’06–SM’13) received the M.Sc. and Ph.D. degrees in electrical engineering from Politecnico di Torino, Turin, Italy, in 1998 and 2002, respectively. He is currently a Professor of Electrical Machines and Drives with the Politecnico di Torino. He is engaged in several research projects with the industry, and one of the authors of the open-source project SyR-e for the design of electrical motors. He was a Visiting Fellow with Aalborg University, Denmark, the University of Nottingham, U.K., and the University of Wisconsin-Madison, USA. He has 50+ IEEE journal papers and three patents. He is an Associate Editor for the IEEE Trans. on Industry Applications and the recipient of seven Best Paper Awards. He is a member of the Power Electronics Interdepartmental Laboratory established in 2017 with the Politecnico di Torino and a member of the Advisory Board of PCIM Europe. He is currently the Vice-President of the CMAEL Association, representative of the scholars in Power Converters, Electrical Machines, and Drives in Italy, and the Rector’s Advisor for Interdepartmental Centers of the Politecnico di Torino.