Adopting the Topology Optimization in the Design of High-Speed Synchronous Reluctance Motors for Electric Vehicles
Andrea Credo, Student Member, IEEE, Giuseppe Fabri, Member, IEEE, Marco Villani, and Mircea Popescu, Fellow, IEEE

Abstract—This article deals with the design of high-speed synchronous reluctance motors for electric vehicle applications. The need to enhance the power density and to lower the cost leads to research on high-speed motors with a reduced amount of rare earth. Pure synchronous reluctance motors potentially operate at high speed and exhibit a cost-effective rotor compared to permanent magnets and induction motors. Nevertheless, they present reduced performances in deep flux weakening operations, in particular when the so-called radial ribs are introduced to increase the mechanical robustness of the rotor. In this article, the introduction of the radial ribs and the related design challenges are investigated and discussed. The adoption of the topology optimization tool that is able to optimize the amount, the positioning, and the sizing of suitable structural ribs is presented. A design flow integrating the topology optimization is presented. The approach leads to an original positioning of the radial ribs able to preserve the performance of the motor at high operating speed enhancing the mechanical integrity of the rotor.

Index Terms—E-mobility, high speed, mechanical analysis, multiphysics approach, optimized ribs, rare earth (RE) free, synchronous reluctance (SynRel) machine, topology optimization (TO).

I. INTRODUCTION

THE electric machines have become the primary candidate for mobility [1]–[3], adopting motor solutions mainly based on high performance permanent magnets (PM) manufactured with rare-earth (RE) materials [4]–[6].

The imminent mass production of the electric vehicles (EV) arises concerns related to RE price volatility, their supply risks, and their sustainable extraction. Therefore, there is a growing attention on alternative solutions that include RE free machines or reduced RE machines [7]. In this context, the designers are pushed to increase the maximum operating speed of motor-drives to enhance the specific power, above all in absence of powerful RE magnets [8].

The previous considerations are supported by Table I, in which the motors with a higher maximum speed are the RE free motors, such as the induction motor and the PMA SynRel. Table I summarizes the main EVs sold in the EU and US markets, reporting the adopted technological solution for traction motors, the maximum operating speed and the main powertrain data, which are based on [6] and [9]. The maximum speed has been estimated by the authors when not available.

Synchronous reluctance motors (SynRel) are becoming of great interest in the recent years due to their potential cost effectiveness, efficiency, and performance [10]–[12]. When compared to the PM motors, conventional SynRel are known for their lower specific (peak) power and specific (peak) torque, higher noise and lower power factor. Nevertheless, adequate performances can be achieved through an optimized rotor design [13]–[15].

In particular, to compete with PM motors, the specific power in SynRel is enhanced by increasing the rotor operating speed and the flux-weakening region. The optimal electromagnetic rotor geometry for performance enhancement is challenging to adopt due to mechanical integrity issues at high speed. The so-called “ribs” (see Fig. 1) are usually included in tangential and radial directions in SynRel’s rotor geometry. They reduce...
TABLE I
TRACTION MOTORS FOR ELECTRIC VEHICLES (2018 AND 2019)

| Vehicle Model | Motor type | Max Power (kW) | Top speed (km/h) | Acceleration 0-100 km/h (s) | Transmission ratio | EM Max speed (rpm) | Battery energy (kWh) |
|---------------|------------|----------------|-----------------|----------------------------|-------------------|-------------------|---------------------|
| Audi e-tron 55 | IM / IM    | 125 / 140      | 200             | 6.6                        | 9.2               | 13000             | 95                  |
| Audi Q4 e-tron | IM / PMSM  | 75 / 150        | 180             | 6.3                        | 9.2               | 12000             | 82                  |
| BMW i3S 42    | - / PMASynRel | - / 135       | 160             | 6.9                        | 9.66              | 11500             | 42.2                |
| BMW i3S 33    | - / PMASynRel | - / 135       | 160             | 6.9                        | 9.66              | 11500             | 33.2                |
| Chevrolet Bolt | PMSM / -   | 150 / -        | 145             | 6.9                        | 7.05              | 8600              | 60                  |
| FIAT 500e     | PMSM / -   | 85 / -         | 141             | -                          | 9.59              | 12000             | 24                  |
| Hyundai e-Kona 64 | PMSM / -   | 150 / -        | 167             | 7.6                        | 7.98              | 10500             | 64                  |
| Jaguar I-Pace | PMSM / PMSM | 147 / 147      | 200             | 4.8                        | 9.04              | 13000             | 90                  |
| KIA Soul EV   | PMSM / -   | 81 / -         | 145             | 11.5                       | 8.21              | 9600              | 31.8                |
| KIA e-Niro 39 | PMSM / -   | 100 / -        | 155             | 9.8                        | 8.21              | 10000             | 39.2                |
| KIA e-Niro 64 | PMSM / -   | 150 / -        | 167             | 7.8                        | 8.21              | 11000             | 64                  |
| Nissan Leaf SL Plus | PMSM / -   | 160 / -        | 159             | -                          | 8.19              | 10500             | 62                  |
| Nissan Leaf SL | PMSM / -   | 110 / -        | 144             | 7.9                        | 8.19              | 9700              | 40                  |
| Renault Zoe R110 | WRSM / -   | 80 / -         | 135             | 11.4                       | 9.3               | 11000             | 45.6                |
| Renault Zoe Q90 | WRSM / -   | 65 / -         | 135             | 13.2                       | 9.3               | 11000             | 45.6                |
| Tesla Model X | IM / IM    | 193 / 375      | 250             | 3.7                        | 9.7               | 17000             | 100                 |
| Tesla Model X SR | PMSM / IM | 193 / 375      | 250             | 2.9                        | 9.7               | 17000             | 100                 |
| Tesla Model 3 | IM / IM    | 147 / 211      | 261             | 3.6                        | 9.7               | 20500             | 79.5                |
| Tesla Model S P100D | IM / IM | 193 / 375      | 250             | 2.4                        | 9.7               | 18000             | 100                 |
| Volkswagen e-Golf | PMSM / -   | 100 / -        | 150             | 9.6                        | 9.7               | 12000             | 35.8                |
| Volkswagen e-up! | PMSM / -   | 60 / -         | 130             | 12.4                       | 8.16              | 10000             | 18.7                |

PMSM = PM Synchronous Motor; IM = Induction Motor; PMASynRel = Permanent Magnet Assisted Synchronous Reluctance Motor; WRSM = Wound Rotor Synchronous Motor.

the mechanical stress in the rotor core and limit the maximum deformation at the airgap due to centrifugal forces. However, the motor performance is negatively affected by these ribs [16].

This article proposes the adoption of a topology optimization (TO) in the challenging tradeoff between the electromagnetic and mechanical design aspects of SynRels.

This article is organized as follows: Section II describes the requirements of the motor with reference to a high-speed liquid-cooled SynRel for full-electric premium vehicles and proposes a suitable electromagnetic design. Section III discusses the possible approaches to guarantee the rotor mechanical integrity at high speed focusing on the adoption of structural ribs. Section IV proposes the optimization of the structural ribs by using a TO and the obtained results are discussed in Section V, and Section VI concludes this article.

II. OPTIMIZED ELECTROMAGNETIC DESIGN OF SYNCHRONOUS RELUCTANCE MOTORS

The design of the SynRel for traction applications requires accurate sizing procedures that differ from the process of an industrial machine, which is designed to mostly operate at rated speed and torque. In traction motors, specific tools and optimization procedures [17]–[19] become essential tools for the design refinement in order to satisfy the challenging requirements over a wide speed range.

Table II reports the application requirements related to a premium EV. It is worth noting that at the base speed (5000 r/min) a high value of torque is requested; moreover, when the motor operates at the maximum speed (18 000 r/min) a significant amount of power is needed. The SynRel works in a deep flux weakening condition (the max-speed base-speed ratio is 3.6). Moreover, the high value of the maximum required speed of the motor is relevant for the specified diameters and it is above the state-of-the-art in Table I.

A high-voltage battery (800 V) has been selected to exploit the characteristics of the latest 1200 V power modules and sustain the performance of the machine at high speed [20].

To reach the severe requirements in Table II, it is useful to remind that the design of SynRels relies on the maximization of the saliency ratio \( \frac{L_d}{L_q} \), achieved by shaping the rotor geometry with several flux barriers per pole [21]. Tangential ribs are usually included in the optimal electromagnetic design for manufacturing reasons (see Fig. 1).

The saliency ratio and the electromechanical torque also depend on the number of poles and different combinations of slots/poles need to be evaluated.

In order to reduce the \( q \)-axis inductance maintaining the same \( d \)-axis inductance, and according to Taghavi and Pillay [22], a low number of poles can be chosen; however, this choice

TABLE II
MOTOR REQUIREMENTS FOR THE TARGET APPLICATION

| Requirements            | Constraints |
|-------------------------|-------------|
| DC Voltage              | V           | 800         |
| Specific Peak Power     | kW/kg       | > 4.0       |
| Specific Peak Torque    | Nm/kg       | > 8.0       |
| Peak Power              | kW          | 200         |
| Peak Torque             | Nm          | 380         |
| Peak Efficiency         | %           | > 95        |
| Maximum Speed           | rpm         | 18000       |
| Power @ Max Speed       | kW          | > 50        |
| Motor Mass              | kg          | < 50        |
| Outer Stator Diameter   | mm          | < 250       |
| Stack Length            | mm          | < 220       |
increases the torque ripple. Therefore, the 2-pole machine maximums the saliency ratio with a higher torque ripple.

Although this is true that the machines with a lower number of poles have a larger stator yoke that reduces the torque density; otherwise for a high number of poles it is hard to arrange a high number of flux barriers, penalizing the saliency ratio. It follows that the number of poles adopted in this type of applications is usually between 4 and 8.

In [1], different numbers of poles have been analyzed, optimized and compared (respectively, 4, 6, and 8), concluding that the 6-pole design presents the best performance.

About the barrier shape, “fluid shape” or “Joukowsky barriers” have been chosen [23]. This type of shape offers benefits in routing the $d$-axis flux increasing the direct inductance, whereas it has the same behavior as of other types of barriers (circular and rectangular) in the obstruction of the $q$-axis flux. Globally, the adoption of fluid shape presents a reduced torque ripple and advantages in the optimization steps.

The variables that are useful for the definition of the rotor shape are shown in Fig. 2.

The analytical expression of these barriers is computed from the following Joukowsky (or Zhukovsky) equation:

\[
 r_k(\theta) = R_s \sqrt{c_k + \sqrt{c_k^2 + 4 \sin^2(p\theta)}} \quad \frac{2 \sin(p\theta)}{c_k} \quad (1)
\]

\[
 c_k = \left(\frac{R_e + (-1)^k X_i}{R_e X_i}\right)^{2p} - 1 \quad (2)
\]

\[
 \{k = 1, \ldots, 2N_b - 1\} \quad i = \text{ceil} \left(\frac{k}{2}\right)
\]

where

- $R_s$ is the radius of the shaft
- $c_k$ is a constant, function of the position and the thickness of the barriers
- $p$ is the number of pole pairs
- $\theta$ is the mechanical angle
- $R_i$ is the position of the $i$th barrier
- $X_i$ is the width of the $i$th barrier
- $r(\theta)$ is the radius of the barrier curve

$N_b$ is the number of the barriers including the notch

$\text{ceil}$ is the function that gives the least integer greater than or equal to the input.

To design each barrier, it is necessary to define two curves and each curve is defined by a proper constant $c$. Since the usage of the Joukowsky equation is, as a matter of fact, a preoptimization of the shape of the barriers, a preliminary design can be easily carried out.

The approach is effective even in the next optimization steps of the rotor geometry; using the fluid shape rotor, the number of variables are contained, the results are very promising, and the computational effort is acceptable.

The pure electromagnetic optimization uses a total of 16 variables, where the constraints are the peak power and the motor mass: the objective functions are the power at maximum speed and the motor efficiency.

In detail, nine variables are related to the rotor: two for each barrier ($X_i, R_i$) and one for the notch ($X_{N_b}$). Four variables for the stator: tooth width, yoke height, number of slots per phase per pole, and number of conductors per slot. Three variables are general: stack length, current amplitude, and current angle.

The design data of the optimized solution are listed in Table III. It reports the main dimensions of the stator and the rotor, and the main performance required by the automotive application (see Table II).

The cross section of the 6-pole design, optimized from the electromagnetic point of view, is shown in Fig. 3. The tangential ribs, supporting the flux carriers, have a low impact on the performance. They are reported in this design only for completeness, but they are not used in the electromagnetic optimization.
III. ROTOR DESIGN CRITERIA FOR HIGH-SPEED SYNRELS

After the electromagnetic optimization, the rotor geometry needs to be refined from the mechanical point of view because it is necessary to guarantee the integrity of the rotor over the full operating conditions. The focus needs to be on the mechanical stress and on the deformation at the airgap caused by the centrifugal forces.

The structure in Fig. 3 is retained only by the thin tangential ribs. The mass and the position of the rotor steel generate high centrifugal forces at high speed, causing great stress on the tangential ribs. The equivalent von Mises stress in the ribs already reach the ultimate tensile strength of the adopted electrical steel (550 MPa) at 4500 r/min.

Different approaches are adopted in literature to mechanically improve the rotor retention with respect to centrifugal forces. The main ones are as follows.

1) Adoption of high strength electrical steel [24]: usually involves steels with lower magnetic properties.
2) Adoption of retaining sleeves [25]: it is problematic since it would require a material substantially stiffer than steel to decrease the radial deflection under inertial load.
3) Novel rotor constructions [26]: they need custom manufacturing process and custom spare parts.
4) Adopting properly rotor interconnecting end plates or interconnecting shaft (dovetails versus press fit) [27]: it is more effective for compact buried PM rotors.
5) Adoption of structural non-magnetic materials (epoxy resins, titanium, others) [25], [28], [29]; these are difficult to be interconnected with the rotor laminations and have an additional cost that has to be accurately evaluated.
6) Adoption of optimized structural ribs [1], [16], [30], [31]: this is one of the most studied research topics in SynRel and PM machines because the adoption of the ribs deteriorates the electromagnetic performance.

Considering the adoption of structural ribs, the approach is to increase the thickness of the tangential ribs and to include radial ribs in the rotor barriers, starting from the inner ones, to retain the rotor’s flux carriers. The number and the thickness of the ribs per pole increase significantly with the rotor speed.

After the optimal electromagnetic shape has been frozen, a mechanical optimization of the thickness of the ribs under centrifugal forces has been carried out. The structural optimization has been done by imposing as boundary conditions the allowable stress (under the yield strength) for the adopted electrical steel and the maximum deformation at the airgap. In detail, the total thickness of the ribs per flux barrier (tangential and radial) has been used as an objective function. This structural optimization allows to minimize the impact of the radial ribs on the machine performance. The optimized rotor geometry is shown in Fig. 4 with the computed equivalent von-Mises stress.

The performance of the motor is degraded by the insertion of the ribs, as expected; the details are provided in Section V, in which it can be seen the comparison between the optimal electromagnetic design and the ones with radial ribs and optimized ribs, respectively.

While the barrier shape has not been modified compared to the optimal shape for the flux, the introduction of the ribs affects the magnetic behavior of the rotor and it globally reduces the motor performance. This happens because a large part of the magnetic flux flows through these ribs, increasing the quadrature inductance \( L_q \).

This effect is more significant in traction applications, where the electric motor usually operates in heavy flux-weakening conditions, in which the quadrature current is predominant with respect to the direct one, restricting the voltage limit. Moreover, in premium vehicles the motor power required at low speeds and the one required at maximum speed are conflicting requirements.

Additionally, the presence of radial and tangential ribs increases the magnetic coupling between direct and quadrature axes, affecting the effectiveness of the control strategy. This leads to a reduction of the motor performances unless a nonlinear model obtained by finite elements (FE) computation is used in the control algorithm [32].

IV. ROTOR MECHANICAL DESIGN AIDED BY A TOPOLOGY OPTIMIZATION ALGORITHM

Referring to the rotor with radial ribs (see Fig. 4), the ribs are affected by the higher stress values; therefore the ribs thickness...
has been increased. It is worth recalling that the lower is the thickness of the ribs, the higher is their saturation, and then the higher are the motor performance. The idea is to reduce the ribs thickness in tangential and radial ribs by increasing their number in order to achieve an improved distribution of the mechanical load.

To improve the performance of the machine, a complete magneto-structural optimization of the rotor is desirable. In order to achieve that, a complex and heavily parameterized model would be needed to represent all the possible geometries; this strongly penalizes the speed of the optimization process. It seems relevant to obtain any possible hints on the optimal geometry to setup the most appropriate model for the magneto-structural optimization.

The optimization of the thickness and the positioning of the ribs seems to match the capabilities of the class of algorithms referred in mechanics as “Topology Optimizers.” [33], [34]

These algorithms are usually adopted to optimize the quantity and the positioning of the mass needed by a mechanical part to sustain the load. Moreover, in literature there are few examples of the TO used for the design of the SynRel. Sato et al. [35] uses the TO optimization with a normalized Gaussian network, but in this work only the average torque and the steel losses are considered. Watanabe et al. [36] focuses on the torque ripple with an ON/OFF TO, but he designs the machine considering only the electromagnetic performance. There are more works for other types of machines. Lee et al. [37] uses the TO for the refinement of the electromagnetic performance of a Switched reluctance motor, but he considers a linear material. Instead, Garibaldi et al. [38] applies the principles of the TO in the multiphysics design of a Surface Mounted PM motor considering the energetic aspects, without considering the torque ripple of the machine. Further studies are necessary to use a magneto-structural TO on the SynRel machine in order to consider both the nonlinearity of the material, the evaluation of the torque ripple, and the maximum stress in the steel.

Here, a FE topology optimization has been used to investigate the optimal positioning and thickness of the ribs attempting to minimize the mass inside the rotor barriers. The constraints imposed are the same maximum stress and the same deformation at the airgap of the analysis in Section III.

The TO method adopted in this study is the Solid Isotropic Microstructural (or Material) with Penalization for intermediate densities method available in a commercial tool. It is sometimes called “material interpolation,” “artificial material,” “power law,” or “density” method.

This method decomposes the solid part in a finite number of elements, referred to as microstructures and usually defined through the application of a mesh. The properties of each element are manipulated basing on a properly defined density $\rho$ [34].

When the element has the properties of the solid material, the density is defined as $\rho = 1$; contrarily, when the element has the properties of the air it is identified by $\rho = 0$. When the element has a density in the range $0 < \rho < 1$, its mechanical properties are between the ones of steel and air.

Initially, the method assigns the same density to all the elements and performs a mechanical analysis in order to evaluate the sensitivity of the density of each element respect to the objective function. Basing on the sensitivity analysis, the algorithm modifies the density of each element and repeats that until the algorithm reaches the convergence.

At the end of the iterative process, the algorithm should return elements with densities $\rho = 0$ (empty element) or $\rho = 1$ (solid element). Even if the optimal mechanical solution could consist of mostly elements with a density $0 < \rho < 1$, the so-called “grey” elements, they are not feasible in practice.

In order to obtain only empty and solid elements, the grey elements are penalized through a penalty coefficient $\gamma$ affecting the mechanical properties of the elements. The application of the penalty coefficient related to the Young modulus is reported in (3) as an example

$$E(\rho) = E_0\rho^\gamma$$  \hspace{1cm} (3)

where $E(\rho)$ is the Young modulus of the element; $E_0$ is the Young modulus of the adopted steel.

Setting the penalty coefficient to infinite, the solution will not have grey elements, but the convergence of the solution might not be reached. Typical values for the penalty coefficient are in the range from 3 to 9.

Fig. 5 reports different steps of the optimization algorithm, showing how the TO modifies the density of the elements in order to distribute the stress by adopting only empty and solid elements. Fig. 5(a)–(f) represent the progressing steps up to the final results.

The resulting geometry has achieved the goal to reduce the thickness of the ribs, finding a conceivable but unusual geometry, where further refinements are needed because:

1) the TO has only considered the mass distribution to counteract the centrifugal forces and not the electromagnetic performance of the machines;
2) the geometry of the fourth barrier has not been solved by the TO;
3) the resulting rotor shape has 6 interior ribs in the first barrier, but two of them are too thin to be manufactured; for this reason, the number of the internal ribs needs to be reduced to 4.

The investigation carried out by the TO provides useful guidelines about the preliminary design of the inner ribs in terms of quantity, positioning, inclination and thickness.

Therefore, the TO results can be adopted to build up a suitable parametric model to be used in a magneto-structural optimization performing independent structural and electromagnetic analyses at each optimization step.

By reducing the problem to half rotor pole for symmetry, each inner rib is described by three variables: position inside the barrier, inclination and thickness. Only the thickness defines the rib in the fourth barrier. The model reaches a total of 20 variables by including the thickness of the tangential ribs. The objective function and the constraints are listed in Table IV. The maximum allowed stress inside the rotor has been fixed at 360 MPa using a
TABLE IV

| Constraints and objective function                                      | Value      |
|------------------------------------------------------------------------|------------|
| Peak Torque @ 5000 rpm                                                 | Nm         | >380       |
| Phase voltage @ 5000 rpm                                               | V          | <400       |
| Torque ripple @ 5000 rpm                                               | %          | <10        |
| Phase voltage @ 18000 rpm                                              | V          | <400       |
| Motor mass (active materials)                                           | kg         | <48        |
| Maximum equivalent von Mises stress @ 18000 rpm                        | MPa        | <360       |

Objective: Maximization of the Torque @ 18000 rpm

safety coefficient of 1.5; this value is considered acceptable for the operating condition of the motor.

The whole design process has led to a new rotor layout with multiple ribs in different positions with respect to the flux barriers (see Fig. 6): a quite original geometry compared to the literature ones.

The magneto-structural optimization furtherly improved the TO results in terms of thickness, positioning, and inclination of the inner ribs. The mechanical equivalent von Mises stress map at the maximum speed (18 000 r/min) is reported in Fig. 7 and the maximum stress values are close to those in Fig. 4; from a mechanical point of view, the two designs have similar performance.

The design steps carried out to achieve the final design of high-speed SynRelS aided by a TO are summarized in Fig. 8.

V. RESULTS AND DISCUSSION

In this section, the three rotor layouts are analyzed and compared: namely, the optimal electromagnetic design with no radial
Fig. 8. Design flow involving the adoption of the topology optimization.

Fig. 9. Deformation at the airgap of the SynRel rotor: radial ribs versus optimized ribs at maximum speed.

The deformation at the airgap of the SynRel rotor: radial ribs versus optimized ribs at maximum speed. The deformation is within 10% of the airgap, ensuring enough margin to avoid the contact between the rotor and the stator. Even if the optimized design has a slightly greater deformation than the radial ribs solution, this is of minor relevance because of its reduced value when compared to the airgap length. Each design assures the needed clearance between the stator and the rotor; moreover, the maximum deformation is reached in the center of the pole (in correspondence of the notch), where the airgap results increased. The deformations in the notch are not critical, whereas outside the notch the optimized solution has a lower deformation than the radial ribs one. Otherwise, the magneto-structural optimization should include the maximum deformation at the airgap as a further constraint to assure the needed clearance.

Fig. 10 presents the saliency ratio over the speed range at the maximum performance of the machine varying the ribs layout. These results confirm a better distribution of the flux all over the speed range when the optimized ribs are used compared to the solution with radial ribs, whereas the “ideal” design with no ribs is still far to be equaled.

Figs. 11 and 12 report the behaviors of the $d$-axis and $q$-axis inductances related to the different layouts of the rotor. Both the inductances ($L_d$ and $L_q$) tend to increase when the ribs are included inside the barriers, and thus increasing the voltage drops into the motor. The adoption of the optimized ribs strongly reduces the values of the inductances in the flux weakening.
operations with respect to the classical radial rib solution. The flux-weakening strategy becomes easier due to the reduced voltage demanded by the motor at high speeds and the motor performance increases.

Figs. 13 and 14 show the performance of the motor over the speed range, respectively, in terms of torque and power varying the adopted ribs layout. The new rotor solution allows to gain up to 65% more power at high speed with respect to the layout with radial ribs. Other performances are listed in Table V, in particular the optimized layout gives also benefits for the power factor, for the efficiency and for the torque ripple.

Despite the complexity of the optimized geometry, no additional cost associated or manufacturing concerns are expected compared to the other presented geometries.

TABLE V

| Performance                      | no radial ribs | radial ribs | optimized ribs |
|----------------------------------|----------------|-------------|---------------|
| Peak torque                      | Nm             | 430         | 358           | 384           |
| Peak power                       | kW             | 287         | 230           | 250           |
| Peak efficiency                  | %              | 97.6        | 96.9          | 97.1          |
| Power @ max speed (18000 rpm)    | kW             | 110         | 35            | 58.5          |
| Power factor @ 200kW             | 0.64           | 0.46        | 0.51          |
| Power factor @ max speed         | 0.61           | 0.41        | 0.46          |
| Torque ripple @ max power        | %              | 8           | 14            | 10            |
| Max deformation @ airgap         | %              | 6.6         | 7.4           |
| Max equivalent von Mises stress  | MPa            | -           | 364           | 361           |

VI. CONCLUSION

Different types of motors are under evaluation for traction applications in e-mobility. Synchronous reluctance motors are becoming of great interest in the recent years and represent a suitable alternative for their simple and rugged construction. In this study, different solutions have been proposed and compared, with particular focus on the coupled electromagnetic and mechanical design aspects. Since the SynRel is designed with a small airgap and its rotor geometry is mechanically weak, the containment of the mechanical stress and of the deformation of the rotor is challenging at high speeds. Hence, in this study, a deep geometry optimization has been carried out with the aim to refine the rotor shape in order to achieve a better tradeoff between the rotor integrity and the motor performance. To this extent, a topology optimization has been used in order to obtain the guideline for the optimal positioning and thickness of the ribs, detailing the impact on the performance. The SynRel motor may not guarantee the same peak performances of IM and PM motors in automotive applications, especially when a high speed is required. Nevertheless, an accurate design can fill the gaps of other technologies and, when the cost aspect is relevant, it can be a valid solution. In particular, the synchronous reluctance
motor represents a potential candidate to reduce the use of RE materials in large mass production scenarios.

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Giuseppe Fabri (Member, IEEE) received the M.S. degree in electronic engineering and the Ph.D. degree in electrical and information engineering from the University of L’Aquila, Italy, in 2009 and 2013, respectively.

He is currently a Researcher in the field of power converter, electrical machines, and drives with the Department of Industrial and Information Engineering and Economics, University of L’Aquila, Italy. In 2013, he was a Research Fellow with the Industrial Electronics Laboratory, Swiss Federal Institute of Technology, Lausanne, Switzerland, where he was involved in the development of a real-time simulator for induction motors. His main research interests include design, development, control, and test of electrical machines and drives mainly related to fault-tolerant systems for aircraft and automotive applications.

Marco Villani received the M.S. degree in electrical engineering from the University of L’Aquila, Italy, in 1985.

He is currently an Associate Professor of Electrical Machines Design for the degree of engineering with the University of L’Aquila. In 1990, he joined the University of Dresden, Germany, as a Research Fellow, and later joined Nagasaki University, Nagasaki, Japan, in 1995. He became an Assistant Professor of power converters, electrical machines, and drives in 1993. He has authored more than 160 technical papers in scientific journals and conference proceedings. His research interests include modeling and design of electrical machines, optimization techniques for the electrical machines design, and design of PM synchronous motors and reluctance motors for industrial, automotive, and aerospace applications.

Mircea Popescu (Fellow, IEEE) received the M.Eng. and Ph.D. degrees in electrical engineering from the Politehnica University of Bucharest, Bucharest, Romania, in 1984 and 1999, respectively, and the D.Sc. degree in electrical machines from the Helsinki University of Technology, (now Aalto University), Espoo, Finland, in 2004.

He is currently a Chief Technology Officer with the Motor Design Ltd., a software and consultancy company headquartered in the U.K., with offices in the U.S., and has more than 30 years of engineering experience. Earlier in his career, he was with the Helsinki University of Technology (now Aalto University), Finland, and with the SPEED Lab, University of Glasgow, U.K. He has authored/coauthored more than 150 papers and is the recipient of the three IEEE Best Paper Awards. His consultancy contributions for industry are incorporated in many state-of-the-art products. His current major projects include electrical machines and drives for hybrid/electrical vehicles, and formula-e racing cars.

Dr. Popescu was an Officer of the IEEE Industry Application Society Electrical Machines Committee from 2010 to 2017.