Third-Order Harmonics in Synchronous Reluctance Motors With an Axially Laminated Anisotropic Rotor and Their Impact on the Motor Losses

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ABSTRACT The phenomenon of third-order harmonics in synchronous reluctance motors (SynRMs) with an axially laminated anisotropic (ALA) rotor is studied. The paper shows that a specific rotor geometry can distort the air-gap flux density and induce third-order currents in the stator winding if it is delta connected. The third-order currents in different phases have the same phase shift angle and cannot, therefore, produce a rotating air-gap flux. Instead, they produce an air-gap flux that pulsates in time, and thus, causes eddy current losses in the rotor conducting parts. The phenomenon was described and proven with finite element simulation (FEM) of a 12 kW high-speed ALASynRM. The research underlines the importance of considering the third harmonic phenomenon in the design of a two-pole ALASynRM intended for high-speed applications, where a specific rotor geometry with a wide magnetically conducting middle layer is required.

INDEX TERMS Axially laminated anisotropic rotor, ALASynRM, delta connection, high speed, high efficiency, inductance difference, saliency ratio, synchronous reluctance motor, slot harmonics, space harmonics, star connection.

I. INTRODUCTION
Synchronous reluctance motors with an axially laminated anisotropic rotor (ALASynRM) have been studied since 1966 [1]. Since then, ALASynRM has been extensively studied in [2]–[9]. The ALASynRM has demonstrated a better performance than the induction motor (IM) as part of an electrical drive with a frequency converter [3], [4]. Some aspects, such as the insulation ratio (defined as a ratio of nonmagnetic to magnetic material along the q-axis) of an ALA rotor have also been considered in the literature [4]–[8]. The natural advantage of the ALASynRM over the IM is the absence of the rotor slip-related losses. However, the ALASynRM has received little attention as a competitor of the IM in high-speed applications. In the references mentioned above, the ALA rotors are built by stacking magnetic and nonmagnetic layers and fixing them together with austenitic bolts. The mechanical strength limit of the bolts does not allow such an ALASynRM to be designed for high-speed applications.

The potential of axially laminated anisotropic rotor synchronous reluctance motors (ALASynRM) specifically in high-speed applications was considered in [9]. It was assumed that the proposed manufacturing methods of heat treatment (such as hot isostatic pressing, explosion welding, and vacuum brazing) can make the anisotropic rotor a solid structure. The validity of the vacuum brazing approach was confirmed with a prototype in [10].

In this paper, possible impacts of the thickness of the rotor middle layer on the electromagnetic performance of the machine are considered. The reason to have a wider middle layer is related to the mechanical robustness of the rotor and the fact that the rotor middle layer position coincides with the peak value of the d-axis air-gap flux density.
The joints between the layers located closer to the middle of the rotor studied in [9] are the most vulnerable points from the mechanical robustness point of view. The mechanical stress is highest in the middle and decreases gradually along the radius of the rotor. Therefore, a wider middle layer made of one piece of material increases the overall strength of the rotor. In addition, a middle layer widening up to a certain extent can increase the inductance difference between the d- and q-axes, providing a larger path for the d-axis flux while only moderately increasing the q-axis inductance. Thus, the optimal thickness of the middle layer can be an optimization target in the electromagnetic design.

The study of the impact of the middle layer on the ALASynRM performance is tightly related to the electric connection of the stator winding. A delta-connected distributed winding in a three-phase system can also conduct circulating third-order current harmonics, which can result in adverse effects as they do not provide torque but only produce losses.

The effect of spatial and time harmonics and their interaction in electrical drives is well known [11]. The higher order harmonics are desired to be attenuated (unless they are not operating harmonics responsible for torque production [12]), as they cause additional losses in different parts of the electrical machine. In machines with a rotating field produced by a three-phase distributed winding, the winding and permeance harmonics are treated as the most adverse ones, while the third-order harmonics of the air-gap flux density are usually not of importance in a star-connected stator winding (neglecting additional iron losses). The third-order harmonics can be caused, for example, by stator or rotor saturation [13]. The third-order saturation harmonics do not produce third-order currents (Joule losses) in a star-connected distributed winding. Rotor losses are also not affected by saturation harmonics as they both rotate with the synchronous speed (in synchronous machines), and no alternating flux penetrates the rotor to induce a Joule loss there. In permanent magnet synchronous machines, the third-order air-gap flux density harmonic can be produced by the permanent magnets [14]–[16] unless they are shaped to a form that provides a purely sinusoidal flux density [17]. In the case of a delta-connected winding, the third-order saturation- or magnet-shape-related flux density harmonics can induce circulating currents in the winding. In this regard, it is preferable to use a star connection. However, in many cases, because of the voltage limitation, a star connection cannot be used, and a delta connection helps in matching the flux linkage level of the machine.

In the present paper, by using an ALASynRM as an example, it is shown that the third-order flux density harmonics can also be produced by a specific rotor geometry, and as a result, the third-order currents can circulate in a delta-connected winding. Moreover, these third-order currents produce a pulsating (nonrotating) magnetic field of their own, which induces additional losses in the conducting rotor parts. The relation between the rotor geometry, the third-order current, and the rotor losses is demonstrated in a 12 kW high-speed ALASynRM with a three-phase delta-connected distributed winding. In the case of study, the efficiency is strongly affected by the rotor eddy currents induced by the third-order pulsating flux density harmonics in the air gap. These pulsating flux density harmonics are produced by the third-order current harmonics circulating in the delta-connected stator winding. In addition, the motor was also simulated with a star-connected stator winding, where no similar adverse effect was observed.

The content of the paper is the following: Section II provides the developed theoretical explanation of the third-order harmonic phenomenon in an ALASynRM with a specific rotor topology. Section III presents the initial data for the current study. In Section IV, the third-order harmonic phenomenon depending on the rotor middle layer thickness and the type of stator winding connection is observed with a finite element method (FEM) simulation. The main achievements of the study are summed up in the conclusion, Section V.

II. THEORY DEVELOPMENT
In a star-connected system, the third-order currents do not have a path to flow, and the losses related to the third-order currents are absent. In a delta-connected winding there is a path for the third-order currents, which may cause additional Joule losses. However, as it is shown in the paper, not only the additional Joule losses in a stator winding are caused by the third-order currents but also a distortion of the air-gap flux density with the third-order harmonics produces additional losses in the rotor conducting material. The sequence of the processes in the phenomenon can be presented as follows:

1) The rotor geometry distorts the rotating air-gap flux density (by means of uneven permeance distribution), producing a third-order component in the air gap. 2) The rotating third-order component of the air-gap flux density induces a third-order back-electromagnetic force (EMF) in the stator winding. 3) The third-order currents flow in the delta-connected winding. 4) These third-order currents have the same phase shift in each phase (it is the same current circulating in the closed loop with a frequency three times as high as that of the fundamental current) and produce a magnetic field of their own, which does not rotate but pulsates in the air gap. 5) The pulsating third-order air-gap flux density induces additional eddy current losses in the rotor conducting material. The given logic is considered in detail in the sections below.

A. AIR-GAP FLUX DISTORTION BY A SPECIFIC ROTOR GEOMETRY
This section schematically shows how the rotor with different geometries may distort the air-gap flux density. For simplicity, it can be assumed that the flux waveform produced by the stator magnetization is purely sinusoidal.

1) HOMOGENEOUS ROTOR
If the rotor is isotropic, the flux will not undergo any distortion caused by the rotor (except in cases where the
rotor saturates). In Fig. 1, the sinusoidal flux produced by the stator is not affected by the rotor as it is isotropic and assumed to have a constant permeability.

2) ANISOTROPIC ALA ROTOR WITH THIN LAYERS
If an ALA rotor is made of magnetic and nonmagnetic layers of equal thickness, the flux waveform will be distorted, because it is easier for the flux to travel through the magnetically conducting segments. Thus, the rotor will cause high-order harmonics in the air-gap flux density distribution with the ordinal equal to the number of layers ± 1. In Fig. 2, the total air-gap flux density contains the fundamental-flux-density- and rotor-geometry-related high-order flux density harmonics. If the layers are relatively thin, the rotor structure should not produce strong third-order harmonics.

3) ANISOTROPIC ALA ROTOR WITH A WIDE MIDDLE LAYER
In the case of an ALA rotor with a relatively wide middle layer, the flux has a less reluctant path in the middle of the rotor, and therefore, it becomes stronger there. Schematically, the total flux can look as shown in Fig. 3 (black line). The spectrum of such a wave has an evident third harmonic.

B. THIRD-ORDER HARMONICS PHENOMENON IN AN ALASynRM WITH A DELTA-CONNECTED WINDING
As it was stated previously, in the case of a relatively thick middle layer of an ALASynRM, the rotor may distort the air-gap flux density with an explicit third-order harmonic. This third harmonic of the flux density rotates with the rotor, Fig. 4. It is a spatial air-gap flux density third harmonic generated by the rotor anisotropy.

This spatial third harmonic of the flux density induces (when the magnetized rotor rotates) a third time harmonic of the back-EMF in the stator winding. If the winding has a nonzero winding factor for the third harmonic and it is delta connected, a third current harmonic will circulate in the closed loop. This third current harmonic is the same in each phase (having the same instantaneous value and phase shift in all three phases), and it can produce only a pulsating magnetic field in the air gap (while the original source of this third
pulsating flux density harmonic is the rotating third flux density harmonic caused by the rotor geometry, Fig. 4). This pulsating field of the third harmonic from the stator cannot synchronously interact with the third harmonic of the field which rotates with the rotor. The pulsating stator field, however, induces eddy current losses in the rotor. Thus, we may conclude that a large middle layer thickness is a reason for a pulsating field from the stator side, and consequently, can be a reason for significant rotor eddy current losses.

In the following analysis, we use the space vector presentation. The peak of the fundamental current was assumed to be equal to 1.1 per unit (pu), and the peak of the third current harmonic was assumed to be equal to 0.1 pu. Based on the current waveforms (Fig. 5), which comprise the fundamental and third current harmonic, the current linkages at the time instants $t_1$, $t_2$, and $t_3$ were estimated (Figs. 6 and 7). The space vector amplitude produced by the fundamental current linkage was assumed to be equal to 1 pu, which corresponds to the peak value of the total phase current in the winding in Fig. 5. In the space vector diagram (Fig. 6), the fundamental of the current linkage in each phase has either a 60-degree or a 120-degree phase shift with other phases in the space domain. The third harmonic of the current linkage in each phase has a phase shift of either 0 or 180 degrees, which is explained by the phase shift of 120 degrees between physical phases. This results in a phase shift of 120 degrees multiplied by 3 for the third current linkage harmonic. Consequently, depending on the direction of the total current linkage in a phase (positive or negative), its third current linkage harmonic has a phase shift of either 0 or 180 degrees as seen in Fig. 6b.

The third-order time harmonic of the current influences the current linkage in phases in such a way that the peaks of both the fundamental and the third harmonic of the current linkage vary in time. However, the total fundamental current linkage (Fig. 7) travels in the air gap over time (with the rotor speed) and has a constant peak value, and correspondingly, has a constant space vector amplitude (Fig. 6a). In contrast, the total third harmonic of the current linkage (Fig. 7) does not travel in the space domain over time but has a pulsating

FIGURE 5. Currents over time in all three phases ($I_U$, $I_V$ and $I_W$) in the study. The overall current (black line) includes the fundamental (red line) and third time harmonic (blue line).

FIGURE 6. Space vector diagrams of the current linkages at the time instants under consideration.

FIGURE 7. Current linkage, its fundamental, and the third harmonic.
behavior, and correspondingly, has a pulsating space vector (Fig. 6b). This third space harmonic of the current linkage, which has an in-time-pulsating behavior, is one of the main sources of the eddy current losses in solid elements of the rotor in the case of a delta-connected stator winding (shown in the following section).

In the case of a star-connected winding, the current linkages in the phases behave differently in comparison with a delta connection as there are no third-order time current harmonics. Detailed analysis of a star connection is well known and can be found, for example, in [11]. It is worth mentioning that at the time instant \( t_2 \), the current linkage harmonics with the star and delta connections are the same, because at that time instant in the delta connection the third-order time current harmonics equal zero, while with the star connection the total third-order current linkage harmonics are always absent.

III. INITIAL DATA FOR SIMULATION

The phenomenon described in the previous section is observed in an ALASynRM with a specific rotor geometry, which is demonstrated in the next section using the data obtained by simulation of the ALASynRM in the FEM software. This section provides the background and calculation of the approach for the simulation. The related data are only partially provided for the sake of readability, while the rest of the data are referenced.

A. RESEARCH BACKGROUND

The initial data were taken from [9]. The 12 kW ALASynRM was designed based on an initial 12 kW IM with a solid rotor equipped with copper end rings; the stator was the same while only the rotor was replaced by an ALA rotor. The detailed data of the stator and rotor of the reference IM can be found in [9]. In the ALASynRM, the rotor materials used for the magnetic and nonmagnetic layers are S355 and Inconel 718, respectively. These materials have similar thermal expansion coefficients, which makes them suitable for rotor manufacturing where heat treatment is involved. The relevant properties of the materials are reported in Table 1.

| Parameter                  | ALASynRM |
|----------------------------|----------|
| Output power, (kW)        | 12       |
| Speed, (rpm)              | 24000    |
| Torque, (Nm)              | 4.775    |
| Peak-to-peak torque ripple, (Nm) | 2.07 |
| Rated phase current RMS, (A) | 28.15 |
| d-axis synchronous inductance, (mH) | 4.43 |
| q-axis synchronous inductance, (mH) | 0.34 |
| Inductance difference, (mH) | 4.09 |
| Salency, \( L_L/L_q \)     | 13.13    |
| Stator winding losses, (W) | 92.67    |
| Stator iron losses, (W)   | 175.53   |
| Rotor Joule losses, (W)   | 205.62   |
| Total losses, (W)         | 473.81   |
| Efficiency, (%)           | 96.2     |
| Power factor              | 0.674    |

TABLE 1. Properties of S355 and Inconel 718.

| Symbol                      | S355     | Inconel 718 |
|-----------------------------|----------|-------------|
| Initial relative permeability | \( \sim 1000 \) | 1.001 (max) |
| Saturation flux density, (T) | 1.9      | -           |
| Electrical resistivity, (Ohm\cdot m) | 25.7\times 10^4 | 124.9\times 10^4 |
| Temperature coefficient of resistivity, (1/K) | 0.0038 | 0.0024 |
| Thermal expansion coefficient, (1/K) | 12.5\times 10^4 | 12.8\times 10^4 |
| Tensile yield strength, (MPa) | 300      | 1100        |
| Tensile ultimate strength, (MPa) | 520      | 1375        |
| Mass density, (kg/m³)        | 7870     | 8190        |

In [9] it was shown that the ALASynRM (designed taking into consideration thermal treatment-based manufacturing methods) provides a higher efficiency than the reference IM with either a smooth solid rotor or a slitted solid rotor with copper end rings. The performance of the 12 kW ALASynRM with a middle S355 layer of 6.5 mm and other layers being of 2 mm is reported in Table 2.

IV. OBSERVATION OF THE THIRD-ORDER HARMONIC PHENOMENON

The ALA rotor innermost joints between the layers experience the greatest mechanical stress during the motor operation. Therefore, from the viewpoint of mechanical robustness, the middle layer is desired to be wider than the layers on the sides. Moreover, the maximum d-axis current linkage takes place along the physical d-axis of the rotor, which makes it reasonable to have a wider magnetically conducting layer along the d-axis to maximize the inductance difference.

The initial 12 kW ALASynRM has a middle S355 layer of 6.5 mm and all other layers of 2 mm thickness. Thus, the increase in the middle layer thickness can be implemented with 8 mm steps (4 mm on each side: the 2 mm nonmagnetic layer becomes magnetic and combines with the next adjacent 2 mm magnetic layer, yielding a 4 mm increase in the
magnetic material on the sides of the middle layer). The procedure of the middle layer variation is shown in Fig. 8.

In the analysis, the initial design of the ALASynRM with the middle layer of 6.5 mm was assumed to be controlled with the maximum torque per ampere (MTPA) logic. However, with an increasing middle-layer thickness, the d-axis inductance and thereby the flux linkage increase with a certain supply current, and the rated voltage does not have a sufficient reserve to operate with the MTPA. Therefore, the current angle was increased above 45 degrees with the increase in the middle layer to stay within the voltage limit. Only the geometry where the middle layer is 6.5 mm was controlled with the MTPA as it does not exceed the maximum voltage. It is also clear that at some point of the middle layer expansion, the motor is not able to provide the rated torque with any control logic because of the weakening anisotropy. Nevertheless, the middle layer thickness was increased up to the point where the rotor became a homogeneous solid piece of S355, which makes sense from the viewpoint of observing the third harmonic phenomenon. At the point where the middle layer thickness became 70.5 mm, the motor could no more provide the rated torque. From that point with a further increase of the middle layer onwards, the supply voltage was kept rated while the supply current was decreased, and the current angle was kept the same as with the middle layer thickness of 62.5 mm. The d-axis and q-axis components of the current source supply can be seen in Fig. 9, where also the phase rms current is shown. In the case of the star connection, the relation between the phase rms current and the d- and q-axis current components follows the equation [18]

$$I_{\text{rms}} = \sqrt{I_d^2 + I_q^2}.$$  \hspace{1cm} (1)

In the case of the delta connection, the rms value of the phase current is not in agreement with equation (1), which is explained by the additional third-order currents circulating in the winding. The d- and q-axis currents of the current source fairly coincide for the delta and star connections.

The spectrum analyses of the phase current as a function of middle layer thickness are provided for the delta and star connections in Figs. 10 and 11, respectively. In both cases, the current fundamental simply corresponds to the d- and q-axis supply currents in Fig. 9. In the case of the delta connection, the third current harmonic is significantly impacted by the middle layer thickness (Fig. 10). The third current harmonic increases with the thickness of the middle layer until the thickness of 70.5 mm. With the further enlargement of the middle layer, the third current harmonic starts to decrease to the value of zero when the rotor becomes isotropic. With the middle layer thickness of the range between 62.5 and 86.55 mm, the third current harmonic exceeds the fundamental, which results in a total harmonic distortion factor of more than 100%. The phase current in the star-connected winding has only a fundamental component (Fig. 11), because purely sinusoidal current sources were used in the simulation, and no third-order currents have a path to flow.

The air-gap flux density spectrum analyses are provided for both the delta and star connections in Figs. 12, 13 and 14, 15, respectively. For the sake of readability, the spectrum analyses are provided only for five rotor geometries, and the corresponding harmonic content is shown only up to the 25th harmonic. The evaluation of the stator and rotor harmonics was made by the two-dimensional fast Fourier
The pulsating third harmonic of the flux density produced by the delta-connected stator winding does not rotate but has the frequency of $\frac{f_{\text{syn}} \cdot \nu}{\nu}$, and according to the logic of separating the stator and rotor harmonics, it should belong to the rotor harmonics. However, as the third harmonic produced by the rotor is the original source of the third harmonic produced by the stator side, the rotor third harmonic suppresses the stator third harmonic. Thus, the total third harmonic of the air-gap flux density rotates with the synchronous speed of the rotor $\omega_{\text{syn}}$ and has a pulsating behavior. The pulsating behavior of the total third harmonic is explained by the fact that the pulsating third flux density spatial harmonic, which is produced by the third current harmonic in the delta-connected winding, opposes the third flux density harmonic with a constant peak, which is produced by the rotor.

In contrast, in the case of the star connection, the total third harmonic of the air-gap flux density is simply the rotor-produced third flux density harmonic. Therefore, the peak of the third flux density harmonic is larger with the star connection than with the delta connection (Figs. 13 and 15). The behavior of the overall third harmonic in the air gap during one electrical period in star- and delta-connected machines is illustrated in Fig. 16 with the example of the ALASynRM with the middle layer thickness of 54.5 mm.
is equal to the rotor diameter, which means that the motor is homogeneous in that case. In principle, such a rotor cannot distort the penetrating flux (Fig. 1), and all the rotor-produced harmonics (including the third order) are absent (Figs. 12–15).

The d-axis and q-axis inductances, inductance difference, saliency, and power factor (Figs. 17, 18) slightly differ in the cases of the delta and star connections because of the third-order currents and the impact of the flux harmonics in the delta-connection case. In Fig. 17, the curves of the d-axis inductance, q-axis inductance, and inductance difference have a logical regularity. At the initial stage of the increase in the middle layer thickness, the d-axis inductance increases stronger than the q-axis inductance. This results in a small increase in the inductance difference. With a further increase in the middle layer thickness, the inductance difference decreases insofar as the q-axis inductance starts increasing stronger with the increasing the middle-layer thickness. In Fig. 18, despite the noticeable decrease in saliency, the power factor does not have such a significant change before reaching 62.5 mm of the middle layer thickness. This is due to the control logic variation. Even though the saliency reduces, the current angle increases to stay in the voltage limit, which partially compensates the power factor drop. When the middle layer is larger than 62.5 mm, the power factor decreases dramatically as both the saliency and inductance difference steeply decline, and the current angle is no more increased.

In Figs. 19 and 20, the losses in different parts of the motor as a function of middle layer thickness are shown for both the delta and star connections, respectively. The winding Joule losses have simply the same profile as the phase RMS currents in Fig. 9, as the Joule losses are proportional to the square of the RMS currents. In Figs. 9, 10, and 19, it can be seen that at a certain point of the increase in the middle layer, the amplitude of the third phase current harmonic is comparable with the fundamental and constitutes a significant part of the winding Joule losses.
In the case of the delta connection, the strongest contribution to the efficiency reduction is caused by the rotor losses. With the relatively thin middle layer, the rotor losses are mostly stator-slotting-effect-caused eddy current losses (winding harmonics are strongly reduced by short pitching). However, when the middle magnetic segment is 38.5 mm or larger (up to 86.5 mm), the rotor losses alone exceed the sum of the stator losses. In cases with a relatively wide middle layer and a delta-connected stator winding, the third phase winding current harmonic in the time domain is the main reason for the large rotor losses.

With an increase in the middle layer thickness in both cases with the star- and delta-connected windings, the proportion of losses in S355 grows and the proportion of losses in Inconel 718 decreases mainly because the amount of S355 increases and the amount of Inconel 718 decreases in the rotor. However, the loss distribution between S355 and Inconel 718 can also be affected by the thickness of the layers themselves (only the middle layer thickness in this case) because the damped energy of the high-order flux density harmonics can be differently distributed between the layers in cases with different thicknesses [19]. This phenomenon is not, however, in the scope of this paper.

The total rotor losses in the star-connected case are dictated by the trends of losses in S355 and Inconel 718. There is a local minimum in the rotor losses at the middle layer thicknesses of 38.5 mm and 46.5 mm. Therefore, if the adjustment of the middle layer can minimize the rotor losses by a larger value than the increase in other loss components, it could be beneficial to have a thicker middle layer with a star-connected winding, especially when the mechanical robustness of the rotor is crucial.

In Fig. 21, the current density distribution is provided for the cases with the delta connection and the middle layer thicknesses of 6.5 mm (b) and 54.5 mm (c), and for the case with the star connection and the middle layer thickness of 54.5 mm (d). As it can be seen in Fig. 21b, the direction of the current in the rotor varies with the stator slot periodicity, because the eddy current losses are mainly caused by the stator slot-opening-caused flux density harmonics. In the case of the star connection with the middle layer thickness of 6.5 mm, the current density distribution in the rotor is similar to the one in Fig. 21b (and is therefore not provided). Thus, when a rotor does not produce the third harmonic, the type of stator winding connection is of no importance. However, in Fig. 21c and d, the current densities in the rotors with middle layers of 54.5 mm differ significantly for the delta and star connections. With the delta connection, the direction of the current density is mainly changed with the evident third harmonic periodicity in the space domain. The stator slot flux density harmonics also induce some currents in the rotor, but they can hardly be observed in the current density map because they are obscured by the dominating third harmonic current. In contrast, with the star connection, the current density has a pattern representing only the stator slot periodicity (similarly to the case with the middle layer thickness of 6.5 mm) because no third stator current time harmonic, which causes the pulsating third flux density space harmonic, is present in the star connection.

Thus, the phase current in the time domain spectra (Figs. 10, 11), the air-gap flux density in the space domain spectra (Figs. 12–15), the behavior of the third harmonic of the air-gap flux density in time (Fig. 16), the rotor losses (Figs. 19, 20), and the rotor current density distributions (Fig. 21) in the motors under study are coherent. The observed regularities related to the third harmonic phenomenon verify the theory described in Section II. This third harmonic phenomenon can be the main source of rotor eddy current losses in the ALASynRM with a certain middle layer thickness and a delta-connected winding.

The stator iron losses change mainly depending on the third flux density harmonic produced by the rotor as the fundamental is kept approximately constant (with a constant terminal voltage), Figs. 12, 14. The dependences of the iron losses differ slightly in the delta and star connection cases, because in the delta connection the third flux density harmonic from the rotor side is reduced by the stator pulsating flux density harmonic, Fig. 14.

Fig. 22 represents the torque ripple dependence on the thickness of the middle magnetic layer. When the winding is star connected, the torque ripple is smaller with the larger thickness of the middle layer, because the number of the magnetic layers interacting with the stator teeth decreases. However, when the winding is delta connected, the torque ripple dependence is different. Even though, similarly to the star connection, with the thicker middle layer the number of magnetic layers interacting with the stator teeth decreases, the pulsating third-order flux density harmonic produced by
the stator additionally distorts the total air-gap flux density. As a result, the torque ripple does not decrease as significantly as in the case with the star connection when the middle layer is increased from 6.5 to 22.5 mm, and with the further expansion of the middle layer, the torque ripple increases as the third flux density pulsating harmonic generated by the stator becomes larger.

The efficiency (Fig. 23) of the delta-connected design is very vulnerable to an increase in the thickness of the middle layer. In the case of the star-connected design, however, the efficiency does not decrease but even improves by some hundreds of percent benefiting from the reduction in the rotor losses when the middle layer thickness is increased up to 38.5 mm. A small reduction in the efficiency is observed when the middle layer thickness is increased larger than 38.5 mm, which comprises 39% of the rotor diameter. Thus, the middle layer can be up to 40% of the rotor diameter without a negative effect on the efficiency when a star connection is used. Such an increase of the middle layer can be useful to stay within the mechanical restrictions and to simplify the manufacturing process.

![FIGURE 22. Peak-to-peak torque ripple as a function of middle layer thickness when the winding is delta or star connected.](image)

![FIGURE 23. Efficiency as a function of middle layer thickness when the winding is delta or star connected.](image)

V. CONCLUSION

The paper has demonstrated the importance of a rotor geometry together with a winding connection in an ALASynRM designed for high-speed applications. It has been shown that the rotor with a special geometry, particularly with a relatively thick magnetically conductive middle layer, can cause strong third-order currents in a delta-connected stator winding. These currents do not have a phase shift in time (in fact, it is a single current circulating in a closed loop). Therefore, they generate a third-order space flux density harmonic, which does not rotate but pulsates in time, inducing eddy current losses in the conducting rotor. A detailed explanation of this phenomenon is provided and supported with 12 kW ALASynRM FEM simulation results.

If the middle layer of the rotor is relatively thin, the motor should not experience a strong third harmonic phenomenon caused by the rotor geometry even when the stator winding is delta connected. However, in a high-speed ALASynRM, a large thickness of the magnetically conducting middle layer can be desired from the mechanical robustness point of view. In this case, the delta connection of the stator winding is advised to be avoided. In contrast, if the winding is star connected, thickening the middle layer until a certain value does not have a negative impact on the electromagnetic performance.

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