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Comparative analysis of cross-saturation phenomenon in the synchronous reluctance machine of a 6 and 3-phase winding

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Abstract: The paper deals with research on the direct and quadrature axis cross saturation effect in the synchronous reluctance machine (SynRM). The comparative analysis between the performance of the 4-pole SynRM of 3-phase and 6-phase windings have been conducted exploiting developed 2D finite element models. In the numerical models of the studied machines, the locked rotor method was adopted in which the direct (d) and quadrature (q) axis currents i_q and i_d were forced to determine magnetic fluxes in the d - q axes, respectively. Next, determined magnetic flux maps have been used to determine a simple analytical model taking into account the cross-saturation effect. The quality of the proposed analytical description of the cross-saturation phenomenon has been evaluated by comparison to the results of simulations in order to assess the possibility of adapting this description in the control algorithms of SynRM drives.

Key words: cross saturation effect, finite element method, multiphase, SynRM

1. Introduction

Research aimed at the development of electromobility is increasingly looking for alternatives to the use of costly and environmentally harmful rare earth materials. Due to the high durability, low cost and development of power electronics, research teams are paying increasing attention to synchronous reluctance machines (SynRM). From a mechanical point of view, when comparing a SynRM and one of the most widely used squirrel-cage induction machines, the differences can only be seen in the rotor design. The SynRM rotor is made of laminated steel plates so that the magnetic circuit is characterised by the greatest possible reluctance asymmetry in the direct (d) and quadrature (q) axes. This design significantly reduces production costs. Furthermore, the absence of permanent magnets eliminates demagnetisation problems at high temperatures and increases endurance [1–3].

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According to the operating principle of SynRMs, the rotor speed remains independent of the applied load. As in other classical synchronous machines, the synchronous speed is determined by the supply frequency and the number of pole pairs. Unfortunately, this means that SynRMs do not have a starting torque and it is necessary to power them from dedicated inverters and control systems [4].

Increasing efforts aimed at improving the durability and fault tolerance of electrical machines have led to growing interest in multiphase machine structures. When implemented in SynRMs, multiphase windings offer several advantages, including enhanced torque capability, reduced torque pulsations, and suppression of higher-order harmonic components [5]. Undoubtedly, the use of multiphase electrical machines is made possible by the dynamic development of power electronics. As the number of phases rises, so does the component count required for a power converter. Economically, such a solution is still viable, assuming that increasing the number of switching circuits distributes the current over more paths. This significantly reduces the power of the switching components used and therefore their price. Furthermore, when considering the previously mentioned endurance of multiphase machines, the term must be broken down into two parts. Reliability, which decreases as the number of components increases because the possibility of failure increases, and immunity, which rises as the number of phases of the system increases because the possible effects of a single-phase failure (power asymmetry) have a lower impact on machine performance, are less. The immunity factor is always greater than the reliability component, which is why the endurance of multiphase machines is greater than that of classic 3-phase designs [5, 6].

Magnetic saturation in AC electrical machines is a well-established phenomenon, and numerous modelling approaches have been developed over the past decades to incorporate its effects into machine design and performance analysis. Nevertheless, experimental investigations conducted under both steady-state and transient operating conditions have repeatedly revealed discrepancies between predicted and measured characteristics. These deviations are primarily attributed to incomplete or insufficiently accurate representation of core magnetic saturation in analytical models.

In the early stages of electrical machine theory, magnetic saturation was determined in design calculations by empirical correction of equivalent circuit parameters. The calculated results were subsequently validated against prototype measurements, and the model parameters were iteratively adjusted to achieve agreement between analytical predictions and experimental performance. Although this methodology remains in use, its applicability in modern design processes is limited due to the economic and time-related costs associated with prototype construction and testing.

Field-based numerical models, particularly those employing finite element methods (FEMs), enable detailed representation of nonlinear magnetic material characteristics and allow accurate assessment of saturation effects without extensive prototyping. However, due to their substantial computational complexity, such models are not directly suitable for real-time implementation in control systems of AC drives.

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In the context of field-oriented control (FOC), which relies on Clarke and Park transformations, magnetic saturation manifests as nonlinear relationships between the stator flux linkages Ψ_d and Ψ_q and the corresponding direct- and quadrature- axis currents i_d and i_q . Importantly, saturation introduces coupling between the axes: the flux linkage Ψ_d becomes dependent not only on i_d but also on i_q , and similarly, Ψ_q becomes dependent on both current components. This mutual interaction is commonly referred to as cross-saturation.

While the cross-saturation phenomenon has been extensively investigated in conventional three-phase synchronous reluctance and permanent magnet machines [7–10], its characteristics in multiphase electrical machines have not yet been comprehensively analyzed. The increased number of phases modifies the spatial harmonic content of the magnetomotive force distribution and alters the magnetic loading conditions, potentially influencing both self-saturation and cross-saturation mechanisms.

Therefore, this paper aims to investigate the influence of multiphase system configurations on the cross-saturation phenomenon in SynRM, with particular emphasis on its modelling implications for control-oriented representations.

In this paper, an attempt has been made to analyse the cross-saturation phenomenon in a SynRM of three winding variants, namely:

- a) 6-phase double layer,
- b) 3-phase single layer and c),
- 3-phase double layer windings.

By applying the locked-rotor method together with the developed numerical field–circuit models of the analysed machines, the magnetic flux linkages along the d and q axes were determined, while considering the influence of the i_d and i_q current components. Interpretation of the results, as well as determination of the analytical model of the cross-saturation effect (CSE), have been carried out using the MATLAB environment. The effectiveness of the proposed analytical description of the CSE was evaluated in the context of its future application in control algorithms of SynRMs.

The paper is organized as follows: Section 2 describes the cross-saturation phenomenon, Section 3 compares 3-phase and 6-phase systems, Section 4 presents the calculation method and analytical model, while Section 5 provides conclusions on the performance of the cross-saturation effect in multiphase machines.

2. Cross saturation phenomenon

The magnetic properties of the materials used in electrical machines impose a nonlinear relationship between the magnetic flux and the armature current. This relationship, which arises from the phenomenon of cross-saturation, is difficult to estimate accurately and efficiently. In most applications, this effect is neglected, and vector control of electric drives is implemented under the assumption of a linear dependence of the magnetic flux on the armature current. Such an assumption is acceptable for machines operating under steady-state conditions, where cross-

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saturation plays only a minor role due to the operating range remaining within the linear portion of the $\Psi = f(i)$ characteristic.

However, this situation changes drastically during dynamic variations in machine speed or load. In such cases, large armature currents are forced, pushing the magnetic flux Ψ beyond the linear part of the characteristic. Consequently, control algorithms fail to accurately reflect the true operating state of the machine, and deteriorate the quality of control. This leads, among others, to increased losses and torque ripples and a series of other undesirable effects [11].

In response to the challenges described above, the dq model provides a practical solution. Originally, the Park transformation was introduced to simplify the control of multiphase electrical machines by replacing the phase vectors of the natural coordinate system with the dq vectors corresponding to the direct and quadrature axes. This method offers an ideal framework for describing the mutual interactions of magnetic flux components in a machine, as these interactions can be represented analogously by the coupling of the orthogonal dq vectors.

In this article, a multiphase synchronous reluctance machine (SynRM) is analysed. To investigate the phenomenon discussed above, it is necessary to formulate a vector model describing the machine's voltage equations. This requires applying the Clarke–Park transformations, which convert the natural coordinate system into an equivalent dq vector system. The transformed vectors can then be expressed by the following equations:

$$v_d = R_s i_d + \frac{d\Psi_d}{dt} - \omega_e \Psi_q, \quad (1)$$

$$v_q = R_s i_q + \frac{d\Psi_q}{dt} + \omega_e \Psi_d, \quad (2)$$

$$\Psi_d = i_d(L_s + L_{dm} + L_{qd}), \quad (3)$$

$$\Psi_q = i_q(L_s + L_{qm} + L_{dq}). \quad (4)$$

where: v_d and v_q are the voltages in the direct and quadrature axes, respectively, R_s is the stator resistance, i_d and i_q are the currents in the direct and quadrature axes, Ψ_d and Ψ_q are the flux components in the direct and quadrature axes, ω_e is the electrical rotor angular speed, L_d and L_q are the inductances in the direct and quadrature axes, L_{qd} and L_{dq} are the mutual inductances between the direct and quadrature axes, L_{dm} and L_{qm} are the direct and quadrature axes magnetizing inductances, respectively, L_s is the stator leakage flux inductance.

At the same time, in order to account for the cross-saturation effect (CSE) in the SynRM, the inductances L_d and L_q (which form the flux components Ψ_d and Ψ_q) must include mutual inductance components L_{qd} and L_{dq} (see (3), (4)), which represent the coupling between the flux linkages. In most standard control algorithms for electrical machines, the magnetic coupling between the direct and quadrature axes, i.e., the impact of the cross-saturation phenomenon, is typically ignored. Under steady-state operating conditions and for machines that are not driven into saturation, this simplification is often acceptable [12]. In contrast, during dynamic transients, the currents in the d and q axes and consequently the magnetic fluxes vary rapidly. Due to the nonlinear nature of the magnetic circuit and its complex geometry, these variations lead to a deterioration of control performance if cross-saturation is not taken into account [13].

To properly incorporate the CSE in the SynRM model, the inductances L_d and L_q in the equivalent circuit must include the mutual inductance term L_{qd} , as illustrated in Fig. 1.

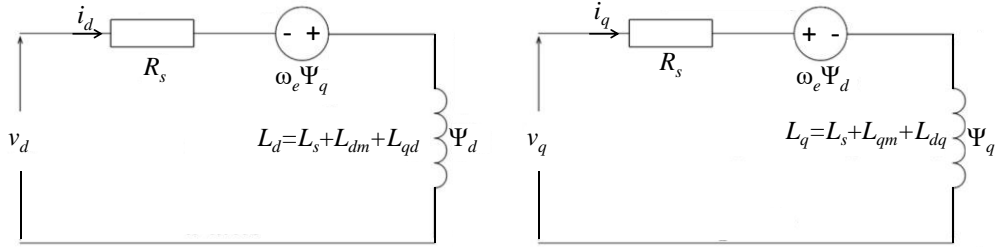


Fig. 1. Equivalent circuit model of SynRM including CSE

3. Analysis of cross saturation effect

In the proposed approach, the inductances L_{dm} , L_{qm} , and L_{qd} , L_{dq} are nonlinear functions of i_d and i_q calculated on the basis of the magnetic field distribution determined by the developed numerical models. In order to compare the CSE phenomenon, three variants of the SynRM motor with the same core geometries and different configurations of coil arrangement in the slots were modelled – see Fig. 2.

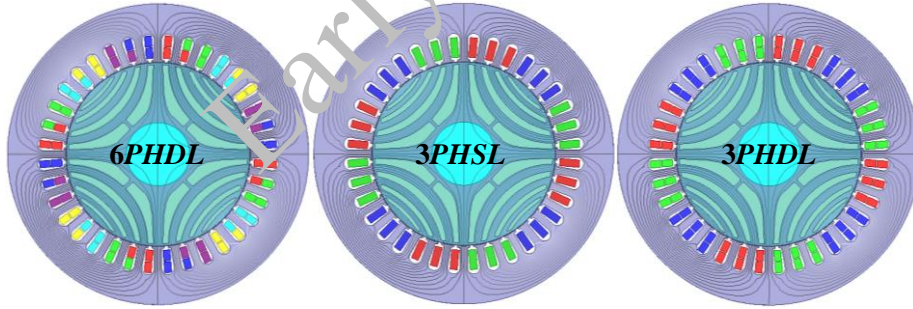


Fig. 2. Considered SynRMs: (a) 6PHDL; (b) 3PHSL; (c) 3PHDL

In order to distinguish between the studied variants, the following nomenclature was adopted: six-phase double layered - 6PHDL, three-phase single layered - 3PHSL, three-phase double layered - 3PHDL. The analysis was performed using the models of the machine described in [14]. Determined dependences of direct Ψ_d and quadrature Ψ_q fluxes and on changes of the i_d and i_q currents for 6PHDL have been illustrated as 3D plots shown in Fig. 3. It can be observed that the greatest flux changes $\Psi_d = f(i_d)$ caused by the current i_q occur at the area of saturation of the magnetic circuit. It follows that the saturated d -axis circuit is most susceptible to the influence of the Ψ_q flux.

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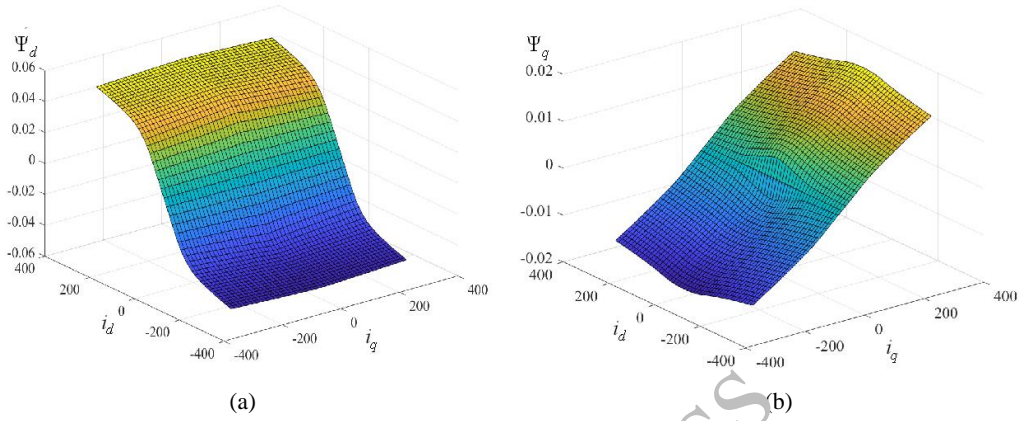


Fig. 3. Magnetic flux as a function of currents i_d i_q (a) Ψ_d ; (b) Ψ_q

The machine's maximum operating current is set to 300 A. By examining the resulting data in two-dimensional plots at the maximum values of i_d and i_q , the precise impact of the currents in the d and q axes can be clearly observed in Fig. 4.

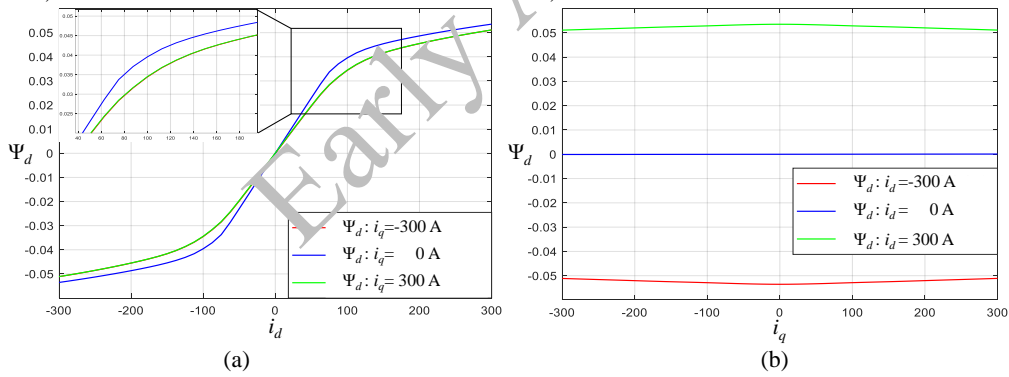


Fig. 4. Influence of i_q and i_d currents on magnetic flux for 6PHDL: (a) $\Psi_d = f(i_d)$; (b) $\Psi_d = f(i_q)$

It can be seen that the effect of i_q on the direct axis flux is symmetrical: regardless of whether i_q is positive or negative, it consistently leads to a decrease in Ψ_d . Given this behaviour, the CSE characteristics of the analysed SynRM machines can be directly compared.

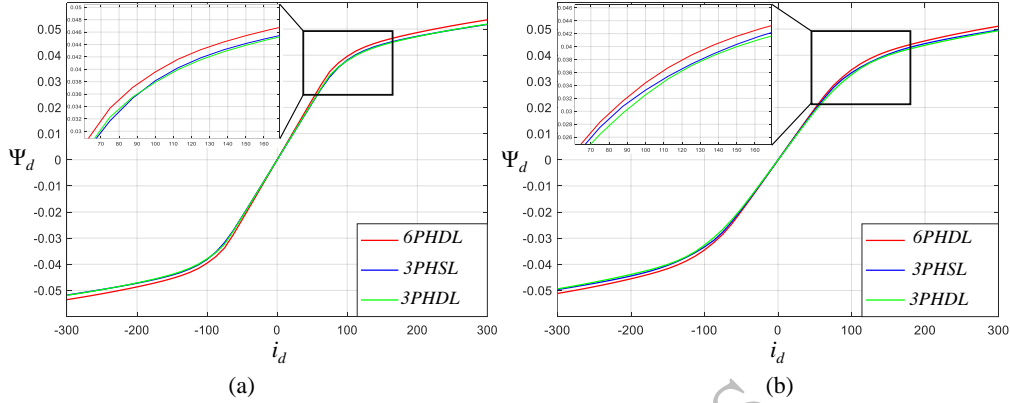


Fig. 5. Comparison of the influence of the i_q current on the Ψ_d flux of studied machines:

(a) $i_q = 0$ A; (b) $i_q = 300/-300$ A

It can be concluded that the CSE is primarily governed by the geometry and magnetic characteristics of the machine's magnetic circuit. From Fig. 5, it is evident that the configuration of the 3-phase winding has a negligible impact on the flux distribution - there are practically no noticeable differences between single-layer and double-layer windings. However, it should be emphasized that altering the number of phases, and thus modifying the field distribution within the machine, leads to a slight increase in Ψ_d in the saturation region.

4. Circuit model of the CSE

As discussed in the introduction Section, direct implementation of field models for controlling SynRMs is not possible due to the high computational complexity of these methods, which exceeds the capabilities of control systems and requires real-time operation. Therefore, to meet the requirements for control systems' performance, the lumped-parameter models are commonly used.

Taking the above considerations into account, the authors proposed an analytical model of a synchronous reluctance machine that considered the cross-saturation phenomenon. To demonstrate the impact of cross saturation on the dynamic performance of the SynRM drive, three cases have been considered:

- linear - in which the inductance values L_d and L_q are assumed to be constant $L_d = L_{d-\text{const}}$, $L_q = L_{q-\text{const}}$ and the CSE as well as core saturation are neglected,
- nonlinear neglecting the CSE - in which the inductance values are assumed to be characteristics $L_d = L_{d-\text{no-cse}} = f(i_d)$ for $i_q = 0$ A and $L_q = L_{q-\text{no-cse}} = f(i_q)$ for $i_d = 0$ A,
- nonlinear with the CSE - in which the inductance values are taken as characteristics $L_d = L_{d-\text{cse}} = f(i_d, i_q)$ and $L_q = L_{q-\text{cse}} = f(i_q, i_d)$.

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To determine the values of inductances L_d and L_q for the lumped parameter model of the synchronous machine on the basis of determined $\Psi_d(i,j)$, $\Psi_q(i,j)$ matrixes, the following formulas are used:

$$L_{d\text{-cse}}(i,j) = \frac{(\Psi_d(i,j) - \Psi_d(i-1,j))}{di_d}, \quad (5)$$

where: $L_{d\text{-cse}}$ is the nonlinear inductance, taking into account the cross-saturation effect, i is the index of the i_d vector, and j is the index of the i_q vector.

$$L_{d\text{-no-cse}}(i-1) = \frac{(\Psi_d(i,i_{q0}) - \Psi_d(i-1,i_{q0}))}{di_d}, \quad (6)$$

where: $L_{d\text{-no-cse}}$ is the nonlinear inductance neglecting the cross-saturation effect, i_{q0} is the index of the q -axis current equal to 0, and i is the index of the i_d vector.

Analogical formulas were used to determine inductances in the q -axis. The linear inductances $L_{d\text{-const}}$, $L_{q\text{-const}}$ were determined as maximum values of $L_d = L_{d\text{-no-cse}} = f(i_d)$ for $i_q = 0$ A and $L_q = L_{d\text{-no-cse}} = f(i_q)$ for $i_d = 0$ A, and are equal to 0.019 H and 0.002 H, respectively.

The characteristics in Fig. 6 show the calculated inductances L_d and L_q as a function of currents i_d and i_q , taking the CSE into account.

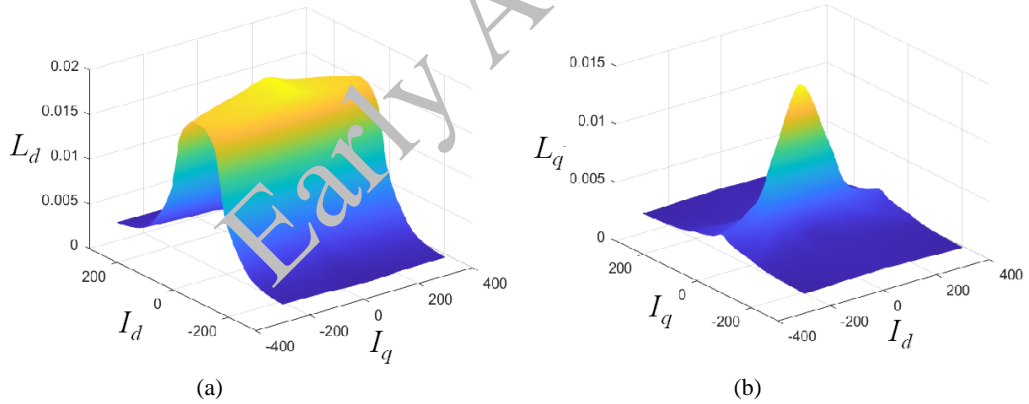


Fig. 6. Direct and quadrature inductances taking into account CSE: (a) $L_d = f(i_d, i_q)$;

(b) $L_q = f(i_q, i_d)$

The developed circuit model of a SynRM drive was implemented in the MATLAB Simulink/Simscape environment. The model of the drive system consists of a SynRM, frequency converter, power supply and control system. The FOC and speed control algorithm were implemented. The SynRM is loaded by mechanical load defined by inertia and torque-load values. The block-diagram of the developed model is shown in Fig. 7.

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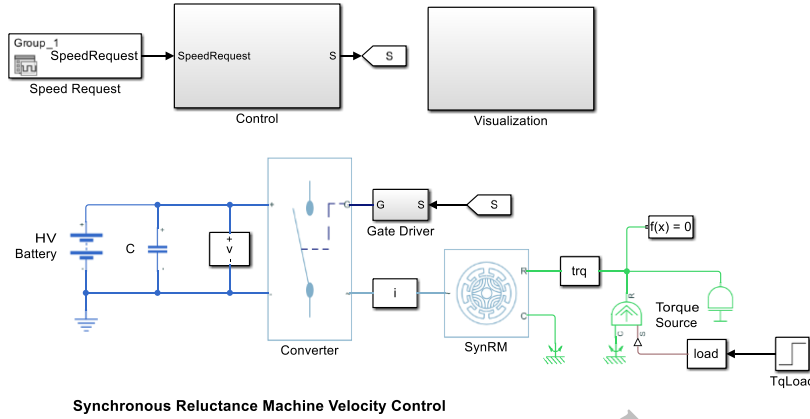


Fig. 7. Block diagram of SynRM drive

Using the developed model, the main parameters of the considered drive system, such as rotational speed, torque, and current, were analyzed considering and neglecting the effect of core saturation and cross-saturation.

The effect of core saturation and the CSE is related to machine load; when load torque is low, the machine operates in the linear part of its $B-H$ characteristic and the effect of core saturation is limited. Therefore, simulations were performed for two values of load torque equal to 90 and 185 Nm, respectively, corresponding to linear and saturated states of the magnetic circuit. In both cases, an identical operating scenario was applied. The machine was initially started under no-load conditions and after a predefined time interval of 0.8 s, the load torque was applied.

The results presented in Fig. 8 demonstrate the impact of incorporating the cross-saturation CSE into the model. In the case of Fig. 8(a), only minor differences can be observed between the linear, nonlinear, and nonlinear models including the CSE. This behaviour results from the relatively low magnetic saturation of the machine at a load torque of 90 Nm. Under these operating conditions, the machine operates within the linear region, where the deviations in the $\Psi_d = f(i_d)$ and $\Psi_d = f(i_d, i_q)$ characteristics remain negligible (see Fig. 4). However, increasing the load torque to 185 Nm (see Fig. 8(b)) and consequently increasing the level of magnetic saturation in the machine, leads to noticeable differences in the speed-settling process. This behaviour demonstrates the actual influence of the CSE on machine operation. It should be noted here that for high load torque, corresponding to high utilization of the magnetic circuit of the SynRM, neglecting the CSE leads to discrepancies between the actual machine behaviour and the signals utilised by the control system.

The difference in current magnitude shown in Figs. 9(a) and 9(b) arises directly from the applied load torque. Figure 9(b) shows a significantly higher current for the CSE model compared to the other approaches, which is a direct result of the machine reaching saturation. The i_d and i_q currents presented in Figs. 10 and 11 exhibit similar trends to those observed in Fig. 9.

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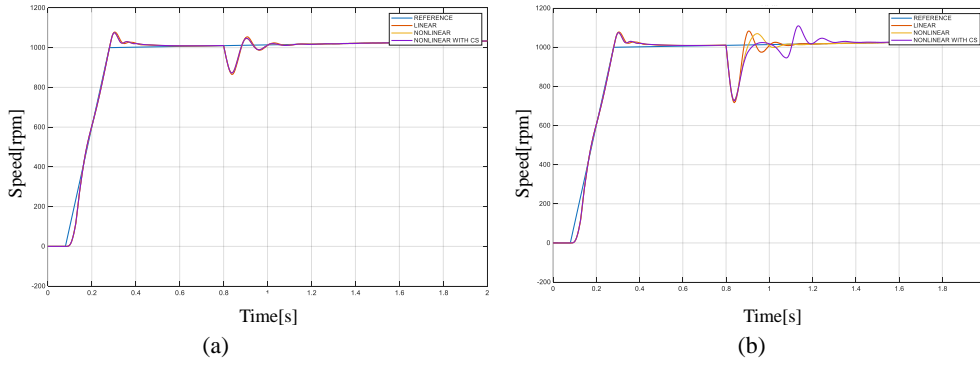


Fig. 8. Comparison of rotational speed depending on CSE consideration and nominal load:
 (a) 90 Nm; (b) 185 Nm

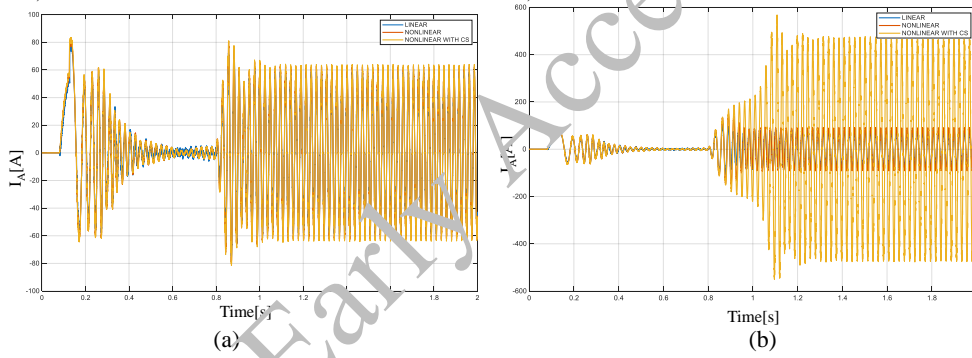


Fig. 9. Comparison of phase current depending on CSE consideration and nominal load:
 (a) 90 Nm; (b) 185 Nm

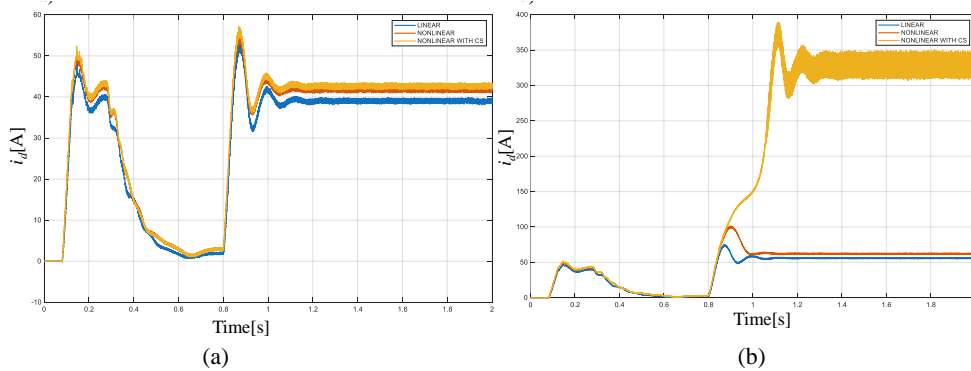


Fig. 10. Comparison of i_d current depending on CSE consideration and nominal load:
 (a) 90 Nm; (b) 185 Nm

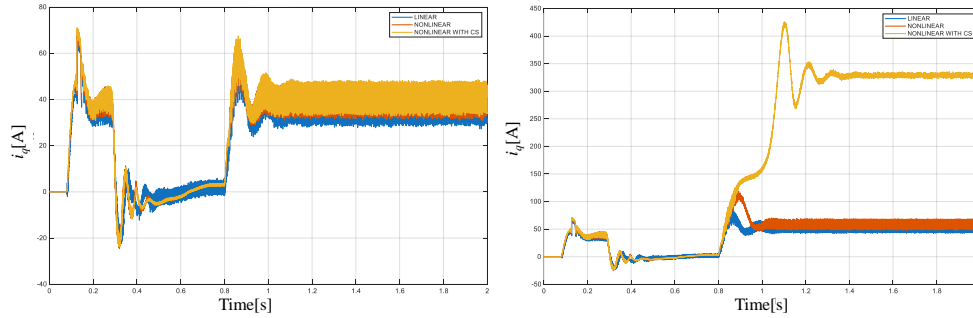


Fig. 11. Comparison of i_q current depending on CSE consideration and nominal load:
 (a) 90 Nm; (b) 185 Nm

5. Conclusion

In this paper, we investigated the cross-saturation effect (CSE) in a 4-pole synchronous reluctance machine by comparing three stator winding variants with identical magnetic cores: 6-phase double-layer (6PHDL), 3-phase single-layer (3PHSL), and 3-phase double-layer (3PHDL). The additional 3-phase double-layer case was included to decouple the influence of the number of winding layers from the influence of the phase number when interpreting cross-saturation impact.

The results of the conducted comparative analysis show that the CSE is dominated primarily by the magnetic circuit geometry and its nonlinear material behavior, rather than by the winding layout itself. In particular, negligible differences in the flux-current relationships when switching between the 3PHSL and 3PHDL are observed, indicating that the single- vs double-layer arrangement does not affect the CSE mechanism for the investigated design. Changing the phase number to a 6-phase system does not eliminate cross-saturation either; it only leads to a minor change of the direct-axis flux level in the saturated operating region, consistent with a slightly altered field distribution while preserving the same underlying saturation-driven coupling.

From a drive-modelling perspective, simulation results obtained using different approaches indicate that the role of cross-saturation becomes particularly significant under conditions of increased magnetic saturation. In such operating regimes, neglecting cross-coupling effects in the inductance model may lead to inaccuracies in the values processed within the feedback control loop. When the machine operates outside the linear region, the interaction between the d - and q -axis currents affects the inductance characteristics, and consequently, the accuracy of the model used for control purposes. As a result, omission of the cross-saturation effect (CSE) may introduce discrepancies between the actual machine behaviour and the signals utilised by the control system. Therefore, under operating conditions involving significant saturation, the

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inclusion of the CSE in the control-oriented model becomes essential to ensure consistency between the physical system and its mathematical representation. In contrast, under low-dynamic or weakly saturated conditions, the impact of cross-saturation remains limited and may be neglected without introducing substantial modelling errors.

In applications requiring operation under high-load conditions and frequent-torque variations (e.g. electromobility), the machine operates at a high level of utilisation of the magnetic circuit. Under such conditions, increased saturation causes the machine to operate beyond the linear region of the $\Psi_d = f(i_d, i_q)$ and $\Psi_q = f(i_d, i_q)$ characteristics, where the cross-saturation effect significantly influences its behaviour. In such cases, the inclusion of the CSE in computational models and control algorithms is recommended to ensure accurate control of the electrical machine within a closed-loop system.

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