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Title

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The Permanent Magnet assisted synchronous reluctance motor (PMSynRelM) is widely used for it's significant advantages of small size, low loss, high efficiency, better performance than plain synchronous reluctance motors SynRelM and wide constant power to speed range. [1, 2]

2.1 Stator and Rotor

There are many solutions on how to connect the stator winding. Research has been carried out for standard Delta or Start winding, but to increase the torque for same stator current the combined Start-Delta winding was proposed. The first research has been caried out for standard SynRelM in [3] and then extended to PMSynRelM prototypes in [4]. The main idea of the hybrid Delta-Star connection is to split the standard phase wiring into two parts. The one part is for the Delta connection, the other for Star connection. Then the coils of wiring are connnected to series. Motors utilizing hybrid stator winding with PMs inserted in the rotor flux bariers exhibit constant power factor over 0.9

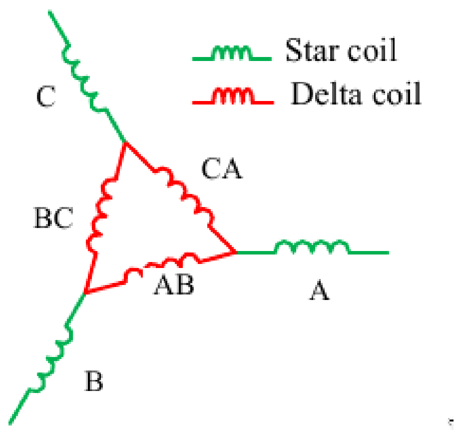

Figure 2 - 1 Hybrid Star-Delta wiring of PMSynRelM. CHANGE THIS IMAGE FOR YOUR OWN, IT IS FROM [4]

In [4] the authors manufactured proposed four prototypes. The prototypes consist of two stators, with either conventional star winding or hybrid star-delta winding, and two rotors, with ferrite permanent magnets or without. Maxwell transient simulations were carried out on the four prototypes, which were then manufactured and experiment using the simulation results was conducted.

According to [4] the researches state, that when using the hybrid stator winding connection, the efficiency increase is rather low compared to efficiency increase when comparing SynRelM with and without PMs.

The design of the PMSynRelM rotor with PM oriented solely in the q-axis is depicted in the figure 2 - 2.

2.2 Magnets

PMSynRelM are very often compared to Permanent Magnet Synchronous Motors (PMSM) used in the automotive field in terms of power and torque density, efficiency and costs. Though the PMSM are very popular [6], the PMs used in their design often consist of rare-earth materials such as neodymium or dysprosium. That is the reason why PMSynRelM motors with rare-earth-free materials are now being the subject of many research studies. Experiments comparing the production-used PMSM and experimental

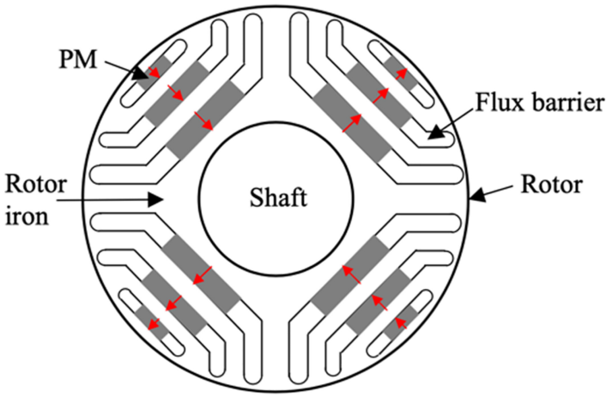

Figure 2 - 2 Rotor design of a Permanent Magnet Assisted Synchronous Reluctance Motor with permanent magnets oriented solely in the q-axis. [5]

prototype PMSynRelM show, that the proposed prototype in [7] achieve close values of power density and an efficiency as rare-earth PMSM counterpart, but with much lower costs [8].

It has been observed, that when inserting the PM in the center of the flux barrier, a magnetic flux lines are forced to pass through the flex barriers in the q-axis. This results in the decreased linked magnetic flux in the q-axis and therefore improves the output torque. [4, 9] The two general types of rotor with embedded PM are depicted in figure 2 - 3.

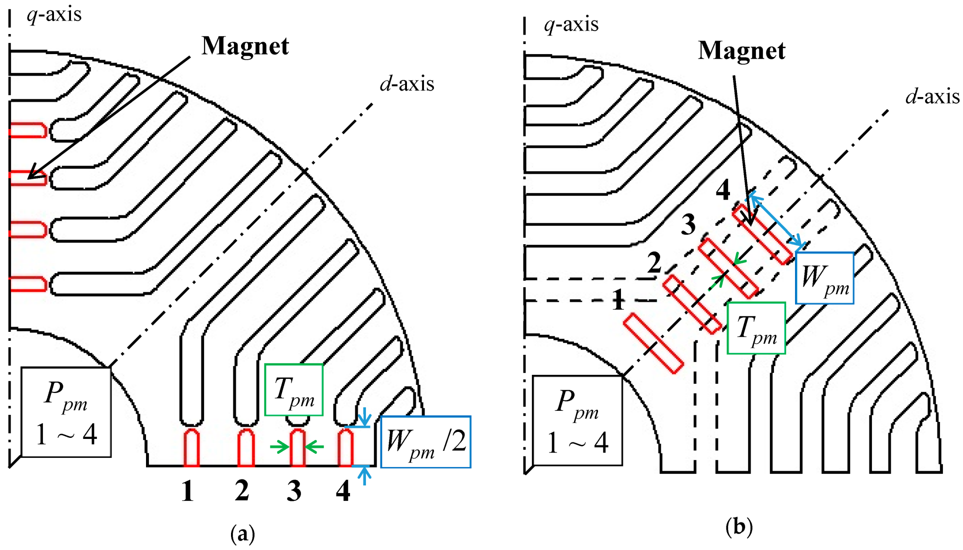

Figure 2 - 3 Different approaches to permanent magnet orientation in the rotor of a Permanent Magnet Assisted Synchronous Reluctance Motor. (a) PM embedded along the flux bariers, facing the q-axis; (b) Permanent magnets are crossing the flux bariers, therefore facing the d-axis. [9]

3 Control

3.1 Mathematical model

The stator voltage equation of PMSynRelM denoted in the general axis k is as follows

$$\underline{u}_1^k = \mathrm{R_s}\underline{i}_1^k + \frac{\mathrm{d}\underline{\psi}_1^k}{\mathrm{d}t} + j\omega_k\underline{\psi}_1^k. \tag{3 - 1}$$

Where $\underline{u}_1^k$ (V) is space vector of stator voltage, R_s (Ω) is stator rezistance, $\underline{i}_1^k$ (A) space vector of a stator current, $\underline{\psi}_1^k$ (Wb) space vector of a stator flux linkeage, ω_k (rad s^{-1}) general angular speed.

The voltage equation denoted in dq-axis is as follows

$$\underline{u}_1^{dq} = \mathrm{R_s}\underline{i}_1^{dq} + \frac{\mathrm{d}\underline{\psi}_1^{dq}}{\mathrm{d}t} + j\omega_1\underline{\psi}_1^k, \tag{3 - 2}$$

where ω_1 (rad s^{-1}) is electrical angular speed of a stator rotating magnetic field. When the equation is denoted in vector components and the subscript "1" for stator is omitted and the axis are newly denoted by the variables subscript

$$\underline{u}_d = \mathrm{R_s}i_\mathrm{d} + \frac{\mathrm{d}\psi_d}{\mathrm{d}t} - \omega_1\psi_q, \tag{3 - 3}$$

$$\underline{u}_q = \mathrm{R_s}i_\mathrm{q} + \frac{\mathrm{d}\psi_q}{\mathrm{d}t} + \omega_1\psi_d. \tag{3 - 4}$$

Equations for flux linkeages denoted in the d, q-axis, when PMs are embedded along the q-axis are

$$\psi_d = \mathrm{L}_d i_\mathrm{d}, \tag{3 - 5}$$

$$\psi_q = \mathrm{L}_q i_\mathrm{q} + \psi_\mathrm{PM}. \tag{3 - 6}$$

Where L_q (H), L_d (H) are inductances in d-axis and q-axis respectively, ψ_PM (Wb) is a flux linkeage of permanent magnets. Very often the PM flux linkeage is oriented negatively in the q-axis when respecting the vector orientation the equation 3 - 6 can be rewritten as

$$\psi_q = \mathrm{L}_q i_\mathrm{q} - \psi_\mathrm{PM}. \tag{3 - 7}$$

The general equation for electromagentic torque is then

$$T = \frac{3}{2}\mathrm{p_p}|\underline{\psi_{dq}} \times \underline{i_{dq}}| = \frac{3}{2}\mathrm{p_p}(\psi_d i_q - \psi_q i_d). \tag{3 - 8}$$

where $\mathrm{p_p}$ (-) is number of pole pairs.

After the substituion of 3 - 5 and 3 - 7 to 3 - 8 the torque euation may be rewritten

$$M = \frac{3}{2}\mathrm{p_p}(\mathrm{L}_d i_d i_q - (\mathrm{L}_q i_q - \psi_\mathrm{PM})i_d) = \frac{3}{2}\mathrm{p_p}(\mathrm{L}_d i_d i_q - \mathrm{L}_q i_q i_d + \psi_\mathrm{PM} i_d). \tag{3 - 9}$$

As can be seen from eq. 3 - 8, when the linkeage flux of PMs is oriented negatively to the q-axis (as presented), higher value of flux linkeages make the electromagnetic torque higher.

Graphical expression of the phasor diagram for the SynRelM is depicted in the figure 3 - 1.

Effect of different layers of PM in rotor on realized the phasor diagram may be observed in [2].

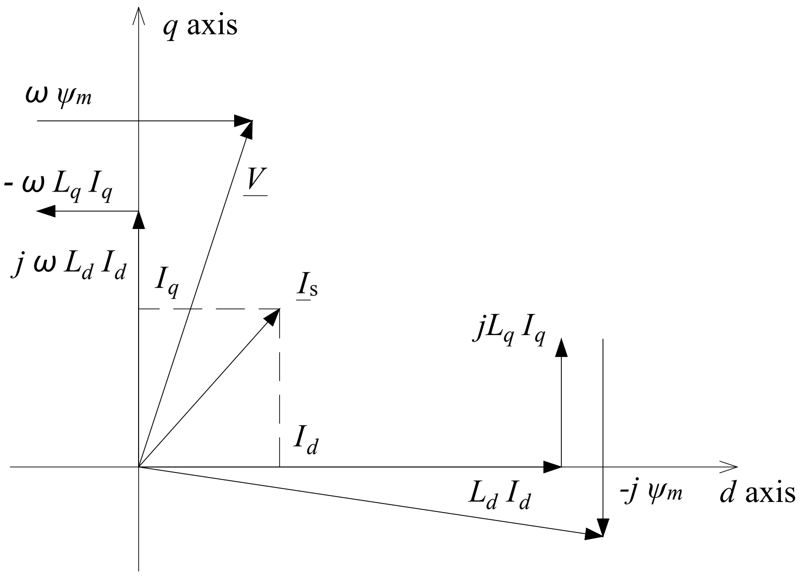

Figure 3 - 1 Phasor diagram for the SynRelM when the flux of permanent magnets ψ_m is oriented in the negative q-axis direction.

3.2 Control strategies

There are many options on how to control the PMSynRelM. The principles may be divided in two major groups: **Scalar Control** and **Vector Control**. The two major subcategories of vector control strategies are **Field Oriented Control** (FOC) and **Direct Torque Control** (DTC). These strategies then may use different aproaches to achieve the desired results of less torque ripple and dynamic performance. [10] The general group decopmosition is depicted in the figure 3 - 2.

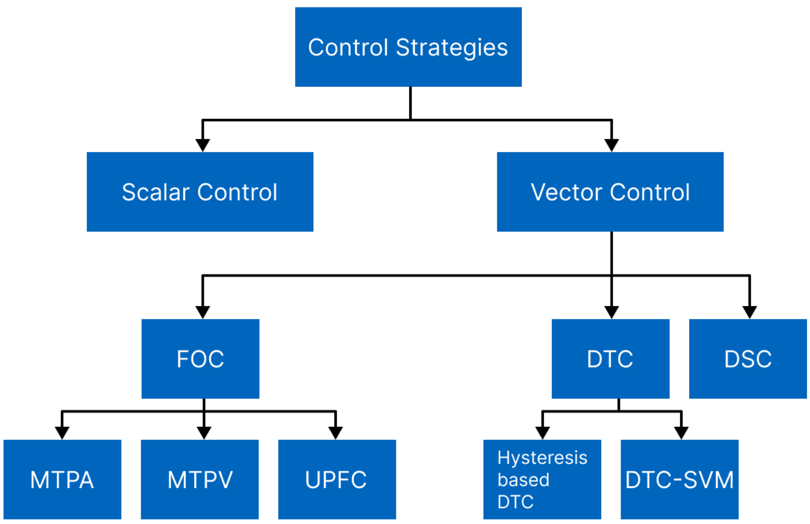

Figure 3 - 2 General diagram depicting major groups of control strategies for PMSynRelM. Graph inspired by [10]

3.2.1 Scalar Control

Scalar drive control is straighforward solution for controlling the drive. It is relatively simple to execute and there is no need of a high performance Digital Signal Processors (DSPs). However Scalar Control can not provide the dynamic performance and speed control compared to FOC and DTC. [10]

Scalar control is mainly known as a V/f (Voltage/frequency) control. The control methods mainly produce output voltage so the ratio between voltage and frequency is kept constant for the magnetizing flux to be the highest possible, so the torque is possibly maximized as well. Another methods use I/f (current/frequency) control based strategies. [11]

3.2.2 Vector Control

Vector control strategies became increasingly popular due to the lower cost and higher computational power of available DSPs. [10]

FOC control mainly uses the theory of space vectors and DTC the theory of controlling the electromagnetic torque and magnetic flux based on the desired speed and magnetization. Control strategies are different but objective is the same. The main aim of vector control strategies is to achieve the desired torque and flux values based on the reference values which are set as an input to the control strategy. [11, 10]

Maximum Torque Per Ampere (MTPA) PMSynRelM control

The main objective of the MTPA strategy is to achieve the reference (desired) torque with minimum value of stator currents in d and q-axis (i_d and i_q). According to [10], there are multiple methods how to realize the MTPA.

The control strategy is parameter dependent. In [12] authors present a robust online parameter estimation technique which improves the control strategy. With calculated and estimated parameters and measured stator currents the torque, which would the machine provide is calculated and then used as a reference value for further calculations. The proposed controller provides increased robustness againts the variations of motor parameters.

4 Comparation to others

5 Usage

Conclusion

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Appendix A: List of symbols and abbreviations

A.1 List of abbreviations

ASM	Asynchronní Motor
PM	Permanent Magnets
PMSM	Permanent Magnet Synchronous Motor
PMSynRelM	Permanent Magnet Assisted Synchronous Reluctance Motor
SynRelM	Synchronous Reluctance Motor

A.2 List of symbols

P_{n}	(W)	jmenovitý výkon