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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

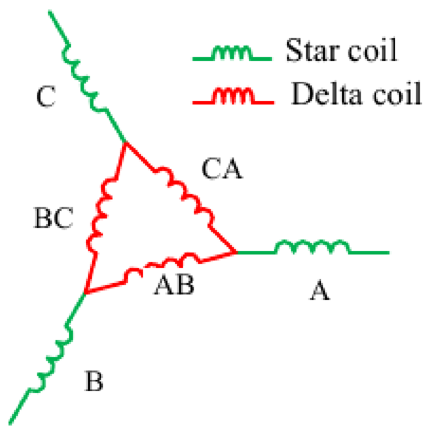

Figure 2 - 1 Hybrid Star-Delta wiring of PMSynRelM. CHANGE THIS IMAGE FOR YOUR OWN, IT IS FROM [4]

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

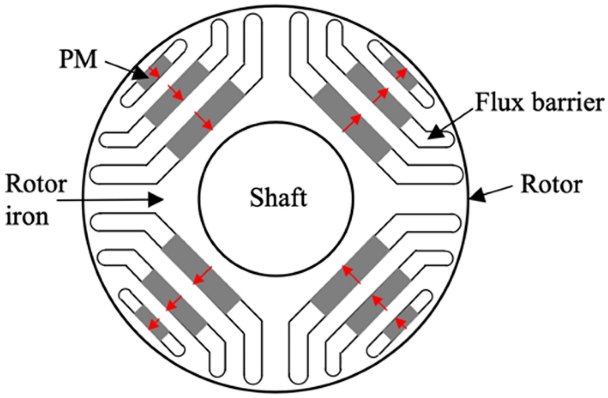

Figure 2 - 2 Rotor design of a Permanent Magnet Assisted Synchronous Reluctance Motor with permanent magnets oriented solely in the q-axis. [5]

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.

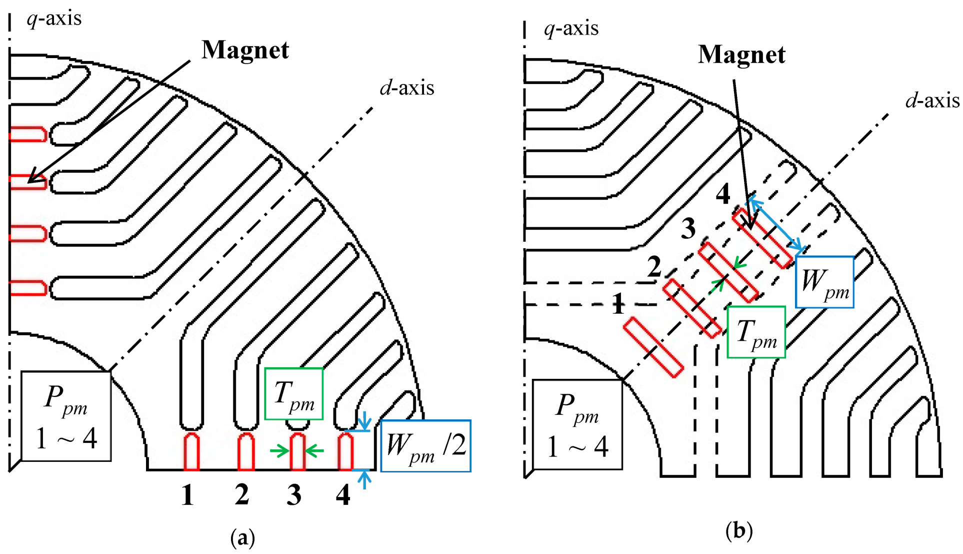

Figure 2 - 3 Different approaches to permanent magnet orientation in the rotor of a Permanent Magnet Assisted Synchronous Reluctance Motor. (a) PM embedded along the flux bariers, facing the q-axis; (b) Permanent magnets are crossing the flux bariers, therefore facing the d-axis. [9]

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].

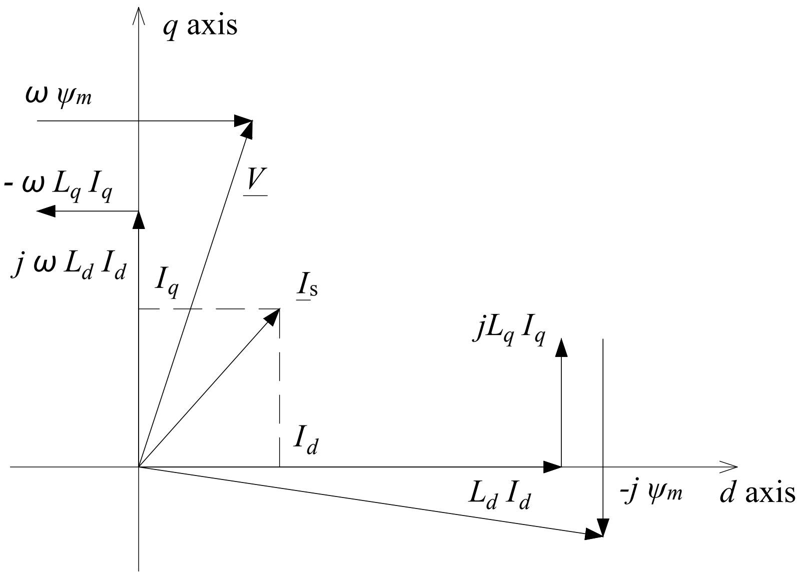

Figure 3 - 1 Phasor diagram for the SynRelM when the flux of permanent magnets ψ_m is oriented in the negative q-axis direction.

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.

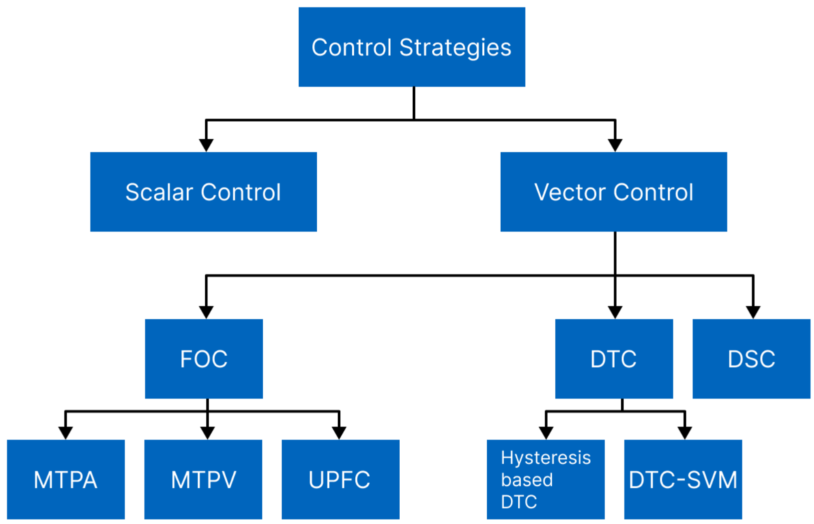

Figure 3 - 2 General diagram depicting major groups of control strategies for PMSynRelM. Graph inspired by [10]

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.

Maximum Torque Per Voltage (MTPV) PMSynRelM control

The higher the speed of rotor, the larger the magnitude of the back electromotive force (EMF), the larger magnitude of voltage provided from source is needed. When speed reaches the value, where nominal source voltage is reached, then the current flowing through stator wires must decrease due to the back EMF. Thus the voltage value restricts the current based on the rotor speed. In [13] the exemplar curves presenting MTPV are depicted. Another mathematical expression of the MTPV trajectoriy is presented in [14]. Cited paper also depicts the exemplar trajectories in the i_d-i_q plane.

The MTPV trajectories are plotted based on the current values in i_d-i_q, where the possible torque is at the peak. The maximum torque value in the diagram is based on the operation speed.

Unity Power Factor Control (UPFC)

In wide variety of applications it is required for the machine to work with maximum power factor. It is preferable to achieve a unity power factor, to eliminate reactive power consumption. In [15] two methods are proposed: *1) controling the d-axis stator current i_d* and *2) controling the angle of stator* *current space vector* i_{stator}.

According to [15] the UPFC allows wider speed range where the torque is constant. This results in a higher output power of the drive.

1) controling the d-axis stator current i_d

Method compares the space angles of stator current and voltage space vectors to achieve the unity power factor. From the unity power factor condition the current i_d may then be expressed. Using the expressed current value, the voltage equations of the machine then may be modified to evaulate the steady-state performance at a unity power-factor. [15]

2) controling the angle of stator current space vector i_{stator}

This method forces the space vector of a stator current to be aligned with space vector of a stator electromagnetic force. When the space vectors of a stator voltage and current will coincide the unity power factor will be achieved. [15]

3.2.3 Direct Torque Control

Compared to vector control the DTC is in fact simpler. It does not requeire the Pulse Width Modulation (PWM). During the sample periode of DSP only one space vector of supply voltage is provided as an output from the inverter. The calculation and control is done in the stationary reference frame (eg. stator linked frame in $\alpha\beta$ axis). Hysteresis based DTC works on keeping the values of torque and magnetic flux (independently) in the hysteresis band of desired/allowed values. DTC needs only a portion of paramaters which are necessary for vector control strategies, thus making the method very convinient. [10]

DTC Space Vector Modulation (SVM) utilizes DTC strategy but instead of hysteresis controllers and switching table to control the inverter the proportional-integral regulators with predictive controller are used. Control strategy proposed in [16] shows that for Permanent Magnet Synchronous Motor the DTC-SVM results in lower torque ripple and harmonic current than conventional DTC.

3.2.4 Direct Self Control

DSC is very similar to the DTC strategy, which was published by Takahashi in [17] in 1989 for induction motor. The Direct Self Control strategy published by Depenbrock in [18] is in fact similar to DTC but the voltage space vectors follow the hexagonal path. In comparision to the DTC this strategy generaly require lower switching frequency of the components.

4 Comparation to other types

5 Usage

Conclusion

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Appendix A: List of symbols and abbreviations

A.1 List of abbreviations

ASM	Asynchronní Motor
DSC	Direct Self Control
DSP	Digial Signal Processor
DTC	Direct Torque Control
EMF	Electromotive Force
FOC	Field Oriented Control
MTPA	Maximum Torque Per Ampere
MTPV	Maximum Torque Per Voltage
PM	Permanent Magnets
PMSM	Permanent Magnet Synchronous Motor
PMSynRelM	Permanent Magnet Assisted Synchronous Reluctance Motor
PWM	Pulse Width Modulation
SVM	Space Vector Modulation
SynRelM	Synchronous Reluctance Motor
UPFC	Unity Power Factor Control

A.2 List of symbols

P_n (W) jmenovitý výkon