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A Brief Report on Permanent Magnet Assisted Synchronous Reluctance Motors

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1 Introduction

This concise report provides a comprehensive overview of Permanent Magnet Assisted Reluctance Motors (PMSynRelM), focusing on essential information to maintain clarity and conciseness. While the covered parts could be expanded further, the brevity of the paper is intentionally preserved to ensure its readability and clarity.

Nowdays the PMSynRelM is being actively used in the automotive and traction applications and for its simplicity, performance and emerging availability could be used in modern electric vehicles.

The references used in this paper were selected based on the criteria such as rating, relevance and publication date. This approach ensures that the paper reflects modern trends in the field to the fullest extent. But certain principles used when designing or controlling PMSynRelM drive were developed in earlier publications when the PMSynRelM structure was not popular as nowdays is. But the controlling principles developed still work and are being improved for todays application requirements.

This paper is organized as follows: Firstly the most used design of the stator and rotor with permanent magnets is presented. Then the general mathematical model used for controlling the machine with corresponding strategies for PMSynRelM and other permanent magnet machines are briefly explained. The next section is dedicated to comparing the PMSynRelM to other popular motor structures used in the automotive and traction field. The paper ends with section briefly presenting the latest research interests in the field of PMSynRelM drives.

2 Design

The (PMSynRelM) is widely used for its significant advantages of small size, low losses, high efficiency, wide constant power range and better performance than general synchronous reluctance motors SynRelM. [1, 2]

2.1 Stator

Numerous methodologies exist for connecting the stator winding. While research papers traditionally focus on standard Delta or Star winding configurations, the authors in [3, 4] proposed a novel configuration which elevates the torque performance without altering the stator current called the Star-Delta hybrid winding. 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 may exhibit constant power factor over 0.9. [4]

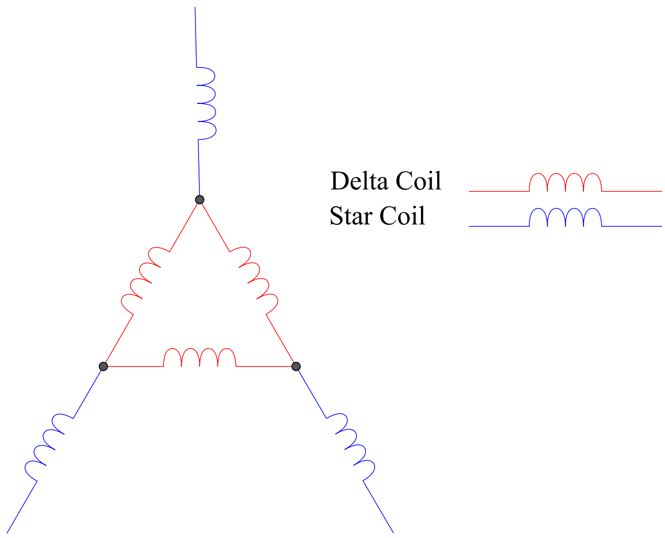


Figure 2 - 1 Hybrid Star-Delta wiring of PMSynRelM.

In [4] the authors manufactured and proposed four prototypes of SynRelM. 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 experimented on.

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, thus creating PMSynRelM. This outcome raises a question: Is the utilization of the hybrid Star-Delta winding truly worthwhile?

2.2 Rotor

Rotor structure of PMSynRelM draws inspiration from the design of a conventional SynRelM, which has undergone years of evolution to achieve wide range of constant power and near unity power factor. Rotor designs may be generally categorized as internal or external. In order to fulfill the requirements of power and power factor values, the target is to design the rotor with minimum inductane in the q axis (L_q)

and maximal inductance in d axis (L_d). The saliency ratio defined in [5] as L_d/L_q should be therefore maximized. The required saliency ratio may be achieved by optimizing shape, placement and number of flux bariers. The bariers are in PMSynRelM filled with an appropriate amount of PMs made of rare earth materials or ferrites. [5]

In [5] authors present mathematical model of PMSynRelM with four flux barriers used to propperly calculate the motor flux density, inductances, back-EMF and developed torque. The proposed rotor design is presented in Fig. 2 - 2. There are not many papers available regarding the external rotor design of PMSynRelM structure. The authors of [6] investigated the rotor structures and compared the internal and external architecture. The two compared designs are depicted in Fig. 2 - 4. Usually the magnetic flux density and motor parameters are analysed using Finite Element Method. The graphical analysis of the proposed four-pole PMSynRelM from [5] is depicted in Fig. 2 - 3.

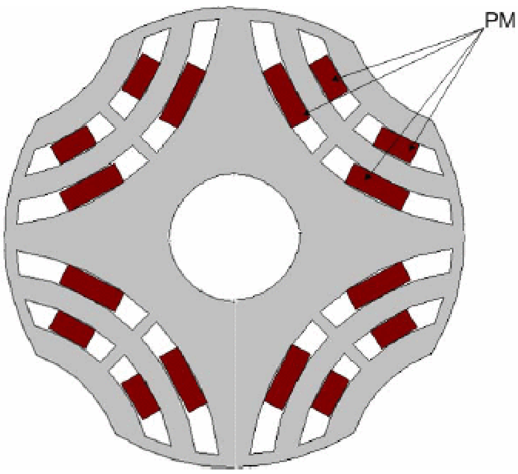


Figure 2 - 2 Four barrier Permanent Magnet Assisted Synchronous Reluctance Motor rotor structure. [5]

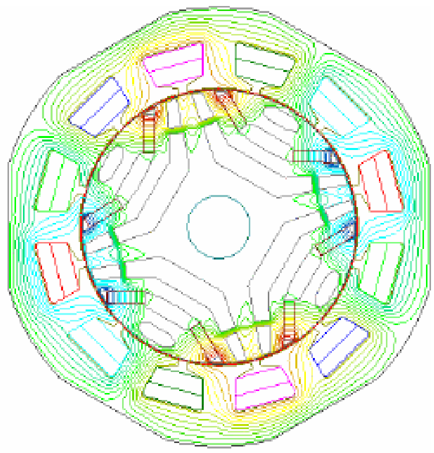


Figure 2 - 3 Four barrier Permanent Magnet Assisted Synchronous Reluctance Motor Permanent Magnet Flux Density Analysis via Finite Element Method. [5]

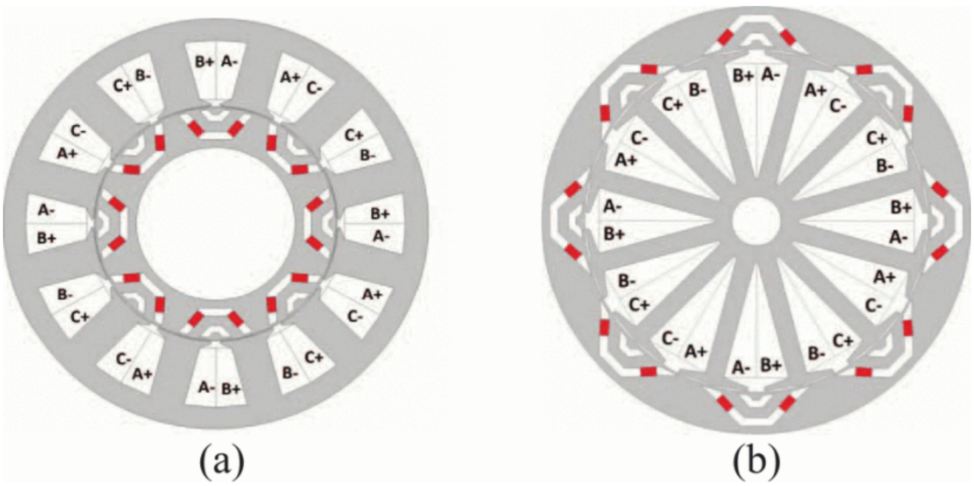


Figure 2 - 4 Proposed (a) internal rotor structure, (b) external rotor structure. [6]

2.2.1 Magnets

PMSynRelM are very often compared to Permanent Magnet Synchronous Motors (PMSM) in terms of power, torque density, efficiency and costs. Both of the machine types are widely used in automotive field. Though the PMSM is very popular [7], the permanent magnets (PMs) used in the conventional design are often made of rare-earth materials such as neodymium or dysprosium. That is the motivation why PMSynRelM motors with rare-earth-free materials are now being the subject of many research studies. Experiments comparing the production-used PMSM and the prototype PMSynRelM show, that the proposed prototype in [8] achieve close values of power density and an efficiency as rare-earth PMSM counterpart, but with much lower cost [9].

It has been observed that strategically placing the PMs at the center of the flux barrier forces magnetic flux lines to traverse through the flux barriers along the q-axis direction. This leads to reduction of a linked magnetic flux along the q-axis and therefore improvement of the output torque. [4, 10] The effect of PM flux may be observed in a vector diagram Fig. 3 - 1.

Possible placement of PMs in the rotor structure of PMSynRelM is depicted in Fig. 2 - 5.

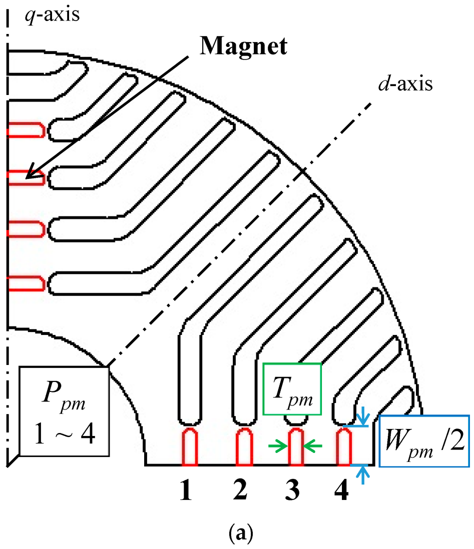
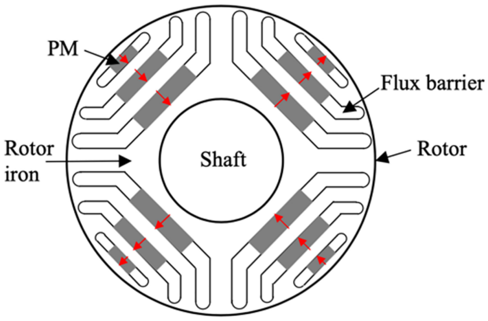
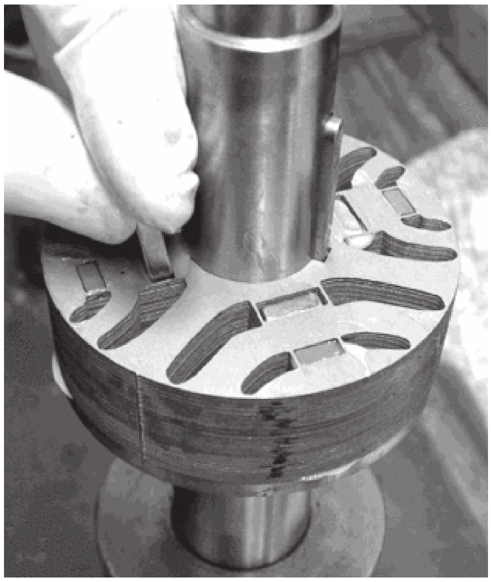


Figure 2 - 5 Different approaches to a permanent magnet orientation in the rotor structure of a Permanent Magnet Assisted Synchronous Reluctance Motor. (a) PM embedded along the flux bariers, facing the q-axis; (b) Permanent magnets are crossing the flux bariers, therefore facing the d-axis. [10]

Design of the PMSynRelM rotor with PMs oriented solely in the q-axis is depicted in the Fig. 2 - 6a. The proces of inserting the permanent magnets to the flux barriers in the rotor is depicted in Fig. 2 - 6b.



(a) Rotor design of a Permanent Magnet Assisted Synchronous Reluctance Motor with permanent magnets oriented solely in the q-axis. [11]



(b) Process of inserting the permanent magnets to the rotor of a Permanent Magnet Assisted Synchronous Reluctance Motor. [12]

Figure 2 - 6 Position of permanent magnets in a rotor design.

3 Control

3.1 Mathematical model

The stator voltage equation of PMSynRelM denoted in the general axis k may be written 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 eq. 3 - 2 is denoted in vector components and the subscript "1" for stator is omitted the equation may be rewritten as

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

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

Equations for flux linkeages denoted in the dq-axis if PMs and flux 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 electromagnetic torque T (Nm) 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 as

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

As evident from eq. 3 - 8, when the linkeage flux of PMs is oriented in the negative direction relative to the q-axis (as illustrated), an increased value of flux linkeages ψ_{PM} results the to a higher electromagnetic torque magnitude.

The phasor diagram is illustrated in Fig. SynRelM is depicted in the figure 3 - 1. Effect of PMs layer and position in rotor on the phasor diagram may be observed in [2].

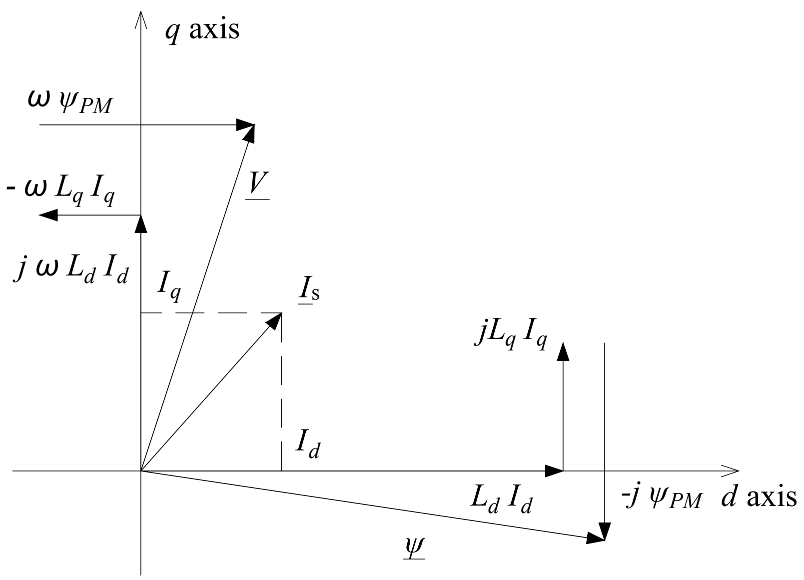


Figure 3 - 1 Vector diagram of the Permanent Magnet Assisted Synchronous Reluctance Motor when the flux of permanent magnets ψ_m is oriented in the negative q-axis direction.

3.2 Control strategies

Numerous options exist for controlling the PMSynRelM. The principles may be broadly categorized into two major groups: **Scalar Control** and **Vector Control**. The primary subcategories of vector control strategies are **Field Oriented Control** (FOC) and **Direct Torque Control** (DTC). These strategies use a different approach to minimize the torque ripple and to achive desirable high dynamic performance. [13] The general group decopmosition is depicted in Fig. 3 - 2.

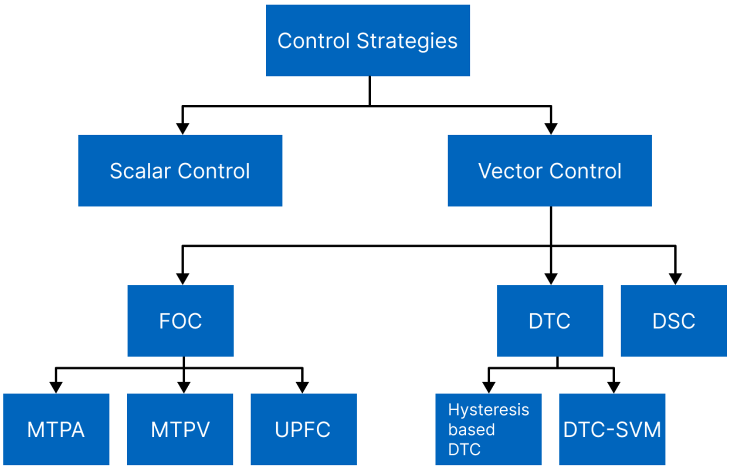


Figure 3 - 2 General diagram depicting major groups of control strategies for PMSynRelM. Graph inspired by [13]

3.2.1 Scalar Control

Executing scalar drive control is relatively straighforward solution, it does not necesitate the use of high performance Digital Signal Processors (DSPs). However Scalar Control does not provide the great dynamic performance and speed provided by FOC and DTC. [13]

Scalar control is mainly known as a V/f (Voltage/frequency) control. The control methods primarily generate output voltage, maintaining a constant ratio between voltage and frequency. The ratio is kept constant for the magnetizing flux to be the highest possible, so the torque is maximized as well. Another methods may use I/f (current/frequency) control based strategies. [14]

3.2.2 Vector Control

Vector control strategies have become increasingly popular, thanks to the combination of lower cost and hightened computational power of general DSPs. [13]

FOC mainly leverages the theory of space vectors, while DTC employs the theory of controlling the electromagnetic torque and magnetic flux directly based on the reference speed and magnetic flux. FOC and DTC strategies differ but objective remains unchanged. The primary goal of vector control strategies is to attain the desired torque and flux values based on the reference values which are set as an input to the control strategy. [14, 13]

Maximum Torque Per Ampere (MTPA) PMSynRelM control

The main objective of the strategy is to achieve the reference torque using minimum value of stator current i_d and i_q. According to [13], there are numerous methods how to realize the MTPA.

The control strategy is parameter dependent which may present a problem. In [15] authors present a robust online parameter estimation technique which improves the general MTPA control strategy. Using calculated and estimated parameters together with measured stator currents the machine torque is calculated and then used as a reference value for further calculations. The proposed controller stands out for its increased robustness againts the variations of motor parameters.

Maximum Torque Per Voltage (MTPV) PMSynRelM control

The higher the rotor angular speed, the larger the magnitude of the back electromotive force (EMF), the larger voltage magnitude supplied from source is needed for machine to work correctly. When rotor speed reaches the value where back EMF is so high that the higher supply voltage than the nominal is required then the current flowing through stator wires decreases. This is due to the back EMF and inability to highten the supply voltage above the nominal. Thus the voltage value restricts the current based on the rotor speed. In [16] the exemplar curves presenting MTPV are depicted. Another mathematical expression of the MTPV trajectory is presented in [17]. Cited paper also depicts the exemplar trajectories in the i_d-i_q plane.

The MTPV trajectories are plotted in the i_d-i_q plane. The trajectories correspond to the operation points where the possible torque is at the peak value. Thus the maximum torque value depends on the operational rotor speed.

Unity Power Factor Control (UPFC)

In various applications, it is required for the machine to operate with the highest power factor possible. Achieving a unity power factor is preferable to eliminate the consumption of reactive power. In [18] two methods for achieving the highest value of power factor are proposed: *1) controlling the d-axis stator current* i_d and *2) controling the angle of stator current space vector* $\underline{i_{stator}}$.

According to [18] the UPFC allows wider speed range with constant torque value. This results in a higher output power of the drive.

1) controling the d-axis stator current i_d

Method compares space angles of stator current and voltage space vectors to achieve the unity power factor. The value of the current i_d which satisfies the unity power factor condition then may be expressed and passed to the stator voltage equations of PMSynRelM. The equations then may be modified to evaulate the steady-state performance and required voltage space vector at a unity power-factor. [18]

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 by modifying the value of the vector components. When the space vectors of a stator voltage and current will coincide the unity power factor will be achieved. [18]

3.2.3 Direct Torque Control

Compared to vector control the DTC is in fact simpler. It does not require the Pulse Width Modulation (PWM) techniques. 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 system).

Hysteresis based DTC

Hysteresis based DTC uses the principle of keeping the values of torque and magnetic flux (independently) in the hysteresis band of allowed values. Hysteresis based DTC needs only a portion of paramaters which are necessary for vector control strategies, thus making the method very elegant and convinient. [13]

DTC Space Vector Modulation (SVM)

DTC Space Vector Modulation (SVM) utilizes general DTC strategy but instead of hysteresis controllers the proportional-integral regulators with predictive controllers are used. Strategy proposed in [19] shows that for Permanent Magnet Synchronous Motor the DTC-SVM results in lower torque ripple and better harmonic composition of stator current than conventional DTC.

3.2.4 Direct Self Control

Direct Self Control DSC is very similar to the DTC strategy, which was published by Takahashi in [20] in 1989 for induction motor. The DSC strategy was published by Depenbrock in [21]. In the proposed strategy the voltage space vectors follow the hexagonal path. In comparision DSC strategy generaly requires lower switching frequency of the components than the DTC.

3.2.5 Other strategies

Numerous research papers have been published regarding the control strategies which leverage the fundamental principe of the general strategies and refines them for the specific application. The example diagram depicting some popular derived strategies is presented in [14].

4 Comparison to other machines

When designing electric drives there are numerous options on which motor to use in the designed application. A comprehensive comparation study was well carried out in [22]. Authors compare the induction machine (IM), synchronous reluctance motor (SynRelM), permanent magnet assisted synchronous reluctance motor (PMSynRelM) and interior permanent-magnet machine (IPM).

The machines are compared based on the design parameters regarding their electromagnetic performance, material cost and temperature. The authors in [22] conclude, that the electromagnetic performance of analyzed ferrite-based PMSynRelM is better than that of the IM and SynRelM which does not use in their design any PMs. The cost of used materials for PMSynRelM is lower than for the IPM. But the torque ripple and the demagnetization of ferrites may be a problem when using the PMSynRelM. [22]

5 Recent research interest

In recent years the research of PMSynRelM has been focused on improving the overall performance, cost and behaviour of permanent magnet assisted machines.

The improvement was achieved:

- by using non-rare earth materials such as ferrites,
- by using novel hybrid stator winding structures,
- by analyzing rotor structure types and motor parameters based on the permanent magnet position and perfecting the design for the specific application.

Some research articles focus on improving well known control strategies to achieve better performance of the drive. When using ferrite based permanent magnets the main concern of the applied control strategies is to minimize (better eliminate) the possibility of a permanent demagnetization which could occur.

New types of motors and control strategies are proposed in [23]. Proposed motors utilize variable flux strategy where high magnitude of stator current i_d for a short amount of time may cause that the ferrite based permanent magnets are demagnetized. When the demagnetization is not needed the stator current i_d may cause the re-magnetization of permanent magnets. The proposed principle is still being developed and published about.

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Appendix A: List of symbols and abbreviations

A.1 List of abbreviations

DSC	Direct Self Control
DSP	Digial Signal Processor
DTC	Direct Torque Control
EMF	Electromotive Force
FOC	Field Oriented Control
IM	Induction Machine
IPM	Interior Permanent-Magnet Machine
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

ω_k	(rad s^{-1})	general angular speed
ω_1	(rad s^{-1})	electrical angular speed of a stator rotating magnetic field
$\mathrm{p_p}$	(-)	number of pole pairs
ψ_{PM}	(Wb)	flux linkeage of permanent magnets
T	(Nm)	electromagnetic torque
$\underline{i}_1^k$	(A)	space vector of a stator current
L_d	(H)	d-axis inductance
L_q	(H)	q-axis inductance
$\underline{\psi}_1^k$	(Wb)	space vector of a stator flux linkeage
R_{s}	(Ω)	stator rezistance
$\underline{u}_1^k$	(V)	space vector of stator voltage