CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Electrical Engineering

Department of Electric Drives and Traction

A Brief Report on Permanent Magnet Assisted Synchronous Reluctance Motors

Petr Zakopal

Prague 2023

TABLE OF CONTENTS

LIST OF FIGURES

1 Introduction

This short report paper presents the most important information about Permanent Magnet Assisted Reluctance Motors (PMSynRelM). The topics discussed in this paper could be extended but the brief paper would loose it's clearance.

The references used in this paper were selected based on the rating, relevance and the publication date to reflect modern trends in the field as much as was possible. Some principles for controlling the machines were developed in much earlier publications when the PMSynRelM were not popular, but the principle developed for earlier machine desings still work today.

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 control strategies used for controlling the 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 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[4]

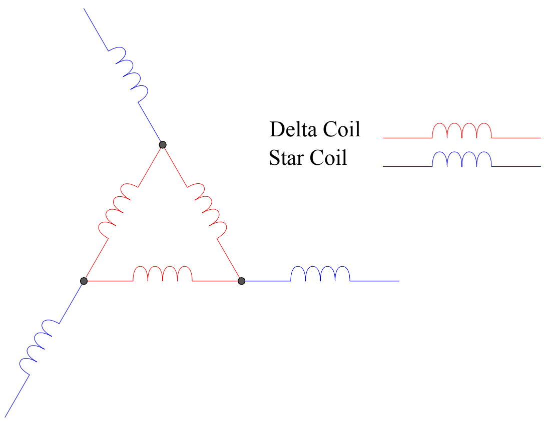
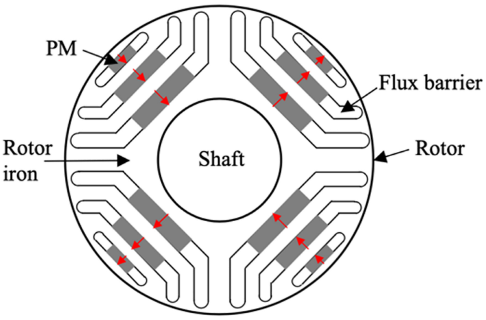


Figure 2 - 1 Hybrid Star-Delta wiring of PMSynRelM.

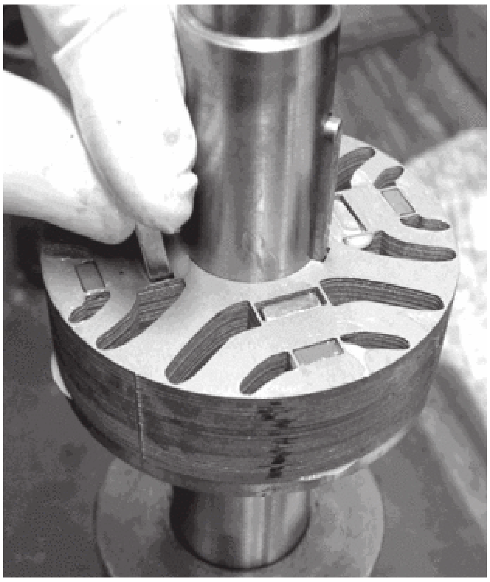
In [4] the authors manufactured proposed four prototypes. The prototypes consist of two stators, with either conventional star winding or hybrid star-delta winding, and two rotors, with ferrite permanent magnets or without. Maxwell transient simulations were carried out on the four prototypes, which 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 - 2a. The proces of inserting the permanent magnets to the flux barriers in the rotor is depicted in Fig. 2 - 2b.



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



(b) Process of inserting the permanent magnets to the rotor of a Permanent Magnet Assisted Synchronous Reluctance Motor. [6]

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 [7], 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 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 costs [9].

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, 10] The two general types of rotor with embedded PM are depicted in figure 2 - 3.

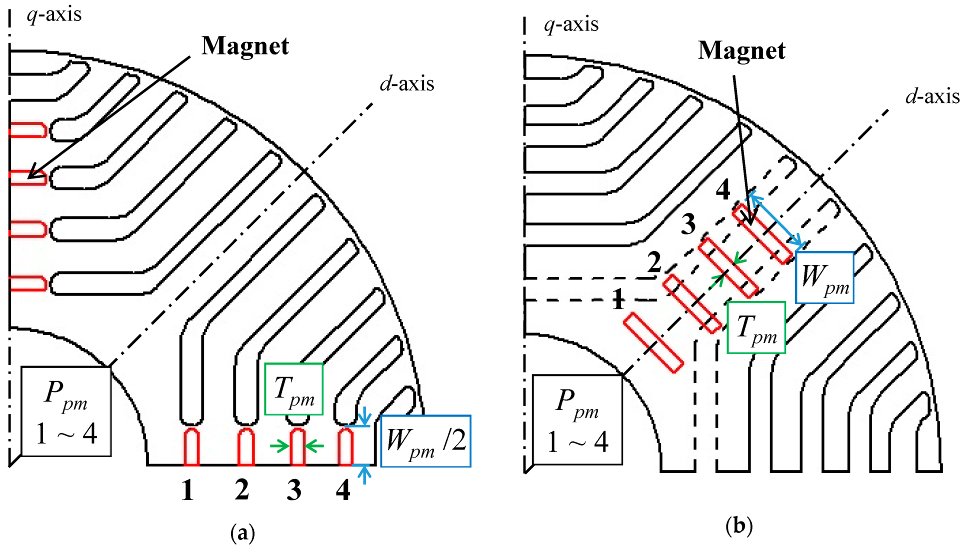


Figure 2 - 3 Different approaches to permanent magnet orientation in the rotor of a Permanent Magnet Assisted Synchronous Reluctance Motor. (a) PM embedded along the flux bariers, facing the q-axis; (b) Permanent magnets are crossing the flux bariers, therefore facing the d-axis. [10]

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.

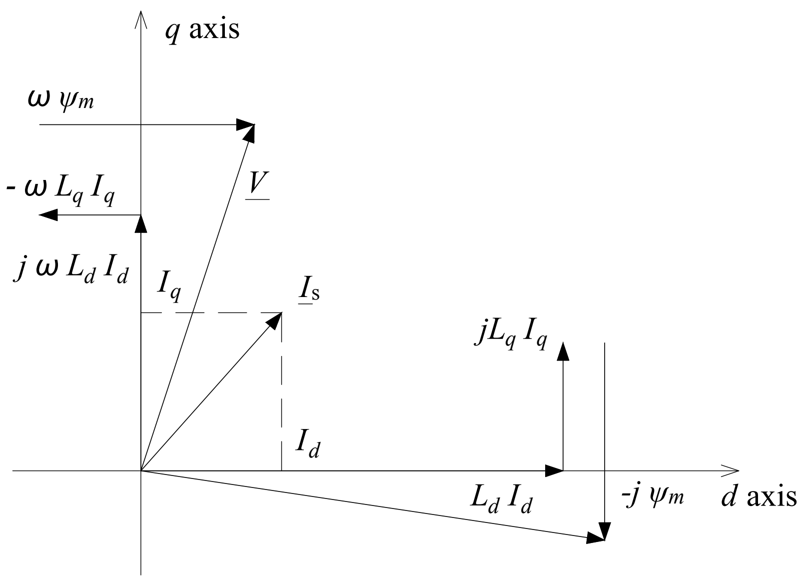


Figure 3 - 1 Phasor diagram for the SynRelM when the flux of permanent magnets ψ_m is oriented in the negative q-axis direction.

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

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. [11] The general group decopmosition is depicted in the figure 3 - 2.

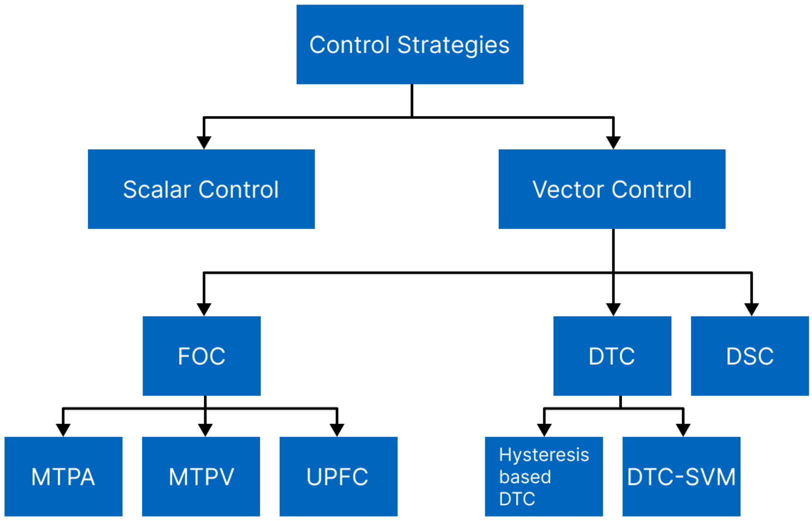


Figure 3 - 2 General diagram depicting major groups of control strategies for PMSynRelM. Graph inspired by [11]

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. [11]

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. [12]

3.2.2 Vector Control

Vector control strategies became increasingly popular due to the lower cost and higher computational power of available DSPs. [11]

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. [12, 11]

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 [11], there are multiple methods how to realize the MTPA.

The control strategy is parameter dependent which may present a problem. In [13] 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 [14] the exemplar curves presenting MTPV are depicted. Another mathematical expression of the MTPV trajectoriy is presented in [15]. 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 [16] 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 [16] 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. [16]

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. [16]

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. [11]

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 [17] 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 [18] in 1989 for induction motor. The Direct Self Control strategy published by Depenbrock in [19] 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.

There are many researches regarding the control strategies which leverage the main idea of presented strategies and perfects them for the specific application. The example diagram depicting selected sub-control strategies is presented in [12].

4 Comparison to other machines

When designing electric drives there are options on which motor to use in the application. That is why the comprehensive comparison of PMSynRelM and other types of motor is handy. This comparison study was well carried out in [20]. Authors compare the induction machine (IM), synchronous reluctance motor (SynRelM), permanent magnet assisted synchronous reluctaaance motor (PMSynRelM) and interior permanent-magnet machine (IPM).

The machines are compared based on the design parameters regarding electromagnetic performance, material cost and temperature. The authors in [20] conclude, that the electromagnetic performance of analyzed ferrite-based PMSynRelM are better than that of the IM and SynRelM without PM. The cost of materials for PMSynRelM is lower than the IPM. The torque ripple and the demagnetization of ferrites may be a problem when using the PMSynRelM. [20]

5 Recent research interest

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

The improvement was achieved:

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

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

New types of motors and control strategies are proposed in [21]. Proposed motors utilize variable flux strategy where high stator current i_d value 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 again cause magnetization of permanent magnets. The proposed principle is still being developed and published about.

References

[1] LI, Xinmin; SUN, Zihan; SUN, Wenbo; GUO, Liyan; WANG, Huimin. Design of Permanent Magnet-Assisted Synchronous Reluctance Motor with Low Torque Ripple. *World Electric Vehicle Journal*. 2023, roč. 14, č. 4. ISSN 2032-6653. Available from DOI: 10.3390/wevj14040082.

[2] HUYNH, Thanh Anh; HSIEH, Min-Fu; SHIH, Kai-Jung; KUO, Hsiu-Fu. Design and analysis of permanent-magnet assisted synchronous reluctance motor. In: *2017 20th International Conference on Electrical Machines and Systems (ICEMS)*. 2017, pp. 1–6. Available from DOI: 10.1109/ICEMS.2017.8056462.

[3] IBRAHIM, Mohamed Nabil Fathy; ABDEL-KHALIK, Ayman S.; RASHAD, Essam M.; SERGEANT, Peter. An Improved Torque Density Synchronous Reluctance Machine With a Combined Star--Delta Winding Layout. *IEEE Transactions on Energy Conversion*. 2018, roč. 33, č. 3, pp. 1015–1024. Available from DOI: 10.1109/TEC.2017.2782777.

[4] IBRAHIM, Mohamed N.; SILWAL, Bishal; SERGEANT, Peter. Permanent Magnet-Assisted Synchronous Reluctance Motor Employing a Hybrid Star-Delta Winding for High Speed Applications. In: *2018 XIII International Conference on Electrical Machines (ICEM)*. 2018, pp. 379–385. Available from DOI: 10.1109/ICELMACH.2018.8506694.

[5] SHAO, Lingyun; TAVERNINI, Davide; HARTAVI KARCI, Ahu Ece; SORNIOTTI, Aldo. Design and optimisation of energy□efficient PM□assisted synchronous reluctance machines for electric vehicles. *IET Electric Power Applications*. 06/2023, roč. 17, č. 6, pp. 788–801. ISSN 1751-8660, ISSN 1751-8679. Available from DOI: 10.1049/elp2.12303.

[6] WANG, Yawei; BIANCHI, Nicola; BOLOGNANI, Silverio; ALBERTI, Luigi. Synchronous motors for traction applications. In: *2017 International Conference of Electrical and Electronic Technologies for Automotive*. Torino, Italy: IEEE, 06/2017, pp. 1–8. ISBN 978-88-87237-26-9. Available from DOI: 10.23919/EETA.2017.7993210.

[7] MORIMOTO, Shigeo; OOI, Shohei; INOUE, Yukinori; SANADA, Masayuki. Experimental Evaluation of a Rare-Earth-Free PMASynRM With Ferrite Magnets for Automotive Applications. *IEEE Transactions on Industrial Electronics*. 10/2014, roč. 61, č. 10, pp. 5749–5756. ISSN 0278-0046, ISSN 1557-9948. Available from DOI: 10.1109/TIE.2013.2289856.

[8] OBATA, Masahiro; MORIMOTO, Shigeo; SANADA, Masayuki; INOUE, Yukinori. Performance of PMASynRM With Ferrite Magnets for EV/HEV Applications Considering Productivity. *IEEE Transactions on Industry Applications*. 07/2014, roč. 50, č. 4, pp. 2427–2435. ISSN 0093-9994, ISSN 1939-9367. Available from DOI: 10.1109/TIA.2013.2294999.

[9] CAI, Haiwei; GUAN, Bo; XU, Longya. Low-Cost Ferrite PM-Assisted Synchronous Reluctance Machine for Electric Vehicles. *IEEE Transactions on Industrial Electronics*. 10/2014, roč. 61, č. 10, pp. 5741–5748. ISSN 0278-0046, ISSN 1557-9948. Available from DOI: 10.1109/TIE.2014.2304702.

[10] NGO; HSIEH. Performance Analysis of Synchronous Reluctance Motor with Limited Amount of Permanent Magnet. *Energies*. 09/2019, roč. 12, č. 18, p. 3504. ISSN 1996-1073. Available from DOI: 10.3390/en12183504.

[11] DWIVEDI, Shruti; TRIPATHI, S. M.; SINHA, S. K. Review on Control Strategies of Permanent Magnet-Assisted Synchronous Reluctance Motor Drive. In: *2020 International Conference on Power Electronics IoT Applications in Renewable Energy and its Control (PARC)*. Mathura, Uttar Pradesh, India: IEEE, 02/2020, pp. 124–128. ISBN 978-1-72816-575-2. Available from DOI: 10.1109/PARC49193.2020.236570.

[12] HEIDARI, Hamidreza; RASSÕLKIN, Anton; KALLASTE, Ants; VAIMANN, Toomas; ANDRIUSHCHENK Ekaterina; BELAHCEN, Anouar; LUKICHEV, Dmitry V. A Review of Synchronous Reluctance Motor-Drive Advancements. *Sustainability*. 01/2021, roč. 13, č. 2, p. 729. ISSN 2071-1050. Available from DOI: 10.3390/su13020729.

[13] NIAZI, Peyman; TOLIYAT, Hamid A.; GOODARZI, Abbas. Robust Maximum Torque per Ampere (MTPA) Control of PM-Assisted SynRM for Traction Applications. *IEEE Transactions on Vehicular Technology*. 07/2007, roč. 56, č. 4, pp. 1538–1545. ISSN 0018-9545, ISSN 1939-9359. Available from DOI: 10.1109/TVT.2007.896974.

[14] SANZ, Alberto; OYARBIDE, Estanis; GÁLVEZ, Rubén; BERNAL, Carlos; MOLINA, Pilar; SAN VICENTE, Igor. Analytical maximum torque per volt control strategy of an interior permanent magnet synchronous motor with very low battery voltage. *IET Electric Power Applications*. 07/2019, roč. 13, č. 7, pp. 1042–1050. ISSN 1751-8660, ISSN 1751-8679. Available from DOI: 10.1049/iet-epa.2018.5469.

[15] FLETCHER, J.; XIAO, D.; RAHMAN, M.F.; DUTTA, R.; EKANAYAKE, S. Operation along the maximum torque per voltage trajectory in a direct torque and flux controlled interior permanent magnet synchronous motor. In: *8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016)*. Glasgow, UK: Institution of Engineering a Technology, 2016, pp. 6 .–6 . ISBN 978-1-78561-188-9. Available from DOI: 10.1049/cp.2016.0326.

[16] MOUSSA, M. F.; HELAL, A.; GABER, Y.; YOUSSEF, H. A. Unity Power Factor control of permanent magnet motor drive system. In: *2008 12th International Middle-East Power System Conference*. Aswan, Egypt: IEEE, 03/2008, pp. 360–367. ISBN 978-1-4244-1933-3. Available from DOI: 10.1109/MEPCON.2008.4562309.

[17] SWIERCZYNSKI, D.; KAZMIERKOWSKI, M.P.; BLAABJERG, F. DSP based direct torque control of permanent magnet synchronous motor (PMSM) using space vector modulation (DTC-SVM). In: *Industrial Electronics, 2002. ISIE 2002. Proceedings of the 2002 IEEE International Symposium on*. L'Ayuila, Italy: IEEE, 2002, 723–727 vol.3. ISBN 978-0-7803-7369-3. Available from DOI: 10.1109/ISIE.2002.1025821.

[18] TAKAHASHI, I.; OHMORI, Y. High-performance direct torque control of an induction motor. *IEEE Transactions on Industry Applications*. 04/1989, roč. 25, č. 2, pp. 257–264. ISSN 00939994. Available from DOI: 10.1109/28.25540.

[19] DEPENBROCK, M. Direct self-control (DSC) of inverter-fed induction machine. *IEEE Transactions on Power Electronics*. 10/1988, roč. 3, č. 4, pp. 420–429. ISSN 0885-8993, ISSN 1941-0107. Available from DOI: 10.1109/63.17963.

[20] DU, Guanghui; ZHANG, Guiyuan; LI, Hui; HU, Chengshuai. Comprehensive Comparative Study on Permanent-Magnet-Assisted Synchronous Reluctance Motors and Other Types of Motor. *Applied Sciences*. 07/2023, roč. 13, č. 14, p. 8557. ISSN 2076-3417. Available from DOI: 10.3390/app13148557.

[21] OSTOVIC, V. Memory motors-a new class of controllable flux PM machines for a true wide speed operation. In: *Conference Record of the 2001 IEEE Industry Applications Conference. 36th IAS Annual Meeting (Cat. No.01CH37248)*. Chicago, IL, USA: IEEE, 2001, sv. 4, pp. 2577–2584. ISBN 978-0-7803-7114-9. Available from DOI: 10.1109/IAS.2001.955983.

[22] M., Popescu. Induction Motor Modelling for Vector Control Purposes. In: *Helsinki University of Technology, Laboratory of Electromechanics* [online]. 2000 [visited on 2023-10-14]. Available from: https://avys.omu.edu.tr/storage/app/public/mustafa.aktas/110896/induction_motor_modelling.pdf.

[23] LIPČÁK, Ondřej; BAUER, Jan. Doprovodný materiál k přednáškám. In: *Materiál k přednáškám a cvičení v př edmětu B1M14EPT* [online]. [B.r.] [visited on 2023-02-28]. Available from: https://moodle.cvut.cz.

[24] BOAZZO, Barbara; VAGATI, Alfredo; PELLEGRINO, Gianmario; ARMANDO, Eric; GUGLIELMI, Paolo. Multipolar Ferrite-Assisted Synchronous Reluctance Machines: A General Design Approach. *IEEE Transactions on Industrial Electronics*. 2015, roč. 62, č. 2, pp. 832–845. Available from DOI: 10.1109/TIE.2014.2349880.

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