PMSM Vector Control Techniques – a Survey

Vladislav M. Bida, Dmitry V. Samokhvalov, Fuad Sh. Al-Mahturi
Faculty of Electrical Engineering and Automation; Department of Robotics and Automation of Industrial Systems
Saint-Petersburg Electrotechnical University "LETI"
Saint Petersburg, Russia

***Abstract*—This paper reviews permanent magnet synchronous motor vector control techniques and existing classifications of such techniques. This paper offers a generalized classification of vector control techniques that combines various principles of vector control and speed control approaches. Methods listed in the classification are characterized by their basic qualitative characteristics. On the basis of comparative analysis of techniques recommendations are given on their practical application.**

Keywords—permanent magnet synchronous motor; vector control techniques classification; field oriented control; direct torque control; direct self control; voltage vector control; passivity based control; nonlinear torque control; feedback linearization

I. Introduction

Currently, permanent magnet synchronous motors (PMSM) are widely used for industrial and transport application. The reasons are their undisputable advantages, such as a high efficiency factor, minimal size and weight parameters, low rotor inertia (resulting in a high speed of response), high reliability, significant life expectancy and practically no need for service during the whole usage period. In addition, control circuits of such motors are simpler than those of other AC machines (induction motor, switched reluctance motor, etc.). Until recently, the widespread use of PMSM was in some cases restrained by relatively high prices for magnetic materials with high specific magnetic energy values (alloys $Ne_2Fe_{14}B$, Sm_2Co_{17}, etc.) necessary for its effective operation, that resulted in higher prices of motors. Over the last years, prices for such materials have significantly decreased [1]. This may imply future growth of PMSM drive systems in the industry and technology.

Efficient operation of PMSM as part of adjustable electric drives demands a careful choice of the control system suitable for the completion of a given objective. There are many ways of designing a PMSM control system. The concept of vector control, which allows controlling such parameters of space vectors of voltage and flux such as magnitude, angular frequency and instant position, is common for modern high-performance AC motor control techniques.

The principle of vector control of an induction motor was proposed for the first time by K. Hasse (indirect field-oriented control) [2] and F. Blaschke (direct field-oriented control) [3] in 1972. In 1989, P. Pillay and R. Krishnan demonstrated the possibility of using a field-oriented control circuit for a PMSM [4]. Over the past decades, many variations of the original circuit with a different component base have been proposed, as well as techniques of vector control that are fundamentally different from the original.

Section II reviews various PMSM vector control techniques without description according to the works published to date and some classifications presented in literature, a generalized classification is proposed. Every technique gets a brief description and a characteristic in terms of their main qualitative properties in Section III.

II. Classificacion

Ocen D. [5] considering the most common control techniques, gives their classification, a fragment of which is shown in Figure 1.

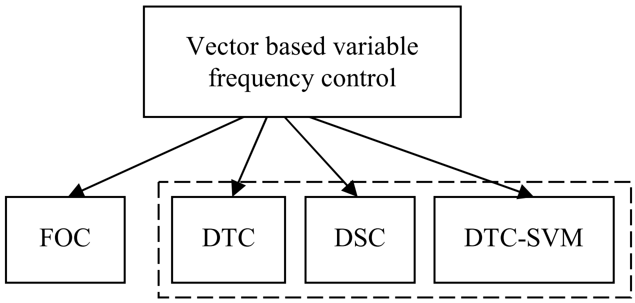

Fig. 1. Some vector based control techniques for PMSM according to [5]. Control methods in the dashed box belong to the DTC family.

This classification is rather concise and can be developed and expanded. It presents the basic and most widely known vector control techniques: field oriented control (FOC) on the one hand and direct torque control (DTC), direct self-control (DSC), direct torque control with space vector modulation (DTC-SVM) on the other hand.

In another paper [6], authors supplement the classification citing another technique – voltage vector control (VVC) – focusing their work on describing and comparing it with the FOC. (Figure 2).

978-1-5386-4340-2/18/$31.00 ©2018 IEEE

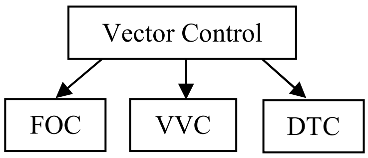

Fig. 2. Vector control techniques according to [VVC].

Considering other classifications, it should be noted that FOC is also distinguished by the reference frame used for the mathematical description of the motor: a rotary and a stator one. The first, in its turn, is divided into the indirect (Hasse) [2] and direct one (Blashke) [3], which is reflected in the classification given in [7] by Kamran Jalili. This classification, just as many others, divides DTC into the *DTC with Space-Vector Modulation*, *DTC with circular flux trajectory* (Takahashi) [8] and *DTC with Hexagonal flux trajectory* (Depenbrock) [9].

In pursuance of the above mentioned approaches systematization, more relevant, generalized classification of vector control techniques is presented in Figure 3. It is also supplemented by some techniques that are noted below in the text.

The traditional *DTC with SVM*, according to [10], can be supplemented and divided into the *Linear DTC* (or *Feedback Linearization DTC*) and *Variable Structure DTC* (or *Sliding Mode DTC*).

Passivity Based Control for PMSM - another interesting technique, noted in the classification by G.S. Buja and M.P. Kazmierkowski [11]. According to the description presented in [12], this approach can be distinguished as a separate independent vector control technique.

As a separate vector control technique, one can also distinguish *A. Lyapunov Technique Approach for the torque control of the PMSM* presented in [13] (or *Nonlinear Torque Control*).

A variety of vector control techniques is also provided by using various speed controllers as part of the FOC circuit. Strictly speaking, these techniques do not differ from one other in principle; however, the characteristics of such systems are different, that is essential from a practical point of view. Hereat circuits for field-oriented control using *PI-Controller, Fuzzy Logic Controller (FLC), Sliding Mode Controller (SMC) and Model Predictive Controller (MPC)* of speed is considered [14].

Following such logic, it can be stated that the field-oriented control like most other techniques having in their circuits pulse width modulation (PWM) can also be classified according to the PWM technique used. However, this classification is not given here.

The given in Figure 3 classification by speed control techniques is valid for both direct and indirect field-oriented control as the presence or absence of a position sensor does not affect the speed controller used in the circuit. Also, this classification misses a possible division of FOC into Rotor Flux Oriented and Stator Flux Oriented, as the last one is not used in practice, because of the more complex mathematical model of PMSM and nonlinear speed-torque characteristic (due to the inconsistency of the rotor flux-linkage), that unjustifiably complicates the control system. Therefore, it is usually assumed that using FOC for PMSM always means using reference frame oriented by the rotor flux linkage.

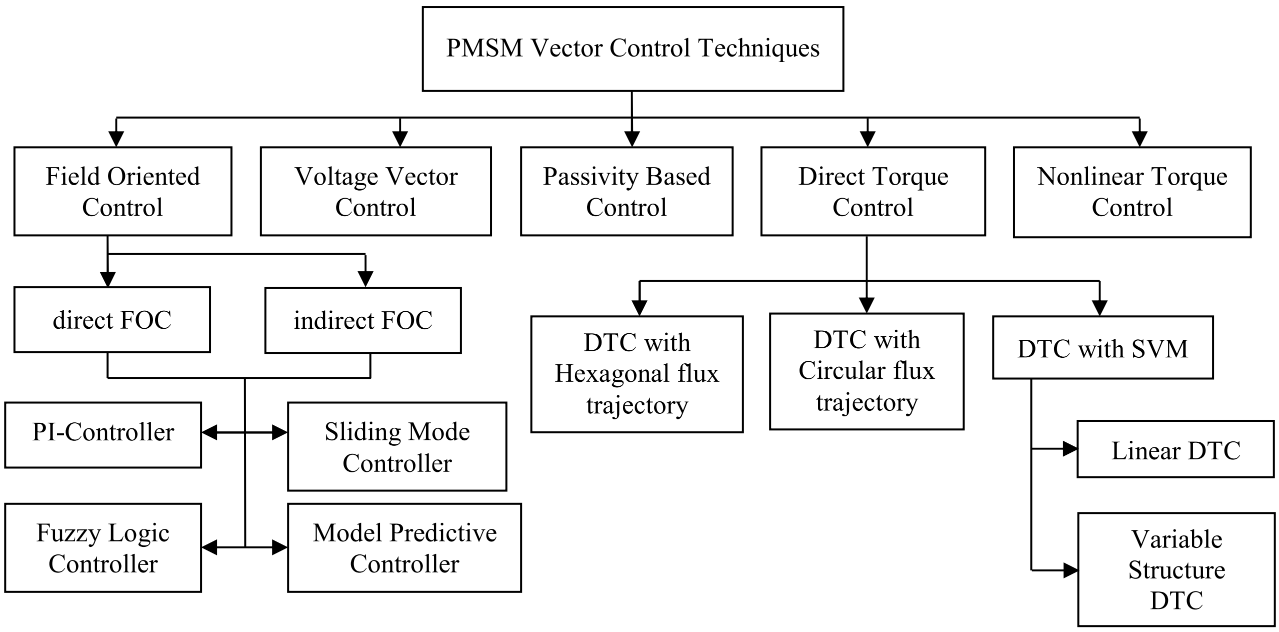

Fig. 3. Proposed classification of PMSM vector control techniques

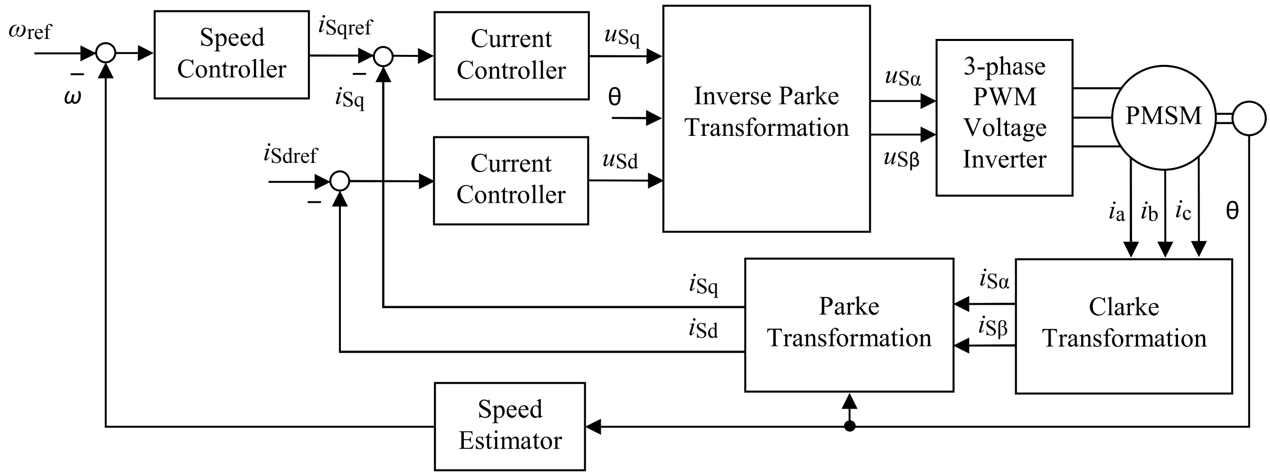

Fig. 4. Field Oriented Control block diagram.

III. VECTOR CONTROL TECHNIQUES DESCRIPTION

This part takes a closer (more detailed) look at some techniques presented above in proposed classification that makes it possible to carry out more careful analysis and give the reasonable determination of application areas for each technique.

A. Field Oriented Control (FOC)

FOC is the most widely known vector control technique. Its simplified block diagram scheme with a rotor position sensor (*direct FOC*) is shown in Figure 4.

In this circuit, currents of the stator phases of the motor are measured and transformed to a two-phase αβ system via Clarke Transformation. The value of the rotor angle from the position sensor (or one calculated indirectly in case of no sensor) is used for the following transformation of currents via Parke Transformation from the static reference frame αβ to the rotated dq one connected with the rotor flux linkage. In accordance with the reference speed signals and the d-component of the stator current, taking into account the feedback signals, a separate control of the torque and the motor excitation flux is carried out. This is the key principle of FOC.

Maintaining the maximum torque with a given stator current value is achieved when one is fully oriented along the q axis, that is, when $i_{sd} = 0$ and $i_{sq} = i_s$. In this case, the classical FOC is implemented. If, in the context of the problem being solved, it is necessary to provide an increased motor speed, the current component along the d axis is set negative, that leads to the field weakening, and, consequently, to the reduction of the speed-limiting back-EMF and acceleration of the motor with increasing stator current magnitude.

The FOC circuit can be constructed with a position sensor (*direct*) and without one (*indirect*). In the first case, the mathematical model of the system is simpler, the control is faster and more precise. According to the information presented in [15], the presence of the sensor provides a 1:1000 speed change with a tolerance of ± 0.01%, while indirect position calculations in the system without a sensor allows the speed to be regulated 1:100 with a tolerance of ± 0.5%. However, with all else being equal, the *sensorless FOC* drive system is cheaper and more reliable than the FOC drive system with a sensor. Also it is difficult enough for position sensors to be used in some drive systems (for technological or operational reasons, e.g., in submersible motor drilling systems).

A comparative analysis of the characteristics of a field-oriented controlled electric drive with a rotor position sensor using various speed regulators (indicated in the proposed classification in Figure 3) is given in [14]. The following assessment is given in the work:

- Sart-up stator current overshoots.
- Transient process period at no-load start-up and at loading in a steady-state.
- Maximum torque and speed overshoot.

According to the Simulink simulation results presented in [14] in graphs of the phase currents, speed and torque of the motor, it can be concluded that the application of PI controller leads to significant current peaks at start-up, relatively long time and large amplitude of overshooting, as well as the torque ripples. MPC provides minimal current peaks and practically zero overshoots of speed and torque. When using SMC, the efficiency of the response to load changes is close to the efficiency of the MPC, but in this case the maximum current peak at start-up is maximal. FLC provides lower overshoot amplitude than the SMC, but the transient time is longer. The peak in currents amplitude at start-up is slightly higher than in case of the MPC.

From the presented comparative analysis it can be concluded that the simplest and at the same time the least efficient regulator is the classical PI-Controller. SMC, FLC and

MPC have approximately the same efficiency, but the application of SMC and MPC allows achieving minimal sensitivity of the system to changes in motor parameters or disturbances. In this case, the SMC is better suited for systems where maximum torque accuracy is required, while MPC is more suitable for ensuring precise and rapid regulation of motor speed.

FOC is a universal vector control technique that provides high accuracy and speed of motor control. The main criticism of FOC concerns the problem of instability of the system that may be caused by possible changes in the motor parameters or by disturbances during operation, as well as a large number of calculations limiting the control speed.

The use of non-classical speed controllers allows a significant reduction in the risk of instability issues. Today's level of microprocessor computer technology and power electronics is capable of providing sufficient speedwork of the system for solving practical problems.

B. *Direct Torque Control Techniques*

In the mid-1980s, vector control techniques alternative to *FOC* were developed. M. Depenbrock suggested a technique titled as *Direct Torque Control with Hexagonal flux trajectory* [9], while I. Takahashi and T. Noguchi suggested *Direct Torque Control with Circular flux trajectory* [8].

DTC circuits have simpler structures than the FOC circuit, they do not require the use of an inverter with PWM, a speed sensor and reference frame transformers. All calculations are performed in the stator reference frame as information about the exact position of the rotor in such systems is not required (except the start-up case of the synchronous motor). The requirements for the computational capabilities of the controllers are relatively low. Such systems have high-quality dynamic characteristics, quickly respond to load changes, and are less sensitive to changes in motor parameters and disturbances. However, their steady-state operation is characterized by high ripples levels of the stator current, flux linkage and torque, especially at low speeds, that greatly limits their use for high-precision drives. At the same time, *DTC with Circular flux trajectory* occurs to be more effective for controlling traction drives, according to [11].

Direct Torque Control with Space Vector Modulation (*DTC with SVM*) is designed to overcome the disadvantages of DTC. *DTC with SVM* uses the pulse width modulation approach to generate the voltage. There are several variations of the circuits that significantly improve the efficiency of the control system, compared to DTC. They provide a certain reduction in the ripple of torque and flux, the control is carried out more smoothly, and start-up and running the motor at low speeds are more stable. At the same time, having high dynamics, this technique still remains incapable of ensuring the accuracy of control provided by FOC [16].

Linear Direct Torque Control (*Linear DTC*) and *Sliding Mode DTC* (*SM DTC*). In the theory of automatic control, the *Feedback Linearization* approach is used to represent a nonlinear system as a linear one, in order to simplify the control process. All the FOC circuits use this approach which is implemented through the transformation of the stator current components from αβ to dq-reference frame, while traditional DTC techniques do not use the linearization.

Work [10] suggests direct torque control techniques using linearized mathematical model of the motor based on the *DTC with SVM* circuit. Depending on the used torque and flux controllers, *Linear DTC* (*PI-controllers*) and *Sliding Mode DTC* (*Sliding Mode controllers*) are distinguished. According to the simulation results presented in [10], it can be concluded that both proposed approaches provide a significant minimization of flux and torque ripples typical for *DTC*, while the system's response speed remains high, just as in case of the *DTC with SVM*. Also, the stability of the system against changes of the motor parameters or disturbances is increased. Nevertheless, at low speeds, ripples remain clearly noticeable, that limits the application of these techniques for high-precision drives.

C. *Voltage Vector Control* (*VVC*)

VVC is described in work [6]. The block diagram scheme of the method is relatively simple. It does not require information about the position of the rotor, however, as in case of the FOC circuit, reference frame transformations are used. At the same time, only the flux-forming component of the stator current is regulated. Both approaches provide a quick enough response to control signals. VVC is less sensitive to motor parameter changes than the classic FOC, its circuit structure and computational algorithms are simpler.

The disadvantages include high torque overshoot amplitude, as well as a higher ripple than in case of using *FOC*, that makes it difficult to use the *VVC* in high-precision drive systems.

D. *Passivity Based Control* (*PBC*)

In terms of complexity, the *PBC* system structure is not simpler than the one of the FOC. It uses position feedback, reference frame transformations, PWM. According to [12], the PBC provides good dynamics in terms of speed, however, the torque peaks in transient processes are significant. The level of ripples is also clearly higher than the one while using FOC. Thus, the accuracy of the presented approach (as well as those of the DTC, VVC techniques) cannot be compared to the FOC.

E. *Nonlinear Torque Control* (*NTC, A. Lyapunov Technique-based Torque Control*)

In the *NTC* scheme, the torque is controlled using the Lyapunov function in accordance with the torque control input, stator current error signals in the dq reference frame and speed. Simulation results from Simulink presented in [13] allow to talk about the high efficiency of this technique. It ensures a low level of torque ripples and a high response speed. In the simulation of an abnormal mode, at which the load torque increased rapidly, the resistance of the stator circuit, inductance (along the d and q axes) of the stator, the flux linkage and rotor inertia were changed, the stator current magnitude and the motor electromagnetic torque remained constant (within the torque ripple magnitude). This allows to talk about the high stability of the system, its independence from disturbances and changes in motor parameters.

IV. CONCLUSION

This review paper covers some vector control techniques and their existing classifications, a generalized extended classification of techniques is proposed. Each of the methods introduced in it is briefly described and analyzed.

From the performed analysis, it can be concluded that all DTC techniques are well suited for use in traction and transport drive systems. The VVC and PBC techniques can be used for traction drives, as well as in industrial and technical systems where high positioning accuracy is not required.

Direct FOC with non-classical speed controller (FLC, SMC, MPC) and NTC are best for high-precision tracking, targeting, coordinating drives. At the same time, the NTC technique provides the highest robustness of the system and its independence from sudden motor parameters changes or external disturbances.

REFERENCES

[1] Torque Motor: Common industrial use prospects, Designer and Machine Builder journal (from russian "Моментный двигатель: перспективы общепромышленного использования, журнал Конструктор. Машиностроитель"), 27/12/2016 Available at https://konstruktor.net/podrobnee-elekt/momentnyj-dvigatel-perspektivy-obschepromyshlennogo-ispolzovanija-1521.html (accesed 24 November 2017).

[2] K. Hasse. “Drehzahlgelverfahren fur schnelle Umkehrantriebe mit strom-richtergespeisten Asynchron-Kurzchlusslaufermotoren: Reglungstechnik”, vol. 20, no. 2, pp. 60–66, 1972.

[3] F. Blaschke. “The principle of field-orientation as applied to the transvector closed loop control system for rotating-field machines: Siemens Rev. ”, vol. 34, no. 1, pp. 217–220, 1972.

[4] Pillay P., Krishnan R. “Modeling, simulation, and analysis of permanent-magnet motor drives. I. The permanent-magnet synchronous motor drive” // IEEE Trans. Industry Applications. – 1989. – V. 25. - №. 3. – P. pp. 265 -273

[5] D.Ocean “Direct Torque Control of a Permanent Magnet synchronous Motor, ” master's thesis, 2005.

[6] S. Dwivedi, M. Laursen, S. Hansen “Voltage Vector based Control for PMSM in Industry Applications,” Danfoss Drives A/S, 6300 Graasten, Denmark, 2010.

[7] K Jalili, “Investigation of Control Concepts for High-Speed Induction Machine Drives and Grid Side Pulse-Width Modulation Voltage Source Converters,” PhD thesis, Electrotechnical Engeneering and Information Technology faculty of Dresden TU, 2008

[8] I. Takahashi and T. Noguchi, “A new quick-response and high efficiency control strategy of an induction machine” // *IEEE Trans. Ind. Applicat.*, vol. IA-22, pp. 820–827, Sept./Oct. 1986.

[9] M. Depenbrock, “Direct self control of inverter-fed induction machines” // *IEEE Trans. Power Electron.*, vol. 3, pp. 420–429, Oct. 1988.

[10] C. Lascu, I. Boldea, F. Blaabjerg, “Direct Torque Control via Feedback Linearization for Permanent Magnet Synchronous Motor Drives” // IEEE [13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), pp. 338-343, 2012]

[11] G. Buja and M. Kazmierkowski, “Direct torque control of PWM inverter-fed AC motors - a survey” // IEEE Trans. Ind. Electron., vol. 51, issue: 4 pp. 744 - 757, 2004.

[12] A. Abdelyazid, “Passivity Based Control for Permanent-Magnet Synchronous Motors, Recent Advances in Robust Control - Theory and Applications in Robotics and Electromechanics”, Dr. Andreas Mueller (Ed.), ISBN: 978-953-307-421-4, InTech, 2011.

[13] M. Ouassaid, M. Cherkaoui, A. Nejmi, M. Maaroufi, “Nonlinear Torque Control for PMSM: A Lyapunov Technique Approach”, World Academy of Science, Engineering and Technology International Journal of Electrical and Computer Engineering, vol. 1, no. 6, 2007.

[14] S. Hussain, M. Bazaz, “Comparative Analysis of Speed Control Strategies for Vector Controlled PMSM Drive”, Int. Conference on Computing, Communication and Automation (ICCCA), 2016.

[15] “Scalar and Vector control in Frequency Changers” (from russian "Скалярное и векторное управление в частотных преобразователях"), Available at http://tehpromcomplect.ru/metody_upravlenia_v_chastotnikax (accesed 26 November 2017).

[16] M. Basar, M. Bech, T. Andersen, P. Scavenius, T. Thomas-Basar, “Comparison of sensorless FOC and SVM-DTFC of PMSM for low-speed applications” // IEEE [4th International Conference on Power Engineering, Energy and Electrical Drives, pp. 864-869, 2013]