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RESEARCH ARTICLE

New Method of Vector Control in PMSM Motors

KRZYSZTOF KOLANO
Department of Electrical Drives and Machines, Lublin University of Technology, 20-618 Lublin, Poland
e-mail: k.kolano@pollub.pl

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ABSTRACT The paper introduces a new method for vector control of PMSM (Permanent Magnet Synchronous Motor) motors called theta-FOC. This method combines the advantages of simple sinusoidal control and Field Oriented Control (FOC). The paper proposes introducing an additional parameter that determines the electrical angle between the motor's voltage space vector and rotor magnetic flux axis. The classical Field Oriented Control was modified to reduce the number of necessary calculations. The proposed method allows for decoupling the calculations from the cyclic PWM (Pulse Width Modulation) signal, enabling calculations to be performed at a frequency different from PWM. This results in the possibility of achieving a higher frequency of the PWM signal. Additionally, the proposed method minimizes the influence of deviation between the actual PWM voltage and the voltage command generated from the controller at high PWM frequencies, leading to better operation of the system in terms of field weakening. This method has been tested under typical operating conditions and has performed similarly to the FOC method, but with a reduced number of calculations, and therefore reduced control time.

INDEX TERMS PMSM motor, field oriented control, field weakening.

I. INTRODUCTION

Permanent Magnet Synchronous Motors are increasingly used in industrial automation, appliances and servo drives. Such motors typically have good torque characteristics, fast dynamic response, high efficiency and long service life. A typical drive of this kind consists of a permanent magnet synchronous motor (PMSM) powered by an inverter. The simplest method of controlling such a drive is the so-called sinusoidal control, which consists in generating the supply voltage space vector shifted by the angle $\Theta_e = 90$ electrical degrees relative to the rotor flux axis. [3], [4], [5], [7]. This method ensures a low level of electromagnetic torque ripple and enables accurate control of themotor shaft position. Unfortunately, the assumption of a constant angle between the voltage vector and the rotor flux is not optimal in the entire operating range. In this type of control, the stator flux is in phase with the current, but the current is not always in phase with the voltage. This means that with sinusoidal control, the motor is not necessarily running at maximum torque. The method called Field Oriented Control brings much better results. The principle of FOC was first proposed by F. Blaschke of Siemens in the early 1970s for controlling induction motors. This method has been developed into a complete theory system within several years of efforts [1], [2]. Due to the rapid progress in power electronics, computer and microelectronics, the vector control technology has been used ever more widely in high performance AC drives in the last twenty years. This method is based on continuous measurements of the motor currents and modification of its supply voltage in such a way that it is possible to control both the motor torque and flux. This procedure is carried out with each PWM cycle of the inverter transistors, hence the requirements for the computing system performance are very high. These requirements increase with the switching frequency of transistors, which is systematically growing along with the progress of power electronics. Another problem considered in the literature is the deviation between the actual PWM voltage and the voltage command generated from the controller. This difference can be modelled by a zero order hold (ZOH) between the voltage command and actual voltage. The ZOH effect can be negligible when PWM frequency/rotational speed is sufficiently high. However at high speed, ZOH might result in the phase delay on the actual voltage. As reported in [7], the ZOH reflected phase delay increases along with increase of the rotor rotational frequency [8], [9].The operation of high-speed drive systems is essential in traction drive applications. For these

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applications, using MPC (Model Predictive Control) is a good alternative. The technique is based on predicting the optimal voltage vector applied to the driver. In the predictive scheme, a discrete-time model of the machine is used to predict the stator current components for seven different voltage vectors generated by the inverter. The voltage vector that minimizes a cost function is selected and applied throughout the sampling period [16], [17].

Both the FOC and MPC based control techniques rely on the sequential measurement of the motor phase currents, and as such, they cannot function in the case of a measurement element malfunction. The author's proposed control method can generate a voltage vector in orientation only relative to the rotor position, without the need to know the motor phase currents. It then operates with limited functionality, but it is able to produce a driving torque. In some applications, this may allow for further operation with limited parameters or for a controlled and safe shutdown of the drive system. The article aims to modify the most widespread control method for PMSM motors, the FOC, by introducing an additional parameter that describes the angle between the voltage space vector generated by the stator winding and the axis of the rotor flux, the Θ_e angle. The use of such a control technique allows for reducing the number of calculations performed by the processor without reducing the quality of the drive operation. This will enable operation with higher PWM frequencies and other computational functions beyond the control of the drive system. Another issue addressed is the impact of the developed control method on operation in the low-frequency range of the PWM signal relative to the rotational frequency of the motor current. The specifics of the proposed method mean that the higher PWM frequency does not affect the operation of the computation unit as intensively as with the FOC, which increases the possibilities of using the proposed control method in the flux weakening range of PMSM motors [7], [13], [14].

II. BASIC CONTROL METHODS FOR PMSM MOTORS

The basic principle of PMSM motor sinusoidal control is the appropriate orientation of the supply voltage space vector in relation to the position of the rotor flux axis $\Theta_e = 90$ electrical degrees-Fig. 1.

Importantly, this method does not require the measurement of phase currents or the use of complex mathematical calculations. The advantage is simplicity, speed and the possibility of precise positioning of the motor rotor. The disadvantage is that the fixed 90 electrical degrees angle between the rotor flux axis and the voltage space vector is not always optimal for torque generation and varies as a function of motor load and rotational speed.This method is similar to the BLDC motor control method and only requires information about the position of the motor shaft to generate the torque. Measurements of phase currents and complex calculations are not mandatory.

A much more advanced PMSM motor control method is the FOC vector control method. Its basic assumption is to

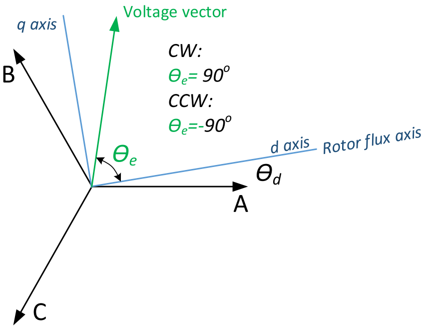

FIGURE 1. The principle of generating the PMSM motor supply voltagevector with sinusoidal control.

determine the q and d axis components of the motor currents, and to modify the supply voltages in such a way that they reach the values desired by the control algorithm. For this purpose, in subsequent PWM control cycles, it is necessary to measure the phase currents, then-calculate the current components using the Clarke and Park transforms and the angular position of the rotor. In the next step, the voltages V_d and V_q are calculated in the regulators and the voltage values of the individual phases forming the voltage vector are determined using the Clarke and Parkinverse transforms (Fig. 2).

What is important in this method is that a full calculation cycle is being performed each time before determining the position of a new voltage vector (Fig. 3).

This results in the need for a significant number of measurements and calculations, which places high demands on the computational systems and often limits the possibility of working with high frequencies of the PWM signal. Too low value of the PWM signal frequency prevents efficient operation in the range of higher rotational speeds of drive systems. Any failure of the current measurement system also prevents the correct operation of the drive controlled in this way.

Despite these drawbacks, the advantages of the FOC method, as well as the increasing performance of microprocessor MCUs, have made it dominant in PMSM motor-based systems and it is considered one of the best methods for ensuring the high efficiency and dynamics of these controlled drive systems. This method is also used to synchronise energy storage inverter systems during grid disturbances [12].

III. COMPARATIVE STUDIES OF SINUSOIDAL CONTROL AND FOC

In order to compare the sinusoidal control method and FOC, a test stand was prepared consisting of two similar PMSM motors with the following parameters:

The control system was based on the STM32G431 microcontroller with the X-NUCLEO IHM008 inverter module. Two control programs were prepared – one vector FOC one, the other sinusoidal. The control was carried out using information about the position of the motor shaft generated by a

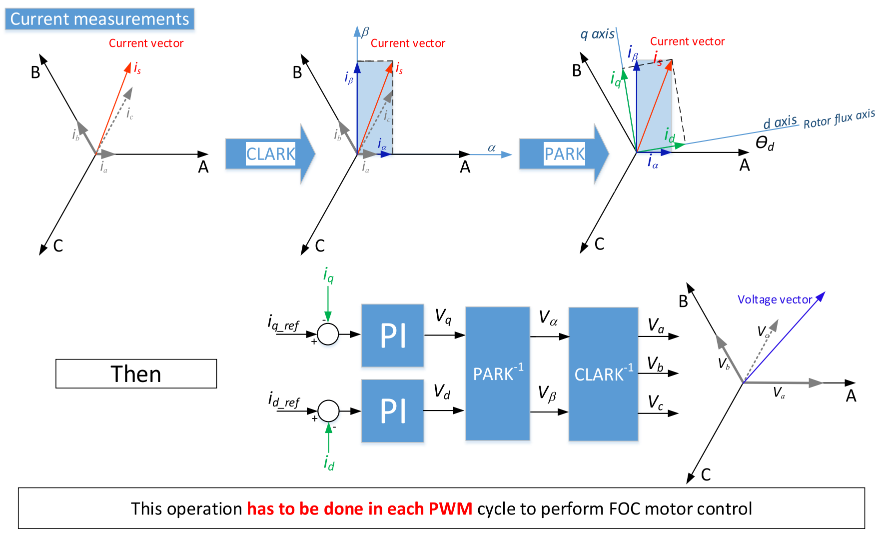

FIGURE 2. Control principle in the Field Oriented Control method.

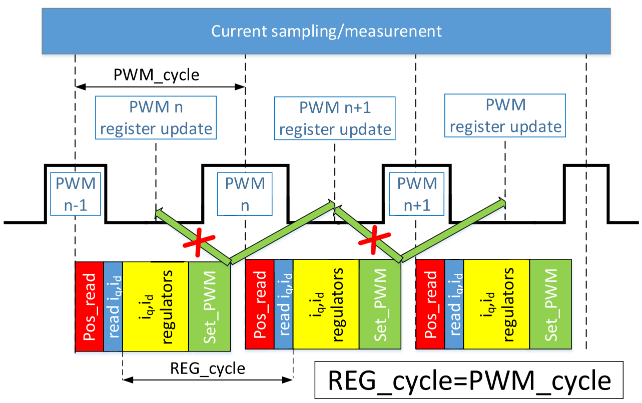

FIGURE 3. PWM update procedure in FOC.

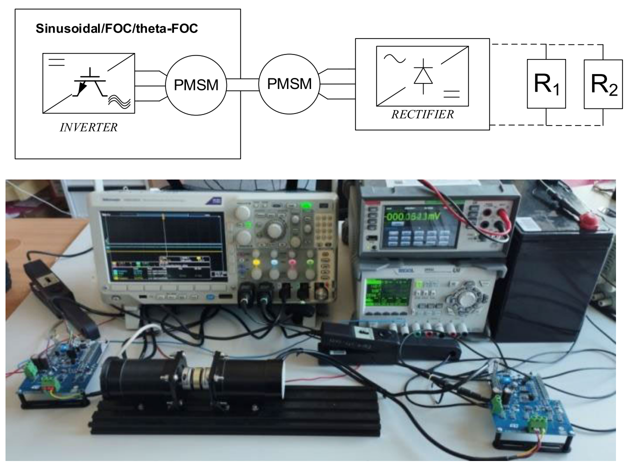

FIGURE 4. Test stand.

14-bit absolute encoder, AS5047. The load of the tested motor was the second motor working as a generator with a regulated resistor load (Fig. 4).

A. MEASUREMENT OF THE D-Q AXIS COMPONENTS OF THE MOTOR CURRENT USING DIFFERENT CONTROL METHODS

In the operating range from 0 to the rated speed, the motor should generate a d-axis component of the current equal to 0 in order to achieve maximum torque/Amp ratio, which then depends on the q-axis component. The analysis of the current component values in both methods will give the opportunity to compare the quality of their operation.

Waveforms of the d-axis current and q-axis current components of motor current controlled by different methods were compared. For this purpose, the set speed of the unloaded drive system was increased from 100 rpm to 1400 rpm. The measurement results are shown in Fig. 5.

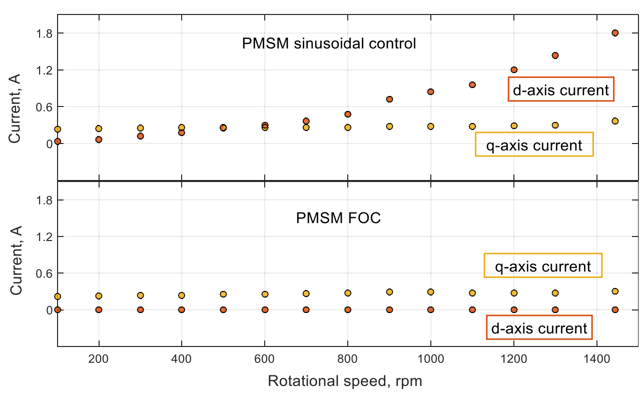

FIGURE 5. Graph of the q-axis current (yellow) and d-axis current (red) of the motor as a function of the set rotational speed at idle state.

Based on the measurements, it can be concluded that the advantage of FOC control over sinusoidal control is much better operation in the range of rotational speeds closer to

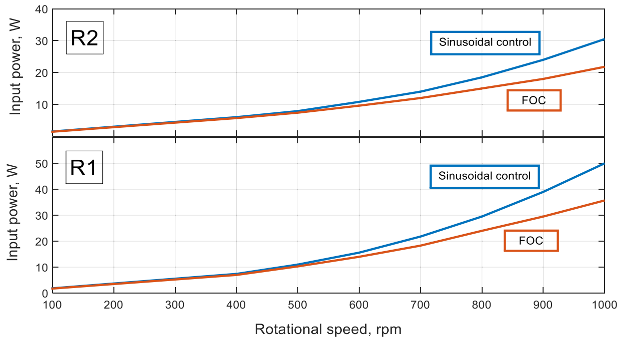

FIGURE 6. Graph of the DC input power of the drive system for two different load resistances for sinusoidal modulation (blue) and FOC (red).

TABLE 1. Motor parameters.

Rated power, W	60
Pole pairs	4
Rated peed, rpm	1000
Rated current, A	3.6
Rated torque, Nm	0.6
Nominalvoltage, V	24
Resistance, Ω	0.94
Inductance, mH	3.22

the nominal value (Fig. 5). This effect results from the fact that the value of the d-axis current component increases with the rotation speed of the sinusoidally controlled motor, which translates into its less effective operation, while its low value in the FOC method is caused by the d-axis component regulator of the motor current.

Then, the input power consumed by the drive system coupled with the generator loaded with two different resistance values was measured (Fig. 6).

The measurements confirm the decisive advantage of the FOC method in terms of efficiency, especially for higher rotational speeds. This advantage is so significant that the sine method is hardly used in industrial practice. Differences in energy consumption for rated speed reach several dozen percent in favour of the FOC method.

Both of these methods - sinusoidal and FOC, have their advantages and disadvantages. The author undertook to develop a vector control method that would combine the advantages of both methods and at the same time eliminate many of their disadvantages. The proposed method has been given a working name of theta-FOC, and the results of the work and research are presented in the next part of the article.

IV. THE PROPOSED CONTROL METHOD

The essence of the vector control method is to selectthe amplitude and position of the voltage vector so that the d-q axis components of the current, reach the set values. Since the successive calculation of the voltage values necessary to produce each phase is crucial for the motor to rotate, this process involves significant hardware resources of the computing unit. For many years, this process was possible only in the fastest computing systems (DSP) and reserved for the most demanding drive systems. With the development of budget microcontrollers equipped with efficient processing units, the FOC method is increasingly used in popular devices. New capabilities of electronic connectors (SIC) increase the possible switching frequency, and thus again raise the bar for computing systems implementing field-oriented control.

A big problem is the need to perform calculations even when the system is in steady-state operation, which means that the computational system is heavily loaded, and the number of additional processes that can be carried out by the control system is seriously limited.

As part of the work carried out by the author, an attempt was made to combine the advantages of low hardware requirements of sinusoidal control and high quality vector control. The developed method consists in redefining the method of shaping the voltage vector used in the FOC method.This was achieved by introducing an additional quantity, the angle Θ_e between the axis of the rotor flux and the supply voltage space vector, we can express the appropriate values of V_q and V_d through the amplitude value of the voltage space vector and the rotor flux angle Θ_e (Fig 7a).

The basic assumption of the author was that the value of the d-axis currentcomponent of the motor current corresponds to the angle Θ_e between the axis of the rotor flux and the supply voltage vector, and the amplitude of the voltage vector corresponds to the torque, assuming $i_d = 0$ (Fig 7a).

The method of the proposed vector control is shown in Fig. 8.

The main advantage of the proposed control method is that the key mathematical operations in the control process are simpler (no inverse calculations of the Clarkeand Park transforms) and, most importantly, the value of the angle Θ_e does not have to be calculated each time in the PWM control cycle of the transistors (Fig. 10). Despite the lack of calculations, the voltage space vector will move with the parameters determined during the last mathematical operations. To sum up, the vector control method was decoupled from the PWM signal controlling the transistors (Fig 9).

The frequency of calculations may increase to the maximum in the dynamic state of the drive operation, while in static states it may be reduced to the minimum values so that the computing unit can perform other tasks of the control system (e.g. diagnostics). In an extreme case, for operation in a static state, it is possible to abandon the calculation of the d-q axis current components and observe, for example, the rotational speed of the drive motor, and the values of the d-q axis current componentswill remain unchanged.

In the FOC method, to change the position of the voltage space vector and, consequently, to change the stator field, it is necessary to perform complex calculations. In the proposed theta-FOC method for changing the position of the stator flux axis, these calculations are not necessary. As a result, calculations optimizing the operation of the system can be performed with different frequency depending on the desired quality

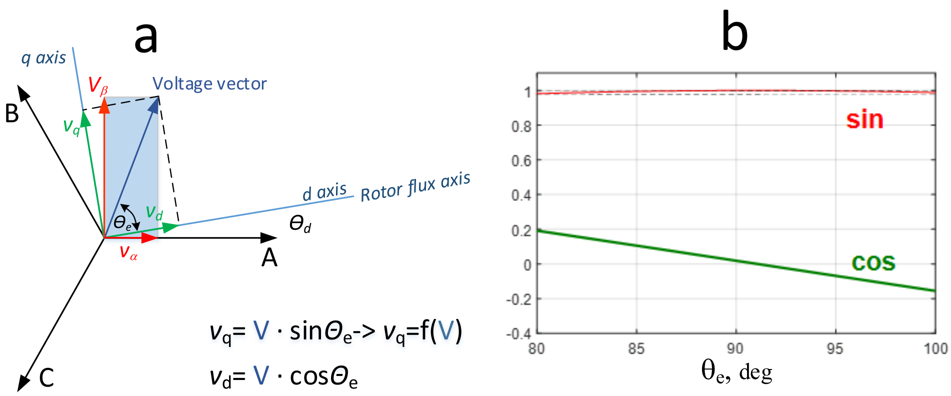

FIGURE 7. Theta-FOC: a) calculations of voltage vector components, b) sin and cosine values in the operating area of Θ_e.

of the optimization of the drive system operation. In static conditions, we can significantly reduce the frequency of these calculations without compromising drive performance.

As part of the work, the duration of computational procedures for the FOC and theta-FOC algorithms was measured (Tab. 2).

TABLE 2. Calculation times of PWM parameters for various control methods.

Computation time, µs		Trigonometric hardware acceleration	Shaft position read	Regulators (torque, flux)	PWM Modulation
FOC	theta-FOC				
13,4	13,4	+	+	+	+
Not applicable	8,5	+	+	-	+
43	30	-	+	+	+
Not applicable	8,5	-	+	-	+

Both the classic FOC method and the theta-FOC method, when performing all activities characteristic of vector control in each PWM control cycle, give a similar load on the processor (approx. 13.4 μs). This is based on the assumption that functions supporting trigonometric calculations are used, usually present in microcontrollers dedicated to drive systems (e.g. CORDIC in STM32G431) [11]. The lack of inverse calculations of the Clarke and Park transforms in the theta-FOC method is compensated by additional calculations of the voltage vector position as a function of PWM modulation, necessary to be performed. When using a typical math library, calculation times increase (FOC 43μs, theta-FOC 30μs). In each of the analyzed cases, steady-state operation without the need to call regulator procedures and use trigonometric functions is possible only for the proposed theta-FOC method, and the calculation time is approx. 8.5 μs.

V. COMPARISION OF THE PROPOSED METHOD AND THE FOC METHOD

In order to assess the operation correctnessof the proposed method, it was decided to compare the FOC method and the proposed theta-FOC method for the same working conditions in static and dynamic states. The parameters of the *d-q* axis current regulatorsin the FOC method were the same as the parameters of the regulator gains Θ_e and the amplitude of the voltage space vector. Both methods were called in every cycle of the transistor control (about 17 kHz). After the system reached the steady state for the theta-FOC method, the procedure for calculating the current components and starting the voltage vector amplitude and angle Θ_e regulators was abandoned. The results of the comparative works are presented below:

A. STEADY STATE, LOAD THE GENERATOR WITH RESISTORS R1=10 OHM AND R2=18 OHM. OPERATION IN A SPEED FEEDBACK LOOP FOR DIFFERENT SPEED REFERENCE VALUES

In the range from the minimum value to the nominal value of rotational speed, both methods give identical results.This means that in steady states, when the system is loaded with a constant torque value, both methods give the same results, but the theta-FOC method burdens the computational unit significantly less. This is because in steady states, the value of the Θ_e angle will be constant, similarly to the value of the voltage space vector amplitude. This, in turn, makes it possible to resign from starting the regulators responsible for the values of the current components. The system will correctly select the PWM modulation parameters using the parameters from the previous cycle and information about the current position of the motor shaft.

B. IDLE STATE OF THE SYSTEM WORKING IN THE SPEED FEEDBACK LOOP

Also in this case, both methods gave the same results.This proves the correct operation of the proposed control method, which in the entire range of rotational speeds gives the same effects as the more complex FOC method.

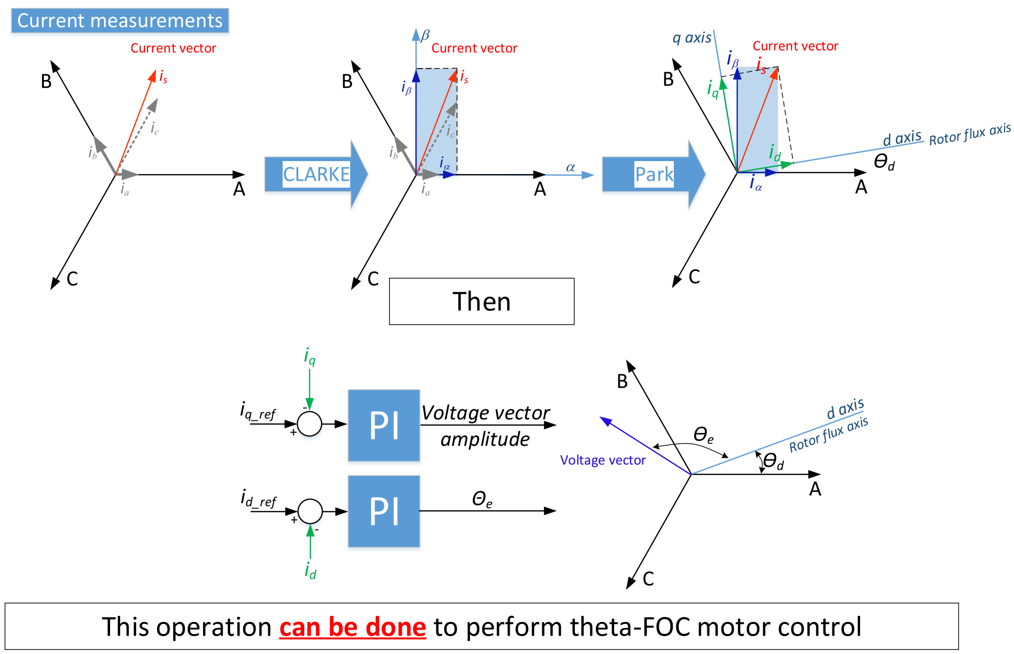

FIGURE 8. The theta-FOC control method.

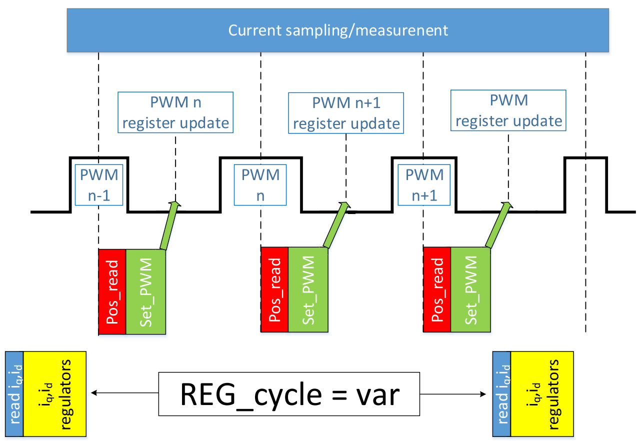

FIGURE 9. PWM update procedure in the proposed theta-FOC method.

C. IDLING MODE OPERATION WITH FLUX WEAKENING, FOR DIFFERENT SET VALUES OF THE d-AXIS CURRENT. THE SATURATION OF THE ANGLE REGULATOR Θ_e OF THE THETA-FOC METHOD WAS SATURATED AT +/-120 ELECTRICAL DEGREES

A controller minimizing the d-axis current component is responsible for the shape of the Θ_e angle variation in the speed range from 0 to 1600 rpm. After exceeding the speed value of 1600 rpm, the voltage induced in the windings by the rotating rotor is too high for the current to flow from the source to the motor. Above this speed, it is necessary to change the reference value of the d-axis current component so that the motor flux is reduced and operation at higher speeds is possible.

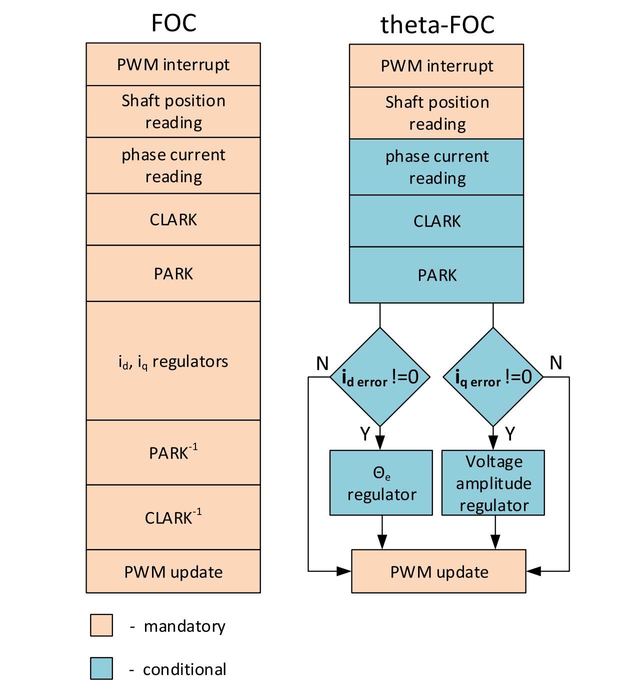

FIGURE 10. FOC control algorithm and the proposed theta-FOC method.

In the proposed control method, after exceeding the speed of 1600 RPM, the amplitude of the voltage vector was maximum, and only the Θ_e angle, responsible for the orientation of the stator field relative to the rotor field, changed. This means that in the second regulation zone (field weakening area), the torque regulator operates in saturation state, and the speed control is effectively performed by the Θ_e angle

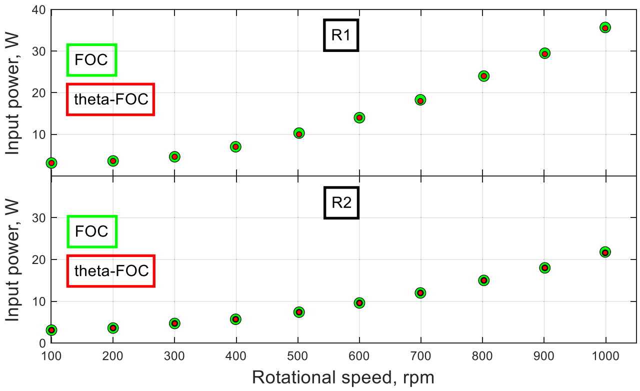

FIGURE 11. The graph of the input power of the drive system for two different load resistances for theta-FOC (red) and FOC (green).

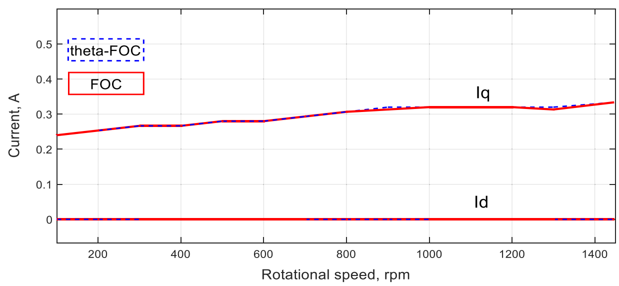

FIGURE 12. Graph of the motor current components as a function of the rotational speed at idle state.

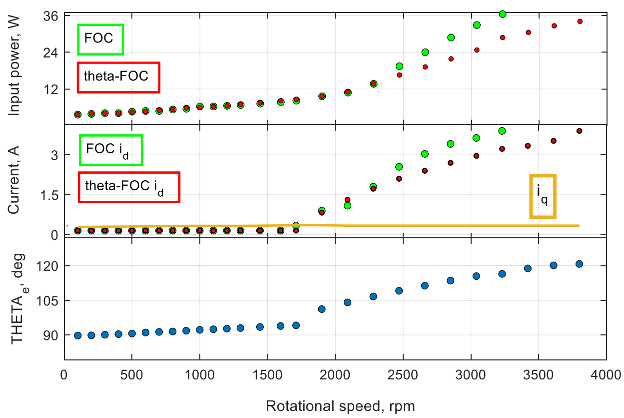

FIGURE 13. Plot of d-q-axis current components, inverter DC power input and Θ_e angle as a function velocity in the flux weakening range. FOC –green, theta-FOC –red.

regulator. During the tests, it was observedthat with the proposed method, when controlling in the range of field weakening, much better results were achieved both in terms of the maximum achievable speed and lower energy consumption for the same operating parameters. A possible explanation may be the fact that the phase lag introduced in the FOC method is missing in the steady states. In the proposed method, this delay does not exist in steady states, because the calculated parameters of the voltage vector amplitude and the Θ_e angle do not change in the steady state for successive

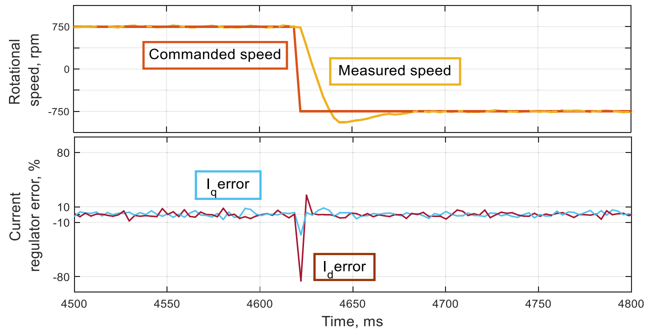

FIGURE 14. FOC transients diagram.

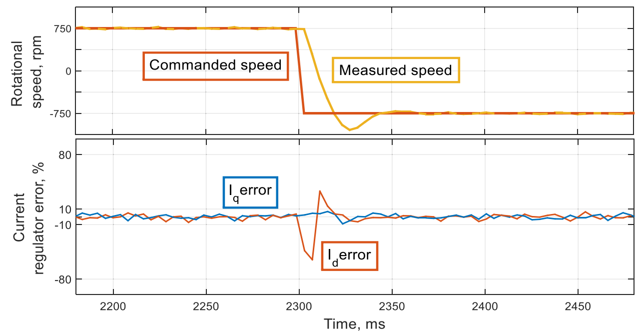

FIGURE 15. Graph of transient states for the proposed theta-FOC control method.

PWM cycles with changing rotor position.The operation of the Θ_e angle regulator is clearly visible, reaching a maximum value of 120 electrical degrees at a speed of about 3.7 times the nominal rotational speed.

D. TESTS IN A DYNAMIC STATE

In order to compare the operation of both methods in dynamic states, the waveforms of the speed values and errors of the *d-q* axis current components values were recorded during the abrupt change of the target speed value from 75% ω_n to $-75\%\ \omega_n$. Analysis of the percentage difference between the reference and actual values of the current components allows for a better comparative analysis. In both cases, the load was the same value of resistance connected to the generator.

The curves of the target speed and the actual speed are comparable. The current components error curves indicate that the proposed method allows to achieve smaller control errors of individual current components. This may be related to the lack of mathematical operations related to inverse Clarke and Parktransformations, which are associated with the formation of small errors depending on the mathematical method of calculation used. In the proposed method, the approximation of the Θ_e angle value is only related to the resolution of the shaft position sensor.

In the course of the work, the recordings of current and speed values in dynamic states were made with the frequency of the regulator equal to the frequency of the PWM transistor operation. Figure 16 shows the operation of the drive

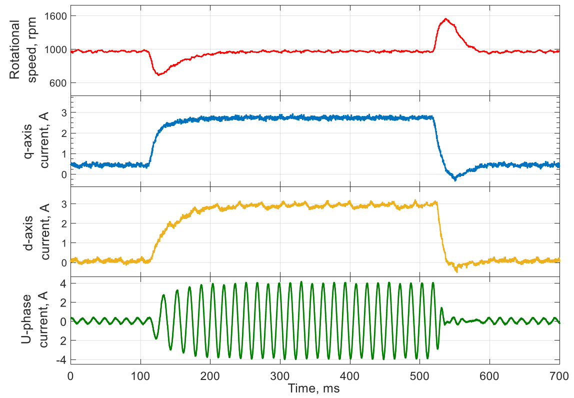

FIGURE 16. **The performance of the Theta-FOC system during a sudden application of load with the Θ_e angle regulator inactive.**

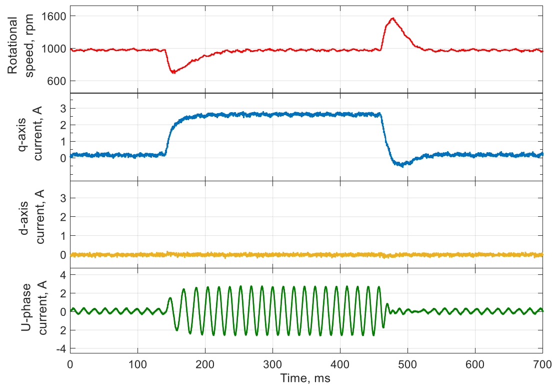

FIGURE 17. **The performance of Theta-FOC system during a step-load activation with an active Θ_e angle regulator.**

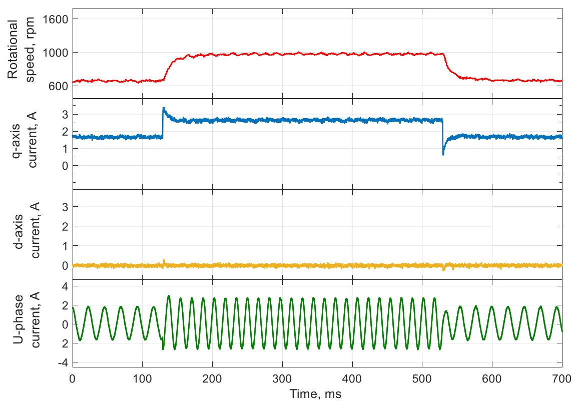

FIGURE 18. **The performance of the Theta-FOC system during a step increase in the reference speed for the current regulator frequency equal to the PWM frequency of the power transistors.**

system during the sudden engagement of the load torque $T = 0.75T_n$ (T_n-nominal torque), sinusoidally controlled without the Θ_e angle regulator. The system worked properly, but the d-axis current reached a significant value, resulting in a large phase current amplitude of the motor.

Next figure shows the system performance with the active Θ_e regulator, where the load equal to $0.75T_n$ was applied for

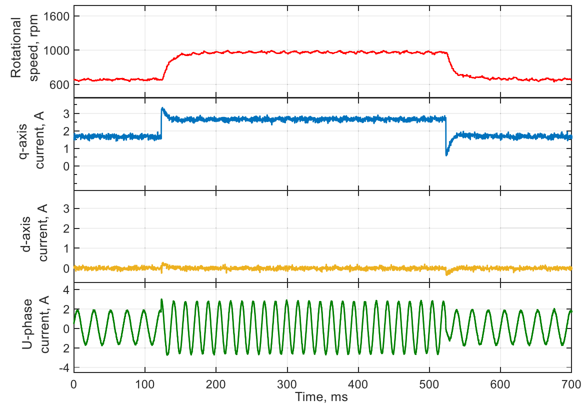

FIGURE 19. **The performance of the Theta-FOC system during a step increase in the set speed for a frequency of current regulators equal to 0.2 times the frequency of PWM power transistor operation.**

a specified time of around 300ms. The Θ_e angle regulator worked correctly by minimizing the q-axis current component to the desired value, significantly reducing the amplitude of the motor phase current.

Figure 18 shows the waveforms for the step-changed set speed of the motor from 650 rpm to 1000 rpm with a load torque equal to $0.75T_n$. During the tests, the system worked correctly, and the d-axis current was at the level set by the control system.

In the next test, the system's operation was tested with a reduced frequency of the current regulators of 0.2 times the PWM frequency of the power transistors. The current regulator settings remained unchanged. The waveforms obtained for the system controlled in this way are shown in Fig 19.

The operation of such a drive system was correct, despite the fact that in dynamic states there was a small difference in the d-axis current waveform, related to the lower frequency of invoking the current regulators procedure.

In steady states, it was possible to completely abandon the operation of the voltage space vector angle and amplitude regulators, which did not change the read values of the q-axis current and d-axis current components, and the drive functioned correctly with the previously calculated optimal settings of Θ_e and voltage vector amplitude.

VI. CONCLUSION

The proposed theta-FOC control method has been implemented and tested in typical drive system operating states and has performed at least as well as the FOC method in comparative tests. Both control methods were implemented using the same components and possibly the same regulator settings (in the case of FOC, d-$q$axis current regulators, and in the case of theta-FOC, regulators of the Θ_e angle and voltage space vector amplitude). It was also confirmed that the system can operate correctly with inactive control blocks in the steady state, which proves that, unlike the FOC method, the deviation between the actual PWM voltage and the voltage command is less significant at lower ratios of PWM frequency to rotation speed. This may result in improved performance of the proposed method in higher rotational speeds (field weakening) during testing. By reducing the processor load and allowing for calculations that are not synchronous with the PWM signal, higher transistor switching frequencies can be achieved with the same computational resources of the logical system. Additionally, the possibility of changing the angle Θ_e and controlling the amplitude of the control voltage space vector is blocked, allowing for non-optimal but correct operation of the drive system, for example, in the event of a failure of the current measurement system, the vector system becomes a sinusoidal control system until the failure is resolved. The work of a reduced frequency current regulator significantly reduces the load on the microcontroller, especially in the high frequency PWM transistor control range, allowing the control system to perform additional control functions for other system elements (such as communication functions). The disadvantage of the proposed method is the strong coupling between the output values of the torque and flux regulators. It should be noted that in the first regulation zone ($0 < \omega < \omega_n$), the operating range of angles Θ_e ($\sin\Theta_e \sim 1$) means that the torque depends only on the amplitude of the voltage vector, while in the second regulation zone, the voltage vector amplitude is maximum and constant, and regulation is performed only by changing the Θ_e angle. Further studies should encompass machines with differences in *d-q* axis inductance (IPMSM), where the MTPA method, along with the developed motor control method, can be applied. The proposed method has been tested and implemented in the passenger lift cabin door drive system, where it confirmed the possibility of relieving the load on the main control system processor.

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KRZYSZTOF KOLANO was born in Lublin, Poland, in 1978. He received the B.S. and M.S. degrees in electrical engineering from the Lublin University of Technology, in 2002, and the Ph.D. degree in electrical engineering, in 2009.

Since 2002, he has been with the Department of Electrical Drives and Machines, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology. His research interests include fault tolerant motor drive systems, elevator optimization control algorithms, and EV drive systems.