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An identification of permanent magnet rotor position using a zero voltage vector method

***Abstract**. The paper describes a simple method of poles position identification of a permanent magnet motor. The method is related to impact of a back electromotive force on current shape produced when a zero voltage vector is applied. The method fulfils a gap between method for initial position detecting e.g. PIPCRM and simple back electromotive force estimation method. There are presented basis of the zero voltage vector method and laboratory results of method applied on 40 kVA axial flux permanent magnet motor in the paper.*

***Streszczenie.** W artykule opisano prostą metodę identyfikacji położenia biegunów wirnika silnika z magnesami trwałymi. Zasada działania metody opiera się na wpływie siły elektromotorycznej na kształt prądu w czasie, gdy zadawany jest zerowy wektor napięcia. Metoda wypełnia lukę pomiędzy metodami identyfikującymi spoczynkowe położenie wirnika np. PIPCRM a metodą estymacji siły elektromotorycznej. Artykuł przedstawia zasadę działania metody oraz wyniki badań laboratoryjnych przeprowadzonych na maszynie o polu osiowym z magnesami trwałymi o mocy 40kVA. (**Identyfikacja położenia wirnika silnika z magnesami trwałymi z wykorzystaniem metody zerowego wektora napięcia**).*

Keywords: sensorless methods, permanent magnet motor, rotor position.
Słowa kluczowe: metody bezczujnikowe, silnik z magnesami trwałymi, położenie wirnika.

Introduction

The control system of the permanent magnet motor using maximum torque strategy requires information about the poles position. Modern control systems have eliminated a mechanical rotor position sensor, replacing it with special algorithms which calculates the poles position from the measured electrical quantities. Such methods, called as sensorless, are recently intensively developed [1], [2], [3], [4]. In [5], the method PIPCRM (Position Identification by Parallel Current Rate Measurement) has been presented. That method can determine the poles position of the permanent magnet machine at standstill or at low speed. The PIPCRM method is based on measurement of the stator current changes during stator core saturation. Saturation of the magnetic circuits of stator coils causes that their self inductance decreases. Therefore, when saturation occurs, the stator currents will increase rapidly. In previous publications [6], the dependence of phase currents as a function of rotor position has been presented . The PIPCRM method can be applied from zero to approximately 5% of rated speed of permanent magnet motor. However, the saturation of the stator core is a kind of nuisance. Therefore, it is proposed to use a Zero Voltage Vector (ZVV) method to identify rotor position. A goal of this method is poles position detection for speed range from 2% of nominal speed of the motor. The ZVV method reduces speed range required by the PIPCRM method. Moreover the proposed ZVV method needs less measurement time. The ZVV method fulfils a gap between method for initial zero (or very low) speed position detecting e.g. PIPCRM and back electromotive force estimation. It can be said that zero voltage method can be extension of the PIPCRM method.

Fundamentals of the ZVV method

Describing the method, it is required to introduce a mathematical model of the permanent magnet motor. The basic model [7] of the permanent magnet machines is quite sufficient to describe the ZVV method idea. It is not necessary to introduce the model which takes into account the magnetic saturation and the saliency of the motor.

Thus, a simple mathematical model is used and it is presented as follows:

$$U_S = R_S \cdot I_S + L_S \cdot \frac{d}{dt} I_S + E \tag{1}$$

where: $U_S = \begin{bmatrix} u_{SA} \\ u_{SB} \\ u_{SC} \end{bmatrix}$, $I_S = \begin{bmatrix} i_{SA} \\ i_{SB} \\ i_{SC} \end{bmatrix}$,

$$L_S = \begin{bmatrix} L_{S0} & M & M \\ M & L_{S0} & M \\ M & M & L_{S0} \end{bmatrix}, \; E = \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix}$$

U_S – phase voltage, I_S – phase current, R_S - resistance of the stator windings, L_{S0} - self inductance of the stator windings, M - mutual inductance of the stator windings

It is assumed that stator resistance R_S and self inductance L_{S0} of each phase are constant, mutual inductance M between phases are equal to each other.

The ZVV method can be provided applying for instance three-leg three phase bridge voltage source inverter (Fig. 2 and 3). To prevent dc-link short-circuit, only one switch may be closed per leg. The inverter can generate eight basic output voltage vectors. All possible vectors are presented in figure 1. The voltage vector can be an “active state” or “zero state”. Vector is called active, when the inverter generates nonzero output voltage. It is for vectors V_1 to V_6. Vectors V_0 and V_7 are called as zero voltage. Output three phase voltages are represented by an equivalent vector V in figure 1. Desired three phase voltages at the output of the inverter can be easily achieved by combining V_0 -V_7 vectors.

The ZVV method of the rotor position identification uses only zero voltage vectors, marked as ‘000’ and ‘111’ in figure 1. The vector is ‘111’ when three top transistors (T1, T3, T5) are switched on. Zero vector ‘000’ occurs when three bottom (T2, T4, T6) transistors are closed. These states of the switches are shown in figure 2 and 3. In both cases, phase voltage U_S equals zero.

When zero voltage vector is applied to stator windings, then the voltage equation of the permanent magnet motor will be written as follows:

$$0 = R_S \cdot I_S + L_S \cdot \frac{d}{dt} I_S + E \tag{2}$$

Neglecting stator resistance R_S and writing for each phases, (2) can be expressed by:

(3) $$i_{SA} = \int \frac{-e_A}{L_{SA}} \cdot dt$$

(4) $$i_{SB} = \int \frac{-e_B}{L_{SB}} \cdot dt$$

(5) $$i_{SC} = \int \frac{-e_C}{L_{SC}} \cdot dt$$

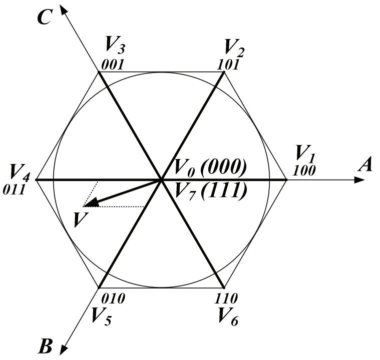

Fig. 1. Diagram of the hexagon of possible switching vectors for a three leg voltage source inverter.

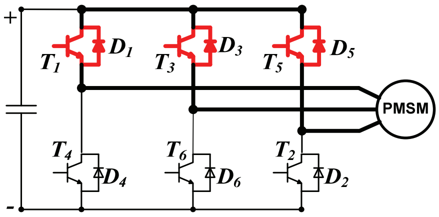

Fig. 2. Diagram showing the states of the switches when the vector '111' is produced by voltage source inverter.

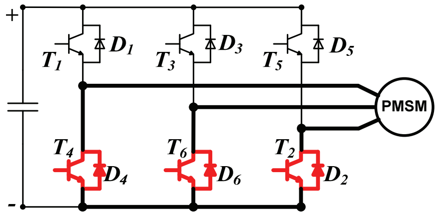

Fig. 3. Diagram showing the states of the switches when the vector '000' is produced by voltage source inverter.

The zero voltage vector method is applied when the rotor of the permanent magnet motor is already in motion. Based on laboratory tests, this speed was determined as about 2 % of the rated speed. The method takes advantage of small values of electromotive force to determine the rotor position. The concept of the method is using the electromotive force generated in the stator coils when rotor speed is a non-zero. Then, if zero voltage vector is applied, the stator windings will be short-circuited. The stator current depends on the transient values of electromotive forces. In case of switch the '111' vector on, the current will flow by the top transistors and diodes of the converter. All possible directions of the stator currents are shown in Fig. 4.

To determine the position of the rotor, presented method uses the measured stator current at the time when zero voltage vector is applied. In the method, the stator current is proportional to transient value of electromotive force. It can be said that electromotive force is indirectly used to determine the poles position. For permanent magnet motor, the back electromotive force is sinusoidal. Therefore the currents generated by zero voltage vector can be sinusoidal also. Dependence of the stator current from the poles position, for the given direction of rotation is shown in figure 5. As known, sequence of back electromotive force phases is dependent on the direction of rotation. Waveforms, which are shown in figure 5, will be shifted by 180 electrical degrees in the case of opposite speed direction.

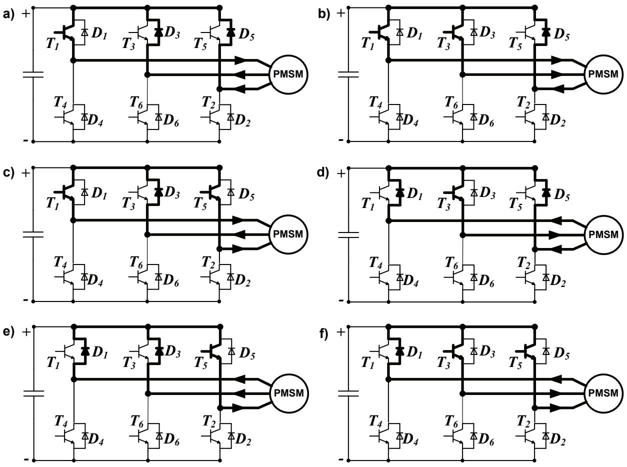

Fig. 4. Possible directions of the stator currents when applying zero voltage vector at non-zero speed.

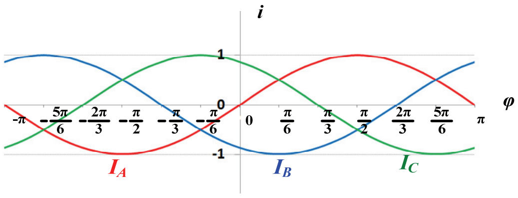

Fig. 5. Theoretical current responses (at zero voltage vector) as a function of rotor position for the positive direction of rotation.

The zero voltage vector should be applied on few switching periods. Then the currents will grow up to proper values, which allow rotor position to be calculated. The value of currents, which are carried out at the end of state of the zero voltage vector, are called as current responses I_A, I_B, I_C. They are taken into rotor position calculation. It is realized simple way. Firstly current responses are transformed to stationary α-β coordinates. As a result, I_α and I_β are obtained.

Electromotive force vector angle is delayed by π / 2 relative to the position of electrical axis of the magnetic flux excitation. Therefore, depending on the direction of rotation, the calculated value of atan must be increased or reduced by π / 2. Finally rotor position φ can be calculated using following equation:

(6) $$\varphi = \tan^{-1}\left(\frac{I_\beta}{I_\alpha}\right) \mp \frac{\pi}{2}$$

Expanding (6), rotor position can be calculated from measured quantities by:

(6) $$\varphi = \tan^{-1}\left(\frac{\frac{\sqrt{3}}{2}\cdot I_B - \frac{\sqrt{3}}{2}\cdot I_C}{I_A - \frac{1}{2}\cdot I_B - \frac{1}{2}\cdot I_C}\right) \mp \frac{\pi}{2}$$

where: I_A, I_B, I_C – current responses - stator currents measured at the end of state of the zero voltage vector.

In the developed method, the zero voltage vector is held by a specified time t_{TEST}. Usually, measurement time t_{TEST} is longer than one period of the carrier wave of the PWM modulator. During t_{TEST} stator current increases as a result of short-circuit the stator coils by the power electronics converter. The current flow, caused by applying the zero voltage vector to the stator coils, is shown in figure 6. The figure indicates the current response also. Figure 7 shows the stator currents, analogous to figure 6, but at the different position of the rotor.

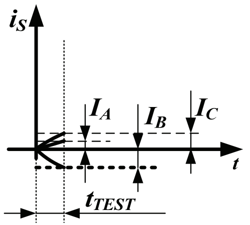

Fig.6. Theoretical current responses (at zero voltage vector) for given rotor position.

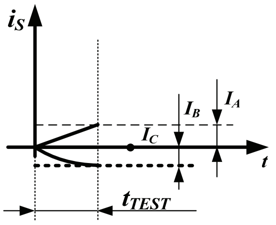

Fig. 7. Theoretical current responses (at zero voltage vector) for rotor position equals to 60 electrical degrees

At given speed, the zero voltage vector produces the stator current, which causes that permanent magnet motor provides electromagnetic torque. Specifically, it is braking torque. However, the current value used to determine the rotor position is typically about 1-2 % of rated current of the permanent magnet motor.

Results of laboratory tests

The laboratory tests have been carried out using axial flux permanent magnet motor. Rated power of the machine is equal 40 kVA at 314 rad/s (3000 rpm). The rotor of tested motor has 16 poles. The laboratory permanent magnet drive set is shown in figure 8. The control system has been implemented using DSP SHARC 21061 combined with FPGA Altera processor (Fig.9).

Such drive system has been designed to provide research related to sensorless control of the axial permanent magnet motor. An achievement of researches is previously presented PIPCRM method [8]. This method can be used to detect an initial rotor position. Combining the PIPCRM method with ZVV zero voltage vector method, the speed range has been extended [9].

Both methods require control called as Detect and Drive [8]. System control which was realized by DSP processor is presented in figure 10. The zero voltage vector generator block has been added to control scheme. The Detect and Drive is labelled as ‘Control - Measurement selection’ in figure 10.

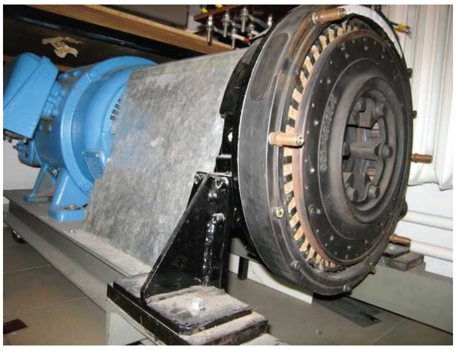

Fig. 8. Laboratory 40 kVA / 16 poles / 3000 rpm axial flux permanent magnet motor.

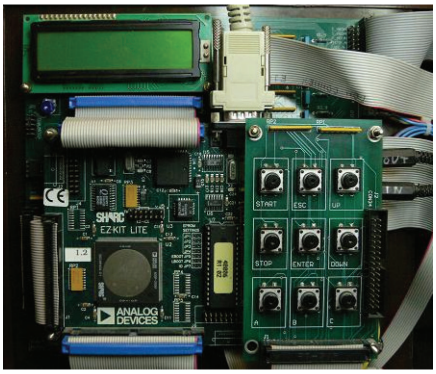

Fig. 9. DSP processor with LCD display and simple keyboard

The Detect and Drive (D&D) switches between position measurement and driving torque production. That characteristic control algorithm has three steps. First is zero-current stage. Load currents are switched off. When currents fall down to zero, next stage will occur. In that part of the D&D procedure, test voltage vector is applied to the stator windings.

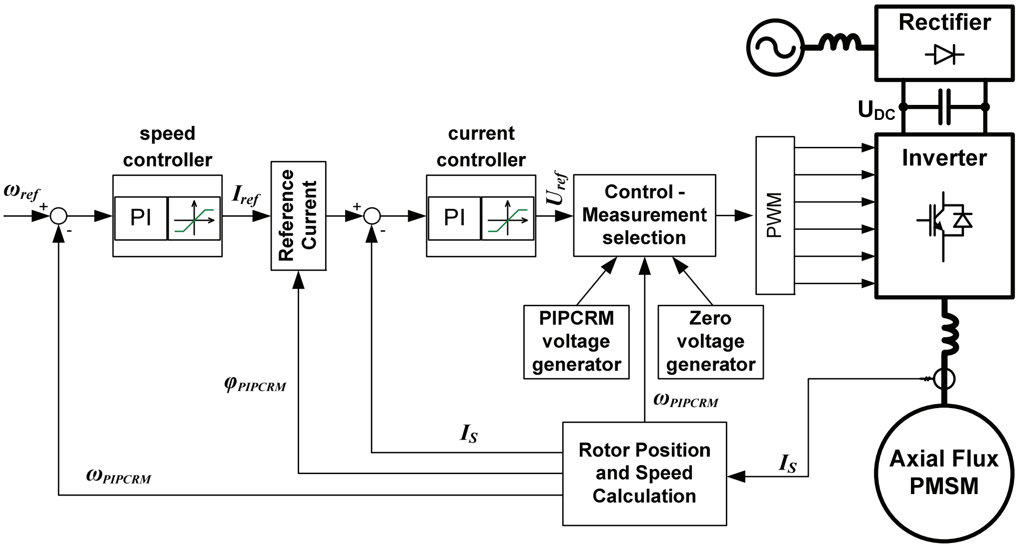

Fig. 10. Block diagram of the sensorless control system for the axial flux permanent magnet motor. Control scheme applicable for standstill and low speed operations.

Next, phase currents are measured and rotor position is calculated. Last part of algorithm is load-current stage. Goal of that stage is driving. It means that torque producing currents are set with respect to the calculated electrical angle. Time sequence of Detect and Drive procedure is shown in figure 11.

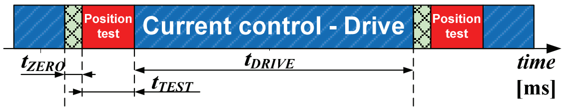

Fig. 11. Time sequence of the Detect and Drive control

Results of the rotor position test by zero voltage vector are shown in figure 12 and 13. The presented waveforms were carried out for same rotor position but different speed. Figure 12 shows stator currents at 12.6 rad/s, figure 13 at 21 rad/s. It can be seen that time of the position test is lower than 200 μs. In comparison to the PIPCRM position test [8], it is about five time less (fig. 14).

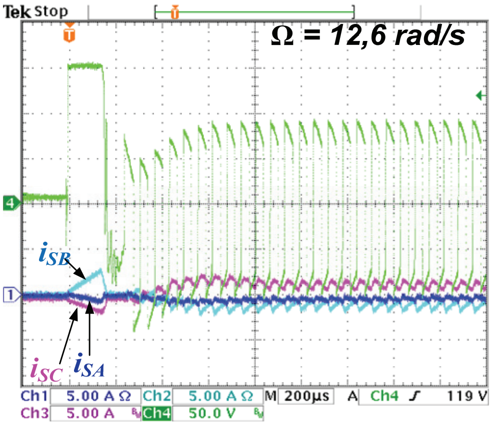

Fig. 12. Experimental results: The voltage and phase currents i_{SA}, i_{SB}, i_{SC}. Carried out at 12,6 rad/s.

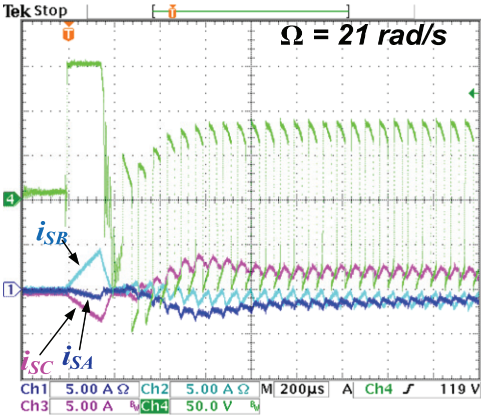

Fig. 13. Experimental results: The voltage and phase currents i_{SA}, i_{SB}, i_{SC}. Carried out at 21 rad/s.

Figure 14 presents the phase currents, which are result of the PIPCRM voltage step. A sudden current increase is related to stator core saturation. Using those currents an initial rotor position is calculated. The state where both methods can be used is presented in figure 15. The back electromotive force makes that current responses are significantly distorted. The PIPCRM method can be used to detect position, however it is advisable to calculate rotor position from zero voltage vector method. In this case current response can be shorter as shown in figure 12 and 13.

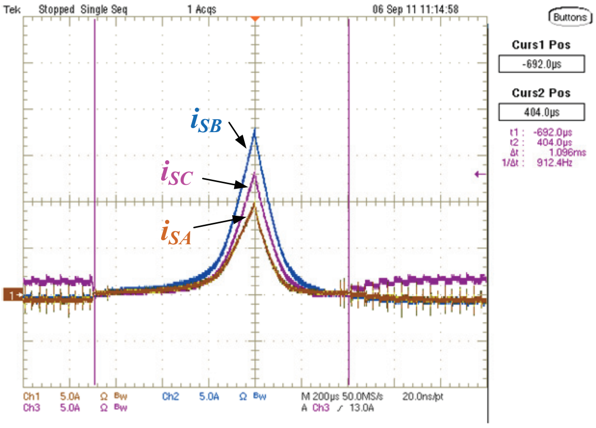

Fig. 14. Experimental results: The voltage and phase currents i_{SA}, i_{SB}, i_{SC}. Carried out at 0.6 rad/s. Phase currents during PIPRCM voltage step.

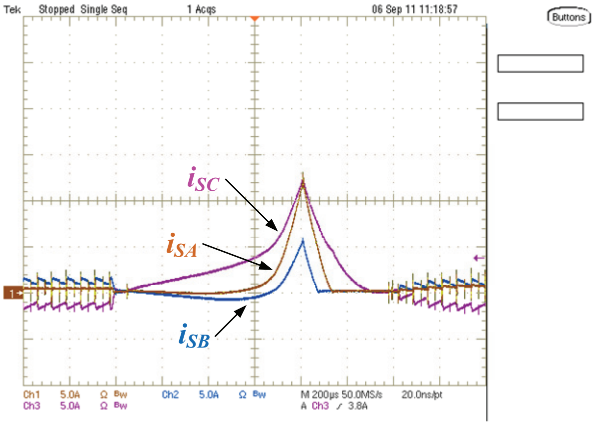

Fig. 15. Experimental results: The voltage and phase currents i_{SA}, i_{SB}, i_{SC}. Carried out at 5.6 rad/s. Phase currents during PIPRCM voltage step.

Experimental results of low speed operation are shown in figure 16 (7,7 rad/s) and figure 17 (21,3 rad/s). Figure 16 shows waveforms, which were carried out at 2,5 % of nominal speed of used permanent magnet motor. However, other laboratory tests show that method can be used up to 15 % of nominal speed. Since driving torque is produced between position measurements only, therefore shorter time of position measurement results the average electromagnetic torque to be increased.

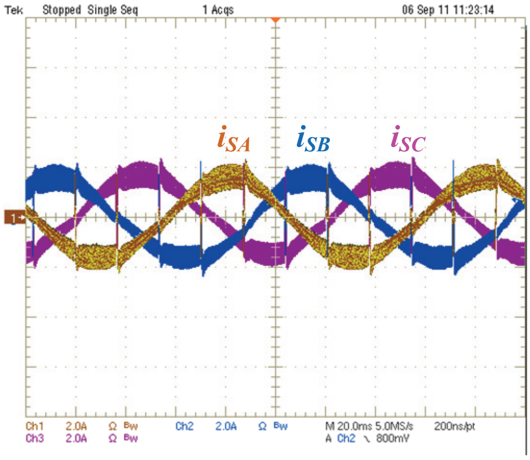

Fig. 16. Experimental results: Low speed operation: phase currents i_{SA} , i_{SB} , i_{SC} . Speed was set to Ω = 7,7 rad/s

Figure 18 shows laboratory result in case of load step. The motor was started without load and passed to reference speed. Next , the 30 Nm load was applied to the motor. The speed was returned to its reference value.

Similar laboratory test is shown in figure 19. The load torque was applied to motor at standstill. Next, the permanent magnet motor was started up with 100 Nm of load to the 36,7 rad/s. The load was produced by a DC machine. In this case the load torque is directly proportional to DC motor armature current.

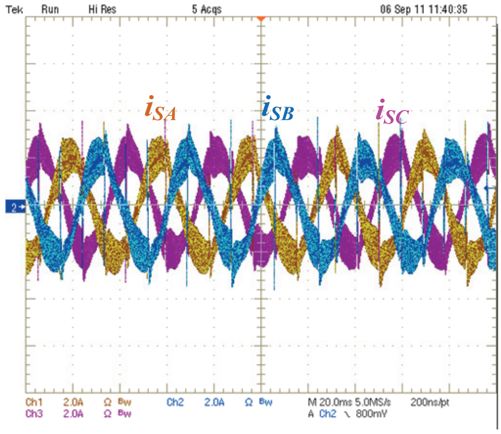

Fig. 17. Experimental results: Low speed operation: phase currents i_{SA} , i_{SB} , i_{SC} . Speed was set to Ω = 21,3 rad/s

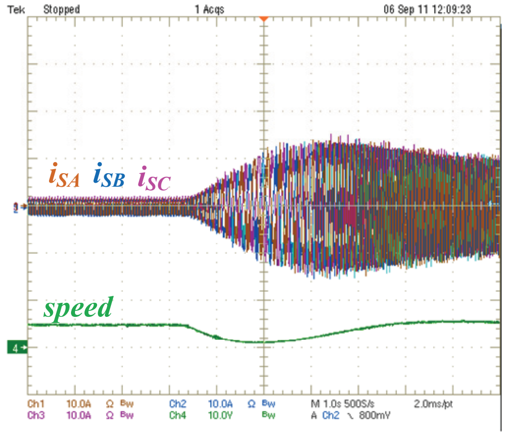

Fig. 18. Experimental results: Load step at low speed operation: phase currents i_{SA} , i_{SB} , i_{SC} . Speed was set to Ω = 13,2 rad/s. Load torque was 30 Nm.

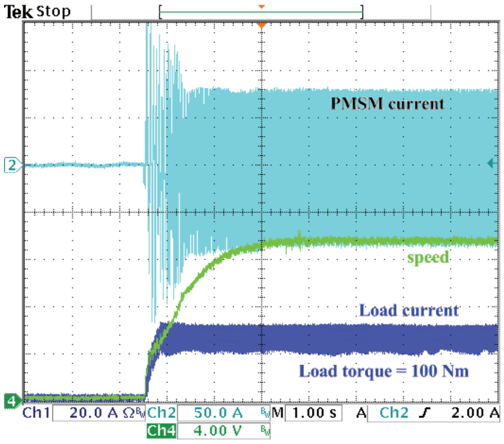

Fig. 19. Experimental results: Sensorless startup of the Arial flux permanent magnet motor from standstill to 36,7 rad/s with 100 Nm load. [8]

Conclusions

The paper describes the ZVV method of poles position identification at low speed. Developed method can be used at control system working from 1-2 % up to about 15 % of nominal speed of the Axial Flux Permanent Magnet Motor. Moreover it is possible to combine zero voltage vector method with the PIPCRM method, what was done, tested in laboratory set and shown in the paper. Results show that both methods combined together can be used to provide startup of the axial flux permanent magnet motor from standstill. Some results from laboratory sensorless startup has been presented.

Achieved top speed makes possibility to apply a back electromotive force estimator. It will be in scope of further works.

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