

Practical realization of propulsion unit with low voltage permanent magnet synchronous motor in electric car

Abstract. The paper deals with the practical implementation of the propulsion unit with the low voltage permanent magnet synchronous motor in the small electric car. The control method is based on the sensorless control. The rotor position and rotor angular speed are calculated from the measurable electric quantities of the permanent magnet synchronous motor using computational block realized by the digital signal processor. The experiments were realized with permanent magnet synchronous motor which was supplied by voltage inverter with low voltage. In conclusion, the experimental results are presented which were obtained by measurement on a laboratory stand with the AC drive and on the small city car.

Streszczenie. W artykule opisano praktyczne wykorzystanie jednostki napędowej z niskonapięciowym silnikiem synchronicznym z magnesami trwałymi w zastosowaniu do małych pojazdów elektrycznych. Zastosowano sterowanie bezczujnikowe. Pozycja wirnika i prędkość kątową są określane na podstawie zmierzonych danych elektrycznych z wykorzystaniem procesora sygnałowego. (Praktyczna realizacja jednostki napędowej pojazdu elektrycznego z niskonapięciowym silnikiem synchronicznym)

Keywords: Sensorless control, AC drive, voltage inverter, permanent magnet synchronous motor.

Słowa kluczowe: Bezczujnikowe sterowanie, napęd pojazdu elektrycznego, silnik synchroniczny z magnesami trwałymi.

Introduction

The most common ways of control of AC controlled drives is Vector Control (VC) and Direct Torque Control (DTC). For the implementation of the VC, it is necessary to know the rotor position of the machine. The rotor angle can be measured by means of mechanical sensors of speed and positions, such as resolvers or incremental sensors. Sensors are additional mechanical elements, which may degrade the good properties of the drive. That is why so-called sensorless methods of control of AC machines are constantly being developed.

More common sensorless methods are methods working with the mathematical model of machines. There are many mathematical models on which a lot of more specific methods are based, such as MRAS, various types of observers, integration methods, Kalman filter etc. [1], [2].

The essence of the model based methods is the use of a particular algorithm for calculation of the speed and rotor position from known or measured variables such as stator currents and voltages, DC link voltage of the voltage inverter (VI) and actual switching combination.

In the paper, an application of the AC drive with the low voltage permanent magnet synchronous motor (PMSM) with sensorless control method based on the reduced Luenberger observer is presented.

List of used symbols

$U_{S\alpha,\beta}$	α, β components of the stator voltage vector
$U_{i\alpha,\beta}$	α, β components of the induced voltage vector
$U_{i\alpha,\beta_est}$	components of the estimated induced voltage vector
$i_{S\alpha,\beta}$	α, β components of the stator current vector
i_{sd}	magnetizing current component in $[d, q]$ system
i_{sq}	torque current component in $[d, q]$ system
i_{sq_ref}	reference torque component of stator current vector
K_E	voltage constant of the PMSM
R_S	stator resistance
L_S	stator inductance
L_d	inductance in the longitudinal axis of the rotor
L_q	inductance in the transverse axis of the rotor
d_L	parameter of the Luenberger observer
z_1, z_2	auxiliary state variables of the Luenberger observer
θ_e	rotor angle
θ_{e_est}	estimated rotor angle
ω_e	electrical rotor angular speed

ω_{e_est}	estimated electrical rotor angular speed
ω_{m_ref}	reference rotor angular speed
ω_m	real rotor angular speed
ω_{m_est}	estimated rotor angular speed

Mathematical model of the PMSM

The permanent magnet synchronous motors may basically be divided according to the type of the placement of permanent magnets (PM) in the rotor perimeter, e.g. Surface Mounted PMSM (SMPMSM), Interior PMSM (IPMSM).

The mathematical model of a machine describes the behaviour of the machine in dependence on the supply voltage and on the load torque. For simplicity the mathematical model ignores many actual properties of electric machines. This affects the accuracy of the mathematical description and limits its use.

The mathematical model of the SMPMSM can be expressed in the coordinates α, β as follows:

$$(1) \quad u_{S\alpha} = R_S i_{S\alpha} + L_S \frac{di_{S\alpha}}{dt} + u_{i\alpha}$$

$$(2) \quad u_{S\beta} = R_S i_{S\beta} + L_S \frac{di_{S\beta}}{dt} + u_{i\beta}$$

$$(3) \quad u_{i\alpha} = K_E \omega_e \cos \theta_e, \quad u_{i\beta} = K_E \omega_e \sin \theta_e$$

Speed estimator

The reduced Luenberger observer is used for the rotor angle and speed estimation. The outputs of the observer are the components of induced voltage vector which is used for calculation of the rotor angle and rotor speed. We can derive the mathematical description of the reduced Luenberger observer from the observer control theory using the mathematical model of the SMPMSM (Eq. 1-3) [3].

If we use estimated values instead of actual values, we get following equations:

$$(4) \quad \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} d_L & 0 \\ 0 & d_L \end{bmatrix} \cdot \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + (R_S + d_L L_S) \begin{bmatrix} d_L & \omega_e \\ -\omega_e & d_L \end{bmatrix} \cdot \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} - \begin{bmatrix} d_L & \omega_e \\ -\omega_e & d_L \end{bmatrix} \begin{bmatrix} u_{S\alpha} \\ u_{S\beta} \end{bmatrix}$$

$$(5) \quad \begin{bmatrix} u_{i\alpha_est} \\ u_{i\beta_est} \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + L_S \begin{bmatrix} d_L & \omega_{e_est} \\ -\omega_{e_est} & d_L \end{bmatrix} \cdot \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix}$$

The rotor angle and speed are calculated as follows:

$$(6) \quad \theta_{e_est} = \arctan2 \left(\frac{u_{i\beta_est}}{u_{i\alpha_est}} \right)$$

$$(7) \quad \omega_{e_est} = \frac{1}{K_E} \sqrt{(u_{i\alpha})^2 + (u_{i\beta})^2} \operatorname{sign} \left(\frac{d\theta_{e_est}}{dt} \right)$$

Control structure of the AC drive

The control structure uses so-called vector control of the SMPMSM with subordinate current control loops in the rotor coordinates d, q (see Fig.1).

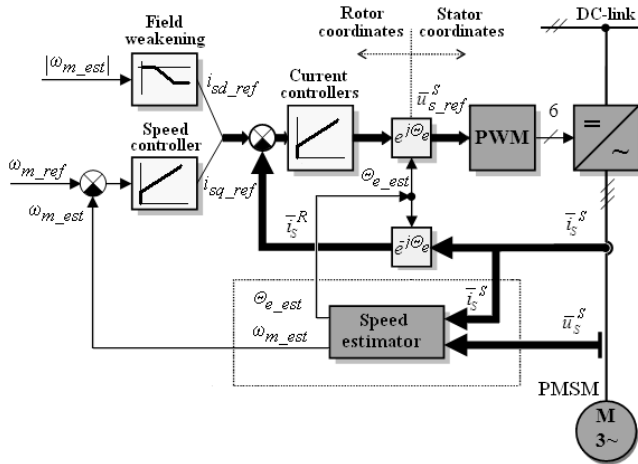


Fig.1. Speed control structure

For the SMPMSM it is most suitable to use the rotating coordinate system oriented on the magnetic flux of the PM. In this coordinate system the quantities are direct in the steady state. So as to ensure the maximum dynamics it is necessary to force the torque current into the stator winding within the shortest possible time.

Range of desired drive speed is limited. The upper limit is determined by the DC link voltage for which the machine is designed, if we do not consider weakening. The minimal speed is determined by the stability of the sensorless control. At minimal value, the AC drive has to be also able to reverse with the load. Let us emphasize that the SMPMSM in this case is supplied by voltage lower than 1 V.

Control quantities for the vector control of SMPMSM are: flux producing component i_{sd} and torque producing component i_{sq} of the stator current vector which determine magnetic flux Ψ_d in the axis d and torque T :

$$(8) \quad \Psi_d = L_S i_{sd} + \Psi_{PM}$$

$$(9) \quad T = \frac{3}{2} p \Psi_{PM} i_{sq}$$

The equations (8), (9) are valid in the case that inductance in longitudinal axis of the rotor L_d is the same as inductance in transverse axis of the rotor L_q ($L_d \approx L_q \approx L_S$).

In the range up to rated speed, the value of the flux producing component i_{sd} is zero. If we consider field weakening, this value has to be negative. The speed estimator with reduced Luenberger observer calculates estimated rotor angle θ_{e_est} and rotor speed ω_{m_est} .

Laboratory stand with the AC Drive

To verify the simulation models and principles as well as sensorless vector control, experimental laboratory workplace was created. The basic parts are machine set, frequency converter, control system with DSP, personal computer and the necessary measuring instruments.

The PMSM from the company TG drives manufactured according to required parameters was used for the laboratory model of the AC drive because in addition to verification of control methods will be used this machine in the propulsion unit of the small electric car.

Construction solution used PMSM utilizes permanent magnets on the rotor surface. Relatively low electrical and mechanical time constant, low supply voltage and high currents are hallmarks of the used machine. The motor due to its power about 1.5 kW has relatively small size.

The PMSM is mechanically connected to the frame and together with typical induction motor from the company Siemens make up machine set. Both machines are mechanically connected by a flexible coupling TYRE-FLEX from the company RATHI. The induction motor is used as the load machine.

PMSM parameters are listed in Tab. 1. The motor parameters have been chosen with regard to the application in a small electric car. Because of battery power, voltage in DC link of the voltage inverter is low and the output currents of the PMSM are significant.

Table 1. Parameters of the permanent magnet synchronous motor

Rated power	1500 W
Number of pole-pairs	3
Rated voltage	30 V
Voltage of DC link	48 V
Rated current	34 A
Maximal current	224 A
Rated torque	4.6 Nm
Maximal torque	21 Nm
Rated speed	3000 rpm
Voltage constant	$8.6 \cdot 10^{-3}$ V/rpm
Torque constant	0.14 Nm/A
Moment of inertia	2.7 kgcm^2

The PMSM is powered by a frequency converter made at the Department of Electronics. Switching elements are IGBT. LEM SA sensors are used for current measurement. The PMSM was designed so that it can be powered from a battery with voltage 48 V.

Realization of control algorithms

In the control system, a Freescale DSP 56F8037 digital signal processor is used. An implementation of the vector control is the first step towards the application of sensorless method. Before creating the control algorithms, it was necessary to norm signals from all input sensors and put into operation output PWM signals. Own algorithm has been established on the basis of the control structure of AC drive with the PMSM. All interrupt routines are listed in Tab. 2.

Table 2. Interrupt routines of control algorithms

Interrupt routine	Priority	Function
Speed estimation	3	Signal adjustment, Luenberger observer
Current control loop	3	PI controllers, transformation, decoupling
Speed control loop	2	PI controller, field weakening
Operation of buttons	1	Parameter setting
Error routine	3	PWM modulator turn off

Sampling frequency of individual loops is: speed estimation loop 20 kHz, current control loop 10 kHz, speed control loop 0.25 kHz.

After DSP reset DSP, initialization part of the algorithm is performed which initializes peripherals. The program continues by writing constants of regulation, measurement offset of AD converters, from which the upper and lower limit values are determined. Everything is then recorded in the appropriate registers.

At the end of the initialization, a voltage vector is a connected to a stator winding and the stator current is controlled to a constant value for a sufficient time. During this time interval, the rotor rotates in the direction of the minimum magnetic resistance and the counter of the rotor position is set to zero at the end of this time interval. The initial position of the rotor is set up and initialization is completed. The interrupt is usually caused by the PWM modulator. In this case, it is the loop securing the current control. The interrupt of the speed control loop is caused by the timer. The interrupt, which switches off the PWM modulator, has the highest priority (error routine). This case occurs if the actual value of the phase currents or DC link voltage is higher than a specified limit. The routine operating pressing buttons or interrupt changing sign of desired speed representing the automatic reversal has the lowest priority.

Distortion and nonlinearity of the measured quantities

The vector control needs to know information about the electrical and mechanical quantities. For the control process, the measurement is very important because determines the maximum accuracy of controlled variable. The vector control needs to know at least two phase currents. The measurement of DC link voltage is used for a software protect of the voltage inverter. It is also possible to state that the accuracy of estimation is given by the measurement accuracy, or quality of compensation of nonlinear phenomena.

For measuring phase currents, the situation is simpler, because the value of stator currents in each phase is measured directly using modern current sensors. The voltage inverter generated supply voltage for the PMSM which causes a ripple of phase currents.

For the control, it is not necessary to know the current waveform during the switching period. It is advantageous to evaluate directly the mean value of the stator currents during the PWM period. The mean value can be easily obtained using the PWM module synchronization with an AD converter.

The stator voltage can be measured directly or indirectly. The direct method is more demanding on the number of sensors. At indirect measurement, we need only a voltage sensor connected to the DC link of the voltage inverter. The stator voltage is then determined by calculation from the actual switching combination. We obtain directly the mean voltage during the switching period which we need for the control. But we must remember that the voltage inverter or the relationship between the control and supply voltage of the PMSM is generally not linear. Nonlinearities are mainly caused by a dead time and real time properties of switching elements.

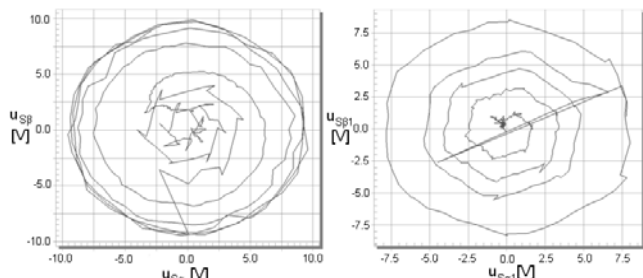


Fig.2. Experimental results of voltage drop compensation (left - before compensation, right - after compensation)

However, the observer needs undistorted terminal voltage of the machine, which can be obtained from measurements. When composing the mathematical model of the machine and the entire control structure we ignore nonlinearities or replace them with linearized dynamic

elements. The observer or estimator composed of these blocks will then be linear. When we bring the distorted voltage to the input of a linear observer, no correct estimated information can be in its outputs. After closing the feedback loops the behaviour of the drive will be significantly unstable if running at all. Therefore the compensation or filtering of the mentioned non-linear effects before bringing them to the observer seems to be the easiest way. Figure 2 shows the experimental results before and after compensation of voltage drops on the switching elements.

There are many ways to eliminate distortion caused by the dead time of the switching elements [4], [5]. The knowledge and experience from the signal curves of the sensorless control with the Luenberger observer offer another way of the problem elimination. This way is very simple and undemanding as far as the algorithm is concerned, and provides interesting results. Its principle consists in replacing the part of the voltage curves in which the dead-time effect appears by another curve - for example by the slope (tangent) of the curve at this point. Therefore it seems advantageous to perform the mentioned elimination on the components of the normalized estimated counter-voltage from which the position is determined. It is a sine and cosine time dependence. The functions are mutual derivatives if the sign is ignored. That is why such an algorithm is very simple as the steepness of one signal corresponds to the magnitude of the other and vice versa.

The practical implementation gives virtually harmonic curves and a less waviness of the estimated position. The data from the real drive is listed in Fig. 3.

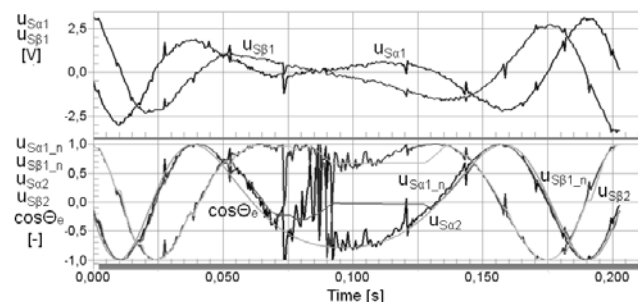


Fig.3. Experimental results of dead time compensation

At first the normalized voltage (see u_{Sa1_n} , u_{Sb1_n}) is created from the measured voltage (see u_{Sa1} , u_{Sb1}) by means of dividing by the current magnitude obtained from the components. Then the curve is replaced in short intervals by the tangent calculated from the vertical component. Transient responses during the dead-time are effectively suppressed (see u_{Sa2} , u_{Sb2}). For the comparison the lower block contains the cosine of the measured position.

It is necessary to note that after the compensation of the dead-time the steepness limiter is applied whose steepness depends on the estimated speed. Thanks to this the curve of the normalized voltage is much more stable and usable especially in the speed area around the zero although it still does not follow the measured quantities.

By applying previous voltage correction, it was achieved stable operation of the sensorless control using Luenberger observer. Problems were removed especially during reversing speed [6].

The quality of estimation and behavior of the sensorless controlled drive were experimentally tested. The experimental results are shown in the following Figure 4 which shows the time courses of characteristic variables that were measured on the laboratory stand.

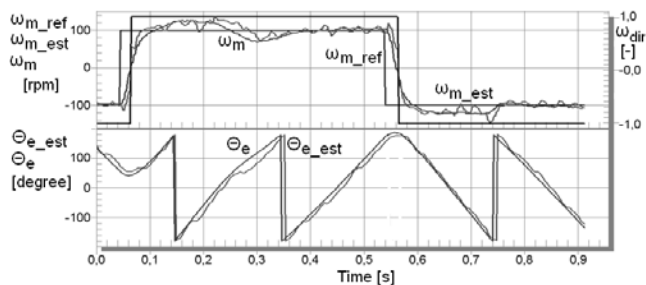


Fig.4. Reversing at sensorless control - low speed area

Application in electric car CityEI

The experimental part of this article also includes the application of vector control in an electric car CityEI (see Fig. 5). It is a small three-wheeled city vehicle for one passenger with a small luggage compartment. Identical PMSM supplied from LiFePo4 battery is used as the propulsion unit. The vehicle has a stand weight 280 kg, total weight 400 kg, length 2741 mm, width 1060 mm and maximal velocity 63 km/h.



Fig.5. Small electric car CityEI

The energy source is a series-parallel connection of modern LiFePo4 cells, which have currently some of the best properties. Parameters of one cell are: nominal capacity $C=40$ Ah, charging voltage 4.25 V, nominal voltage 3.2 V, the maximum charge and discharge current 3 CA, discharge pulse current 10 CA, operating temperature -25 to 75 °C and weight 1.6 kg. Total number of cells is 48. Two cells are connected in parallel in pairs and the pairs are connected in series, thereby we get the battery voltage 80V.

Although the PMSM is designed for DC link voltage 48V, in the electric car is powered by a supply voltage 80 V. This implies less charge and discharge current of the battery. The voltage inverter for supplying the PMSM was made at the Department of Electronics. The power part of the voltage inverter is realized using MOSFET. A power resistor can be connected to the DC link of the voltage inverter for counteracting excess energy. The control system uses DSP 56F8037 again. The motor drives the rear wheels via a belt with the transfer 7.1 [6].

The driver controls the vehicle through the pedal connected to the control system, which can enter the desired torque current, or desired speed (in this mode, the vehicle recuperates). The vehicle obviously has a mechanical brake.

Measurements were performed in the laboratory using automobile brake, which measures the speed of the vehicle and allows specifying braking force.

The experimental measurements show starting the vehicle without load (see Fig. 6) and response to change of reference value of the torque component i_{Sq_ref} at the constant load by braking force 120 N (see Fig. 7).

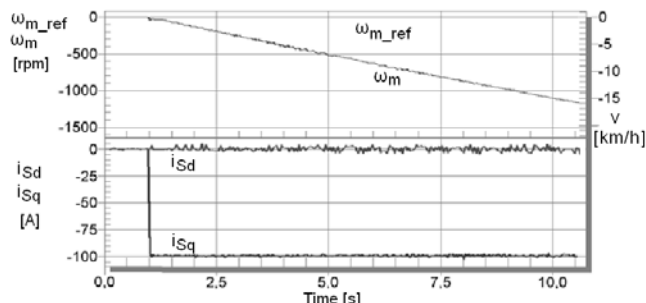


Fig.6. Electric car driving at load and different torque

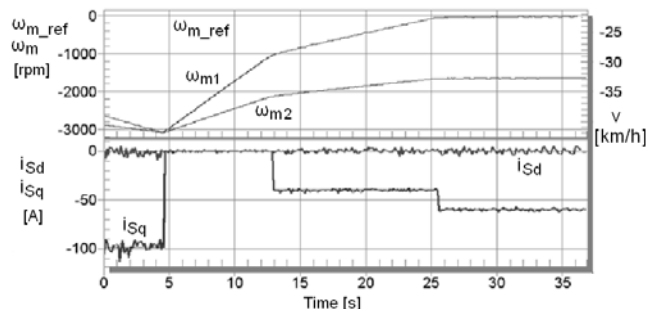


Fig.7. Electric car driving at load and different torque

Conclusion

The paper is focused on the AC drive with the SMPMSM which uses sensorless control method based on the mathematical model of the machine using the reduced Luenberger observer. The paper shows the possibilities for removing distortion of supply voltage for the SMPMSM and implementation of the control method into control system with Freescale DSP 56F8037. The experimental results confirmed successful implementation of the AC drive which is used as the propulsion unit for small electric car CityEI.

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