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Estimation of PMSM Magnetic Saliency Using Injection Technique

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***Abstract*—The permanent magnet synchronous motor (PMSM) has very attractive properties such as: high dynamics, small size, high efficiency, low maintenance, small size and mass to power ratio, which make it suitable for the use in industrial drives. In particular its higher efficiency means that PMSM may be used in applications where the energy savings compensate the higher initial cost. For the best utilization of PMSM properties is very important to use some of modern control techniques. But the techniques require information about rotor position. Rotor position measurement is performed using sensors that are expensive and mainly reduce the reliability of the drive. This fact is the reason for interest in sensorless control techniques. In the article, emphasis is placed on sensorless control of PMSM using voltage signal injection, which requires magnetic saliency of the machine. Magnetic saliency and machine suitability for sensorless control using injection methods can be determined in advance using a measurement method whose mathematical analysis is presented in the article. The measurement method was simulated using software product Matlab-Simulink and experimentally verified on a laboratory stand with the AC drive.**

***Index Terms*—Injection measurement technique, permanent magnet synchronous motor, sensorless control, variable speed drive.**

I. INTRODUCTION

In the last few years, much attention has been paid to the control of the position or speed of AC drives without a speed sensor. This trend is connected with the development of the microprocessor technology, especially with the progress of modern digital signal processors (DSP). These DSP enable the real-time processing of the basic quantities, such as voltage and current, according to very complicated algorithms and calculations. The word “sensorless” means that the structure of the electric drive does not contain the position sensor or speed sensor. Nevertheless, in spite of the term “sensorless control”, current and voltage sensors are integral parts of the drive. For the transformation of the quantities to a rotating rotor coordinate system and for the feedback of the speed or position loop it is necessary to know the position of the rotor [1], [2].

However, if the control algorithm is able to perform the control task without the rotor position sensor and only from the measured current and voltage values, it is so-called sensorless control. This method of machine control has several essential advantages: (a) reduction of the total cost of the drive (this applies especially to smaller drives), (b) easier installation of the drive (thanks to the reduction of the number of cables), (c) reduction of the drive volume, (d) increase of the drive reliability.

The objective of sensorless control is to find the estimation of the rotor position or speed, which is used for the vector rotation of the respective quantities and for the position or speed feedback loop. If the position estimation is derived from the model of the machine, it is so-called sensorless control with machine model. Otherwise we speak about methods not utilizing the machine model, which include so-called injection methods. The last mentioned methods have been the subject of research in the last few years. The research deals with the area of zero and very low speeds of all AC machines. The injection methods utilize the inherent magnetic saliency of the machine [1], [2].

II. PERMANENT MAGNET SYNCHRONOUS MOTORS

Permanent Magnet Synchronous Motors (PMSM) may be divided as follows according to the magnetic flux direction: (a) radial magnetic flux, (b) axial magnetic flux.

PMSM with radial magnetic flux are common. Axial types are very rare; they are only used in applications needing high power density and strict requirements for the drive’s dynamics [3], [4].

PMSM may be further divided according to the type of the placement of permanent magnets (PM) in the rotor perimeter. There are countless ways of placement of PM aiming to achieve the best possible properties of the machine. However, all these variants can be divided into two main types: (a) non-salient-pole PMSM or Surface Mounted PMSM (SMPMSM), (b) salient-pole PMSM or Interior PMSM (IPMSM) [5].

There are also special designs of PMSM, for example external rotor construction, which has been developed for use in traction applications starting with light single-track vehicles and up to low-floor trams. These are so-called hub motors or external rotor motors. In this case the rotor containing PM is fixedly connected with the wheel and embraces the stator with three-phase winding.

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The position of PM in the machine plays a key role. It enables to influence the magnetic flux path and thus also the change of inductance in dependence on the rotor position. So the influence on the longitudinal and transverse inductance of the machine is an important effect of the PM position.

The modern variant of PMSM contains a rotor with permanent magnets made of rare earths. Permanent magnets of rare earths are developed most often on the basis of SmCo and NdFeB. These materials have significantly higher values of coercivity H_c or residual remanence B_r in comparison with traditional permanent magnets such as steel, AlNiCo or ferrites.

The magnetic flux in PMSM is created by PM. The mentioned property forms the major advantage of the machines with PM. For keeping constant magnetic field it is not necessary to supply energy from outside. In comparison with synchronous motors with excitation winding we will also spare the controller of the excitation DC current of the rotor and the needed power electronics circuits.

In traditional synchronous machines, the energy needed for the rotor flux decreases during de-excitation. However, PMSM need flux-producing current component for the de-excitation, which reduces the torque-producing current component. Therefore it is clear that PMSM are most suitable for operation up to the rated speed. During de-excitation the efficiency of PMSM decreases.

In general, PMSM can be characterized by the following benefits: elimination of rotor losses in copper, higher power density, lower moment of inertia, better coverage and more robust structure of the rotor.

The disadvantages of PMSM include: loss of the possibility to control the rotor flux and possible demagnetizing effect. Obviously there are more benefits, which are the main reason for the constantly increasing application of PMSM [6]–[8].

III. SENSORLESS CONTROL USING INJECTION METHODS

Methods based on the mathematical model of the machine are not suitable for applications that require the machine to operate at very low speeds. On the basis of this requirement, so-called methods not utilizing the machine mathematical model have been developed, for example injection methods.

The way in which the permanent magnets are placed gives the machine certain properties. For the injection methods, so-called magnetic saliency of the machine is important. The magnetic saliency detection for the estimation of the rotor position was published for IPMSM in the early 1990s [9], [10]. The monitoring of magnetic saliency projected in the variation of stator inductance uses measurement of the response to additional voltage or current signal, the frequency of which is higher than the frequency on the supply. Some authors utilized the measuring of the change of steepness of the current (and thus the measuring of inductance) during the application of the hysteretic controller [10]. However, this method is not suitable for the standard PWM modulation. That is why a method of injecting a measuring signal has been designed; it can be injected either in the form of discrete voltage test pulses [9], [10] (or modified PWM) or in the form of a continuous signal superposed on the basic supply frequency [11].

The advantage of the mentioned methods is their independence from the machine speed, because the change of inductance is the function of the rotor position. This fact predetermines them for the rotor position estimation at extremely low and zero speeds.

IV. MAGNETIC SALIENCY OF THE PMSM

The problem of magnetic saliency is very complex and hardly quantifiable without the help of the finite elements method or experimentally measured data.

There are several sources of magnetic saliency in the machine: (a) geometric saliency, (b) saliency caused by the saturation of iron parts of the machine, (c) saliency caused by the eccentricity of the rotor, (d) saliency caused by eddy currents, (e) saliency caused by the slotting of the rotor and stator, etc. [12]. The following text deals with the first two sources, as they are most dominant in PMSM.

Magnetic saliency of the machine is defined as the difference between axial inductances L_q and L_d. In the case of PMSM it is better to perform such analysis in a system connected with the rotor. The synchronous inductances in the transverse and longitudinal axes can be expressed as $L_d = L_{\sigma d} + L_{md}$, $L_q = L_{\sigma q} + L_{mq}$, where $L_{\sigma d}$ and $L_{\sigma q}$ are leakage inductances representing the leakage inductances of the slots, teeth and faces of the machine and L_{md} and L_{mq} correspond to magnetizing inductances representing the main magnetic flux passing through the air gap.

Magnetic saliency is caused by two dominant effects: (a) construction of the machine causing different inductance in the longitudinal and transverse axes, which is particularly specific to IPMSM, and (b) saturation of the stator by the magnetic flux from the permanent magnets, which is common for all types of PMSM. Both these effects influence the main as well as the leakage inductances. The injection methods enable the monitoring of both types of saliencies in the leakage as well as in the main inductances. Then, in practice, $L_q = (1.05 \div 1.15)\, L_d$ for the saliency of SMPMSM and $L_q = (2 \div 3)\, L_d$ for IPMSM.

V. VOLTAGE SIGNAL INJECTION IN STATOR COORDINATES

Voltage equations of PMSM with magnetic saliency can be expressed in the stator coordinate system [α, β] in the following form:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = R_S \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \frac{d}{dt}\left\{ \mathbf{L} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \Psi_{PM} \begin{bmatrix} \cos(\theta_r) \\ \sin(\theta_r) \end{bmatrix} \right\}, \tag{1}$$

$$\mathbf{L} = \begin{bmatrix} L_S - \Delta L_S \cos(2\theta_\delta) & -\Delta L_S \sin(2\theta_\delta) \\ -\Delta L_S \sin(2\theta_\delta) & L_S + \Delta L_S \cos(2\theta_\delta) \end{bmatrix}, \tag{2}$$

where $\theta_\delta = \theta_r + \Delta\theta$ is angle of magnetic saliency and inductances are $L_S = (L_\delta + L_\gamma)/2$, $\Delta L_S = (L_\gamma - L_\delta)/2$, u_α, u_β – stator voltage components in [α, β] coordinate system; i_α, i_β – stator current component in [α, β] coordinate system; Ψ_{PM} – maximum value of magnetic flux created by PM; R_S – stator resistance; $\mathbf{L}$ – matrix of inductances in [α, β] system; L_S – mean value of the stator and magnetizing inductance; ΔL_S –

amplitude of the stator inductance; θ_r – electrical rotor angle; $\Delta\theta$ – angle shift of the magnetic saliency.

For injection of the voltage signal in the stator coordinates [α, β] [13], [14], we can define voltage vector $\mathbf{u}^{vf}_{\alpha\beta}$ with amplitude U_{vf} which rotates with an angular frequency ω_{vf} in stator coordinates [α, β] as follows

$$\mathbf{u}^{vf}_{\alpha\beta} = U_{vf}\begin{bmatrix} -\sin\left(\omega_{vf}t\right) \\ \cos\left(\omega_{vf}t\right) \end{bmatrix}. \tag{3}$$

where $\mathbf{u}^{vf}_{\alpha\beta}$ – vector of the injected high frequency voltage in [α, β] coordinate system; U_{vf} – amplitude of the injected high frequency voltage; ω_{vf} – angular speed of the injected high frequency voltage.

The frequency of the injected voltage signal is usually in the range of 0.5 - 1.0 kHz. At this frequency is valid that $\omega_{vf} L_s >> R_s$ and (1) can be simplified

$$\begin{bmatrix} u^{vf}_{\alpha} \\ u^{vf}_{\beta} \end{bmatrix} = \frac{d}{dt}\left\{\begin{bmatrix} L_s - \Delta L_s\cos\left(2\theta_\delta\right) & -\Delta L_s\sin\left(2\theta_\delta\right) \\ -\Delta L_s\sin\left(2\theta_\delta\right) & L_s + \Delta L_s\cos\left(2\theta_\delta\right) \end{bmatrix}\begin{bmatrix} i^{vf}_{\alpha} \\ i^{vf}_{\beta} \end{bmatrix}\right\}. \tag{4}$$

By substituting (3) into (4) we get after adjustment two components of resulting high frequency current:

$$\begin{bmatrix} i^{vf}_{\alpha} \\ i^{vf}_{\beta} \end{bmatrix} = \frac{U_{vf}}{\omega_{vf} L_\delta L_\gamma}\begin{bmatrix} L_s\cos\left(\omega_{vf}t\right) + \Delta L_s\cos\left(2\theta_\delta - \omega_{vf}t\right) \\ L_s\sin\left(\omega_{vf}t\right) + \Delta L_s\sin\left(2\theta_\delta - \omega_{vf}t\right) \end{bmatrix}, \tag{5}$$

$$\mathbf{i}^{vf}_{\alpha\beta} = \frac{U_{vf}}{\omega_{vf} L_\delta L_\gamma}\left(L_s e^{j\omega_{vf}t} + \Delta L_s e^{j\left(2\theta_\delta - \omega_{vf}t\right)}\right), \tag{6}$$

where $\mathbf{i}^{vf}_{\alpha\beta}$ vector of the injected high frequency current in [α, β] coordinate system; L_δ, L_γ stator inductances in [δ, γ] coordinate system; θ_δ – angle of the magnetic saliency.

Both components rotate with opposite speed, which facilitates demodulation process. From (5) and (6), it is clear that the current response contains information about the position of the magnetic saliency θ_δ.

VI. BAND PASS FILTER

For obtaining usable signal that carries information about the position of magnetic saliency, a demodulator is used which includes the band-pass filter. This filters out from the stator current the high frequency current.

Naturally, it is best so that filter dismissed only signal with injected frequency and, therefore, that the bandwidth of the filter was as narrow as possible. The principle of filtering is shown in Fig. 1.

The used filter is based on an integrated circuit LTC 1068 from company Linear Technology. Design of the filter parameters depending on the desired amplitude and phase characteristics was performed using the program FilterCAD. This software was developed by company Linear Technology for fast and efficient design of filters using integrated circuits own production.

The principle of current signal processing with spectral analysis is shown in Fig. 2.

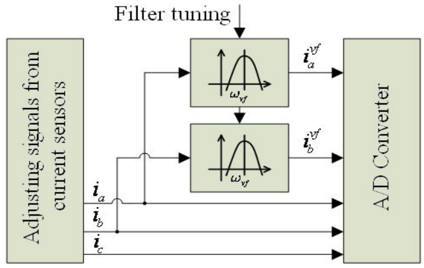

Fig. 1. Principle diagram for evaluation of the injected current.

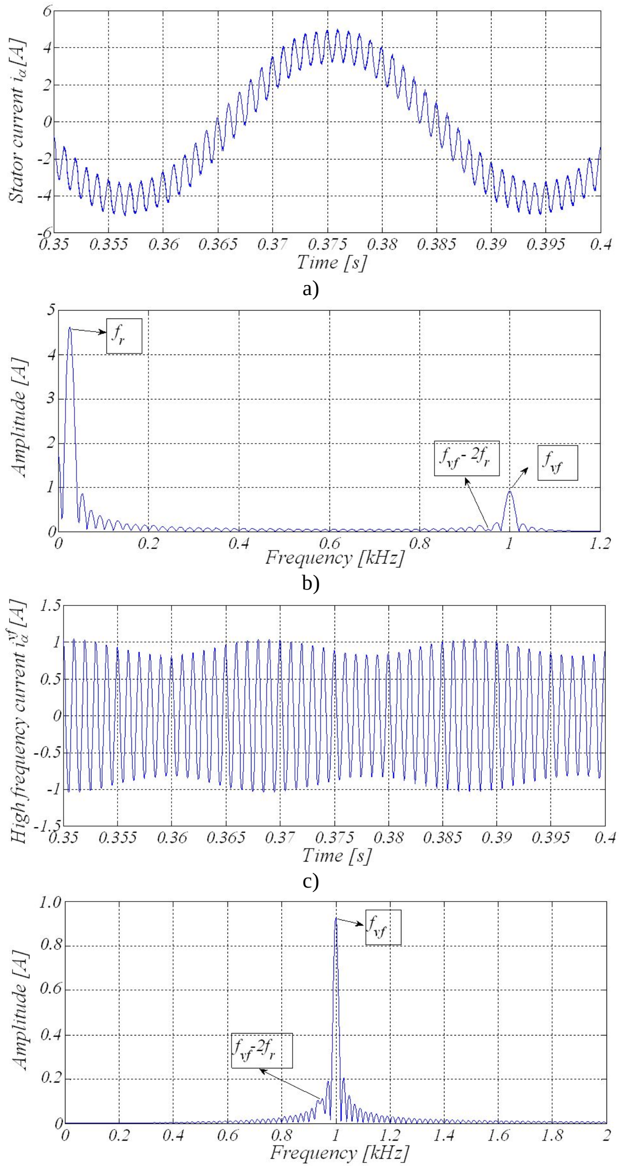

Fig. 2. Current signal processing (simulation).

The high frequency current is given by (5) and (6). It is evident that the frequency of the component containing the information about the rotor position is dependent on actual speed of the rotor. This means that using the hardware filter introduces a speed-dependent phase shift in the positional component. For this reason, the filter should not be designed to the narrowest frequency band, but it should be designed with regard to the phase shift of the signal. The best solution would be filter retuning in dependence on the speed of the rotor.

The characteristic frequency of the filter ω_0 is chosen equal to the injected frequency ω_{vf}. Figure 3 shows the amplitude and phase characteristics of the proposed filter.

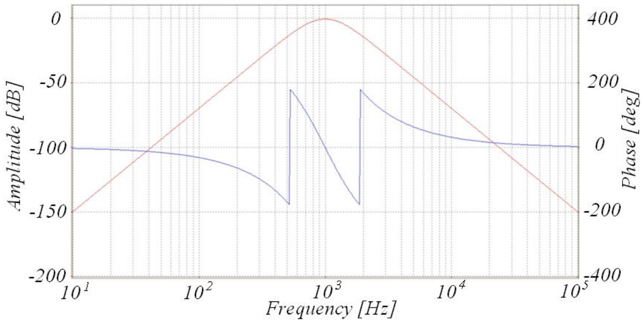

Fig. 3. Frequency characteristics of the used band pass filter.

The phase characteristic of the filter is not linearly dependent on the frequency (see Fig. 3). However, this characteristic may be considered as linear in the area around the characteristic frequency of the filter. Such dependence can be approximated by a linear equation. Approximate slope of the line around the characteristic frequency of the filter can be derived from following

$$\frac{\Delta\varphi}{\Delta f} = \frac{6,691}{20} = 0,33455 \ [°/Hz]. \tag{7}$$

The result from (7) represents the change rate of phase shift of the component that contains the rotor position on deviation 1 Hz from the characteristic frequency of the filter. Position component is then affected by double supply frequency of the machine. The result of demodulation is the position of magnetic saliency $2\theta_\delta$, which means that the change in phase φ defines a phase shift in the estimation of the magnetic saliency position. It is clear that this approximation is valid only for low supply frequencies.

VII. MEASUREMENT METHOD OF MAGNETIC SALIENCY

The study of magnetic saliency to estimate the position or speed of the rotor by the injection of a signal with high frequency has been the subject of global scientific research for several years. Scientific works deal with the techniques for various types of PMSM, as well as for synchronous reluctance machines (SynRM) or asynchronous machines (AM). Originally these methods were designed for electric machines with geometric magnetic saliency, such as IPMSM and SynRM. Generally it is assumed that SMPMSM are magnetically symmetrical contrary to IPMSM.

In general, the monitoring of magnetic saliency is more difficult for the AC machines without geometric magnetic saliency. For this reason the scientific effort is now focusing on the smooth rotor machines (SMPMSM and AM). Naturally the magnitude of the magnetic saliency depends on the magnetic design of the machine and it is proved that it is much lower than for IPMSM.

The injecting voltage signal with high frequency into α-axis is described by following equation [15]

$$u_\alpha^{vf} = U_{vf} \begin{bmatrix} -\sin(\omega_{vf} t) \\ 0 \end{bmatrix}. \tag{8}$$

By substituting (8) into the simplified equation (4) and following adjustment it is valid:

$$\begin{bmatrix} i_\alpha^{vf} \\ i_\beta^{vf} \end{bmatrix} = \frac{U_{vf}}{\omega_{vf}\left(L_s^2 - \Delta L_s^2\right)} \mathrm{L} \begin{bmatrix} \cos(\omega_{vf} t) \\ 0 \end{bmatrix}, \tag{9}$$

$$\mathbf{L} = \begin{bmatrix} L_s + \Delta L_s \cos(2\theta_\delta) & \Delta L_s \sin(2\theta_\delta) \\ \Delta L_s \sin(2\theta_\delta) & L_s - \Delta L_s \cos(2\theta_\delta) \end{bmatrix}, \tag{10}$$

where $L_\beta(\theta_r) = L_s + \Delta L_s\cos(2\theta_\delta)$ is inductance in β-axis.

Considering stator current only in α-axis we obtain a simplified form of equation (9)

$$i_\alpha^{vf} = \frac{U_{vf} L_\beta(\theta_r)}{\omega_{vf}\left(L_s^2 - \Delta L_s^2\right)} \cos(\omega_{vf} t). \tag{11}$$

By demodulation of amplitude modulated current i^{vf}_α we get the expression for inductance in β-axis

$$L_\beta(\theta_r) = \frac{\omega_{vf}\left(L_s^2 - \Delta L_s^2\right)}{U_{vf}} I_\alpha(\theta_r). \tag{12}$$

From the analysis of (11), it is evident that the amplitude of the injected current with high frequency has the same distribution along θr as inductance in β-axis. Parameters Ls and ΔLs can be derived from (12), which can be rewritten in the form (13)

$$L_s + \Delta L_s \underbrace{\cos(2\theta_r)}_{\substack{\max=1 \\ \min=-1}} = \frac{\omega_{vf}\left(L_s - \Delta L_s\right)\left(L_s + \Delta L_s\right)}{U_{vf}} \underbrace{I_\alpha(\theta_r)}_{\substack{I_{\alpha\max} \\ I_{\alpha\min}}}. \tag{13}$$

If we know the maximum and minimum value of the demodulated current $I_{\alpha max}$ and $I_{\alpha min}$, then from (13) it is valid for parameters:

$$L_s + \Delta L_s = \frac{U_{vf}}{\omega_{vf} I_{\alpha\min}} \rightarrow \Delta L_s = = \frac{U_{vf}}{2\omega_{vf}} \left(\frac{I_{\alpha\max} - I_{\alpha\min}}{I_{\alpha\min} I_{\alpha\max}} \right), \tag{14}$$

$$L_s - \Delta L_s = \frac{U_{vf}}{\omega_{vf} I_{\alpha\max}} \rightarrow L_s = = \frac{U_{vf}}{2\omega_{vf}} \left(\frac{I_{\alpha\max} + I_{\alpha\min}}{I_{\alpha\min} I_{\alpha\max}} \right). \tag{15}$$

Consequently

$$L_\beta(\theta_r) = \frac{U_{vf}}{\omega_{vf} I_{\alpha\max} I_{\alpha\min}} I_\alpha(\theta_r). \tag{16}$$

Resulting waveform of inductance can be quantified using (14), (15) and (16).

The relationships are derived assuming only the basic harmonic of magnetic saliency and therefore the spectral content of the injected current should be limited to the carrier frequency ω_{vf} and side bands $\omega_{vf} \pm 2\ \omega_r$. Therefore, harmonics created from other sources (for example, resulting from the current measurement), are filtered for the determination of magnetic saliency.

VIII. LABORATORY STAND

A laboratory stand contains a machine set of PMSM and asynchronous motor supplied from frequency converters, a control system with DSP, an operating and measuring station. Block diagram of the laboratory stand is shown in Fig. 4 [16].

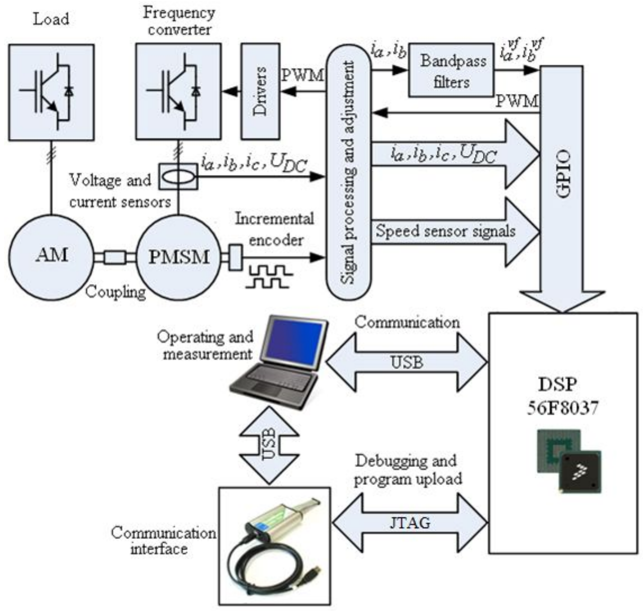

Fig. 4. Structure of the laboratory AC drive with PMSM.

The mechanical part of the drive consists of the PMSM and working mechanism, which is simulated in laboratory conditions by an asynchronous machine. The PMSM is mechanically connected to the frame and together with the asynchronous machine make up machine set (see Fig. 5). The PMSM is equipped with an incremental encoder with 2048 pulses per revolution.

For experimental verification of the described measuring method, the IPMSM was used. This machine has a radial configuration of the rotor magnets. The main parameters of the IPMSM are shown in Table I.

TABLE I. PARAMETERS OF THE SYNCHRONOUS MOTOR.

Nominal torque	7.7 Nm
Nominal current	5.65 A
Maximal demagnetizing current	26 A
Nominal speed	3000 rpm
Number of magnetic pole pairs	2
Nominal power	2.42 kW
Voltage constant	0.7 V/rad
Longitudinal inductance	1.75 mH
Transverse inductance	4.9 mH
Stator resistance	1.11 Ω
Moment of inertia	17.41 kgcm^2

In the control system, the digital signal processor Freescale 56F8037 was used. Development board with the DSP contains among other converter of serial line to USB. Communication and data collection thus proceed through the USB interface. Program debugging and recording then proceed via USB, where for converting USB to JTAG interface the USB TAP already mentioned company Freescale is used.

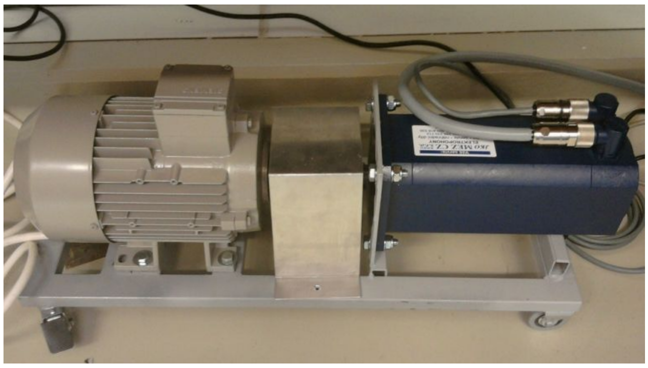

Fig. 5. Machine set - AM (left) and PMSM (right).

Development board receives measurement signals and sends control signals using general DSP inputs and outputs (GPIO) through an expansion board.

The expansion board adapts, strengthens and adjusts sub-signals that the DSP was able to evaluate these necessary signals. It also protects the GPIO of the processor.

IX. SIMULATION AND EXPERIMENTAL RESULTS

Because the sensorless PMSM drive based on injection methods and vector control is quite a complex system, it is suitable to validate the whole system before the implementation of the theoretical considerations by computer simulation. Simulations were performed in software environment MATLAB/SIMULINK.

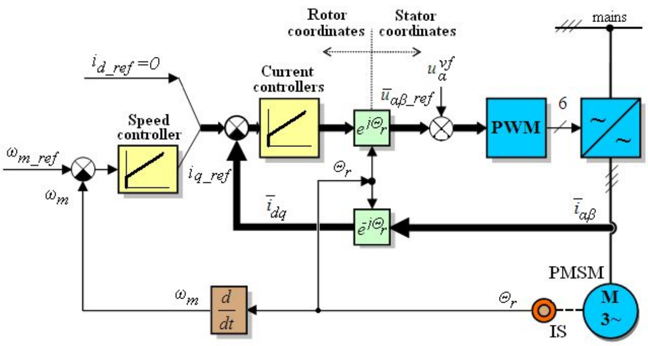

Fig. 6. Control structure of the AC drive with the PMSM.

For simulation of the measuring method for determining the magnetic saliency, a control structure was used which is shown in Fig. 6. A principle and meaning of each block of the control structure is obvious from Fig. 6.

The measuring method was tested in the different conditions of the rotor angular speed (or stator frequency) and load torque. Presented simulation and experimental results were obtained at stator frequency 26 Hz.

The injected voltage was chosen U_{vf} = 37.5 V and the frequency $f_{vf} = 1\ kHz$. Figure 7 shows the simulation result for the IPMSM with the parameters listed in Table I.

Figure 8 shows the experimentally measured time course of the inductance L_β, depending on the electrical rotor angle and as a parameter is load of the machine. For this measurement, voltage signal with frequency $f_{vf} = 1\ kHz$ and amplitude $U_{vf} = 37.5\ V$ was injected [16].

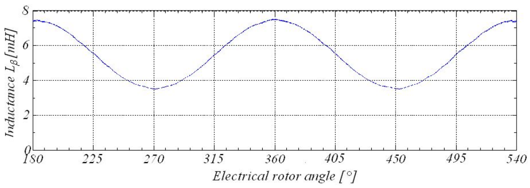

Fig. 7. Waveform of stator inductance $L_\beta = f(\Theta_r)$ (simulation).

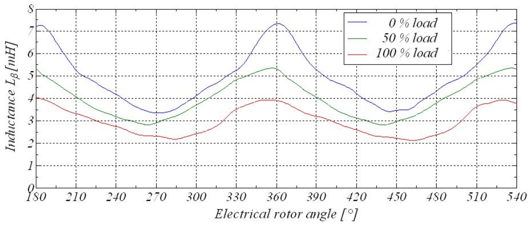

Fig. 8. Magnetic saliency used PMSM for different loads.

In Figure 8, the phase shift can be seen, which does not exceed 15 degrees at full load, and reducing the longitudinal and transverse inductance at increasing load of the machine. However, the ratio L_q/L_d is ≈ 2. Phase of measured magnetic saliency indicates that the high frequency current is modulated by changing the magnetizing inductance of the stator inductance and not stator leakage inductance. This measurement confirmed that the used PMSM is suitable for injection methods.

X. Conclusions

The article shows the own authors' approach in implementing the method utilizing the injection of a signal of high frequency into a specific control system with digital signal processor. This measurement method is not only suitable for the estimation of the rotor position for AC machines in the area of low and zero speeds, but also for the analysis of the magnetic saliency of AC machines.

The measuring method is based on direct measurement of the stator inductance by injecting voltage signal with the high frequency into α-axis of the stator coordinate system which produces the high frequency stator current in the stator of the AC machine. Getting envelope of the stator current with the high frequency is done by demodulation and for eliminating the harmonics is used low-pass filter. The resulting high frequency stator current is composed of two components. The first component is proportional to the mean value of the stator inductance. This component does not contain information about the rotor position. The second component is directly proportional to the difference of inductances (magnetic saliency) and carries useful information about the rotor position. Although the change of the inductance is not almost perfectly sinusoidal, so only the fundamental harmonic of this change gives useful information about the position. Therefore, the aim of this test is only fundamental harmonic.

The measurement technique of magnetic saliency is suitable for arbitrary PMSM in order to quantify the size of magnetic saliency and its position depending on the load. Although in this work the IPMSM is available, the measurement technique is particularly suitable for the SMPMSM or IM, where doubts may arise about the existence of magnetic saliency.

In particular, the measuring method can be used for the analysis of the machine's magnetic saliency and for the assessment of whether or not it is suitable for sensorless control using the injection method, which proves described method of measuring magnetic saliency. By repeating the measurement for different loads of the machine, the measuring method allows to acquire a dependence of the stator current on the position of magnetic saliency.

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