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Determining parameters of a three-phase permanent magnet synchronous machine using controlled single-phase voltage source

***Abstract**. This paper compares and evaluates different experimental methods for determining permanent magnet synchronous machine (PMSM) parameters. They are based on numerical integration, analysis of current time-response and harmonic analysis combined with calculation of phasors and impedances. The results presented in the paper show that the parameters of two-axis PMSM dynamic model can be determined with sufficient accuracy even when the three-phase PMSM with appropriately connected windings is supplied with a single stepwise changing voltage.*

Streszczenie.**.W artykule porównano i ewaluowano różne metody eksperymentalne dla określenia parametrów maszyn synchronicznych z magnesem trwałym. Metody te bazują na numerycznym całkowaniu, analizie prądowych odpowiedzi czasowych, oraz analizie harmonicznej połączonej obliczaniem fazorów i impedancji. Wyniki przedstawiane w artykule pokazują, że parametry dwuosiowego modelu silnika mogą być wyznaczone z wystarczającą dokładnością nawet wtedy, kiedy trójfazowy silnik zasilany jest z pojedynczego z krokowo zmiennego napięcia.* ***(Określanie parametrów trójfazowej maszyny synchronicznej z magnesem trwałym przy użyciu jednofazowego źródła napięcia)

Keywords: permanent magnet synchronous machine, experimental methods, controlled voltage source, parameters.
Słowa kluczowe: maszyna synchroniczna z magnesem trwałym, metody doświadczalne, źródło ze sterowanym napięciem, parametry

Introduction

Parameters of three-phase AC machines are normally determined by means of measurements of current and voltage on the terminals of the machine supplied with three-phase voltages. An inverter or an electric grid can be used as a three-phase voltage source. Standard methods for determining parameters of AC machines are normally based on tests performed at no-load, different loads and locked rotor, where the machine is supplied with sinusoidal voltages at rated frequency, using Fourier analysis and root-mean-square values of measured currents and voltages. However, there exist also several alternative experimental methods suitable for determining parameters of permanent magnet synchronous machines (PMSMs), which are often mathematically described and controlled in the d-q reference frame. In such cases the PMSM is supplied with inverter generated voltages, measurements of which are difficult due to the applied pulse width modulation (PWM). The obtained results can be also influenced by the iron core losses due to the eddy currents, when the tests are performed at higher frequencies of supply voltages. In order to overcome at least some of aforementioned problems, this paper proposes and evaluates different experimental methods for determining PMSM parameters. They are based on test performed on PMSM supplied with single- and three-phase linear rectifier generated voltages.

Dynamic models of PMSM are presented in [1-3]. The authors in [4, 5] introduced several experimental methods for determining magnetically nonlinear characteristics of electromagnetic devices. Some of these methods were applied for determining parameters of synchronous reluctance motor supplied with voltages from d-q reference frame controlled voltage source inverter (VSI) [6]. Different VSI supply based methods for determining parameters of PMSMs are presented in [7, 8]. A single-phase grid voltage supply is applied in [9] for determining parameters of a synchronous reluctance machine.

This paper proposes and discusses different experimental methods appropriate for determining parameters of PMSMs. The discussed methods are based on tests performed at locked rotor while the PMSM is supplied with different wave forms of supply voltages. The single- and three-phase supply voltages are generated by controlled linear amplifiers. In this way, the applied periodically changing low frequency voltages can be easily measured, while the impact of eddy currents on obtained results is low. The paper shows a very good agreement between inductances determined from the tests performed with single-phase voltage source and those determined from the tests performed with three-phase voltage source controlled in the d-q reference frame.

Theoretical background

Voltage balances in the phase windings of a PMSM can be described by matrix equation (1):

$$\mathbf{u}_{\mathrm{abc}} = \mathbf{R}_{\mathrm{abc}}\mathbf{i}_{\mathrm{abc}} + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{abc}} \tag{1}$$

where $\mathbf{u}_{\mathrm{abc}}$ is the vector of phase voltages, $\mathbf{i}_{\mathrm{abc}}$ is the vector of phase currents, $\boldsymbol{\psi}_{\mathrm{abc}}$ is the vector of flux linkages in phase windings and $\mathbf{R}_{\mathrm{abc}}$ is the matrix of ohmic resistances of individual stator windings.

For determining parameters of PMSM, the two-axis PMSM model written in the d-q reference frame is often used. The d-axis is defined with the flux linkage vector due to the permanent magnets, while the q-axis is displaced for electrical $\pi/2$. The three-phase model and the d-q model are related with the Clarke transformation, which can be composed of three-phase to two-phase transformation and rotational transformation. In the given case, the surface permanent magnet synchronous machine is discussed. Voltage equations of its magnetically linear model are given by (2):

$$\begin{aligned}\mathbf{u}_{\mathrm{dq}} &= \begin{bmatrix} R_{\mathrm{d}} & 0 \\ 0 & R_{\mathrm{q}} \end{bmatrix}\mathbf{i}_{\mathrm{dq}} + \frac{\mathrm{d}\theta}{\mathrm{d}t}\begin{bmatrix} 0 & L_{\mathrm{q}} \\ L_{\mathrm{d}} & 0 \end{bmatrix}\mathbf{i}_{\mathrm{dq}} \\ &+ \begin{bmatrix} L_{\mathrm{d}} & 0 \\ 0 & L_{\mathrm{q}} \end{bmatrix}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i}_{\mathrm{dq}} + \sqrt{\frac{3}{2}}\psi_{\mathrm{m}}\frac{\mathrm{d}\theta}{\mathrm{d}t}\begin{bmatrix} 0 \\ 1 \end{bmatrix}\end{aligned} \tag{2}$$

where $\mathbf{u}_{\mathrm{dq}}$ and $\mathbf{i}_{\mathrm{dq}}$ are the vectors of voltages and currents written in the d-q reference frame, R_{d}, R_{q} and L_{d}, L_{q} are the resistances and inductances written in the d-q reference frame, ψ_{m} is the flux linkage due to the permanent magnet while θ is the rotor position expressed with electrical angle .

If current excitation is applied in the d-axis, the rotor position changes in such a way that the flux linkages due to the permanent magnet and due to the current excitation support each other. This condition can be achieved even, when the stator winding of the tested PMSM is supplied from a single-phase voltage source, as shown in Fig. 1.a). The d-axis of the permanent magnet shown in Fig. 1.c) is aligned with the magnetic axis of the phase 'a' winding shown in Fig. 1.a). In this position the d-axis inductance can be determined from the measured changing voltage and responding current. Different voltage wave forms can be applied. If sinusoidal supply voltage is applied when rotor is slowly moved using and external source of torque, the rotor position with maximal current value, corresponding to the one shown in Fig. 1.d), can be determined. After locking the rotor in this position, the q-axis inductance can be determined from the measured changing voltage and responding current in the same way as in the d-axis. The applied sinusoidal and stepwise changing supply voltages and responding currents are shown in Fig. 2.

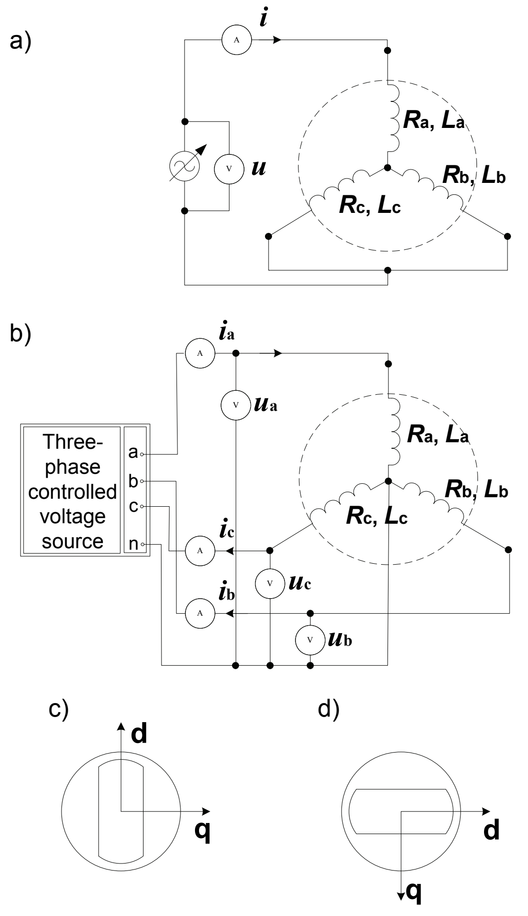

Fig.1. Schematic presentation: a) single-phase voltage source supplied stator winding, supply and sensors; b) three-phase voltage source supplied stator winding, supply and sensors; c) rotor position for determined d-axis inductance; d); rotor position for determined q-axis inductance

In order to confirm methods for determining PMSM parameters based on the tests with single-phase voltage source, the tested PMSM is supplied also with the three-phase voltage source (Fig. 1. b)). It is composed of three linear amplifiers controlled in the d-q reference frame. During the tests, d-axis is first aligned with the magnetic axis of the phase 'a' winding by supplying this winding with DC voltage. In the given position the rotor is locked for all tests. The tests are performed in the d-q reference frame by supplying the tested machine with stepwise changing and sinusoidal voltages (Fig. 2.) as in the case of single-phase supply. The d- and q-axis inductances are determined in the same way as in the case of single-phase supply.

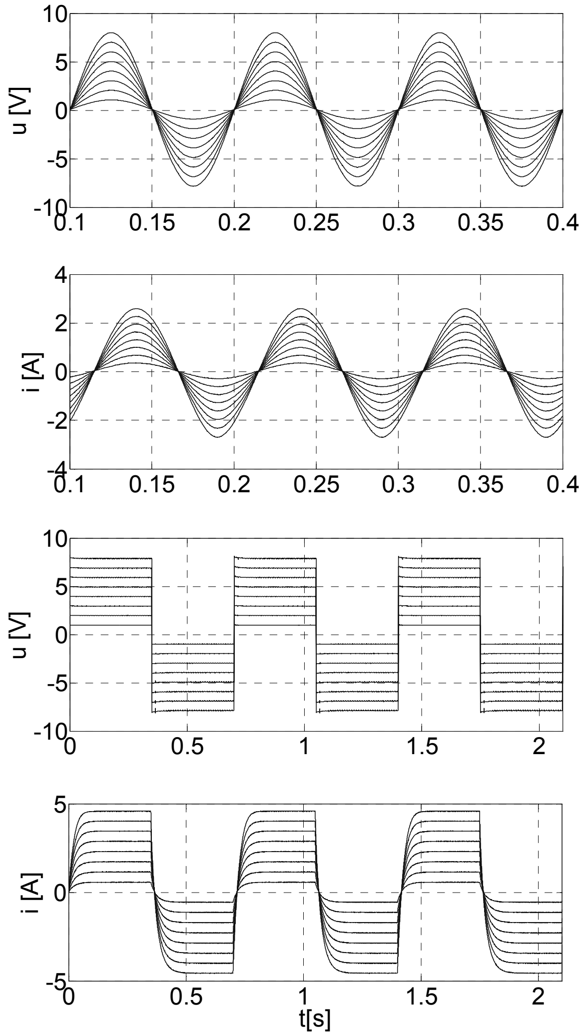

Fig.2. Measured sinusoidal and stepwise changing voltages u and responding currents i

Methods of determining parameters of permanent magnet synchronous machine

This paper presents four different methods for determining parameters of PMSM. They are based on measurements of applied voltages and responding currents. In all methods applied voltages with variable amplitudes, different wave forms and low constant frequency are used. All results are presented in the form of $\psi(i)$ characteristics. The $\psi(i)$ characteristics are determined by considering voltage equation (1) and Faraday's law by numerical integration, by Fourier analysis and calculation of impedances and by analyzing the current time-response. The reference voltages are sinusoidal or stepwise changing. Their amplitudes change while the frequency is kept constant. The same methods are applied on measured time behaviors of currents and voltages in the cases of single-phase and three-phase voltage supply.

Method I: Applied sinusoidal voltage and responding current are measured. The measurements are performed at variable amplitudes (1 - 7 V) and constant frequency (10 Hz) of supply voltage. The first method is based on numerical integration described by (3):

$$\psi(t)=\int_{0}^{t}\left[u(\tau)-Ri(\tau)\right]\mathrm{d}\tau+\psi(0) \tag{3}$$

where $\psi(0)$ is the initial condition representing the remanent flux which is normally set to zero.

This method is very sensitive to the changes in ohmic resistance R, which varies due to the heating. The incorrect value of resistance R in (3) causes drifts in calculated $\psi(i)$ characteristics, which are often given in the form of hysteresis loops. The correct value of ohmic resistance cannot be determined directly by the method I.

Method II: This method differs from the previous one only in the wave form of applied voltage. In this case the stepwise changing voltage supply is used. The measurements are performed at variable amplitudes (1 - 7 V) and constant frequency (1.43 Hz) of supply voltage. This method is also very sensitive on incorrect value of resistance R. However, the correct value of ohmic resistance can be calculated after each individual step-change of supply voltage using steady-state values of measured currents and voltages. $\psi(i)$ characteristics are determined by numerical integration of measured applied voltage and responding current (3).

Method III: The third method can be applied only for sinusoidal voltages with constant frequency. The measurements are performed at variable amplitudes (1 - 7 V) and constant frequency (10 Hz) of supply voltage. It is based on Fourier analysis combined with calculation of phasors and impedances. Considering only the fundamental harmonic components, expressions (4), defined below, can be used to determine the $\psi(i)$ characteristic. The flux linkage is calculated using the R.M.S. (root-mean-square) values of voltage and responding currents (4):

$$(4)\qquad Z=\frac{U}{I},\ R=\frac{P}{I^2},\ L=\frac{1}{2\pi f}\sqrt{Z^2-R^2},\ \psi=\sqrt{2}LI$$

where Z is the impedance, U and I are the R.M.S. value of measured voltage and current, P is the active power, R and L are the ohmic resistance and the inductance.

Method IV: This method can be applied only for stepwise changing voltage. The measurements are performed at variable amplitudes (1 - 7 V) and constant frequency (1.43 Hz) of supply voltage. The inductances L and $\psi(i)$ characteristics are determined from the time constant τ (5) of current time-response. The current time response is treated as a response of first order element (Fig. 3). After the change, the applied voltage and responding currents must reach the steady-state. Their quotient is used to determine the resistance R required in (5). The time constant is determined form the measured current time response.

$$(5)\qquad \tau=\frac{L}{R}\ \Rightarrow\ L=R\tau,\ \ \psi(i)=Li$$

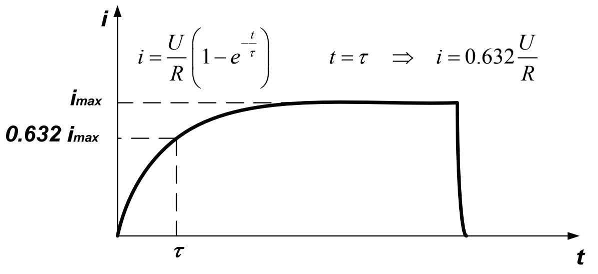

Fig.3. Current time response in form of first order element

Results

The end points of individual hysteresis loops $\psi(i)$ determined by methods I and II and individual points on unique $\psi(i)$characteristics determined by methods III and IV are used for comparison of obtained results. The obtained results in the form of characteristics $\psi_d(i_d,\ i_q=0)$ and $\psi_q(i_d=0,\ i_q)$ are compared for the single- and three-phase supply.

Fig. 4. shows the comparison of $\psi_d(i_d)$ characteristics determined by the four methods for d-axis in the case of single-phase voltage supply. The agreement among obtained results is very good.

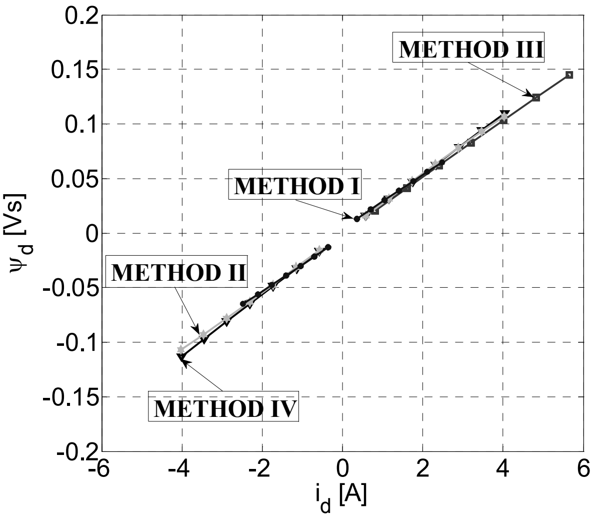

Fig.4. $\psi_d(i_d)$ characteristics for d-axis determined with single-phase voltage supply

Fig. 5. shows the comparison of $\psi_d(i_d)$ characteristics determined by the four methods for q-axis in the case of three-phase voltage supply. In this case the q-axis current equals zero. The results obtained by the methods II to IV are close, while the results obtained by the method I differs a bit more due to the extremely high sensitivity to the incorrect values for ohmic resistance.

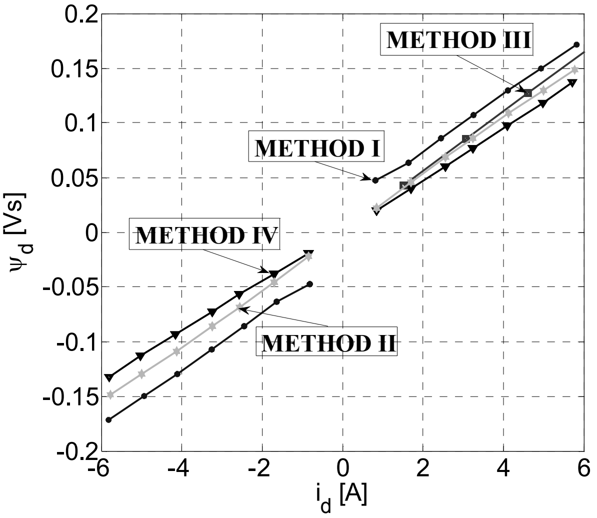

Fig.5. $\psi_d(i_d)$ characteristics for d-axis determined with three-phase voltage supply, $i_q = 0$

Fig. 6. shows the comparison of $\psi_q(i_q)$ characteristics determined by the four methods for q-axis in the case of single-phase voltage supply. The agreement among characteristics obtained by all four methods is excellent.

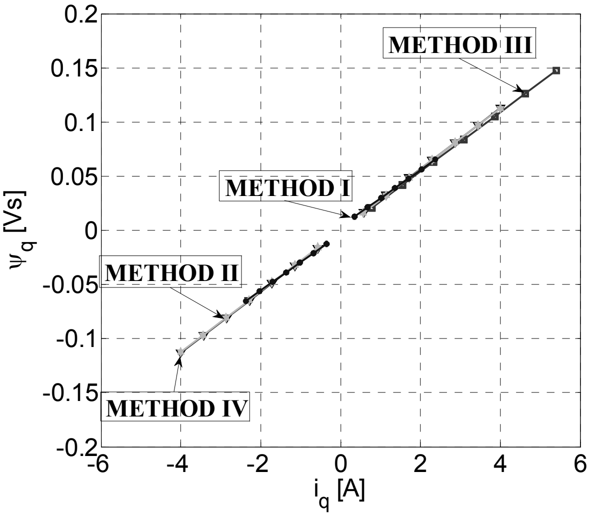

Fig.6. $\psi_q(i_q)$ characteristics for q-axis determined with single-phase voltage supply

Fig. 7. shows the comparison of $\psi_q(i_q)$ characteristics determined by the four methods for q-axis in the case of three-phase voltage supply. In this case, the conclusions are similar as in the previous case (Fig.5.). The results determined by the method I differs form the results obtained by the other methods due to the high sensitivity on incorrect values of ohmic resistance.

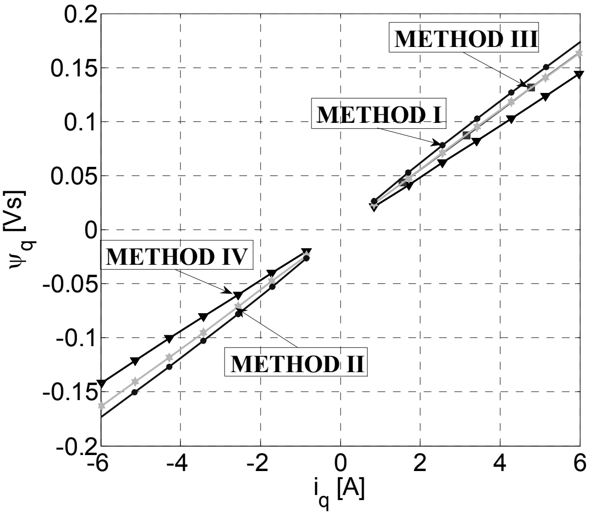

Fig.7. $\psi_q(i_q)$ characteristics for q-axis determined with three-phase voltage supply, $i_d = 0$

Conclusion

The paper discusses four different methods for determining parameters of PMSM. Sinusoidal and stepwise changing voltages of different amplitudes at constant frequency are applied. Single-phase and three-phase voltages are generated with linear amplifiers. The three-phase amplifiers are controlled in the d-q reference frame. The frequency can be low to minimize the influence of eddy currents, while the voltages can be easily measured because they are not PWM generated. The PMSM parameters are determined using measured applied voltages and responding currents. The described methods are based on numerical integration, calculation of impedances and analysis of first order element response. The integration based methods are very sensitive on incorrect values of ohmic resistances – especially in the case of sinusoidal supply voltages. The results are presented and compared in the form of $\psi(i)$ characteristics. It is shown that a single-phase voltage supply can be used to determine inductances of a three-phase PMSM with sufficient accuracy to be used in control design based on two-axis d-q dynamic models of PMSM.

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