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NOVEL METHODS FOR PARAMETERS INVESTIGATION OF PM SYNCHRONOUS MOTORS

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ABSTRACT: The paper describes the unconventional methods for electrical parameters investigation of a Permanent Magnets Synchronous Motor (PMSM). Plenty of known methods have been using for the resistance and inductance measurement however the standard techniques do not support the estimation of inductances saturation curves. New approaches described in the paper offer a possibility to measure whole inductances characteristics which reflect to the behavior of electric parameters at different operational points of the motor. Based on the real measurement, the acquired parameters are compared and properly evaluated. Presented methods will be further processed and used for microcomputer implementation in order to determine the electric drive parameters.
KEYWORDS: synchronous motor, parameters, inductance, BH characteristic

INTRODUCTION

The information about motor parameter is very important for the machine designer however, is becoming important also for the operator of modern electrical drives. Electric drive represents a set of several systems such as electric motors, voltage source inverter, control unit and various types of sensors. The quality of motor control depends on the parameters of overall system but mainly on the parameters of controlled motor.

The PMSM motors are mostly controlled by employing the principles of Field Oriented Control (FOC) in a cascade control structure with relevant feedbacks. Despite the fact that the cascade control structure with PI controllers has the capability to eliminate various nonlinearities; there are still plenty of reasons why the topic of motor parameter determination is so hot.

For example the simulation purposes, implementation of various types of controllers or several motor control structures. However, there is also a special group of advanced motor control algorithms that are based on motor mathematical model and therefore the motor parameters are required as precise as possible.

Nowadays, there are various methods that can be used for the parameters evaluation [1, 2]. The parameters can also be measured by using of a proper device, for instance the RLC meter. This approach is sufficient for rough measurement and it is not recommended for very precise and complex measurement due to scale or range limitation, mid-level accuracy, low test current [3] and so on.

Very known and widely used methods for parameter investigation are methods based on principles of Ohm's law. The electric circuit of the motor is considered as a simple RL circuit that is excited by a voltage and current flowing through the winding is measured. In case of DC voltage excitation a standstill DC current is measured. Then the Ohm's law yields to a resistance of the motor. In case of AC voltage excitation the AC current's magnitude and phase response are measured. By utilizing Ohm's law it is possible to get an impedance of the motor and consequently the resistance and inductance. Such approach is also known as Standstill Frequency Response Test [1]. One of the most popular strategies for parameter estimation is a standstill DC step or DC decay test. These strategies can be used to determine both machine resistance and inductance, but they are mainly used for inductance calculation which is derived from the time electrical constant of the RL circuit.

Taking into account that PMSM motors are mostly operated at their operational point, the motor base parameters are supposed not to be changed and therefore the aforementioned techniques are enough precise for motor parameters determination. However there is lot of industrial applications where the motor runs out of ideal operational point and the parameter are then affected by a saturation phenomenon. Proposed approaches presented in the paper describe the way how to estimate the parameters in the wide operational region of the motor.

All described strategies have been verified on the real PMSM motor.

DQ Model in Stationary Reference Frame

The main objective of the paper is to describe unconventional methods to obtain dq model

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parameters from physically measured data. Therefore, a two phase orthogonal dq model in synchronous reference frame has been used to analyze the synchronous reluctances of the machine. The mathematical model of PMSM motor is as follows:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = R_S \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + + \omega_e \begin{bmatrix} 0 & -L_q \\ L_d & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_e \psi_{PM} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (1)$$

where R_S is stator phase resistance, L_d, L_q are synchronous inductances in dq axes and ψ_{PM} represents a flux of permanent magnets.

All tests were executed at standstill or very slow rotary movement, therefore cross-coupling terms in both d- and q-axis as well as the back-EMF voltage component in q-axis are canceled and the PMSM model is linearized as follows:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = R_S \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (2)$$

From motor control perspective, the equation (2) describes the model of the plant for d and q current loop. Electrical torque in dq reference frame is developed by contribution of synchronous and reluctance torque, and is derived as follows:

$$T_e = \frac{3}{2} pp\left(\psi_{PM} i_q + \left(L_d - L_q\right) i_d i_q\right) \quad (3)$$

To establish a dq frame model of a given PM synchronous motor, there are four motor parameters that are to be determined. These are stator resistance R_S, inductances L_q and L_d, and PM flux linkage ψ_{PM}.

A. Connection scheme definition

Due to the mutual magnetic coupling between the three phases, for stationary tests with single-phase excitation, the inductance should be measured with all three phases excited as shown in Figure 1 [3]. In order to investigate the behavior of inductances in both d- and q-axis, the same scheme can be used, but the rotor has to be locked at two different positions. For d-axis measurement the rotor flux ψ_{PM} must be aligned with the resulting armature flux ψ_{ABC} and for q-axis measurement the angle between rotor flux and resulting armature flux must be 90 degrees, Figure 1.

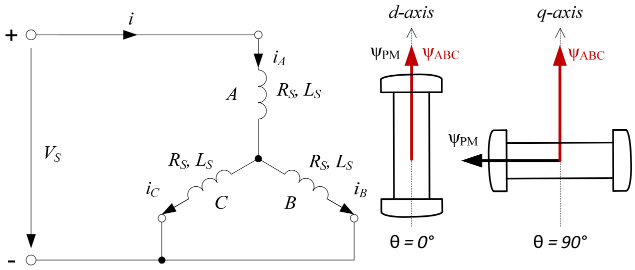


Figure 1. Connection scheme arrangement

B. D- and Q- axis rotor alignment

In order to locate the d- and q-axis in PMSM the easiest way is to apply DC voltage to the terminal of the motor. Using the connection shown in Figure 1, the rotor will follow the resulting armature flux ψ_{ABC} and consequently the rotor flux will align with it. Then the d-axis of the rotor is aligned with the center of stator phase A and acquired inductance of the circuit will be equivalent to L_d inductance [4].

Q-axis alignment requires a certain modification of the connection scheme according to Figure 2.

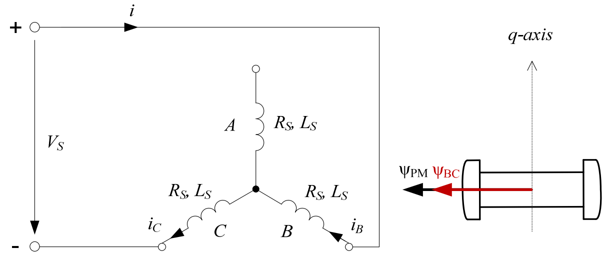


Figure 2. Connection scheme performing q-axis alignment

As it shown in Figure 2, the scheme considers only two motor phases energized and the phase A is disconnected. This approach causes generation of the armature flux ψ_{BC} that is 90 degrees shifted against the resulting armature flux ψ_{ABC} depicted in Figure 1. The rotor moves to the position of the armature flux ψ_{BC} and aligns with it. It means that the q-axis of the rotor is now aligned with the center of stator phase A and acquired inductance of the circuit will be equivalent to L_q inductance. Once the rotor is aligned, the shaft of the motor must be mechanically locked. Having the rotor aligned and properly locked, the connection for measurement purposes has to be changed to the one shown in Figure 1.

MOTOR PARAMETER CHARACTERISTICS

A. Stator resistance R_S

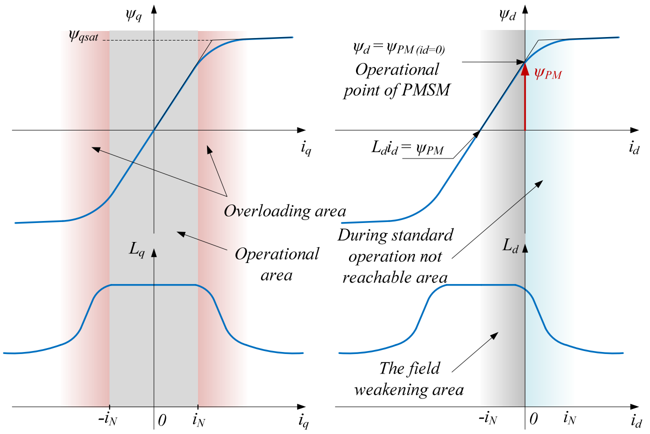
Generally, parameter R_S defines a phase resistance measured between line-to-neutral points. In the most common PMSMs, the midpoint of Y-connected winding is not accessible and therefore line-to-line resistance has to be measured. The measurement can be provided either according to the scheme in Figure 1 or scheme in Figure 2. In first case, the phase resistance will be two-thirds of measured line-to-line resistance, in second case the phase resistance will be half of measured line-to-line resistance.

During measurement an attention has to be paid because winding resistance value is highly temperature-dependent.

B. Synchronous inductances L_d and L_q

Synchronous inductances measurement assumes the connection scheme shown in Figure 1. As it has been mentioned, the stator winding is Y connected without any neutral line for external access and the only line-to-line value can be measured. When the rotor's d-axis/q-axis are aligned with the stator phase A, the synchronous inductance L_d and L_q can be derived from equivalent line-to-line inductance L_{L-L} as two-thirds of L_{L-L}, depending on the rotor angle θ. This assumption can be accepted only in case of simplification, where the mutual inductances are not taken into account.

Since inductance in the motor is also subject of saturation phenomena, the way to correctly monitor the inductances is to measure them at various current levels. The nonlinearity $\psi=f(i)$, $L=f(i)$ are caused by the saturation of iron parts of the stator and has the same shape as magnetizing curve B=f(H). This dependency is described in Figure 3, where the relations ψ=f(i), L=f(i) in both axes are presented.



a) q-axis dependences b) d-axis dependences

Figure 3. The effect of saturation, ψ_{dq} and L_{dq} as a function of i_{dq}

To analyze the effect of saturation in q-axis, Figure 3a, the rotor q-axis has to be aligned with the stator phase A. If the motor is assumed to be under vector control, with no field weakening i_d=0, the increasing load will result in increased stator current in q-axis. When there is no load applied to the rotor, i_q=0, the linkage flux ψ_q =0. Increasing load results in an increase of i_q and ψ_q, and will cause saturation of the stator teeth around q-axis, which in turn decrease L_q.

To analyze the effect of saturation in d-axis, Figure 3b, the rotor d-axis has to be aligned with the stator phase A. To make the analysis easier, the effect of demagnetization or magnetization is studied without influence of the armature reaction, i_q is kept at zero. All the flux existing in the machine is created purely by the permanent magnets and therefore the area around d-axis is mildly saturated even if there is no current flowing through the stator winding.

In case that the stator current (i_d) increases and the direction of magnetic flux generated by the current is the same as the flux of permanent magnets, a magnetizing effect will occur. In this situation, the area of stator around d-axis will be even more saturated with increasing current, further lowering L_d. This operation area is not common for standard control techniques of PMSM.

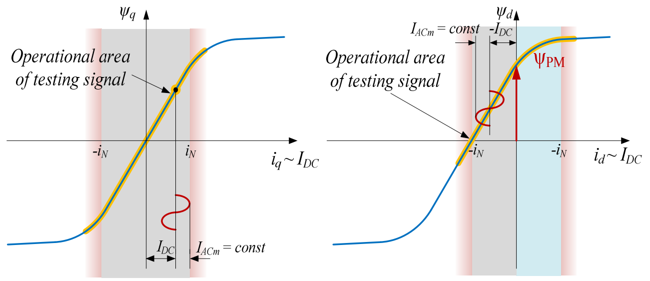
If the stator current ($-i_d$) increases and the direction of magnetic flux generated by the current is in opposite to the flux generated by permanent magnets, a demagnetizing effect will occur. Increasing the amplitude of the stator current will pull the area of stator around d- axis out of saturation. This phenomenon results in increase of stator d-axis inductance L_d. This is an important conclusion, since it will affect the design of the field weakening control loop, which is commonly used in controlling of PM synchronous motors [5].

To measure the inductances as precise as possible and to have a capability to cover also saturation region, several methods can be used. The rough division of suitable methods depends on the type of voltage exciting signal and subsequently on the signal processing. There are three different approaches presented in this paper.

MOTOR PARAMETER MEASUREMENT

A. Superposition of DC and AC excitation signal

The method utilizes compounded DC and AC voltages as an excitation signal. The major signal is DC voltage that will be adjustable during the test. The magnitude and the frequency of AC signal are set by a voltage source and will be fixed during the test. Such excitation signal is connected to the terminal of the motor according to the scheme in Figure 1. The idea of proposed approach is clearly visible in Figure 4.



a) q-axis dependences b) d-axis dependences

Figure 4. Impact of compounded excitation signal on the operational point on the BH curve

DC current I_{DC} has been changing in order to reach saturation area in both d- and q- axes. The DC voltage has been set such way, that the response of the current changed in a range I_{DC} = (-1,2I_N ÷ 1,2I_N). It has been expected that 20 percent higher current than its nominal value would allow reaching the saturation region during q-axis test, Figure 4a, and lowering L_q inductance will be seen. The same current range has been applied to the motor during d-axis alignment in order to see the whole knee of BH characteristic, caused by the saturation due to the flux of permanent magnets.

As seen in Figure 5, the excitation signal consists of DC value V_{DC} and AC value at certain frequency and magnitude V_{ACm}. The current response also contains two components, the first one is DC value I_{DC} and the second one is an alternating signal I_{ACm}. The DC current signal affects the operating point on magnetizing characteristic and moves it up and down as it is shown in Figure 4. By changing the position of operating point on BH characteristic the amount of saturation changes too.

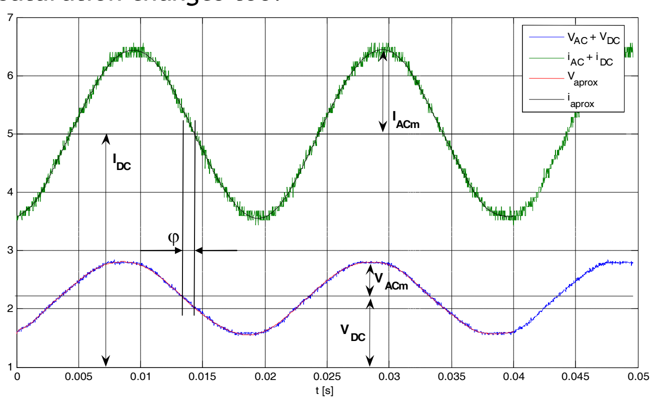


Figure 5. Excitation voltage and the current response

The DC values of voltage and current can be used for the resistance measurement.

$$R_S = \frac{2}{3} R_{L-L} = \frac{2}{3} \frac{V_{DC}}{I_{DC}} \quad (4)$$

The peak values of the voltage AC component and current AC component and the phase shift between them is used for inductance calculation as follows:

$$L_{d(\theta=0)}=L_{q(\theta=90)}=\frac{2}{3}\frac{1}{2\pi f}R_S tg(\varphi) \qquad (5)$$

$$L_{d(\theta=0)}=L_{q(\theta=90)}=\frac{2}{3}\frac{1}{2\pi f}\frac{V_{ACm}}{I_{ACm}}\sin(\varphi) \qquad (6)$$

Equations (5) and (6) offer two possibilities to calculate the line-to-neutral inductances. The important information for both calculations is the phase shift φ. In order to extract this value from the waveforms shown in Figure 5 a proper modulation technique has to be used.

B. Instantaneous Flux Linkage

This method utilizes only AC voltage as an excitation signal for measuring the inductance saturation curves. The same test arrangement as shown in Figure 1 is used. Due to the fact that rotor is mechanically locked the voltage equations (2) is taken into account and used for linkage flux calculation. By applying mathematical rules to (2), a new set of equations can be derived:

$$\psi_d = L_d i_d = \int (U_d - R_S i_d)dt \qquad (7)$$

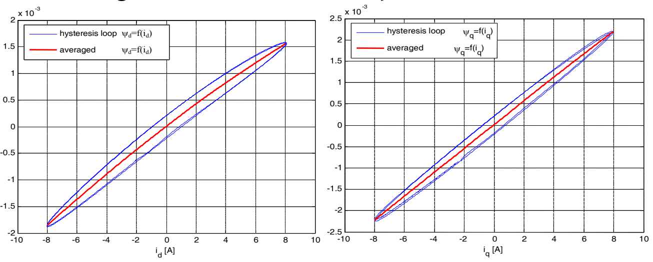
$$\psi_q = L_q i_q = \int (U_q - R_S i_q)dt \qquad (8)$$

Estimated linkage fluxes are shown in Figure 6. Then the inductances are calculated as follows:

$$L_d = \frac{\psi_{d\_avg}}{i_d} \qquad (9)$$

$$L_q = \frac{\psi_{q\_avg}}{i_q} \qquad (10)$$

The current and voltage waveforms were measured by an oscilloscope and processed in Matlab. In order to increase the accuracy of calculation, several periods of current/voltage waveforms were stored and averaged values were used for calculation.



a) **b)**

Figure 6. Flux linkage a) $\psi_d=f(i_d)$ and b) $\psi_q=f(i_q)$ determined by measurement

Averaged linkage flux values ψ_{d_avg}, ψ_{q_avg} from Figure 6 are then used for L_d and L_q determination based on (9, 10).

C. Partial current step changes - decay test

A method known as DC decay test has also been used for inductances investigation. The saturation curves can be acquired from several partial measurements at different level of saturation. The current difference during each measurement causes a transient that is characteristic by the time electrical constant. The test setup has been arranged according to Figure 7.

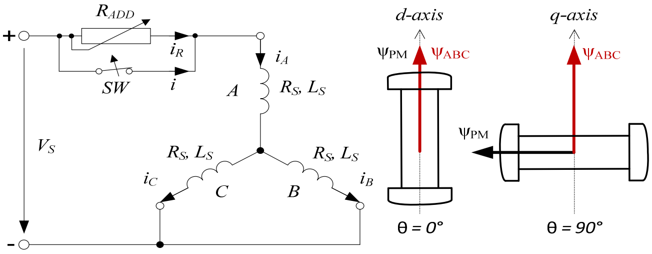


Figure 7. DC decay test connection scheme

The default state of the circuit shown in Figure 7 assumes the switch SW in the ON state and the current i flows through the winding. By switching off the switch SW, new current i_R will flow through the circuit. An additional adjustable resistance R_{ADD} allows setting the current i_R according to the required current step change Δi as it is described in Figure 8.

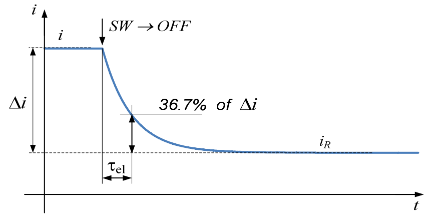
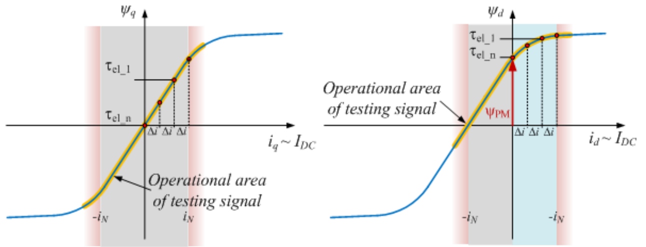


Figure 8. The current transient during DC decay test

The principles and effect of a partial current excitation is graphically described in Figure 9.



a) *q-axis dependences* ***b)*** *d-axis dependences*

Figure 9. Different levels of inductance saturation curves excited by DC current step change

It can be observed from Figure 9, that the particular regions of saturation curves relate to the particular time electrical constants due to changed inductance. This phenomenon is valid for both axes and can be used for synchronous inductances calculation. The current transient has to be plotted by the oscilloscope and by using cursors the time electric constant has be found for every step change. The data would be triggered on switch SW change from ON to OFF state.

Then the synchronous inductances depend on the rotor position and can be calculated according to an expression:

$$L_{d(\theta=0)}=L_{q(\theta=90)}=\frac{2}{3}\tau_{el}(R_{ADD}+R_{L-L}) \qquad (11)$$

EXPERIMENTAL RESULTS

The chapter offers the experimental results determined during the measurement on a real PMSM. The parameters of the PMSM given by manufacturer are shown in Table 1.

TABLE 1. MANUFACTURER PARAMETERS OF USED PMSM

TGT2 - 0032 - 30 - 24		TG Drives	
U_N	18V	2p	6
I_N	5,2A	Ke	3,6 V/1000rpm
M_N	0,3 Nm	R_{2ph}	0,594
n_N	3000 rpm	L_{2ph}	0,44mH

A. Compounded excitation signal

Equations (5, 6) were used for inductances and saturation curves estimation in d- and q-axis, Figure 10, 11.

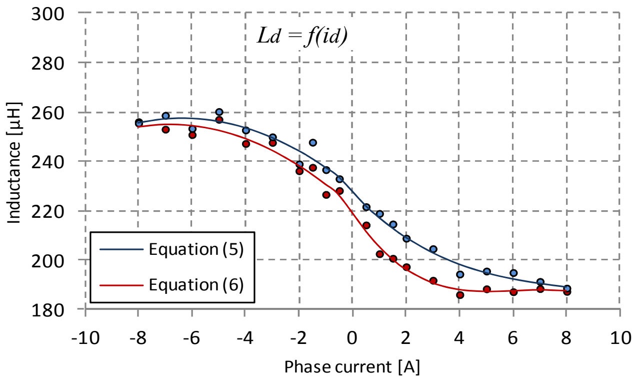


Figure 10. Measured d-axis saturation curves

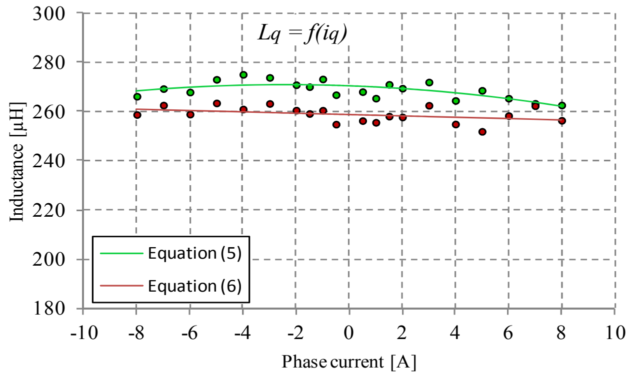


Figure 11. Measured q-axis saturation curves

The results plotted in Figure 10 and 11 are slightly deferent in depends on the approach (5) or (6) of final estimation. The reason of these differences is most likely caused by incorrect calculation, because approach with (5) utilized the same R_S value for whole current range calculation. On the contrary, the approach with (6) utilized instantaneous values of V_{ACm} and I_{ACm} for every current step. So the calculation with (6) can be considered as more correct and also the shape of saturation curve is nearer to the theoretical assumption shown in Figure 3.

B. Instantaneous Flux Linkage

The fluxes ψ_d, ψ_q estimated by (7, 8) are shown in Figure 6. A simple mathematical rule must be used to get averaged values ψ_{d_avg}, ψ_{q_avg}. Then the saturation curves, depicted in Figure 12 for d-axis and in Figure 13 for q-axis, are calculated by applying (9, 10).

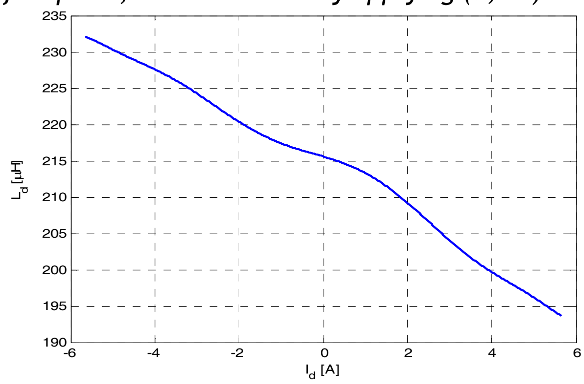


Figure 12. Measured d-axis saturation curve

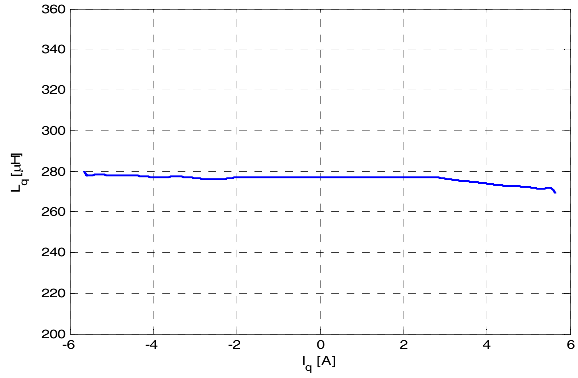


Figure 13. Measured q-axis saturation curve

The method is sensitive for correctly estimated fluxes. An issue can arise during the calculation, by using (7),(8), because of a DC offset that can appear in the current or voltage waveforms. This can be a reason why the saturation curves are slightly misaligned in comparison with the other methods.

C. Partial current step changes- decay test

For testing purpose, a current range from -7 up to 7Amps has been chosen with current step change Δi =1A. The resulting saturation curves for d- and q-axis can be seen in Figure 14.

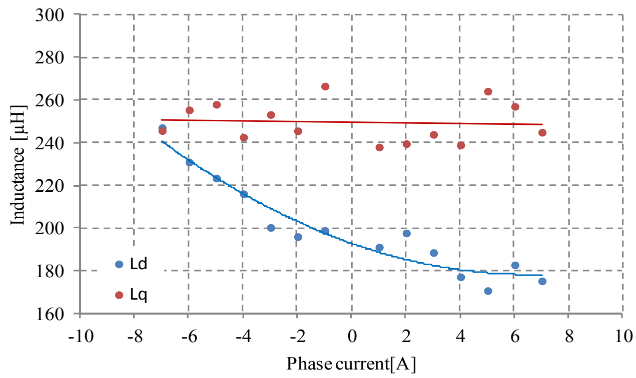


Figure 14. Measured d-and q-axis saturation curves

The shape of the curves has an expected behavior. The temperature of the winding plays significant role during the test, where the value of resistance can be changed. This can have a negative impact to the results, as it can be seen in Figure 14, where a certain misalignment can be observed in comparison with inductance curves depicted in Figure 13 and Figure 14.

CONCLUSIONS

The aim was to propose and verify the methods for PMSM motor parameters investigation that can be later used for microprocessor implementation. Three different approaches for inductance saturation curves measurement are presented in the paper. Comparing the results it can be seen, that the inductance curves taken from all methods are roughly similar. The small differences are caused by signal measurement and processing.

The method utilizing compounded AC/DC signals offers a possibility to estimate the resistance as well as both inductances in dq coordinates. A huge advantage of this approach is a variability that allows measuring and verifying the motor parameters and their behavior within a wide operational range of the motor. On the contrary, requirement of flexible AC-DC source and consequently complicated *demodulation method for phase shit estimation can be considered as a certain drawback.*

Instantaneous flux method requires a very precise flux estimator. An issue can arise during the flux estimation process caused by integration. The acquired waveforms of motor quantities like current and voltage are affected by a small DC signal that is introduced by a measuring process (offset of ADC channels). Then the integrated offset generates the varying offset in the time which makes drift of the resulting fluxes. To avoid any drift in flux waveforms, the input signals of the estimator have to be pure sinusoidal waveforms without any DC offset. Due to this fact this method is quite laborious.

The last method, shown in the paper, is a simple current step change – decay test. The success and the final precision of this method is linked with the time electric constant. The more accurate the time constant is deducted from the acquired exponential waveform the more accurate parameters are reached. The modification of origin decay test to the partial step current changes allows investigation of the motor parameters in the wide operational range.

The PMSM motor has been chosen because of its popularity in servo-driven application. Respecting the trend that only few applications require neutral point to be accessible; the standard Y-connected PMSM motor without any access to the neutral point has been chosen and used during all tests. In such case, the only line-to-line inductances are measured and then converted to the phase inductance value according to the winding connection during the test. Such approach is enough precise for resistance measurement, but certain differences can be expected in inductances behavior, because the mutual inductances are not taken into account.

The same PMSM motor is planning to be used for further work. The proposed solutions for parameters estimation will be implemented into the microcontroller and used for parameters estimation of overall electric drive. The aim is to verify the influence of the voltage inverter to the system parameters and consequently to the quality of motor control.

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