EXPERIMENTAL METHOD FOR ESTIMATING THE PARAMETERS OF A SYNCHRONOUS MACHINE EQUIVALENT SCHEME, WITH CONSIDERATION OF SKIN EFFECT INFLUENCE

Ion Daniel ILINA[1], Constantin GHIȚĂ[2]

În lucrare se prezintă o metodă de estimare experimentală a parametrilor schemei echivalente a maşinii sincrone, metodă ce utilizează modelul matematic în coordonate d, q al maşinii. Astfel sunt estimate rezistentele şi inductanțele de dispersie ale multicircuitelor rotorice ce simulează influența efectului peliculai. Procedeul experimental constă în probe de răspuns în frecvență în axa d şi respective axa q a maşinii sincrone la valori reduse ale curenților cu maşina în stare de repaus.

The paper presents a method for experimental determination of the parameters of the synchronous machine electric equivalent scheme. The method uses the d,q machine's coordinates. The resistances and leakage inductances of the rotor multi-circuit are estimated taking into account the eddy currents. The experimental tests consist in reading the frequency response in d and q axes of the synchronous machine, at low currents and stand still rotor.

Keywords: synchronous machine, skin effect, experimental determination, static method

1. Introduction

The skin effect is present in massive conductors and massive parts of electrical machines, such as: massive rotor poles (in synchronous machines and DC machines with inverse construction), normal squirrel cage rotors and damper cages (in asynchronous and synchronous machine, respectively), massive stator poles (DC machine) [1-5]. Accurate determination of the skin effect can be achieved by numerical computation. That, however, implies knowing all machine dimensions and the exact material proprieties.

On the other hand, the study of electrical machines for various operating regimes is achieved in general using a mathematical model (with steady or variable parameters, using phases or orthogonal coordinates). The model is obtained from the circuit equations of the machine to which are added, usually,

[1] Assist. eng., Faculty of Electrical Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: ilinadaniel@yahoo.com
[2] Prof., Faculty of Electrical Engineering, University POLITEHNICA of Bucharest, Romania

the electromagnetic torque equation and mechanical equation of the machine-drive system. Considering all aspects regarding the construction of the iron core, but also the material dependence with stress and temperature, the equations and subsequently the mathematical model become rather complex and often unpractical.

Mathematical models using orthogonal axes with optimal positioning according to the type of machine and operating regime, may offer significant simplification in solving the equations and in determining the machine's parameters. For these mathematical models, the skin current effect is taken into account by considering the dependence with frequency of coils resistance and leakage inductance. The resistances and leakage inductances dependency on frequency makes difficult to use these variable parameters to simulate various transient processes. Therefore, *replacing the equivalent mono-circuits with variable parameters, with equivalent multi-circuits with constant parameters* [1-4], is preferred. Such multi-circuits are approximating well the frequency variation of the resistance and equivalent leakage inductance throughout the entire larger frequency interval. In Fig. 1 is presented how an equivalent single-circuit with variable parameters can be replaced with an equivalent multi-circuit with constant parameters.

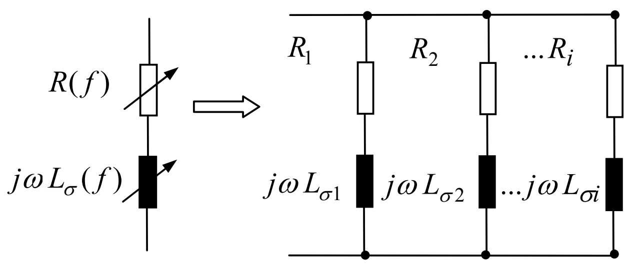


Fig. 1. Replacement of equivalent single-circuit with variable parameters, with and equivalent multi-circuit with constant parameters

The number of circuits connected in parallel depends on desired precision, machine's construction and power. At the beginning a lower number of circuits may be used; subsequently the number of circuits can be increased comparing experimental results with model results until optimal solution is achieved. For small machines and reduced frequency domain, simpler models with one or two circuits can be used [1-3].

In order to determine the parameters as precise as possible, different identification, estimation and validation methods have been established and used. The estimation methods have been based on tests with stand-still rotor (using the response in frequency and damping the current [1-4], [6-9]), methods that offer real practical advantages.

The current paper presents the estimation of rotor resistance and leakage inductances, using frequency response tests, and taking into account the skin current influence in creating the orthogonal model of the synchronous machine.

2. The orthogonal model of synchronous machine

The real synchronous machine has a 3AC-phase winding in the stator and a DC excitation winding and a damper cage in the rotor. The damper cage can be decomposed in two fictive components: along *d*-axis and *q*-axis, respectively (*D* and *Q*) (Fig. 2). [1-8]

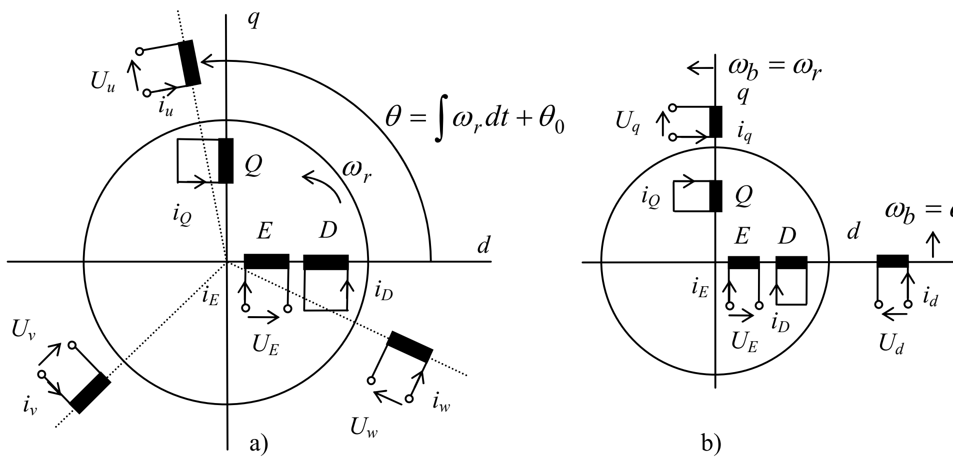


Fig. 2. 3-Phase synchronous machine: a) The real model b) The orthogonal model [1-3]

The equivalence between the real machine and its orthogonal model is done using Park transformation [1-3], [6-8].

The orthogonal model proposed by Park is based on the following assumptions:

- anisotropic machine;
- the windings of the induced are three-phase, symmetrical and distributed sinusoidal, without spatial harmonics;
- the field coil is placed in the longitudinal axes;
- supplementary thin short-circuited coils D_i , Q_i are placed in the pole axes (*d*), and respectively the inter-pole axes (*q*);
- the generator sign rule for voltage and current applies to all coils.

Considering the orthogonal model of a synchronous machine (presented in Fig. 2), and taking into account that $U_D = U_Q = 0$, the general equations of the orthogonal model in rotor co-ordinates is written, as follows:

$$i_d R_s - U_d = -\frac{d\Psi_d}{dt} + \omega_r \Psi_q \;;\; i_q R_s - U_q = -\frac{d\Psi_q}{dt} - \omega_r \Psi_d$$
$$i_E R_E - U_E = -\frac{d\Psi_E}{dt},\; i_{Dj} R_{Dj} = -\frac{d\Psi_{Di}}{dt},\; i_{Qj} R_{Qj} = -\frac{d\Psi_{Qi}}{dt};\; j = 1...3 \quad (1)$$

The skin effect is considered by adding an additional short-circuit in d and q axes (D_j , Q_j ,$j = 1...3$). Also, the fluxes and currents can be determined [1], [2] taking into account saturation and by segregating the main fluxes Ψ_{dm} , Ψ_{qm} :

$$\Psi_d = L_{s\sigma} i_d + \Psi_{dm} \;;\; \Psi_q = L_{s\sigma} i_q + \Psi_{qm} \;;\Psi_E = L_{E\sigma} i_E + L_{ED\sigma}(\sum_j i_{Dj} + i_E) + \Psi_{dm}$$
$$\Psi_{Dj} = L_{Dj\sigma} i_{Dj} + L_{ED\sigma}(\sum_j i_{Dj} + i_E) + \Psi_{dm} \;;\Psi_{Qj} = L_{Qj\sigma} i_{Qj} + \Psi_{qm} \;,\; j = 1...3 \quad (2)$$

The main fluxes Ψ_{dm} , Ψ_{qm} depend on the total magnetization current i_m and its components i_{dm} , i_{qm} [1], [2]:

$$\Psi_{dm} = L_{dm}(i_m) i_{dm} \;,\; \Psi_{qm} = L_{qm}(i_m) i_{qm} \quad (3)$$

where:

$$i_{dm} = i_d + i_E + \sum_j i_{Dj} \;,\; i_{qm} = i_q + \sum_j i_{Qj} \;,\; i_m = \sqrt{i_{dm}^2 + i_{qm}^2} \;,\; j = 1...3 \quad (4)$$

The orthogonal model takes into account both saturation and skin effect, but separately (by different parameters) and provides better results when studying different dynamic and steady regimes. Thereby, in order to estimate the parameters of the orthogonal model, static experimental methods can be used, which have the advantage of being simpler, with lower costs and energy requirements.

- Tests for *current damping* in d and q axes, for determination of magnetisation curves along the two axes, and the magnetisation synchronous and differential inductivities [16], [19], [20].

- Tests using *frequency response* in d and q axes, for low currents, to determine resistances and leakage inductivities of the rotor circuit considering the skin effect [9-15], [17], [18].

These static methods used to determine the orthogonal model parameters, by time and frequency analysis, are known since 1950-1960. For example, the frequency response represents in fact a generalization of the static method for determination of supra-transient reactances (tested at rated frequency) proposed by Park and Roberson in 1928 [8].

The current variable speed drives using static converters and time command, require usage of the orthogonal model, knowing the parameters and the estimation methods, respectively.

3. Estimation the parameters of orthogonal model to synchronous machines that simulates the influence of skin effect

As it is intended to separate the saturation of the main field path from skin effect, this test is performed at low current values (approx. 15% of rated current). Also, in order to analyze separately the phenomena on both *d* and *q* axes, it is necessary to position the rotor and connect the windings in a particular way, which takes into account the relationship between the "real machine" and Park orthogonal transformation.

3.1. Estimation the parameters in *d*-axis of synchronous machine

During the experimental test, the rotor is positioned with *d*-axis along *u*-phase direction. This is achieved by connecting *v* and *w* phases in series and supplying them with AC power, while the excitation winding is short-circuited with an ammeter. The rotor is turned slowly while watching the ammeter in the excitation circuit. When the ammeter indicates zero, the right positioning is achieved.

Afterwards, *u*-phase is connected in series with phases *v* and *w,* which are in connected in parallel, while the stator circuit is supplied from a variable frequency power source (Fig. 3). The excitation circuit can be either open or short-circuited [1], [2]. The voltage, current, and phase angle or power, are acquired with a data acquisition system.

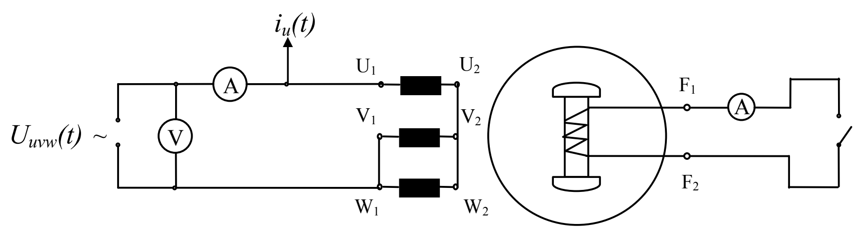


Fig. 3. Wiring scheme for estimate the skin effect influence in *d*-axis of a synchronous machine

Taking into account that the machine is at no speed, considering the general equations of the orthogonal model of the synchronous machine (1) and fluxes relations (2), (3) and (4), an equivalent circuit can be established to simulate the skin effect influence in *d*-axis (Fig. 4).

In order to simplify the calculations, the circuit excitation was considered opened, hence the inductances and resistances representing the excitation winding could be neglected. Also, two rotor circuits were used to simulate the skin effect.

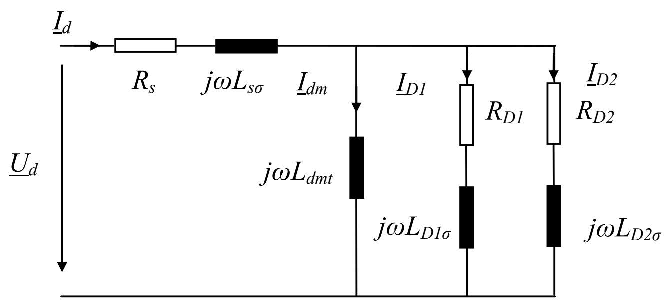


Fig. 4. Equivalent circuit in *d*-axis of a synchronous machine considering the skin effect

The equivalent impedance of the circuit in Fig. 4 can be written, as follows:

$$\underline{Z}_d(j\omega) = R_s + j\omega L_d(j\omega) = \frac{\underline{U}_d}{\underline{I}_d} \tag{5}$$

The experimental test was performed on a real machine. The relations between voltages and currents of the equivalent machine and voltages and currents of the real machine were obtained using Park transformation [1], [2]:

$$\underline{U}_d = \underline{U}_{uvw} \cdot \sqrt{2/3}\ ,\ \underline{I}_d = \underline{I}_u \cdot \sqrt{3/2}\ ,\ \frac{\underline{U}_d}{\underline{I}_d} = \frac{2 \cdot \underline{U}_{uvw}}{3 \cdot \underline{I}_u} \tag{6}$$

During this experimental test the voltage U_{uvw} and the current I_u are measured. Using relations (5) and (6), the equivalent impedance ($\underline{Z}_d(j\omega)$) and subsequently the equivalent inductance ($L_d(j\omega)$) are obtained for the entire frequency range used during the measurements. On the other hand, by resolving the equivalent circuit in Fig. 4, another equivalent impedance can be determined. This impedance depends on the time constants of the circuits that are connected in parallel and were used to model the skin effect. The time constants must be chosen in such a way the resulting equivalent impedance approximates accurately enough the equivalent impedance $\underline{Z}_d(j\omega)$ for an as wide as possible frequency range. A similar logic used for the inductance $L_d(j\omega)$ cane be done for the impedance $\underline{Z}_d(j\omega)$. Further in the paper, due to a simplification made in the approximation methods, the author will operate with inductance $L_d(j\omega)$.

a) <u>One rotor circuit model</u> ($R_{D1}, L_{D1\sigma}$)

In this case, resolving the equivalent circuit in Fig. 4, the equivalent impedance is obtained, as follows [1], [2]:

$$\underline{Z}_d = R_s + j\omega L_{s\sigma} + j\omega L_{dmt} \cdot \frac{1 + j\omega T_{1d}}{1 + j\omega T_{2d}} = R_s + j\omega(L_{s\sigma} + L_{dmt}) \cdot \frac{1 + j\omega T_{1d}}{1 + j\omega T_{2d}} \tag{7}$$

Comparing relations (5) and (7), it results:

$$L_d(j\omega) = (L_{s\sigma} + L_{dmt}) \cdot \frac{1 + j\omega T_{1d}}{1 + j\omega T_{2d}} \tag{8}$$

where T_{1d} and T_{2d} are calculation time constants written as analytic relations depending on equivalent circuit parameters in *d* axis.

Using relations (5) and (6), after some mathematical calculations, it results:

$$\underline{U}_{uvw} - (3/2) \cdot \underline{I}_u \cdot R_s = L_d(j\omega) \cdot \left[(3/2) \cdot \underline{I}_u \cdot j\omega\right] \tag{9}$$

The values of $\underline{U}_{uvw}$ and $\underline{I}_u$ are measured at different frequencies, while stator resistance R_s is obtained from measuring in DC [16].

A transfer function ($L_d(j\omega)$) that will approximate accurately the equation (9) in amplitude within a wide range of frequencies must be identified. From relation (8) it can be seen that this transfer function is first order, with unknowns: $L_{s\sigma} + L_{dmt}$; T_{1d} ; T_{2d} .

b) <u>The two rotor circuit model</u> (R_{D1} , $L_{D1\sigma}$, R_{D2} , $L_{D2\sigma}$)

Resolving the equivalent circuit (Fig. 4) the equivalent impedance is obtained [1], [2]:

$$\begin{aligned} \underline{Z}_d &= R_s + j\omega L_{s\sigma} + j\omega L_{dm} \cdot \frac{(1 + j\omega T_{1d})(1 + j\omega T_{3d})}{(1 + j\omega T_{2d})(1 + j\omega T_{4d})} = \\ & R_s + j\omega(L_{s\sigma} + L_{dmt}) \cdot \frac{(1 + j\omega T_{1d})(1 + j\omega T_{3d})}{(1 + j\omega T_{2d})(1 + j\omega T_{4d})} \end{aligned} \tag{10}$$

where T_{1d}, T_{2d}, T_{3d}, T_{4d} are calculation time constants written as analytic relations depending on equivalent circuit parameters in *d*-axis.

Using relations (5) and (10), it results:

$$L_d(j\omega) = j\omega(L_{s\sigma} + L_{dmt}) \cdot \frac{(1 + j\omega T_{1d})(1 + j\omega T_{3d})}{(1 + j\omega T_{2d})(1 + j\omega T_{4d})} \tag{11}$$

To be noted that in this case, the sought transfer function ($L_d(j\omega)$) has second order with the unknowns: $L_{s\sigma} + L_{dmt}$; T_{1d} ; T_{2d} ; T_{3d} ; T_{4d} .

3.2. Estimation the parameters in *q*-axis of synchronous machine

In this case, the rotor of machine has connected the *d*-axis which is in direction of *u*-phase. The stator windings are connected as to Fig. 5 and are supplied from a variable frequency source.

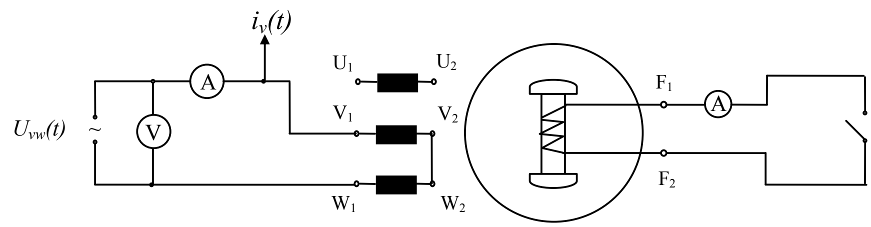


Fig. 5. Wiring diagram for estimate the skin effect influence in q-axis of a synchronous machine

The voltage, current, and either phase angle or power, are acquired with a data acquisition system. Considering that the machine is at no-speed and knowing the general equations of the orthogonal model (1) and fluxes relations (2), (3) and (4), the equivalent circuit considering the influence of the skin effect in q-axis can be obtained (Fig. 6).

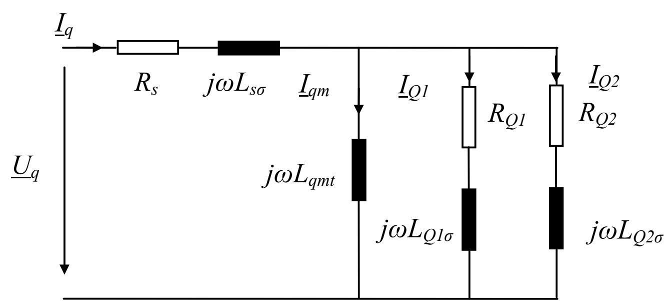


Fig. 6. Equivalent circuit of a synchronous machine in q-axis considering the skin effect

From this equivalent circuit, the equivalent impedance can be computed, as follows [1], [2]:

$$\underline{Z}_q(j\omega) = R_s + j\omega L_q(j\omega) = \frac{\underline{U}_q}{\underline{I}_q} \tag{12}$$

The relations between voltages and currents of the model and voltages and respectively the currents of the real machine, are obtained using Park transformation:

$$\underline{U}_q = \underline{U}_{vw} / \sqrt{2}\ ,\ \underline{I}_q = \underline{I}_v \cdot \sqrt{2}\ ,\ \frac{\underline{U}_q}{\underline{I}_q} = \frac{\underline{U}_{vw}}{2 \cdot \underline{I}_v} \tag{13}$$

During the experimental test the voltage U_{vw} and the current I_v are measured, and using relations (12) and (13), an equivalent impedance ($\underline{Z}_q(j\omega)$) and respectively an equivalent inductance ($L_q(j\omega)$) for the entire frequency range for which the measurements were made, are determined.

Using relations (12) and (13), after some mathematical calculations, it results:

$$\underline{U}_{vw} - 2 \cdot \underline{I}_v \cdot R_s = L_q(j\omega) \cdot \left[2 \cdot \underline{I}_v \cdot j\omega\right] \qquad (14)$$

In a similar way as for *d* axes, in will be analysed the case with one circuit in the rotor to simulate the skin effect, and respectively the case with two circuits connected in parallel. Analogous, it must be determined a transfer function that must approximate the equation (14) for the widest frequency interval. For one circuit case to simulate the eddy current effects, the transfer function is a function of first order having as unknowns: $L_{s\sigma} + L_{qmt}$; T_{1q} ; T_{2q}; in the case of using two circuits to simulate the eddy current effects, the transfer function will be of second order with the following unknowns: $L_{s\sigma} + L_{qmt}$; T_{1q} ; T_{2q} ; T_{3q} ; T_{4q}.

4. Experimental results

4.1. Equivalent circuit parameters of the synchronous machine, in *d*-axis

Experimental determinations were performed on a synchronous machine with salient poles, with rated data:

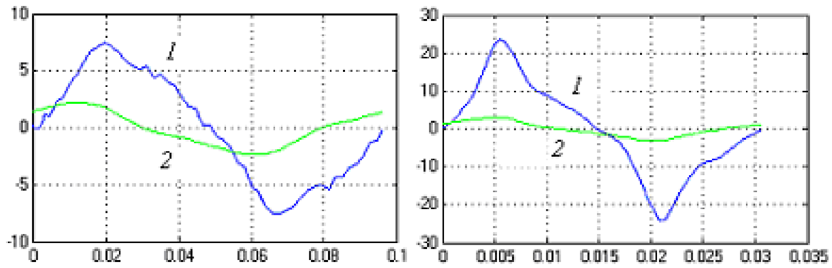
$S_n = 2500[VA]$; $U_n = 208/120[V]$; $I_n = 7/12[A]$; $U_{exn} = 120[V]$

$p = 2$; $R_s = 1.2[\Omega]$

The curves of voltage and current waves have been acquired with a grid tester with memory (Chauvin-Arnoux CA8334**).** The mathematical calculus of acquired data has been achieved using a electric scheme modelled with Matlab/Simulink [21]. There have been 50 measurements for the 10-60 Hz interval, at low voltage and current values in order to separate magnetic saturation from skin effects. The tests have been conducted with cold machine, at the environment temperature. The temperature dependency has been neglected due to low value currents and Joule effect.

Fig. 7 shows two waves of the acquired data (voltage and current) at different frequency of supplied voltage. Although the curves and not sinusoidal, the model implemented in Matlab/Simulink used only the first order (fundamental) harmonic.

The amplitude inductance $L_d(j\omega)$ variation versus frequency is plotted in Fig. 8, and was determined from measured voltage ($\underline{U}_{uvw}$) and current ($\underline{I}_u$), using the relation (9).



a) b)

Fig. 7. Voltage waveform (*curve 1*) and current waveform (*curve 2*) for:
a) $f = 10.3$ [Hz]; $U_{uvw} = 6.552$ [V]; $I_u = 2.066$ [A]
b) $f = 32.50$ [Hz]; $U_{uvw} = 16.24$ [V]; $I_u = 2.556$ [A]

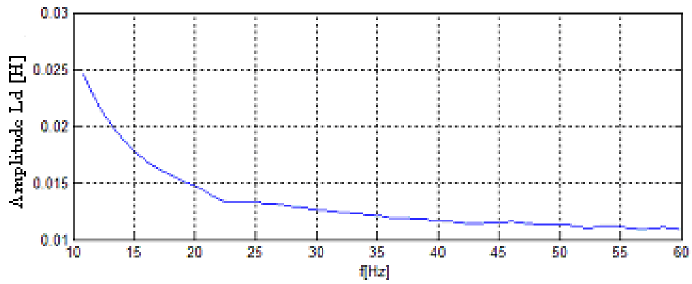


Fig. 8. Inductance amplitude variation $L_d(j\omega)$ versus frequency

Mathematical calculations and estimation of the transfer functions of first and second order were done with the help of Matlab/Simulink software, and using an estimation block (Output-error model estimator) which can determine a transfer function based on incoming and outgoing data, with minimal error. The estimator block utilises a recursive algorithm using the following equation:

$M_{out}(t) = H(z) \cdot M_{in}(t - n_k) + e(t)$,where: $M_{out}(t)$ - output value; $M_{in}(t)$ - input value; $H(z)$ - estimated transfer function; $e(t)$ - estimation error.

Taking into account relation (9) in the amplitude range, it is possible to determine the input and respectively the output values of the estimator.

$$M_{out} = \sqrt{\left[\Re e(\underline{U}_{uvw}) - (3/2) \cdot \Re e(\underline{I}_u) \cdot R_s\right]^2 + \left[\Im m(\underline{U}_{uvw}) - (3/2) \cdot \Im m(\underline{I}_u) \cdot R_s\right]^2}$$

$$M_{in} = (3/2) \cdot I_u \cdot \omega$$

When considering *one rotor circuit* (R_{D1} , $L_{D1\sigma}$) and setting up the parameters of the estimation block for a first order transfer function, after simulation, it results the following relation for inductance $L_d(j\omega)$, with estimation error shown in Fig. 9.

$$L_d(j\omega) = 0.023 \cdot \frac{1 + j\omega \cdot 0.0888}{1 + j\omega \cdot 0.1851} \tag{15}$$

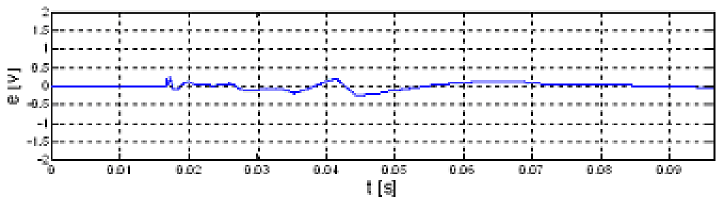


Fig. 9. Estimation error of the transfer function $L_d(j\omega)$ with two time constants

Comparing relations (8) and (15) it results:

$$L_{s\sigma} + L_{dmt} = 0.023\ ;\ T_{1d} = 0.0888\ ;\ T_{2d} = 0.1851 \tag{16}$$

The leakage inductance can be approximated with a homopolar inductance and determined as in [22], which yields $L_{s\sigma} = 0.00499[H]$. Knowing the values of the calculate time constants T_{1d} and T_{2d}, it results a system of equations with the unknowns R_{D1}, $L_{D1\sigma}$. Resolving the system it yields:

$$\begin{aligned} &R_s = 1.2[\Omega]\ ;\ L_{s\sigma} = 0.00499[H]\ ;\ L_{dmt} = 0.01801[H] \\ &R_{D1} = 0.1464[\Omega]\ ;\ L_{D1\sigma} = 0.009097[H] \end{aligned} \tag{17}$$

In case of the *two rotor circuits* ($R_{D1}, L_{D1\sigma}, R_{D2}, L_{D2\sigma}$), proceeding the same way, setting parameters for the estimation block for a second order transfer function, it results the following expression for the inductance $L_d(j\omega)$:

$$L_d(j\omega) = 0.023 \cdot \frac{(1 + j\omega \cdot 0.09226) \cdot (1 + j\omega \cdot 0.000049251)}{(1 + j\omega \cdot 0.19235) \cdot (1 + j\omega \cdot 0.000049986)} \tag{18}$$

Using relations (11) and (18), it results:

$$T_{1d} = 0.09226\ ;\ T_{3d} = 0.000049251\ ;\ T_{2d} = 0.19235\ ;\ T_{4d} = 0.000049986 \tag{19}$$

From relation (19) results a system of equations in which unknowns are the parameters of the equivalent circuit. Resolving this system the following expressions for the parameters are obtained:

$$\begin{aligned} &R_s = 1.2[\Omega]\ ;\ L_{s\sigma} = 0.00499[H]\ ;\ L_{dmt} = 0.01801[H] \\ &R_{D1} = 0.1409[\Omega]\ ;\ L_{D1\sigma} = 0.009082[H] \\ &R_{D2} = 4494.83[\Omega]\ ;\ L_{D2\sigma} = 0.2186[H] \end{aligned} \tag{20}$$

Taking into account the transfer functions (15) and (18), their amplitude versus frequency have been plotted with the help of Matlab/Simulink program (Fig. 10).

In the figure, the graphs noted with *1* correspond to the first order transfer function (eq. 15), while the graphs noted *2* correspond to the second order transfer function (eq. 18).

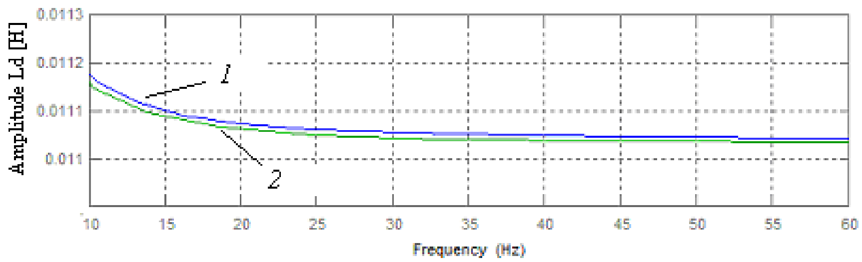


Fig. 10. Amplitude transfer function used to estimate the inductance $L_d\,(j\omega)$, versus frequency

4.2. Equivalent circuit parameters of the synchronous machine, in *q*-axis

For mathematical calculations and estimating the transfer functions of first and second order Matlab/Simulink software, and respectively an Output-error model estimator were used. The input and output functions required by the estimator were determined using relation (13), in amplitude, and they are given by:

$$M_{out} = \sqrt{\left[\Re e(\underline{U}_{vw}) - 2\cdot\Re e(\underline{I}_v)\cdot R_s\right]^2 + \left[\Im m(\underline{U}_{vw}) - 2\cdot\Im m(\underline{I}_v)\cdot R_s\right]^2}$$
$$M_{in} = 2\cdot I_v\cdot\omega \qquad (21)$$

The variation of amplitude inductance $L_q(j\omega)$ versus frequency (Fig. 11) was computed from acquired voltage ($\underline{U}_{vw}$) and current ($\underline{I}_v$) and using the relation (14).

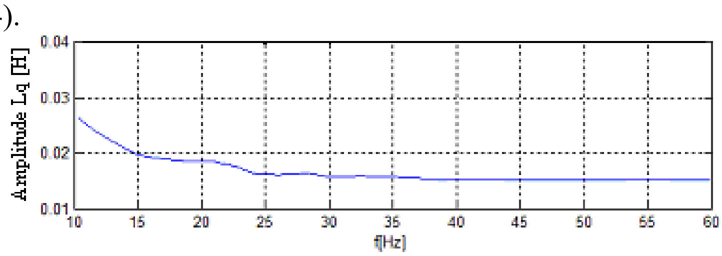


Fig. 11. Amplitude variation of inductance $L_q(j\omega)$ versus frequency

For *one rotor circuit* model (R_{Q1}, $L_{Q1\sigma}$), setting parameters for the estimation block for a first order transfer functions, after simulation, the following relation for inductance $L_q(j\omega)$ has resulted:

$$L_q(j\omega) = 0.034\cdot\frac{1 + j\omega\cdot 0.102}{1 + j\omega\cdot 0.243} \qquad (22)$$

Results:

$$L_{s\sigma} + L_{qmt} = 0.034\ ,\ T_{1q} = 0.102\ ,\ T_{2q} = 0.243 \qquad (23)$$

Based on the values obtained for the calculation time constants T_{1q} and T_{2q} it results a system of equations with unknowns $R_{Q1}, L_{Q1\sigma}$. Resolving the system, it yields:

$$R_s = 1.2[\Omega]\,;\; L_{s\sigma} = 0.00499[H]\,;\; L_{qmt} = 0.02901[H] \\ R_{Q1} = 0.1755[\Omega]\,;\; L_{Q1\sigma} = 0.01364[H] \tag{24}$$

In case of the *two rotor circuit* model ($R_{Q1}, L_{Q1\sigma}$, R_{Q2}, $L_{Q2\sigma}$), setting parameters for the estimation block for a second order transfer functions, it results the following relation for inductance $L_q(j\omega)$:

$$L_q(j\omega) = 0.034 \cdot \frac{(1 + j\omega \cdot 0.10328)\cdot(1 + j\omega \cdot 0.000049079)}{(1 + j\omega \cdot 0.24396)\cdot(1 + j\omega \cdot 0.00005001)} \tag{25}$$

Results:

$$T_{1q} = 0.10328\,;\; T_{3q} = 0.000049079\,;\; T_{2q} = 0.24396\,;\; T_{4q} = 0.00005001 \tag{26}$$

Using relations (26), a system of equations with unknowns the parameters of equivalent circuit is written. Resolving the system results:

$$R_s = 1.2[\Omega]\,;\; L_{s\sigma} = 0.00499[H]\,;\; L_{qmt} = 0.02901[H] \\ R_{Q1} = 0.1759[\Omega]\,;\; L_{Q1\sigma} = 0.01391[H] \\ R_{Q2} = 6580.98[\Omega]\,;\; L_{Q2\sigma} = 0.3197[H] \tag{27}$$

The amplitude of the transfer functions variations versus frequency (Fig. 12) are obtained considering the transfer functions (22) and (25), and using Matlab/Simulink software. In Fig. 12, the graphs marked with *1* represent the first order transfer functions (22), and the graphs marked with *2* represent the second order transfer functions (25).

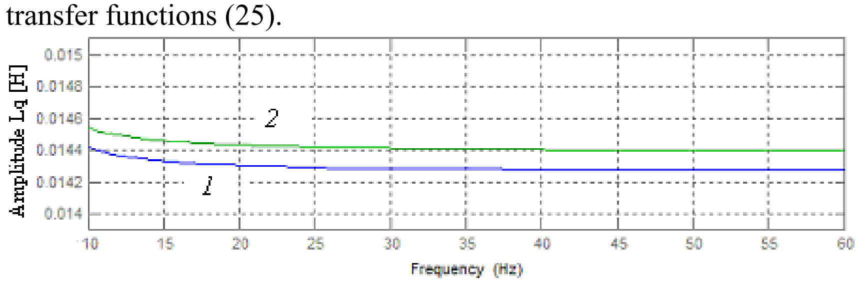


Fig. 12. Amplitude transfer function used to estimate the inductance $L_q(j\omega)$ versus frequency

4.3. Verifying results

The presented experimental method takes part of the category of methods for determining the parameters of the orthogonal, mathematical model of the synchronous machine. The literature presents the testing of machine connected to the grid at load operation, as validation tests. These tests, however, imply high costs and require powerful electric sources, especially when testing large machines. Therefore, for validation of machine parameters, it can be used the frequency response test, at load operation, obtained by overlapping an alternative component of low value and variable frequency, over a continuous voltage of main field [1-3]. This validation test has not been accomplish in this paper due to insufficient equipment, but it represents a future priority for the author.

Nevertheless, a validation of the estimated results can be achieved, as shown in chapter 2, the frequency response test being a generalisation of the static methods for determination of the supra-transient reactances at rated frequency [8]. On the other hand, the inductances $L_d(j\omega)$ and $L_q(j\omega)$, and their respective reactances, can be computed for one or two circuits (chapter 4) at 50 Hz frequency, using relations (15), (18), (22), (25).

It must be mentioned that for the frequency response test, in order to simplify the calculation, the excitation circuit was considered open. Taking this into account, and for being able to make a comparison between results, during the static method for determining the supra-transient reactances, the excitation circuit was kept open. Therefore, the obtained reactances are not the ones known in literature; he current reactances being noted with $X_d^{'0}$ and $X_q^{'0}$ respectively. The static method was used to determine the supra-transient reactances [23] at the same value of currents and environment temperature, as for the frequency response test. Obtained results are presented in *Table 1*.

Tabelul 1

Reactance $X_d^{'0}$, $X_q^{'0}$ and reactance estimated by frequency response test

$X_d^{'0}$ [Ω]	X_d [Ω] with one circuit	X_d [Ω] with two circuit	$X_q^{'0}$ [Ω]	X_q [Ω] with one circuit	X_q [Ω] with two circuit
3.57	3.46	3.47	4.76	4.48	4.52

5. Conclusions

Taking into account the experimental tests for determining the parameters of the orthogonal mathematical model of the synchronous machine that considers the eddy current effects, and as presented in the previous chapters and analysing the obtained results, the following conclusions can be drawn:

- The estimation method is a static method and can be achieve relatively easy, with reduced costs, being useful for large and very large machines. The method can be used without affecting the driving system connected to the machine.

- The original elements of this paper consists in providing clear algorithms for the estimation method, utilises special numerical estimators in Matlab/Simulink that serve to determine the parameters that take into account the skin effect with reduced errors and computation time. Depending on desired accuracy, it can be used one, two or more circuits to simulate the eddy current effects, obtaining simpler or more complex equivalent schemes.
- Analysing graphics plotted in Fig. 10 and Fig.12, taking into account relations (18) and (25), it can be noticed that the influence of the second simulation circuit is small, especially for the frequency range used for testing the machine. Therefore, using the machine in the range of 10-60 Hz, simulating the skin effects in *d* and *q* axes can be achieved with sufficient accuracy with only one circuit, thus simplifying significantly the equivalent scheme.
- Comparing the graphics in Fig. 8 and Fig. 10, and in Fig. 11 and Fig.11, respectively, it can be noticed that there are errors between the measured and computed characteristics, errors obtained mainly due to the relatively reduced number of experimental determinations and limited frequency range. Reducing errors can be achieved by conducting as many data readings within a widest frequency range possible.
- It must be mentioned the necessity of results validation by a frequency response test, at load operation, a test that consists a priority research theme for the future that will be presented in a subsequent paper. Nevertheless, the verification, even punctual, of results (*Table 1*) provides the hope in confirmation of the method.
- Determining the AC electrical machines parameters is a continuously growing preoccupation as the measurement and computing equipment becomes increasingly efficient [23 – 25].

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