

USING DC DECAY TESTS FOR DETERMINING THE MAGNETIZATION PARAMETERS OF THE AC ELECTRICAL MACHINES

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The paper presents the use of a static experimental method (DC decay test) for determining the magnetization parameters of AC electrical machines. The magnetization characteristics, synchronous and differential magnetization inductances as functions of the total magnetizing current, were determined for two types of synchronous machines and an induction machine, respectively. The orthogonal d - q mathematical model in rotor coordinates was used, and the calculations were performed using MATLAB-Simulink. For the experimental tests, high-performance professional measuring devices were used.

1. INTRODUCTION

Static experimental methods are frequently used to determine the parameters of electrical machines because they offer real advantages, including ease of practical implementation, low cost, low energy consumption, and immunity to the system in which the machine is integrated [1–8].

On the other hand, the analysis of electrical machine operation involves the use of mathematical models that include the equations of the machine's electrical circuits and, respectively, the equations of motion of the electrical drive system.

Mathematical models can be in phase coordinates or in orthogonal axes. Mathematical models in phase coordinates consider the real machine, the parameters being variable in time with respect to the rotor position, and solving the equations is easy only in symmetrical regimes and at constant speed. Mathematical models in orthogonal axes, with an optimal positioning of the axes, for the different types of machines and, respectively, operating regimes, can provide considerable simplifications in solving the equations and determining the parameters of the electrical machine [9].

Also, in many cases, the machine parameters are considered constant. However, for a correct analysis of the operation of electrical machines, one cannot neglect an electromagnetic phenomenon that frequently manifests itself in different operating regimes, namely, magnetic saturation. Magnetic saturation can be accounted for by treating magnetization as a variable inductance [9,10]. At the same time, for the most accurate determination of the parameters, various analytical, numerical, and experimental methods can be used [11–14].

Numerical methods used for electromagnetic field computation provide precise results but require exact knowledge of the materials used and the constructive geometric dimensions of the machine, information that is not always accessible [15–17].

Therefore, certain experimental methods are used, among which DC decay tests can be noted, tests that present the advantages mentioned above.

DC decay tests, used in this paper, allow the determination of magnetization characteristics, synchronous and differential magnetization inductances as a function of the total magnetization current, thus highlighting the phenomenon of magnetic saturation.

2. AC ELECTRICAL MACHINES MATHEMATICAL MODEL

2.1 SYNCHRONOUS MACHINE

The real synchronous machine is provided in the stator

with a three-phase symmetric winding system and in the rotor with a field winding and a damping cage, respectively. The damping cage is decomposed into two fictitious components along the d -axis and along the q -axis.

In the case of the d - q mathematical model, the three-phase winding system of the synchronous machine is replaced with two windings located on the orthogonal axes d and q .

Through the Park transformation, the relations between the quantities of the real synchronous machine and the quantities of the orthogonal mathematical model are obtained. The general equations of the orthogonal mathematical model of the synchronous machine with one cage after each axis, in rotor coordinates, are the following [1–3]:

$$i_d R_s + U_d = -\frac{d\Psi_d}{dt} + \omega_r \Psi_q, \quad (1)$$

$$i_q R_s + U_q = -\frac{d\Psi_q}{dt} - \omega_r \Psi_d, \quad (2)$$

$$i_E R_E - U_E = -\frac{d\Psi_E}{dt}, \quad (3)$$

$$i_D R_D = -\frac{d\Psi_D}{dt}; \quad i_Q R_Q = -\frac{d\Psi_Q}{dt}, \quad (4)$$

where: $i_d, i_q, i_E, i_D, i_Q, U_d, U_q, U_E, \Psi_d, \Psi_q, \Psi_E, \Psi_D, \Psi_Q$ represent the currents, the voltages and the magnetic fluxes corresponding to the d - q mathematical model; R_s – stator winding resistance per phase; R_E – field circuit resistance; ω_r – angular speed of the rotor.

On the other hand, the relations between fluxes and currents are also considered [1–3,10]:

$$\Psi_d = L_{s\sigma} i_d + \Psi_{dm}; \quad \Psi_q = L_{s\sigma} i_q + \Psi_{qm},$$

$$\Psi_E = L_{E\sigma} i_E + \Psi_{dm}; \quad \Psi_D = L_{D\sigma} i_D + \Psi_{dm}, \quad (5)$$

$$\Psi_Q = L_{Q\sigma} i_Q + \Psi_{qm},$$

where: Ψ_{dm} and Ψ_{qm} represent the components along d and q axes of the main magnetic flux; $L_{s\sigma}$ is the leakage inductance of the stator winding; $L_{E\sigma}, L_{D\sigma}, L_{Q\sigma}$ are the leakage inductances of the field circuit and of the D and Q circuits corresponding to the damping cage.

Optimal consideration of magnetic saturation can be achieved by defining the magnetization characteristics (corresponding to the d and q axes) as the dependence of the main magnetizing magnetic fluxes on the total magnetizing current of the machine [1–3,10],

$$\Phi_{dm}(i_m); \quad \Phi_{qm}(i_m); \quad i_m = \sqrt{i_{dm}^2 + i_{qm}^2} \quad (6)$$

where:

$$i_{dm} = i_d + i_D + i_E; \quad i_{qm} = i_q + i_Q \quad (7)$$

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Considering the previously defined magnetization characteristics, the components of the main magnetic flux are determined by introducing two new inductances [1–3,10]:

$$\begin{aligned} \Psi_{dm} &= \frac{\Phi_{dm}(i_m)}{i_m} \cdot i_{dm}; L_{dm}(i_m) = \frac{\Phi_{dm}(i_m)}{i_m}, \\ \Psi_{qm} &= \frac{\Phi_{qm}(i_m)}{i_m} \cdot i_{qm}; L_{qm}(i_m) = \frac{\Phi_{qm}(i_m)}{i_m}. \end{aligned} \quad (8)$$

At the same time, for the most accurate consideration of electromagnetic phenomena in transient regimes, differential magnetization inductances can also be considered [1-3, 10]:

$$L_{dm(dif)}(i_m) = \frac{d\Phi_{dm}(i_m)}{di_m}; L_{qm(dif)}(i_m) = \frac{d\Phi_{qm}(i_m)}{di_m} \quad (9)$$

2.2 INDUCTION MACHINE

The induction machine is provided with a three-phase symmetric winding system in the stator and a squirrel-cage winding (short-circuited rotor) or a three-phase winding (wound rotor) in the rotor. The rotor cage can be equivalent, in the general case, to a symmetrical three-phase winding. The equivalence between the real machine and the orthogonal model is achieved by using the Park transformation applied to the stator and the rotor.

The equations of the orthogonal mathematical model of the induction machine are like those of the synchronous machine, excluding the field circuit. Equations (1), (2), and (4) are considered. Also, the relations between fluxes and currents are similar. And in the case of the induction machine, optimal consideration of magnetic saturation can be achieved by defining the magnetization characteristics (corresponding to the d and q axes) as the dependence of the main magnetizing magnetic fluxes on the total magnetizing current of the machine. Thus, it considers the relation (6) in which:

$$i_{dm} = i_d + i_D; i_{qm} = i_q + i_Q. \quad (10)$$

Also, as in the case of the synchronous machine, the synchronous and differential magnetizing inductances are considered dependent on the total magnetizing current relations (8) and (9). It should be mentioned that, in general, the induction machine presents geometric symmetry; thus, the two magnetization curves, defined for the two axes, as well as the inductivities mentioned above, can be considered identical.

3. DETERMINATION OF MAGNETIZATION PARAMETERS THROUGH DC DECAY TESTS

3.1 SYNCHRONOUS MACHINE

The DC decay tests require that the rotor of the machine be positioned so that the d -axis is aligned with phase U. For this, the windings of phases V and W are connected in series and supplied with a reduced AC voltage. The field circuit is short-circuited by means of an ammeter, and the rotor is driven slowly, following the ammeter indication. When the ammeter indicates zero, the positioning is completed.

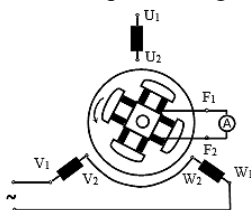


Fig. 1 – Synchronous machine: rotor positioning for DC decay tests.

3.1.1 DETERMINATION OF MAGNETIZATION PARAMETERS IN THE LONGITUDINAL AXIS (D)

To perform d -axis DC decay tests, the U phase winding is connected in series with the V and W phase winding, which are connected in parallel.

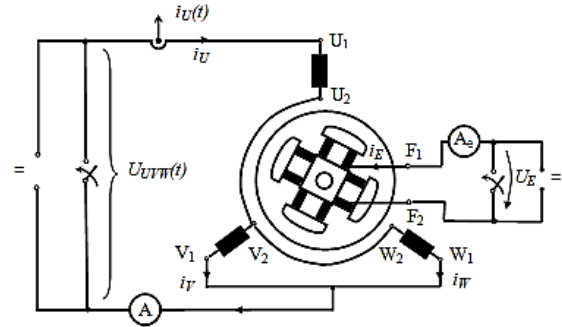


Fig. 2 – Synchronous machine: connecting the windings for the d -axis DC decay test

To perform the test, the field circuit and the stator circuit are supplied with DC at the specified values I_{E0} , I_{U0} . The stator circuit is short-circuited, the field circuit remains connected, and the stator current is acquired. Considering the connection mode of the stator windings results $i_V = i_W = i_U/2$. Using the Park transformation, under static conditions ($\theta=0$) results in the following relations [1–3]:

$$\begin{aligned} i_d &= \sqrt{3/2} \cdot i_U; U_d = U_{UVW} \cdot \sqrt{2/3}, \\ i_q &= 0; U_q = 0. \end{aligned} \quad (11)$$

From eq. (1) of the orthogonal mathematical model for the static-state ($\omega_r=0$) and the realization of the short-circuit ($U_{UVW} = 0$), results in the equation corresponding to the d -axis of the stator circuit:

$$i_d R_s = -\frac{d\Psi_d}{dt}. \quad (12)$$

If is integrate the previous equation and use the relations between fluxes and currents as well as relations (5) – (8) and relation (11), respectively, after performing some mathematical calculations, result a mathematical relation for the magnetization characteristic in the d -axis and for the total magnetization current [1–3]:

$$\Phi_{dm} = \sqrt{3/2} \cdot \left(R_s \cdot \int_0^{t \rightarrow \infty} i_U dt - L_{s\sigma} I_{U0} \right) + (\Phi_{dm})_f \quad (13)$$

$$i_m = \sqrt{3/2} \cdot I_{U0} + I_E. \quad (14)$$

The quantities in previous relations are known or can be determined. Thus, the stator winding resistance (R_s) can be determined by measurement in DC current and the leakage inductance ($L_{s\sigma}$) can be approximated by the homopolar inductance. The quantity $\int_0^{t \rightarrow \infty} i_U dt$ is determined from the current decay characteristic. $(\Phi_{dm})_f$ represents the final flux produced by the field circuit alone. This flux, produced exclusively by the field circuit, can be determined from a DC decay test of the field current with the stator circuit open by acquiring the voltage obtained at the winding stator. In this case, the eq. (1) becomes [1–3]:

$$U_d = -\frac{d\Psi_d}{dt}. \quad (15)$$

Integrating this equation and using relations (5) – (8) and

(11) yields

$$(\Phi_{dm})_f = \sqrt{2/3} \cdot \int_0^{t \rightarrow \infty} U_{UVW} dt. \quad (16)$$

From relations (13) and (16) result the expression of the longitudinal magnetization characteristic (d -axis):

$$\Phi_{dm} = \sqrt{3/2} \cdot \left(R_s \cdot \int_0^{t \rightarrow \infty} i_U dt - L_{s\sigma} I_{U0} \right) + \sqrt{2/3} \cdot \int_0^{t \rightarrow \infty} U_{UVW} dt \quad (16)$$

On the other hand, from relations (8), (9), (14) and (16) one can determine the synchronous magnetizing inductance (L_{dm}) and the differential magnetizing inductance ($L_{dm}(dif)$) respectively, depending on the total magnetizing current (i_m).

3.1.2 DETERMINATION OF MAGNETIZATION PARAMETERS IN THE TRANSVERSAL AXIS (q)

To perform these tests, the rotor is positioned with the d -axis in line with the U phase, and the V and W phase windings are connected in series (Fig. 3).

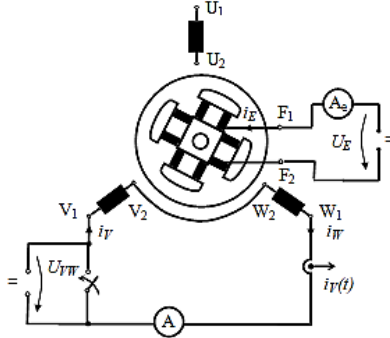


Fig. 3 – Synchronous machine: connecting the windings for the q -axis DC decay test.

The stator circuit and the field circuit are supplied with DC at the value I_{V0} , I_{E0} that the stator circuit is short-circuited, and the stator current is acquired.

Using the Park transformation, under static conditions ($\theta=0$), and considering the connection mode of the stator windings, for which $i_U = 0$, $i_V = -i_W$ result the following relations [1-3]:

$$\begin{aligned} i_q &= \sqrt{2} \cdot i_V; U_q = U_{VW} / \sqrt{2} \\ i_d &= 0; U_d = 0 \end{aligned} \quad (17)$$

If the stator circuit is short-circuited ($U_{VW} = 0$) with the machine at static-state ($\omega_r = 0$), the equation corresponding to the q -axis will result:

$$i_q R_s = -\frac{d\Psi_q}{dt}. \quad (18)$$

The integration of this relation and using the relations (5) to (8) and (17) respectively, yields the mathematical expression of the magnetization characteristic in the q -axis and the expression of the total magnetization current:

$$\Phi_{qm} = \left(R_s \cdot \int_0^{t \rightarrow \infty} i_V dt - L_{s\sigma} I_{V0} \right) \cdot \sqrt{\left(I_{E0} / I_{V0} \right)^2 + 2}, \quad (19)$$

$$i_m = \sqrt{I_{E0}^2 + 2 \cdot I_{V0}^2}. \quad (20)$$

The quantities in the previous relations are known or can be

determined and $\int_0^{t \rightarrow \infty} i_V dt$ are determined from the decay stator current characteristic. Also, using the relations (8), (9), (19) and (20) it determines the synchronous magnetizing inductance (L_{qm}) and the differential magnetizing inductance ($L_{qm}(dif)$) depending on the total magnetizing current (i_m) [1–3].

3.2 INDUCTION MACHINE

To perform DC decay tests experimentally, the machine will be in a static state, the stator windings V and W are connected in series, and supplied with DC. The stator circuit is short-circuited, and the current is acquired. Given the geometric symmetry of the rotor of the induction machine, in this case, it is not necessary to position the rotor. In this regard, the calculations and experimental determinations will be performed, for example, on the q -axis.

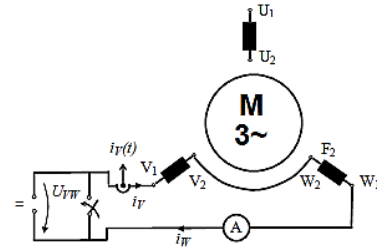


Fig. 4 – Induction machine: connecting the windings for the q -axis DC decay test.

Considering the orthogonal mathematical model of the induction machine, presented in the previous section, as well as the previous mentions, an analogy with the synchronous machine can be considered, namely, the determinations for the q -axis.

Thus, to determine the magnetization characteristic, the synchronous and differential magnetization inductance, respectively, the following relations are used: (8), (9), (19) and (20), with mention that, in this case $I_E = 0$.

4. EXPERIMENTAL RESULTS

The experimental tests were performed for two synchronous machines and one induction machine.

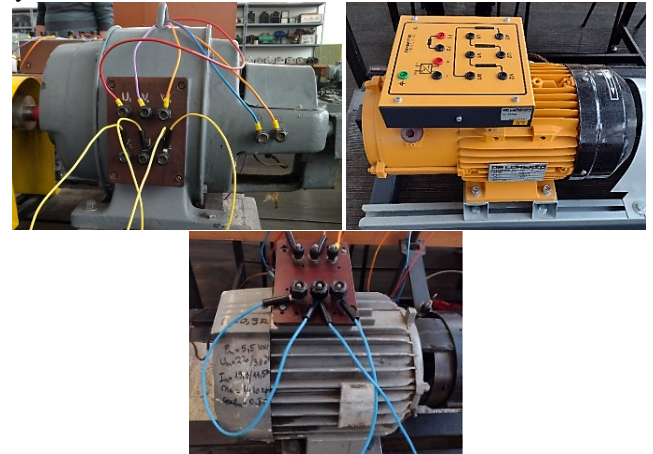


Fig. 5 – Electrical machines studied.

The rated data of the electrical machines used are as follows.

Synchronous machine 1: $S_n = 2500$ VA, $U_n = 208/120$ V, $I_n = 7/12$ A, $n_n = 1500$ rpm, $U_{en} = 110$ V, $I_{en} = 2.5$ A, $\cos\phi_n = 0.7$, $f_n = 50$ Hz, $p = 2$, salient poles.

Synchronous machine 2: $S_n = 2400$ VA, $U_n = 220/380$ V, $I_n = 6.3/3.65$ A, $n_n = 1500$ rpm, $U_{en} = 120$ V, $I_{en} = 2.5$ A, $\cos\phi_n = 1$, $f_n = 50$ Hz, $p = 2$, *round-rotor*.

Induction machine: $P_n = 5500$ [W]; $U_n = 220/380$ V; $I_n = 19.9/11.5$ A; $n_n = 1410$ rpm; $\cos\phi_n = 0.85$.

Also, in Fig. 7, the wire diagrams used to perform experimental tests are presented. It should be noted that the DC decay tests involve short-circuiting the stator and field circuits, respectively. In this regard, to perform these tests, a DC generator with shunt excitation is used as a DC source, as this type of generator allows a short circuit to be created at its terminals.

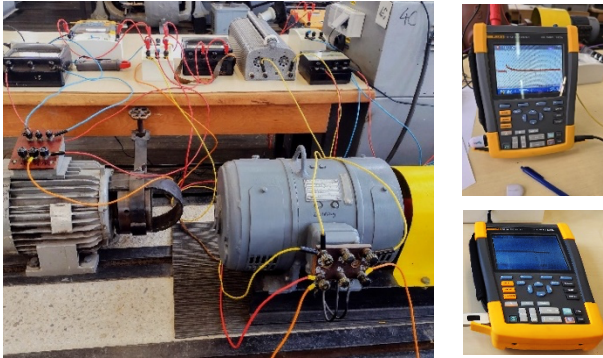


Fig. 6 – Photo of the experimental testing platform

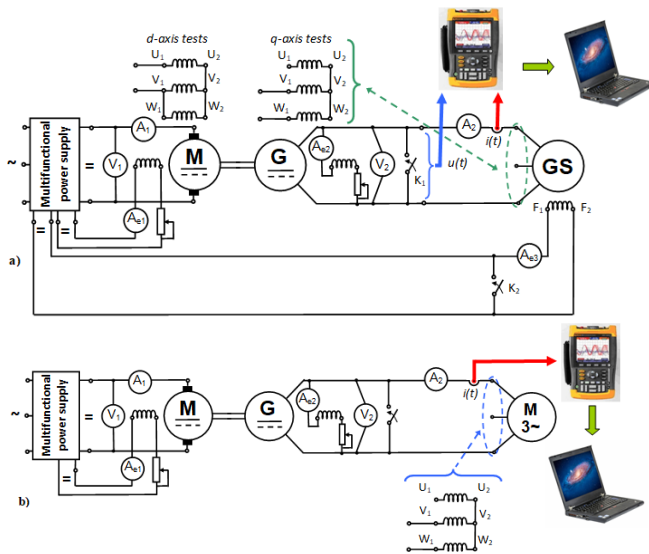


Fig. 7 – The wire diagrams used to perform DC decay experimental tests: a) for a synchronous machine; b) for an induction machine.

A memory oscilloscope (FLUKE 190-102 ScopeMeter 100 MHz 2-Channel Handheld Oscilloscope 1.25 GS/s) was used to acquire the current and voltage decay curves. Mathematical calculations were performed using the MATLAB-Simulink program. The following presents the experimental tests and the results obtained for the studied electric machines.

4.1 SYNCHRONOUS MACHINE

It should be mentioned that *synchronous machine 1* has salient poles, so that experimental determinations were made for both d and q axes. *Synchronous machine 2* has a round rotor, presenting a geometric symmetry of the rotor, and the parameters on the two axes coincide. Thus, for this machine, determinations were made only for one axis, namely the q -axis.

As mentioned in the previous section, to determine the magnetization parameters of the synchronous machine, the

phase resistance of the stator winding (R_s) and the leakage inductance ($L_{s\sigma}$) must be known. Thus, the phase resistance of the stator winding was also determined by DC measurement, resulting in the value:

Synchronous machine 1: $R_s = 1 \Omega$

Synchronous machine 2: $R_s = 2.4 \Omega$

On the other hand, the stator winding leakage inductance must also be determined. This inductance can be approximated by the homopolar inductance, and the homopolar inductance can be determined experimentally.

Homopolar resistance and reactance are considered when the phases of the stator winding are traversed by a homopolar system of currents, currents that determine a null useful magnetic field in the air gap. In this case, the homopolar sequence currents produce only leakage magnetic fields [18,19]. For the experimental determination of these homopolar parameters, the single-phase power supply method can be used by connecting the stator windings in series. Also, for this test, the machine is driven at synchronous speed, and the field circuit is open. The stator winding is supplied with voltage U_0 and the current I_0 , and the absorbed power P_0 is measured [18,19].

Having these known quantities, the following are determined: resistance, impedance, reactance, and homopolar inductance, resulting in these values:

Synchronous machine 1: $Z_0 = 1.196 \Omega$; $R_0 = 1.192 \Omega$; $X_0 = 1.588 \Omega$; $L_0 = 0.00505$ H. So, the resistance of the phase stator winding will have the value $R_s = 1 \Omega$, and the leakage inductance will be $L_{s\sigma} = 0.00505$ H.

Synchronous machine 2: $Z_0 = 6.23 \Omega$; $R_0 = 2.643 \Omega$; $X_0 = 5.642 \Omega$; $L_0 = 0.01795$ H. The result is that the resistance of the phase stator winding will have the value $R_s = 2.4 \Omega$, and the leakage inductance is $L_{s\sigma} = 0.01795$ H.

4.1.1 DETERMINATION OF MAGNETIZATION PARAMETERS FOR THE D -AXIS - RESULTS

As mentioned in the previous section, the stator circuit is short-circuited when the field circuit is supplied, and the stator current decay curve is acquired. On the other hand, the decay of the voltage appearing in the stator circuit is obtained through the field current decay tests with the stator circuit open.

Having determined these quantities, the magnetic flux produced by the field circuit alone can be calculated, and the longitudinal magnetization characteristic, as well as the synchronous and differential magnetization inductances, can be determined using the relations mentioned in subsection 3.1.1.

These steps are repeated for different values of the stator current and, respectively, the field current, in increasing order.

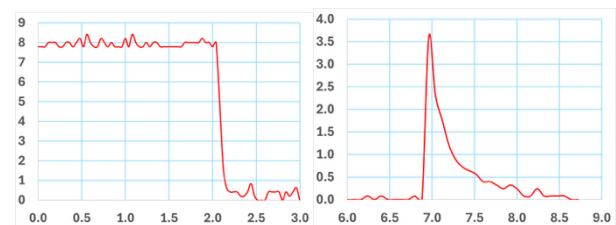


Fig. 8 – Synchronous machine 1: curve of current and voltage decay for $I_{L0} = 8$ A and $I_{E0} = 2.5$ A.

Thus, the longitudinal magnetization characteristic, the synchronous inductance, and the differential magnetization inductance are obtained in tabular form or graphically represented.

For *synchronous machine 1*, Fig. 8 shows the acquisition of the stator current decay and the voltage decay at the stator

winding terminals for a particular value of the stator current and the field current, respectively.

Figure 9 shows the magnetization characteristic, synchronous inductance, and differential magnetization inductance as functions of the total magnetization current.

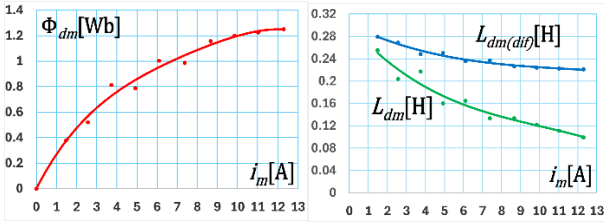


Fig. 9 – Synchronous machine 1: magnetization characteristic in the d -axis and the variation of synchronous and differential magnetization inductances.

4.1.2 DETERMINATION OF MAGNETIZATION PARAMETERS FOR THE Q -AXIS - RESULTS

The stator circuit is short-circuited, the field circuit is supplied, and the stator current is acquired.

Thus, by applying the procedure and relations presented in subsection 3.1.2, the magnetization characteristic in the q -axis and, respectively, the synchronous inductance and the differential magnetization inductance are obtained.

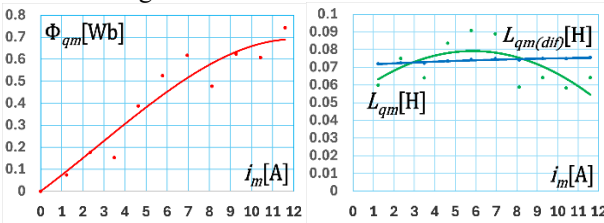


Fig. 10 – Synchronous machine 1: magnetization characteristic in the q -axis and the variation of synchronous and differential magnetization inductances.

Analyzing the results presented in the previous graphs, it can be observed that *synchronous machine 1* (with salient poles) exhibits saturated magnetization in the d -axis and unsaturated magnetization in the q -axis. This was expected because the machine has only four salient poles and the interpolar zone is significant. Also, a pronounced variation of the synchronous and differential magnetization inductance in the d -axis and a small variation in the q -axis is observed.

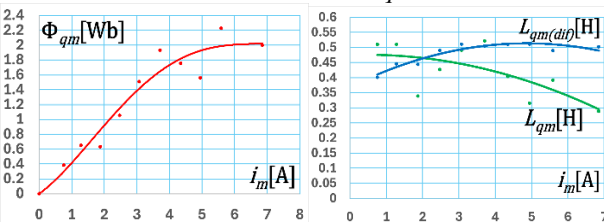


Fig. 11 – Synchronous machine 2: magnetization characteristic in the q -axis and the variation of synchronous and differential magnetization inductances

In the case of *synchronous machine 2* (with round-rotor), the magnetization characteristic saturates quickly, and the synchronous and differential magnetization inductances show a pronounced variation.

4.2 INDUCTION MACHINE

Considering the specifications in subsection 3.2, for the induction machine, experimental determinations are made only for the q -axis by applying the procedure presented for the synchronous machine.

It should also be mentioned that the phase stator winding

resistance (R_s) and the leakage inductance ($L_{s\sigma}$) must be known. The phase resistance of the stator winding was also determined by DC measurement, resulting in the value: $R_s = 1 \Omega$. At the same time, the leakage inductance of the stator winding can be determined experimentally from the short-circuit operation test [18, 19]. From this experimental test, the following was obtained: $L_{s\sigma} = 0.007135$ H.

Considering the previous mentions, the following results were obtained from the experimental tests.

Thus, the following figure shows the magnetization characteristic as well as the synchronous and differential magnetization inductances as a function of the total magnetization current.

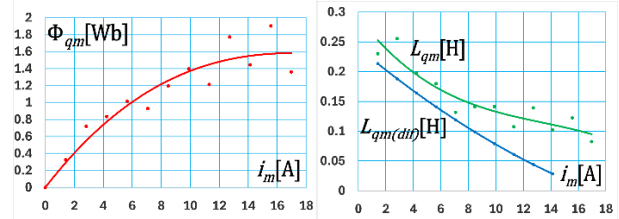


Fig. 12 – Induction machine: magnetization characteristic in the q -axis and the variation of synchronous and differential magnetization inductances.

The induction machine has a magnetization characteristic that saturates at a total magnetization current of approximately 16 A (approximately the rated current), and the synchronous and differential magnetization inductances show a significant variation.

5. DICUTIONS

Understanding and determining the parameters of electrical machines is of interest because precise knowledge ensures optimal use in electrical drives and energy systems, as well as accurate numerical modeling.

Analytical methods, numerical methods, and experimental methods can be used to determine the parameters. Analytical methods involve laborious calculations, and the results are not always appropriate. Numerical methods provide precise results but require exact knowledge of the materials used and the constructive geometric dimensions of the machine.

Thus, experimental methods represent a solution. In this regard, many experimental methods for determining parameters are presented in specialized literature and applied in practice.

Two categories of methods can be distinguished: with the machine in a rotating state and with the machine in a static state.

On the other hand, in the case of the synchronous machine, the experimental methods generally fall into three categories: determining the reactances by separately AC supplying the winding, determining the reactances and time constants from the oscillograms of the transient regimes, and determining the reactances from the characteristics of the stabilized regimes.

Some parameters can be determined by several methods; other parameters can be determined only by certain methods. When possible, methods that are simple and provide appropriate precision are preferred. On the other hand, the sudden short-circuit test, which can determine the subtransient, transient, and steady-state parameters, can negatively affect the electric machine.

The static methods are distinguished by many advantages: easy to implement, low-cost and low-energy consumption, do not require detailed geometric or material data for the machine, and do not affect the system in which the machine is integrated. In this regard, two static methods (DC decay tests and frequency response tests) are preferred in the case of high-power

machines. However, in industrial applications of DC decay tests, the results are less accurate, and the phenomenon of magnetic saturation is usually not detected, because the tests are performed at low-current values. Also, in the case of these high-power machines, rotor positioning is difficult.

6. CONCLUSIONS

In this paper, DC decay tests are applied to determine the characteristics and magnetization parameters for two synchronous machines (with salient poles and with round-rotor) and an induction machine.

DC decay tests fall into the category of static methods for determining parameters, methods that stand out for several advantages.

These tests are generally known, but the paper explicitly and coherently presents both the theoretical foundations and the experimental implementation steps. The winding connection diagrams as well as the wire diagrams are presented in detail. Thus, the paper has important practical relevance in the domain of electrical machine engineering.

The magnetization characteristics are determined as a function of the total magnetization current, highlighting the phenomenon of magnetic saturation accordingly.

Also, the synchronous magnetizing inductances (considered constants in many cases) are determined as functions of the total magnetizing current, and the differential magnetizing inductances are also considered and determined.

All this leads to a more precise image of the parameters of the electrical machines studied, providing important results for modeling, simulation, use, and control of AC electrical machines.

Although low-power electrical machines were used in this paper, static methods are usually used for high-power machines; the results obtained confirm and support the validity of the methods used.

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