

Full Length Research paper

Modelling and simulation of electrical machines on the basis of experimental frequency response characteristics

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The mathematical models of the Asynchronous Electrical machines developed on the basis of the experimental frequency-response characteristics are proposed in this paper. The latter ones are recommended for investigating the transient processes occurring at short-circuits and connections of the electrical machines to the bus bars of electrical system taking into account of their rotor speed changes.

Key words: Asynchronous machines, frequency-response, networks connections short-circuit.

INTRODUCTION

Methods of frequency-response characteristics have received wide acceptance in the scientific-research and engineering practical activity for investigating and evaluating the transient conditions of the AC machines in electrical systems (Khemliche et al., 2004; Shiqin et al., 2008; Canay, 1994). These methods make possible to carry out the direct application of the experimental initial data in the form of frequency-response characteristics of the separate electrical system elements or of the system as a whole. Such approach, in some special cases when the system internal structure is indeterminate, has much potential for yielding the more precise calculations of the transient processes.

The calculation technique for determining the transients by the use of the frequency-response characteristics of synchronous machine stator admittance in the direct, $Y_d(js)$, and quadrature, $Y_q(js)$, axes or the circle diagram of an induction motor was proposed in (Khemliche et al., 2004; Shiqin et al., 2008; Liuchen, 1996; Guha and Kar, 2006). The graphic-analytical methods for determining the armature current and electromagnetic torque of the synchronous machine were developed in the cited monograph too. The methods being considered allow carrying out more accurate calculations of the transient processes taking into account the following characteristic features:

- Electromagnetic asymmetry of the rotor;

- Representation of the turbogenerator solid rotor by means of the equivalent circuits corresponding to the high order transfer function of the damper system;
- Current displacement in the windings of electrical machines;
- Saturation phenomenon in the main and leakage paths of the magnetic fluxes of the AC machines;
- External impedance inserted in the armature winding of the AC machine.

Methods of frequency-response characteristics did not get wide dissemination in due course though. In fact, the great amount of information on the frequency-response characteristics of the synchronous machines and induction motors compiled by now and availability of the developed method designed for synthesizing the equivalent circuits adequately reflecting the initial frequency-response characteristics of the AC electrical machines open up fresh opportunities for improving and further development of the frequency-response methods for investigating the transients in electrical machines.

The objective of this paper is to develop the mathematical models of the asynchronous machines based on the experimental frequency-response characteristics for investigating the transients at short-circuits and connections of the AC machines in electrical system taking into consideration the occurring speed changes of the AC machine rotor.

BASIC RELATIONS

The mathematical relations realizing the graphic-analytical approach (Khemliche et al., 2004; Shiqin et al., 2008; Liuchen, 1996) to determine the components of the stator phase current and electromagnetic torque at short-circuits or connections of the synchronous machines rotating at the synchronous speed to the electrical system are obtained in (Burakov and Arkkio, 2007; Lam and Yee, 1998; Arjona and MacDonald, 1999; Houdouin and Gilles, 2004). When the machine with the rotor asymmetry operates at the short-circuit with the speed changes relative to the synchronous speed or it is connected to the network at the given slip, determining the components of the generalized stator current vector is carried out in the following way:

We find the average value of the steady-state current $I_{s0_{av}}$ for the s at the first instant of the transient process:

$$I_{s0_{av}} = Y_{av}(js)_{s0} \quad (1)$$

Where

$$Y_{av}(js) = \frac{Y_d(js) + Y_q(js)}{2}$$

We determine the pulsating component of the steady-state current

$$\Delta I_{s0} = (R_e[\Delta Y(js)_{s0}] - j \cdot \text{Im}[\Delta Y(js)_{s0}]) e^{-j2\delta_0} \quad (2)$$

Where

$$\Delta Y(js) = \frac{Y_d(js) + Y_q(js)}{2}, \quad \delta_0 = \text{angle between}$$

The q-axis of the rotor and the voltage vector at the infinite bus of an electrical system; We find the changes in the steady-state current with time, taking into account the difference in the rotor parameters on axes of its electrical and magnetic symmetry,

$$I_{S0}(t) = (I_{S0_{av}} + \Delta I_{S0} e^{-j2st}) \cdot e^{j\omega t} \quad (3)$$

We determine the aperiodic current component

$$I_{S1_{av}} = Y_{av}(js)_{-(1-s)} \quad (4)$$

And the periodic current of the frequency close to the doubled one

$$\Delta I_{S1} = (\text{Re}[\Delta Y(js)_{-(1-s)}] + j \cdot \text{Im}[\Delta Y(js)_{-(1-s)}]) e^{-j2\delta_0} \quad (5)$$

Aperiodic current and the current component caused by the rotor asymmetry are changed in accordance with the

following expression

$$I_{S1}(t) = -[I_{S1_{av}} \cdot e^{j\omega_n \omega t} - \Delta I_{S1} \cdot e^{-j2(1-s-\omega_n)\omega t}] e^{-t/\tau_a} \quad (6)$$

The natural angular frequency of the aperiodic current vector, ω_n and the time constant of its decaying, τ_a , are defined for the average complex admittance $Y_{av}(js)$ at the slip $s = -(1-s)$ by equations

$$\omega_n = \text{Im}[Y_{av}(js)_{s=-(1-s)}] \cdot R_{S0} \quad (7)$$

$$\tau_a = \frac{1}{\omega_n = \text{Im}[Y_{av}(js)_{s=-(1-s)}] \cdot R_{S0} \cdot \omega} \quad (8)$$

The initial value of the periodic component of the transient current, I_{S2} is determined by recognizing that

$$I_{S0}(t)_{t=0} + I_{S1}(t)_{t=0} + I_{S2}(t)_{t=0} = 0$$

Generally, the initial value of the current vector $I_{S2}(t)_{t=0}$ does not coincide with the d-axis of a rotor (including the connections of the synchronous machine occurring at the angle ($\delta_0 = 0$)) resulting in aperiodic current components in both axes of the rotor symmetry.

Implementation of the method proposed is associated with representing the initial frequency-response characteristics in the form of equivalent circuits in the d- and q-axis of a synchronous machine. The latter ones, e.g., the equivalent circuit in d-axis shown in Figure 1 may be used for determining the changes in the periodic current components with time (Ronkowski, 2008).

The mentioned equivalent circuits allow obtaining the initial values ($I_{S2_{dk}}, I_{S2_{ql}}$) and the time constants (τ_{dk}, τ_{ql}) of the exponential components of the periodic armature current $I_{S2}(t)$ so in the d- and q-axis we have;

$$\tau_{dk} = \frac{x_{kd}}{\omega \cdot r_{kd}}, I_{S2_{dk}} = \frac{1}{x_{kd}}, k = 1, 2, \dots, N; \quad (9)$$

$$\tau_{ql} = \frac{x_{lq}}{\omega \cdot r_{lq}}, I_{S2_{ql}} = \frac{1}{x_{lq}}, l = 1, 2, \dots, M$$

From the above, it might be assumed that the time-dependence of the periodic current follows the law;

$$I_{S2}(t) = \left(\sum_{k=1}^N I_{S2_{dk}} \cdot e^{-t/\tau_{dk}} \right) \cdot e^{j(1-s)\omega t} \cdot e^{j\delta_0} + \left(\sum_{l=1}^M I_{S2_{ql}} \cdot e^{-t/\tau_{ql}} \right) \cdot e^{j(1-s)\omega t} \cdot e^{j\delta_0} \quad (10)$$

Where N, M= quantity of the elementary equivalent

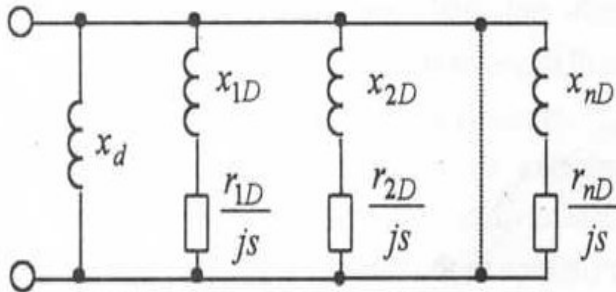


Figure 1. Equivalent circuit of the synchronous machine rotor.

rcuits of the rotor in d- and q-axis, respectively.

In the general case the initial I_{S2} current components in the d- and q-axis should be converted in proportion to the projection of the I_{S2} current vector on the direct, I_{S2d} , and quadrature I_{S2q} rotor axes, e.g.,

$$\begin{aligned} I_{S2d} &= \text{mod}[I_{S2}(t)_{t=0}].\cos(\varphi - \delta_0), \\ I_{S2q} &= \text{mod}[I_{S2}(t)_{t=0}].\sin(\varphi - \delta_0) \end{aligned} \quad (11)$$

Where φ = argument of the $I_{S2}(t)_{t=0}$ current vector (the angle between the current vector and the real axis of the complex plain).

Then;

$$\begin{aligned} I_{S2dk} &= \frac{1}{x_{kD}} \cdot \frac{I_{S2d}}{\sum \frac{1}{x_{kD}}}, \\ I_{S2qt} &= \frac{1}{x_{lQ}} \cdot \frac{I_{S2q}}{\sum \frac{1}{x_{lQ}}} \end{aligned} \quad (12)$$

The total generalized vector of the transient armature current comprises the vector sum of separate components:

$$I_S(t) = U \cdot [I_{S0}(t) + I_{S1}(t) + I_{S2}(t)] \quad (13)$$

Where V= voltage across the terminals of an armature

winding at the short-circuit condition or connection of a synchronous machine to the network.

The instantaneous values of the phase currents are determined as a projection of the generalized current vector on the motionless time axes of the appropriate phases:

$$\begin{aligned} i_A(t) &= \text{mod}[I_S(t)].\cos(\alpha(t) + \gamma_0), \\ i_B(t) &= \text{mod}[I_S(t)].\cos(\alpha(t) + \gamma_0 - \frac{2}{3}\pi), \\ i_C(t) &= \text{mod}[I_S(t)].\cos(\alpha(t) + \gamma_0 + \frac{2}{3}\pi) \end{aligned} \quad (14)$$

Where $\alpha(t)$ =time-dependent argument of the total generalized vector of the armature current.

It is evident that the dynamic properties of an induction machine can be described in full measure by means of a single frequency-response characteristic $Y(js)$. In this case, the expressions obtained above will not contain the additional current components ΔI_{S0} and ΔI_{S1} they are no needs in decomposition of the I_{S2} current on the d- and q-axis components either (Kirtley, 1994).

In accordance with the general approach the electromagnetic torque is determined using the current and flux linkage complexes, regardless of the rotor symmetry of the AC machine, by the expression:

$$T = \text{Re}[j\psi_s^* \cdot I_s] = R_e[j(\psi_{S0} + \psi_{S1})^* (I_{S0} + I_{S1} + I_{S2})] \quad (15)$$

The magnetic linkages in (15) can be presented more detail as follows:

$$\psi_S = \psi_{S0} - \psi_{S1} = e^{j\alpha\tau} - e^{j\omega_h t} e^{-t/\tau_a} \quad (16)$$

As may be seen from the Equations (15) and (16), the electromagnetic torque can be presented as the sum of the vector products of the currents by flux linkage components. For example, the product of the vector I_{S0} by the vector ψ_{S0} produces the steady-state torque being numerically equal to the vertical projection of the current vector at the rated voltage across the terminals of the stator winding.

The influence of the separate current and torque components on the features of the transient process having been analyzed, it is possible to simplify the mathematical model of an electrical machine with the given accuracy.

At researching the electromechanical transients connected with the speed variations of AC machine rotor one should consider the simultaneous solution of the equations deduced above and the supplementary equation of the rotor relative motion. The latter one can be written in the following form:

$$M \frac{ds}{dt} = T - T_{mech} \quad (17)$$

Where T_{mech} =shaft torque developed by the prime mover; M =inertia constant.

PARAMETERS OF THE ALGORITHM

If the influence of the rotor acceleration is not taken into account the following problem algorithm considering the rotor speed changes can be suggested:

The transient process is divided into small uniform intervals of time;

The speed increment over the given interval is determined by solving the Equation (17) as follows:

$$\Delta s = \frac{T - T_{mech}}{M} \Delta t;$$

The sustained component of the I_{S0} current is calculated at the constant speed obtained for the given time interval. The amplitude of the I_{S1} current component decaying with the time constant τ_a is calculated at the initial value of the rotor speed (at the beginning of the first interval).

The natural angular frequency, ω_n , and the time constant, τ_a , of the aperiodic current component are re-counted using Equation (7),(8) in relation to the slip changes of a rotor.

The amplitude of the I_{S2} current component caused by the transient currents in the rotor circuits is determined at the rotor slip corresponding to the first instant of the process.

It should be pointed out that the angular speed of the I_{S2} current being taken into account in (Lam and Yee, 1998) varies with the slip changes. The rotor slip dependence of the natural angular frequency and the time constant of decaying the magnetic flux ψ_{S1} are taken into account by equation (Lei and Namuduri, 2009).

ESTIMATION OF MODEL VALIDITY

The efficiency of application of the frequency-response characteristics for calculating the transient process can be demonstrated with the following examples:

1. Short-circuit at the terminals of the stator winding and connection to the network without excitation of the model

turbo generator of the MT-3type:

$$(S_n = 30KVA, V_n = 414V, I_n = 41.8A, x_d = 1.453; x_q = 1.394; R_{S0} = 0.00624 p.u.)$$

In the case being considered the influence of the sign and initial slip value at connecting the generator to the network as well as the influence of the rotor speed changes at the transient conditions were analyzed.

2. Connection to the network of the unexcited turbo generator of the TGB-200 type:

$$S_n = 235MVA, V_n = 15.75KV, I_n = 8635A, x_d = 1.9; x_q = 1.89; R_{S0} = 0.0012 p.u.$$

When calculating the electromechanical transients the errors being brought about by simplifying the complicated equivalent circuits, reflecting the electromagnetic of the solid rotor, were considered.

3. Starting of the induction motor of the ДА30-1914-10/12A type:

$$P_n = 1500KW; I_n = 204A; V_n = 6000V$$

From the no-load condition, and three-phase short-circuit at its terminals.

Estimation of the results obtained, when using the techniques proposed above, was carried out by comparison with the appropriate calculations made by the use of algorithms based on numerical integrating the system of the differential Parc-Gorev equations. The frequency-response characteristics reflecting the dynamic properties of the AC machines being studied were obtained experimentally from the DC decay in the armature winding at standstill test (Canay, 1994; Satish and Saravanakumar, 2008; Dehkordi et al., 2005).

Computer programs realizing the above mentioned algorithms for calculating the electromechanical transients in AC machines were elaborated within the framework of the MathCAD 7.0.

The time-dependence of changing the generalized stator current vector and the electromagnetic running torque at connection the unexcited model generator to the network under the various initial rotor slips were carried out without the account and in view of changing the rotor speed at transient. The invariable rotor speed was simulated by way of setting the great value of the inertia constant (Bacalao et al., 1995).

As follows from comparison of the results obtained for the given slip values, equal to 0, 0.01, 0.03, 0.05 and 0.1 put, the changes in the time-dependence of the generalized stator current vector and electromagnetic torque practically does not differ from the analogous calculations made on the basis of the Parc-Gorev

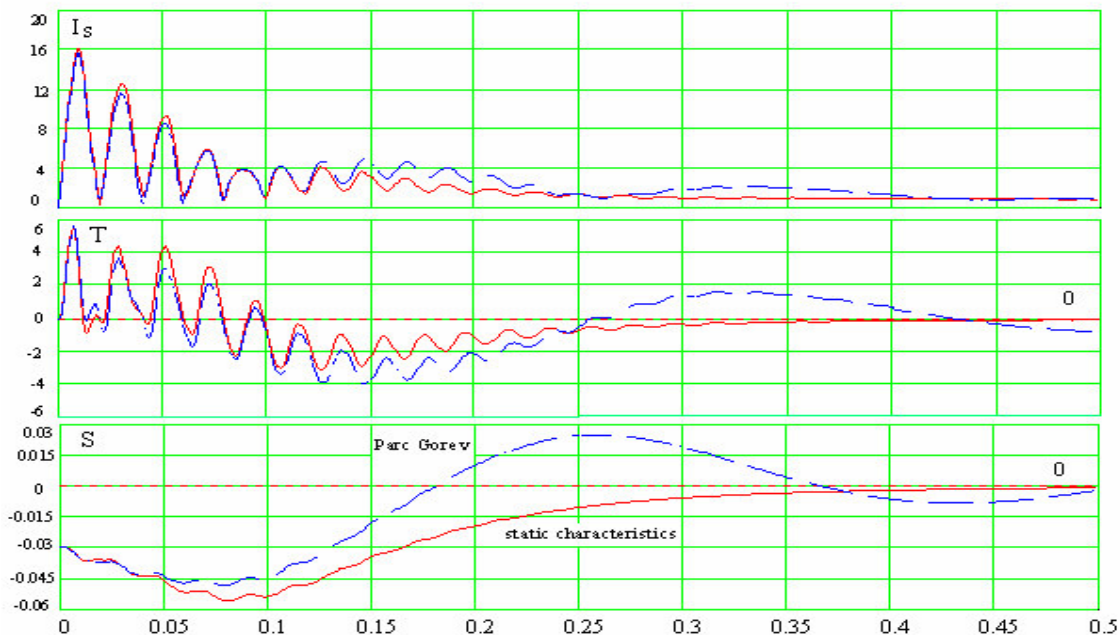


Figure 2. Connection to the network of the unexcited model turbo generator.

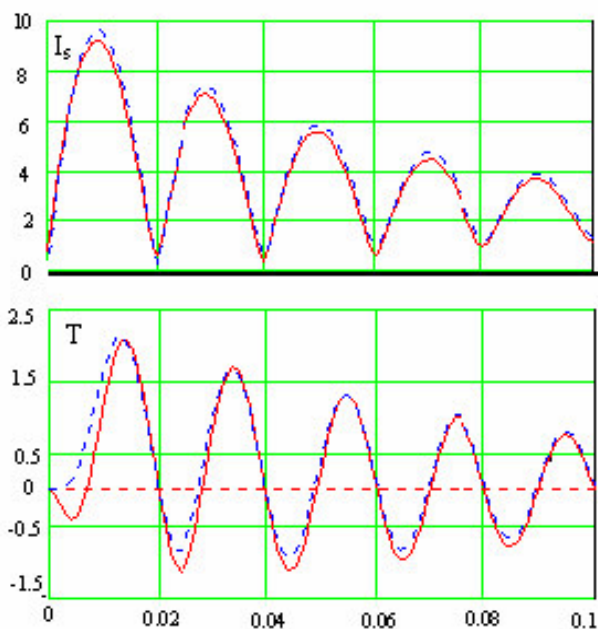


Figure 3. Short-circuit on the terminals of the induction motor.

equations. In these cases the difference in the maximum values of the similar operating variables being compared did not exceed 10.4%. The typical changes in the transients differ not at all. So, when making use of the static frequency-response characteristics, one can infer

that the electromagnetic processes may be identified with a sufficiently high degree of accuracy.

The analysis of the transients calculated with taking into consideration the rotor speed changes, following the connection of the model generator, points to some differences in the time-dependent variables. For example, in the Figure 2 are shown the results of calculating the transients at connection the unexcited model machine to the network with the field winding short-circuited.

The calculations carried out in compliance with the system of Parc-Gorev equations (see dotted line) reflect the features connected with changes in the current I_s , and electromagnetic torque, T , with the rotor speed changes. The time dependence of the slip in the case under consideration has the oscillatory character. Mathematical simulation based on the static characteristics (see solid line) brings about the monotonous changes in the rotor slip under the transient process. Meanwhile, the resultant time of approaching the rotor speed to the synchronous one, being estimated at the instant a rotor slip for the second time passes through zero, practically agrees with the time being determined from the solid line obtained at simulating the transients by means of the method proposed.

Distinguishing features of the variables being considered are in close agreement; their maximum values appearing at the initial stage of the transient process correlate well with the data got without regard for speed changes of the rotor. In the Figure 3 are given the curves reflecting the changes in the variables at the

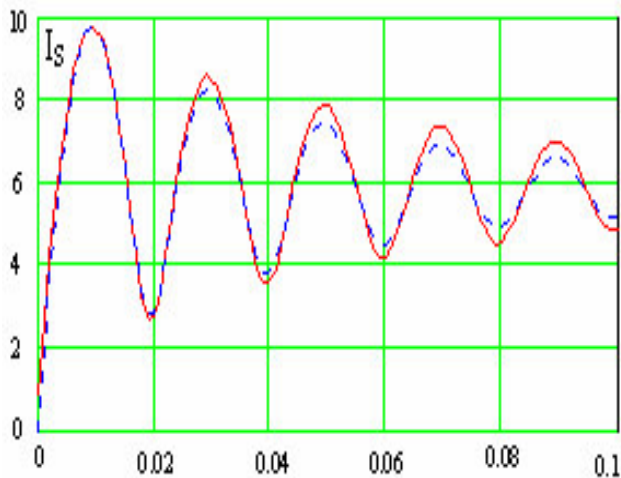


Figure 4. The time-dependence of the generalized vector of the stator current at connecting the induction motor.

short-circuit on the terminals of the induction motor ДАЗО-1914-10/12А type.

The quantities of the motor equivalent circuits synthesized in accordance with (Guha and Kar, 2006; Lam and Yee, 1998) having three parallel branches and the magnetizing one, separated in the manner as is shown in the Figure 1, are as follows (in per unit on machine base):

$$X_{\delta} + X_{\gamma} = 2.19; X_1 = 0.271; X_2 = 1.179$$

$$X_3 = 0.717; R_1 = 0.0055; R_2 = 0.1139$$

$$R_3 = 0.624$$

The comparative analysis of the results obtained by calculating the generalized stator current vector, I_s , and electromagnetic torque, T , calculated by various methods points to their close agreement because of the maximum values of the mentioned variables differ less than 7,8%.

The analysis of the electromechanical transients at starting the non-loaded motor also indicates to the satisfactory coinciding of the results obtained by using the mentioned calculation techniques. In particular, the starting time determined by the technique proposed differs from the same parameter obtained through the use of the Parc Gorev equations less than 9,2%.

As is seen from the Figure 4, the electromagnetic transients within the time interval from 0 up to 0.1 s correspond closely with the results obtained by the Parc Gorev equation (see dotted line).

The mentioned acceptable results are attributable to the fact that the change in the motor speed takes place at the small rotor acceleration. In this case, the application of the frequency-response characteristics of a machine does not introduce large errors into calculation of the

transient processes. When the rotor speed is close to the rated value there are considerable deviations in the changes of the current and electromagnetic torque with time.

As may be inferred from the research, the mentioned deviations decrease with increasing the inertia constant, M , and the loading factor of the induction motor. The transients in this case are accompanied by the less acceleration of a rotor.

The investigation of the transients called forth by connection of the unexcited turbo generator ТГВ-200 type to the network was carried out with the use of the equivalent circuits containing five parallel branches in d- and q-axis [6]. It was ascertained that the errors being introduced in the transient processes by reducing the quantity of the circuit branches, describing the physical properties of the solid rotor, to three do not exceed the errors in a frequency domain equal to 11%.

Conclusion

In this paper, we presented a survey about the methods of frequency-response characteristics used for investigating and evaluating the transient conditions of the AC machines in electrical systems. In fact, a mathematical models of the asynchronous electrical machines based on the experimental frequency-response characteristics are presented. These models allow us to investigate the transients processes at short-circuits and the connection of the machines to the network without solution of the conventional differential equations. In order to lead to this task, we take into consideration the occurring speed changes of the AC machine rotor.

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