Research Related Electromechanical Processes in an Asynchronous Traction Motor - Asynchronous Generator with Common Shaft Based on Field Model

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Abstract. *Creating energy efficiency traction induction motors with frequency control for hybrid drive vehicles defines practical interest for new methods of testing and simulation. Tests of these machines, it is desirable to carry out with energy recovery in the motor-generator, where a common shaft unites the machines. At present, the system simulation of motor-generator is carried out on simplified models without saturation, surface effect, jagged cores, and non-sinusoidal voltage of frequency converters. A refined interrelated mathematical model of asynchronous motor and generator operating with a common shaft, based on the theory of electrical circuits and field theory. Models allow the related modelling and study of static and dynamic modes electrical machines taking into account the saturation, skin effect, toothed cores, non-sinusoidal voltage of the frequency inverter, and variation parameters of the windings.*

Keywords

Circuit theory, field model, induction generator, induction motor.

1. Introduction

For modern vehicles promising application of hybrid power systems, including the internal combustion engine, electric atraction motor, and generator, frequency converters, reduces fuel consumption and reduce harmful emissions. Tests of traction induction machines such installations, it is desirable to carry out in the asynchronous motor-generator system with energy recovery, where induction motors are united by a common shaft, and one of the induction motor operates with a frequency converter. Currently, system modeling three-phase motor-generator is carried out on simplified models in a converted two-phase coordinate system without saturation, skin effect, toothed cores, non-sinusoidal voltage of frequency converters [7], which does not correctly simulate and explore the modern testing equipment.

Correct modeling of steady-state and dynamic processes in such systems, especially with powerful induction motors requires the use of interrelated models of electric machines, running on a common shaft, linking the electromagnetic torque. Develop an accurate model of connected machines in the traction system is suitable based on the theory of the electromagnetic field. There are different stages of the application field models of electric machines to solve the problem:

- The calculation in circuit models using known values of the parameters dependencies windings from saturation and skin effect [1].
- Using the results of calculations of the electromagnetic field of electrical machines in chain models.
- The dynamic relationship of several two-dimensional field models of asynchronous machines operating with a common shaft.

Refined circuit model can be developed based on the model of the induction machine in the natural (three-phase) coordinate system [6], which allows taking into account the effect of the saturation and skin effect in the rotor bars at startup. The air gap adopted smooth. The squirrel-cage rotor is represented as rotating three-phase winding. At 50 Hz winding of machine are considered as a lumped-parameter circuit, since the length of the electromagnetic wave is much greater than the linear dimensions of the windings. It is assumed that each phase of the stator and rotor windings creates a fundamental spatial harmonic of the magnetic field in the gap [7]. Model of the induction machine are the differential equations of the phase voltages and the equation of motion of the rotor shown in Eq. (1), [2].

$$\begin{cases} u_{1A} = R_1 \cdot i_{1A} + \dfrac{\mathrm{d}\Psi_{1A\Sigma}}{\mathrm{d}t}; \\ \dots \\ \sum\limits_{k=A,B,C} i_{1k\Sigma} \sum\limits_{n=a,b,c} i_{2n\sigma} \cdot \dfrac{\mathrm{d}L_{kn}}{\mathrm{d}t} - M_{load} = \\ = J \cdot \dfrac{\mathrm{d}\Omega}{\mathrm{d}t}. \end{cases} \tag{1}$$

The system of differential equations describes the transients in a three-phase asynchronous machine. In the presence of the second asynchronous machine, which is connected to the first by a shaft (Fig. 1), the system of equations is supplemented with the equations of the phase voltages and torque equation for the second asynchronous machine, and has the form shown in Eq. (2).

$$\begin{cases} u_{1GA\Sigma} = R_{1G} \cdot i_{1GA\Sigma} + \dfrac{\mathrm{d}\Psi_{1GA\Sigma}}{\mathrm{d}t}, \\ u_{1GB\Sigma} = R_{1G} \cdot i_{1GB\Sigma} + \dfrac{\mathrm{d}\Psi_{1GB\Sigma}}{\mathrm{d}t}, \\ u_{1GC\Sigma} = R_{1G} \cdot i_{1GC\Sigma} + \dfrac{\mathrm{d}\Psi_{1GC\Sigma}}{\mathrm{d}t}, \\ 0 = R_{2G} \cdot i_{2Ga\Sigma} + \dfrac{\mathrm{d}\Psi_{2Ga\Sigma}}{\mathrm{d}t}, \\ 0 = R_{2G} \cdot i_{2Gb\Sigma} + \dfrac{\mathrm{d}\Psi_{2Gb\Sigma}}{\mathrm{d}t}, \\ 0 = R_{2G} \cdot i_{2Gc\Sigma} + \dfrac{\mathrm{d}\Psi_{2Gc\Sigma}}{\mathrm{d}t}, \\ u_{1MA\Sigma} = R_{1M} \cdot i_{1MA\Sigma} + \dfrac{\mathrm{d}\Psi_{1MA\Sigma}}{\mathrm{d}t}, \\ u_{1MB\Sigma} = R_{1M} \cdot i_{1MB\Sigma} + \dfrac{\mathrm{d}\Psi_{1MB\Sigma}}{\mathrm{d}t}, \\ u_{1MC\Sigma} = R_{1M} \cdot i_{1MC\Sigma} + \dfrac{\mathrm{d}\Psi_{1MC\Sigma}}{\mathrm{d}t}, \\ 0 = R_{2M} \cdot i_{2Ma\Sigma} + \dfrac{\mathrm{d}\Psi_{2Ma\Sigma}}{\mathrm{d}t}, \\ 0 = R_{2M} \cdot i_{2Mb\Sigma} + \dfrac{\mathrm{d}\Psi_{2Mb\Sigma}}{\mathrm{d}t}, \\ 0 = R_{2M} \cdot i_{2Mc\Sigma} + \dfrac{\mathrm{d}\Psi_{2Mc\Sigma}}{\mathrm{d}t}, \\ M_G = \sum\limits_{k=A,B,C} i_{Gk\Sigma} \cdot \sum\limits_{n=a,b,c} i_{2Gn\Sigma} \cdot \dfrac{\mathrm{d}L_{Gkn}}{\mathrm{d}\gamma}, \\ M_M = \sum\limits_{k=A,B,C} i_{Mk\Sigma} \cdot \sum\limits_{n=a,b,c} i_{2Mn\Sigma} \cdot \dfrac{\mathrm{d}L_{Mkn}}{\mathrm{d}\gamma}, \\ (M_G + M_M) - M_{load} = (J_M + J_G) \cdot \dfrac{\mathrm{d}\Omega}{\partial t}, \\ \Omega = \Omega_0 + \displaystyle\int_0^t \dfrac{\mathrm{d}\Omega}{\mathrm{d}t}\mathrm{d}t. \end{cases} \tag{2}$$

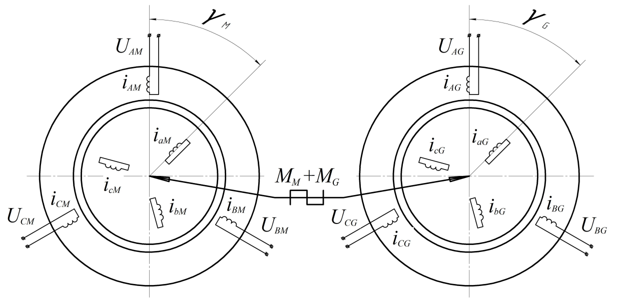

Fig. 1: The system of the engine-generator with a common shaft.

Flux expressed through currents and relevant inductance represented by Eq. (3).

$$\begin{aligned} \Psi_{1A\Sigma} = L_{AA\Sigma} \cdot i_{1A\Sigma} + L_{AB\Sigma} \cdot i_{1B\Sigma} + \\ L_{AC\Sigma} \cdot i_{1C\Sigma} + L_{Aa\Sigma} \cdot i_{1a\Sigma} + \\ L_{Ab\Sigma} \cdot i_{1b\Sigma} + L_{Ac\Sigma} \cdot i_{1c\Sigma}. \end{aligned} \tag{3}$$

In this model, inductance and winding resistance can be taken as dependent variables of the differential equation. This allows taking into account the effect of saturation of the magnetic circuit and the crowns of the teeth of the stator and rotor, the skin effect, using the known analytical dependence or addiction, determined from the calculation of the field. This model developed in Mathcad. For modeling, we used two traction induction motor with the following parameters: rated power $P = 70$ kW, synchronous speed $n = 1500$ rpm and rated line voltage $V = 400$ V.

For this model required the following input data - leakage inductance of the windings, mutual inductance stator-rotor, winding resistance, moment of inertia of the rotor. The change in resistance of the windings under the action of surface effect and saturation takes into account by known methods, described in [1] by adjusting the values of resistances and inductances during the solution of the system of differential equations shown in Eq. (2).

Figure 2, Fig. 3 and Fig. 4 show the electromechanical transients start of two three-phase asynchronous machines, connected by a common shaft, linking by electromagnetic torque, working by a scheme of the mutual load with energy recovery in the power source. One machine is started and running in motor mode, supplyingvoltage with a frequency of 3 Hz more than the othermachine. The second machine is operating in regenerative mode. Is supplied the voltage lower frequency ($f = 50$ Hz) and receives mechanical energy from the shaft of the first machine.

After applying a voltage to the stator winding, machines run, mutually loading each other. Registered surge current (Fig. 2) transient start-up, after the currents were reduced, leaving a steady state in which the phase currents motor and generator set in opposition.

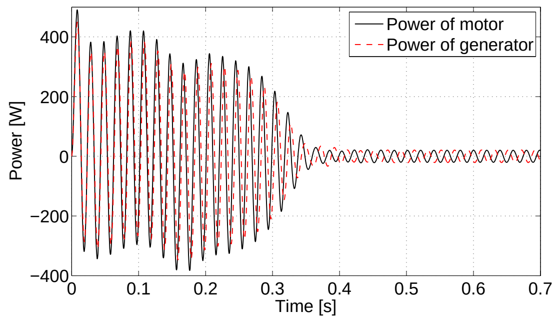

Fig. 2: Currents of stator on generator and motor.

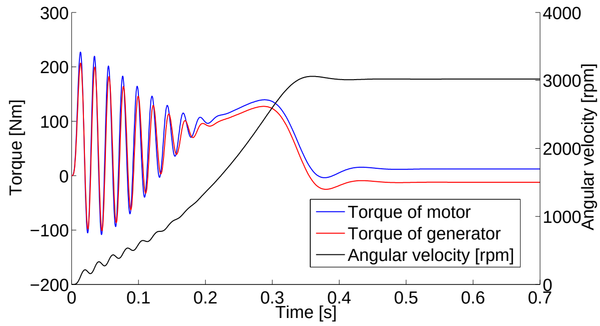

Fig. 3: The electromagnetic torque of the motor and generator, the acceleration curve.

Figure 3 shows the curves of the electromagnetic torque of the two machines at start and acceleration curve of the machines. In steady-state electromagnetic moments have different signs, indicating that the mutual load machines. Figure 4 shows the power consumed by the network for both machines. Power in steady state also has different signs.

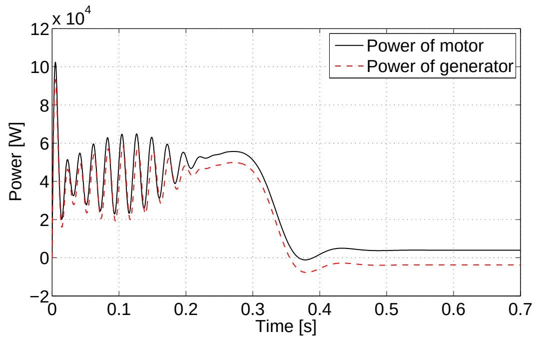

Fig. 4: Power, consumed by machines.

The model described above provides sufficient accuracy for the transient in the system of induction motor - generator when tested traction asynchronous machines by mutual load. Its accuracy may be improved by taking into account changes in the parameters of the winding induction machines under the action saturation and the skin effect. However, for modeling modern installations accuracy of such circuit models of asynchronous machines when powered by frequency converters without a correct account of non-sinusoidal voltage, saturation, the skin effect, toothed cores, may be insufficient. Therefore, the feasibility of developing and applying models based on the calculation of the electromagnetic field of both machines, linking the electromagnetic torque. The electromagnetic field applied to the theory of electrical machines, may be described by the Maxwell equations [4]. Consideration of a plane-parallel field allows us to go to the Eq. (4):

$$\frac{\partial}{\partial x}\left[\frac{1}{\mu}\cdot\frac{\partial A}{\partial x}\right]=\vec{j}+\gamma\frac{\partial A}{t}+\gamma\left(\vec{v}\times\mathrm{rot}\ \vec{A}\right), \quad (4)$$

where $\vec{A}$ - magnetic vector potential, $\vec{j}$ - current density vector, γ - electric conductivity, $\vec{v}$ - velocity vector conductive parts which moving in an electromagnetic field, μ - magnetic permeability (variable, function of the intensity of the field).

The curl of the vector magnetic potential is the magnetic field $\vec{B}=\mathrm{rot}\ \vec{A}$. Then the induced voltage shown in Eq. (5):

$$E\left(t\right)=-\frac{\partial\Psi}{\partial t}=-\frac{\partial}{\partial t}\sum_{i=1}^{N_k}\left(A_2-A_1\right)w_{ki}l_\delta. \quad (5)$$

When applying the finite elements method, [3], [4] the value of the flux density and current density within each finite element calculated area presented unchanged. For calculation of the electromagnetic field in asynchronous machines, need to solve a system of equations, the dimension of which is equal to the number of finite elements. The task is complicated by the fact that every time the changes of the angle of rotation of the rotor changes the geometry of the computational domain, and this leads to the need to rebuild the finite element mesh. To simplify the solution of Eq. (4), the partial derivative with respect to time of the vector magnetic potential seems finite difference approximation.

$$M_G+M_M=M_{load}-\left(J_G+J_M\right)\frac{\mathrm{d}\Omega}{\mathrm{d}t}, \quad (6)$$

Rotation of the rotor in model is taken into account at each iteration corresponding angle of rotation of the rotor, which allows you to take simultaneously into account the change in the geometry of the computational domain. For this purpose, the equation is supplemented by motion equation of rotor as describes Eq. (6), in which the derivative of the angular velocity with respect to time is also expressed in finite difference form. Mechanical balance is formulated in Eq. (7).

The value of the electromagnetic torque may be obtained through the integration of the surface density of

$$\oint_V = \vec{r_1} \times \left(\vec{j_M} \times \vec{B_M}\right) \mathrm{d}V + \oint_V \vec{r_1} \times \left(\vec{j_G} \times \vec{B_G}\right) \mathrm{d}V - M_{load} = (J_M + J_G) \frac{\mathrm{d}\Omega}{\mathrm{d}t}. \tag{7}$$

$$M_\Sigma = l_{\delta G} \cdot \oint \left[\vec{r_1} \times \left[\vec{j_G} \times \vec{B_G} - \frac{H_G^2}{2} \mathrm{grad}\, \mu_M\right]\right] \mathrm{d}S_1 + l_{\delta M} \cdot \oint \left[\vec{r_2} \times \left[\vec{j_M} \times \vec{B_M} - \frac{H_M^2}{2} \mathrm{grad}\, \mu_M\right]\right] \mathrm{d}S_2 \tag{8}$$

the electromagnetic force [4]. Omitting the mathematical operations, give the final form of the formula for the two asynchronous machines are available in Eq. (8), where $\vec{r_1}$ and $\vec{r_2}$ – the radius vectors to the current point rotor of the motor or generator. The integration is over the surface surrounding the rotor corresponding machine and passing through the center of the air gap.

Solve of the electromagnetic field equations in partial derivatives of the finite element method for unstable grid is reduced to a cyclic algorithm, at each iteration of which the solution of the equations for constant within each iteration of the grid.

In determining the current transient and accounting frontal resistance stator and rotor windings must be joint with the field solution of the balance equations of the phase voltages in Eq. (9):

$$U(t) = -E(t) + i(t) \cdot r_{fr} + L_{fr} \cdot \frac{\mathrm{d}i}{\mathrm{d}t}, \tag{9}$$

written in accordance with the equivalent circuit [6] shown in Fig. 5.

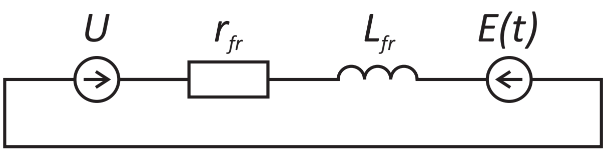

Fig. 5: Equivalent circuit of phase stator.

Based on this approach, with using modern simulation programs of electric machines developed field model of induction motor - asynchronous generator with a common shaft taking into account saturation, skin effect, toothed cores, non-sinusoidal voltage frequency converter (Fig. 6).

The input data for the field model are the geometry of the machines, the winding diagram of the stator, magnetization curves of the materials stator and rotor, the moments of inertia of the rotating parts of the model.

The developed model can correctly simulate two interconnected by a common shaft asynchronous machine, to investigate the static and dynamic modes of induction machines, interlinked electromagnetic fields, and electromechanical processes in them. Studies show that the neglect of local saturation, manifestations of skin effect, toothed cores, non-sinusoidal voltage frequency converter, changing the parameters of the wind-

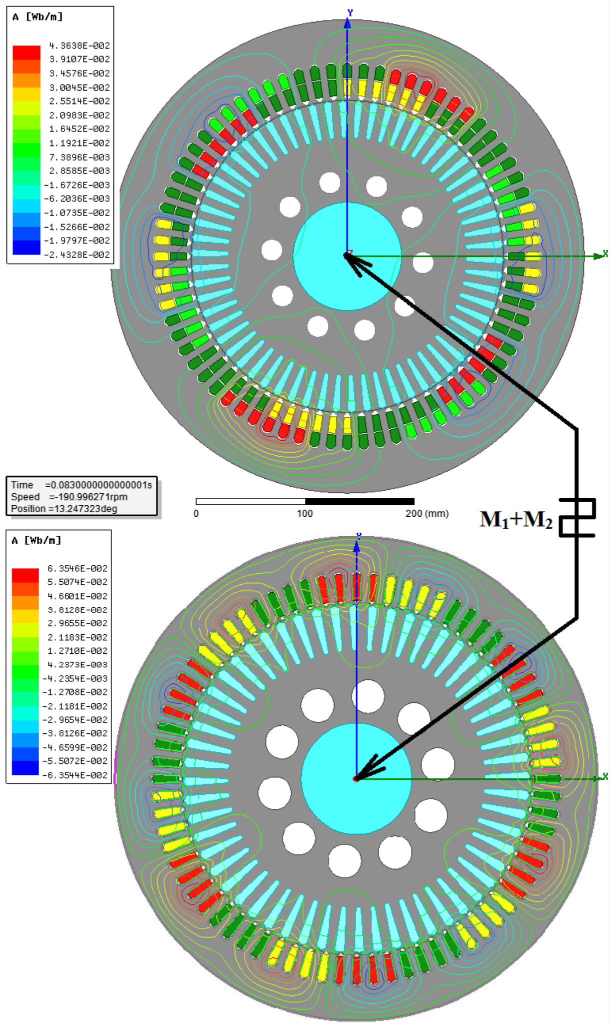

Fig. 6: Interconnected model of electromagnetic fields in the induction motor - asynchronous generator with a common shaft.

ings can lead to errors of calculation of electromagnetic quantities up to 10 %.

2. Conclusion

A refined interlinked mathematical model of the system of two electric machines: asynchronous motor - asynchronous generator working with a common shaft, based on circuit theory and field theory.

Neglect in simplified models of local saturation, surface manifestations of the effect, timing cores non-sinusoidal voltage of frequency converters, variable winding parameters can lead to errors of calculation of electromagnetic quantities up to 10 %.

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