Modernization of gas-turbine engines with high-frequency induction motors

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Abstract. Main tendencies of growth of electric energy consumption in general and mining industries were analyzed in the paper. A key role of electric drive in this process was designated. A review about advantages and disadvantages of unregulated gearboxes with mechanical units that are commonly used in domestically produced gas-turbine engines was made. This review allows one to propose different gas-turbine engines modernization schemes with the help of PWM-driven high-frequency induction motors. Induction motors with the double rotor winding were examined. A simulation of high-frequency induction motors with double rotor windings in Matlab-Simulink software was carried out based on equivalent circuit parameters. Obtained characteristics of new motors were compared with serially produced analogues. After the simulation, results were implemented in the real prototype.

1. Introduction

An electric motor has shown itself as a good and reliable machine in different industrial branches during many decades of their maintenance. They find a wide range of applications in mining complex, avionics industry, machinery building, mechatronics, etc. It can be said that almost every industrial branch and even everyday human life are deeply connected and rely on the efficiency and quality of electric motors. A quick shift in manufacturing semiconductor elements allowed one to create powerful automotive systems designed for electric motors control. These inventions and quick development of control systems allows one nowadays to use an electric drive for modernization of old less effective and slower equipment such as pneumatic or hydraulic drives.

However, price of progress has its own hidden disadvantages. Now electric machines are one of the main consumers of electric energy. According to [1] in 2016, 23 Trillion kw/h of electric energy were produced. 42% of this amount is spent for industrial processes, where 2/3 is consumed only by electric motors (it should be mentioned that 95% of these machines are induction motors with squirrel cage rotors). Hence, it is possible to make a conclusion that 28% of electric energy generated worldwide is consumed only by electric motors. This number equals 6.44 Trillion kw/h. With reference to power consumption growth forecast, humanity will generate up to 84% more electricity that will equal 42.32 Trillion kw/h by the year 2050. Therefore, taking into account the growth of the number of electric motors and electric drives, it is easy to forecast that they will consume much more than 28% of the generated electricity.

Therefore, a task of creation of economical, small dimensional and cost-effective electric motors’ models remains vital. Analysis of [2] shows that using modernization technologies that are already available, one can increase efficiency of electric motors up to 60-65% without huge investments.
2. Gas-turbine engine’s accessory gearbox and modernization possibilities

Design analysis of gas-turbine engines revealed the fact that all existing models, beside main modules, such as a compressor, a turbine, a combustion chamber, have many secondary systems, which are necessary for their full-fledged operation. In addition, almost every gas-turbine engine model has an accessory gearbox in its structure. It is necessary for power transmission from a gas-turbine engine’s rotor to the different accessory units during the operational mode and for power transmission in the reverse direction from the starter to the engine’s rotor during the starting mode.

The idea of this improvement consists in total replacement of an accessory gearbox with mechanical units and its replacement with compact high-frequency induction motors, with PWM-inverters that drive universal oil and fuel units. According to the gas-turbine engines’ design schemes not all mechanical parts can be removed completely. That is why this article proposes two schemes with different modernization levels. Figure 1 shows both of these variants, where 1a is the first one, which proposes removing almost every mechanical part except the central drive, which should remain in order to transmit power from the starter to the rotor shaft during the starting mode and to feed the main generator. The generator is necessary for avionics engines and can be replaced by different solutions in ground-based gas-turbine engines. Scheme 1b shows a deeper modernization level. It differs from the first one by removing the generator from the gearbox zone and placing it into the gas-air pass of the compressor.

It is worth mentioning that the third modernization scheme is also possible [3]. However, the modernization concerns removal of the lubrication system and a complete change of classical bearings to electromagnetic prototypes. Due to construction inconsistencies between old and new parts and problems with vibration compensation, this variant was not revealed here.

Figure 1. The proposed modernization schemes: a – first level; b – second level
3. Induction motor mathematical model
A MATLAB-Simulink program complex was chosen for induction motor parameters’ calculation. Entire modelling was performed in the SimPowerSystems module. The equivalent circuit of a three-phase induction motor with a double-cage rotor was chosen as the modelling prototype for calculations of high-frequency induction motor’s parameters [4]. Figure 2 shows the steady-state equivalent circuit. The equivalent scheme contains seven values, which are machine’s electrical values: $R_s$ is an active stator resistance (ohm or pu), $L_{s}$ is a stator inductance (H or pu), $R_{1r}$ is an active resistance of rotor winding 1 (inner winding, ohm or pu), $L_{1r1}$ is a reactive resistance of rotor winding 1 (inner, H or pu), $R_{2r}$ is an active resistance of rotor winding 2 (outer winding, ohm or pu), $L_{1r2}$ is a reactive resistance of rotor winding 2 (outer winding, H or pu), $L_{m}$ is a magnetic induction resistance.

![Figure 2. The equivalent circuit of a three-phase induction motor with a double squirrel cage rotor](image)

The biggest challenge was to calculate all these values easily using only manufacturer’s data. It was done with the help of special Simulink algorithm. The `power.AsynchronousMachineParams` function [5, 6] computes the seven machine parameters by solving the nonlinear equations in the form of $f(x) = 0$ with:

$$
f_1(x) = \frac{T_n - T(s_n)}{T_n}; \quad f_2(x) = \frac{I_n - I(s_n)}{I_n}; \quad f_3(x) = \frac{pf - pf(s_n)}{pf}; \quad f_4(x) = \frac{I_{st} - I(1)}{I_{st}}, \quad (1)
$$

where $f = (f_1, f_2, f_3, f_4, f_5, f_6)$ and $x = (R_s, L_{ls}, R_{1r}, L_{1r1}, R_{2r}, L_{1r2})$. The $L_{ls}$ parameter is obtained by assuming that the stator and outer cage leakage inductances are equal ($L_{ls} = L_{ls}$). $s_n$ and $s_{br}$ are the slip at nominal and breakdown torque, respectively. $T_n$, $I_n$, $pf$, $I_{st}$, $I_{br}$, $T_{st}$ are the standard manufacturer specifications of the machine [5, 6].

4. Simulation models
Figure 3 shows a 10 kW induction motor with a speed regulation and PWM converter that was chosen as a serially manufactured prototype for the simulation experiment. Scalar control was chosen as the control method. It is based on an original concept of frequency converters where a signal with a certain determined ratio between voltage and frequency (V/f) is sent to the clams of the induction motor and this ratio is kept as a constant in the whole frequency range in order to keep the induction motor’s magnetizing flux constant [7, 8]. Scalar control is normally used when there is no necessity for quick response to rapid change of torque and speed settings. This is particularly used when one converter controls rotation speed of several connected electric motors. Hence, these statements and theory can be implemented for modelling gas-turbine electrically driven units extremely well.

The simulation model contains following elements a tree-phase voltage source, a rectifier, a DC-voltage LC-filter, an inverter, an AC-voltage RC-filter, measurement equipment, a high-frequency induction motor, a starting characteristics function, oscilloscope blocks, a reference voltage generator, a voltage regulator, and a pulse generator (PWM-geerator). In the beginning, voltage with 380 V
Magnitude and 50 Hz frequency energizes the circuit. At the first stage, it is being straightened through the rectifier based on the diode bridges. After that, rectified voltage is smoothed on the LC-filter and it comes to the inverter input, which generates pulses with 800 Hz frequency. Further voltage is filtered again with the help of the RC-filter and finally it comes to the input of the high-frequency induction motor [9]. Motor’s output characteristics are registered in oscilloscopes with the help of Furies converters that consist of Furies links set to the necessary frequency.

Figure 3. High-frequency induction motor with PWM Inverter and power source in Simulink

Every frequency converter is a non-linear load that additionally brings disturbances to the network in a form of harmonics components [10]. Their influence on normal power users and different methods for their influence minimization is observed in [11,12].

Data about current voltage are sent from the measurement complex to the PWM-generator that controls opening and closing of inverter keys. It operates on an open loop and generates pulses indefinitely. Control pulses are created according to one of the common laws where output voltage is compared with the triangle-form reference signal. Output linear voltage in this case behaves as an input DC-voltage and a modulation index \( m \) function:

\[
V_i = \frac{m}{2} \frac{\sqrt{3}}{\sqrt{2}} \cdot V_{const}. \tag{2}
\]

The control performed without feedback and speed maintenance accuracy is a function of motor slip that depends on load, since the frequency is superimposed on the stator winding. In order to improve performance, some electric drives use special functions such as slip compensation (reduction of the speed change as a function of the load) and torsion torque increasing (increasing the V/f factor for voltage drop across the stator compensation) so that the engine’s torsion torque is kept constant. This algorithm is one of the most commonly used control methods due to its simplicity and due to the fact that most of the applications do not require high precision or fast speed change [8, 11].

5. Simulation results

Induction motor 4A162S2Y3, 50 Hz was chosen as a serially manufactured prototype in order to compare its output parameters with high-frequency motors’ characteristics. Its manufactured parameters were recalculated according to part 4 of this article keeping synchronous speed at 3000 rpm level for 400 HZ and 800 Hz models. Figure 6 shows output values for all the simulated motors. They are speed curves, stator and rotor currents and electromagnetic torque. The upper curve belongs to the 50 Hz motor, the middle – to the 400 Hz model, and the lower – to the 800 Hz one.

Figure 4a shows that stator currents of high-frequency induction motors almost have no oscillations and pulsations. They also have overregulation currents and current peaks during transient modes and load surge modes. At the same time, peak values of starting currents were reduced approximately by 6% for the 800 Hz model. This fact plays an important role in those cases where motors are connected to the power source directly without soft-starters or PWM-inverters. This fact makes them beneficial for implementation in overloads power networks, where big current pulsations can cause voltage sags.
or pulsations and as a result lead to emergency stop of all working motors and even other equipment [11, 12]. At the same time, the reduction of starting and stator’s current values leads to the extenuation of warm losses and prolongs isolation lifetime.

![Figure 4](image1.png)

**Figure 4.** Output parameters of the simulated motors: a – stator currents; b – electromagnetsic torque

High-frequency induction motor’s electromagnetic torque form in figure 6d also stays in a stable zone with the maximum load in contrast to the serial motor’s torque. There are no pulsations and overregulation. Besides this fact, small V/f ratio correlations in the frequency converter allow one to achieve a 20% better torque on the motor’s shaft for a 800 Hz model [13].

Performed calculations’ and modelling results confirm better performance in working characteristics of high-frequency induction motors as compared to serially produced prototypes. Besides this fact, increased frequencies allow one to reduce engines’ geometry and mass significantly. Based on results for designed 400 Hz prototype and by preliminary assessment, for 800 Hz machine this economy can achieve 40% for a 400 Hz model and up to 60-65% - for 800 Hz models. The bigger engine’s nominal power, the greater the economy’s value. Moreover, an opportunity for speed range widening becomes possible. If a 50 Hz model has maximum nominal speed 3000 rpm, for 400 Hz - 24000 rpm is possible and a 800 Hz prototype can achieve 48000 rpm without multiplication gearboxes. According to figure 6, these motors together with PWM-inverters can operate within the extended speed range without losses [14].

6. Experimental results

In order to prove the proposed models advantages, a generator prototype for the implementation on a small-dimensional gas-turbine engine was developed. Its photo in a protective casing is shown in figure 5.

![Figure 5](image2.png)

**Figure 5.** Prototype’s photo

The total output power equals 2.2 kW and generator has two outputs: the first - with a stable
voltage level for feeding pumps, and the second - with a variable for the electronics operation. The generator is prepared to be installed into an air-gas channel of a high power compressor and rotates with a speed of 24000 rpm. The stator winding is made from permanent magnet alloy. The testings of the generator inside an engine demonstrated its operability and advanced functionality as compared to the serial prototypes. Also, the decreased generator’s mass and dimension helped to save 4 kg of the total gas-turbine engine’s mass.

7. Discussion
Fast industrial development and quick shift in power electronics design allow one to create new control models for a common electric drive and developing models. Energy consumption growth and digital control methods, based on Clark transformation and Instantaneous Power Theory, make it possible to control new electric models with improved characteristics and energy efficiency.

8. Conclusion
The results of mathematical modeling by the example of high-frequency induction motors with PWM control show their fast performance and huge range of possible application schemes. For example, achieved improvement in a peak starting current value allowed one to decrease it for 6%, thus, resulting in possibility of using these motors in more loaded networks. Also the torque value was increased by 10% and both transient modes for current and torque were diminished 2.5 times. Proposed modernization methods for avionics and ground-based gas-turbine engines can help in improvement of dimension, mass and control characteristics of many secondary equipment that is used nowadays. Reduction in mass and total energy consumption helps to make high-frequency electric motors more efficient.

9. Acknowledgments
The presented results were obtained as a part of scientific research according to contract № 11036GU/2016 “The development of the power network condition controller with blackout prevention possibility” provided by the Foundation for Assistance to Small Innovative Enterprises in Science and Technology (FASIE).

The presented results were obtained as a part of scientific researches according to the contract № 13.3746.2017.8.9 “The designing on the basis of systematic and logic probability evaluations of the rational and economically proved structure of centralized, autonomous and combined power supply systems with a high reliability and stability level with usage of alternative and renewable power sources for uninterrupted power supply of enterprises with a continuous technological cycle”.

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