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Mathematical Modeling as an Educational Method of Synchronous Generator Operating Modes in a Diesel Power Plant

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Abstract

Mathematical modeling is widely used to study the performance of technical objects. So, it is very important nowadays for electrical engineering specialists to be a master in modeling of electromechanical converters. The course *Mathematical Simulation in Electromechanics* is intended to teach students to use mathematical modeling methods. It is necessary to connect the academic process with practical needs of engineers in order to form strong knowledge and practical skills. The modeling process described in this paper shows that software simulation of a real system can be successfully combined with a traditional form of electromechanical converter's studying. The practical task of researching the synchronous generator operating at a variable speed is considered to provide the professional content in students' education. The modeling process on example of a diesel power plant's synchronous generator is described.

Keywords: Professional content; mathematical simulation in electromechanics; electromechanical converters; mathematical model; synchronous generator; MatLab; model adequacy; operating characteristics; generalized external characteristic.

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1. Introduction

The development and design of modern electromechanical converters are based on computer mathematical models. Using these models, one may predict the behavior of electromechanical converters with given parameters in various modes, and also optimize parameters to achieve the best performances. Electrical engineering specialists should master mathematical simulation methods to work successfully. The course *Mathematical Simulation in*

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Electromechanics is aimed to study up-to-date mathematical modeling methods to solve the problems of electromechanics (Chuchalin, et al., 2002).

Nowadays the programming system MatLab is widely used along with the traditional tools in simulation (Hassell, et al., 2013). It allows expanding possibilities for modeling, making it more mobile and flexible. However, regardless of simulation forms, the most important thing is a practical content of simulation. It is necessary to use vivid examples in teaching. Therefore, much attention in students' education should be paid to the conjunction modeling with practical engineers' tasks or scientific researches.

This paper demonstrates the software simulation of a real life system combined with a practical experiment and the traditional approach (using of characteristics) of electromechanical converter's studying. It is considered on an example of modeling the synchronous generator of a diesel power plant.

2. Diesel power plant's structure

In modeling, it is necessary, first of all, to research the object of simulation, to study its structure and operation, to clarify tasks of simulation as shown below.

Nowadays diesel power plants (DPP) are considered to be one of the primary sources for Russian mobile power. It is necessary for decreasing fuel consumption and increasing efficiency to change the diesel engine speed when changing the load and stabilize the output parameters (voltage and speed) by semiconducting converters (Lukutin, et al., 2009; Leuchter, et al., 2004; Tolbert, et al., 2001).

The structure of considered DPP (Fig. 1) consists of a diesel engine (DE), a synchronous generator (SG) with electromagnetic excitation, a fuel pump regulator (FPR) providing automatic control of engine operating modes according to the preset law, and a generator's voltage regulator (VR) that controls the field winding current. Stabilization of output voltage and frequency is provided by means of the semiconducting cascade that consists of a controlled rectifier-converter (RC), a filter (F), and an independent voltage inverter (AVI). Along with transformation of a three-phase alternating voltage to a constant one the rectifier-converter provides stabilization of output voltage under all operating modes of a generator and a power factor equaled to one. Controlling the DPP operating modes requires the generator operating characteristics' researching for frequency range of 30-50 Hz. The mathematical model is used to solve this problem

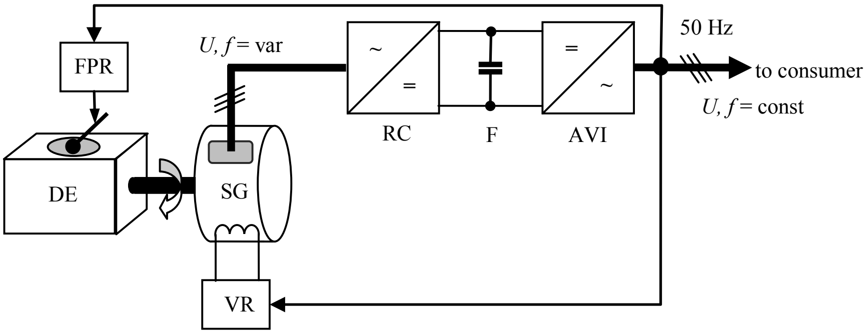

Fig. 1. DPP structure.

The purpose of this work is mathematical modeling of operating modes of the synchronous generator (SG) functioning as a part of the inverter diesel power plant.

3. Synchronous Generator's Model

The object of modeling is a synchronous generator with an electromagnetic excitation and a diesel engine. Changing rotation speed according to the load for minimizing fuel consumption is the feature of synchronous generator operating as a part of DPP system.

The external (voltage-current) characteristic $U = f(I)$ and efficiency are the main performances of a synchronous generator in steady-state modes. Therefore, the SG model as a part of DPP can be presented by the relation between input parameters (rotor's rotation speed, field current and load) and output ones (voltage, armature current and efficiency).

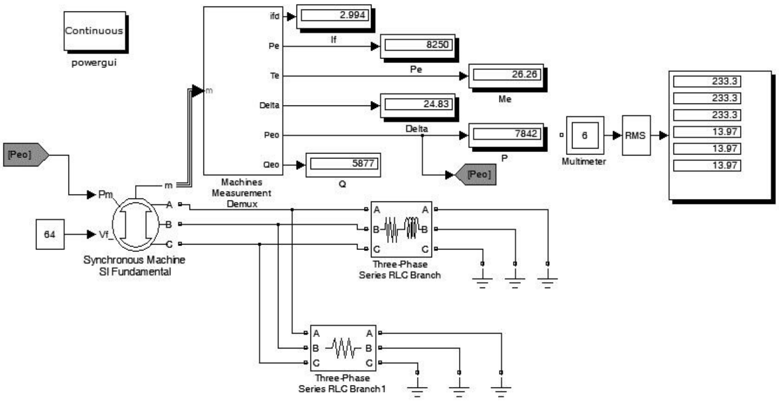

Fig. 2. Synchronous generator model.

The programming systems MatLab, Simulink and SimPowerSystem were used to develop the SG mathematical model (Fig. 2). The model of the synchronous generator in SI units is taken as the basis model that allows considering magnetic circuit saturation in *d* axis by means of the open-circuit characteristic which can be obtained experimentally or calculated. The reactances of the generator are determined with open-circuit and short-circuit experimental data (Voldek, 1978). The verification of mathematical model was made with a help of calculated and experimental data comparison.

4. Test Bed

It is important to realize that the mathematical model should be verified and the best way to test the model is a physical experiment. So, experiments were carried out for a diesel power plant with a described test bed.

The test bed is constructed on the base of KDE12EA3 (Kipor, China) and consists of four-stroke KM2V80 diesel engine (nominal angular speed equals 3000 rpm) and the salient pole synchronous generator KTS12 with an independent excitation.

The synchronous generator has the following ratings: nominal angular speed $n_r = 3000$ rpm, output voltage frequency $f = 50$ Hz, rated apparent power $S_r = 9.5$ kVA, rated phase voltage $U_r = 230$ V, rated current $I_r = 13.7$ A, power factor $\cos\varphi = 0.8$, efficiency $\eta = 0.82$, rated field current $i_{fr} = 3$ A, armature phase winding resistance $r = 0.7$ Ohms, field winding resistance $r_f = 28$ Ohms. The stator winding is Y-connected.

Model adequacy's checking by calculating the nominal operating mode, external and control characteristics at various frequencies shows that the model provides the acceptable steady state accuracy of the operating modes reproduction. The difference of the calculated and experimental data for all operating modes is no more than 5 %.

5. Synchronous Generator Characteristics

The results of modelling can be presented as characteristics.

The SG external characteristics calculated at active load, various field currents (the curve 1 – $i_f = 1.7$ A, the curve 2 – $i_f = 2.33$ A, the curve 3 – $i_f = 3$ A) and frequency of 50 Hz are presented in Fig. 3(a).

External characteristics ($i_f = 3$ A) at different frequencies are illustrated in Fig. 3(b) (the curve 1 – $f = 50$ Hz, the curve 2 – $f = 40$ Hz, the curve 3 – $f = 30$ Hz).

As the short-circuit current at a preset field current doesn't depend on a frequency, the final point of the characteristic ($U = 0$) remains without changes. The initial point of the characteristic (the open-circuit EMF) changes in direct ratio rotation speed. Decreasing rotation speed leads to essential reduction of the open-circuit EMF. At the same time the possibility to regulate voltage is limited by heating of the field winding. So, it is impossible to get nominal voltage at a frequency of 30 Hz even at the open-circuit.

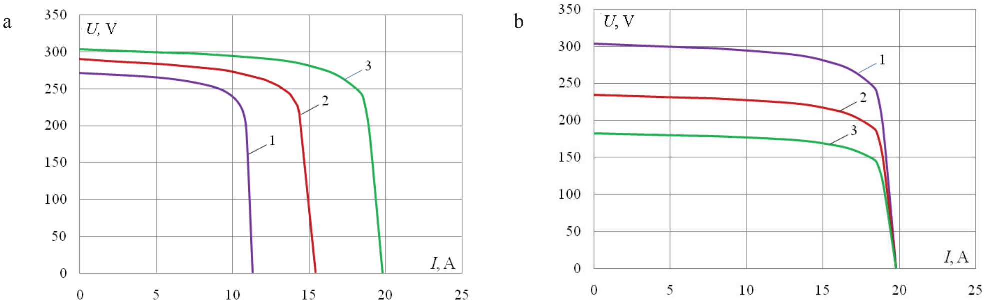

Fig. 3. External characteristics $U = f(I)$.

The control characteristic, constructed at $U_r = 230$ V (the curve 1, Fig. 4) by means of the external one, is well agreed with the experimental curve (the line 2, Fig. 4), that confirms the model accuracy.

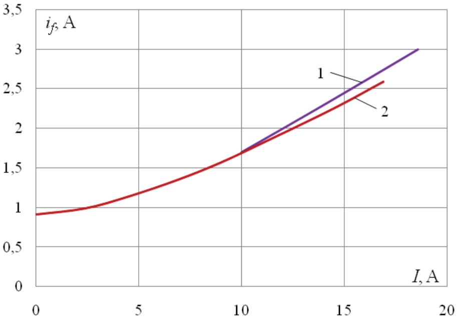

Fig. 4. Calculated (the curve 1) and experimental (the curve 2) control characteristics $i_f = f(I)$.

If the field winding has an independent or controlled DC power supply, a field current and, therefore, a magnetic flux don't depend on rotation speed. In this case it is more convenient to use generator characteristics in per unit (p.u.) values because these characteristics are suitable to study operating modes of synchronous generators with a number of powers that are typical for DPP. Thus, external and control characteristics can be constructed according to open-circuit and short-circuit characteristics.

As the magnetic system saturation remains invariable and there is a linear relationship between rotation speed and open-circuit EMF, so it is possible to describe all family of open-circuit curves with a one curve constructed in per unit values (the curve 1, Fig. 5(a)). The curve 2 corresponds to the synchronous machine's normal characteristic.

It is convenient to take the nominal rotation speed as a basic one, because generator ratings (voltage, power and currents) are identified. The experimental open-circuit characteristic can be obtained at any frequency (in our case it is defined at 30 Hz). The rated field current i_{fr0} at $U = U_r$ in the open-circuit mode (it equals 0.915 A for the studied generator) and the open-circuit EMF E_{r0} corresponding to this field current and a rated frequency are taken as basic values.

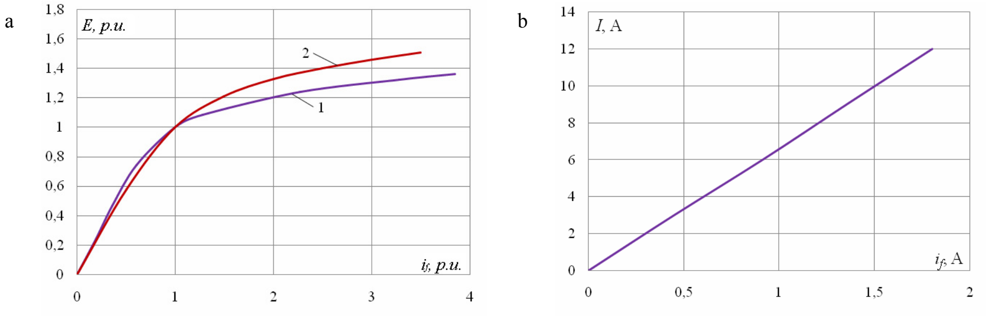

Fig. 5. (a) open-circuit and (b) short-circuit SG characteristics.

To construct the open-circuit characteristic and determine the open-circuit relative EMF E^*_{r0} at any rotation speed n it is possible to use equation:

$$E^*_{0n} = E^*_{r0} \cdot \left(\frac{n_r}{n}\right) \; or \; E^*_{0n} = E^*_{r0} \cdot \left(\frac{f_r}{f}\right) \tag{1}$$

The open-circuit characteristic (Fig. 5(a)) and the ratio (1) allow defining a field current i_{f0}, corresponding to the rated voltage U_r at frequency changing. So, if the point with coordinates $E^*_{r0} = U^*_r = 1$ and $i^*_{fr0} = 1$ corresponds to the rated frequency $f = 50$ Hz, that point with coordinates $E^*_0 = 1.25$ and $i^*_{fr0} = 2.3$ corresponds to the rated voltage and $f = 40$ Hz, i.e. a field current owing to a magnetic circuit saturation increases sharply at decreasing SG rotation speed. EMF $E^*_0 = 1.66$ and field current $i^*_{f0} > 3.28$ correspond to the rated voltage at $f = 30$ Hz (in our case it equals to the rated field current $i^*_f = 3.28$). Thus, at $f = 30$ Hz the possibility of a field current regulation is limited with heating. In this case it is impossible to get a rated voltage even at the open-circuit. Limiting frequency when the rated voltage can be got at $f = 38.5$ Hz.

It is shown that twice decreasing of the frequency in relation to rated one doesn't cause decreasing of a short circuit current if $\beta_d = 2\pi f L_d / r \geq 10$ (L_d – d axis inductance, r – armature phase winding resistance) (Bertinov, 1959).

It is enough to define experimentally only one characteristic of a three-phase symmetric short-circuit (Fig. 5(b)), because this ratio, as a rule, is carried out at the power range of 10-100 kW. It is necessary to note that a power range of 10-100 kW is typical for synchronous generators of the inverter diesel power plants.

The open-circuit and short-circuit characteristics define basic points of external characteristics, and they also give the opportunity to calculate L_d, q axis inductance that is usually $L_q = (0{,}5 - 0{,}7)L_d$.

It is necessary to determine the corresponding external characteristics at each rotation speed, because generators of diesel power plants unlike the general application generators need to be operated with a variable rotation speed.

The external characteristics in per unit values (corresponding to the certain field current the short-circuit current and the open-circuit EMF are taken as the basic values) shown in Fig. 6 demonstrate that it is appropriate to use one curve in the narrow range representing the practical interest of a field current changing.

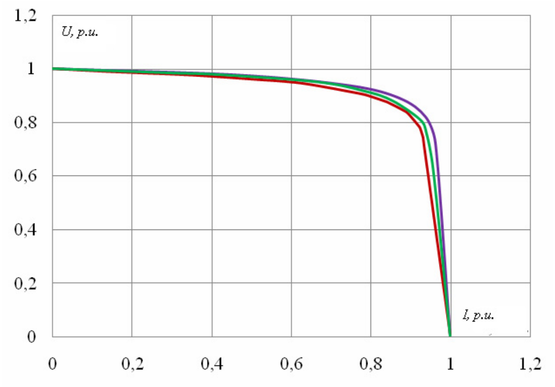

Fig. 6. External characteristics of the generator in per unit values $U^* = f(I^*)$.

Relative changing of voltage doesn't depend on the frequency, if the relation U/f remains invariable at frequency changing (a steady-state condition of a magnetic circuit), therefore in per unit values external characteristics are practically the same at different rotation speeds.

Thus, the generalized characteristic (Fig. 6) to construct the external characteristics at any field current and frequency values can be well used. The basic points (basic voltage and basic current at the preset field current and frequency values) are determined by open-circuit and short-circuit characteristics.

The generalized characteristic is practical results of modeling. The practical value of the characteristic is that it allows evaluating different modes of the generator and it suits to develop a control algorithm of the generator.

6. Conclusion

Mathematical modelling is widely used to solve engineering and scientific problems. So, for present students it is necessary to be successful in work that means to be very good in simulation. As for teachers, they should supply a practical and professional content when he or she teaches students to model, to use modern tools for modelling and to show how modern tools of software modelling can be coordinated with a classical form of investigations of technical objects.

The synchronous generator's modelling described in the paper demonstrates those aspects in teaching of electrical engineering students in the course of *Mathematical Simulation in Electromechanics*.

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