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„ИЗСЛЕДВАНЕ И АНАЛИЗ НА ПРОЦЕСИ И РЕЖИМИ ”

10.09.2021

09:00-11:00 **Зала: 1**
Председател: доц. д-р инж. Людмил Стоянов
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Modeling of experimental bench for grid connection of synchronous machine

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***Abstract*— The goal of this work is to develop a mathematical model of an experimental test bench used for laboratory works on the discipline ''Electrical machines part 2". This model will be presented to the students during their distance learning, imposed by the COVID-19 pandemic. The test bench in mind is used to consider the process of connecting a synchronous generator to the electrical grid. The generator's parameters are measured and applied to a model of the machine in the Matlab/Simulink environment. The simulation results are compared with the experimental ones and show good correspondence.**

Keywords— distance learning, synchronous machine modeling, machine parametrization.

I. INTRODUCTION

In the past two years, the COVID-19 pandemic imposed the need for distance learning practices all over the world and Bulgaria [1-6]. In a recent article [7], the authors presented a web-based Matlab application for laboratory exercises on Electrical machines for the needs of the students in the Technical University of Sofia.

The aim of the present work is to improve the presented web-based models of the studied electrical machines, so that the students be able to compare the results, obtained by the simulations with experimental results, obtained by the actual test benches. For this purpose, the main parameters of the simulated synchronous generator in mind must be determined with corresponding tests [8], [9], so that they can be used in a mathematical model of the machine based on the generalized theory of the electrical machines [10], which is then transformed to a Matlab web-based app.

Fig. 1. The experimental test bench modelled in this study.

II. SYNCHRONOUS GENERATOR MODELLING

The web applications that are used to present the laboratory exercises to the students are based on modelling the test benches in the Matlab/Simulink and Matlab/Simscape environments [11]. The test bench, presented in this work (see Fig. 1) is used to familiarize the students to the process of connecting a synchronous generator to the electrical grid. To model the studied synchronous generator the equations of the generalized theory of the electrical machines are used [12]. The generator's main parameters are presented in Table I.

TABLE I. PARAMETERS OF THE MODELLED SYNCHRONOUS MACHINE

Parameter	Dimension	Value
Rated power, P	kVA	10
Rated voltage, V	V	400
Frequency, f	Hz	50
Excitation current, I_f	A	20.5
Stator resistance, R_s	Ω	0.527
Leakage inductance, L_σ	H	0.0116
d-axis inductance, L_d	H	0.0392
q-axis inductance, L_q	H	0.0306
Field winding resistance, R_f'	Ω	0.6
Field winding inductance, L_f'	H	0.0073
d-axis damper resistance, R_{kd}	Ω	4.772
d-axis damper inductance, L_{kd}	H	0.0263
Inertia, J	$kg.m^2$	0.0923
Pole pairs, p	-	2

To simulate the currents and voltages in the synchronous generator the following equations are used:

$$\left| \begin{array}{l} \dfrac{d\Psi_d}{dt} = U_d + \omega_r \Psi_q + R_S \dfrac{\Psi_{md} - \Psi_d}{L_{\sigma s}} \\ \dfrac{d\Psi_q}{dt} = U_q + \omega_r \Psi_d + R_S \dfrac{\Psi_{mq} - \Psi_q}{L_{\sigma s}} \\ \dfrac{d\Psi_f}{dt} = U_f + R_f \dfrac{\Psi_{md} - \Psi_f}{L_{\sigma f}} \\ \dfrac{d\Psi_{kd}}{dt} = R_{kd} \dfrac{\Psi_{md} - \Psi_{kd}}{L_{\sigma kq}} \\ \dfrac{d\Psi_{kq}}{dt} = R_{kq} \dfrac{\Psi_{md} - \Psi_{kq}}{L_{\sigma kq}} \end{array} \right. \quad (1)$$

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$$\begin{cases} i_d = \dfrac{\Psi_d - \Psi_{md}}{L_{\sigma s}} \\ i_q = \dfrac{\Psi_q - \Psi_{mq}}{L_{\sigma s}} \\ i_f = \dfrac{\Psi_f - \Psi_{md}}{L_{\sigma f}} \\ i_{kd} = \dfrac{\Psi_{kd} - \Psi_{md}}{L_{\sigma kd}} \\ i_{kq} = \dfrac{\Psi_{kq} - \Psi_{mq}}{L_{\sigma kq}} \end{cases} \quad (2)$$

here U_d and U_q represent the stator voltages for both axes (d – direct, q – quadrature), U_f is the voltage of the field winding, R_s is the resistance of the stator winding, R_f is the resistance of the field winding, R_{kd}, R_{kq} are the resistances of the damping winding of both axes of the rotor. The projections of the current for both axes are represented by i_d and i_q and the projections of the magnetic flux vectors for both aes are represented by Ψ_d and Ψ_q. The current and the magnetic flux of the field winding are represented by i_f and Ψ_f and i_{kd}, Ψ_{kd}, i_{kq} and Ψ_{kq} are the currents and magnetic fluxes in the dampening winding. The leakage inductances of the stator, field and dampening windings are represented by $L_{\sigma s}$, $L_{\sigma f}$, $L_{\sigma kd}$ and $L_{\sigma k}$. The mutual induction flux linkages of the machine are Ψ_{md} and Ψ_{mq}.

The equation for the modelled machine's electromagnetic torque is:

$$T_e = \frac{3}{2} p\left(\Psi_d i_q - \Psi_q i_d\right) \quad (3)$$

here T_e is the electromagnetic torque and the pole pair number is represented by p, which in this case equals 2.

These equations require the knowledge of the synchronous inductances *Ld* and *Lq* as well as the stator resistance *Rs*. These parameters are determined experimentally and used in the presented equations to simulate the operation of the studied electrical machine.

III. Determination of the Generator's Parameters

There are various methods, presented in the literature for determination of the synchronous inductances *Ld* and *Lq* of a synchronous machine [9]. The method that is used here is called DC-attack of the stator winding and is presented in [8]. This method consists of connecting the stator phase of the studied synchronous machine to a DC voltage source (Fig. 2). The transient of the current in the stator winding is registered with an oscilloscope and then, using the following equations the synchronous inductances are determined.

The transient of the *id* or *iq* current (Fig. 3) is represented by:

$$i_{d,q}(t) = K_0^{'} - K_1^{'} e^{-\frac{t}{T_1^{'}}} - K_2^{'} e^{-\frac{t}{T_2^{'}}} \quad (4)$$

The constants $K_0^{'}$, $K_1^{'}$, $K_2^{'}$, $T_1^{'}$, $T_2^{'}$ are determined from the registered currents by using Matlab's Curve fitting tool as shown in Fig. 3.

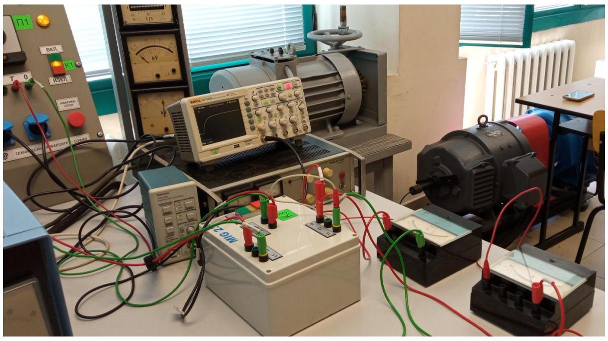

Fig. 2 The experimental setup, used to perform the DC-attack test for determination of the synchronous inductances.

Different parameters can be determined with the obtained constants. The first one is the stator resistance, which can be measured or determined using the following equation:

$$R_s = \frac{E^{'}}{K_0^{'}} \quad (5)$$

The inductances *Lad* and *Laq* can be calculated using the constants $K_0^{'}$, $K_1^{'}$, $K_2^{'}$, $T_1^{'}$, $T_2^{'}$ by:

$$L_{ad,aq} = T_1^{'}.R_s \frac{1 + \dfrac{K_2^{'}}{K_1^{'}}\dfrac{T_2^{'}}{T_1^{'}}}{1 + \dfrac{K_2^{'}}{K_1^{'}}} \quad (6)$$

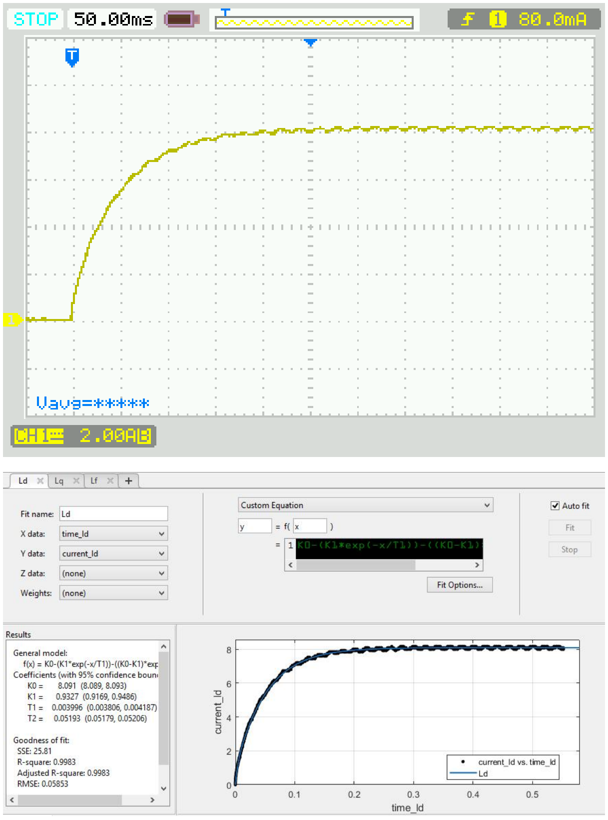

Fig. 3. Measured current from the experiment for determination of the L_d inductance (top) and results from Matlab's Curve Fitting Tool (bottom).

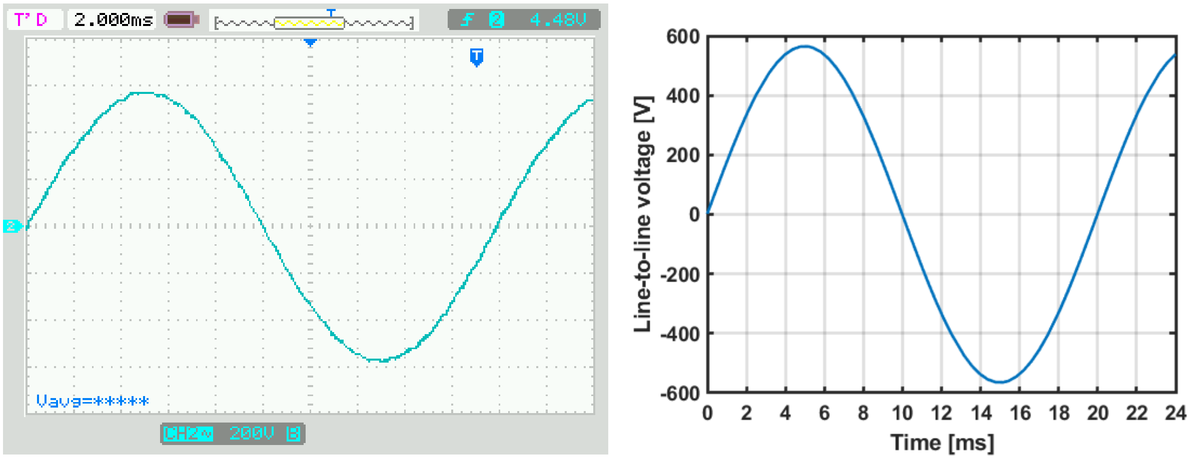

Fig. 2. Measured (left) and simulated (right) line-to-line voltage of the modelled synchronous generator at rotational speed n=1500 rpm.

The synchronous inductances *Ld* and *Lq* are calculated by:

$$L_{d,q} = \frac{3}{2} L_{ad,aq} \tag{7}$$

The registered transient current during the measurement of the *Ld* synchronous inductance, as well as a screenshot of the Matlab's Curve fitting tool used for determination of the constants presented in eq. (4) are shown in Fig. 3. Using these parameters, the synchronous inductances are determined.

The experimentally obtained values of the synchronous inductances *Ld* and *Lq*, as well as the stator resistance *Rs* are presented in Table I.

These values are used in the model of the synchronous generator, which is validated experimentally. A comparison of the measured and simulated waveforms of the phase voltage of the synchronous generator, operating at similar conditions is presented at Fig. 4. The results from the simulations of the generator show good correspondence with the experimental results, which permits the use of the developed model for further use.

IV. Results

The presented model of the synchronous generator is used to simulate the connection of the machine to the electrical grid. During the laboratory exercise, the students connect the generator to the grid while all of the necessary conditions for branching a synchronous generator to the grid are fulfilled. These conditions are [13]:

- The voltages of the generator U_{SG} and the grid U_{grid} must be equal;
- The frequency of the generator f_{SG} and the frequency of the grid f_{grid} must be equal;
- The phase order of the synchronous generator and the grid must be equal;
- The connecting of the generator to the grid must be done in the moment when the generator's voltage is in phase with the grid's voltage.

The developed model permits the simulation of the cases where at least one of these conditions is not met, which would help demonstrate the students the processes taking action during imperfect coupling of the generator to the electrical grid, without posing risk to their health. Such imperfect connections are also studied on the real experimental bench, but the deviations are smaller to protect the machines and apparatus. The following figures (Fig. 6) present the currents and voltages of the modelled synchronous generator during perfect and imperfect couplings to the grid. The imperfections are difference in the phases of generator's and grid's voltages and difference in their amplitude.

The presented model is also used to determine the V-curves of the synchronous generator. These curves represent the relation between the armature current *I* and the field winding current I_f: $I=f(I_f)$ while the load is kept constant. By knowing this relation the reactive power supplied to or consumed from the electrical grid can be controlled. The simulated and the experimentally obtained V-curves of the studied synchronous machine are shown at Fig. 5.

The correspondence between the measured and simulated shapes of the V-curves of the synchronous machine proves the adequacy of the developed model and permits its use in the distance learning process. Using this model the students will be able to understand the relation between the field current of the machine I_f and the power factor during different modes of operation – as a synchronous motor, generator or compensator.

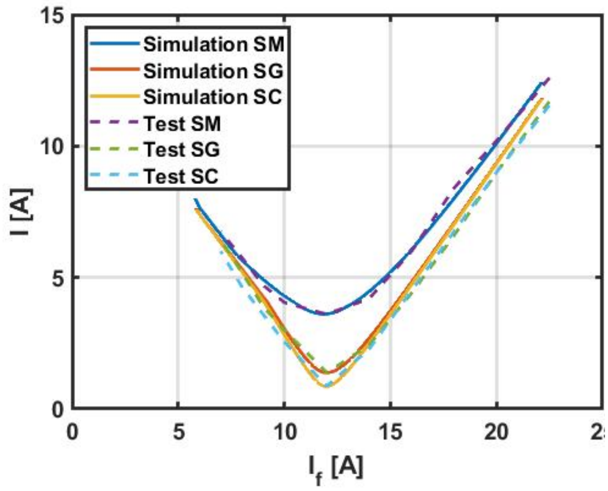

Fig. 5 Simulated and measured V-curves of the studied synchronous machine.

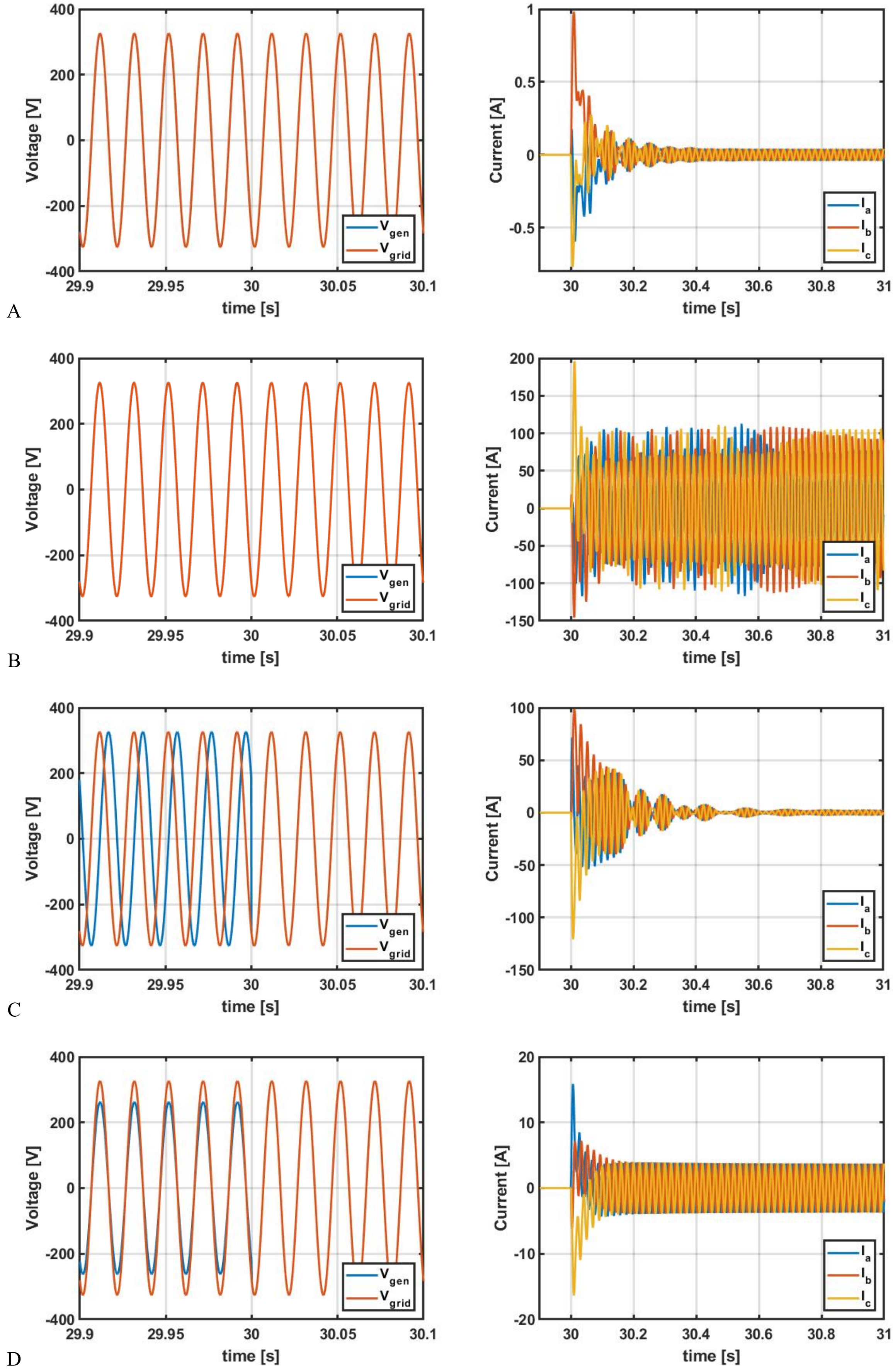

Fig. 6 Simulated voltages at the moment of branching the synchronous generator to the electrical grid (left) and currents of the synchronous generator right before and after the coupling (right) of the studied cases. From top to bottom: **A** - Ideal coupling to the electrical grid; **B** - Different phase order (ABC-ACB); **C** - Different voltage phases before the coupling; **D** - Different voltage amplitudes before the coupling.

V. CONCLUSION

This work presents the development and the improvement of a mathematical model of a synchronous generator, used in a Matlab web application for the purposes of distance learning. The developed model is presented to the students of the Technical University of Sofia during their laboratory works on Electrical machines part 2. The model is validated experimentally and the results show acceptable accuracy. This model can simulate different scenarios of branching a synchronous generator to the electrical grid, some of which can not be done with high deviations during the laboratory exercises, due to the risk they impose to the lab equipment and the students' health. This model can be used to improve the quality of education in the Specialty Electrical engineering in the Technical University of Sofia and other higher schools.

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