Application of Synchronous Machines' Models for Distance Learning Purposes

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Abstract—**This paper presents the creation of a set with appropriate web applications, using Matlab Web Apps. The set's aim is to ease the teaching process in distance learning for Engineering specialties in Electrical engineering. This set represents an adaptation of the existing test benches in the laboratory exercises of the discipline Electrical Machines part II, especially for the synchronous machines. The developed web applications propose a user-friendly and realistic user interface. The machines are modeled following the generalized theory of the electrical machines in the Matlab environment. The models are then transformed in web applications. The presented simulation and experimental results show good correspondence, which justify the applications' accuracy.**

Keywords—*distance learning, synchronous machine modeling, Matlab Web Apps.*

I. INTRODUCTION

In recent years distance learning is becoming more popular across Europe and the world [1]. The COVID-19 pandemic [2] further augmented the need of distance learning practices in all fields of education amongst students all over the world [3], [4]. The distance learning in the Engineering field is very challenging because of the practical exercises, characteristic for the engineering education. This imposes the need of adaption of the laboratory works to the distance learning process.

The aim of this work is the creation of a software-based environment for simulation of laboratory works for the discipline Electrical machines part II, that comprises synchronous and DC machines. The environment is developed with the aid of Matlab/Simulink and Matlab/Simscape libraries. The aim is to develop simulation models of the real laboratory experimental stands. The models of the synchronous machines are based on the equations of the generalized theory of electrical machines, which has proven to be the most correct way of modelling the transient modes of operation of this type of electrical machines [5], [6]. This allows the creation of a library of simulation models of the different laboratory works.

The developed models of the electrical machines are used to simulate their operation during stationary and transient operation modes. The models allow repeatability of the conducted experiments, development of control algorithms etc. The use of simulation models provides a tool for the observation of the ongoing processes in the studied machine without the need of its physical presence, as well as a means to predict the machine's behavior during different operation modes. This circumstance is exceptionally useful for the process of distance learning.

The laboratory exercises modelled in this work are aimed at consideration of different aspects of the synchronous machines for the students by:

- determination of the SG's no-load, short-circuit and inductive load characteristics;
- study the current transients of the SG during three phase, two phase and single phase to neutral short circuit;
- study of the transients of the SG's current during perfect and imperfect coupling to the electrical grid and determination of the machine's V-curves;
- determination of the operational characteristics of a synchronous reluctance motor;
- determination of the losses and the performance of a synchronous generator.

The above-mentioned laboratory practices have proved their importance over the years in forming the students' knowledge in the field of synchronous machines. The practices combine classical experiments and improvements in the frame of project in the Human resources development operational program of the European Union.

II. MODELLING

This work is focused on the modelling of synchronous generators for the use in the distance learning process. The models of the studied electrical machines are based on the equations presented in [7] and [8], as well as models from the Matlab's Simscape library [9]. The following classical assumptions have been made during the modeling process:

- the iron losses and mechanical losses in the generators are neglected;
- the magnetic circuit is considered linear and the saturation effects are neglected;
- the rotor variables are referenced to the stator, with a factor k_f=1.11;
- the synchronous generators operate in parallel with an infinitely powerful electrical grid.

The models in the Matlab/Simulink environment allow the simulation of the saturation and autonomous operation mode.

The classical equations describing the voltage behavior, the currents and the flux linkages of the synchronous machine are summarized in two equation systems:

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

$$\left|\begin{aligned} i_d &= \frac{\Psi_d - \Psi_{md}}{L_{\sigma s}} \\ i_q &= \frac{\Psi_q - \Psi_{mq}}{L_{\sigma s}} \\ i_f &= \frac{\Psi_f - \Psi_{md}}{L_{\sigma f}} \\ i_{kd} &= \frac{\Psi_{kd} - \Psi_{md}}{L_{\sigma kd}} \\ i_{kq} &= \frac{\Psi_{kq} - \Psi_{mq}}{L_{\sigma kq}} \end{aligned}\right. \qquad (2)$$

where U_d and U_q are the stator voltages for the direct (d) and quadrature (q) axes respectively, U_f – the field winding voltage, R_s – the stator winding resistance, R_f – the field winding resistance, R_{kd}, R_{kq} – the resistances of the damping winding of the rotors d and q axes, i_d and Ψ_d are the projections of th,e current and the magnetic flux vectors on the direct axis (d); i_q and Ψ_q are the projections of the current and flux vectors on the quadrature axis (q); i_f and Ψ_f are the current and the magnetic flux of the field winding; i_{kd}, Ψ_{kd}, i_{kq} and Ψ_{kq} are the currents and magnetic fluxes in the dampening winding; $L_{\sigma s}$, $L_{\sigma f}$, $L_{\sigma kd}$, $L_{\sigma kq}$ are the leakage inductances of the stator, field and the d and q dampening windings respectively; Ψ_{md} and Ψ_{mq} are the mutual induction flux linkages.

The equation for the synchronous machine's electromagnetic torque, which is used in the machine's drive train, is:

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

where T_e is the electromagnetic torque and p is the pole pair number.

The above mentioned model needs different parameters of the synchronous machine to represent its behavior. the synchronous inductances L_d and L_q, the field winding inductance L_f and the stator and field winding resistances R_s and R_f must be determined experimentally. These values are determined according to the methods presented in [10].

The parameters of the synchronous machine, available at the Laboratory of Electrical machens II are presented in Table I.

TABLE I. PARAMETERS OF THE MODELED SYNCHRONOUS GENERATOR

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	0.655
Leakage inductance, L_σ	H	0.0045
d-axis inductance, , L_d	H	0.0506
q-axis inductance, L_q	H	0.0263
Field winding resistance, R_f'	Ω	1.2
Field winding inductance, L_f'	H	0.388
d-axis damper resistance, R_{kd}	Ω	3.142
d-axis damper resistance, R_{kq}	Ω	4.772
Inertia, J	kg.m^2	0.0923
Pole pairs, p	-	2

The presented model has been implemented in Matlab/Simulink environment and experimentally validated by comparison of experiment and simulation. Fig. 1 presents a comparison of the simulated and experimentally measured line-to-line voltages of the machine for a rotational speed of 1500 rpm, which shows good overlap of both graphs. The comparison between the simulated and experimentally obtained results confirms the adequacy of the developed model. This confirmation permits the transformation of the model to a Matlab Web App [11]. Web apps are applications that use Matlab in background and can run in a web browser, without the need to install any software. The transformation of the model in application follows several steps – export of the model in C code, graphical interface and interconnection between them by compilation. The first and the last steps are visualized on Fig. 2.
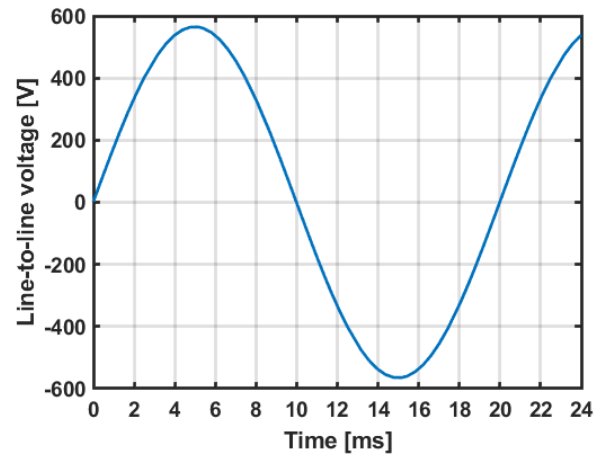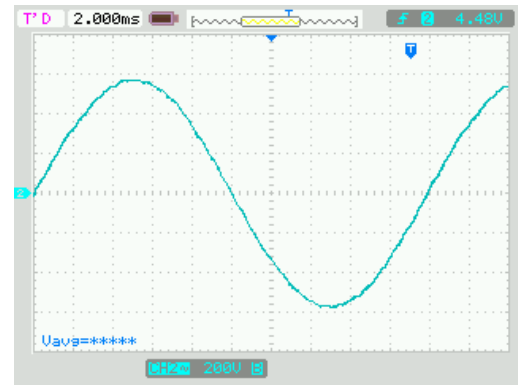

Fig. 1 Measured (top, 200V/div and 2 ms/div) and simulated (bottom) line-to-line voltage of the synchronous generator.
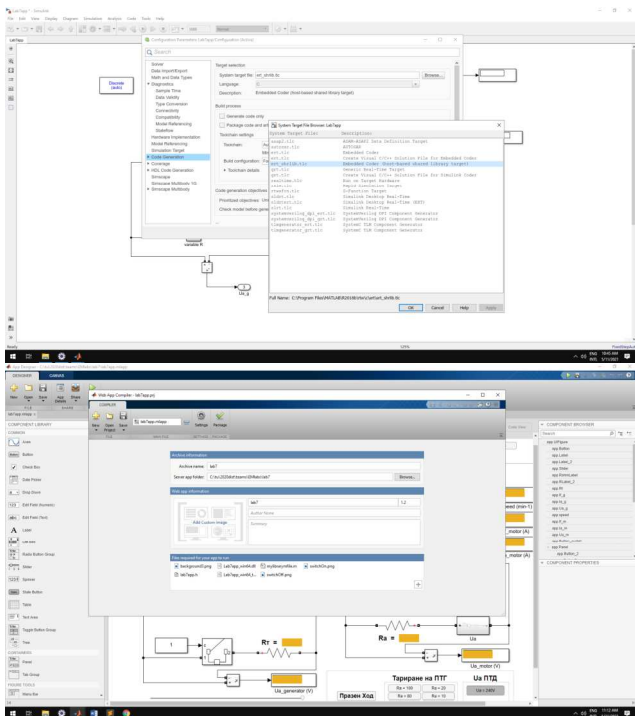
Fig. 2 Compilation of the Simulink model to a C-code (top) and compilation of the developed Web App (bottom).

Each web app has a unique URL address that can be accessed from a web browser. The server has a home page listing all available hosted at the moment web apps. These URL's are sent to the students who then can access the developed model through their web browsers, without the need of buying a Matlab license.

III. WEB APP DEVELOPEMENT

The process of developing the Web Apps is based on studying the experimental test bench and establishing the required measurements, that have to be made for each laboratory work. The machines in the test benches are modelled trough the presented equations or by using the available models in the Matlab Simscape library. A validation of the developed models is made by comparing the simulated results with results obtained from the laboratory test benches. After the mathematical models have been validated and their adequacy has been confirmed, the developer can proceed to the creation of the web apps. First the created Simulink model must be transformed into a C code with the aid of Matlab's Simulink Coder (Fig. 2 up). Then, the generated code is built into a library, which is used in the Matlab Web App designer to develop the app for the desired laboratory work. The developed Web App is then compiled to a *.mlapp file (Fig. 2 down) and uploaded to the Web App server. The server has its unique URL address, that is sent to the students at the beginning of each laboratory work, so that they could perform the experiments themselves.

IV. RESULTS

The main result of this work is the created set of models and developed MATLAB Web Apps – Fig. 3. An example for the stages in the realization of the library is presented on Fig. 4, where the real experimental bench for study the coupling process of a synchronous generator to the electrical grid is shown with the respective 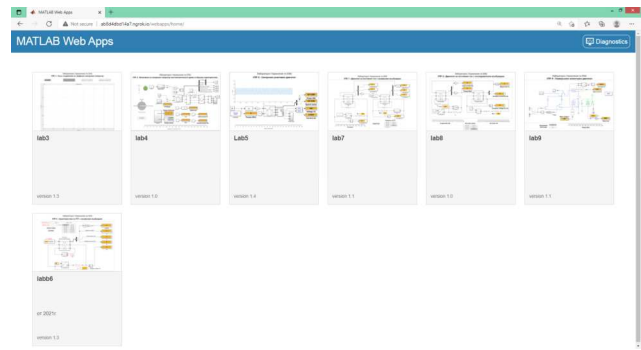simulation model and the web app. The MATLAB Web App set allows the students to access the developed models and to perform their exercises without

Fig. 3 Matlab Web App library developed for the laboratory works.

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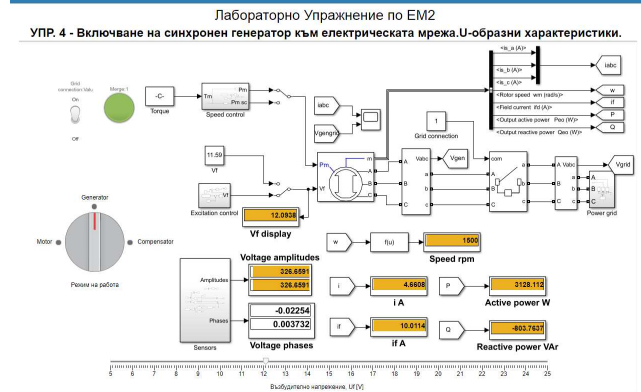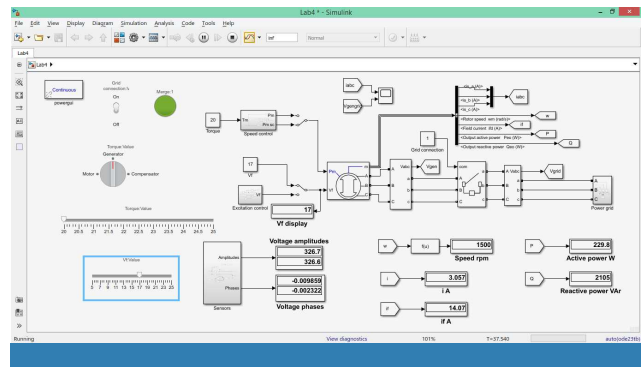

Fig. 4 Experimental test bench (up), simulation model (middle) and web app (down) used to study the coupling process of a synchronous generator to the electrical grid.

risking their health in the current COVID-19 pandemic. The V-curves of the modeled synchronous machine, obtained by the developed Web App are presented at Fig. 5.

Another result is presented at Fig. 6, which illustrates experimental (from the real test bench) and Web app incorporated curves of the phase currents, obtained during the
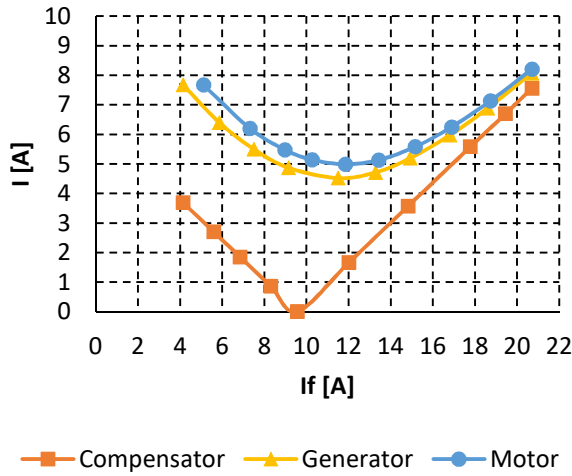
Fig. 5   Web App obtained V-curves of a synchronous machine, operating as a synchronous generator (yellow triangles), motor (blue rounds) and compensator (orange squares).
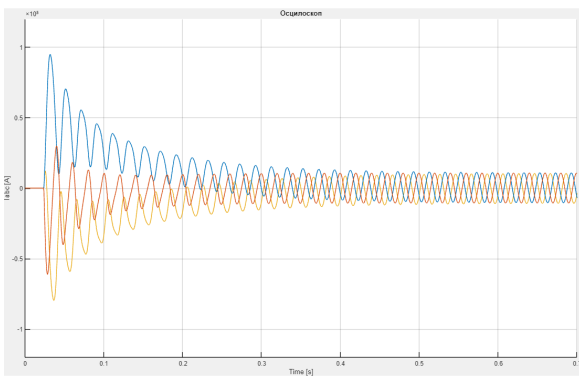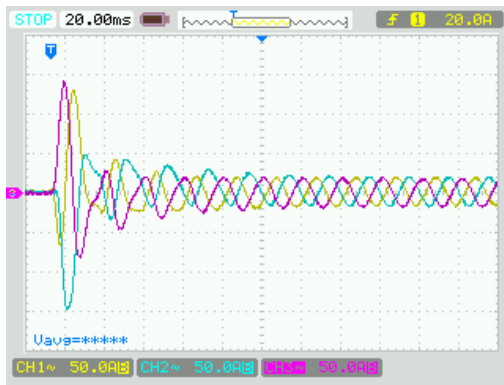

Fig. 6   Experimental (up) and Web app (down) results of the phase currents of the synchronous generator in the case of three-phase short-circuit.

study of currents' transient during three phase short circuit of synchronous generator. Due to the model's assumptions the comparison shows differences in the transient process but the overall behavior of the machine is represented by the realized web app and thus the app can be used for distance learning of the students.

The developed Web App of a laboratory work studying the operation of a reluctance motor is presented at Fig. 7. There the phase current of the motor is visualized along with the other required measurements. Thus the students can see how overloading the tested reluctance motor affects it and the difference in the synchronous and asynchronous operation

mode. The operation characteristics of such motor, obtained through web app and experimental bench are presented at Fig. 8. The comparison of the characteristics shows similar behaviour of the real and simulated motor, because the main difference between both graphs is the variables' scale – the web app uses parameters of motor with greather rated power,

V.   CONCLUSION

The paper presents the realization of web-based library with models of the laboratory works on Electrical machines
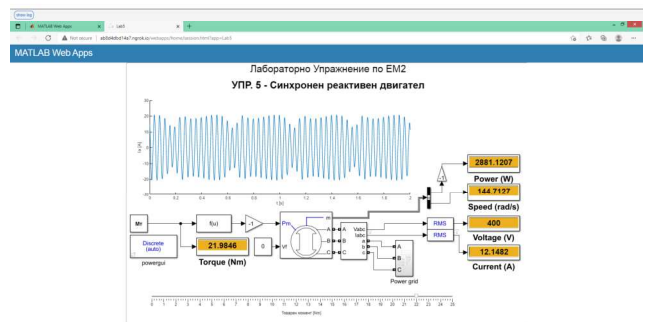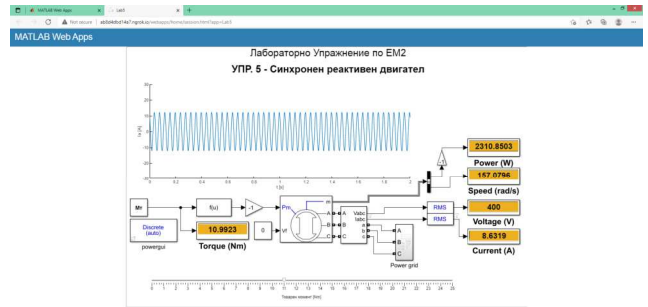

Fig. 7   Laboratory work, presenting a reluctance motor, operating at synchronous (top) and sub-synchronous (bottom) speed.
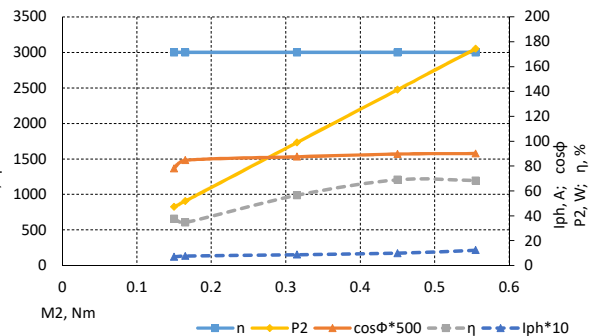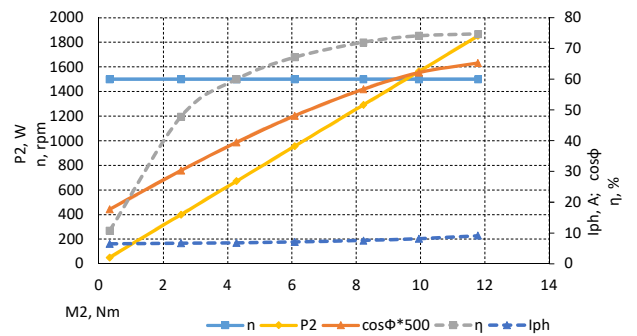

Fig. 8   Operation characteristics of a reluctance motor obtained by the developed Web Apps (up) and during a laboratory work and real experimental bench (down).

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part II with synchronous machines. On the basis of the experimental benches in the laboratory at Technical University of Sofia, different simulation models are created to simulate the procedures during the real laboratory works. Finally, the models are transformed in web apps, which can be used by the students without specialized product license. The results of the performed simulations of the laboratory exercises show good correspondence with the experimentally obtained results. This shows the adequacy of the developed models and permits their use in the learning process. The developed set of models and respectively apps will permit to the students to simulate and explore different operating scenarios of the studied electrical machines. This set will also permit the study of different faults like short circuits or incorrect connection of the machine's phase outlets to the electrical grid without danger for the studied machine or the students' health.

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