Real-Time Control of Synchronous Generator in Island Mode Based on LabVIEW Software for Education Purpose

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Abstract: - In the last decades, Personal Computers are becoming powerful with acceptable prices. This has conduct in emergent requests for very sophisticated applications, which not only offer reliable simulations for the dynamic systems, but also to generate codes for real-time control of the electric drives. In this paper is presented a virtual system for monitoring and control of a salient-pole synchronous generator. This synchronous generator is connected to a DC motor acting as a turbine. The system is able to control the motor speed and the voltage of the generator stator windings. It consists of a portable PC and a Desktop PC connected in host/target configuration. The application is created in the LabVIEW environment. This system is fully available for the master degree students of Electrical Engineering Faculty of Tirana and recommended as a low cost alternative for education purpose.

Key-Words: - Real-Time Control**,** Synchronous generator, LabVIEW, host/target configuration, low cost alternative

1 Introduction

Nowadays, the real-time control of the electrical machines is becoming more popular in the engineering fields because of the quick progress in the power semiconductor technologies. Because of the advent of software tools like Matlab/Simulink with *Real Time Workshop* and *Real Time Windows Target* or LabVIEW with *Real Time Module,* the real-time issues are becoming more evident for the control of the electric machines [1], [2].

In the literature [3] is presented an educational simulation tool for Power System studies created in Matlab and in literature [4] are shown some applications created in LabVIEW, to demonstrate its advantages as a software for simulations, visualizations and process control.

To achieve the goal, that will be shown later through this paper, we will use LabVIEW. The principal reason is because of some LabVIEW abilities.

One of the LabVIEW ability is to get data from the real world through multifunctional DAQ (data acquisition) devices, process them in the block diagram and send the results back to the physical environment [5].

It is also compatible with most of the well-known operating systems and in this point of view the Virtual System, that will be presented here, can be recreated in the Control System Laboratories for education purpose and for other targets.

2 System description

Synchronous machines are widely used as generators for electrical power generation. There are several ways of the synchronous generator connection to the electrical grid. One of them is the island mode connection. In this case the machine is disconnected from the Power System and its rotor speed depends by the mechanical power applied to it and the changes of the load in the stator windings [6].

Figure 1 shows the overall functional block diagram of the synchronous generator bench built in the laboratory, in order to test the generator speed controller and voltage controller.

The main parts of the control system are the custom-built AC-DC converters, three phase quantity measurements module, motor speed measurement module, voltage controller and speed controller module, and monitoring module.

Although in the diagram we have included the synchronization of the generator to the electrical grid, it is possible only manually for the moment. In future we forecast to do this process automatically from the target PC in real-time, with the help of LabVIEW.

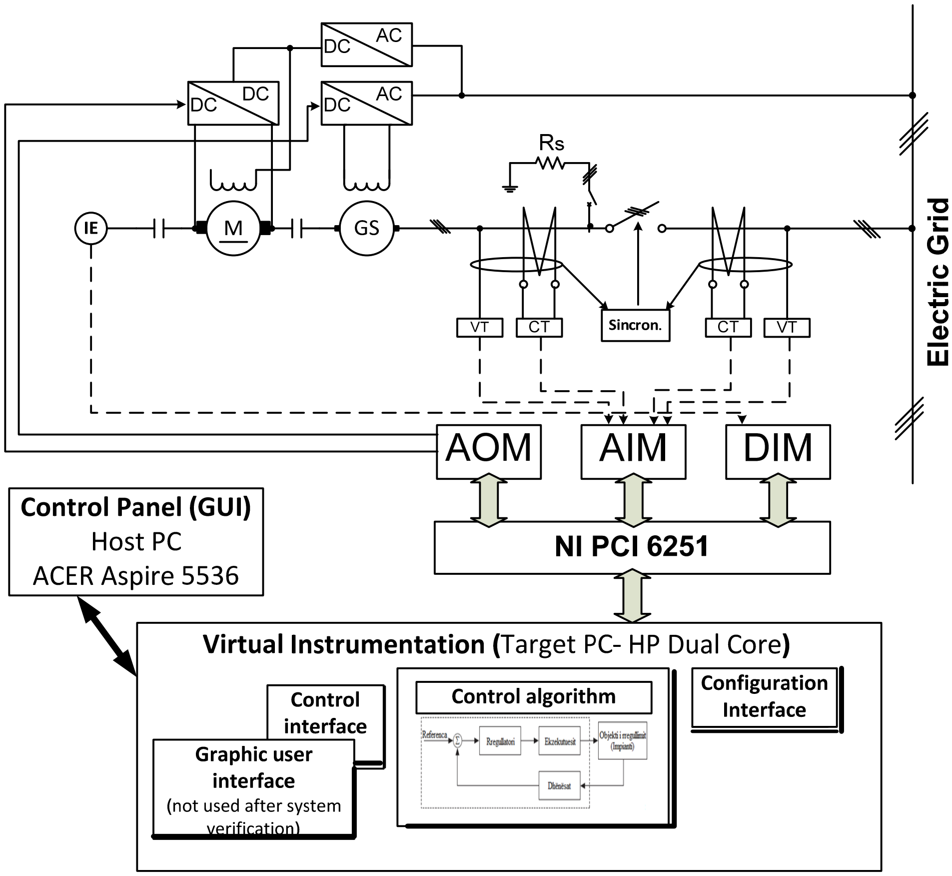

Fig. 1 Overall block diagram of the synchronous generator control and monitoring system in LabVIEW

2.1 Three phase electrical quantities measurement module

Figure 2 shows the custom-build three phase system electrical quantities measurement module - **AIM (Analog Inputs Module)**. It consists of three Hall Effect sensors for measuring the 3-phase AC voltages in the range 0-275V r.m.s. and three other Hall Effect current sensors, which are calibrated for AC phases currents measurement in the range of 0-1A r.m.s.

The module includes also six conditioning circuits and six variable resistors to convert and isolate the instantaneous values of the 3-phase voltages and currents. The output values of the module are taken from six resistors (2 for each phase) and the range is 0-3,5V. The module response (delay) for each sensor is 20 µsec-100µsec.

2.2 DC Motor Speed measurement Virtual Instrument

Figure 3 shows the front panel of the virtual instrument created in LabVIEW for speed measurement of the DC Motor. The incremental encoder (IE) used, gives 1024 impulses/revolution, and for the rated motor speed of 1500 rev/min we have a 25,6 kHz pulse train.

The virtual instrument is calibrated using a signal generator instrument. During test, we saw that for the speed value of 1500 rev/min, the best accuracy we achieved with the instrument running in Windows 7, was 0,5%.

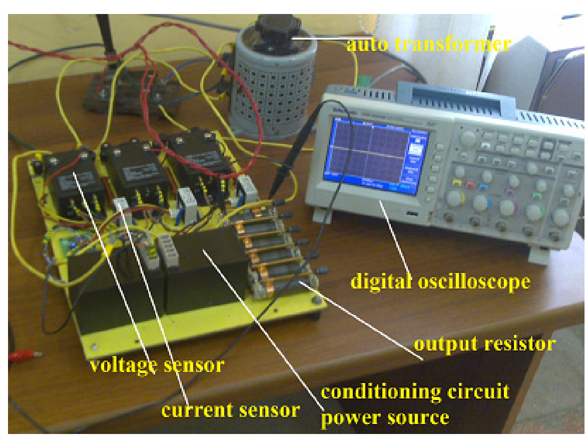

Fig. 2 Three-phase electrical quantities measurement module

Because we wanted an accuracy of 0,05%-0,1% we configure a desktop PC to run a real-time operating system. In this manner we could iterate the pulses acquisition loop in the order of 400 μsec.

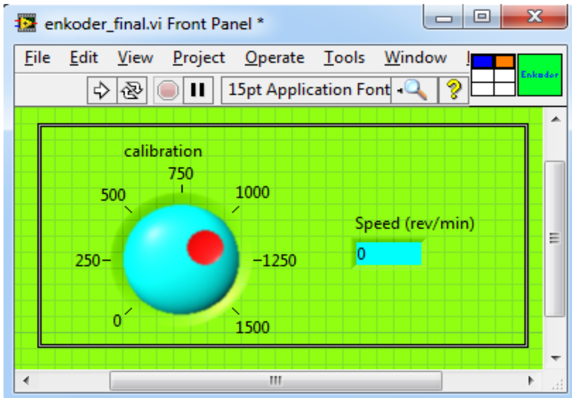

Fig. 3 Front Panel of speed measuring virtual instrument

The use of real-time computer is justified because the delay introduced by encoders in the speed control in closed loop is the main reason of instability of the digital speed control system [7].

In figure 1 it is shown that the DC motor is mechanically coupled to the synchronous generator. Controlling the motor speed is equal to control the generator electrical frequency at its stator windings, because of the relation between rotor mechanical angular velocity (**Ω**) with the stator electrical frequency (**f**), that is:

$$\Omega = \frac{2\pi f}{p} \tag{1}$$

or the speed in rev/min:

$$n = \frac{60 f}{p} \tag{2}$$

where:

p- number of the rotor pair of poles

In appendix (Table 2-3) are shown the types and parameters of the DC machine and Synchronous machine used in this work.

The major problem we faced during instrument programming in LabVIEW, was the counter reset in the **- DIM (Digital Inputs Module),** which was successfully solved by following the solution given in [8].

2.3 Custom-built AC-DC converters

For the speed and voltage control of the synchronous generator (SG) in island mode we designed 2 almost identical AC-DC converters.

We chose to command the converter output through a PWM signal generated by comparing a 20kHz triangle signal generated by the converter circuit with a constant DC voltage generated from the multifunctional DAQ NI PCI 6251 (fig 1).

This solution is very comfortable, if we want in the future to replace the real-time desktop PC with a limited capacity microcontroller based platform.

Figure 4 shows custom-built AC-DC converter. It can produce a variable DC voltage in the range 0-250V with a current up to 8A. The converter output can be controlled manually using a knob (potentiometer) or programmatically using one of the analog outputs (AO) of the NI PCI 6251 interfaced by the **AOM (Analog Outputs Module)**. The duty cycle depends on the reference voltage level from the AO of the PCI 6251 in the range 0V-2V DC. As final stage, we have used IRF 840 MOSFet transistors.

The variables that will be controlled are:

1) Speed of the DC motor, changing its armature voltage while maintaining constant its voltage of the field (excited) winding.
2) Voltage of the SG generator stator windings, changing its DC voltage of the field winding.

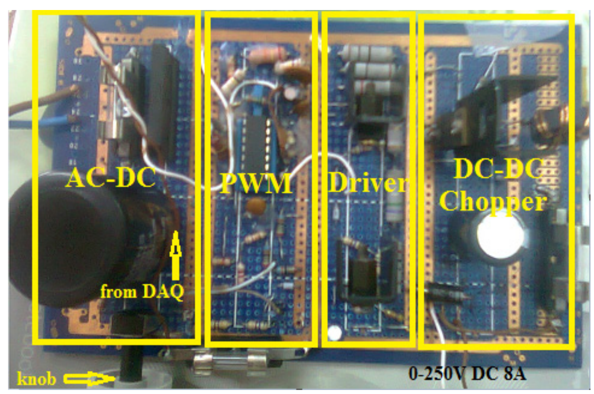

Fig. 4 Custom-built AC-DC converter

2.4 Host PC and Target PC

Host PC is a computer used only for the visualization of the desired process variables. It is used also for sending to the control system the controller coefficients if we want to interact with the Synchronous generator or DC motor. It is also possible to send the set point and to do different calculation with the measurement values coming from the Target PC through a LAN cable.

We have chosen as Host PC a portable computer ACER Aspire 5536 Dual Core. The Host PC parameters does not influence too much to the virtual system performance.

The main part of the system that will be presented below in this paper is the Target PC or the Real-Time Computer.

Figure 5 shows the monitor of the Real-Time desktop PC. It is a HP Dual Core with 1GB of RAM, 40GB of HDD and 1 Gb of Network card. It was configured as a Real-Time PC using the information given in [9].

Fig. 5 PC with Real-Time Operating System

All the programs are created in the LabVIEW environment in the Host PC. They are deployed to the Target PC when the Virtual Instrument created in LabVIEW starts running. It can work, if we want, also as a stand-alone PC.

2.5 Inputs and Outputs chosen for DC Motor and SG

Figure 6 shows the DC motor and SG blocks with the inputs and outputs chosen for their control and monitoring. The DC machine field winding is fed with a constant voltage of 220V DC, and the armature winding with a variable 0-250V DC voltage from the output of DC-DC chopper of one of the AC-DC converters. As output, it is chosen the motor speed.

Experimentally, the maximum speed for the motor with a 1 p.u. three-phase balanced active load in the SG stator windings was 1640 rev/min.

The SG field winding is also fed with a 0-250V DC voltage produced from the DC-DC chopper of the other AC-DC converter.

Experimentally, the maximum voltage in the stator windings was 241V (n=1500rev/min). It is because we limited the SG field winding voltage to have a field current not more than 20% over the field winding rated current. The balanced resistive load of SG has a value of 1 p.u.

All the limitations were inserted in the Virtual System graphical code of the SG.

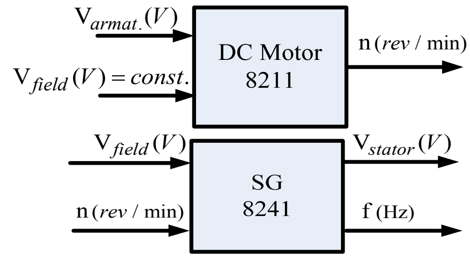

Fig. 6 DC Motor an SG blocks with the inputs and outputs for controlling and monitoring

3 DC Motor model identification and speed control design using LabVIEW

In order to control the DC motor speed, one must have its mathematical model. There is plenty of literature for DC machine modelling, but they require that all machine parameters must be known. Sometimes it is difficult to have all the parameters in explicit form for the model. In these cases it is better to identify the transfer function (mathematical model) for desired input-output and then designing the control system to maintain the system output inside required limits and performance.

We will see the DC motor as a black-box because this approach has the advantage to estimate different model structures. The appropriate mathematical model then is chosen by a comparison of the structures identified [10].

Figure 7 shows the experimental identification of the DC motor transfer function with a virtual instrument created in LabVIEW environment.

We did some preliminary tests in order to have for the motor speed an output step response of 50%, starting from 750 rev/min to the rated speed of 1500 rev/min. SG is loaded to 0.6 p.u. during those tests.

As it can be seen, the input voltage for the DC motor converter is changed from 0,925V to 1,25V.

If we divide by Δn=750rev/min the transfer function of the DC Motor model becomes:

$$G_{H}(\mathrm{s}) = e^{-0.02s}\frac{0,753}{1+0,28s+0,02s^{2}+0,0014s^{3}} \quad (3)$$

Initially, we tested this virtual instrument (fig. 7) with known transfer function of different orders of numerator and denominator. After successful validation we used this instrument for the DC Motor model identification and then for the SG model identification.

As it can be seen, the estimated curve (red line) is approximated to the experimental curve (yellow line). So, the model that will be accepted for further analysis and control design is that shown in expression (3).

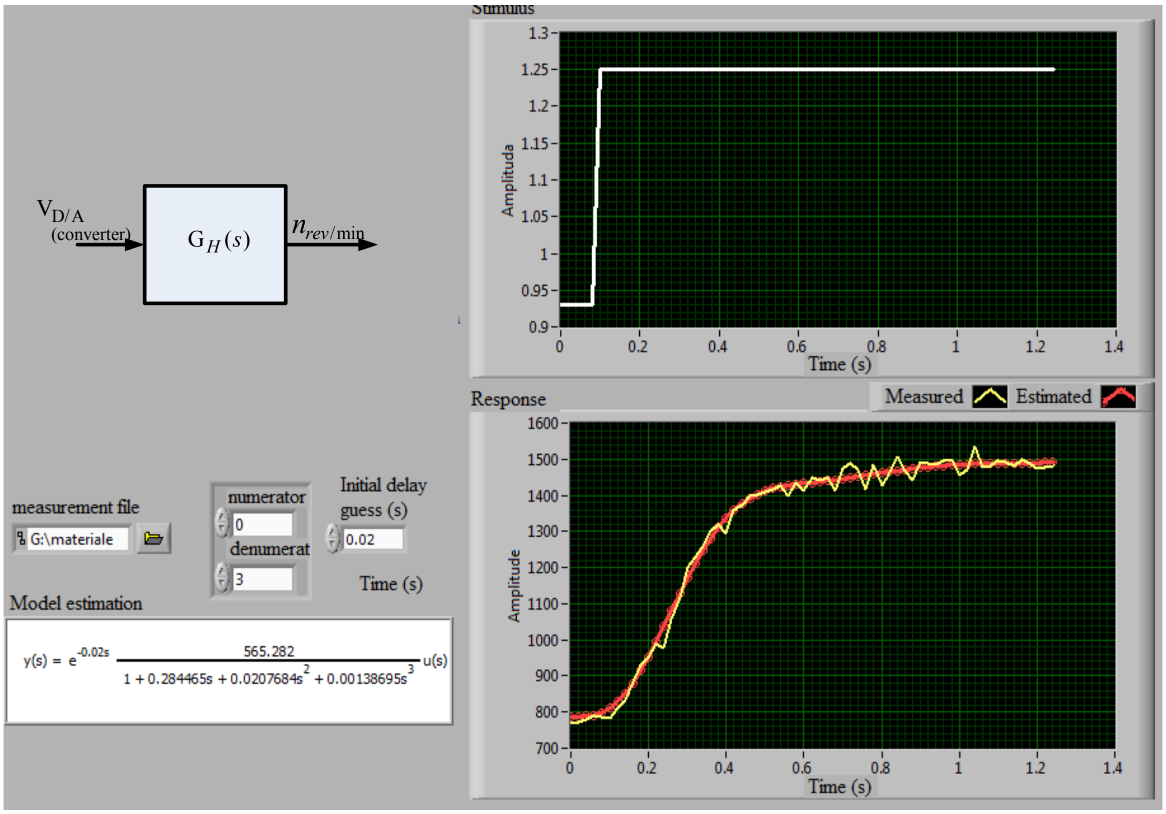

Fig. 7 Front Panel of the instrument for DC Motor mathematical model identification in LABVIEW

Figure 8 shows the calculation of the DC Motor transfer function. It is approximated with a first order model with time delay.

$$G_H(s) = e^{-\tau s}\frac{K}{1+Ts} = e^{-0.1s}\frac{0,75}{1+0,24s} \qquad (4)$$

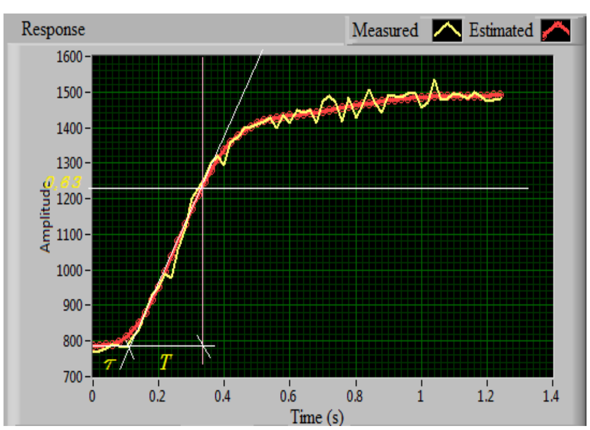

Fig. 8 DC Motor open loop identification of the transfer function

Using the Ziegler-Nichols empiric tuning rule [11] we obtained the PID controller coefficients. The PID controller transfer function is:

$$G_{RASH}(s) = \frac{0.025s^2 + 0,5s + 2,5}{s} \qquad (5)$$

This controller will be implemented digitally (Z-transform) in the control algorithm, because the calculated sampling time T_s is:

$$T_s = \frac{2\pi}{\omega_s} = \frac{2\pi}{35\omega_n\sqrt{1-\zeta^2}} = \frac{2\pi}{35\cdot 12,5\sqrt{1-0,389^2}} = 15,6ms \qquad (6)$$

But the sampling time we will use is T_s=10 ms, so the digital control system can be studied as analog one.

4 SG model identification and voltage control design using LabVIEW

For the SG model identification and voltage control design the same way as for the DC Motor is chosen.

It is also possible to use the classic approach in the control design of SG based on the dynamic model based on LabVIEW [12]. However, in this work we have chosen the model identification from the Step Response technique. First, we did some preliminary experiments and then identified the model in similar way like the DC Motor of section 3.

Since the SG is in island mode, we tested first the speed control system and then did the step response of the field winding voltage, to obtain the change in the stator phase voltage.

During the experiment the Speed controller was inserted in the closed loop of the Speed Controlling System so as to maintain the speed of the DC Motor as close as possible to its rated value of 1500rev/min. This solution is acceptable because there is a weak coupling between the excitation control and speed control of SG and so the controllers can be designed separately [13].

Figure 9 shows the experimental identification of the SG transfer function with the same virtual instrument used for the DC motor model identification.

For voltage control system design, we take into account that the minimum sampling period is 20ms, period of a cycle for a AC voltage with a frequency of 50 Hz. So, we must wait 20ms in order to calculate the voltage r.m.s. value of the SG stator windings. If we calculate the sampling period, we see that it must be:

$$T_s = \frac{2\pi}{\omega_s} = \frac{2\pi}{35\omega_n\sqrt{1-\zeta^2}} = \frac{2\pi}{35\cdot 60,6\sqrt{1-0,371^2}} = 3,19ms \tag{8}$$

So, the model should be transformed in Z-plane and then we can design the voltage control system.

After the controller design in Z-plane, the digital PID controller for the voltage control of the SG is:

$$\frac{0,7258z^2 - 0,4435z + 0,05376}{z^2 - 1} \tag{9}$$

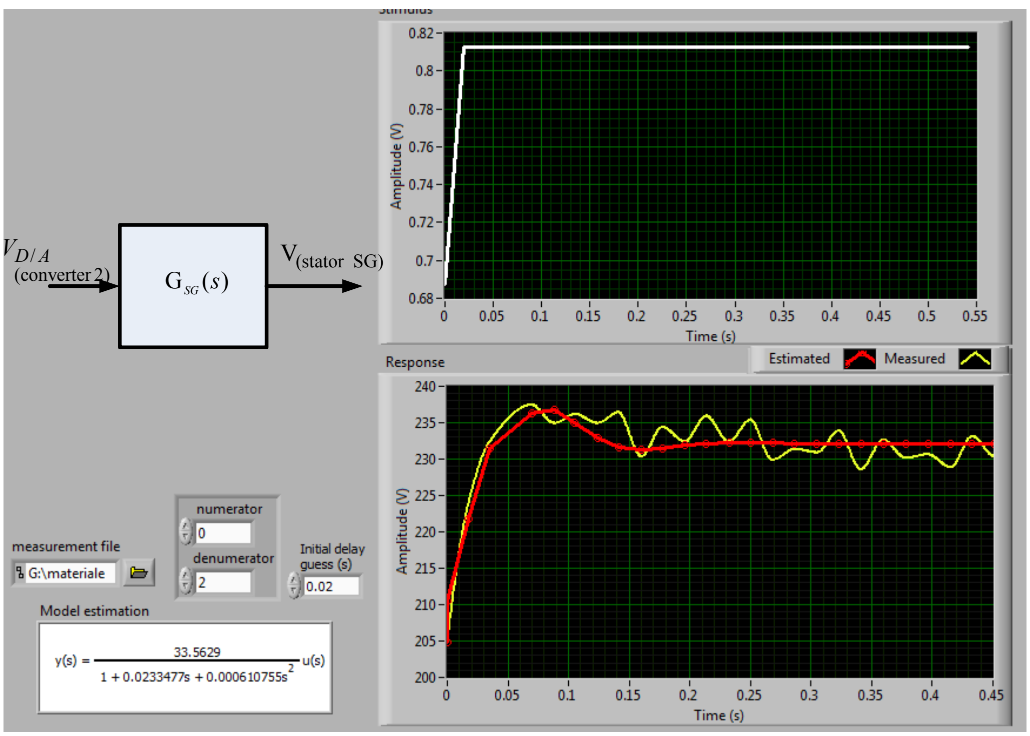

Fig. 9 Front Panel of the instrument for SG mathematical model identification in LabVIEW

As it can be seen, the input voltage for the SG converter is changed from 0,685V to 0,815V, while the stator voltage changes from 204V to 239V.

If we divide by ΔV=35V the transfer function of the SG model becomes:

$$G_{SG}(s) = \frac{0,958}{1 + 0,0233s + 0,00061s^2} \tag{7}$$

For the control system design of the Speed control of the DC motor and Voltage control of the SG, we relied on literature [11].

5 Virtual System for Real-Time control and monitor of the SG in LabVIEW environment

In this section a presentation of the Virtual System for Real-Time control of the SG model 8241 from Lab-Volt will be done.

This system is structured in such a way in order to fulfill some objectives as:

1. SG speed and voltage monitoring
2. Control algorithm execution
3. Communication between Target PC-Host PC
4. User interfacing

LabVIEW developers recommend structuring the application in a Project. To build the Real-Time Project in LabVIEW we followed the instruction given in [14].

Figure 10 shows the Real-Time Project for SG control and monitoring. It can be seen that the project consist of two parts.

One part is for the Host PC with the main file called **host-network-RT (separate).vi**. This file is the User Interface of the Virtual System. In this file are placed all the input and output variables to the System. The input variables can be changed during program execution. The communication to the Target PC is done by shared variables through LAN network.

The other part is for the Target PC (Real-Time PC). The main file is called **target-multi rate-variables-fileIO.vi**. In this file are placed all the loops and function for the real-time control of the SG generator.

Using LabVIEW modularity we added the file called **gjenerator funksioni.vi**, which was created for other target and inserted in the Project as a **soft-starter** for the DC Motor, to start it from standstill to the rated speed.

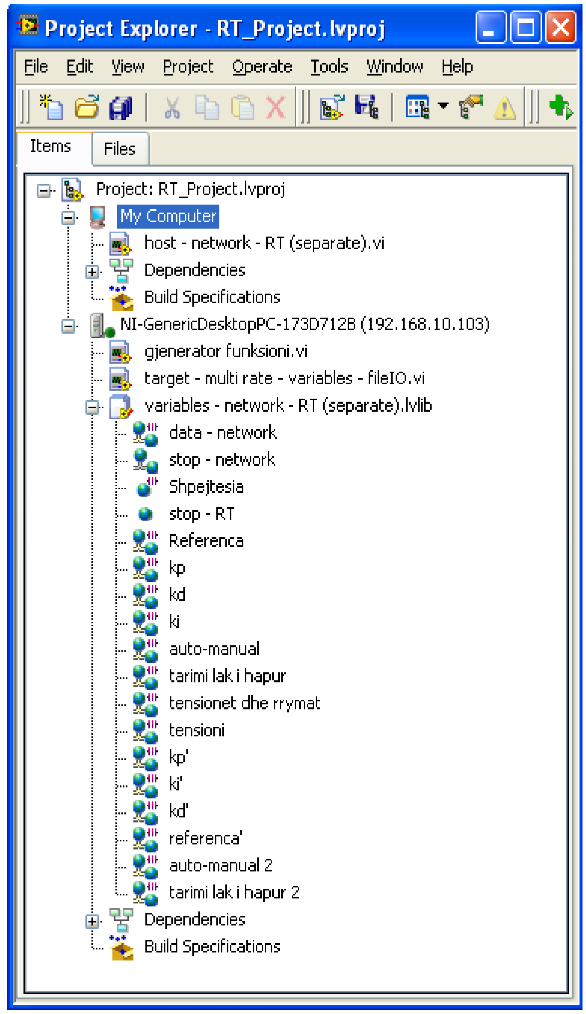

Fig. 10 Project organization for the Real-Time control and monitoring of the SG

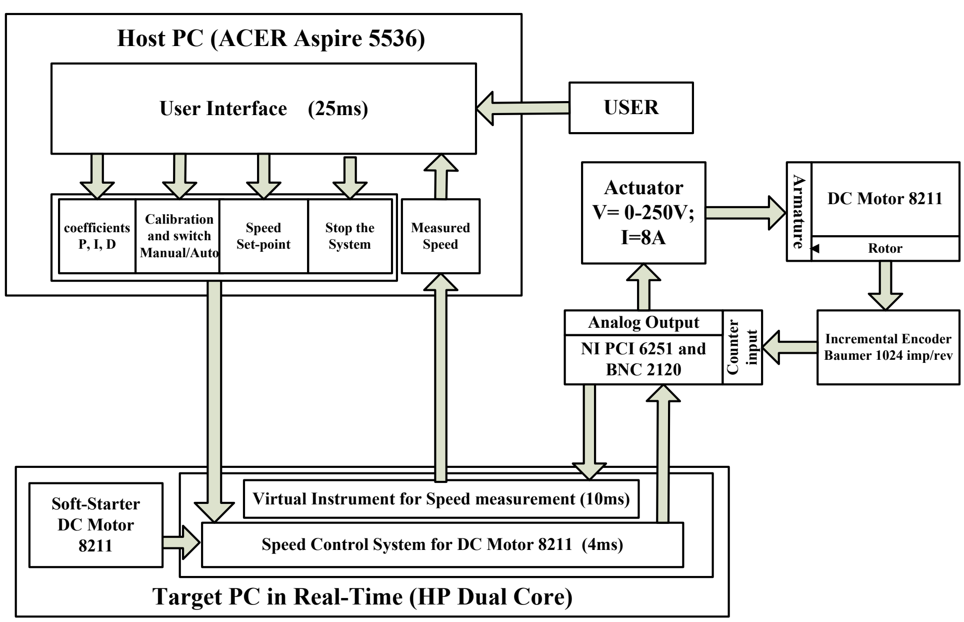

Fig. 11 Functional block diagram of the Speed Control and Monitoring System

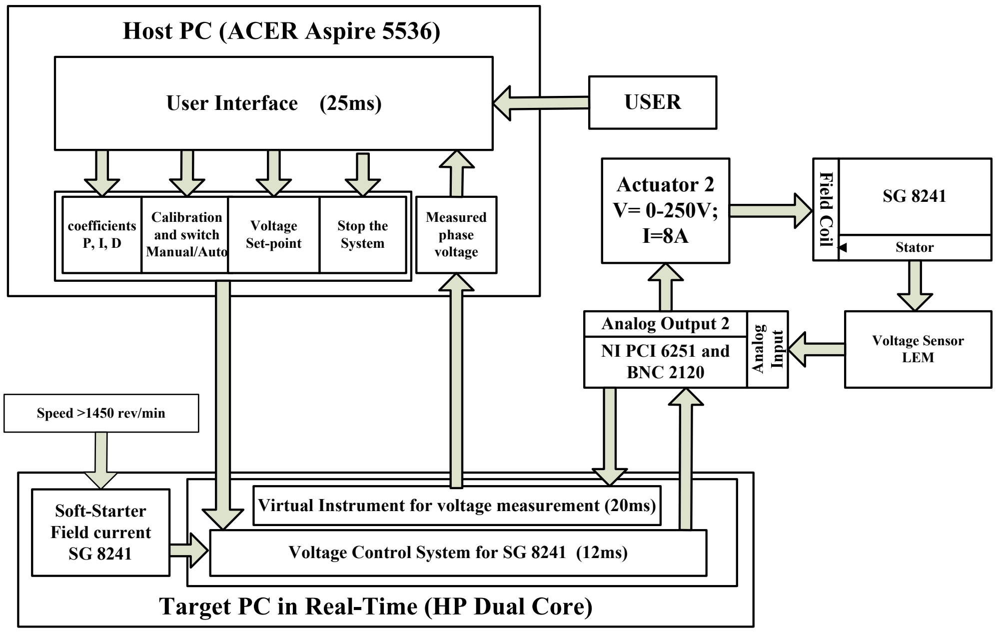

Fig. 12 Functional block diagram of the Voltage Control and Monitoring System

Figure 11 shows the functional block diagram of the DC Motor control and monitoring part of the Virtual System and figure 12 shows the functional block diagram of the SG voltage control and monitoring part of the Virtual System.

Initially, the voltage control system waits until the speed reaches 96% of its rated value. Then the system speed part and voltage part are independent from each other.

6 Virtual System User Interface and Closed Loop Control Systems testing

Figure 13 illustrates the Front Panel of the application created in LabVIEW for the SG control and monitoring.

It consists of 4 interfacing windows labelled as follow:

- Virtual System description
- Motor
- Generator
- Monitoring

6.1 Virtual System description

This window is accessible by selecting the first tab (default). It explains the connection of the parts of the system.

The text at the right informs the user for the application usage and the automated SG starting operation.

At the bottom-left corner of the window it is placed a rectangular button for Virtual System starting. This button, when pushed, force the program in the Target PC to start the SG and then to wait for other commands from this interface on the Host PC.

6.2 Motor

This window is accessible by selecting the second tab. Through this window the user is able to monitor the DC motor speed in real-time; to change the value of the speed; to calibrate in open loop the DC motor output and to change in real-time the PID controller coefficients (not recommended).

6.3. Generator

This window is accessible by selecting the third tab. Through this window the user is able to monitor the SG stator phase voltage in real-time; to change the value of the phase voltage; to calibrate in open loop the SG output and to change in real-time the PID_2 controller coefficients (also not recommended).

6.4 Monitoring

This last window is accessible by selecting the fourth tab. Through this window, the user is able to monitor simultaneously, in real-time, the DC motor speed and the SG stator phase voltage in real-time.

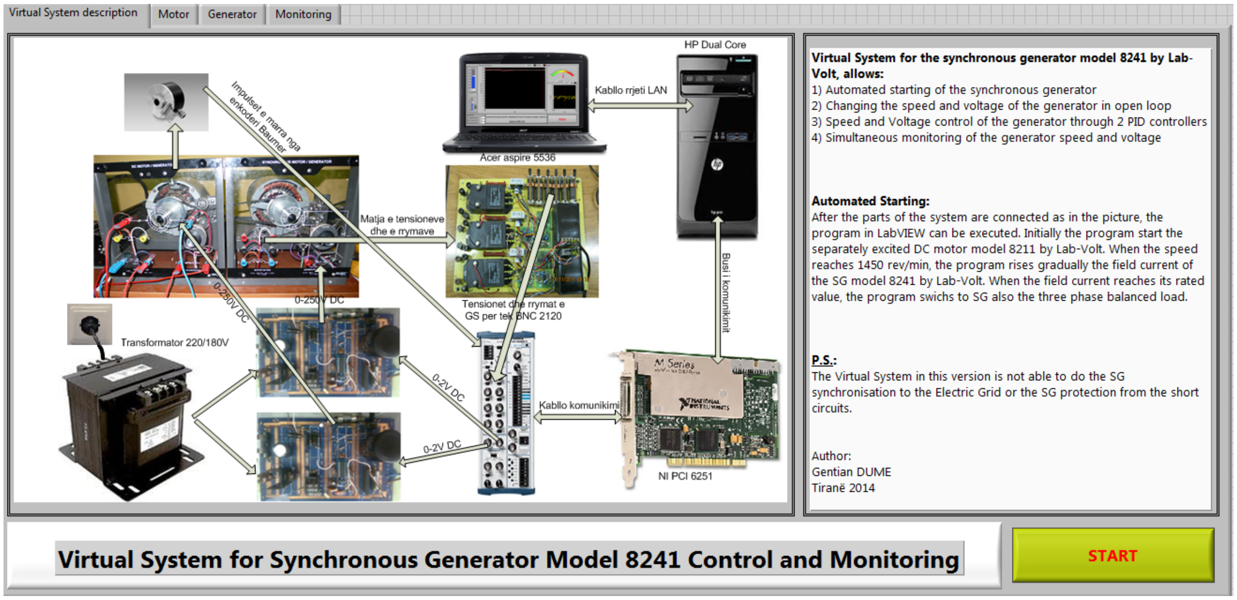

Fig. 13 Front Panel of the Virtual System for SG 8241 control and monitoring

It is also possible through this window to change the speed set point and the voltage set point in % of their respective rated values. This window lets the user to see reciprocal interaction of the speed control loop with the voltage control loop.

7 Verification of the SG 8241 Control System

This last section shows some experiments done with SG experimental bench in order to prove the performance of the Virtual System proposed.

The tests include verification of the response of the control system fort changes of the speed and voltages set point (not simultaneously) around their rated respective values, and then for the step changes of the three phases balanced resistive load.

Figure 14 shows the SG bench during experiments.

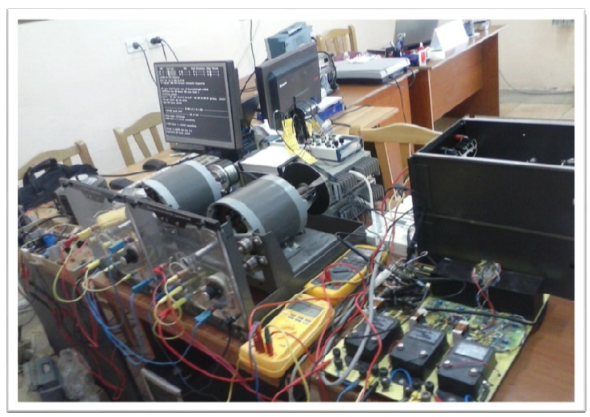

Fig. 14 SG bench during Virtual System experimental verification

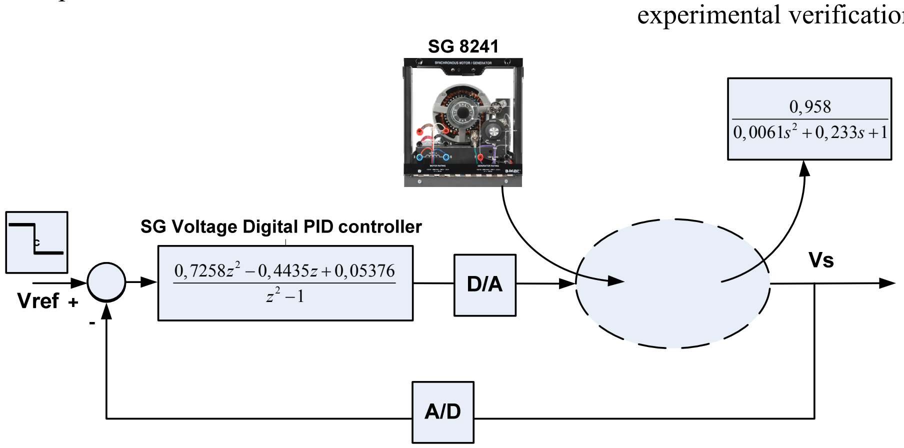

Fig. 15 SG 8241 voltage control closed loop using HIL

7.1 Voltage Control System test

Figure 15 shows the closed loop of the SG voltage control system when the model of the SG is replaced with the real SG 8241 using the so called HIL (Hardware in the Loop) technique [1].

The test consist in changing in steps the set-point of the desired SG voltage value (V_{ref}) and then monitoring the action of the voltage control system, and the speed control system to bring back the measured voltage and speed to their respective set-point.

Figures 16-18 shows some tests we did for the worst case (100% of step changes in the voltage set point).

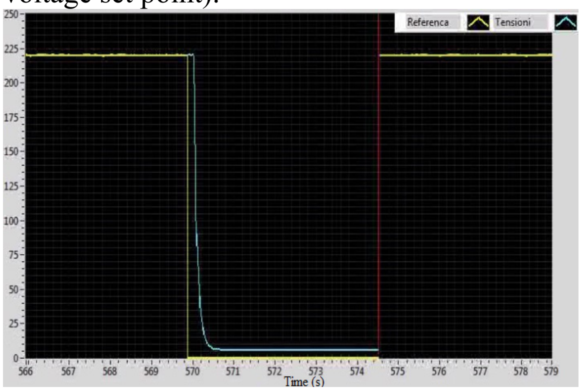

Fig. 16 SG voltage control response for -100% step (220V to 0V) in the voltage set-point

In this experiment (fig. 16); the SG stator voltage does not reach the value 0V because of the residual flux in its field winding.

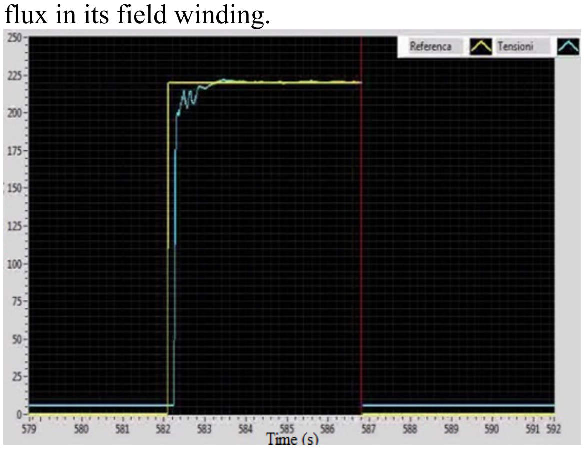

Fig. 17 SG voltage control response for +100% step (0V to 220V) in the voltage set-point

In this experiment (fig. 17), the SG stator voltage oscillates and reaches the desired value in 0,52 sec.

If we monitor the interaction of the changes in SG field voltage to the speed it can be seen (fig 18) a small influence.

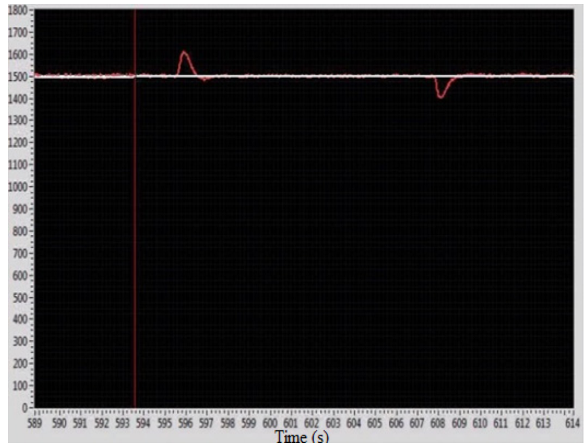

Fig. 18 SG field voltage changes influence to the speed control loop

7.2 Speed Control System test

Figure 19 shows the closed loop of the DC motor speed control system, when the model of the DC motor is also replaced with the real DC motor 8211, using the same technique.

Also in this case, the test consist in changing in steps the set-point of the desired DC motor speed value (n_{ref}) and then monitoring the action of the voltage control system, and the speed control system to bring back again the measured voltage and speed to the respective set point.

Figures 20-22 shows some tests we did (5%, 10%, 15% of step change in the speed set-point).

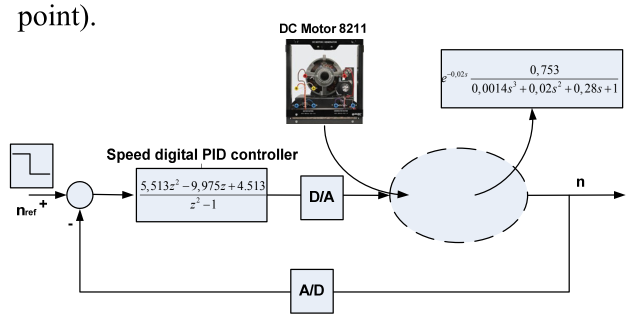

Fig. 19 SG bench during Virtual System experimental verification

The Speed digital PID controller is obtained from the analog PID controller of expression (5) for a sampling time T_s = 10ms.

As it can be seen (fig. 20-22), the influence of changes in the speed values to the stator voltage of the SG are evident. However, the speed control system is working very well. The voltage control system has an acceptable response for small changes in the SG speed.

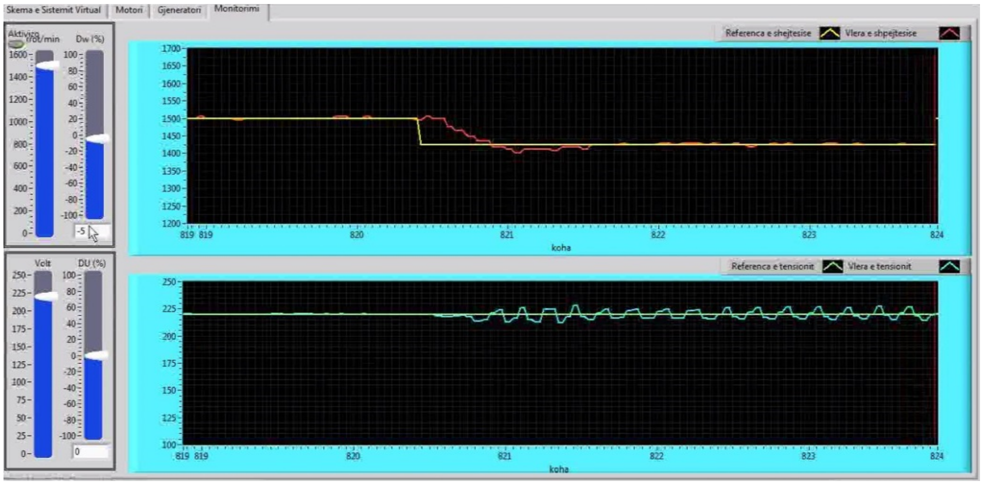

Fig. 20 SG 8241 step responses for 5% decrement of DC Motor 8211 speed set-point

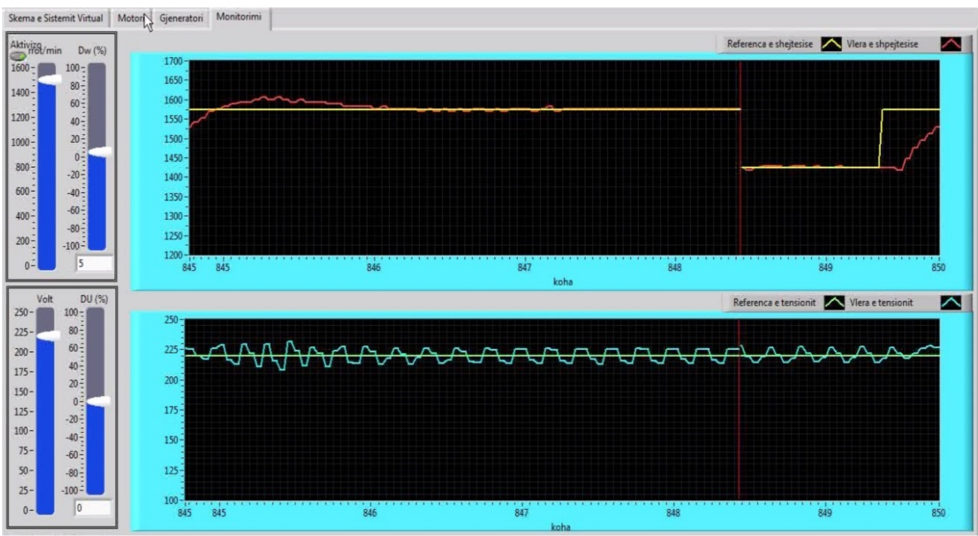

Fig. 21 SG 8241 step responses for 10% increment of DC Motor 8211 speed set-point

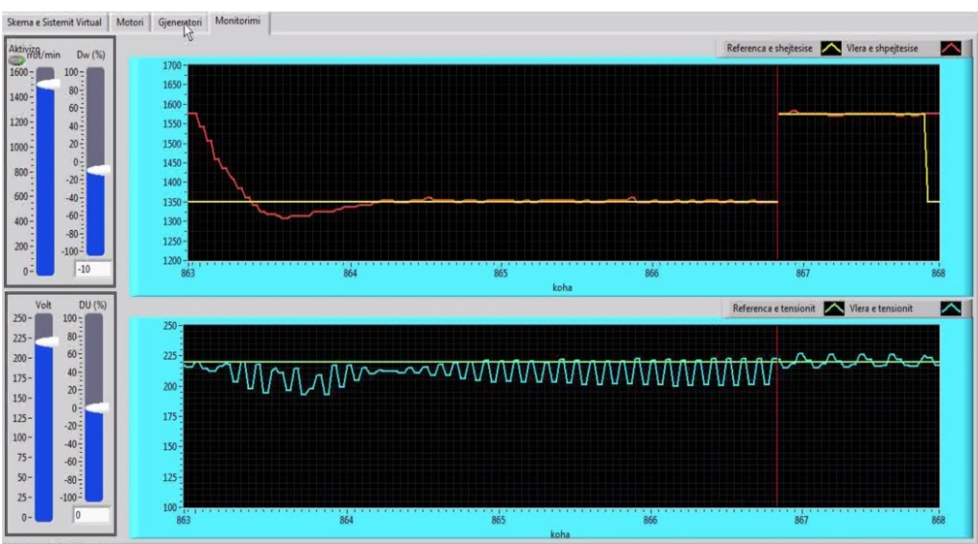

Fig. 22 SG 8241 step responses for 15% decrement of DC Motor 8211 speed set-point

7.3 Voltage and Speed Controlling for step changes in GS balanced resistive load test

Last tests were done to see the responses of the controlling system for external disturbances.

As disturbance, we chose to do a step change in the SG three-phase balanced load. Figures 23-25 shows the responses of the SG speed control and voltage control system for different step changes in the balanced resistive load (R_S).

7.4 Results from the tests

From all the tests in table 1 are collected the results extracted from the system step response for each test.

They are:

1. m_{rr} - overshoot (%)
2. ε - steady-state error (%)
3. t_r – settling time (sec.)

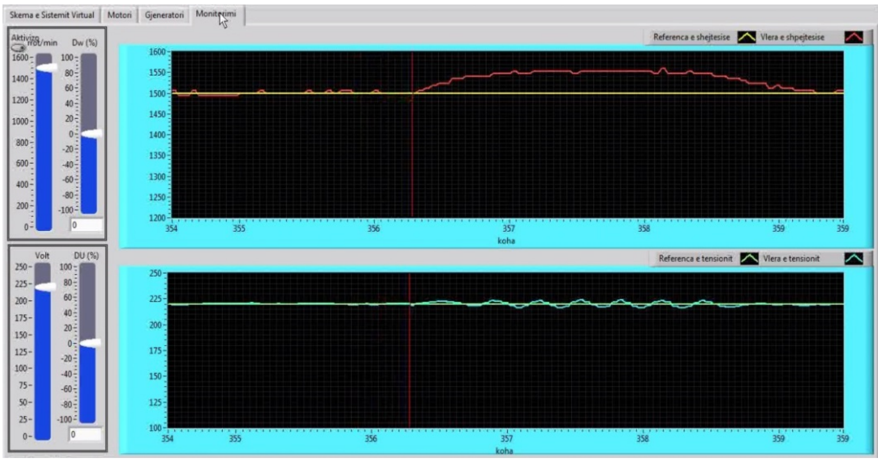

Fig. 23 SG 8241 step responses when the three-phase resistive load decrease from 1 p.u. to 0,6 p.u.

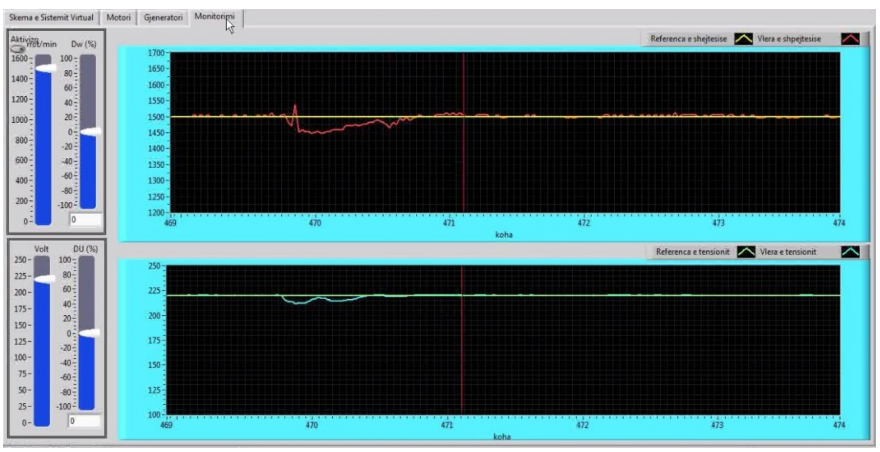

Fig. 24 SG 8241 step responses when the three-phase resistive load increase from 0,3 p.u. to 0,6 p.u.

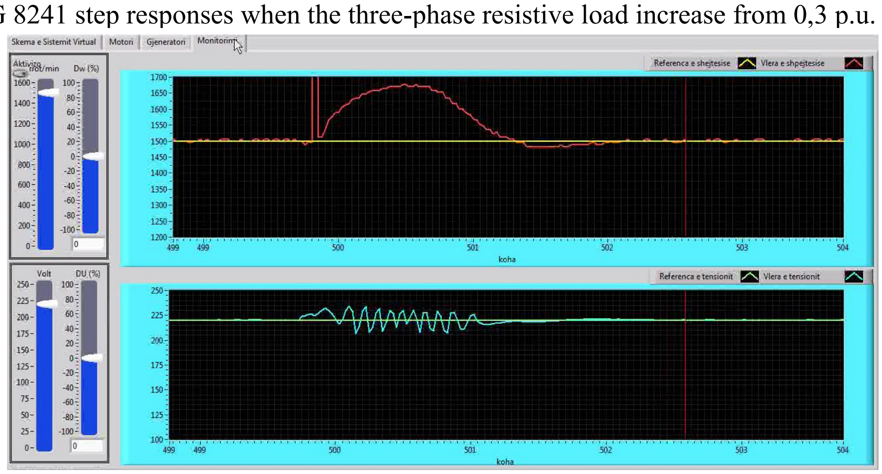

Fig. 25 SG 8241 step responses when the three-phase resistive load decrease from 1.p.u. to 0 p.u.

Table 1 Experimental result from SG 8241 speed and voltage control system test

	Step change (%)		m_{rr-n} (%)	t_{r-n} (s)	ε_n (%)	m_{rr-Vs} (%)	t_{r-Vs} (s)	ε_{Vs} (%)	Notes
n_{ref}	100→95	-5	-2,3	1,15	0,3	-3.4	0,4	2,3	V_{ref}=220V R_s=1 p.u. n_{ref} ≠
	95→105	+10	+2,5	1,4	0,3	+4,5	0,6	2,7	
	105→90	-15	-3	1,25	0,3	-4,5	0,45	-2,27	
	90→110	+20	0	1,1	-2	+4,5	0,6	6,8	
V_{ref}	100→95	-5	0	0	0,3	0	0,13	0,02	V_{ref}=≠ R_s=1 p.u. n_{ref}=1500rev/min
	95→105	+10	0	0	0,38	0	0,2	0,027	
	105→90	-15	+1,67	0,75	0,38	0	0,15	0,031	
	90→110	+20	-1,67	0,65	0,3	0	0,17	-4,5	
	100→0	-100	+6,67	1,6	0,3	0	0,56	+3,18	
	0→100	+100	-6,5	1,2	0,3	1,5	0,52	2	
R_{s-n}	100→60	-40	+3,33	3,2	0,3	+2,2	2,7	0,9	V_{ref}=220V R_s≠ n_{ref}=1500rev/min
	30→60	+30	-3,5	1,25	0,3	-4,5	0,65	0,9	
	100→0	-100	+12	2,15	0,3	+6,8	1,9	1	

8 Conclusion

The Virtual System presented here, is a low cost alternative and thus, it can be used to teach real-time control systems for synchronous generators and other electrical machines.

Since the controller code is implemented in LabVIEW environment, there are no limitations in the type of the controller used in real-time in the closed loop control system. In this point of view academics and researchers can test their own controller without the need to build it physically.

The custom-built AC-DC converters and SG stator quantities measurement module can be used to add other functionalities to the Virtual System. Some of them are for SG protection, Power quality monitoring and on-line SG fault diagnostics through stator current spectral analysis.

The model identification and the HIL methods through LabVIEW show the superiority of this software as an indispensable tool in engineering fields where there is a high gap between the theory and practice.

In the education point of view, the SG bench and the Virtual System is fully available for the master degree students of the Electrical Engineering Faculty of Tirana.

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Appendix

Table 2 Direct Current Motor ratings

Manufacturer	Lab-Volt®
Model	8211
Motor Output Power	175W
Armature Voltage	220V - DC
Shunt Field Voltage	220V - DC
Full Load Speed	1500 r/min
Full Load Motor Current	1,3A

Table 3 Synchronous Generator ratings

Manufacturer	Lab-Volt®
Model	8241
Generator Output Power	110VA
Stator Voltage	220V/380V 3-phase 50Hz
Rotor Inductor Voltage	220V - DC
Speed	1500 r/min
Full Load Generator Current	0,17A