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Modeling, Simulation and Analysis of Excitation System for Synchronous Generator

[1]Yousif I. Al Mashhadany, [2]Farqad Amir, [3]Najlaa Anwer

[1,2,3]Electrical Engineering Department, Engineering College, University of Anbar, Anbar, Iraq
[1]*Email: yousif.almashhadany {at} uoanbar.edu.iq*

ABSTRACT— ***Mechanical energy converted into electrical energy by synchronous generator. The turbine converts some kinds of energy (steam, water, wind) into mechanical energy. This work discusses the problems in modeling, simulation and analysis of excitation system for synchronous generator, it has an active DC load. The work consists of two main parts: one is the mathematical model of an excitation system, explains the fundamentals, and defines the scope of work of the synchronous generator; another presents the simulation and analysis of the mathematical model discussed. The simulation was done on Matlab Ver. 2013a with satisfactory results, allowing conclusion that the modeling is accurate and feasible for practical implementation.***

Keywords— Synchronous generator, Excitation System, modeling and simulation.

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1. INTRODUCTION

Synchronous generators are rotating machines that convert mechanical power into three-phase alternating electrical power. They are the principle source of electrical energy in a power system, hence their performance influence a power network operation. Their characteristics merit careful study in any attempt at studying a power system [1-3].

Excitation systems are an important part of synchronous generators. They comprise machines, devices, and appliances intended to supply the generator field winding by current directly and this current is regulation. They are also responsible for control and protection of the power system. The excitation system is an important control unit for synchronous generator, and its dynamic performance has immediate impact on a generator's stability and reliability. When the behavior of a synchronous machine is to be simulated accurately in a power system stability case, the excitation system must be modeled sufficiently [4].

A synchronous generator is a device that converts the mechanical power of a prime mover into AC electric power at a specific voltage and frequency. The term synchronous refers to the machine's electrical frequency that is locked in (synchronized) with its mechanical rate of shaft rotation. Synchronous generators produce the bulk of the world's electric power. Two parameters are caused internal generated voltage: the rate of shaft rotation and the field flux [5 - 7].

An induction motor contrasts with slip to produce torque. It operates synchronously with line frequency. The excitation current is the current producing the required magnetic flux in the air gap; it is the field winding current at a particular load (or rated load) [8 - 10]. The mathematical model, simulation, and analysis of an excitation system will be described next before the paper is concluded.

2. TYPES OF EXCITATION SYSTEMS

On the basis of their excitation power gain these are the types of excitation systems [11-13]:

- Independent - exciter unconnected to the grid thus excitation parameters have no direct connection with the grid parameters; turbine mechanical power is used for the excitation.
- Dependent - exciter utilizes the generator power or connects to the grid; in terms of the excitation source these are further classifications of excitation systems:
  - DC
  - AC
  - Static

DC excitation systems : define as the systems are providing current to the rotor of the synchronous generator through the slip rings directly; exciter placed on the same shaft or is separately by a motor and self–excited or separately excited, with a permanent magnet. *AC excitation systems* describes as the exciter is typically placed on the same shaft as the turbine. The AC is rectified by controlled or non-controlled rectifiers and provides DC to the generator field winding.

Stationary and rotating AC rectifier systems are the ones in present use. The DC output is fed to generator field winding by slip rings at stationary rectifiers. Rotating rectifiers do not need slip rings, brushes and DC is directly fed to generator as the armature of the exciter and rectifiers rotate with the generator field. Such systems are known as *brushless systems* and were developed to avoid problems with the brushes when extremely high field currents of large generators are applied. In *static (ST) excitation systems* have stationary status for all elements. Such systems use slip rings which directly provide excitation current to synchronous generator field winding. Rectifiers in ST systems gain generator power through auxiliary windings or step-down transformers. In such systems the generator itself is a power source, i.e., the generator is self-excited. The generator is unable to produce any voltage without excitation voltage, so it must have an auxiliary power source to provide field current and energize itself. Station batteries are the usual additional power source, used in what is termed *ield flashing.* Different excitation systems have different relative advantages and disadvantages; Table I lists the main ones.

Table 1. Excitation systems advantages and disadvantages [12]

Parameter	**DC**	**AC**		**ST**
		Stationary	***Brushless***	
Excitation Transform supply	Small	Small	Small	Transform
Length of machine	Medium	Medium	Long	Short
Response time	Slow	Medium	Medium	Very fast
Components requiring maintenance	Sliprings and commutator	Sliprings	-	Sliprings
De-excitation	Medium	Medium	Slow	Fast

3. MATHEMATICAL MODEL OF EXCITATION SYSTEMS

A modeling of a synchronous generator can be written by mathematical model of second, third, fifth, or seventh order. Seventh-order model describes synchronous generators most accurately and is the most complex [14]. It is used for analysis of dynamic behaviors in normal conditions and in conditions of generator failure.

Fifth-order model neglects the DC components in stator and the AC components in rotor windings. It is used because it is simpler than seventh-order model, often to model electro-energetic systems for studying transient stability when Kirchoff Law for electric grid are written for the stationary state [15].

Third-order model is crucial to studying the control systems of synchronous generators as well as their synthesis. It neglects frequency deviations, high-order harmonics, and behavior in damped windings. Used for its simplicity and good dynamic decryption has the higher usage for analysis and synthesis of control system.

The simplest model of synchronous generators is second-order model; it describes only the dynamics of a moving rotor [16,17].

A. *Mathematically describing for an excitation system*

An exciter's equations can be written as follows:

$$\tilde{v}_{ed} = -R_{es}\tilde{i}_{ed} + w_e\left(L_{eis} + L_{emq}\right)\tilde{i}_{eq} - \left(L_{eis} + L_{emd}\right)\frac{d\tilde{i}_{ed}}{dt} + L_{emq}\frac{d\tilde{i}_{efd}}{dt} \quad (1)$$

$$\tilde{v}_{eq} = -R_{es}\tilde{i}_{eq} + w_e\left(L_{els} + L_{emd}\right)\tilde{i}_{ed} + w_e L_{emd}\tilde{i}_{ed} - \left(L_{eis} + L_{emq}\right)\frac{d\tilde{i}_{eq}}{dt} \quad (2)$$

$$\tilde{v}_{efd} = R_{efd}\tilde{i}_{efd} - L_{emd}\frac{d\tilde{i}_{ed}}{dt} + \left(L_{elfd} + L_{emd}\right)\frac{d\tilde{i}_{efd}}{dt} \quad (3)$$

When combining linearized model of the generator/rectifier with the exciter's DC load model will get:

$$\tilde{v}_{edc} = K_{138}\tilde{v}_{ed} + K_{239}\tilde{v}_{eq} \quad (4)$$

$$\tilde{\iota}_{ed} = K_4\tilde{\iota}_{edc} + K_5K_8\tilde{v}_{ed} + K_5K_9\tilde{v}_{eq} \tag{5}$$
$$\tilde{\iota}_{eq} = K_6\tilde{\iota}_{edc} + K_7K_8\tilde{v}_{ed} + K_7K_9\tilde{v}_{eq} \tag{6}$$
$$K_{138} = K_1 + K_3K_8 \tag{7}$$
$$\mathrm{K}_{239} = \mathrm{K}_2 + \mathrm{K}_3\mathrm{K}_9 \tag{8}$$

The winding equation of the main generator's field describes the exciter's DC load as:

$$\tilde{v}_{afd} = R_{afd}\tilde{\iota}_{afd} - L_{amd}\frac{d\tilde{\iota}_{ad}}{dt} + \left(L_{alfd} + L_{amd}\right)\frac{d\tilde{\iota}_{afd}}{dt} + L_{amd}\frac{d\tilde{\iota}_{akd}}{dt} \tag{9}$$

Now, the voltage equation of the main generator's field can be written as:

$$\tilde{v}_{afd} = t_a\tilde{v}_{edc} \tag{10}$$

Similarly, for currents

$$\tilde{\iota}_{afd} = \frac{1}{t_a}\tilde{\iota}_{edc} \tag{11}$$

Combining (9), (10), and (11) produces the following exciter load equation:

$$\tilde{v}_{edc} = \frac{R_{afd}}{t_a^2}\tilde{\iota}_{edc} - \frac{L_{amd}}{t_a}\frac{d\tilde{\iota}_{ad}}{dt} + \frac{(L_{alfd}+L_{amd})}{t_a^2}\frac{d\tilde{\iota}_{afd}}{dt} + \frac{L_{amd}}{t_a}\frac{d\tilde{\iota}_{akd}}{dt} \tag{12}$$

The mathematical expressions for $\tilde{v}_{ed}$ and $\tilde{v}_{eq}$ can be written by eliminating $\tilde{v}_{edc}$ as:

$$\tilde{v}_{ed} = r_{edd}\tilde{\iota}_{ed} + l_{edd}\frac{d\tilde{\iota}_{ed}}{dt} + r_{edq}\tilde{\iota}_{eq} + l_{edq}\frac{d\tilde{\iota}_{eq}}{dt} - K_9l_{ae}\frac{d\tilde{\iota}_{ad}}{dt} + K_9l_{ae}\frac{d\tilde{\iota}_{akd}}{dt} \tag{13}$$

$$\tilde{v}_{eq} = r_{eqd}\tilde{\iota}_{ed} + l_{eqd}\frac{d\tilde{\iota}_{ed}}{dt} + r_{eqq}\tilde{\iota}_{eq} + l_{eqq}\frac{d\tilde{\iota}_{eq}}{dt} - K_8l_{ae}\frac{d\tilde{\iota}_{ad}}{dt} + K_8l_{ae}\frac{d\tilde{\iota}_{akd}}{dt} \tag{14}$$

Where:

$$K_{det} = K_4K_7(K_9K_{138} - K_8K_{239}) + K_5K_6(K_8K_{239} - K_9K_{138}) \tag{15}$$

$$r_{edd} = \frac{K_6K_{239} + K_7K_9\frac{R_{afd}}{t_a^2}}{K_{det}} \tag{16}$$

$$l_{edd} = \frac{K_7K_9(L_{alfd}+L_{amd})}{t_a^2K_{det}} \tag{17}$$

$$l_{edq} = \frac{K_5K_9(L_{alfd}+L_{amd})}{t_a^2K_{det}} \tag{18}$$

$$r_{edq} = \frac{K_6K_{138} + K_7K_8\frac{R_{afd}}{t_a^2}}{K_{det}} \tag{19}$$

$$r_{edq} = \frac{K_4K_{138} + K_5K_8\frac{R_{afd}}{t_a^2}}{K_{det}} \tag{20}$$

$$l_{eqd} = \frac{K_7K_8(L_{alfd}+L_{amd})}{t_a^2K_{det}} \tag{21}$$

$$l_{eqq} = \frac{K_5K_8(L_{alfd}+L_{amd})}{t_a^2K_{det}} \tag{22}$$

$$l_{ae} = \frac{K_4K_7 - K_5K_6}{t_aK_{det}}L_{amd} \tag{23}$$

Similarity with the main generator's field current:

$$\tilde{\imath}_{afd} = h_{aed}\tilde{\imath}_{ed} + h_{aed}\tilde{\imath}_{eq} \quad (24)$$

Where;

$$h_{aed} = \frac{K_{138}K_7K_9 - K_{239}K_7K_8}{t_a K_{det}} \quad (25)$$

$$h_{aeq} = \frac{K_{239}K_5K_8 - K_{138}K_5K_9}{t_a K_{det}} \quad (26)$$

Linear state-space representation can be get by substituted equations (14) and (15) with (1) and (2). The final description of the model can be done by reduce the system order by one. [5].

B. ***The Mathematical model for generator***

The mathematical model for the generator that used in this work to simulate the exciter's model can be explain by substituted the main generator's field current is according to (24), giving [5, 17]:

$$v_{ed} = -R_{as}i_{ed} + w_a(L_{als} + L_{amq})i_{eq} - w_a L_{amq} i_{akq} - (L_{als} + L_{amd})\frac{di_{ad}}{dt} + L_{amd}\frac{d(h_{aed}i_{ed} + h_{aeq}i_{eq})}{dt} + L_{amd}\frac{di_{akd}}{dt} \quad (27)$$

$$v_{eq} = -R_{as}i_{eq} - w_a(L_{als} + L_{amd})i_{ad} + w_a L_{amd}(h_{aed}i_{ed} + h_{aeq}i_{eq}) + w_a L_{amd} i_{akq} - (L_{als} + L_{amd})\frac{di_{ad}}{dt} + L_{amd}\frac{di_{akd}}{dt} \quad (28)$$

$$0 = R_{akd}i_{akd} - L_{amd}\frac{di_{ad}}{dt} + L_{amd}\frac{d(h_{aed}i_{ed} + h_{aeq}i_{eq})}{dt} + (L_{alkd} + L_{amd})\frac{di_{akd}}{dt} \quad (29)$$

$$0 = R_{akq}i_{akq} - L_{amq}\frac{di_{aq}}{dt} + (L_{alkq} + L_{amq})\frac{di_{akq}}{dt} \quad (30)$$

The mathematical representation of generator's load will explain by using $\tilde{\imath}_{load}$ equation as:

$$\tilde{\imath}_{adc} = C\frac{d\tilde{v}_{adc}}{dt}\tilde{\imath}_{load} \quad (31)$$

New expressions for $\tilde{v}_{ad}$ and $\tilde{v}_{aq}$ by eliminate $\tilde{\imath}_{adc}$ as follow:

$$\tilde{v}_{ad} = r_{add}\tilde{\imath}_{ed} + r_{adq}\tilde{\imath}_{aq} + h_{addc}\tilde{v}_{adc} + c_{addc}\frac{d\tilde{v}_{adc}}{dt} + r_{adl}\tilde{\imath}_{load} \quad (32)$$

$$\tilde{v}_{aq} = r_{aqd}\tilde{\imath}_{ed} + r_{aqq}\tilde{\imath}_{aq} + h_{aqdc}\tilde{v}_{adc} + c_{aqdc}\frac{d\tilde{v}_{adc}}{dt} + r_{aql}\tilde{\imath}_{load} \quad (33)$$

Where:

$$c_{det} = \frac{1}{c_5c_{10} - c_6c_9}$$
$$r_{add} = c_{det}c_{10}$$
$$r_{adq} = -c_{det}c_6$$
$$h_{addc} = -c_{det}(c_6c_8 - c_4c_{10})$$
$$c_{addc} = -c_{det}(c_6c_7 - c_3c_{10})C$$
$$r_{adl} = c_{det}(c_6c_7 - c_3c_{10})$$
$$r_{adq} = -c_{det}c_9$$
$$r_{aqq} = c_{det}c_5$$
$$h_{aqdc} = c_{det}(c_4c_9 - c_5c_8)$$
$$c_{aqdc} = c_{det}(c_3c_9 - c_5c_7)C$$
$$r_{aql} = c_{det}(c_3c_9 - c_5c_7)$$

In (32) and (33), $\tilde{\imath}_{load}$ must be treated as a system input; they will be used to substitute with armature voltages, respectively in (27) and (28).

4. SIMULATION AND ANALYSIS OF EXCITATION SYSTEM

The simulation was done on Matlab/Simulink Ver. 2013a. The excitation system was provided by a small synchronous machine connected by same shaft as main synchronous machine. Current rectification was by a rotating diode bridge mounted on the synchronous machine shaft, doing away with slip rings when providing DC power to the synchronous machine field. The synchronous machine was a 2MVA, 400V, 50Hz, 1500 rpm machine driven by a diesel motor (see Fig. 1).

The real voltage applied to the rotor can be mask as nominal field current (I_{fn}) of 100A. It resulted in a nominal field voltage of 9.2837V. The exciter was an 8.1kVA, 400V, 50Hz, 1500 RPM synchronous machine (Preset model No. 1). A 400V/12V transformer adapted the 400V output voltage of the exciter to the rectifier.

Filtering was not required because of the large field inductance. The field terminal voltages of the synchronous machine model were measured by the field connections subsystems. The voltage across the current source, which had to be applied to the V_f Synchronous generator block input (see **Figure. 1**). Details of the exciter system are as shown in **Figure. 2**.

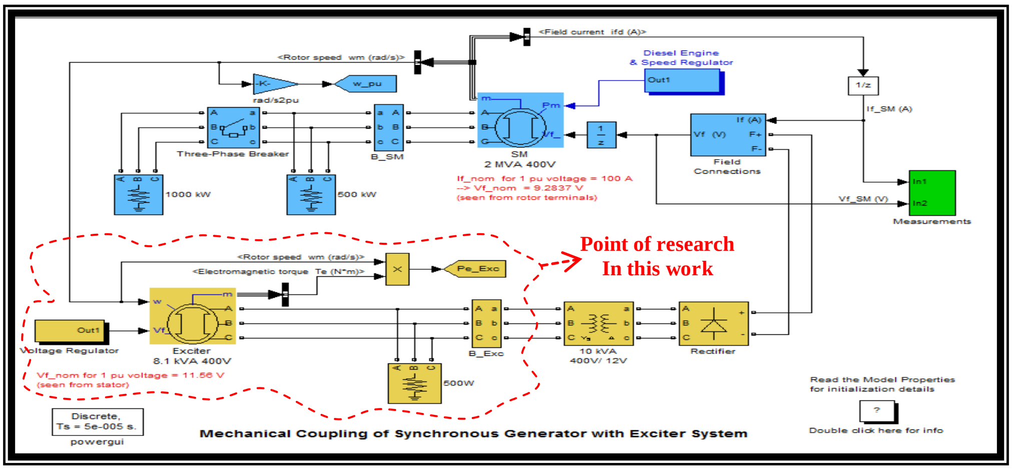


Figure 1. Simulating the synchronous generator with the exciter system

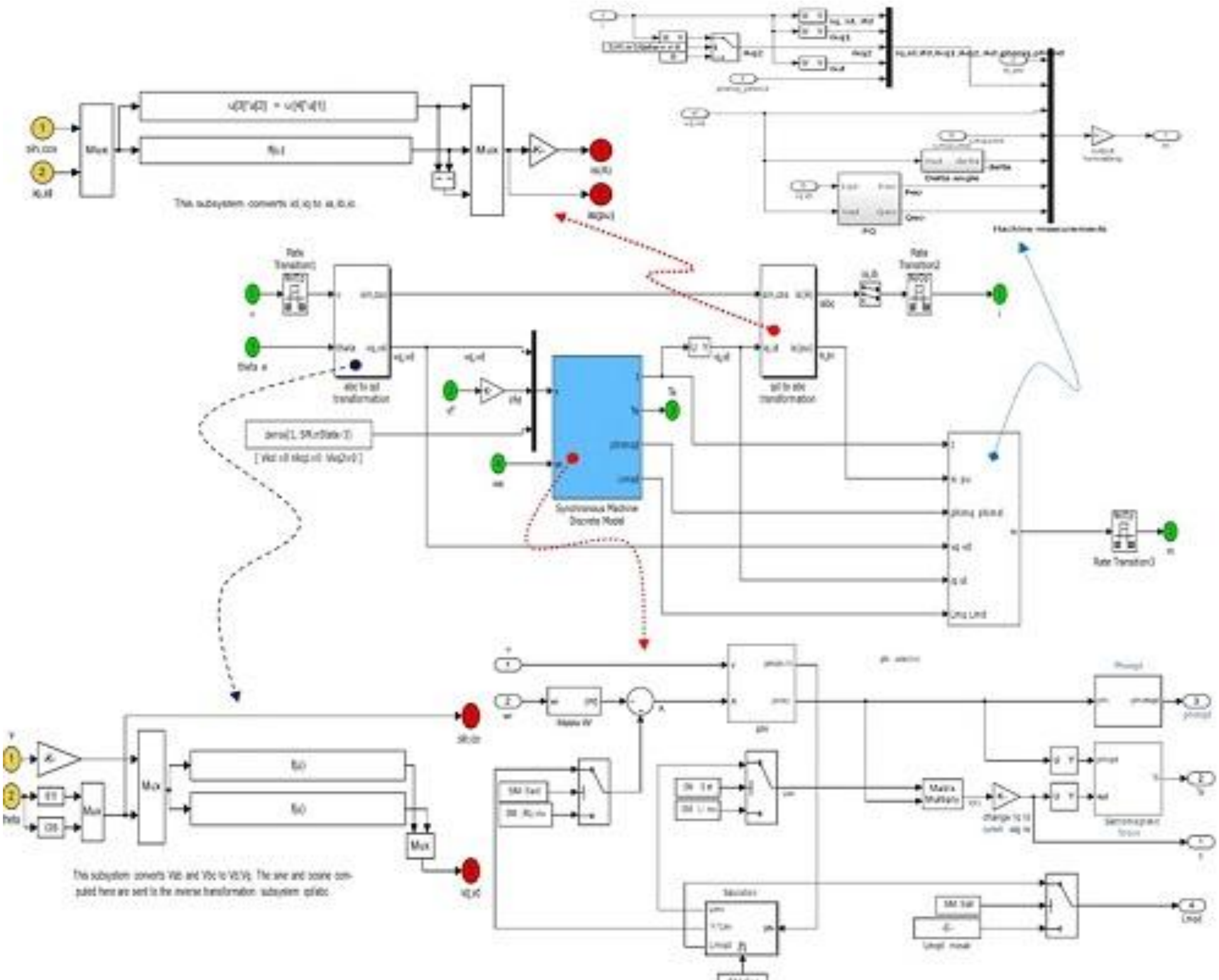
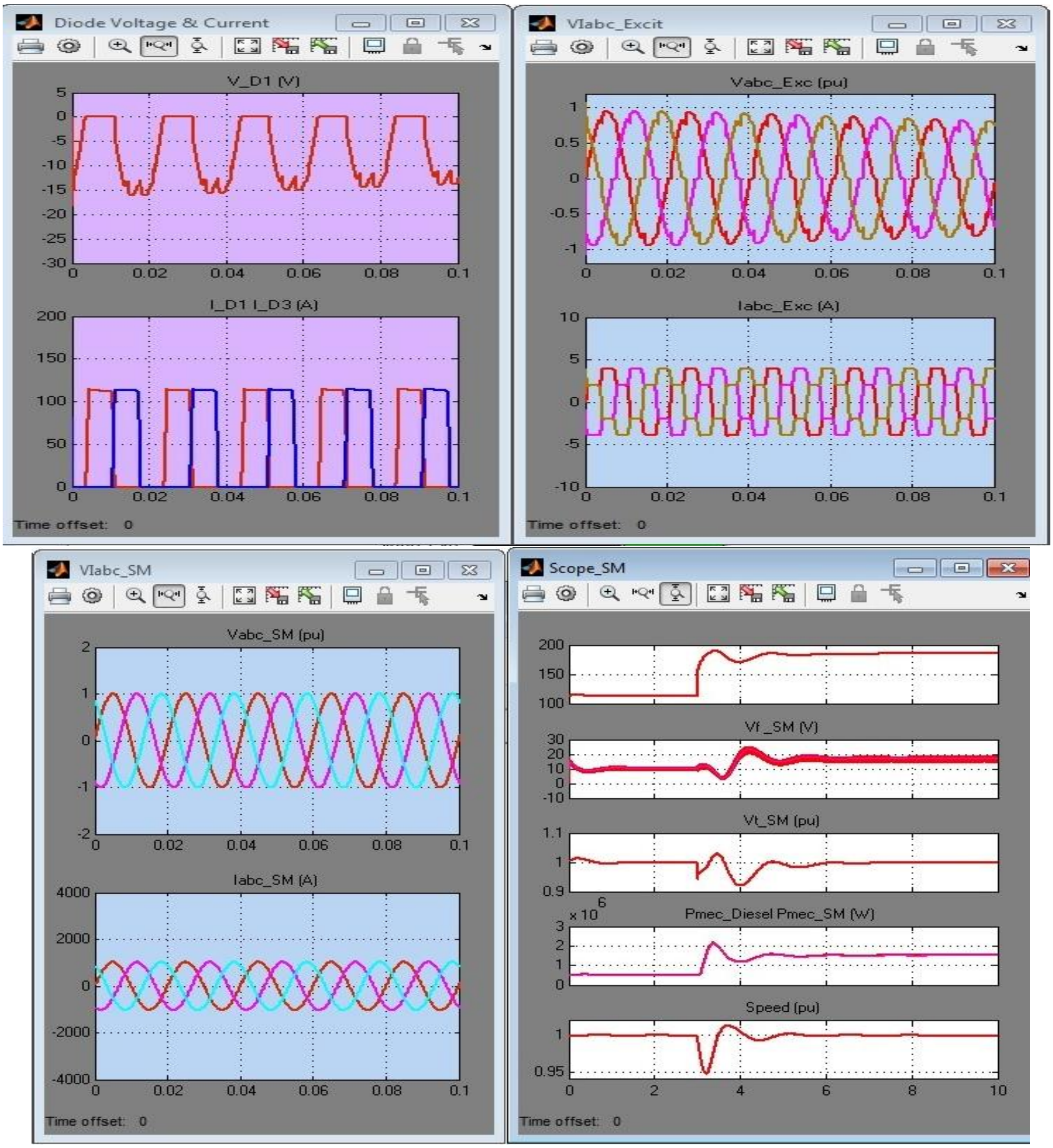


Figure 2. The exciter system

The synchronous-generator voltage was regulated by controlling the exciter field voltage. The controller (PI type) was done, which compared the measured voltage (positive sequence voltage) with a 1 pu reference. Discretized (Ts=50 us) was used to increase the simulation speed. All simulation results can be explain by **Figure 3(a,b).**



3.b

Figure 3.a,b: The simulation results

5. CONCLUSIONS

a. Modeling in Matlab/Simulink and use of Sim-Power Systems allows full analysis (both static and dynamic states) and simulation. An extension into studying the procedures for identification of the parameters of a synchronous generator and determination of generator work chart. The best way to explain the mathematical model and present it on Simulink is by describing it in a set of mathematical equations and then reconstructing the set of equations on Simulink.

b. The analysis of model after connection between Matlab Simulink model and Matlab editor can be done with many facilities can be used control system analysis and it could be used for estimation of load angle determination and generator stability studying. The simulation is highly effective and can be considered a first step to implementing the system in a practical application.

c. Future work could include comparing the simulation results (which could use an intelligent controller) with those of a practical model.

6. *ACKNOWLEDGMENT*

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Table 2. List of symbols

Symbol	Detail
L_Q	quadrature reactance for Self-inductance
K_{MD} , K_M	winding resistance of stator to damper
K_{MQ} , K_M	winding resistance of stator to quadrature
r	current of stator winding
r_F	resistance of field winding
r_D	damper winding resistance at d-axis
r_D	damper winding resistance at q-axis
I_q	armature current at q-direction
I_F	current of field
I_D	damper winding current at d-axis
I_d	damper winding current at q-axis
R	resistance matrix
N	matrix of inductance coefficients for speed voltage
L	matrix of constant for mat inductances
L_d	Reactance of equivalent direct-axis
L_F	Self –inductance of filed winding
L_D	Self-inductance of damper winding
L_q	Equivalent reactance at quadrature-axis
U_f	Voltage of the field winding
W	Rotor speed SG
j	The total moment of inertia
M_T , M_E	Torque of the turbine and generator electromagnetic
I_s , φ_E	The resulting stator current vector and flux linkage
y	Rotation angle of the rotor, the angle between the d-
U_{fnem}	Nominal value of the excitation voltage
U_{shom}	Nominal voltage of the stator
U_s	Rms voltage of the stator
K_f	The multiplicity of field forcing
V_d	terminal voltage of armature at d-axis
V_q	terminal voltage of armature at q-axis
I_d	terminal current of armature at d-axis
I_q	terminal current of armature at q-axis
V_{fe}	terminal voltage of field winding
I_{fe}	terminal current of field winding