DYNAMIC MODELING AND SIMULATION OF THE SYNCHRONOUS GENERATOR

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Abstract

In this paper, the modeling and simulation of the synchronous generator are presented by using qd0 reference of frame. The capability of the model to approximate the non-linear operating characteristics of the generator is illustrated. At the beginning, the results of the model are compared with that obtained by PSS Tecquipment NE9070. Finally, similarity-based model validity tests are performed. The all results demonstrate the adequacy of the generator model.

Keywords: synchronous generator, *qd0* reference of frame, PSS Tecquipment NE9070

1. Introduction

The models of synchronous generators widely employed in various areas play important roles in many studies such as stability and control analysis. Different synchronous generator models have been developed [1], [2], [3], [4]. Simple generator models are good for analysis studies but not accurate enough for predicting generator performance for control studies. However, the higher order models improve the validity of the results.

This paper presents an effective approach for modelling and simulation the large synchronous generator under steady-state operation. This approach allows a user to simulate different kinds of loading operation conditions of the generator easily. In addition, the user can learn GUI (Graphical Unit Interface) capabilities to construct a user-friendly software package for learning the synchronous generator.

In visual software, the synchronous generator blocks are designed to be balanced model and connected to a grid networks. Unfortunately, the user may be difficult to represent the framework of three-phase synchronous generator. It is why three-phase balanced synchronous generator complete model will be presented in this study. The proposed model is based on the electrical circuit of the machine. As a basis for developing an easy-to-use educational software tool, some of GUI functions are implemented in creating an active link with this model. A brief explanation about modeling of the synchronous generator model is defined on Section II. Section III presents the demonstration. Section IV presents the final conclusion obtained with the present study.

2. Synchronous Generator Model

For constructing the synchronous generator model (Figure 1), there were the following assumptions:

1. a symmetrical tri-phase stator winding system is assumed,
2. one field winding is considered to be in the machine,
3. there are two amortisseur or damper windings in the machine,
4. all of the windings are magnetically coupled,

5. the flux linkage of the winding is a function of the rotor position,
6. the copper losses and the slots in the machine are neglected,
7. the spatial distribution of the stator fluxes and apertures wave are considered to be sinusoidal,
8. stator and rotor permeability are assumed to be infinite.

It is also assumed that all the losses due to saturation and slots can be neglected.

The six windings are magnetically coupled. Since the magnetic coupling between the windings is a function of the rotor position, the flux linking of the windings is also a function of the rotor position.

The machine equation in three-axes framework can be written as:

$$\begin{aligned} v_{abc} &= -r_s \cdot i_{abc} + \frac{d}{dt}\Psi_{abc} & \qquad v_f &= r_f \cdot i_f + \frac{d}{dt}\Psi_f \\ 0 &= r_{kq} \cdot i_{kq} + \frac{d}{dt}\Psi_{kq} & \qquad 0 &= r_{kd} \cdot i_{kd} + \frac{d}{dt}\Psi_{kd} \end{aligned} \quad (1)$$

Where i_{kd} and i_{kq} are the currents of direct and tranverse damper windings, Ψ_{kd} and Ψ_{kq} are the total flux of direct and tranverse damper windings, Ψ_{abc} is the stator total flux and Ψ_f is the main field total flux.

The two stator electromagnetic fields which traveling at rotor speed were identified by decomposing each stator phase current under steady-state into two components, one in phase with the electromagnetic field and other shift by 90^{O}. An air-gap field with its maxima aligned to *d*-axis and other is aligned to the *q*-axis (Figure 1).

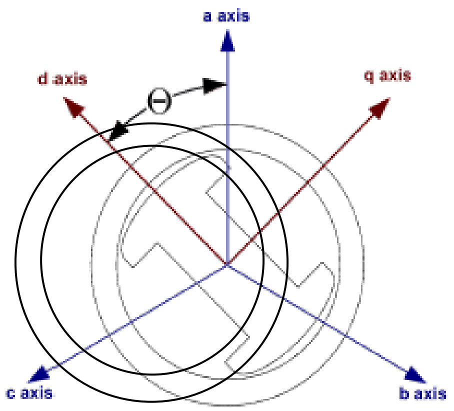


Figure 1. The generator frames, *abc* and *qd0*

The differential equations of electrical dynamic that describe the stator and rotor windings are shown in (3) and are written in *qd0* reference of frame by utilizing Park's transformation matrix. The following relationship given by Park's transformation is:

$$i_{dq0} = P \cdot i_{abc} \qquad i_{abc} = P^{-1} \cdot i_{dq0} \qquad (2)$$

Where the current vectors are $i_{dq0} = [i_0 \quad i_d \quad i_q]^T$ and $i_{abc} = [i_a \quad i_b \quad i_c]^T$ and Park's transformation matrix is:

$$P = \sqrt{\frac{2}{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ i_a \cos\theta & i_b \cos\left(\theta - \frac{2\pi}{3}\right) & i_c \cos\left(\theta - \frac{4\pi}{3}\right) \\ i_a \sin\theta & i_b \sin\left(\theta - \frac{2\pi}{3}\right) & i_c \sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix}$$

where i_a, i_b and i_c are the phase currents and θ is the angle between the phase current i_a and the current i_d.

The first three equations describe the stator winding (subscript *s*) and the following three equations describe the rotor winding (superscript *r*). The subscrip*k* is used for the damping windings while the subscript *f* is used for the field winding.

$$\begin{gathered} v_{qs}^r = -r_s i_{qs}^r + \frac{\omega_r}{\omega_b}\psi_{ds}^r + \frac{p}{\omega_b}\psi_{qs}^r \\ v_{ds}^r = -r_s i_{ds}^r + \frac{\omega_r}{\omega_b}\psi_{qs}^r + \frac{p}{\omega_b}\psi_{ds}^r \\ v_{0s}^r = -r_s i_{0s}^r + \frac{p}{\omega_b}\psi_{0s}^r \qquad v_{kq}^r = -r_{kq} i_{kq}^r + \frac{p}{\omega_b}\psi_{kq}^r \\ v_{kd}^r = -r_{kd} i_{kd}^r + \frac{p}{\omega_b}\psi_{kd}^r \qquad v_{fd}^r = -r_{fd} i_{fd}^r + \frac{p}{\omega_b}\psi_{fd}^r \end{gathered} \tag{3}$$

In these, *v* represents the voltage of windings and *i* represents the electrical current flowing in the winding. The magnetic flux linking the winding is represented by ψ, differential operator (d/dt) is represented by *p*, while ω_r and ω_b were angular speed of the rotor referred to a two pole generator and reference angular speed corresponded to the rated frequency, respectively.

The magnetic flux ψ for each winding is drawn in (4). The value of v_{kq}^r and v_{kd}^r are null since the damping windings are short-circuited.

$$\begin{aligned} \psi_{qs}^r &= -x_{ls} i_{qs}^r + x_{mq}\left(-i_{qs}^r + i_{kq}^r\right) \\ \psi_{ds}^r &= -x_{ls} i_{ds}^r + x_{md}\left(-i_{ds}^r + i_{fd}^r + i_{kd}^r\right) \\ \psi_{0s}^r &= -x_{ls} i_{0s} \\ \psi_{kq}^r &= x_{lkq} i_{kq}^r + x_{mq}\left(-i_{qs}^r + i_{kq}^r\right) \\ \psi_{kd}^r &= x_{lkd} i_{kd}^r + x_{md}\left(-i_{ds}^r + i_{fd}^r + i_{kd}^r\right) \\ \psi_{fd}^r &= x_{lfd} i_{fd}^r + x_{md}\left(-i_{ds}^r + i_{fd}^r + i_{kd}^r\right) \end{aligned} \tag{4}$$

where r_s, r_{kq}, r_{kd}, r_{fd}, x_{ls}, x_{lkq}, x_{lkd}, x_{lfd}, x_{mq} and x_{md} are the electrical

fundamental parameters of synchronous generator. The direct-axis reactance x_d and the quadrature-axis reactance x_q are given by (5).

$$x_d = x_{ls} + x_{md} \qquad x_q = x_{ls} + x_{mq} \tag{5}$$

The mechanical part of the generator is described by two differential equations as described in (6).

$$\begin{gathered} p\delta = \omega_r - \omega_s \\ \frac{2H}{\omega_s} p\omega_r = T_m - \left(\psi_d i_{qs} - \psi_d i_{qs}\right) - T_{damp} \end{gathered} \tag{6}$$

In (6), H is an inertia constant of the turbine generator set, T_m is the mechanical torque of the turbine and T_{damp} is a damping torque. The damping torque represents the rotational losses of the rotating parts which consist of the magnetic losses and the mechanical losses.

Visualization of synchronous generator system block and the inside of generator block can be seen in Figure 2 and Figure 3, respectively.

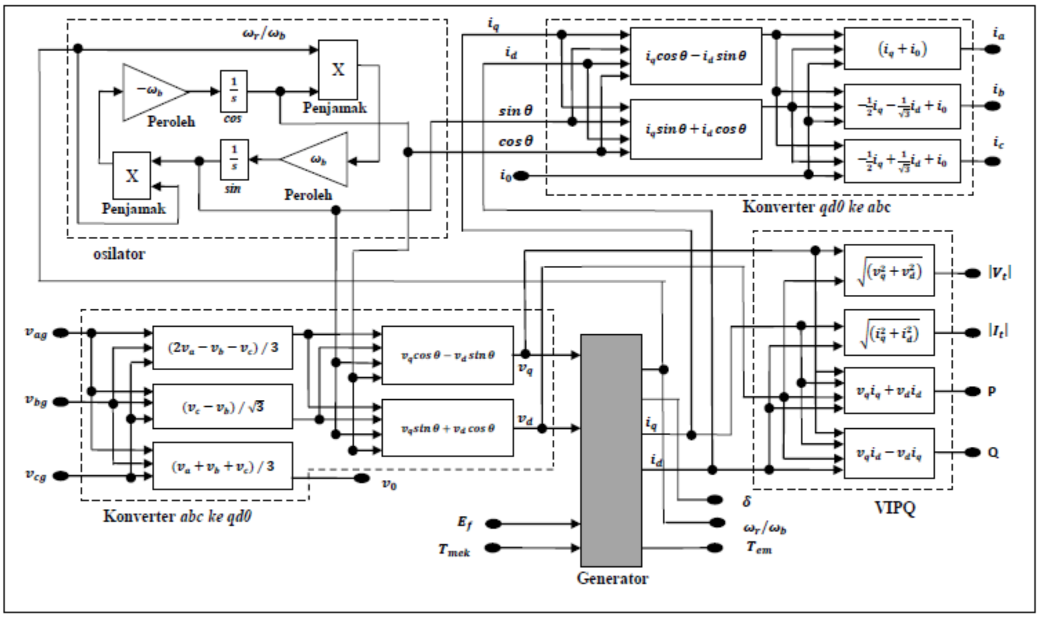


Figure 2. The model of synchronous generator

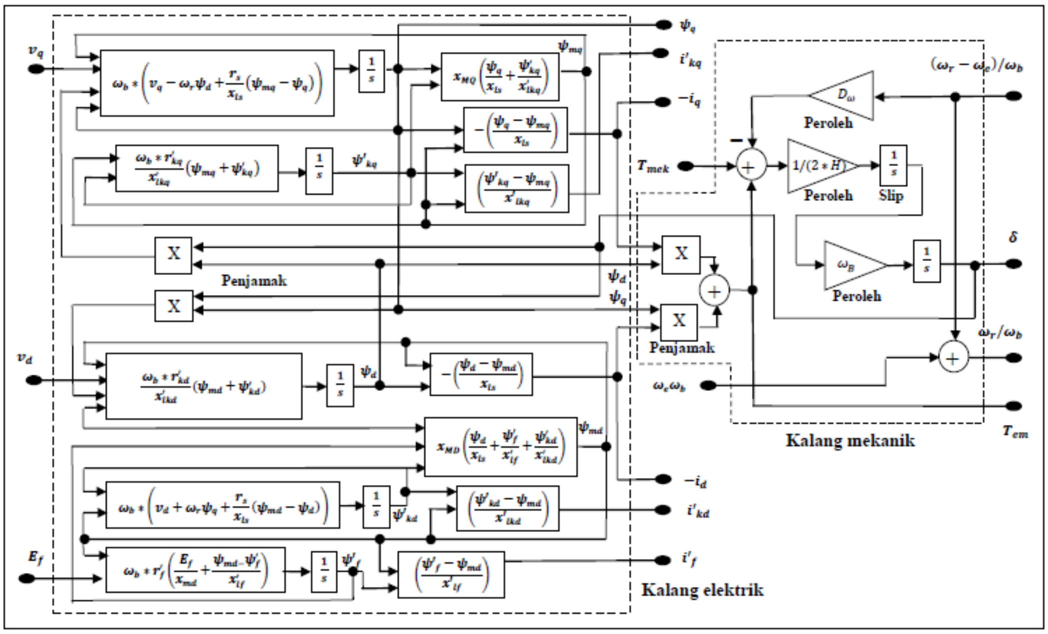


Figure 3. The inside of synchronous generator block

The user can access GUI facilities to develop a poweful and attractive software package for learning synchronous generator (see Figure 4). Main program is used to run the internal process which based on visualization. It consists of varies logic behind GUI and acts as a general interface between GUI and visual program. This program is also used to get or import and to send or export the physical test data. As an example of using GUI capabilities, menu and plotting commands are implemented in a script file to provide interactive windows with varies operating conditions. The main menu, which is displayed after running the file, is shown in Figure 5 and Figure 6.

The verification of the generator model is judged through comparing between generator's respon by PSS Tecquipment NE9070 (see Figure 7) and by the proposed simulator under no load, balanced and conditions, respectively (Sugiarto *et al*, 2013) .

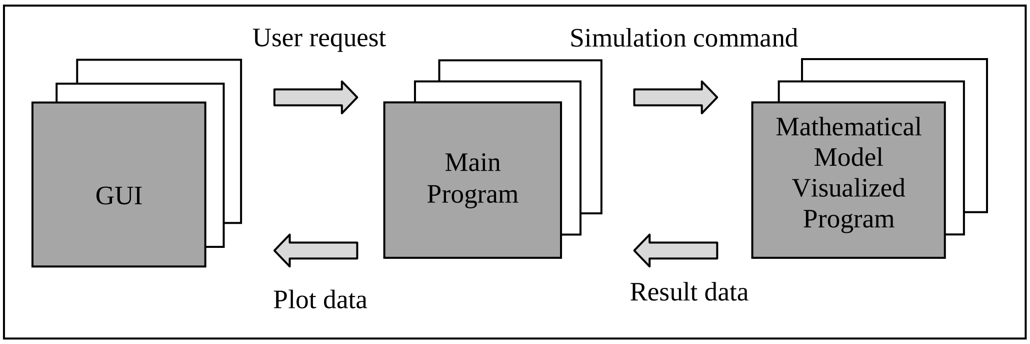


Figure 4. The configuration of synchronous generator simulator

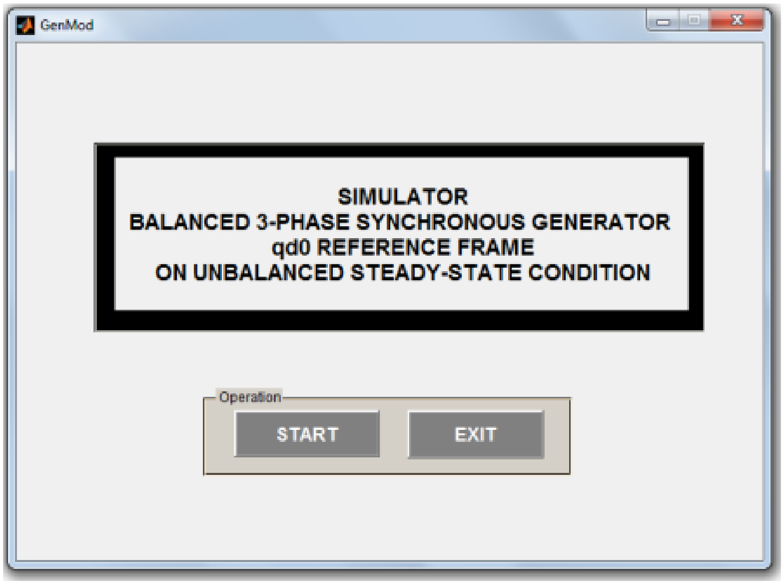


Figure 5. The main window of the developed software tool

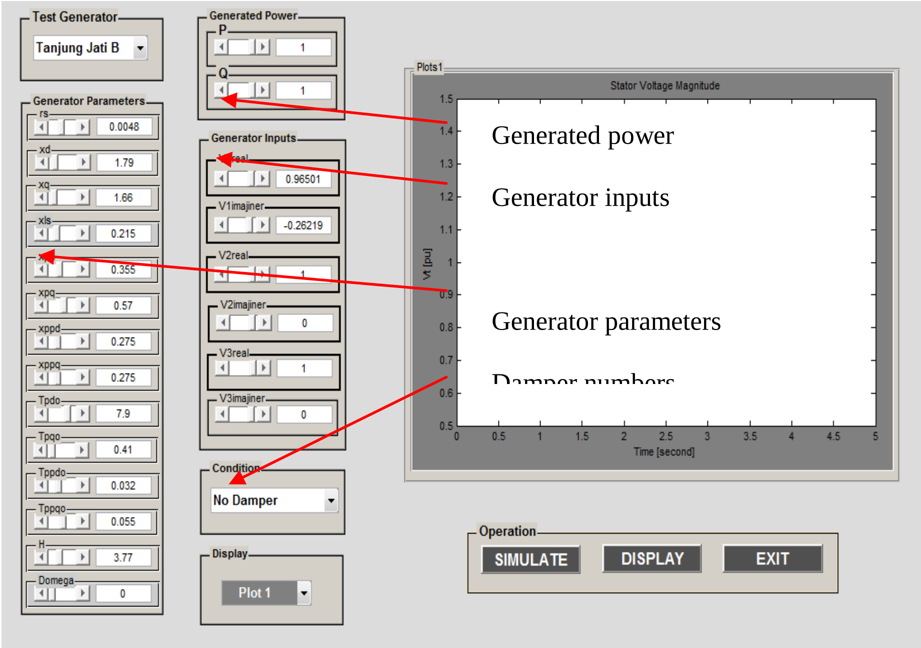


Figure 6. The window of inserting the inputs for the desired generator

Figure 7. PSS Tecquipment NE9070

Under no load, the output respons of PSS Techquipment NE9070 are non-sinusoidal with varied excitations shown in Figure 8, eventhough the P.F value is more than 0.8. The generator's outputs are always non-sinusoidal under stand-alone operation. The waveform of it will change into sinusoidal form when the generator is connected to the grids.

The results of proposed generator's model simulation considering P.F variations are described in Figure 8. It is shown that output respons are in non-sinusoidal forms although the value of P.F excitation is reached up to 0.81. Comparing the result between Fig. 8 and Figure 9 concludes that the output respons of proposed generator model have similar trend to the output PSS Techquipment NE9070.

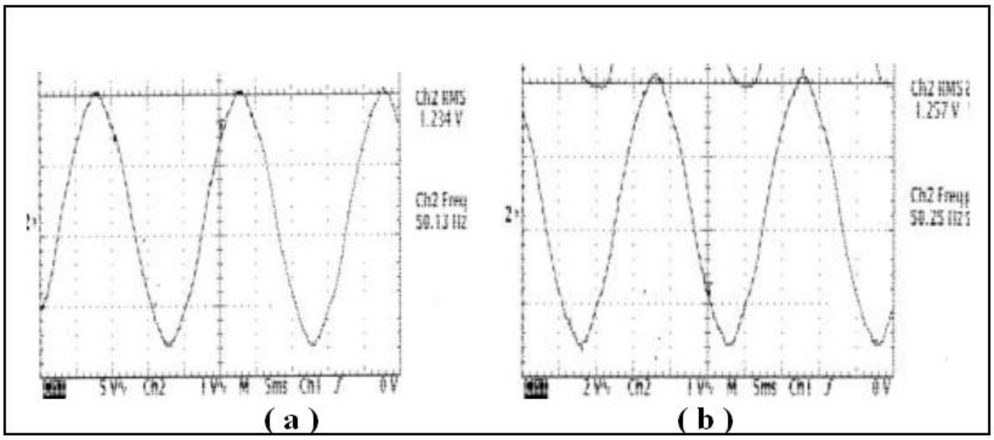
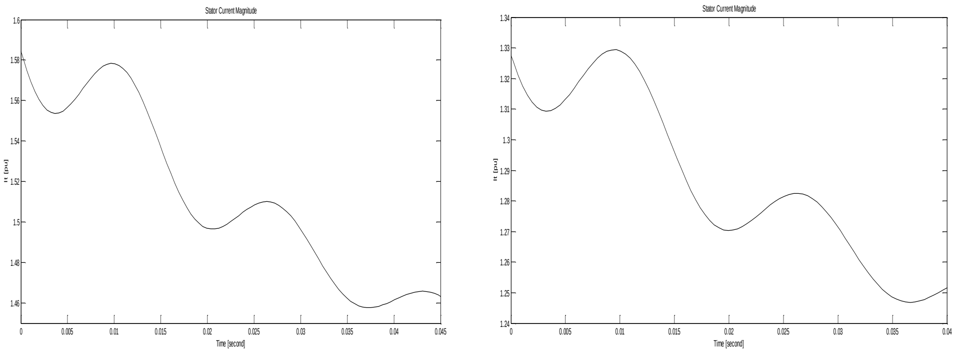


Figure 8. The output of PSS Tecquipment NE 9070 with:
a. 0.72 PF excitation b. 0.81 PF excitation



(a) (b)

Figure 9. The output of proposed standalone generator model with:
a. 0.72 PF excitation. b. 0.81 PF excitation.

Figure 10 presents the respons of PSS Techquipmen NE9070. When generator is under unbalanced load condition (Figure 10.a) , its steady state respon will oscillates less than under balanced load condition (Figure 10.b). The oscillation magnitude of unbalanced load during transient condion is bigger than balanced loads counterpart.

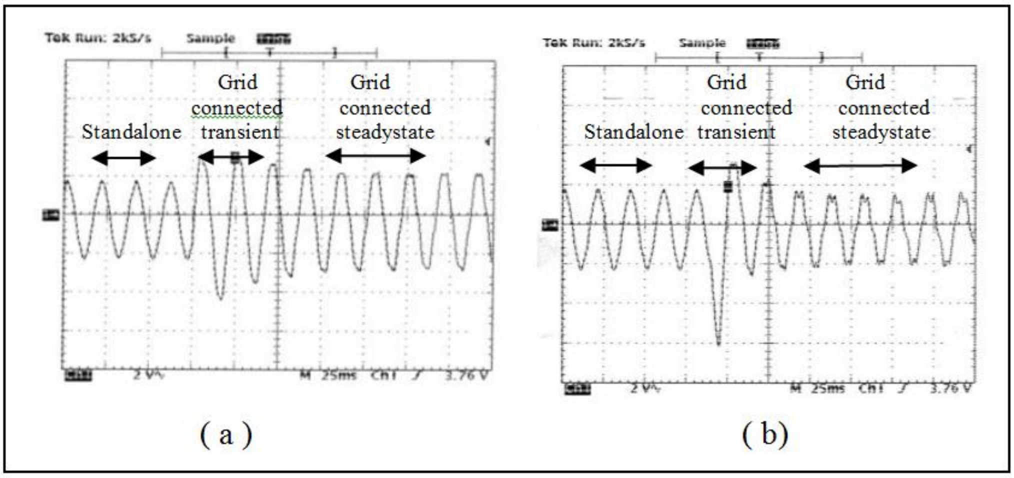
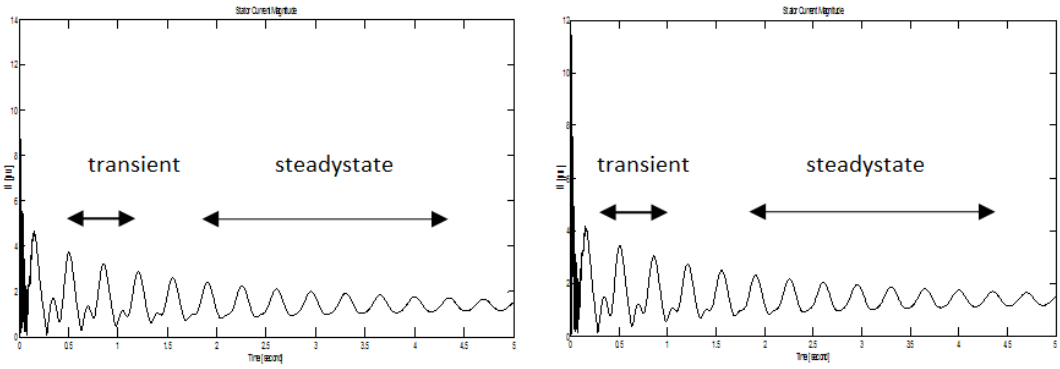


Figure 10. Outputs of the PSS Tecquipment NE 9070
a. Unbalanced Loads b. Balanced Loads



(a) (b)

Figure 11. The outputs of the proposed generator model

a. Unbalanced Loads b. Balanced Loads

This condition is also occured during simulation of the proposed synchronous model shown in Figure 11. The oscillation of stator voltage of synchronous generator during interconnecting with 7.5% unbalanced grid is bigger than it is connected to balanced grid. Concludely, the proposed model is valid as a synchronous generator test model.

3. Demonstration

The simulation of the proposed generator model is carried out by visual program. As an inputs of this generator model, which are stator voltages, is derived by giving an arbitrary values. The process of numerical simulation method can be presented by the block diagram of Figure 12.

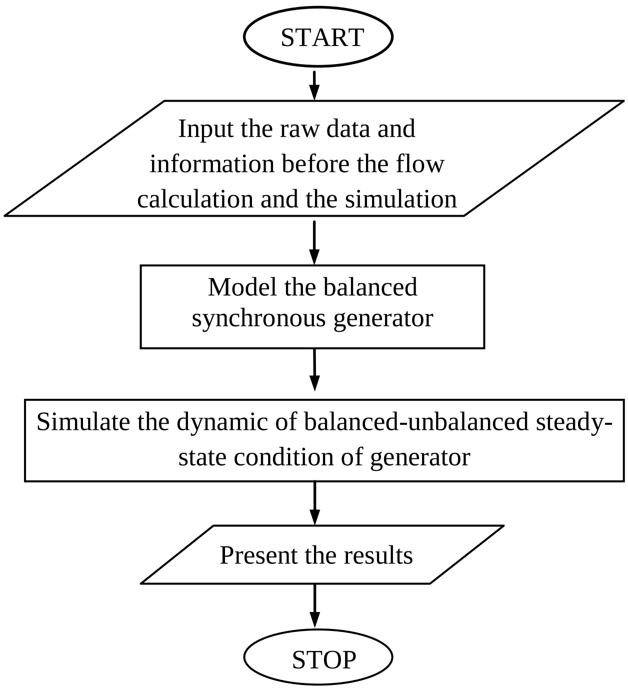


Figure 12. Simulation flowchart

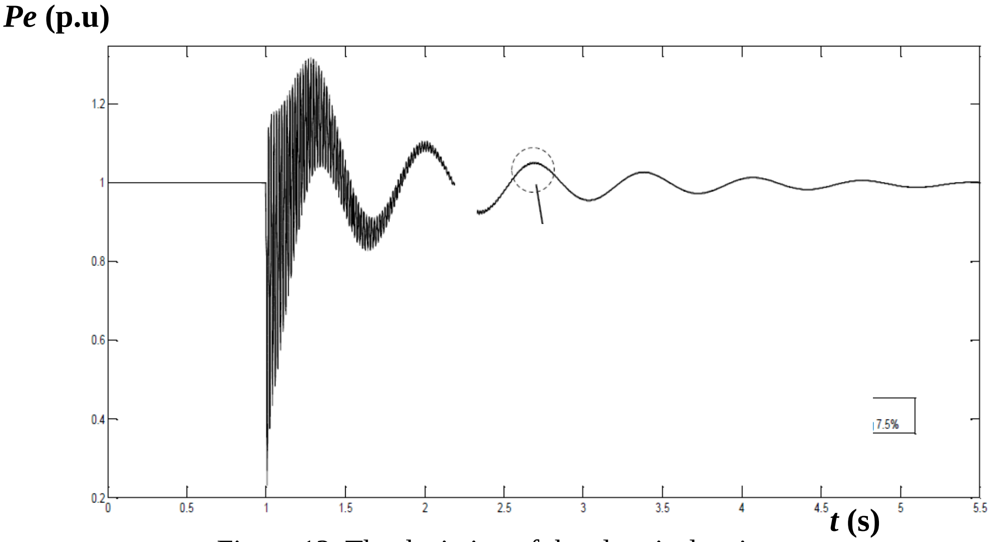


Figure 13. The deviation of the electrical active power.

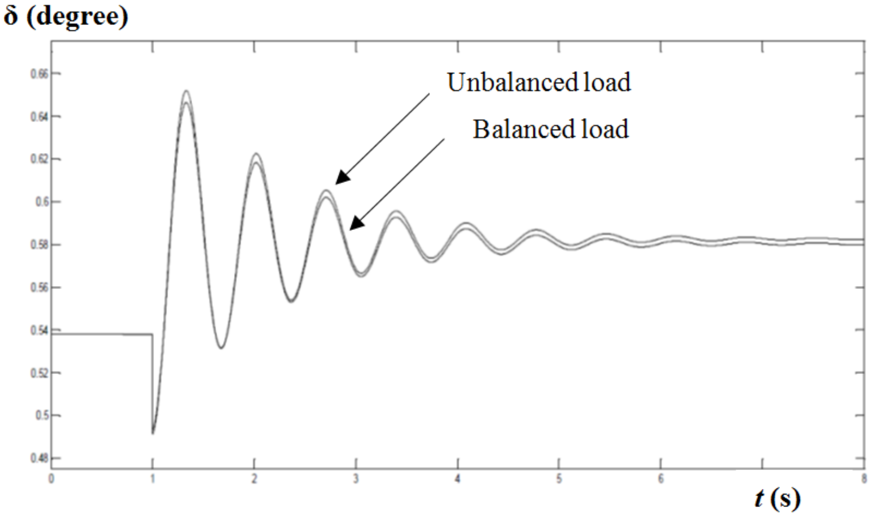


Figure 14. The deviation of the rotor angle

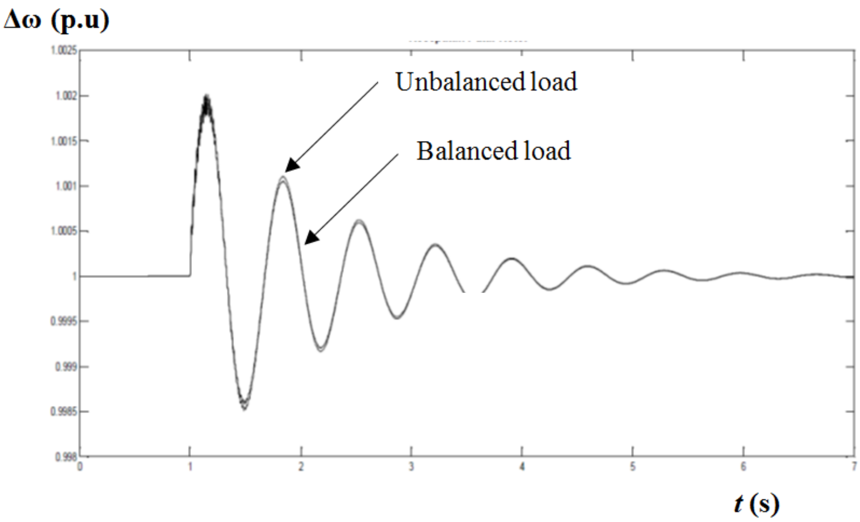


Figure 15. The deviation of the angular speed

4. Conclusion

A useful approach for learning a three-phase synchronous generator under steady-state operation has been presented in this paper. Two operation conditions of the synchronous generator, such as balanced and unbalanced loads, are mathematically modeled then simulated using visual program. The designed tool is made easy to use by providing an active link with the simulated models using some of GUI functions. The given examples demonstrate helpfulness of the designed tool for learning the generator dynamic under steady-state operation.

References

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