

Synchronous Generator Modeling Using Matlab

Spoljaric, Zeljko ; Miklosevic, Kresimir & Jerkovic, Vedrana

Department of Electromechanical Engineering

Faculty of Electrical Engineering, University of Osijek, Croatia

kresimir.miklosevic@etfos.hr, zeljko.spoljaric@etfos.hr, vedrana.jerkovic@etfos.hr

Abstract Mathematical model of third and seventh order that describes the synchronous generator is given. Basic principle, application field and equivalent circuit of synchronous generator are explained. Simulation model of synchronous generator using Matlab is given. Model made in SimPowerSystems is explained. Essential parameters used for simulation are given. Usage of model for different testing and analysis is proposed.

Keywords— analysis, Matlab, model, simulation, synchronous generator.

I. INTRODUCTION

The main problem of this paper is building simulation model of synchronous generator by using one of programs for modeling called Matlab and specially part of Matlab program called SimPowerSystems. Paper describes all four mathematical models with necessary equations. It is well known that mathematical model of synchronous generator can be presented with model of second, third, fifth and seventh order. Model of seventh order is the most complex and it describes generator most accurately [1]. This model is used for analysis of dynamic behaviors in normal conditions and in conditions of generator failure. The fifth order model neglect DC components in stator and AC components in rotor windings. It is used because it is simpler than model of seventh order. The fifth order model is often used for modeling of electro-energetic systems for purpose of studying transient stability when Kirchhoff laws for electric grid are written as for stationary state [2]. The third order model is of crucial interest for studying control systems of generator as well as their synthesis. The third order model neglects frequency deviation, higher harmonics and behaviors in damping windings. This model of generator because of its simplicity and good dynamic description has the higher usage for analysis and synthesis of control system. The second order model is the simplest model of synchronous generator which describes only the dynamics of rotor moving [2]. In literature this model is often called “the model with constant electro-motive force behind transient reactance”. There are many examples of usage of mentioned mathematical models for different purpose.

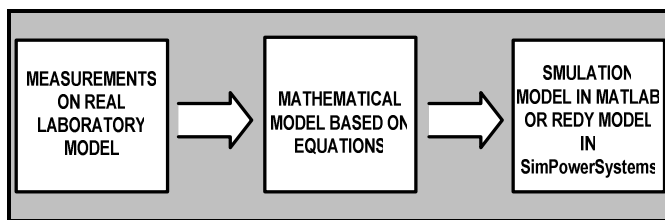


Figure 1. Model building process.

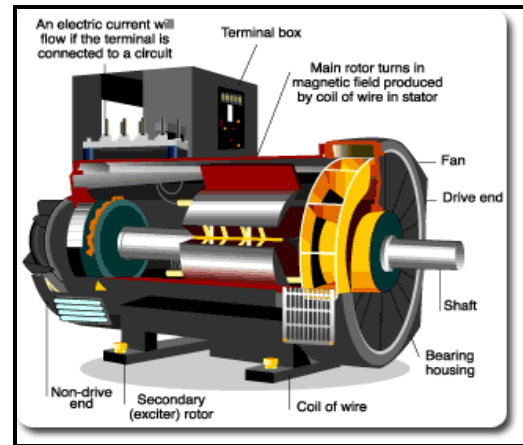


Figure 2. Laboratory synchronous generator.

In [3] is given description of analysis of generator angular stability in dependence on excitation systems. The paper elaborates non-linear mathematical model of third order of electric power system with several generators. This model is used for testing angular stability in the circumstances of extensive disruptions in electric power system in two cases. The first case is generator with separate excitation and the second case is generator with self-excitation system. In [4] is given description of load angle estimation process by usage of neural networks. This model is also based on third order equations and reveals the applicability of estimation method based on dynamic neural networks. The third order model is also used for nonlinear state space model identification of synchronous generators as given in [5]. The method uses theoretical relations of machine parameters and the Prony method to find the state space model of system which will be further used for controller design and stability tests. The necessary theory for understanding equations which describes synchronous motors and generators is also given in [6]. This paper is specially oriented on synchronous generator model which is used in SimPowerSystems as part application in Matlab program. SimPowerSystems library contains different kinds of models for typical power equipment. This library includes models of: electric transformer, asynchronous motor, synchronous motor and generator, DC motor and some other power electronics elements. Similar paper given in [7] discusses about modeling of DC motor and in [8] is discussed about synchronous motor modeling in Matlab SimPowerSystems and in Simulink. Also in [9] are presented problems and modeling of asynchronous motor in Matlab Simulink and SimPowerSystems. SimPowerSystems library provides 6 different models or blocks for modeling dynamical behavior of

three phase synchronous generator with highlighted and non-highlighted poles [10]. Models can be used in SI or in pu units. The building of generator model is based on mathematical equations. Process of model building process is shown on Fig.1. These equations can be found in numerous literatures. In this paper equations are used from [1, 2 and 6]. The object of modeling is presented with one smaller laboratory generator unit. These units have power range from 5 to 10 kVA and are mostly used for laboratory testing.

II. MATHEMATICAL MODEL

Any kind of modeling of electrical machine such as synchronous generator starts with measurements on real model because it is necessary to determine all essential parameters. The other possibility is to obtain generator parameters from manufacturer or determinate our own parameters if generator prototype is being build [8]. After that generator model can be made by using all mathematical equations which describe the generator. As scientific method modeling reduces research work on theoretical relevant values [10]. The result is sequence of generalizations of some parts of reality bonded with defined laws. It all leads to reduction of complexity as attempting to make this reality more understandable. Mathematical model which describes the behavior of original is created as result of all embracing investigation of research object. Mathematical model must include all essential parameters of some behaviors described with differential equations. It could be said that research connected with modeling consists of three work steps: building a model, research of its behavior and its evaluation [10]. Solution of simulation task can be resolved in few steps: defining a problem, restoring of mathematical model, development of simulation program, testing of simulation model, performing simulation procedure, evaluation of results, returning on previous step or exit. Further it will be given all four models with their belonging equations which describe the synchronous generator mathematical model. Model of generator can be derived from its equivalent circuit as presented on Fig.3. [11]. This is a starting point for formation of essential equations. A synchronous machine, as the name indicates, must rotate at synchronous speed which is uniquely related to the supply frequency [12]. The stator winding is three-phased but rotor winding carries direct current. The equivalent circuit per phase of synchronous generator (Fig. 2.) links the stator and moving rotor windings. Main elements of equivalent circuit are stator and rotor resistance (R_s , R_f), stator and rotor leakage inductance (L_{ls} , L_{lf}), output (stator) voltage (V_s), excitation or speed emf (V_f), stator and field (rotor) current (I_s , I_f), magnetizing current (I_m), core-losses resistance (R_m) and

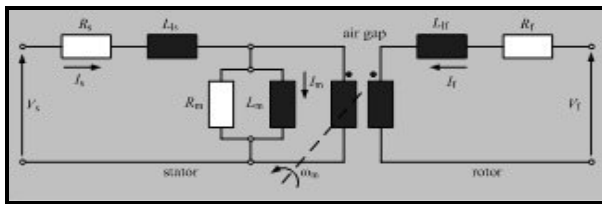


Figure 3. Equivalent circuit of a synchronous generator [11].

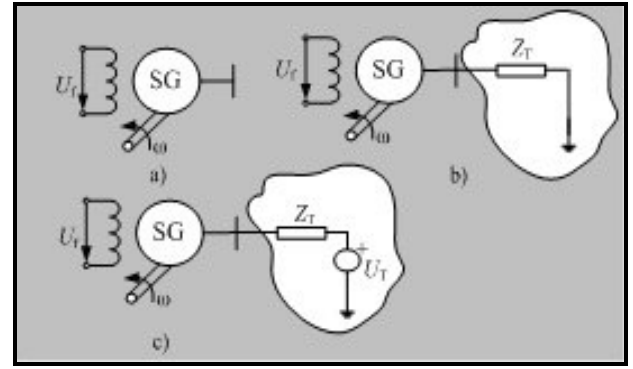


Figure 4. Synchronous generator for different work regimes: a) unbiased generator, b) stand alone generator, c) generator on electric grid [1].

magnetizing inductance (L_m) [8].

A. Standard or seventh order model

This is the most complex mathematical model of synchronous generator. This model is used in Matlab SimPowerSystems and it neglects asymmetry of stator windings, higher harmonics of flow in air gap, parameter changing because of external condition (such is temperature), nonlinearity of iron magnetic characteristics, skin effect in stator and rotor windings and iron losses. For needs of analysis and synthesis of excitation system from mathematical model of any kind of complexity, equations are determined for different kind of work modes. This is shown on Fig.4. [1]. Standard model of generator in relative terms is described with differential equations in which the first two a matrix and second two are algebra equations [1 and 6]:

$$\mathbf{u}_s = -\mathbf{R}_s \mathbf{i}_s + \omega \mathbf{P} \boldsymbol{\Psi}_s + \frac{d}{dt} \boldsymbol{\Psi}_s \quad (1)$$

$$\mathbf{u}_r = \mathbf{R}_r \mathbf{i}_r + \frac{d}{dt} \boldsymbol{\Psi}_r \quad (2)$$

$$2H \frac{d\omega}{dt} = m_t - m_e \quad (3)$$

$$\frac{d\delta}{dt} = \omega - \omega_s \quad (4)$$

The equations which describe connection between fluxes, currents and electromagnetic moment are:

$$\boldsymbol{\Psi}_s = -\mathbf{L}_s \mathbf{i}_s + \mathbf{L}_{sr} \mathbf{i}_r \quad (5)$$

$$\boldsymbol{\Psi}_r = -\mathbf{L}_{sr}^T \mathbf{i}_s + \mathbf{L}_r \mathbf{i}_r \quad (6)$$

$$m_e = \boldsymbol{\Psi}_d \mathbf{i}_q - \boldsymbol{\Psi}_q \mathbf{i}_d \quad (7)$$

In the equations all bolded letters are vectors with their belonging elements. Standard model of synchronous generator

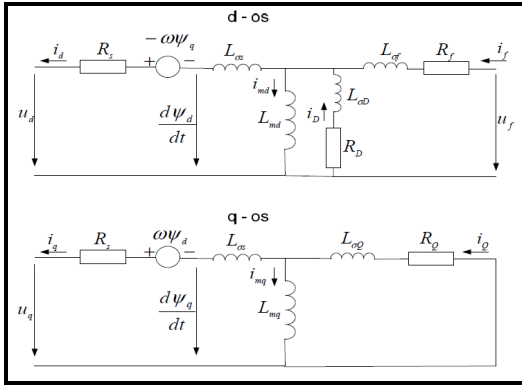


Figure 5. Schematic circuit of standard model [1].

can be presented schematically as shown on Fig. 5. Product of angular rotor speed and stator flux in equation (1) and product of fluxes and currents in equation of electromagnetic moment (7) makes the standard model nonlinear. Because of this usage of seventh order model for synthesis of control system is not recommendable. This model is used for analysis of dynamic and transient behavior. If used model includes iron core nonlinearity it becomes more complex. This is shown in [6]. If the mention model could be used for linear analysis and control system synthesis it is necessary to make that model linear. Standard model can be presented in state space (state model) which is suitable for synthesis of control system. Matrix equation of linear seventh order model synchronous generator in space state is:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \quad (8)$$

where is:

$$\mathbf{A}(\omega_0, \Psi_{d0}, \Psi_{q0}, i_{d0}, i_{q0}, U_{s0}, \delta_0) = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & 0 & a_{16} & a_{17} \\ a_{21} & a_{22} & 0 & 0 & a_{25} & a_{26} & a_{27} \\ a_{31} & 0 & a_{33} & a_{34} & 0 & 0 & 0 \\ a_{41} & 0 & a_{43} & a_{44} & 0 & 0 & 0 \\ 0 & a_{52} & 0 & 0 & a_{55} & 0 & 0 \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix} \quad (9)$$

and

$$\mathbf{B}(\delta_0) = \begin{pmatrix} b_{11} & 0 & 0 & 0 \\ b_{21} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & b_{63} & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \quad (10)$$

Dynamic system matrix $\mathbf{A}$ and input matrix $\mathbf{B}$ are in the function of work point in which synchronous generator is. Space vector $\mathbf{x}$ and control vector $\mathbf{u}$ are defined in the following equations:

$$\mathbf{x} = (\Delta\Psi_d \quad \Delta\Psi_q \quad \Delta\Psi_f \quad \Delta\Psi_D \quad \Delta\Psi_Q \quad \Delta\omega \quad \Delta\delta)^T \quad (11)$$

$$\mathbf{u} = (\Delta u_s \quad \Delta u_f \quad \Delta m_t \quad \Delta\omega_s)^T \quad (12)$$

Seventh order model can be scientifically simplified with third order model if synchronous generator is unbiased.

B. Third order model

Third order model is used for analysis and synthesis of excitation system of synchronous generator. This model must explain dynamic behavior of excitation system but not all physical behaviors in generator. Model must be flexible which means that it must explain different dynamics which will appear in real work condition. It must be economical which is reference to have less parameters for describing synchronous generator but not harm quality of dynamic behavior explication. Further it must have good numeric characteristics. Third order neglect asymmetry in grid voltage and higher harmonics, deviousness of angular speed of rotor from synchronous speed of rotation, influence of damper windings in sub transient state and work resistance of stator windings. Differential equations which describe the third order model of generator connected on electrical grid using Thevenine supplemental are:

$$u_f = R_f i_f + \frac{d}{dt} \Psi_f \quad (13)$$

$$2H \frac{d\omega}{dt} = m_t - m_e \quad (14)$$

$$\frac{d\delta}{dt} = \omega - \omega_s \quad (15)$$

The equations which describe connection between fluxes, currents and electromagnetic moment are:

$$\mathbf{u}_s = \omega \mathbf{P} \Psi_s \quad (16)$$

$$\Psi_s = -\mathbf{L}_s \mathbf{i}_s + \begin{pmatrix} L_{md} \\ 0 \end{pmatrix} i_f \quad (17)$$

$$\Psi_f = -L_{md} i_d + L_f i_f \quad (18)$$

$$m_e = \Psi_d i_q - \Psi_q i_d \quad (19)$$

Third order model takes in to consideration dynamic of rotor and excitation system and neglects dynamics of other physical quantities. In this model grid voltage is symmetrical without higher harmonics. In third order model it is possible to use instead of: flux, angular speed, load angle, d-q currents and d-q voltages, variables of vector diagram (Fig. 6.): $e', e, \omega, \delta, \bar{i}_s, \bar{u}_s$. First variable represents transient electromotive force, second variable is phase electromotive

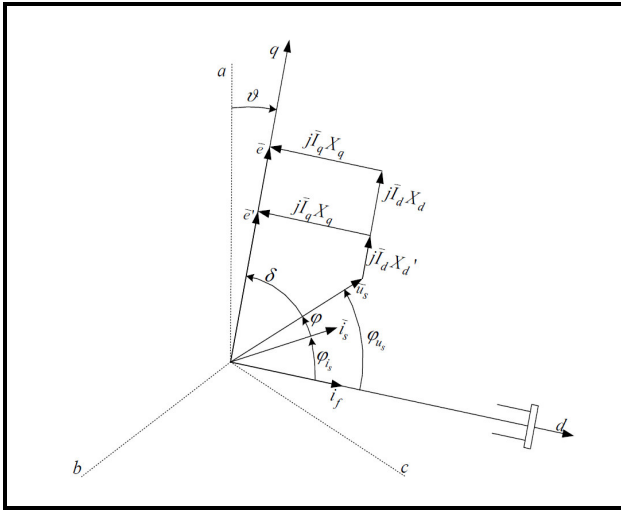


Figure 6. Synchronous generator vector diagram [1].

force of stator, third is angular speed, fourth is load angle, fifth is phase current of stator and the last is phase voltage on stator.

C. Second and fifth order model

Second order model of Synchronous generator describes only dynamics of rotor rotation. Dynamic behaviors are considered to be finished and values have reached stationary amounts. This model neglects dynamic processes of damper rotor windings on rotor movement. Influence of speed on armature voltage is completely neglected which means that electromagnetic moment (m_e) is equal to force (p_e). Model is used for grading transient stability of electric power systems using direct operations [2].

The fifth order model is used for the needs of study of transient stability in models elect energetic systems where Kirchhoff laws for grid are written for stationary state. This model is much more complex as it is shown in Fig. 7. In fifth order model Park equations are used for armature circle with belonging matrix and vectors.

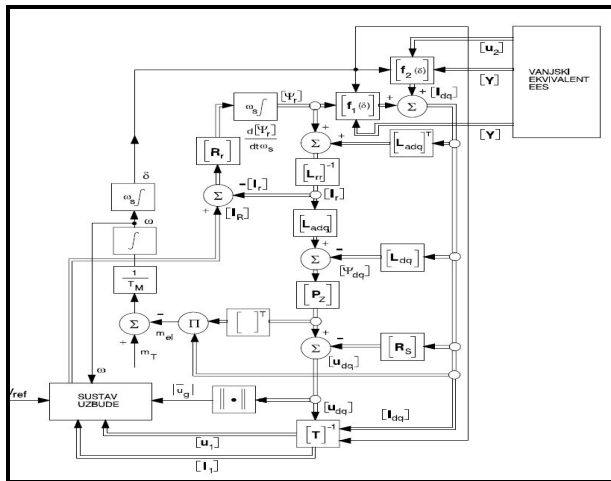


Figure 7. Fifth order model of synchronous generator and synchronous generator excitations system [2].

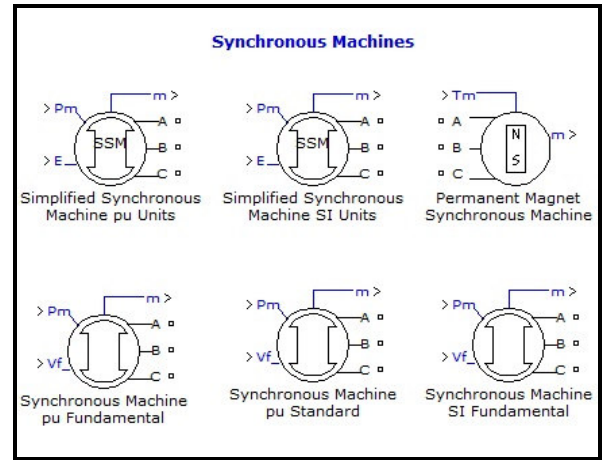


Figure 8. Possible blocks of synchronous generator model [10].

III. SIMPOWERSYSTEM MODEL

As mentioned, SimPowerSystems is part of Matlab Simulink and contains a library (*powerlib*) with synchronous, asynchronous and DC machines. Powerlib contains 6 different models of three phase synchronous machines (Fig. 8.) with parameters in SI units or in pu [8]. In upper row there are simplified models of generators with permanent magnets on rotor. Down row will be used for reconsideration in this paper because it can represent the generators used in power plants. Synchronous machine can operate in motor or in generator regime depending on definition of mechanical power direction. In generator regime this data is positive constant or function [10].

In Fig. 9 standard model of seventh order in pu of synchronous generator first subsystem level. It is shown that this system is presented with electrical and mechanical model. For all two models it is possible to measure different values as: stator and rotor current, currents in d-q axes, excitation currents, load angle, power, rotor speed and so on. We can say that under the measurement list two groups are possible to view: electrical and mechanical list. On Fig. 10 electrical model subsystem is presented as system of sixth order and mechanical part (Fig. 11.) is presented as system of second order. As explained before, all equations are implemented in these blocks. Electrical model is consisting of several subsystems. First

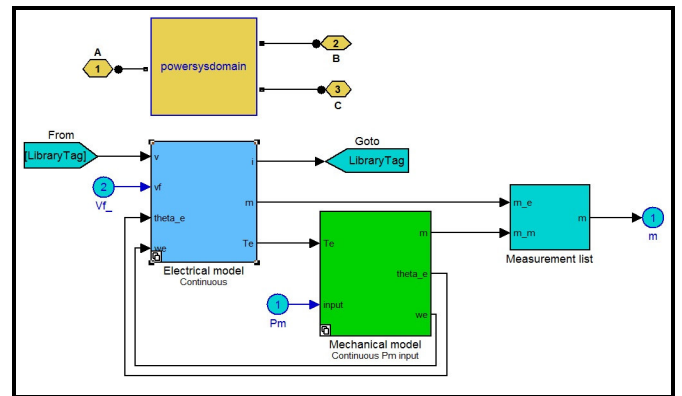


Figure 9. Standard model of seventh order of synchronous generator [13].

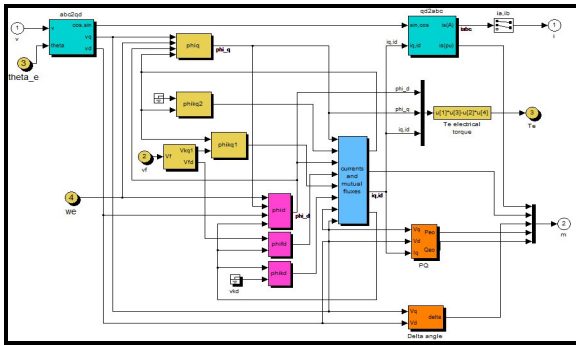


Figure 10. Electrical model (subsystem) of synchronous generator [13].

converts voltages from abc system to $d-q$ system. The other part uses sine and cosine transformation from $d-q$ to abc system. The other part converts currents. Third part converts fluxes to $d-q$ system. One of the subsystems compute mutual fluxes as well as all direct and quadrature axis currents. There are parts of subsystems which compute the direct, field and direct axis dumper flux. Some parts compute work and reactive power and load angle. In Fig. 11 mechanical subsystem model is presented. Masking of mechanical system provides definition of input and output variables. Input variables are electrical moment and mechanical power and output variables are angle speed, angle of rotor and vector m (which consists of 6 measurement signals). Angle speed is determinate over moment of inertia J or inertia constant H like showed in Fig. 11.

In Fig. 12 simplified model of third order is shown. Like in seventh order model this model consists of electrical (Fig. 13.) and mechanical (Fig. 14.) subsystem model but more simplified. There are less value showed on measurement list. For the user is more simple to parameter this model because it demands much less data. There are several subsystems of electric model. There are: subsystem of wattmeter, voltage, internal impedance of the generator and other measurement signals. Mechanical subsystem model of synchronous generator is shown in Fig. 14. It consists from two input values and two output values. Connection between these two values is given in mechanical differential equation mentioned before. Like showed in [8] for asynchronous motor Fig. 15. shows synchronous generator parameters in third and seventh order model. The meaning of some index is similar to those for asynchronous motor parameter definition except those which

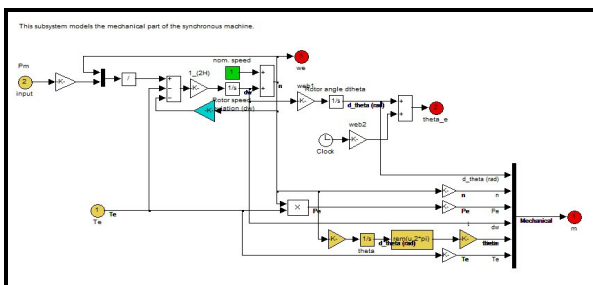


Figure 11. Mechanical model (subsystem) of synchronous generator used in seventh order model [13].

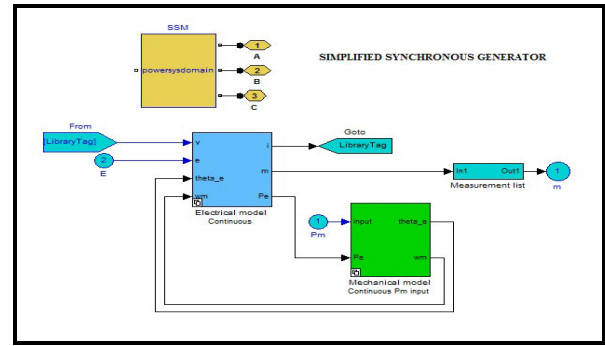


Figure 12. Simplified model of third order of synchronous generator [13].

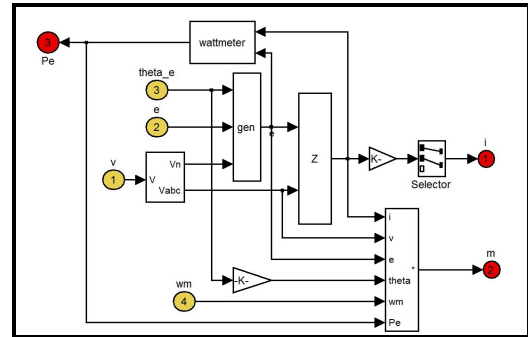


Figure 13. Electrical model (subsystem) of synchronous generator in third order model [13].

are related with dumper windings in rotor. Some data for seventh order parameters are synchronous, transient and sub transient reactance. They must be entered separately for d and for q axis. Time constant also must be entered in that way. The other indexes are common and will not be explained.

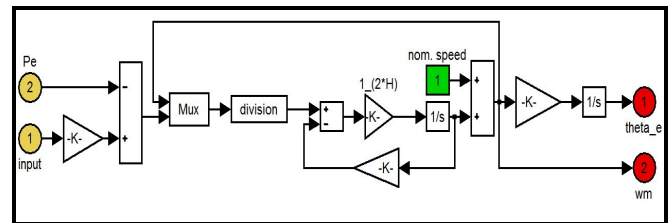


Figure 14. Mechanical model (subsystem) of synchronous generator used in third order model [13].

A. Example for generator 3-phase fault on gird

In Fig. 16 the example for testing synchronous generator for 3-phase fault to ground test is given. The example is used from [13]. In example the used three phase generator is rated with 200 MVA, output voltage is 13.8 kV, rotor speed is 112.5 rpm. The generator is connected to 230 kV gird over three phase transformer (210 MVA). Fault occurs at $t = 0.1$ s at 230 kV bus. The fault is terminated after 6 cycles (0.2 s). This example illustrates use of the synchronous generator associated with turbine and excitation system blocks and use of the load flow to initialize machine currents like showed in Fig. 17. Usage of mentioned model can also be implemented

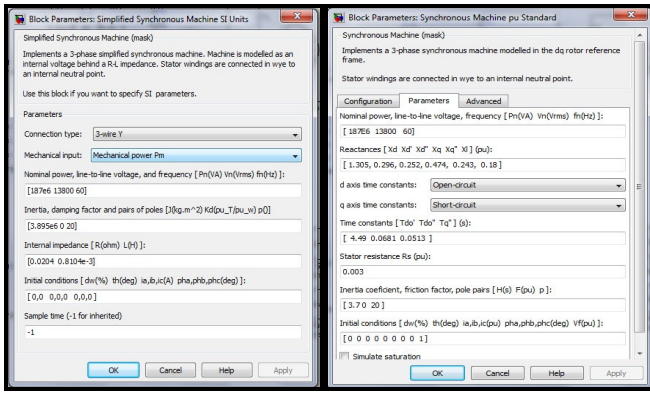


Figure 15. Synchronous generator parameters in third (left) and seventh (right) order model [13]

for testing different excitation types and parameter identification.

IV. CONCLUSION

This paper gives over section of used mathematical models for modelling synchronous generator. It is mentioned that generator can be presented with model of second, third, fifth, and seventh order. As the order grows, model becomes more complex. Each model is used for testing and determination of different behaviours. Seventh order model is the most complex and it is used for analysis of dynamic behaviors in normal conditions and in conditions of generator failure. The fifth model is often used for modeling of electro-energetic systems for purpose of studying cross over stability when Kirchhoff laws for electric grid is written as for stationary state. The third order model is of crucial interest for studying control systems of generator as well as their synthesis. The second order model is the simplest model of synchronous generator which describes only the dynamic of rotor moving. Each model have some neglecting. Modeling in Matlab and SimPowerSystems provides complete static and dynamic state analysis, and testing by using simulation model instead original. Specialty in the paper is explained the model of third and seventh order which is used in SimPowerSystems. This will further be used for studying procedures of synchronous generator parameter identification and determination of generator work chart. Also it could be used for estimation of load angle determination and generator stability studying.

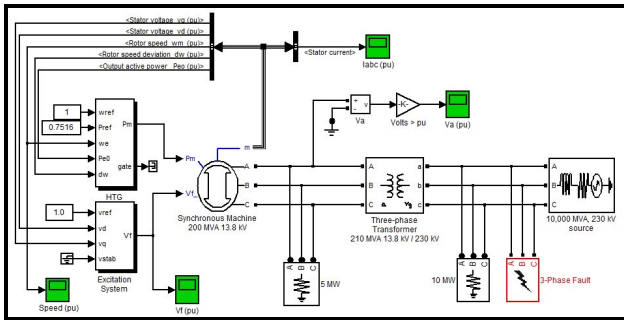


Figure 16. Example of testing synchronous generator for 3-phase fault to ground test [13]

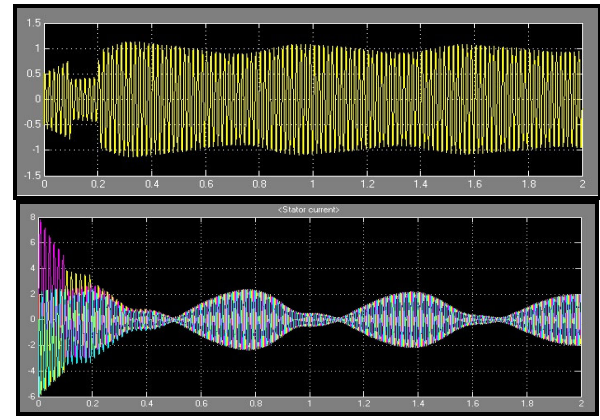


Figure 17. Voltages and currents response for three phase fault to ground [13]

The last implementation is based for studying different types of excitation systems for generator controll.

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