Dynamic Modeling and simulation of 200MVA Generator and Network for static exciters using a real-time Simulator

Mohammad Esmaeil Iranian *, Amin Zabihinejad **,
*6th km Malard Road, Fardis, Karaj 31176, Iran, iranian@mapnaec.com
**6th km Malard Road, Fardis, Karaj 31176, Iran, zabihinejad@mapnaec.com

Abstract: Exciters are designed for synchronous generators to keep three phase terminal voltages in their appointed set-point. This context means to present a mathematical model of a real synchronous generator and its network, in an attempt to simulate electrical sections of a 200MW gas power plant. It also meant to demonstrate the real and simulated function tests of an excitation system. Real system is formed by Synchronous generator, Breaker, Excitation cubicle and Gas turbine. This sophisticated simulator provides engineers with a safe environment to analyze the performance of exciters and test their restraints and above all tuning and verifying of different brands of exciter's Power System Stabilizer (PSS). The applied method contains dynamic and transient analysis of synchronous machine introduced by linear differential equations. Governor, Turbine, Infinite bus and Generator are given and all are implemented in SIMULINK yet, communication with the real excitation cubicle, simulink (SIT-DLL) and TDM, TDMS database were linked by National Institute LabVIEW 2009.

Keywords: AVR, Synchronous Machine, Simulator, Transient states, Dynamic response.

1. Introduction

Synchronous generator excitation control is one of the most important measures to enhance power system stability and to guarantee the quality of electrical power it provides. The main control function of the excitation system which is presented by weedy and Cory (1998) [1] is to adjust the field voltage with respect to the variation of the terminal voltage. It must be able to respond quickly to a disturbance enhancing the transient stability and the small signal stability. The excitation system controls the generated EMF of the generator and therefore controls not only the output voltage but the power factor and current magnitude as well.

Classical methods that make use of linear models for designing controllers are valid only on small variation around an operating point. A number of new control theories and methods have been introduced to design high performance excitation controllers to deal with the problem of transient stability for nonlinear synchronous generator models. Among them the Lyapunov method which is described by Machowski et al. (1998) [9] and Salem et al. (2003) [10], singular perturbation methods, feedback linearization and sliding mode control presented by Loukianov et al., (2004) [8] and Jiang and Wu (2002) [5], linear optimal control presented by Wen et al (1998) [11], the adaptive control method associated with neuron technique presented by Werner et al (2003) [12], the fuzzy logic control theory presented by Hassan et al. (1994) [4] and the nonlinear controller along with an observer are the most commonly used ones. Damm, G., 2004 [6] calculate stability function with non linear controller. Leon-Morales (2001) [7], calculate stability function with robust controller.

A model of the synchronous machine with full degrees is given in this work which is presented by Krause Paul C. (1986) [3], for a transient stability investigation. The mathematical modeling of this system is described in this paper and then this system is transferred into transfer function. Simulation result (time response) obtains from this transfer function.

For the implementation of the virtual laboratory LabVIEW, a product of National Instruments Inc. will be used. Clark, C., 2005 [2] showed it is a flexible, general-purpose graphical programming tool intended for a broad spectrum of applications.

This paper attempt to present a digital fast simulator intended to probe dynamic state of excitation system in a typical power system using Simulink software to implement network and generator transient equations. NI LabVIEW will also provide an instant communication from Simulator to Excitation Cubicle. The considered synchronous machine has a rated power capacity of 200MVA and rated voltage of 15.75 kV.

2. Mathematical Modelling of Synchronous Machine

The mathematical description of the synchronous machine is obtained if a certain transformation of variables is performed. Park's transformation is simply transforming all stator quantities from common phase a, b and c into equivalent DQ axis. Krause Paul C. (1986) [3], has presented below relations.
Whereas,
\[ \theta = \omega_r t \]
\[ \theta_{\text{ref}} = 0 \]

Following equation is the generator linkage flux equations in the rotor frame of reference are described in Per-unit. The machine equation in the rotor frame of reference becomes

\[
\begin{bmatrix}
\frac{d}{dt} i_\alpha & \frac{d}{dt} i_\beta \\
\frac{d}{dt} q & \frac{d}{dt} d
\end{bmatrix}
= 
\begin{bmatrix}
R_{\text{eq}} & L_{\text{eq}} \cos \theta
\\
L_{\text{eq}} \sin \theta & -R_{\text{eq}}
\end{bmatrix}
\begin{bmatrix}
i_\alpha & i_\beta \\
q & d
\end{bmatrix}
+ 
\begin{bmatrix}
E_{\text{m}} \sin \theta
\\
E_{\text{m}} \cos \theta
\end{bmatrix}
\]

Whereas,
\[ e_{\text{m}} = v_{r} \frac{X_{\text{eq}}}{s} \]

Now to calculate currents,

\[
\begin{bmatrix}
i_\alpha & i_\beta \\
q & d
\end{bmatrix}
= 
\begin{bmatrix}
i_{\text{ref}} \sin \theta & i_{\text{ref}} \cos \theta
\\
q_{\text{ref}} \sin \theta & q_{\text{ref}} \cos \theta
\end{bmatrix}
\]

Electrical torque value will be calculated by,
\[ T_e = (\varphi_{\alpha} i_{\beta} - \varphi_{\beta} i_{\alpha}) \]

Rotor speed equations have been written as,
\[ \rho \omega_r = \frac{\omega_r (T_e + T_j - (W_R - W_e) \omega_r)}{2H} \]

\[
H = \frac{1}{2} \left( \frac{2}{p} \right)^2 J \omega_r^2
\]

\[ \omega_r = \frac{1}{\rho} \omega_r + \omega_r (0) \]

And finally Rotor angle,
\[ \theta_r = \frac{1}{\rho} \omega_r + \theta_r (0) \]

### 3. Simulation setup

Owing to the fact that MATLAB - Simulink is one of the best mathematical software equipped to deal with every advanced equations, all dynamic equations of synchronous machine was modeled in Simulink environment.

Being exceptionally flexible, LabVIEW™ was chosen to establish an external bridge from Simulator to exciter. It is also the upper level software and human interface. All Charts and graphs were placed in its environment and that is beside data storing in TDM & TDMS databases, server client communications, implication of Governor and preset test programs.

Last but not least to make a SLI communication between Simulink and LabVIEW™, C++ has been used to materialize bilateral communication among them. There is also a server client possibility through Local Ethernet Network which has been equipped simulator with a chance to be controlled remotely or even be paired with another simulator. Fig.1

![Fig. 1: Schematic Diagram of Simulator in LabVIEW Software](image)

### 4. Real data setup

Real data has been gathered from an Iranian operational gas power plant located in north of Persian Gulf. Generator's model is a 200MVA AnsaldoEnergia with two poles, rotating 3000RPM -50Hz- and studied Exciter were provided by ABB Corps.

Functional tests of generator are secondary phase of commissioning. General concepts in these tests are based on IEC 60034-1 and IEC 146-1-1 standards. A normal procedure contains a vast number of tests but, some of the most important ones have been demonstrated here to prove the exactitude of the Simulator's values in comparison with the real data of an online gas generator.

#### 5. Real and simulation data result

##### 5.1 AVR

Automatic Voltage Regulation is one of the most important functions of any exciter, aimed to keep the generator’s voltage close to its current set-point level. In this mode, \( U_g \) set-point will be monitored by Static Excitation Equipment. Exciter will use rotor’s current to incline or decline \( E_f \) and as a result minimum deviation of \( U_g \) will be maintained automatically. This test has been applied in site by 8% increase in \( U_g \) set-point. Outcome has been shown in fig. 2.
As it was expected, by an increase in $U_g$ set-point, $I_f$ – Excitation current – Stepped up instantly. This action led to an increase in generator’s terminal voltage and an enlargement in amount of $Q$, the Reactive power.

To perform this test in Network and Generator Simulator, it is needed to run the software while exciter is in AVR mode. When simulator passed the transient moments and became stable, $U_g$ Set-point can be increased either by DCS toolkit, or directly in exciter’s controller. It depends on whether you are in remote or local mode. Outcome of this test has been displayed in Fig. 3. These graphs are illustrating 0.5% increase in set-point of generator’s voltage.

$$E_f = X_m \left( \frac{V_f}{r_f'} \right)$$

(12)

Simulink part of Simulator will convert the exciter voltage to $E_f$.

## 5.2 $U_g$ step response (Field voltage regulation)

Step response analyses are a common exciter test to investigate dynamic responses of the equipment. Exciter reactions during this test will provide required data for tuning PID values in exciter controller. This will lead us to gain optimum level of speed and accuracy in normal operation. To have this function examined, a sudden decline in $U_g$ set-point will be sent to exciter, while system reactions will be recorded in a fast recorder.

After some seconds by inclining $U_g$ Set-point, it will go back to its previous value. Fig. 4 illustrates mentioned test result in field.

Almost similar action will be measured to test the field voltage regulation in the factory using Network and Generator simulator. 3% up step in $U_g$ set-point value will lead to system natural reactions displayed in fig. 5.

As it was expected increasing $U_g$ set-point will be followed by an increase in exciter’s voltage and...
inevitably generated reactive power level. By declining 3% of $U_g$ set-point and returning to preset value, all other factors will also go back to their original levels.

5.3 Limitations - Under and over excitation limits

A set of limitations will be set for every power generation machine to keep it in an optimum work condition. When excitation current decreases, inevitably there will be a decline in amount of reactive power. This will also increase load angle $\delta$ and instability will come along if $\delta$ value goes beyond $\frac{\pi}{2}$; hence, to prevent such a misfortunate event an under-excitation limit level has been adjusted in every Exciter. In most exciters this limit has been set on level of negative reactive power level and when $Q$’s value gets close, Excitation systems will try to push it back to the work area in which load angle is $\delta_{\text{min}} < \delta_{\text{ss}}$.

![Fig. 6: Testing under excitation](image)

Fig. 6 displays a moment in which by displacing machine’s limit from -60 MVar to -36MVar and decreasing $U_g$ set-point, under excitation limit has been activated.

![Fig. 7: Testing under excitation limit in 60MW (Software)](image)

When in simulating environment there will be no danger to play with generator set-points. And as AnsaldoEnergia generator supplier suggested to enable under excitation limit in -60Mwar, this value has been set in Exciter.

As it has been shown in fig. 7, to activate this limitation, $U_g$ set-point has been declined to 0.92PU but before reaching to that level, under excitation limit was activated and by increasing $E_f$, reactive power has been forced back to safe work area.

Upper limit level of excitation current is totally dependent on the generator’s structure and its nominal power. As a result of exciter’s current accretion, beside reactive power, generator current will also increase. Normally as current flows in stator, its temperature will get intensified. Fig. 8 provides exciter behaviors in time of changing over-excitation limit level from 200MWAR to 75MWAR in real situation.

![Fig. 8: Testing Over excitation limit](image)

Fig. 9 is over excitation limit test in Network and Generator simulator. $U_g$ Set-point has been set to 1.02PU or 16014KV while network voltage was 0.994PU. As it has been shown in the figure after some seconds over Excitation limit has been activated and by decreasing $E_f$ reactive power has been plunged back to its green zone.

![Fig. 9: Testing Over excitation limit in 60MW (Software)](image)
Acknowledgements

The authors would like to acknowledge the active participation and financial support of the MAPNA Electrical and Control Engineering and manufacturing company.

References

Books:

Periodicals: