Automated Monitoring and Performance Assessment of a Grid Connected Synchronous Generator Considering Power System Stabilizer

MohammadHadi Rouhani  
Student Member, IEEE  
Dept. of Power and Control Eng.  
Shiraz University  
Email: mohammadhadi.rowhani.2014@ieee.org

Mohammad Mohammadi  
Dept. of Power and Control Eng.  
Shiraz University  
Email: m_mohammadi@shirazu.ac.ir

Mohammad Mehdi Arebi  
Dept. of Power and Control Eng.  
Shiraz University  
Email: arefi@shirazu.ac.ir

Abstract—In this paper the performance of a grid connected synchronous generator is evaluated. This is achieved by monitoring the influence of two parameters of the power system stabilizer on the synchronous machine parameters. A performance index taken into account the automatic monitoring of generator parameters is implemented. The aim is to reach an optimum operating point for the power system stabilizer so as to dampen the fluctuations of rotor angle, field circuit flux linkage and the output of the power system stabilizer. A classical model is considered for the synchronous machine. The assessment is based on a record of waveforms taken from monitoring of the synchronous generator parameters using expert systems. The work shows that it is applicable to increase the gains of the power system stabilizer to mitigate the oscillations of the synchronous machine. In addition this work shows the sensitivity of the synchronous machine to each parameter of the power system stabilizer.

Index Terms—Automated monitoring, Excitation system, Performance assessment, Power system stabilizer, Steam Turbine.

I. INTRODUCTION

Synchronous generators provide reliable and high quality power. They are designed to be driven by reciprocating engines, steam and gas turbines, hydro turbines, or various gas expanders. Synchronous condensers are sometimes used as means of providing reactive power compensation and controlling voltage [1]. The primary task of these machines is to convert the energy exerted from fossil fuels into mechanical and then change to electrical energy and eventually deliver to consumers. The complexity of synchronous machines arises from the dynamical and electrical characteristics of their operating behavior. This behavior causes various stability problems which force a synchronous machine to be synchronous with the connected grid.

The operation of a synchronous generator is very essential. Since most of the loads of a grid is synchronized in terms of frequency by the grid connected synchronous generators. It is very useful to parameterize these important factors and reach an optimum point for the operation of generators in a power system. As the result, frequency dependent loads can operate in a safe and reliable condition.

Disturbances occurring in power system due to load fluctuations can cause oscillations in the grid frequency and should be damped effectively to maintain the power system stability. Electromechanical oscillations are categorized in two main types (i) Local Plant Mode Oscillations; which is related to units at a generating station swinging with respect to the rest of the power system. The frequency oscillations are typically in the range of 0.8Hz to 2.0Hz, (ii) Inter-area Oscillations; which is associated with the swinging of many machines in one part of the system against machines on the other parts. The range of frequency fluctuation for this type is 0.1Hz to 0.7Hz [2]. The stability of a single machine connected to an infinite bus under load changes is analyzed in many literatures. The effect of the excitation control system on synchronous machine stability is presented in [3]. In recent decades the concept of dynamic stability of the generator under severe load changes has received much attention. The need for a supplementary excitation control for improving the stability of the machine has gradually increased. Power System Stabilizers (PSS)s have been introduced to enhance the stability of the synchronous machines. The initial development and application of PSS were in the early 1960s on four hydraulic plants on the Moose River in Northern Ontario. The control design and tuning procedures of power system stabilizers have a very significant influence on their effectiveness in enhancing overall system stability. The parameters selected for the PSS should be applicable to enhance steady state and transient stability of both local plant mode and inter-area mode in large interconnected systems. There are other modes which may be detected by PSS, such as, torsional modes and control modes associated with the excitation system and the field circuit [2]. Therefore, the contribution of the excitation control system is to:

• Maximize the damping torque of the local plant mode as well as inter-area mode oscillations without interfering the stability of other modes;
• Enhance system transient stability;
• Not adversely affect system normal operation during major system upsets which cause large frequency excursions;
• Mitigate the consequences of excitation system malfunction due to component failures.

Thus it is very useful to determine efficient and optimum parameters for PSS. This control system is composed of a phase-lead compensation (for some systems two series of compensation is implemented), stabilizing signal washout and stabilizer gain. In order to enhance the performance of PSS, a set of procedures should be carried out for selection of PSS parameters. Several researches introduces numerous methods for parameter tuning and selection [4]–[7]. Some literatures implements an adaptive controller with self-adjusting gains [8], [9]. Adaptive fuzzy PSS is also presented in [10]–[13]. It should be noted that these procedures should not over design the PSS parameters. In other words, an excessive amount of a particular parameter may result in overcompensation.

In this paper it is taken into account to evaluate the performance of a grid connected synchronous generator in terms of its PSS function. It is convenient to observe the stabilizing signal and reach an optimum point operation with the aid of parameter selection. The results are very useful for online monitoring of a synchronous generator to obtain an optimum point for the operation of the synchronous machine. A performance index is introduced to evaluate the operation of the synchronous generator under different values of the stabilizer gain and washout time constant. A coefficient is also considered for each parameters in order to prioritize them in terms of their effects on the power system operation.

The rest of the paper is organized as follows: Section II represents a grid connected synchronous generator with all the controlling systems. Section III defines the operating index and the objective function considered to optimize the operation of the synchronous generator. In section IV the result of the simulations is presented. Finally section V summarizes a conclusion.

II. SYNCHRONOUS MACHINE MODELING

A. Power System Modeling

The synchronous generator considered in this paper is represented by the classical model that all resistances neglected. It is connected to a large power system through transmission lines. A generic system configuration is depicted in Fig. 1.

Fig.1a is the reduced form of Fig.1b. A simplified analytic block diagram of the Fig. 1 is shown in Fig. 2. The active power delivered from the synchronous generator to the grid can be easily derived [1].

B. Synchronous Generator Control Systems Modeling

The machine presented in this paper consists of (i) stator and rotor windings, (ii) excitation system (iii) steam turbine and governing system (iv) PSS. A load change in power system is considered to evaluate the operation of the synchronous generator. As the load increases, the frequency of the grid slightly deviates at first. As the result, a signal to change the position of the valves is assigned and the CVs start to open the input vessel and flow of fuel starts to rise. Hence the steam turbine starts to rotate faster to compensate the deviation in the frequency of the grid. Fig. 3 shows the valve position of the steam turbine control system and the mechanical torque ∆T_m applied by the turbine to the synchronous generator under load changes. As it can be seen from Figs. 3a and 3b, The CV position due to load changes and therefore the applied mechanical torque increases to compensate the active power required.

The complete state-space model for this configuration can be formed as follows:

\[
\begin{bmatrix}
    \Delta \omega_r \\
    \Delta \delta \\
    \Delta \psi_{fd} \\
    \Delta \psi_1 \\
    \Delta \psi_2 \\
    \Delta \psi_s
\end{bmatrix} = \begin{bmatrix}
    x_{11} & x_{12} & x_{13} & 0 & 0 & 0 \\
    x_{21} & 0 & 0 & 0 & 0 & 0 \\
    0 & x_{32} & x_{33} & x_{34} & 0 & x_{36} \\
    0 & x_{42} & x_{43} & x_{44} & 0 & 0 \\
    x_{51} & x_{52} & x_{53} & 0 & x_{55} & 0 \\
    x_{61} & x_{62} & x_{63} & 0 & x_{65} & x_{66}
\end{bmatrix} \begin{bmatrix}
    \Delta \omega_r \\
    \Delta \delta \\
    \Delta \psi_{fd} \\
    \Delta \psi_1 \\
    \Delta \psi_2 \\
    \Delta \psi_s
\end{bmatrix}
\]

where the \( x_{ij} \) values are:

\[
x_{11} = -\frac{K_D}{2H} \quad x_{12} = -\frac{K_1}{2H} \\
\]

\[
x_{13} = -\frac{K_2}{2H} \quad x_{21} = \omega_0 = 2\pi f_0 \\
\]

\[
x_{32} = -\omega_0 \frac{R_{fd}}{L_{fd}} \frac{E_B}{D} (X_{Tq} \sin \delta_0 - R_{T} \cos \delta_0) \frac{L_{ads} L_{fd}}{L_{ads} + L_{fd}} \\
\]

\[
x_{33} = -\omega_0 \frac{R_{fd}}{L_{fd}} \left[ 1 - \frac{L_{ads}}{L_{ads} + L_{fd}} \right]
\]
By solving (1) different parameters of the synchronous generator can be found. A complete list of the coefficients mentioned above is presented in chapter 12 of [1]. The simplified small signal diagram of the synchronous machine is shown in Fig. 4. The synchronous machine parameters are listed in tables I and II.

1) **Stator and Rotor Windings:** The state-space modeling of the stator and rotor windings are given in (1).

2) **Excitation System:** A typical excitation control system consists of exciter, regulator, terminal voltage transducer and load compensator, power system stabilizer, limiters and protective circuits. For simplicity, it is considered to ignore time constants of the excitation system components and is modeled with time constant $T_A$ and gain $K_A$.

3) **Steam Turbine & Governing System:** A generic model of steam turbine consists of a steam chest, a high pressure turbine, a reheater, an intermediate pressure turbine, a crossover and some low pressure turbines. The block diagram and small signal modeling of a fossil-fueled steam turbine are shown in Fig. 5.

The governing system considered for this synchronous generator is a mechanical-hydraulic control steam turbine governor. This model includes overspeed control function. It corresponds to changes of Control Valve (CV) and Intercept Valve (IV) and an auxiliary governor for limiting overspeed. A complete model of the governing system is presented in Fig. 6.

4) **Power System Stabilizer:** The gain determines the amount of damping introduced by the PSS. The stabilizer gain $K_{STAB}$ is chosen by examining the effect for a wide range of values. Ideally the stabilizer gain should be set at a value corresponding to maximum damping. However, in some cases this value should be well below the limiting value due to the other considerations. It is also convenient to restrict the level of generator terminal voltage fluctuation during transient conditions by imposing limits to the PSS output. The signal washout block functions as a High-Pass Filter (HPS) and the time constant $T_W$ is high enough to allow signals related to oscillations in $\omega_r$ to pass unchanged.

![Graph](image)

**Fig. 3: Mechanical Changes in Steam Turbine under Load Changes**

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| TABLE I |
|------------------|------------------|
| **STEAM TURBINE AND GOVERNING CONTROL SYSTEM** |
| Steam Turbine   |                 |
| $T_{CH}$        | 0.3             |
| $T_{GO}$        | 0.5             |
| FLP             | 0.4             |
| Governing Control System |       |
| $K_g$           | 20              |
| $K_{AB}$        | 149             |
| TSR             | 0.7             |
| TSM             | 0.23            |

| TABLE II |
|------------------|------------------|
| **CLASSICAL MODEL FOR SYNCHRONOUS GENERATOR** |
| Synchronous Machine |                 |
| $T_R$             | 0.02            |
| $K_D$             | 0.5             |
| $K_1$             | 0.7643          |
| $K_3$             | 0.3230          |
| $K_5$             | -0.1463         |
| Power System Stabilizer |          |
| $T_1$             | 0.1540          |
| $T_2$             | 0.0330          |
| $T_W$             | 0.89            |
| $K_{STAB}$       | 9.5             |

| Excitation System |                 |
| $K_A$             | 187             |
| $T_A$             | 0.89            |
For stabilizing signal washout, the value of time constant $T_W$ is not critical and can be selected in the range of 1 to 20 seconds. However, the main consideration is that this value be long enough to pass stabilizing signals at the frequencies of interest relatively unchanged. The phase compensation transfer function implements an adequate phase-lead characteristic to compensate the phase lag between the exciter input and the generator electrical torque. In phase-lead compensation parameter selection it should be noted that the parameters selected are acceptable for a desired range of frequencies (normally in the range of 0.1 to 2.0 Hz). Thus this results in less optimized damping. The parameter tuning for phase-lead compensation is not considered in this paper.

III. POWER SYSTEM STABILIZER AUTOMATED MONITORING AND PERFORMANCE ASSESSMENT

A. Automated Monitoring

Samples of signals can be obtained from synchronous generator control circuitry. These samples can be set as input to automated expert systems. The aim of the expert system is to record samples and events occurred meanwhile the control system of the synchronous generator is changing the PSS parameters.

B. PSS Performance Assessment

The performance index considered here for PSS evaluation is the Integral Square Error (ISE) which is given by:

$$ISE = \int_{0}^{+\infty} e^2(t)dt$$  \hspace{1cm} (2)

$e(t)$ is the steady state error when a step input is applied to control system. (2) is used when a signal is oscillatory
damped. PSS performance objective is to minimize $M_E$. This parameter is defined in (3). Where $\alpha$, $\beta$ and $\gamma$ are the coefficients of the errors of the three signals and their values are relevant to the significance of the signal. $e_{\Delta \delta}$, $e_{\Delta \Psi_{fd}}$ and $e_{\Delta V_S}$ are the error of rotor angle, field circuit flux linkage and PSS output from steady state value, respectively.

$$M_E = \alpha ISE_{\Delta \delta} + \beta ISE_{\Delta \Psi_{fd}} + \gamma ISE_{\Delta V_S}$$

$$= \alpha \int_{0}^{+\infty} e_{\Delta \delta}^2(t) dt + \beta \int_{0}^{+\infty} e_{\Delta \Psi_{fd}}^2(t) dt + \gamma \int_{0}^{+\infty} e_{\Delta V_S}^2(t) dt$$

(3)

IV. SIMULATION RESULTS

Two cases has been considered in order to obtain a relatively optimum point for the effect on the rotor angle oscillation ($\Delta \delta$), the field circuit flux linkage ($\Delta \Psi_{fd}$) and the PSS output ($\Delta V_S$). $\Delta \delta$ should be considered to mitigate the damping of the rotor angle oscillation, $\Delta \Psi_{fd}$ signal should be evaluated to control output voltage. $\Delta V_S$ is monitored so as to control the output of the PSS.

A. Case 1

The washout time constant $T_W$ is considered as a variable parameter and $M_E$ is evaluated. Fig. 7. shows the parameter $M_E$ with respect to $T_W$ and it can be seen that as the amount of $T_W$ increases, $M_E$ decreases which shows that total error of the three signals mitigates. It should be noted that at $T_W = 3.44$ the oscillation of rotor angle reaches its minimum rate. For values above 3.44 the oscillation of the parameters start to increase and it may bring instability to the synchronous machine. Decrement of rotor oscillation is of great interest since this may affect the amount of active power delivered by the synchronous generator; also damping the oscillations of rotor can increase the stability of the machine under heavy load changes. Fig. 8 shows the variations of $\Delta \delta$, $\Delta \Psi_{fd}$ and $\Delta V_S$ for $T_W = 0.89$ as the typical value and $T_W = 3.44$ as the optimum point. The typical value for the washout time constant is derived from [1].

![Fig. 7: $M_E$ Value in terms of $T_W$](image)

B. Case 2

In this case the stabilizer gain $K_{STAB}$ is considered as the variable parameter in the PSS and generator parameters are evaluated. Variation of $M_E$ with respect to $K_{STAB}$ is shown in Fig. 9. The optimum point for the stabilizer gain is also determined. Thus it is convenient to assess generator parameters in the case of optimal $K_{STAB}$. Fig. 10 shows the machine parameters for $K_{STAB} = 9.5$ as the typical value derived from [1] and the optimum point $K_{STAB} = 49.5$.

![Fig. 8: Synchronous Generator Parameters for Case 1](image)
A performance assessment for a synchronous machine connected to an infinite bus is carried out in this paper. The classical model is considered for the machine and several control systems are implemented to monitor various parameters of the synchronous machine. ISE index is considered in this work for the generator parameters. The index is analyzed via the simulation of the synchronous generator under load change and is determined for two cases. Simulation results show that the optimum value for both cases deviates the oscillations of the synchronous machine parameters. The results also show that although the washout time constant can be obtained arbitrarily, but at high value of $T_w$ the synchronous machine may be unstable. Also the sensitivity of the synchronous machine to $T_w$ is higher than the stabilizer gain $K_{STAB}$. The parameter tuning of the phase-lead compensation is not considered in this paper.

REFERENCES