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Improvement of Transient Stability of Multi-Machine Power System by Optimal Tuning of Selected Governors

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Abstract

The paper describes a method to improve transient stability of multi-machine power system (MMPS) by optimal tuning of selected governors. The power system generally consists of many generators, transmission lines, and power loads. Also the generators have several controllers to improve transient and voltage stability in operation of the power system. Especially, the governor is used to improve transient stability and balance electric power supply and demand. Therefore, the paper deals with how to select the effective generators and tune their governors in order to improve transient stability. The performance of the proposed method is verified by applying disturbances to MMPS modeled with nonlinear differential and algebraic equations.

Keywords: *Governor, nonlinear dynamics, optimal tuning, power system, transient stability.*

1. Introduction

Dynamic behavior of power system has complex interaction between linear and nonlinear devices. Generators can be the high order nonlinear differential equations and algebraic equations. Also, the controllers used in power system have differential equations and switching actions such as tap change or saturation limiters. Especially, the governor is used to improve transient stability and balance electric power supply and demand. Also, exciter and power system stabilizer are used to regulate generator's terminal voltage and improve low-frequency oscillation damping performance. Therefore, many researches have been reported to model the nonlinear power system [1]-[5] and design controllers for improving system stability [6]-[8].

Generally, power systems can be mathematically constructed with differential-algebraic equations (DAEs) in order to simulate in a realistic environment and analyze performances of power system controllers. However, due to the complex and nonlinear interactions of many devices, analysis of power system dynamic behavior is difficult and complicated, yet system integrity is reliant on thorough understanding of complex behavior power system [9].

In this study, the governors in multi-machine power system (MMPS) are optimally tuned by two steps. One is how to find the governors to be tuned in MMPS. There are many generators and their governors in physical power system. Therefore, we need to select the governors working well when they tune. This step can be performed by

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analyzing the behaviors of governors when various disturbances are applied in power system. The second is how to tune the selected governors to improve transient stability. As mentioned before, the power system will be modeled in nonlinear modeling techniques in the paper. The conventional tuning methods such as ad-hoc and eigenvalue analysis cannot be applied in the study. Therefore, optimization technique based on iterative method can be applied. The performance of the proposed method is verified by applying disturbances to MMPS in time domain simulation.

The paper is organized as follows: Section 2 presents how to model the MMPS including power system controllers by nonlinear modeling technique. Section 3 describes how to find the governors to be tuned in MMPS and how to tune the selected governors to improve transient stability. Then, simulation results of case studies with MMPS modeling are given in Section 4. Finally, the conclusions are given in Section 5.

2. Nonlinear Power System Modeling

2.1. Mathematical Approach for Power System Model

A power system is a mathematical model of a physical process consisting of an interacting nonlinear and linear dynamics including discrete event system. This means that discrete states can influence dynamics of power system.

As mentioned in Section 1, power system can be modeled with the high order nonlinear differential and algebraic equations. A power system model with the DAEs can be presented as (1) ~ (3).

$$\dot{\underline{x}} = \underline{f}(\underline{x}, y) \tag{1}$$

$$0 = g(\underline{x}, y) \tag{2}$$

$$0 = \begin{cases} g^{(i-)}(\underline{x}, y) & y_{d,i} < 0, \\ g^{(i+)}(\underline{x}, y) & y_{d,i} > 0, \end{cases} \quad i = 1, \cdots, d \tag{3}$$

where x represents the continuous dynamic states, for example generator angles, speed, and fluxes in a power system; y represents algebraic states, e.g. load bus voltage magnitudes and angles; f represents nonlinear differential and equations; g represents algebraic equations.

2.1. Power system modeling with DAEs

The single machine connected to infinite bus (SMIB) system in fig. 1 is first presented to introduce several controllers used in a generator. As shown in Fig. 1, the governor, exciter, and PSS are main controllers for the generator (G) [9].

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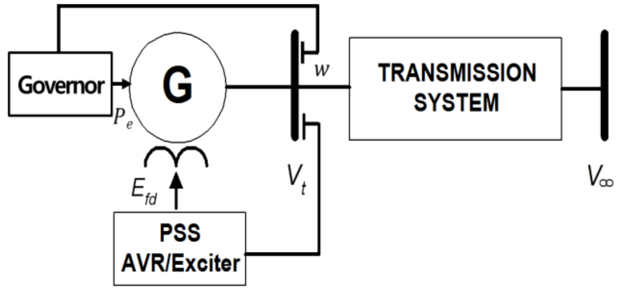

Figure 1. Single-machine infinite bus (SMIB) system

The generic models for three controllers are given in Figs. 2 and 3. In the figures, w means angular velocity of the system, V_t represents the terminal voltage of the generator. T_{mech} is the torque which is the reference value for the turbine. And, P_e represents the reference value of the electric power to the generator.

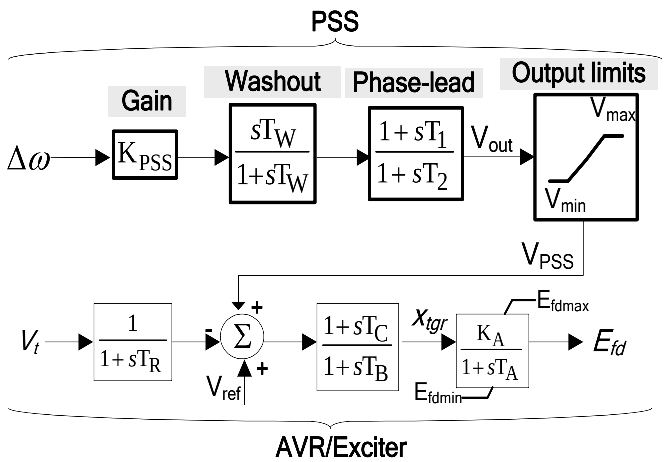

Figure 2. Excitation system with PSS, Exciter, and AVR

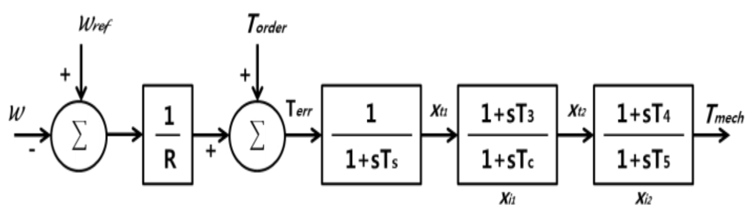

Figure 3. Governor model in SMIB system

Then, the mathematical models for all components in Fig. 1 can be constructed by DAEs. The all equations of DAEs for the governor in Fig. 3 are given in Eqs. (4) and (5), where y_1 is w, y_2 is T_{mech}, y_3 is T_{err}, y_4 is x_{t2}. Especially, Eqs. (4) and (5) are excerpted equations among all DAEs for Fig. 2 to show mathematical models for the limiters. Note that the parameters used in the equations are shown in the figures. In the same way, all components in Fig. 1 including the generators can be modeled with DAEs. Then, the performances of the controllers can be verified by applying some disturbances to the power system model.

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$$\begin{aligned} \dot{x}_1 &= \frac{1}{R}(y_3 - x_1) \\ \dot{x}_2 &= (x_1 - y_4) \\ \dot{x}_3 &= (y_4 - y_2) \end{aligned} \tag{4}$$

$$0 = \begin{cases} g_1 = T_{order} - \frac{1}{R} y_1 - y_3 \\ g_2 = T_C y_4 - T_3 x_1 - x_2 \\ g_3 = T_5 y_2 - T_4 y_4 - x_3 \end{cases} \tag{5}$$

$$\begin{aligned} & y_1 = \mathrm{V}_{\max} - \mathrm{V}_{\mathrm{out}}; \\ & y_2 = \mathrm{V}_{\mathrm{out}} - \mathrm{V}_{\min}; \\ & 0 = \begin{cases} g_1^{(i-)}(\underline{x}, y) = \mathrm{V}_{\mathrm{PSS}} - \mathrm{V}_{\max} \quad y_1 < 0, \\ g_2^{(i-)}(\underline{x}, y) = \mathrm{V}_{\mathrm{PSS}} - \mathrm{V}_{\min} \quad y_2 < 0, \\ g_1^{(i+)}(\underline{x}, y) = g_2^{(i+)}(\underline{x}, y) = \mathrm{V}_{\mathrm{PSS}} - \mathrm{V}_{\mathrm{out}} \quad y_1 > 0, y_2 > 0. \end{cases} \end{aligned} \tag{6}$$

$$\begin{aligned} & y_3 = \mathrm{E}_{\mathrm{fdmax}} - E_{fd}; \quad y_4(\text{upper limits switch}):(+\text{ when } y_3 < 0) \\ & y_5 = E_{fd} - \mathrm{E}_{\mathrm{fdmin}}; \quad y_6(\text{lower limits switch}):(+\text{ when } y_5 < 0) \\ & 0 = \begin{cases} g_3^{(i-)}(\underline{x}, y) = y_4 - 1 \quad y_3 < 0, \\ g_4^{(i-)}(\underline{x}, y) = E_{fd} - \mathrm{E}_{\mathrm{fdmax}} \quad y_3 < 0, \\ g_5^{(i-)}(\underline{x}, y) = y_6 - 1 \quad y_5 < 0, \\ g_6^{(i-)}(\underline{x}, y) = E_{fd} - \mathrm{E}_{\mathrm{fdmin}} \quad y_5 < 0, \\ g_3^{(i+)}(\underline{x}, y) = g_5^{(i+)}(\underline{x}, y) = y_4 = y_6 \quad y_3 > 0, y_5 > 0, \\ g_4^{(i+)}(\underline{x}, y) = g_6^{(i+)}(\underline{x}, y) = \mathrm{K_A} \cdot x_{trg} - E_{fd} \quad y_3 > 0, y_5 > 0. \end{cases} \end{aligned} \tag{7}$$

3. Optimal Tuning of Governors

3.1. Selection of Governors for Tuning

In the section, we will discuss how to select governors to be tuned in MMPS. Actually, the governors are initially tuned at the generator design stage. Also, all power generation companies periodically have regular inspection for the governors whether they operate normally. However, this test is carried out on individual generators. Therefore, the operation performance of the governors can be different when all generators are connected to the grid and have a complex interaction each other.

In the paper, the complex interactions against disturbances are analyzed and the generators that has less effective on stability are selected.

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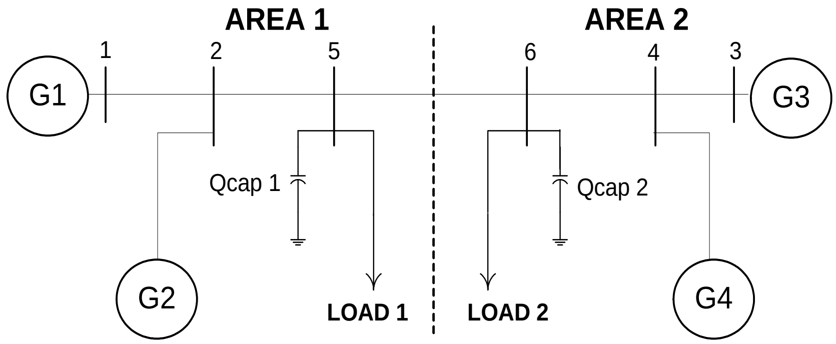

Figure 4. IEEE benchmark four-machine two-area test system

Figure 4 shows IEEE benchmark four-machine two-area test system. There are four generators and they have all controllers in Figs. 2 and 3. Then, assume that 50 % of load 1 is tripped at 1 sec. Then, system frequency and all real power responses of the generators are analyzed. Figure 5 shows the system frequency response. The peak value is about 61.5 Hz after the load trips and then it takes 4 seconds for the system to be stabilized after the disturbance. Figure 6 shows the deviations of the real power outputs for four generators. As shown in Fig. 6, G1, G3, and G4 have slow responses except G2 immediately after the disturbance. The real power responses are completely dependent on the governors' performance. Therefore, if the governors in G1, G3, and G4 are tuned well, we can predict that the responses could be better.

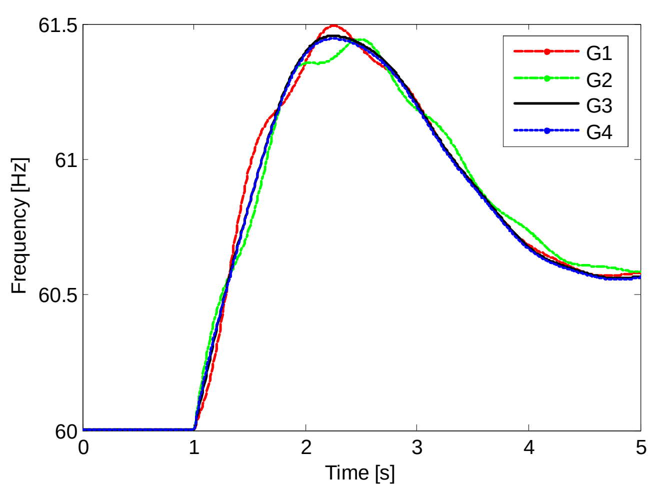

Figure 5. System frequency response with initial values [Hz]

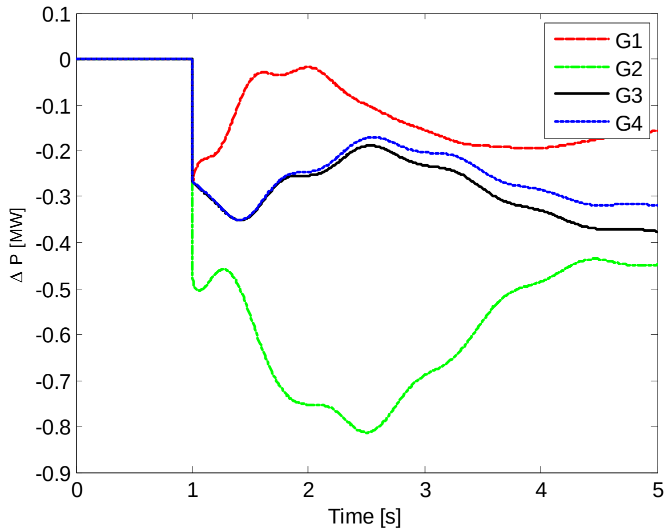

Figure 6. Deviations of real power responses with initial values [MW]

3.2. Optimal Tuning Process

Once the governors to be tuned are selected, an optimization process can be applied. As mentioned before, iterative optimization technique must be applied because the MMPS has nonlinear behaviors. In the paper, steepest descent algorithm [10], which is a simple and well-known optimization technique, is used. The iterative equation is as follow. The fixed step-length α (= 0.2) is used.

$$\lambda_{k+1} = \lambda_k + \alpha \cdot \nabla \mathbf{J}(\lambda) \tag{8}$$

The partial derivatives required to calculate these gradients are obtained by using the approximation of first-order derivatives, which is called the *finite-difference derivative approximation* [10], as follows.

$$\frac{\partial \mathbf{J}}{\partial x_i} = \nabla \mathbf{J}(x_i) \approx \frac{\mathbf{J}(x_1,\ldots,x_i+\Delta x,\ldots,x_n) - \mathbf{J}(x_1,\ldots,x_n)}{\Delta x_i}. \tag{9}$$

Given the availability of gradient information, many numerical optimization methods based on the *first-order* gradients can be applied to minimize the function **J** as steepest descent method. The gradient of an objective function **J** at a point is the direction of the most rapid increase in the value of the function at that point. The descent direction is the negative of the gradient direction. The series of steps to be taken is given below [12]:

Algorithm: Steepest Descent

Given the starting point λ_0, N (number of iterations), $\varepsilon_1, \varepsilon_2$ (positive stopping criteria), $k \leftarrow 0$;

while $(k < N)$ and $(f_{tol\_1} \rangle \varepsilon_1)$ and $(f_{tol\_2} \rangle \varepsilon_2)$

Compute search direction $p_k = -\nabla \mathbf{J}(\lambda_k)$.

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Set $\lambda_{k+1} = \lambda_k + \alpha_k p_k$ where α_k is the step length.
$k \leftarrow k + 1$;
end (while)

Before applying the optimization technique, the object parameters to be optimized are selected. Then, the objective function must be defined in order to solve maximum/minimum value of the objective function. In the paper, the parameters are selected that have a large impact on transient stability are selected and given in Table I with their initial values. In practice, the parameters in Table I have their proper range. Therefore, tuning range of each parameter has to be considered as a constraint.

Table 1. Object parameters for optimization

Parameter	R	T_S	T_C	T_3
Initial value	0.05	0.4	0.1	3

Also, in order to investigate the effect of the optimal parameters of the governors on the MMPS with respect to the transient stability, the objective function **J** in (10) is defined for the application to the MMPS as

$$\mathbf{J}(\lambda) = \sum_{i=1}^{4} \int_{t_0}^{t_f} \left(\begin{bmatrix} \omega_i(\lambda,t) - \omega_i^s \\ V_{t,i}(\lambda,t) - V_{t,i}^s \end{bmatrix}^T \mathbf{V} \begin{bmatrix} \omega_i(\lambda,t) - \omega_i^s \\ V_{t,i}(\lambda,t) - V_{t,i}^s \end{bmatrix} \right) dt, \tag{10}$$

where **V** is the weighting matrix. The ω^s and V_t^s are the post-contingency steady state values of ω and V_t, respectively.

Note that the diagonal terms in the matrix **V** are determined by considering the balance of the conflicting requirements on the speed and voltage deviations [6].

4. Simulation results

In order to find optimal values of the parameters in Table-1 by which the objective function **J** become the lowest value. After seventh iterations, the objective function **J** can be minimized. Also, the initial and optimal values of the parameters for each generator are given in Table-2. The R has significantly changed and the others have changed slightly.

Table 2. Initial and optimal values of object parameters

Parameter	R	T_S	T_C	T_3
Initial value	0.05	0.4	0.1	3
Optimal value of G1	0.042	0.3	0.2	2.5
Optimal value of G3	0.035	0.45	0.12	3.2
Optimal value of G4	0.03	0.42	0.08	3.1

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Figure 7 shows the system frequency responses with optimal parameters. As shown in Fig. 7, the peak value of the frequency is less than 61 Hz. This means that the optimal parameters can make the system stable over initial parameters. Also, the deviations of the real power outputs are shown in Fig. 8. The G1, G3, and G4 have rapider responses shortly after the disturbance than before. Even though G2 still has the fastest response in order to make the frequency stable, the others with the optimal parameters reduce the real power output faster than those with initial ones.

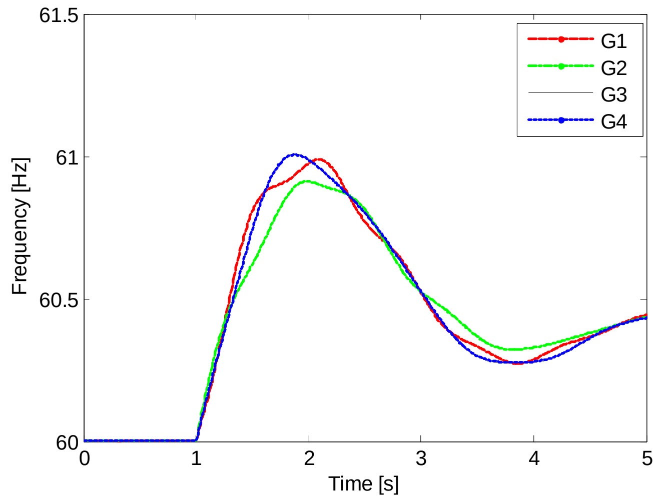

Figure 7. Comparison of system frequency responses with optimal values [Hz]

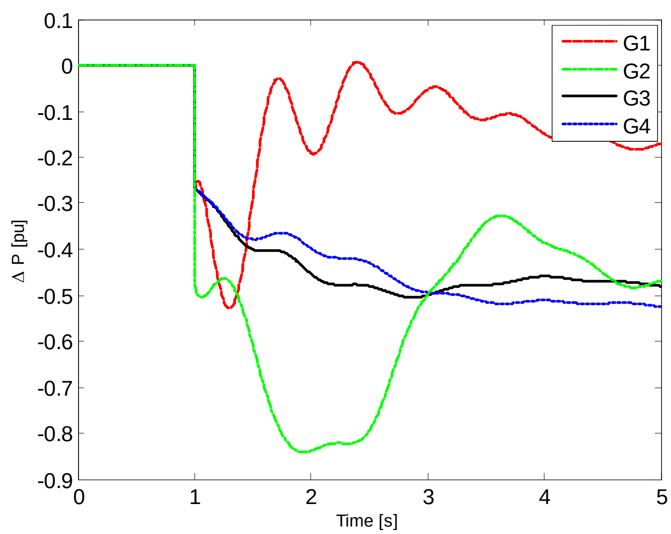

Figure 8. Deviations of real power responses with optimal values [pu]

5. Conclusions

This paper proposed a method to improve transient stability of multi-machine power system (MMPS) by optimal tuning of selected governors. The power system generally consists of many generators, transmission lines, and power loads. Also the generators have several controllers to improve transient and voltage stability in operation of the

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power system. In order to improve transient stability of power system, the paper presented two stages. One is how to find the governors to be tuned in MMPS. The other is how to tune the selected governors to improve transient stability. Due to the nonlinear behavior, optimization technique based on iterative method was applied at the second stage. The performance of the proposed method was verified by applying disturbances to MMPS in time domain simulation. The selected generators performed rapid responses after the disturbance and the system frequency became quite stable and quickly restored to the nominal values when optimal parameters are applied. Therefore, the proposed method can give a framework for industrial applications to improve overall system dynamics in power system.

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