Improve the oscillations damping in a single machine system with coordinating power system stabilizer and generator excitation control based on linear optimal control

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A B S T R A C T

In this paper, a method for stabilizing the network is presented to reduce the volatility caused by the connection of synchronous machine. One of the methods for stabilizing and reducing the volatility is PSS (Power System Stabilizer) that minimizes network volatilities and LOC (Linear Optimization Control) is used for optimizing the maximum stability. The solution presented in this paper used both methods, and minimizes the volatility and instability of the network.

I N T R O D U C T I O N

Dynamic stability of power systems means damping the electromechanical volatilities. The volatility range is between 0.2 to 2 Hz. For example, the volatility arises when the system is connected to large power systems and is usually damped after a few seconds. In some cases it continues and its range increases resulting in the loss of synchronization of generators or cut the communication lines and disconnect the system [1,3]. So many factors can cause volatility in the system, such as a short circuit in the network, the sudden change of load, disconnected load or loss of transmission lines [2]. One of the methods for stabilizing and reducing the volatility is PSS (Power System Stabilizer) that minimizes network volatilities and LOC (linear optimization control) is used for optimizing the maximum stability.

Application of PSS:

Power System Stabilizer is a supplementary controller that improves the power system dynamic performance by adding supplementary signal to the excitation system. The stabilizer usually uses signals such as rotor speed, frequency and power of generator terminals and has a favorable effect on the stability of the system by damping the low frequency oscillations [5,6]. Power system stabilizer is the most economical method of damping electro-mechanical oscillations. PSS is mainly used for damping those various modes that are undamped due to the use of an excitation system with high efficiency and fast response, in terms of network load and long transmission line [10].

Dynamic model of the system:

System under study is a single machine system that used Heffron & Phillips model grade 3 for determining the dynamic model of the system. Also according to the formula of Heffron & Phillips model K1 and k6 values are obtained [11].

Heffron Phillips model grade 3:

This model is nothing more than a linear model grade 3 of the second type of the synchronous machine. One of the modes of using the above model is the study of low frequency oscillation (LFO) and sustainable...
design power systems (PSS). Since in both cases, AVR voltage control system has an important role, adding the voltage control loop on the above model is important.

**Synchronous generator model:**
In this paper, the model of synchronous generator is used in dq machine in which voltage equations are written in terms of Flux to second to only have a derived operator in equations. It is necessary to only have one derived operator to solve the differential equations by numerical solution method.[7]

\[
\begin{align*}
\psi_{qs} &= w_b \left[ v_{qs} - \frac{w_r}{w_q} \psi_{ds} + \frac{r_s}{x_{qs}} \left( \psi_{mq} - \psi_{qs} \right) \right] \\
\psi_{ds} &= w_b \left[ v_{ds} - \frac{w_r}{w_q} \psi_{qs} + \frac{r_x}{x_{qs}} \left( \psi_{md} - \psi_{qs} \right) \right] \\
\psi_{qs1} &= w_b \left[ v_{ls1} + \frac{r_s}{x_{ls}} \left( \psi_{md} - \psi_{ls1} \right) \right] \\
\psi_{qs2} &= w_b \left[ v_{ls2} + \frac{r_x}{x_{ls}} \left( \psi_{md} - \psi_{ls2} \right) \right] \\
\psi_{fd} &= w_b \left[ v_{id} + \frac{r_m}{x_{id}} \left( \psi_{md} - \psi_{id} \right) \right] \\
\psi_{fd} &= w_b \left[ v_{qd} + \frac{r_m}{x_{id}} \left( \psi_{md} - \psi_{qd} \right) \right]
\end{align*}
\]

**Linear dynamic model of single machine system:**
According to the above equations, linear dynamic model is expressed as follows. In these equations the elements of $L_d, L_q, D_d, D_q, E_q, E_d$ are functions of $v_{xd}, v_{xq}, x^\prime_d, x^\prime_q, X, B$ that are obtained from the Linearization of the equations.[8,9]

\[
\begin{bmatrix}
\dot{v}_d \\
\dot{v}_q
\end{bmatrix} = \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix} e^\cdot - \begin{bmatrix}
0 & x_d \\
-x_q & 0
\end{bmatrix} \begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
\]

\[
\begin{bmatrix}
\dot{\Delta i}_d \\
\dot{\Delta i}_q
\end{bmatrix} = \begin{bmatrix}
D_d - E_q i_q & \Delta i_d \\
L_d - E_d i_d & \Delta i_q
\end{bmatrix}
\]

However, for the Linearization of grade 3 equations of synchronous machine and thus obtaining the equations of linearization process can be expressed as follows:

Given the momentum equations, we have:

\[\dot{\delta} = W_b \Delta w\]

\[p \dot{\delta}_{avr} = \frac{\Delta P_m - \Delta P_o}{M}\]

with Linearization of the relationship between output generator power and its replacement in the above equation we have:

\[\Delta w_r = \frac{\Delta P_m}{M} - K_1 \Delta \delta - K_2 \Delta e_q - K_p \Delta I_{sh}\]

The coefficients are defined as follows:

\[K_1 = \left( (x_q - \dot{x}_d) i_{d0} + e \cdot i_{q0} \right) D_q + \left( (x_q - \dot{x}_d) i_{d0} \right) D_d\]

\[K_2 = -\left( (x_q - \dot{x}_d) i_{d0} + e \cdot i_{q0} \right) E_q - \left( (x_q - \dot{x}_d) i_{d0} \right) E_d + i_{q0}\]

\[K_p = \left( (x_q - \dot{x}_d) i_{d0} + e \cdot i_{q0} \right) L_q + \left( (x_q - \dot{x}_d) i_{d0} \right) L_d\]

Considering the excitation model as follows, its linear equation is obtained it this way:

\[p \Delta e_q = \frac{\Delta e_{fd} - K_4 \Delta \delta - K_3 \Delta e_q - K_p \Delta I_{sh}}{\tau_{d0}}\]

The coefficients of this equation are defined as follows:

\[K_4 = 1 - \left( (x_d - \dot{x}_d) E_d \right)\]

\[K_4 = (x_d - \dot{x}_d) D_d\]

\[K_q = (x_d - \dot{x}_d) L_q\]

With respect to the excitation system model that can be expressed as follows, these equations can be made linear as follows:
p\Delta e_{fd} = \frac{-\Delta e_{fd} + K_A (-\Delta v_t + u_E)}{T_A} \tag{17}

P\Delta e_{fd} = (-\Delta e_{fd} + K_A (u_E - K_5 \Delta \delta - K_6 \Delta e_q' - K_7 \Delta I_{sh})) \tag{18}

where the equations of coefficients are as follows:

\begin{align*}
K_5 &\triangleq x_qD_q \sin(\delta_0) - x_d' D_d \cos(\delta_0) \tag{19} \\
K_6 &\triangleq -x_q E_q \sin(\delta_0) + (1 + x_d' D_d) \cos(\delta_0) \tag{20} \\
K_v &\triangleq x_q L_q \sin(\delta_0) - x_d' L_d \cos(\delta_0) \tag{21}
\end{align*}

Equations of the system mode are expressed as $X = AX + BU$ in which the state vector is $[\Delta \delta, \Delta v_t, \Delta e_q', \Delta e_{fd}]^T$ and control vector is as $[u_E, \Delta B]^T$. Also the matrices of $A$ and $B$ that are respectively known as system and control matrices are calculated as follows.[11]

\begin{align*}
A &= \begin{bmatrix}
0 & \omega_p & 0 & 0 \\
-M & 0 & -K_2 & 0 \\
-K_4 & 0 & \frac{-1}{\tau_d'} & -K_5 \\
\frac{-T_A}{K_A} & \frac{-T_A}{K_6} & \frac{1}{\tau_d'} & \frac{-T_A}{T_A}
\end{bmatrix} \\
B &= \begin{bmatrix}
0 & 0 & -K_p & 0 \\
0 & M & 0 & -K_q \\
0 & 0 & \frac{-T_A}{K_A} & \frac{-T_A}{T_A}
\end{bmatrix} \\
\end{align*} \tag{22, 23}

**LOC Optimization:**

Based on the theory of optimal control with feedback of the linear combination of state variables to input some or all of the value can be shifted to the imaginary axis and thereby the system stability increases and better dynamic is recoverable.[4] The main objective of LOC in a power system is minimizing an energy function that is shown below.

\[ J = \frac{1}{2} \int [X^T Q X + u^T R u] dt \tag{24} \]

By minimizing the above equation, linear optimal control signal LOC is obtained as follows: using feedback control law:

\[ u = -R^{-1}B^T K X \tag{25} \]

\[ A^T K + K A - KB R^{-1} K^T + Q = 0 \text{ constant} \tag{26} \]
Simulation & result:

For simulation in this article Matlab software is used. The results are shown as impulse response and step response graph and are compared to a mode when the system enters into the circuit. The results show that in stabilization of the PSS and the optimization to LOC faster oscillations are damped. By observing the step response, we found that fluctuations in the system are damped at 0/8 seconds while damping time of the system after stabilization reach to about 0/5 seconds and by optimizing the time reduces to 0/1 second. Impulse response graph is given for better understanding the behavior of the system.

![Step Response](image1)

**Fig. 1:** System response before the stabilization and Optimization

![Step Response](image2)

**Fig. 2:** Step response after the stabilization of PSS

![Impulse Response](image3)

**Fig. 3:** Impulse response after the stabilization of PSS
Conclusion:

In this paper, the coordinated control of generator excitation in the increase of damping oscillations caused by electrical faults that enters the network was examined. Continued or increased volatility range of possible damage to the network.

The control method for the system under consideration, the proposed function of the system state variables is measurable. Linear combination of multi-variable excitation controller network mode, the feedback coefficients of these variables are obtained from PSS method. Optimizing the design and reference signals corresponding to excitation system applied to car has been developed. The proposed method on a single-machine system under study and the responses were analyzed stability control with different methods. The simulation results can be expressed as the coordinated control of PSS and LOC made faster oscillations are damped oscillation damping and transient stability of power system dynamics quickly recover.

Appendix:

In the studied system the initial values are considered as follows:

\[ p_g = 0.5 \]
\[ X_d = 0.32 \]

\[
\begin{align*}
D &= 0 \\
k_d &= 0 \\
k_e &= 200 \\
V_i &= 1.0 \\
H &= 5 \\
E_{q0} &= 1.3279 \\
v_{d0} &= -0.5836 \\
T_1 &= 0.0307
\end{align*}
\]

\[
\begin{align*}
I_{q0} &= 0.3765 \\
T_{qprin} &= 6.66 \\
X_d &= 1.6 \\
M &= 2 \times H \\
V_{t0} &= 1 \\
T_2 &= 0.0672
\end{align*}
\]

\[
\begin{align*}
zeta &= 0.1 \\
f_0 &= 60 \\
T_w &= 2 \\
X_n &= 1.55 \\
F_s &= 0.5025 \\
k_s &= 14 \\
T_e &= 0.05
\end{align*}
\]

REFERENCES