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Damping of Low Frequency Oscillation in Power System using QFT FESS controller

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ABSTRACT
In this paper, a robust flywheel energy storage system (FESS) controller using quantitative feedback theory (QFT) is designed to damp low frequency oscillations in spite of uncertainties and various disturbance of power system. To design the QFT FESS controller, the target performance specifications of the closed loop system and system uncertainties are converted to QFT bounds. Through the iterative loop shaping procedure, the FESS controller is designed to satisfy all QFT bounds at all frequencies.
To verify control performance of the QFT FESS controller, nonlinear dynamic simulations are performed under various disturbance. The control characteristics with QFT FESS controller have been compared with that of the conventional power system stabilizer (PSS). The simulation results show that the QFT FESS controller provided better dynamic responses in comparison with the conventional PSS controller.
Keywords - Flywheel energy storage system (FESS), Loop shaping, Low frequency oscillation, Power system stabilizer (PSS), Quantitative feedback theory (QFT)

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I. INTRODUCTION

The Flywheel Energy Storage System (FESS) converts electrical energy into rotational kinetic energy and stores it. When electrical energy is needed, it can be used to convert stored rotational kinetic energy into electrical energy.

The FESS can be extensively applied to many fields such as UPS that can be used in an emergency, storage of distributed power sources such as solar power and wind power, etc. and regenerative power storage generated in elevators, cranes, and electric trains [1].

Although the transient stability has been improved by the increase of the synchronizing torque through the adoption of the rapidly excitation system to the generator in the electric power system recently, the damping torque of the generator is weakened to adversely affect the small signal stability and low frequency oscillation phenomenon occurs.

A supplementary excitation control method using a power system stabilizer (PSS) most commonly has been used in modern power system due to its simple structure and its ease of implementation to improve power system stability [2-3].

Since FESS has fast response due to the recent development of power electronics technology, it is possible to power input/output within several cycles after disturbance occurrence in the power system. Therefore, when the power unbalance occurs, the power flow control can be performed quickly, so that the stability can be improved by damping the low frequency oscillation generated in the power system.

In this paper, the application of FESS to improve the stability of power system has been proposed. However the power systems have system uncertainties due to various generating and loading conditions, variation of system parameters and system nonlinearity, etc [4]. The increase of these uncertainties make the optimal control of the power system difficult. In order to improve the robustness of the FESS controller against system uncertainties, the controller design method using quantitative feedback theory (QFT) [5-6] is proposed. The QFT is able to deal with the controller design problem of the power system including the complicated uncertainties.

The dynamic characteristic responses by means of time domain simulations have been investigated to verify the robustness of the FESS controller under various operating conditions. The simulation results show that the QFT FESS controller provided better dynamic responses in comparison with the conventional PSS controller.

II. POWER SYSTEM MODEL

2.1 Generation system

Fig. 1 shows the single machine infinite bus power system which has the FESS and local load admittance Y in a generator bus, and transmission line impedance Z.

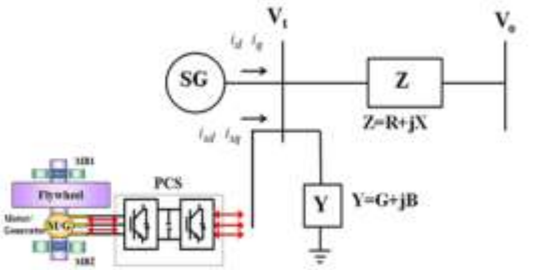


Fig. 1. A single machine infinite bus power system with FESS

The generator is modeled by three first-order nonlinear differential equations as following equations [2].

$$\frac{d}{dt}\omega = P_m - P_e - P_{fess} - D(\omega - 1))/M \quad (1)$$

$$\frac{d}{dt}\delta = \omega_b(\omega - 1) \quad (2)$$

$$\frac{d}{dt}E_q' = (E_{fd} - (x_d - x_d')i_d - E_q')/T_{d0}' \quad (3)$$

where ω is the rotor speed, ω_b is the synchronous speed and δ the rotor angle. M is inertia constant, D is damping coefficient, T_{do}' is the open circuit field time constant, E_q' is internal voltage and P_{fess} is the active power of the FESS.

The IEEE Type-ST1 excitation system can be describes as [2]

$$\frac{d}{dt}E_{fd} = (K_A(V_{ref} - v_t + u_E) - E_{fd})/T_A \quad (4)$$

where E_{fd} is the field voltage v_t is terminal voltage, u_E is control input

2.2 FESS Model

The FESS can control the active power and reactive power. However, the active power only is controlled to effectively damp low frequency oscillation of power system in this study. The active power of the FESS can be represented as a first-order differential equation as shown in (5) [7].

$$\frac{d}{dt}P_{fess} = K_{fess}(-P_{fess} + u_{fess})/T_{fess} \quad (5)$$

where P_{fess} is the active power of the FESS, u_{fess} is the control signal of the FESS and T_{fess} and K_{fess} is the time constant and the gain of the FESS, respectively.

III. QFT FESS CONTROLLER DESIGN

A basic idea of the QFT design is the translation of closed-loop frequency-domain specifications into the Nichols chart domains specifying the allowable range of the nominal open-loop response and then to design a controller by using a gain-phase loop shaping technique [8].

3.1 Templates generation for power system

The parameters representing the mathematical modeling uncertainties of power system are selected by active power Pe, reactive power Qe and line parameter X. The range of each parameter value are as follows.

$$0.4 \le P_e \le 1.2$$
$$-0.2 \le Q_e \le 0.2 \quad (6)$$
$$0.6 \le X \le 1.2$$

Then we can get the transfer function for the uncertain plant sets $G(S) \in$ G. After selecting the uncertain plant sets using (6), the frequency points were selected as follows.

ω_i = [0.1, 1, 2, 3, 4, 6, 7, 8, 10, 50] rad/sec (7)

Then, the plant templates of the uncertain plant sets $G(j\omega_i)$ are calculated at the selected all frequency points ω_i .

3.2 QFT bound calculation and controller design

An arbitrary stable transfer function in the plant sets is chosen as the nominal plant $G_o(s)$. And after selecting the robust stability and disturbance attenuation specifications, the QFT bounds are calculated at all frequency points ω_i . The robust stability and disturbance attenuation specifications are as follows

$$\left|\frac{L_0(j\omega)}{1 + L_0(j\omega)}\right| \le 1.4 \quad (8)$$

$$\left|\frac{G(j\omega)}{1 + L_0(j\omega)}\right| \le 0.008 \quad (9)$$

At each selected frequency ω_i , combining the stability and performance specifications bounds in terms of the nominal plant, the QFT bounds for all frequency ω_i have been calculated. Then the worst case bound at the same frequency yields a single QFT bound.

As the last stage for the QFT controller design, the loop shaping must be accomplished until the QFT bounds at all frequency are satisfied and the closed-loop nominal system is stable [5]. The manual loop shaping procedure is very difficult and takes long time.
The designed FESS controller is as follow.

$$K_{fess}(s) = \frac{323.08 s^2 + 1386.9 s + 171.76}{s^2 + 13.605 s + 2.4578} \qquad (10)$$

IV. SIMULATION RESULTS

Fig. 2 shows the calculated QFT bounds for the plant templates and the nominal open loop transfer function $L_0(s) = G_0(s)K_{fess}(s)$ according to ω_i .

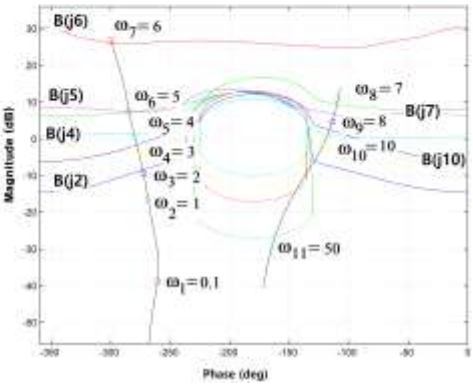


Fig. 2. QFT bounds and loop shaping result

It is confirmed that the nominal open loop transfer function $L_o(s) = G_o(S)K_{fess}(s)$ satisfied the QFT bounds at all selected frequency as shown in Fig. 2.

To verify the robust performance of the designed QFT FESS controller, the dynamic simulations were performed under the various disturbances and parameters variation of the power system. The robust performance and output characteristics of the proposed QFT FESS controller have been compared to those of the conventional PSS1 [2] and PSS2 [3]. The dynamic simulations have been performed under normal load and heavy load in case that the initial value of the rotor angle is changed by 0.1 rad and when a 3-phase short circuit occurs near the infinite bus. To assess robust performance, dynamic characteristics simulation has been performed in case of the line constant change.

The system parameters for simulation are shown in Table. 1 [2-3].

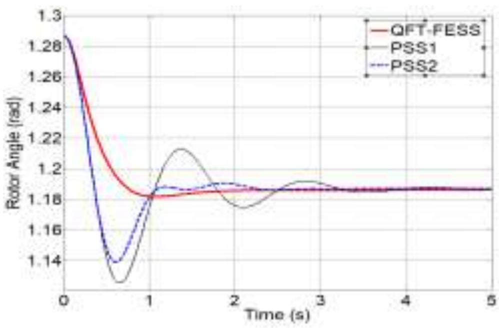
Table. 1. Power system parameters

Generator parameters	M=9.26, D=0, T_{do}' =7.76, x_d =0.973, x_d' =0.19, x_q =0.55
Exciter parameters	K_A =50, T_A =0.05
Line parameters	R=-0.034, X=0.997, G=0.249, B=0.262
FESS parameters	K_S =1, T_S =0.2
Initial conditions	P_{e0} =1.0, Q_{e0} =0.015, V_{t0} =1.05

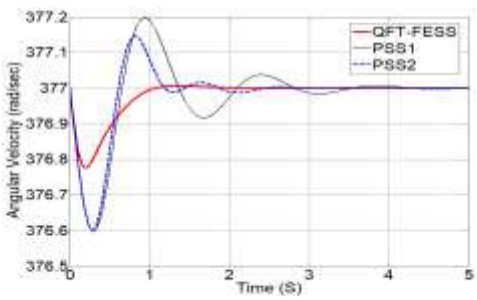
4.1 Normal load condition

Fig. 3 shows the simulation results for angular velocity, rotor angle and terminal voltage with the FESS, PSS1 and PSS2 in case that the initial value of the rotor angle is changed by 0.1 rad under normal load (P_{e0} =1.0, Q_{e0} =0.015). Maximum deviation of angular velocity using the FESS controller is smaller than that using the PSS1 and PSS2. Settling time with the FESS controller is faster than that with the conventional PSS1 and PSS2. It can be seen that the oscillation are damped rapidly and the settling time is very fast through the rapid active power output of FESS.

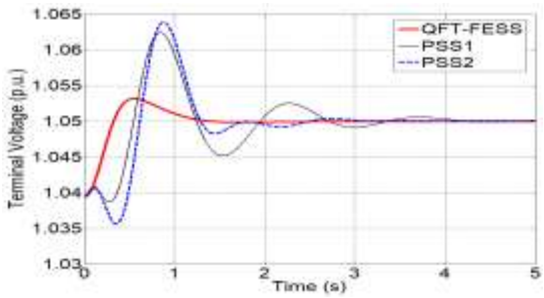
Fig. 4 shows the simulation results for angular velocity, rotor angle and terminal voltage with the FESS, PSS1 and PSS2 under normal load (P_{e0} =1.0, Q_{e0} =0.015) in case that a 3-phase short circuit occurs near the infinite bus at 1.0s and is cleared at 1.1s without the power system configuration change. The FESS output power limit of -0.5≤ P_{fess} ≤0.5 (p.u.) is considered. Maximum deviation of angular velocity and rotor angle using the FESS controller is smaller than that using the PSS1 and PSS2. Settling time with the FESS controller is faster than that with the conventional PSS1 and PSS2.



(a) Rotor angle

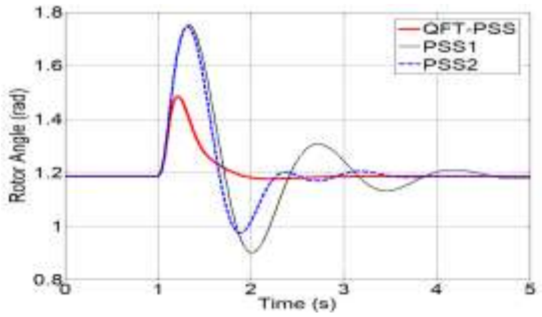


(b) Angular velocity

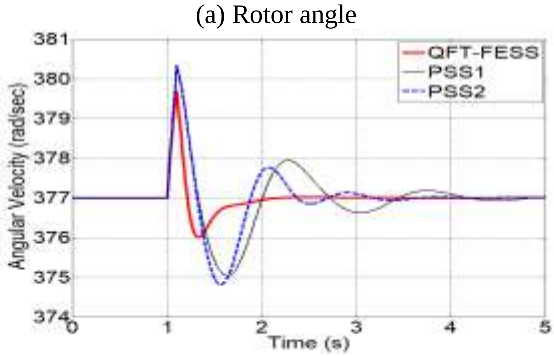


(c) Terminal voltage

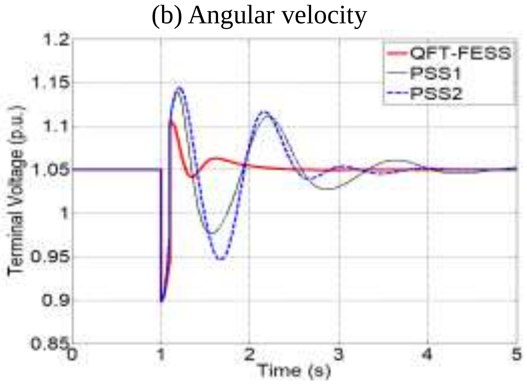
Fig. 3. Dynamic responses in case that the initial value of the rotor angle is changed by 0.1 rad under normal load (P_{e0} =1.0, Q_{e0} =0.015).



(a) Rotor angle



(b) Angular velocity

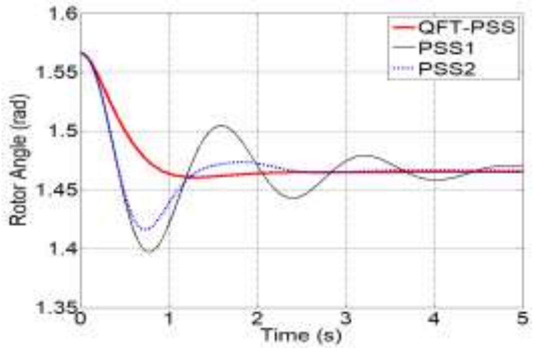


(c) Terminal voltage

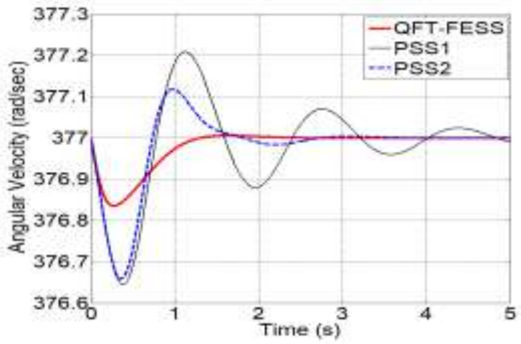
Fig. 4. Dynamic responses in case that a 3-phase short circuit occurs near the infinite bus for 0.5s under normal load (P_{e0} =1.0, Q_{e0} =0.015).

4.2 Heavy load condition

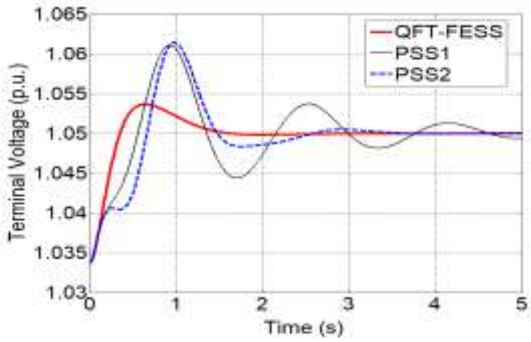
Fig. 5 shows the simulation results for angular velocity, rotor angle and terminal voltage with the FESS, PSS1 and PSS2 in case that the initial value of the rotor angle is changed by 0.1 rad under heavy load (P_{e0} =1.2, Q_{e0} =0.2). Maximum deviation of angular velocity using the FESS controller is smaller than that using the PSS1 and PSS2. Settling time with the FESS controller is faster than that with the conventional PSS1 and PSS2. It can be seen that the oscillation are damped rapidly and the settling time is very fast through the rapid active power output of FESS.



(a) Rotor angle



(b) Angular velocity

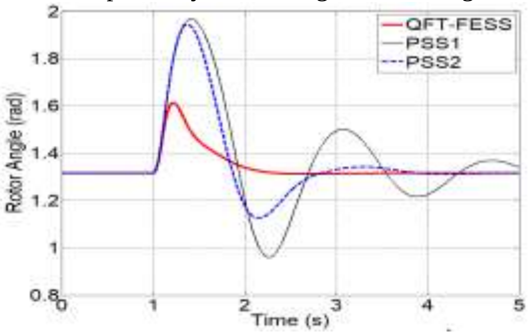


(c) Terminal voltage

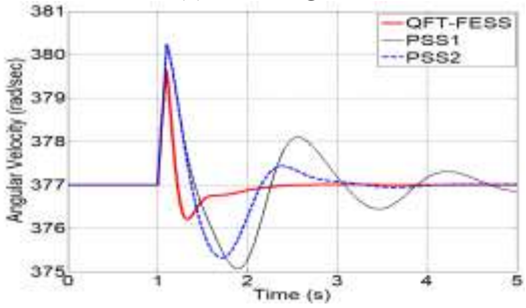
Fig. 5. Dynamic responses in case that the initial value of the rotor angle is changed by 0.1 rad under heavy load (P_{e0} =1.2, Q_{e0} =0.2).

4.3 Parameter variation

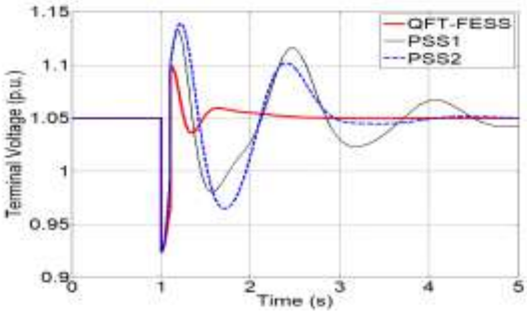
Fig. 6 shows the simulation results for angular velocity, rotor angle and terminal voltage with the FESS, PSS1 and PSS2 under normal load (P_{e0} =1.0, Q_{e0} =0.015) and line parameter change (X=1.2) in case that a 3-phase short circuit occurs near the infinite bus at 1.0s and is cleared at 1.1s without the power system configuration change.



(a) Rotor angle



(b) Angular velocity



(c) Terminal voltage

Fig. 6. Dynamic responses in case that a 3-phase short circuit occurs near the infinite bus for 0.5s under normal load and line parameter change (P_{e0} =1.0, Q_{e0} =0.015, X=1.2).

The QFT FESS controller installation can more significantly enhance the transient stability of power systems comparing with conventional PSS1 and PSS2. It can be seen that the FESS controller is more robust than conventional PSS1 and PSS2.

V. CONCLUSION

In this paper, the QFT FESS controller has been designed to damp power system oscillation and to enhance power system stability despite uncertainties of the power systems. The robust performance of the proposed QFT FESS controller has been compared to those of the conventional PSS.

It is confirmed that the proposed method can significantly improve the disturbance suppression ability compared to the conventional PSS, and shows excellent robustness against the system parameter variation of the power system.

The conventional PSS is an indirect method of controlling the active power output through the excitation control of the generator. However, since the FESS can directly control the active power output, it is confirmed that the proposed QFT FESS controller can be a very effective method to damp low frequency oscillation of power system.

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