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Application of flywheel energy storage to damp power system oscillations

***Abstract**. Flywheel energy storage system (FESS) is believed to be a potential solution for power quality improvements. This paper proposed a new idea of using a large-mass varying-speed flywheel as an energy storage element to damping power system electromechanical oscillations. In the paper, the FESS is studied in the context of a single-machine infinite-bus (SMIB) power system. The mathematical model of the SMIB power system including a FESS is established, and the Phillips-Heffron control structure of the power system is described. Based on the principle of the complex torque coefficient (CTC) method, the expression of the complex electromagnetic torque of the entire power system including the FESS unit is derived. A 10 kW prototype of FESS, which consists of a double-fed induction machine (DFIM) and a voltage-source pulse width modulation (PWM) rectifier-inverter used as an AC exciter, is developed. Simulation and experiment results demonstrate that it is effective in damping the power system oscillations.*

***Streszczenie.** System magazynowania energii typu FESS (z kołem zamachowym) może być potencjalnym rozwiązaniem problemu poprawy jakości energii. Artykuł omawia szastosowanie systemu FESS do tłumienia oscylacji w systemach mocy. Przedstawiono model matematyczny systemu ze strukturą sterowania typu Philips-Heffron. Bazując na metodzie współczynnika momentu wyprowadzono model momentu elektromagnetycznego w systemie mocy. Zabadano model prototypu 10 KW z podwójnie zasilaną maszyną indukcyjną i źródłem napięcia typu PWM. Symulacje i eksperymenty potiwrdziły zdolnosć tłumienia oscylacji. (**Zastosowanie systemu z kołem zamachowym do tłumienia oscylacji w układach mocy**)*

Keywords: *Power system oscillation, Phillips-Heffron model, Flywheel energy storage system (FESS).*
Słowa kluczowe: jakość energii, tłumienia oscylacji, koło zamachowe.

Introduction

Electromechanical oscillations have been observed in many interconnected power systems worldwide [1]-[4]. These oscillations may exist locally in a single generator or a generation plant (local oscillations), or they may involve a number of generators that are widely separated geographically (inter-area oscillations). Local oscillations often occur when a fast exciter is used on the generator. To stabilize these oscillations, power system stabilizers (PSSs) were developed. Inter-area oscillations may appear as the system loading is increased across the weak transmission links in the power systems which exhibit local oscillations [4]. If not controlled appropriately, these oscillations may lead to full or partial power interruptions [2].

It is known that the power transmission over long distances may exhibit some poorly damped or even negatively damped oscillations under certain disturbance conditions [3]. These oscillations are normally a result of the electromechanical synchronizing swings across long tie lines. Several stabilizing methods such as PSSs commissioned on a generator, static var compensators (SVCs) on the transmission line, etc have been investigated [5], [6]. In many power systems constrained by stability, the primary limiting factor is not the swing stability but the damping of system oscillations. The traditional method used to increase the damping of a power system is by adding a PSS in the excitation system of a generator. It has been proved that the PSS alone may not be sufficient to suppress these oscillations [7].

Flywheel energy storage system (FESS) used for power supply improvement has also attracted attention in the recent years [8]. A new FACTS device, which consists of a flywheel energy storage system based on DFIM, is proposed in this paper. This paper is an attempt to study the electromagnetic torque contributed by the FESS in damping low-frequency oscillations, and the proposed control strategy can give excellent dynamic performance and considerably enhance the stability of power system.

The studied system

In this paper, we consider a single-machine infinite-bus power system, whose single-line diagram is shown in Fig.1. The model for the generator unit studied here is a detailed 3rd-order model with the dynamic behavior of the exciter. The FESS unit is located at the bus bar near the generator terminal.The nonlinear dynamic behavior of the investigated model is described by the following equations:

$$(1)\qquad \begin{cases} \dfrac{d\delta}{dt} = \omega - \omega_0 \\ T_j \dfrac{d\omega}{dt} = P_m - P_e - D(\omega - \omega_0) \\ T'_{d0} \dfrac{dE'_q}{dt} = E_f - (x_d - x'_d) i_d - E'_q \\ T_f \dfrac{dE_f}{dt} + E_f = K_f (V_{t0} - V_t) \end{cases}$$

where $T_e = P_e / \omega$, $P_e = U_d i_d + U_q i_q$, $V_t = \sqrt{U_d^2 + U_q^2}$. U and i are terminal voltage and current of the generator respectively, d and q indicate the direct and quadrature axis components under the rotation synchronizing reference frame. δ is the rotor angle of the generator. ω and ω_0 are the rotor and synchronous angular speed of the generator respectively. P_e and P_m are the electromagnetic and mechanical power of the generator respectively. x_d and x'_d are d-axis synchronous reactance and d-axis transient reactance of the stator winding. E'_q is the q-axis transient voltage. E_f is the field exciter voltage. V_t is the terminal voltage of the generator. T_j is the inertia constant. D is the mechanical damping coefficient of the generator. T'_{d0} is the d-axis transient time constant. K_f is the exciter gain. T_f is the exciter time constant.

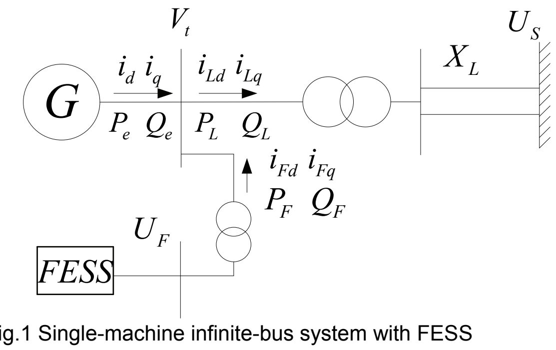


Fig.1 Single-machine infinite-bus system with FESS

It is assumed that the active power and reactive power supplied by the FESS unit can be decoupled and controlled independently. P_F and Q_F are the active and reactive powers of the FESS unit injected into the power system. When the FESS unit is connected to the power system, the following equations hold:

(2)
$$\begin{cases} P_F = U_d i_{Fd} + U_q i_{Fq} \\ Q_F = U_q i_{Fd} - U_d i_{Fq} \\ i_{Ld} = i_d + i_{Fd} \\ i_{Lq} = i_q + i_{Fq} \end{cases}$$

The model mathematically described in this section will be used below to form the Phillips-Heffron model of the power system with a FESS unit installed.

Phillips-heffron model of power system with FESS

In this section, we will derive a Phillips-Heffron model for the studied power system when the FESS only injects active power into the power system to damp low frequency oscillations [6]. From Fig.1 and (1), we can deduce that the d-axis and q-axis components of the generator terminal voltage V_t are

(3)
$$\begin{cases} U_d = U_s \sin\delta - x_l(i_q + i_{Fq}) = i_q x_q \\ U_q = U_s \cos\delta + x_l(i_d + i_{Fd}) = E_q^{'} - i_d x_d^{'} \end{cases}$$

where U_s is the infinite-bus voltage. And the d-axis and q-axis components of the generator terminal currents are

(4)
$$\begin{cases} i_d = \dfrac{E_q^{'} - x_l i_{Fd} - U_s \cos\delta}{x_{d\Sigma}^{'}} \\ i_q = \dfrac{U_s \sin\delta - x_l i_{Fq}}{x_{q\Sigma}} \end{cases}$$

where $x_{d\Sigma}^{'} = x_d^{'} + x_l$, $x_{q\Sigma} = x_q + x_l$, $i_{Fd} = \frac{U_d P_F}{V_t^2}$, $i_{Fq} = \frac{U_q P_F}{V_t^2}$

The electromagnetic power output from the generator is given by

(5)
$$P_e = U_d i_d + U_q i_q = E_q^{'} i_q - (x_d^{'} - x_q) i_d i_q$$

From the nonlinear dynamic model of the power system in Fig.1, by linearising (1) around the steady state operating point it is possible to obtain

(6)
$$\begin{cases} \dfrac{d\Delta\delta}{dt} = \omega - \Delta\omega_0 \\ T_j \dfrac{d\Delta\omega}{dt} = -\Delta P_e - D\Delta\omega \\ T_{d0}^{'} \dfrac{d\Delta E_q^{'}}{dt} = \Delta E_f - (x_d - x_d^{'})\Delta i_d - \Delta E_q^{'} \end{cases}$$

Then by linearising (4) it is possible to obtain

(7)
$$\begin{cases} \Delta i_d = \dfrac{\Delta E_q^{'} - x_l \Delta i_{Fd} - U_s \sin\delta_0 \Delta\delta}{x_{d\Sigma}^{'}} \\ \Delta i_q = \dfrac{U_s \cos\delta_0 \Delta\delta - x_l \Delta i_{Fq}}{x_{q\Sigma}} \end{cases}$$

where $\Delta i_{Fd} = \dfrac{U_{d0}}{V_{t0}^2}\Delta P_F$, $\Delta i_{Fq} = \dfrac{U_{q0}}{V_{t0}^2}\Delta P_F$ .Thus (7) can be rewritten as

(8)
$$\begin{cases} \Delta i_d = \dfrac{1}{x_{d\Sigma}^{'}}\Delta E_q^{'} - \dfrac{U_s \sin\delta_0}{x_{d\Sigma}^{'}}\Delta\delta - \dfrac{x_l U_{d0}}{x_{d\Sigma}^{'} V_{t0}^2}\Delta P_F \\ \Delta i_q = \dfrac{U_s \cos\delta_0}{x_{q\Sigma}}\Delta\delta - \dfrac{x_l U_{q0}}{x_{q\Sigma} V_{t0}^2}\Delta P_F \end{cases}$$

By linearising (3) and substituting Δi_{Fd} , Δi_{Fq} into the linearized equation, it is possible to obtain

(9)
$$\begin{cases} \Delta U_d = \dfrac{U_s x_q \cos\delta_0}{x_{q\Sigma}}\Delta\delta - \dfrac{x_l x_q U_{q0}}{x_{q\Sigma} V_{t0}^2}\Delta P_F \\ \Delta U_q = \dfrac{x_l}{x_{d\Sigma}^{'}}\Delta E_q^{'} - \dfrac{x_d^{'} U_s \sin\delta_0}{x_{d\Sigma}^{'}}\Delta\delta + \dfrac{x_l x_d^{'} U_{d0}}{x_{d\Sigma}^{'} V_{t0}^2}\Delta P_F \end{cases}$$

so it is possible to obtain

(10)
$$\Delta V_t = \frac{U_{d0}}{V_{t0}}\Delta U_d + \frac{U_{q0}}{V_{t0}}\Delta U_q = K_1 \Delta E_q^{'} + K_2 \Delta\delta + K_v \Delta P_F$$

where

$$K_1 = \frac{U_{q0} X_L}{V_{t0} X_{d\Sigma}^{'}}, \quad K_2 = \frac{U_s}{V_{t0}}\left(\frac{U_{d0} X_q \cos\delta_0}{X_{q\Sigma}} - \frac{U_{q0} X_d^{'} \sin\delta_0}{X_{d\Sigma}^{'}}\right),$$

$$K_V = \frac{U_{d0} U_{q0} X_L}{V_{t0}^3}\left(\frac{X_d^{'}}{X_{d\Sigma}^{'}} - \frac{X_q}{X_{q\Sigma}}\right)$$

Linearising the last equation of (1) yields

(11)
$$\Delta E_f = \frac{K_f}{1 + T_f s}\Delta V_t$$

Then by substituting (10) into (11) and substituting ΔE_f and (8) into (6), we have

(12)
$$\Delta E_q^{'} = \frac{\Delta E_f + K_4 \Delta\delta + K_q \Delta P_F}{K_3 + s T_{d0}^{'}}$$

Where

$$K_3 = \frac{X_{d\Sigma}}{X_{d\Sigma}^{'}} \quad K_4 = \frac{-(X_d - X_d^{'}) U_s \sin\delta_0}{X_{d\Sigma}^{'}}, \quad K_q = \frac{(X_d - X_d^{'}) U_{d0} X_L \sin\delta_0}{X_{d\Sigma}^{'} V_{t0}^2}$$

By linearising (5) and substituting (8) and (12) into the linearized equation, it is possible to obtain

(13)
$$\Delta P_e = K_5 \Delta\delta + K_6 \Delta E_q^{'} + K_p \Delta P_F$$

where

$$K_5 = \frac{[E_{q0}^{'} - (X_d^{'} - X_q) i_{d0}] U_s \cos\delta_0 X_{d\Sigma}^{'} - (X_d^{'} - X_q) i_{q0} U_s \sin\delta_0 X_{q\Sigma}}{X_{q\Sigma} X_{d\Sigma}^{'}}$$

$$K_6 = \frac{X_{q\Sigma}\, i_{q0}}{X_{d\Sigma}^{'}}$$

$$K_p = \frac{(X_d^{'} - X_q) i_{q0} X_L U_{d0} X_{q\Sigma} - [E_{q0}^{'} - (X_d^{'} - X_q) i_{d0}] X_L X_{d\Sigma}^{'} U_{q0}}{X_{q\Sigma} X_{d\Sigma}^{'} V_{t0}^2}$$

Hence the linearized model of (6) including a FESS unit can be shown by Fig.2.

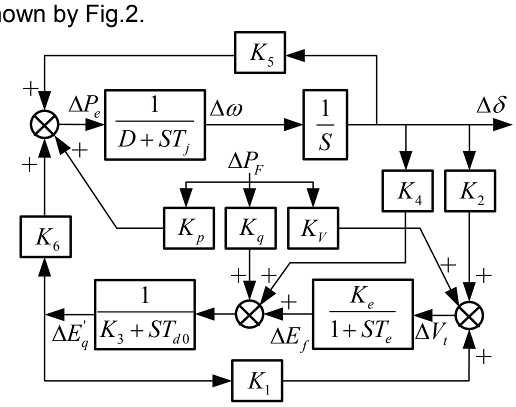


Fig.2 Control block diagram of a single machine infinite bus system

Analysis of power system stability enhancement by FESS

The FESS exchanges active power from the power system, resulting in a change of the damping characteristic, when power system low-frequency oscillations occur. The influence on the damping of power system oscillations based on the Phillips-Heffron model is investigated in this paper. The control diagram of the single-machine infinite-bus power system including a FESS is shown in Fig.2, where ΔP_F is input variable and $\Delta\delta$ is output variable. Since $P_e=T_e\omega$, when the power system is working in steady state (ω =1 p.u.), $\Delta T_e=\Delta Q_e$. Thus from (13), the electromagnetic torque of power system excluding FESS is

(14) $$\Delta T_{e1} = K_5\Delta\delta + K_6\Delta E_{q1}^{'}$$

(15) $$\Delta E_{q1}^{'} = \frac{\Delta E_f + K_4\Delta\delta}{K_3 + sT_{d0}^{'}}$$

Substituting (10) and (11) into (15) it is possible to obtain

(16) $$\Delta E_{q1}^{'} = \frac{K_f K_2 + K_4 + K_4 T_f s}{(1+T_f s)(K_3 + T_{d0}^{'} s) - K_1 K_f}\Delta\delta$$

Supposing $\Delta\delta$ is sine-disturbance and its angular speed is ω_s, $d\delta/dt=j\omega_s\Delta\delta=\omega_0\Delta\omega$ is given. Substituting this expression and (15) into (14) and letting $s=j\omega_s=\omega_0\Delta\omega$ then the electromagnetic torque of the system can be written as

(17) $$\Delta T_{e1} = (K_E + j\omega_s D_E)\Delta\delta = K_E\Delta\delta + D_E\omega_0\Delta\omega$$

where K_E is the synchronizing torque coefficient and D_E is the damping torque coefficient. Substituting (17) into (6), we can obtain

(18) $$\frac{T_j}{\omega_0}\frac{d^2\Delta\delta}{dt^2} + (D_E + \frac{D}{\omega_0})\frac{d\Delta\delta}{dt} + K_E\Delta\delta = 0$$

The eigenvalue of the differential equation are then found as

(19) $$\lambda_{1,2} = \frac{-(D/\omega_0 + D_E) \pm \sqrt{(D/\omega_0 + D_E)^2 - 4K_E T_j/\omega_0}}{2T_j/\omega_0}$$

Generally speaking, D is a very small positive number and the value of ω_0 is far larger then D; then we can consider $D/\omega_0\approx 0$. Meanwhile, T_j is commonly a relatively big number. Analyzing the eigenvalue expressed by (19) under the condition mentioned above it is possible to obtain the results:

1) when $K_E>0$，and $D_E>0$,the system is stable;；
2) when $K_E<0$，or $K_E=0$ and $D_E<0$，or $K_E>0$ and $D_E \le -\sqrt{4K_E T_j/\omega_0}$, the system occurs non-oscillating loss of synchronism;
3) when $K_E>0$ and $-\sqrt{4K_E T_j/\omega_0} < D_E < 0$, the system occurs oscillating loss of synchronism;
4) when $K_E>0$ and $D_E=0$, the system exhibits constant amplitude oscillation；
5) when $K_E=0$ 且 $D_E\ge 0$, the situation of the system is uncertain.

Fig.3 shows the electromagnetic torque variable and its stable region for a single-machine infinite-bus power system. By considering ΔT_e as the complex electromagnetic torque in the $\Delta\delta_0$-$\omega_0\Delta\omega$ coordinate system, correspondingly, K_E and D_E are the abscissa and ordinate of the complex torque respectively. From the analysis mentioned above, when a low-frequency oscillation occurs in the power system, the complex torque locates in the first quadrant or in the forth quadrant area which is close to $\Delta\delta$ axis. In this condition, the real part of the system eigenvalue is a positive number or negative number which has relatively little absolute value. Meanwhile the system manifests as low-frequency oscillation and its amplitude decays slowly or increases slowly. Theoretical analysis of the complex electromagnetic torque suggests that the damping ability is enhanced by forcing the complex torque curve to be closer to the $\Delta\delta_0$-$\omega_0\Delta\omega$ axis in the first quadrant of the $\Delta\delta_0$-$\omega_0\Delta\omega$ coordinate through controlling the output power of the FESS. In this case the real part of the system eigenvalue is a negative number which has a relatively large absolute value, and the oscillation can be damped rapidly so as to recover the power system stability.

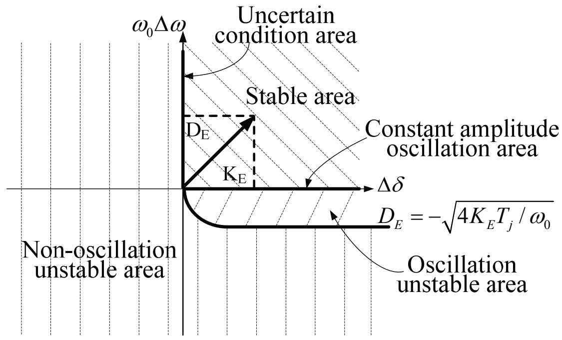


Fig.3 Electromagnetic torque variance and stability region schematic diagram of a single machine infinite bus system

When the FESS works in the power system, the electromagnetic torque of the system can be written as (13). Using the same method as that used to deduce (17), it is possible to obtain

(20) $$\Delta T_{e2} = \Delta T_{e1} + K_p\Delta P_F + \frac{K_6[K_q(1+T_f s) + K_f K_v]}{(1+T_f s)(K_3 + T_{d0}^{'} s)}\Delta P_F$$

In this equation, the second part is the direct electromagnetic torque provided by K_p and the third part is the indirect electromagnetic torque provided by K_q and K_v.

Under ideal conditions, the rotor angular speed variable of the generator $\omega_0\Delta\omega$ can be used as the input of the FESS damping controller. From earlier research of FESSs, the power modulation characteristics of FESSs can be written as a first-order inertia loop $1/(1+T_1 s)$. Considering the outer controller of the FESS adopting a proportional control loop K_c as the system damping controller, the electromagnetic torque provided by the FESS can be written as

(21) $$\Delta T_{e3} = \frac{K_p K_c \omega_s^2 T_1}{1+\omega_s^2 T_1^2} + j\frac{K_p K_c \omega_s}{1+\omega_s^2 T_1^2}\Delta\delta + \frac{K_6 K_c[K_q(1+jT_f\omega_s) + K_e K_v]}{(1+jT_f\omega_s)(K_3 + jT_{d0}^{'}\omega_s)(1+jT_1\omega_s)}$$

If neglecting the indirect electromagnetic torque provided by the FESS in (20), it can be seen from (21) that the effect of the FESS on damping the low-frequency oscillation is equivalent to superimposing a first-quadrant torque to the original electromagnetic torque, which demonstrates how the FESS unit can help to mitigate the low-frequency oscillation.

In addition, in practical applications it is difficult to measure the rotor angular speed variable $\omega_0\Delta\omega$ accurately. To meet the need of practical applications, it is feasible to adopt the active power variable $\Delta P_e=P_{e0}-P_e$ where the FESS is parallel to the system as the input of the damping controller. Neglecting the active power losses in the transformer and the transmission line, this active power variable can be seen as the output active power variable of the generator. In this way, the electromagnetic torque variable can be derived as

(22) $$\Delta T_{e4} = \Delta T_{e1} + K_P G(j\omega_s)\Delta T_{e4} + \frac{K_6[K_q(1+jT_f\omega_s) + K_f K_v]}{(1+jT_f\omega_s)(K_3 + jT_{d0}^{'}\omega_s)(1+jT_1\omega_s)}G(j\omega_s)\Delta T_{e4}$$

where G ($j\omega_s$) represents the transfer function of the damping controller of the FESS unit. From (22), it is possible to obtain

$$\Delta T_{e4}=\frac{\Delta T_{e1}}{1-\left[K_P+\frac{K_6[K_q(1+jT_f\omega_s)+K_fK_v]}{(1+jT_f\omega_s)(K_3+jT'_{d0}\omega_s)(1+jT_1\omega_s)}\right]G(j\omega_s)} \quad (23)$$

Obviously in this way, the FESS functions as providing an additional electromagnetic torque for the power system. When the parameter of the system is fixed, it is possible to adjust the parameters of the controller to achieve an angle of the rotating electromagnetic torque that is slightly less than 90°. Therefore, when power system low-frequency oscillation happens, the original electromagnetic torque that was close to the first or forth quadrant can be modulated to be closer to the $\omega_0\Delta\omega$ axis in the first quadrant. Consequently the power system low-frequency oscillation can be damped well through controlling the output power of the FESS.

Power controller for the FESS

In order to enhance the damping characteristics and stability of the power system, a power control strategy is proposed for the FESS unit connected to the power system shown in Fig.1. When power system oscillation, the power fluctuations are detected fast and correctly. And then the power reference which can damp power system oscillation is calculated by power controller. The proposed block diagram of the power controller is given in Fig.4.

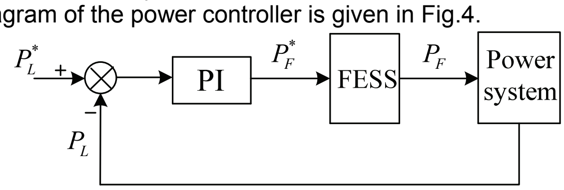


Fig.4 Block diagram of power controller

The input reference of the power controller is P_L^* which is the transmission power before power system oscillation. P_L^* is compared with the measured power P_L and the error is fed to a PI regulator. The output of the PI regulator is set as the power reference of FESS. And then, FESS exchanges power from the power system to damp power system oscillation.

Power system transient stability enhancement by FESS

A. Simulation results

The single-machine infinite-bus power system used for simulation is shown in Fig.5. The FESS is located at point A as shown in Fig.5. The fault which is occurred at 12s considered here is a 0.1 second symmetrical three-phase short-circuit fault at point K of the transmission line followed by a successful reclosing. The performance of Power system transient stability enhancement by FESS is simulated using EMTDC/PSCAD.

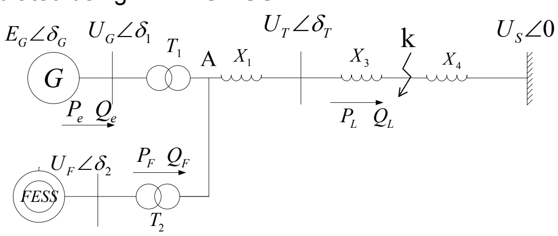
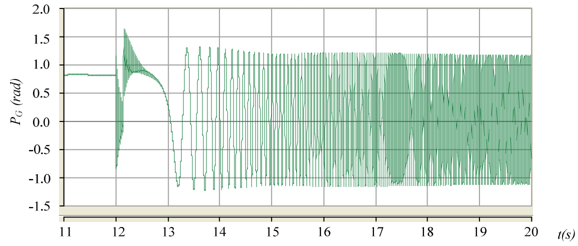
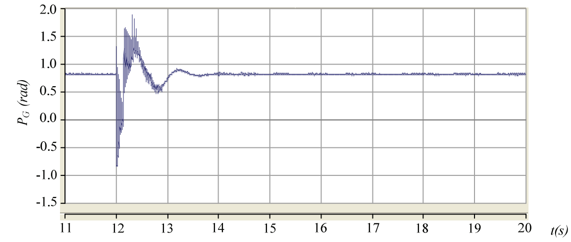


Fig.5 Simulation of primary wiring connection of FPC

It is indicated that from Fig.6 to Fig.8 the effectiveness of the FESS unit with the proposed controller in controlling the active power, power angle and the frequency of the generator at the operation condition of P_0 =0.8 (p.u.). The curves of the active power exchanging between the FESS unit and the power system are shown in Fig.6. It is evident that with the FESS unit employing the proposed controller, the oscillation of the power system is damped out quickly and the stability of the power system is enhanced tremendously. On the contrary, without the FESS unit, the power system is prone to the occurrence of the oscillation under the fault.

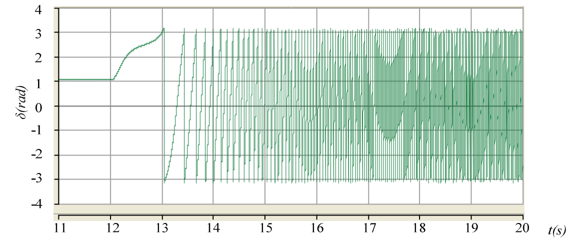


(a) without FESS

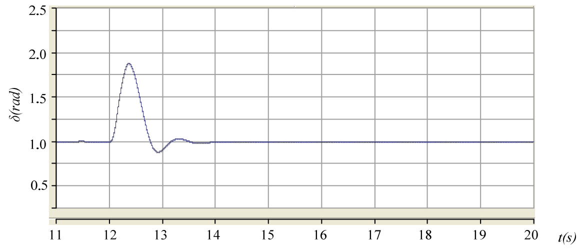


(b) with FESS

Fig.6 Active power of the generator

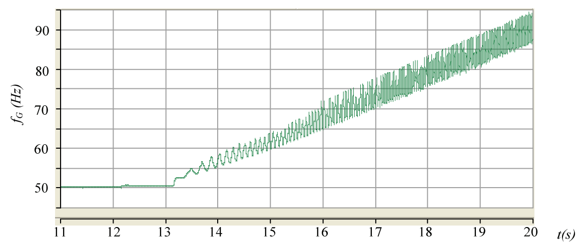


(a) without FESS

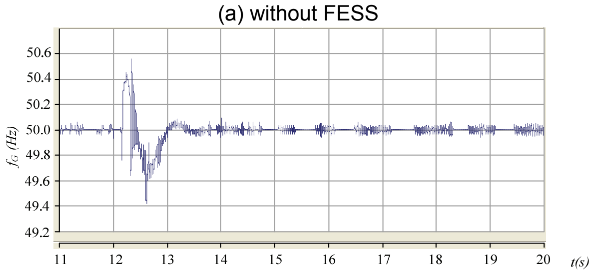


(b) with FESS

Fig.7 Power angle of the generator



(a) without FESS



(b) with FESS

Fig.8 Frequency of the generator

Fig. 7 and Fig. 8 present the response of the rotor angle and frequency of generator under the fault. With the FESS unit employing the proposed controller, the rotor angle remains and frequency are stable. They also indicate that the stability limit of the power system is expanded successfully. However, without the FESS unit, the generator obviously loses its synchronization.

B. Experiment results

An experimental system is constructed for testing this control strategy. The model DFIM of the FESS is 10kw. The DFIM, flywheel and the back-to-back converters is shown in Figure.9

Figure.9 Experimental set with a DFIM , flywheel and back-to-back converters

The single-machine infinite-bus power system and the FESS used for experiment are shown in Fig.10. The parameters of the generator are show as follows. S_e=5kVA，P_e=4kW，V_e=230V，I_c=12.55A，cosφ=0.8，X_d=0.676，X_d'=0.121 ， X_d''=0.073 ， X_q''=0.08. The disturbance considered here is cut off one of the transmission line by switch S.

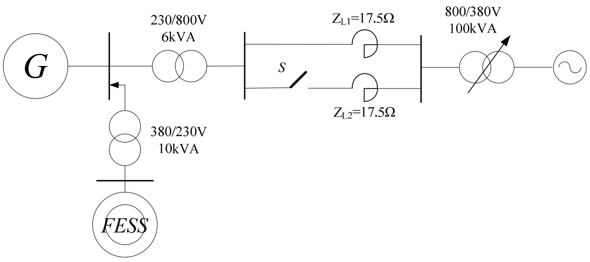
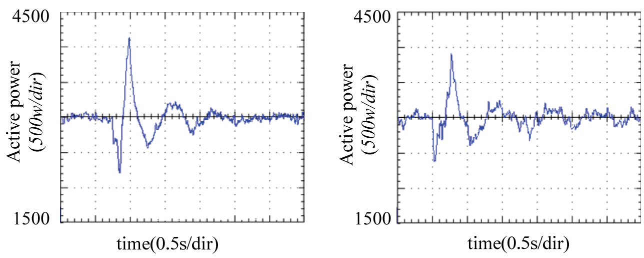
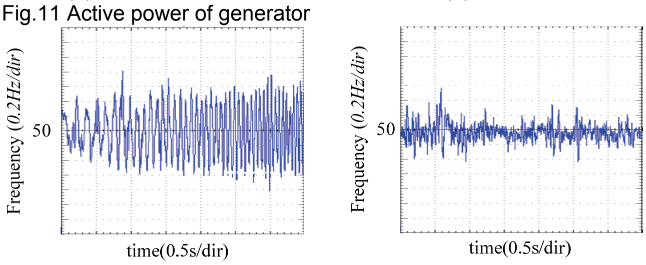


Fig.10 Single-machine infinite-bus system with FESS on experiment



(a) without FESS (b) with FESS

Fig.11 Active power of generator



(a) without FESS (b) with FESS

Fig.12. Frequency of generator

It is indicated that from Fig.11 to Fig.12 the effectiveness of the FESS unit with the proposed controller in controlling the active power and the frequency of the generator. It is shown that, without the FESS unit, active power and the frequency of generator fluctuates because of the disturbance of transmission line, and it is steady at last because of the PSS commissioned on a generator. On the other hand, with the FESS unit, active power and the frequency of generator steady quickly and the amplitude value is reduced. It is indicated that the FESS unit contributes to stability of power system.

Conclusion

In this paper, the Phillips-Heffron model of the single-machine infinite-bus power system including a FESS unit is established. Based on the principle of the complex torque coefficient method, the expression of the electromagnetic torque of the entire power system including the FESS unit is derived. It is demonstrated that the oscillations of the power system can be damped well through controlling the output power of the FESS. Simulation and experiment results indicate that the proposed controller can effectively enhance the dynamic performance of the power system and improve the power angle stability of the generator where the FESS unit is installed.

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