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Feasibility Analysis on FESS Damping for Power System Oscillation

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***Abstract*—Application of Flywheel Energy Storage System (FESS) to damp multi-mode oscillations is investigated in multi-machine power systems. The feasibility of damping multi-mode oscillations with FESS is proved by application of Damping Torque Analysis (DTA). Making use of the characteristic of the independent of the active and reactive power control loops of the FESS, the method of the single FESS to damp multi-mode oscillations is proposed by superposing stabilizers on each control loop, which damp different oscillation mode respectively. The control loop and feedback signal are selected for each mode base on control theory, and the parameters of FESS-based stabilizers are tuned by Particle swarm optimization (PSO). Finally, with a four-machine power system case investigated, the eigenvalue and non-linear simulation results show that single FESS has ability of damping power system multi-mode oscillations.**

***Index Terms*—Flywheels, energy storage, control theory, particle swarm optimization.**

I. INTRODUCTION

In the recent years, researchers all over the world have done a lot of work on using FESS to improve the stability of power system consisting of doubly-fed induction motors (DFIM) [1], [2]. However, there are few research papers on applying FESS to damp multi-mode oscillation in multi-machine system. The usual solution is to configure stabilizers in multi-machine system according to each oscillation mode respectively [3]. However, there is a problem called "eigenvalue deviation" because the stabilizers would affect each other [4]. To address it, some researchers put forward optimization algorithm to tune the parameters of the stabilizers [5], [6].

FESS has two independent loops to control active power and reactive power respectively. Because both of its loops can be configured with stabilizers, FESS device has the ability to damp multi-mode oscillation in power systems.

This paper mainly describes the theory on damping power system multi-mode oscillation using FESS. Firstly, damping torque analysis is applied to prove that FESS has the ability to damp the multi-mode oscillation. Then, control loops and feedback signals are chosen based on control theory, and particle swarm optimization (PSO) is used to tune the parameters of the stabilizers. Finally, a four-machine power system case was investigated to testify the validity of the proposed method.

II. LINEARIZED MODEL OF THE MULTI-MACHINE SYSTEM WITH FESS

Compared with other energy storage technology, FESS, composed by doubly fed induction motor (DFIM), is paid more attentions owing to its advantage in economy and practice [2], [7], [8]. As energy is stored in its rotating rotor, FESS can exchange energy with the system via DFIM by adjusting the speed of the flywheel (Fig. 1).

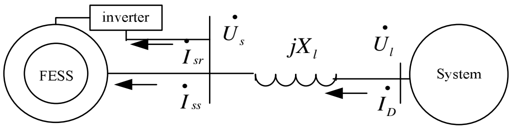

Fig. 1. FESS connected to power system.

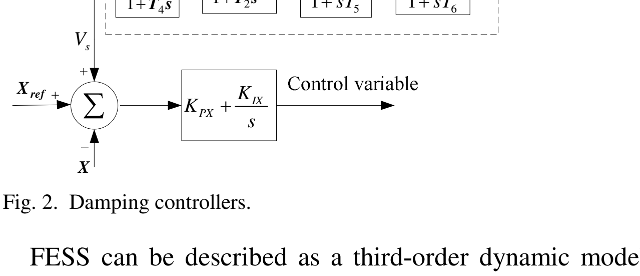

Fig. 2. Damping controllers.

FESS can be described as a third-order dynamic model. Generally, Stator flux orientation is chosen as its excitation control strategy because it can accomplish the decoupling control of active and reactive power. Meanwhile the reactive power can be replaced by voltage control.

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When FESS is used to damp low frequency oscillation, stabilizers can be configured for its active power and voltage control loops. The schematic diagram is shown in Fig. 2. where: Ks is the gain of stabilizer; KPX and KIX are respectively proportional integral factors. It is assumed that FESS damping controllers are configured in active power and voltage control loops respectively and the output signals are Vsp and Vsu.

Combine the network algebraic equations and with linearized model of FESS, the linear equation of whole system can be written as

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{z} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 \\ -K_J & -D_J & -A_{J23} \\ A_{J31} & A_{J32} & A_{J33} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta z \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ B_{Jp} \end{bmatrix} \Delta v_{sp} + \begin{bmatrix} 0 \\ 0 \\ B_{Ju} \end{bmatrix} \Delta v_{su}, \quad (1)$$

where Δδ is the deviation in generator power angle; Δω is the deviation in generator speed; ΔZ is the state variables of generator (except power angle and speed), including state variables of FESS devices (except stabilizer). B_{JP} and B_{Ju} are respectively the transfer functions from the input signals (ΔV_{sp} andΔV_{su}), to the state variables.

(1) can also be demonstrated as Fig. 3.

The output signal that is the feedback signal can be expressed in the following equation

$$\Delta y = C\left[\Delta\delta \quad \Delta\omega \quad \Delta z\right]^T, \quad (2)$$

where C is the transfer function from the state variables to y.

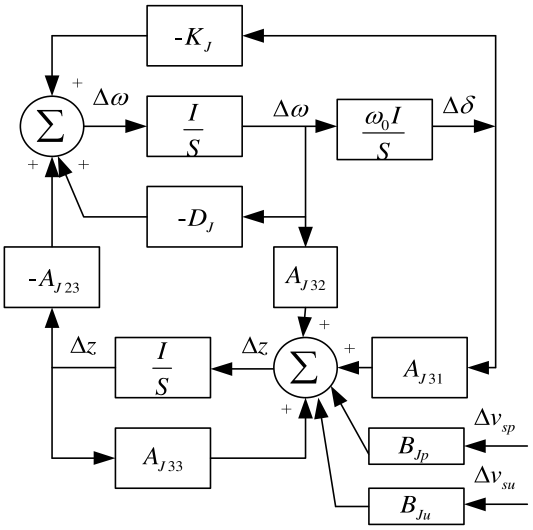


Fig. 3. Block diagram of linearized model with FESS.

$G_p(s)$ and $G_u(s)$ are respectively the transfer functions in active power and voltage control loops attached with damping controllers, then ΔV_{sp} andΔV_{su} can be written as (3):

$$\begin{cases} \Delta v_{Sp} = G_p(s) \cdot \Delta y_p, \\ \Delta v_{Su} = G_u(s) \cdot \Delta y_u, \end{cases} \quad (3)$$

where Δy_p and Δy_u, are respectively the deviations in active power and voltage damping controllers' input signals, which can be achieved from (2).

(1)–(3) are the linearized model of the multi-machine system with FESS.

III. FEASIBILITY ANALYSIS ABOUT MULTI-MODE OSCILLATION DAMPING WITH FESS

FESS has two independent loops, controlling active power and reactive power respectively. Both loops can be configured with damping controllers independently.

According to (1) and Fig. 3, total influence to the mode λ_i of two additional stabilizers can be calculated as follows [9]

$$\Delta\lambda_i = \sum_{j=1}^{N} S_{ij}\left(H_{pj}\angle\varphi_{pj}\Delta G_p(\lambda_i) + H_{uj}\angle\varphi_{uj}\Delta G_u(\lambda_i)\right). \quad (4)$$

where: S_{ij} is the sensitivity coefficient, defined as mode λ_i partial derivative of T_{Dij}, which is the damping torque of electro-mechanical oscillations in the j-th generator. $H_{pj}\angle\varphi_{pj}$ and $H_{uj}\angle\varphi_{uj}$ are the forward channel from the damping controllers to electro-mechanical oscillations in the j-th generator.

From (4), it is obvious that the damping controllers supply damping torque to *N* generators with through N channels firstly and then *N* generators distribute the damping torque to each mode in the system via sensitivity coefficient. It shows how these two damping controllers restrain the multi-mode oscillation, and prove the feasibility that FESS can suppress the multi-mode oscillation.

IV. TUNING PARAMETERS OF FESS DAMPING CONTROLLERS

For damping multi-mode oscillation in the power systems, it is necessary to select appropriate FESS control loops, feedback signals, and parameters tuning of the damping controllers based on control-ability and observe-ability. Furthermore, owing to its high efficiency and the ability to find the optimal global solution, PSO algorithm is adopted to tune the parameters [10].

According to the control theory, the performance index b_{iK} of mode λ_i can be written as (5)

$$b_{iK} = \left|W_i^T B_K\right|, \quad (5)$$

where W_i^T is the left eigenvector of system state matrix A corresponding to mode i. B_K is the column vector in (1) where B_{Jp} and B_{Ju} are, controlling ΔV_{sp} andΔV_{su}, respectively.

The observe-ability index c_{iK} of mode λ_i, can be written as follows

$$c_{iK} = \left|\boldsymbol{CV}_i\right|, \quad (6)$$

where V_i is the right eigenvector of system state matrix A corresponding to mode *i*.

From (5) and (6), control loops and feedback signals can be selected according to the performance indicators of controllability and observe-ability, respectively.

From (4), it is obvious that two damping controllers influence each other when they are used to restrain multi-mode oscillation. Therefore, PSO algorithm is adopted to tune the parameter of the damping controllers in FESS.

The structure of the controller is shown in Fig. 2. The time constants of measuring sector and DC block sector, marked as T_5 and T_6, are given. Lead and lag sectors have the same time constants, that is to say, $T_1= T_3$, $T_2= T_4$. Hench each controller has three unknown parameters, time constant T_1, T_2 and gain Ks. Then there are totally six unknown parameters. The objective function is maximizing the minimum of damping ratios of two weak damping modes, marked as ξ_1, ξ_2. So it can be written as:

$$\begin{cases} max\left[min\left(\xi_1,\xi_2\right)\right], \\ s.t.\ r_{K\alpha\_min} \le K_\alpha \le r_{K\alpha\_max}, \\ r_{T\alpha\_min} \le T_\alpha \le r_{T\alpha\_max}, \end{cases} \qquad (7)$$

where K_α is the gain of two controllers; T_α is the time constant of the lead and lag links in the controllers.

(7) is a typical optimization problem with constraints, which can be dealt by PSO to achieve coordinated tuning.

V. CASE STUDY

A four-machines power system was investigated in this paper [11], shown in Fig. 4, assuming FESS connected at node 7. According to the eigenvalue, there are three weak damping modes:

1) Regional mode, λ_1=0.05259±j3.9484, the damping ratio is -0.013 (unstable).

2) Part mode between generator G1 and G2, λ_2= -0.3167±j6.0250, the damping ratio is 0.052 (weak damping mode).

3) Part mode between generator G3 and G4, λ_3= -0.3070±j6.1364, the damping ratio is 0.050 (weak damping mode).

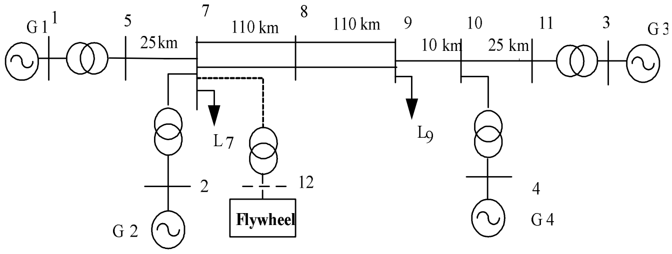


Fig. 4. FESS connected to four-machines power system.

Since FESS is set in node 7, which is far from generator G3 and G4, the effect towards mode 3 will be not so well. Therefore, FESS is used to restrain λ_1 and λ_2.

According to (5), the controllability indices of FESS active and reactive power control loops towards λ_1 and λ_2 can be calculated and summarized in Table I.

TABLE I. CONTROLLABILITY INDICES OF DIFFERENT CONTROL LOOP.

FESS control loop	**Controllability index of λ_1**	**Controllability index of λ_2**
Active power control loop	0.24644	0.05977
Reactive power control loop	0.21484	0.01561

The results in Table I show that:

1) FESS can control regional mode λ_1 effectively, while it is not very ideal to control part mode λ_2.

2) Both indices show that active power control loop performs better than voltage control loop.

According to (6), the observe-ability indices of FESS to regional mode λ_1 and part mode λ_2 can be calculated and shown in Table II.

From Table II, oscillation power P_{78} of line 7-8 is suitable to be taken as the feedback signal to restrain regional mode λ_1, and the integral of the power difference between line 5-7 and line 2-7 ($\int(P_{57}-P_{27})$) is suitable to be taken as the feedback signal to restrain part mode λ_2.

TABLE II. OBSERVABILITY INDICES OF DIFFERENT FEEDBACK SIGNALS.

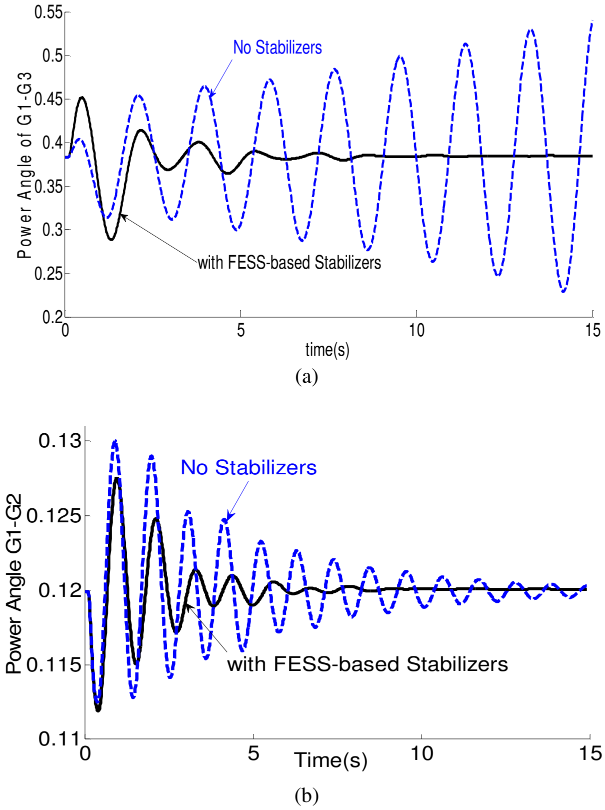
Mode	**P_{78} as Feedback signal**	**$\int(P_{57}-P_{27})$ as Feedback signal**
Regional mode λ_1	0.7631	0.1364
Part mode λ_2	0.02659	6.99670

Taking maximum of the minimum damping ratios of λ_1 and λ_2 as the objective function, stabilizer's parameters can be achieved based on PSO algorithm, which is shown in Table III.

TABLE III. PARAMETERS OPTIMIZATION OF FESS STABILIZERS.

Parameter of stabilizers	**Control loop of λ_1**	**Control loop of λ_2**
T1=T3	0.023	0.312
T2=T4	0.054	0.105
Ks	5.11	1.23

Applying such parameters into operation control, the eigenvalues of λ_1 and λ_2 can be recalculated as Table IV shows. It is obvious that oscillation of λ_1 and λ_2 are restrained.



(a)

(b)

Fig. 5. Damping of regional mode ((a) for mode λ_1 and (b) for mode λ_2).

TABLE IV. INFLUENCE OF DAMPING BY FESS STABILIZERS.

λ_2		λ_1	
Eigenvalue	**Damping ratio**	**Eigenvalue**	**Damping ratio**
-0.3167±j6.0250	0.052	-0.05259±j3.9484	-0.013
-0.5986±j5.8140	0.102	-0.3513±j3.3098	0.106

Considering there was a three-phase short-circuit fault occurred at bus 8 which lasts 0.1s, simulation results shown in Fig. 5 also verify the validity of the proposed stabilizers.

VI. CONCLUSIONS

It has been proved in this paper that FESS can restrain multi-mode oscillation in power system based on the analysis of damping torque.

Optimization algorithm can be utilized for parameters tuning for the design of FESS stabilizer.

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