

# Power System Damping Enhancement Using Combined Operation of Robust Energy Capacitor System and Power System Stabilizer

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## ABSTRACT

High damping ratio and fast settling time are very challenges for improving the stability performance in power system. In this paper, an energy capacitor system (ECS) is applied in a two-area multi-machine power system to provide the transient stability enhancement. The algorithm for designing the robust damping controller of the ECS is based on the loop shaping control. The results from the design are the control parameters of the ECS damping controller with the constraint that the size of the ECS must satisfy the criteria of damping consideration. From the simulation results, it can be found that the ECS can effectively enhance the damping of power system oscillations. Moreover, the combination of ECS and the existing power system stabilizers (PSSs) allows exceptional performance and more desirable size of ECS.

**Keywords:** Energy Capacitor System,  $H_\infty$  loop Shaping Control, Power System Damping, Robust Control

## 1. INTRODUCTION

Recently, the trend of power system is the large interconnected network that possesses the advantages of not only being able to deliver sufficient power to the loads but also increasing the reliability in term of the economic significance as well. However, the large interconnected power system may bring to the issue of inter-area low frequency oscillations that can degrade the damping characteristics of power systems [1]. As a result, inter-area oscillations can affect the stability when there is the sudden change of load or fault in the power system. In order to reduce the oscillations of the rotor angle at low frequency in the range of 0.8 to 2.0 Hz, the Power System Stabilizer (PSS) equipped with the Automatic Voltage Regulator (AVR) is introduced to increase the damping

of power system. For the power system equipped with only PSS, it might not be possible to withstand the disturbances in some cases. As a result, various attempts have been brought to solve this problem including the adoption of energy capacitor system (ECS) into the power system [5-6].

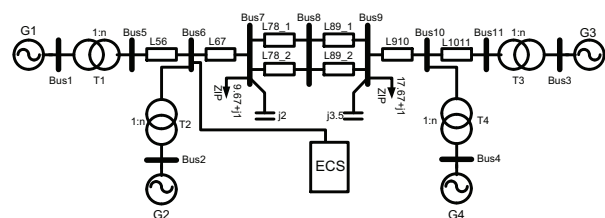
This paper presents the use of ECS to increase the damping effect of the power system. Moreover, the cooperation between PSS and ECS in the power system is also studied. The important keypoint in applying both ECS and PSS into the power system is the design of ECS and PSS to match each other, of which the ECS design is done by  $H_\infty$  loop shaping control.

In order to verify the effectiveness of the proposed control, the performance analysis of the simulated power system after applying both ECS and PSS into the power system is performed. From the results, it reveals that with the installation of both ECS and PSS, the power system stability is improved and the Megawatt (MW) and Megajoule (MJ) sizes of the ECS are reduced under various operating conditions.

## 2. THE SIMULATION MODEL OF THE ECS AND THE POWER SYSTEM USED FOR THIS STUDY

### 2.1 The configuration of the study power system

Fig. 1 shows the single line diagram of a study power system consisting of four generators connected to each other [4], of which the ECS is installed at Bus 6. Each generator of each area is represented by the 6th order synchronous machine model equipped with a 1<sup>st</sup> order exciter, a 1<sup>st</sup> governor and a 2<sup>nd</sup> order PSS.



**Fig.1:** The single line diagram of a study power system.

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## 2.2 The simulation model of ECS

The ECS is applied to distribute the energy in case of the main power system is interrupted in order to keep the continuity of the power flow to loads and to increase the stability of the power system. ECS can be used to charge or discharge the real and reactive power [6]. It is developed to store the energy at higher density than the normal lead-acid battery. The fundamental mathematical model of ECS and the controller is shown in Fig. 2 [7].

From Fig. 2,  $P$  is the real power from the main power system,  $V$  is the voltage at the bus installed with ECS,  $P_{ECS}$  and  $Q_{ECS}$  are the real and reactive power distributed by the ECS to main grid of power system consecutively.  $P_{ECS,max}$ ,  $P_{ECS,min}$ ,  $Q_{ECS,max}$  and  $Q_{ECS,min}$  are the maximum and minimum of real and reactive power of the ECS accordingly. In this study, it can be concluded as:

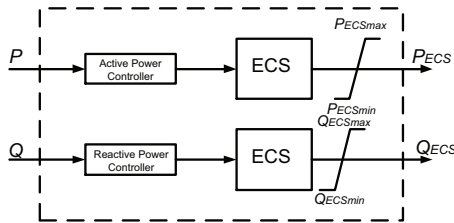
$$P_{ECS,min} = -P_{ECS,max} \quad (1)$$

$$Q_{ECS,min} = -Q_{ECS,max} \quad (2)$$

$P_{ECS,max}$  and  $Q_{ECS,max}$  can be expressed as:

$$\sqrt{P_{ECS,max}^2 + Q_{ECS,max}^2} \leq S_{ECS,max} \quad (3)$$

In this study, the value of  $S_{ECS,max}$  is set to be 0.2 pu. The maximum and minimum energy storage levels are 0.0225 pu. and -0.0225 pu., respectively.



**Fig.2:** The simulation model of ECS.

$I_d$  and  $I_q$  can be calculated from (4) and (5) as follows:

$$I_d + jI_q = I_{ECS} \quad (4)$$

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \frac{1}{V_d^2 + V_q^2} \begin{bmatrix} V_d & V_q \\ V_q & -V_d \end{bmatrix} \begin{bmatrix} P_{ECS} \\ Q_{ECS} \end{bmatrix} \quad (5)$$

Where  $I_{ECS}$  is the current fed into the ECS,  $I_d$  is the d-axis component of the current fed into the ECS,  $I_q$  is the q-axis component of the current fed into the ECS,  $V_d$  is the d-axis component of the voltage and  $V_q$  is the q-axis component of the voltage.

## 3. THE ECS CONTROLLER DESIGN

There are 3 steps in the design procedure as follows:

Step 1: Loop shaping.

In this step, two weighting functions,  $W_1$  (lead compensator) and  $W_2$  (lag compensator) are applied such that  $G_s = W_2 G_0 W_1$  as the bold line of Fig. 3.

Step 2:  $H_\infty$  robust control boundary definition.

The shaped plant  $G_s$  is expressed in the left co-prime factorization  $G_s = M_s^{-1} N_s$  where  $G_\Delta$  is given by

$$G_\Delta = \{(1M_s + \Delta M_s)^{-1}(N_s + \Delta N_s) \mid \|\Delta N_s \quad \Delta M_s\|_\infty \leq \frac{1}{\gamma}\} \quad (6)$$

Where  $\Delta M_s$  and  $\Delta N_s$  are the transfer function of the uncertainties of the plant  $G_0$ . From the  $H_\infty$  robust stability problem,  $G_\Delta$  and  $K_C$  can be synthesized as in Fig. 3. Not only the robust controller design can preserve the stability of the nominal plant  $G_0$ , but it also keeps the stability of  $G_\Delta$  by the factor of  $1/\gamma$  as the boundary definition of the robust stability according to (6).

The maximum boundary of the stability of the power system with uncertainties  $\gamma$  can be given as the possible minimum value as  $\gamma_{min}$ . Therefore,  $\gamma_{min}$  is the uncertainty of the power system having the maximum size that can be closed-loop stabilized as in Fig. 4. The  $\gamma_{min}$  can be calculated from:

$$\gamma_{min} = \sqrt{1 + \gamma_{max}(XZ)} \quad (7)$$

Where  $\gamma_{max}(XZ)$  is the maximum eigenvalue of  $XZ$  for the given matrix  $(A, B, C, D)$  of the  $G_s$ . In order to get the minimum value,  $X$  and  $Z$  must be the nonrepeated summation so as to solve the following Riccati equations.

$$\begin{aligned} (A - BS^{-1}D^T C)^T X + X(A - BS^{-1}D^T C) \\ - XBS^{-1}B^T X + C^T R^{-1}C = 0 \end{aligned} \quad (8)$$

$$\begin{aligned} (A - BS^{-1}D^T C)^T Z + Z(A - BS^{-1}D^T C)^T \\ - ZC^T R^{-1}CZ + BS^{-1}B^T = 0 \end{aligned} \quad (9)$$

Where  $R = 1 + DD^T$  and  $S = I + D^T D$ . In order to assure the stability of the nominal plant, the  $\gamma_{min}$  is set to be 1.1. If the result is not satisfied, the function of weight can be adjusted.

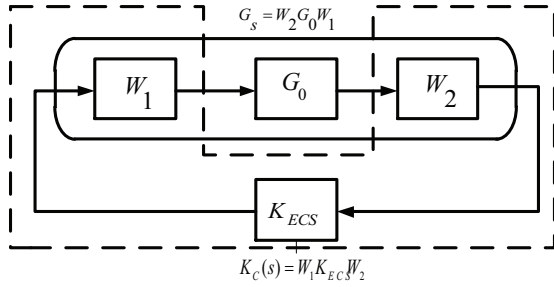
Step 3: The calculation of the robust controller.

$\bar{K}_{ECS}$  as in Fig. 3 can be calculated from

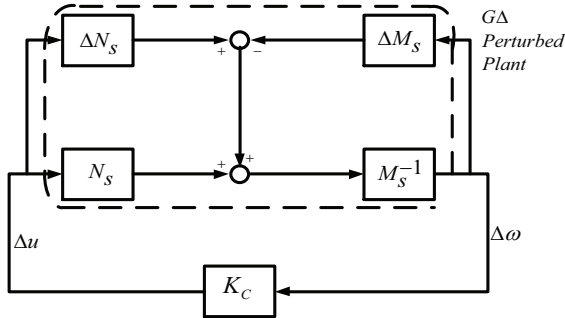
$$K = \begin{bmatrix} A + BF + \gamma^2(L^T)ZC^T(C + DF) & \gamma^2(L^T)ZC^T \\ B^T X & -D^T \end{bmatrix} \quad (10)$$

Where  $F = -S^{-1}(D^T C + B^T X)$  and  $L = (1 - \gamma^2)I + XZ$ . Then, the robust controller  $K_C(s) = W_1 K W_2$  must be complied with the condition of

$$\left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I - G_s K_\infty)^{-1} \begin{bmatrix} I & G_s \end{bmatrix} \right\|_\infty \leq \gamma \quad (11)$$



**Fig.3:** The plant  $G_s$  and the robust controller design.



**Fig.4:** The  $H_\infty$  robust stability problem.

#### 4. THE SIMULATION RESULTS

In this section, the study of the simulation model having four generators is carried out. The simulation process is done by using MATLAB and Dymola [3]. The non-linear simulations of three different operating conditions, i.e. light, normal and heavy loads, are performed under the disturbance that a three-phase to ground fault is applied on the transmission line between Bus 7 and Bus 8 at  $t = 2.0$  s and the faulted line is cleared at  $t = 2.07$  s. The light, normal and heavy load conditions are defined as the amount of tie-line power flow  $P_{tie}$  of 2.0 pu., 4.0 pu. and 6.8 pu., respectively. In this paper, the proposed ECS damping controller is designed at the normal load condition and the operating condition is varied to light and heavy load condition respectively so as to verify the effectiveness of the proposed controller. Under three dif-

ferent operating conditions, the following four cases are performed and are compared the results.

Case 1: No ECS and PSS.

For the power system without any damping controller, it turns out that there is a severe oscillation of the generator speed deviation at the normal load condition as shown in Fig. 5. For the case of light load condition, the long-period oscillation can be observed as shown in Fig. 6. The oscillation leads to the instability at the heavy load condition as shown in Fig. 7.

Case 2: Only PSS.

The parameters of the lead-lag controller for the PSS are acquired from [4]. The transfer function of the lead-lag controller  $K_{PSS}$  shown in (12) is applied for the PSS. It can be found that the oscillation can be damped out by the PSS in case of normal and light load conditions. In case of heavy load condition, the oscillation leads to the instability as shown in Fig. 7.

$$K_{PSS} = \left( \frac{0.050s + 1.000}{0.020s + 1.000} \right) \left( \frac{3.000s + 1.000}{4.000s + 1.000} \right) \quad (12)$$

Case 3: Only ECS.

By applying the  $H_\infty$  loop shaping design, the ECS damping controller  $H_{ECS1}$  can be obtained as in (13) with the weighting functions specified in (14) and (15). It can be found from Fig. 5 to Fig. 7 that the oscillation can also be damped out by the ECS. However, the performance of power system stabilization can be degraded significantly when changing the load conditions.

$$K_{ECS1} = \frac{(s^2 + 0.344s + 4.517)(s + 0.343)}{(s^2 + 0.372s + 12.928)(s + 0.299)} \quad (13)$$

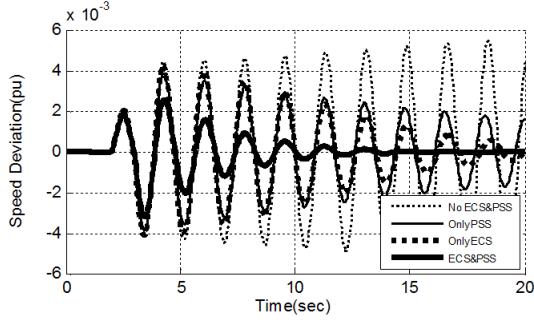
$$W_1 = \frac{50s + 5}{s + 0.3} \quad (14)$$

$$W_2 = 1 \quad (15)$$

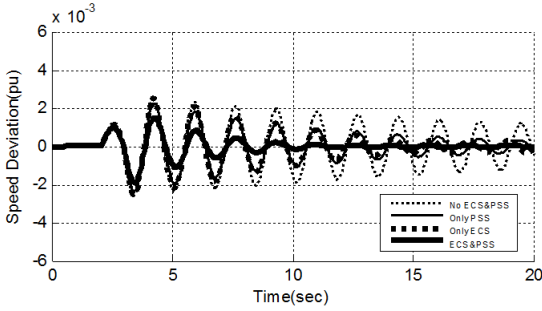
Case 4: ECS and PSS.

The  $H_\infty$  loop shaping design is applied to design the ECS damping controller while considering the installation of PSS as (12) for each generator. The ECS damping controller  $K_{ECS2}$  can be obtained as in (16) with the same weighting functions specified in (14) and (15). It is obviously that with ECS and PSS, the oscillation of the speed deviation of generator is damped out significantly for the three load conditions as shown in Fig. 5 to Fig. 7. It can be said that the combined operation of ECS and PSS is robust to uncertainties in the load conditions.

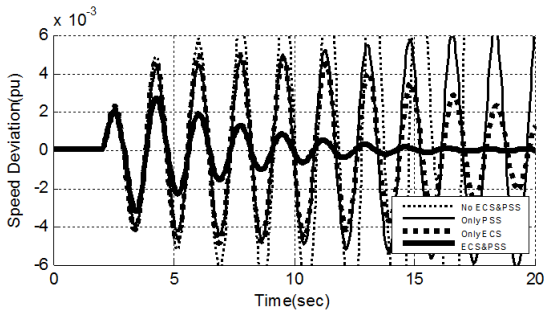
$$K_{ECS2} = \frac{(s^2 + 36.700s + 346.299)(s + 0.115)}{(s^2 + 1.000s + 12.910)(s + 0.299)} \quad (16)$$



**Fig.5:** The generator speed difference in normal load.

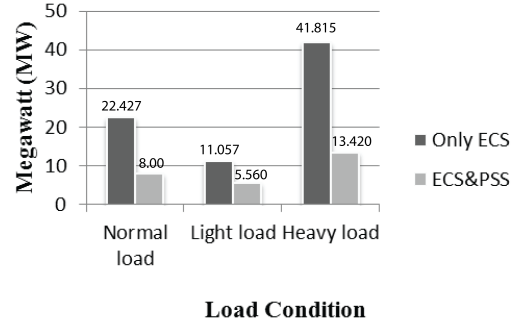


**Fig.6:** The generator speed difference in light load.

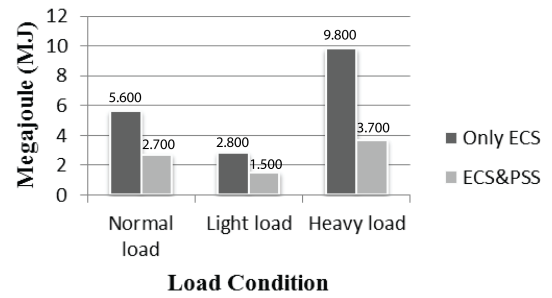


**Fig.7:** The generator speed difference in heavy load.

After the short-circuit event occurs, the system voltage is dramatically decreased leading to the loss of power transfer capability. ECS can help improve the system voltage by supplying and absorbing active and reactive power on the transmission network. If the system voltage is maintained, PSS can suppress the oscillations effectively resulting to the lower power oscillations, and then the lower power and energy injected by ECS. Therefore, with the combined operation of ECS and PSS, the stabilizing performance is significantly enhanced. In this study, the MW and



**Fig.8:** Comparison results of MW of the ECS under different load conditions and control strategies.



**Fig.9:** Comparison results of MJ of the ECS under different load conditions and control strategies.

MJ of the ECS under difference load conditions and control strategies are calculated as shown in Fig.8 and Fig.9. From the Fig.8 and Fig.9, it reveals that with the combined operation of ECS and PSS, the power system stability is improved and the MW and MJ values of the ECS are reduced significantly under various operating conditions.

## 5. CONCLUSION

This paper presents a method to improve the stability of the power system by using the ECS. From the simulation results, it is obviously found that the ECS with  $H_\infty$  loop shaping control can be used to effectively enhance the damping of the power system. The performance of the combined operation of ESS and the existing PSS is better than only the ECS or PSS. Moreover, it is found that by using the combined operation, not only the stability of power systems is improved significantly, it can also reduce the MW and MJ values of the ECS. This implies that the smaller size of ECS can be obtained when applying the cooperative control. By using the proposed robust control method, however, the order of the obtaining controller is usually high in the large-scale power systems. Reducing the order of the controller should be done appropriately; otherwise, the reduced-order controller may adversely affect the stabilizing performance.

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