Eigenvalue Based Stability Improvement of Electric Power Systems through Voltage Regulation

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Abstract- In power systems operation, it is increasingly important to keep the bus voltage within a permissible range for the reliable operation of power systems. This paper presents an eigenvalue based real time stability evaluation scheme and a real time stability control scheme through voltage and reactive power regulation to keep the stability margin within a pre-specified range. Reactive power regulation is realized on a small sized energy capacitor system composed of electrical double-layer capacitors for the stabilization control. Voltage control is also achieved through the reactive power regulation on the energy capacitor system. Nonlinear simulations for efficient demonstration of the proposed stability control scheme are carried out on a model of multi-machine system developed in Matlab/Simulink environment. In the simulations, full sets of the excitation systems including power system stabilizers and the speed governing control systems including the turbine systems are utilized. Simulations results clearly show the efficiency of the proposed stability control.

Keywords- Reactive power control, voltage control, energy capacitor system, fuzzy logic control, eigenvalue.

1. Introduction

Due to the increasing size and complexity of electric power systems, and also due to the high rate of growth of electric power demand, power systems are operated in a more stressed state and a lower stability margin. In power system operation, it is increasingly important to keep the bus voltage within an allowable range for the reliable operation of power systems. Following the variation of power demand, the bus voltages vary and occasionally violate the acceptable level. In power utilities, different types of devices are utilized for the regulation of bus voltages such as shunt capacitors, shunt reactors, transformers with tap changers, and static VAR compensators.

In this paper, an effective stabilization scheme has been presented by using a fuzzy logic controlled new energy storage device, electrical double-layer energy capacitor system (ECS) to enhance the overall stability of electric power systems [6]. The absorption and also the injection of the active and/or reactive power are possible on the ECS. The reactive power flow signal at the location of the ECS utilized to generate switching control signals for the absorption and the injection of the reactive power on the ECS [1, 2].

In actual power systems, there always exist low-frequency global modes of background oscillations caused by the unbalance between power generation and uncertain variation of power demand by loads. Therefore, the stability of the target power systems can be evaluated through the investigation and processing of the propagated background oscillations by the target system[3].

This paper also utilizes a new scheme for the real time stability evaluation based on the background oscillations. In the proposed scheme, the stability of target system has been examined through the real time eigenvalue analysis for the identified discrete time target system model after identifying its and from the target system. The propagation of the injected background oscillations through the study system clearly indicates the stability level of the study system [4].

To demonstrate the efficiency of the proposed stability control scheme and stability evaluation scheme, nonlinear simulations have been performed in Matlab/Simulink environment. A longitudinal four-machine system has been utilized as a study multi-machine power system [5]. In addition, the ECS model has been developed for the simulation based on the experiment results on the 70Wh (250 kJ) ECS in the 220V three phase laboratory system.

2. Configuration of the System

A longitudinal four-machine infinite bus system is selected as a study system to demonstrate the efficiency of the proposed stabilization control. The study system is illustrated in Fig. 1

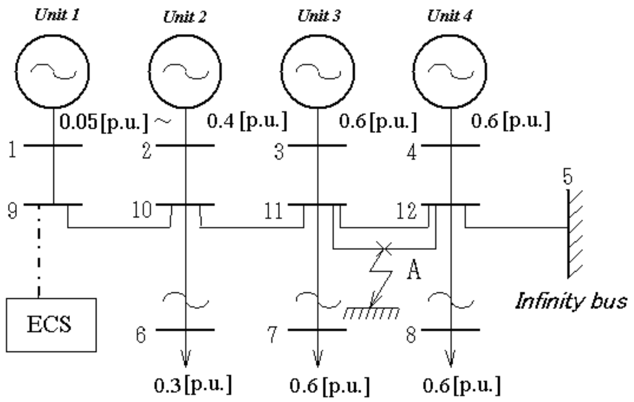

Fig. 1. A Longitudinal four-machine infinite bus system

Each unit is a thermal unit, and Units 1 and 4 have a self excited excitation control system, and Units 2 and 3 have a separately excited excitation control system. Each unit has a full set of governor-turbine system: governor, steam valve servo-system, high-pressure turbine, intermediate-pressure turbine, and low-pressure turbine. The configurations of the excitation systems are shown in Fig. 2 and Fig. 3. The configuration of the conventional power system stabilizer (CPSS) is shown in Fig 4.

The study system includes two types of oscillation modes: local mode of oscillation around 1Hz for each corresponding unit, and a low-frequency inter-area global mode of oscillation around 0.3 Hz. In the study system, the instability occurs on the global mode of oscillation.

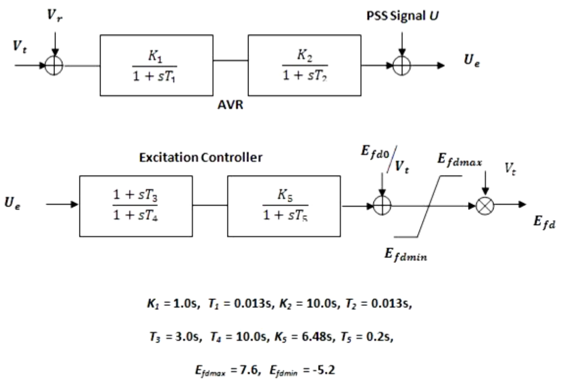

Fig. 2. Conventional excitation control system for Unit 1 and Unit 4

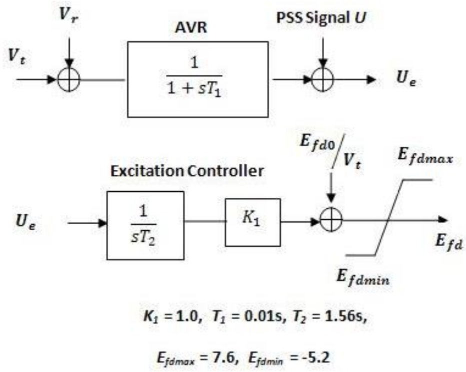

Fig. 3. Conventional excitation control system for Unit 2 and Unit

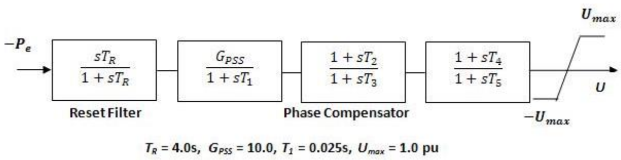

Fig. 4. Conventional power system stabilizer (CPSS)

In transient stability simulations, a three-phase to ground fault is applied to system during 0.07 s as a disturbance. To inquire into the critical power flow to the infinity bus, the real power output is increased from 0.05 pu to its critical power output by 0.05 pu steps. Real power output settings of the Unit 2, 3 and 4 are fixed to the values given in Fig 1.

3. Modelling of Energy Capacitor System

The basic configuration of the mathematical model for ECS is given in Fig. 5.

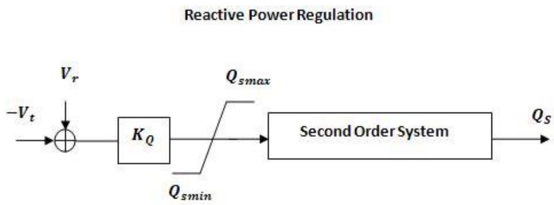

Fig. 5. Basic Configuration of mathematical model for ECS

On the ECS, the injected current is regulated at the AC side by using the PWM type inverter to satisfy the reactive power absorption or injection. The dynamics of the ECS is represented by the second order system following the experimental results performed on the 70Wh (250kJ) actual ECS at the laboratory.

In Fig. 5, the terms *Vt* and *Vr* denote the voltage measured at the location of the ECS and its reference, respectively. The output *Qs* gives the reactive power from the ECS to the transmission network. The terms *Qsmax* and *Qsmin* give the maximum and minimum reactive power output from ECS, respectively. Here, it must be noted that the following relations have been specified in this study.

$$Q_{Smax} = -Q_{Smin} \tag{1}$$

3.1. Artificial Neural Network Based Fuzzy Logic Switching Control Scheme

Fig. 6 shows the basic configuration of the proposed fuzzy logic switching controller. The controller has only one fuzzy logic control loop. The voltage signal V_t is utilized at the location of Energy Capacitor System (ECS) to generate the switching control signal *U(k).*

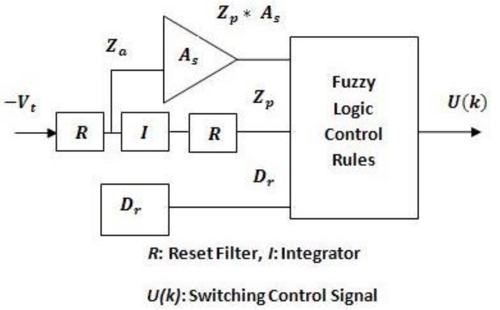

Fig. 6. Fuzzy Logic Switching Controller

Z_a and Z_p measurements are extracted from local voltage signal V_t by using the blocks shown in Fig. 6. When obtaining the optimum A_s and D_r coefficients Artificial Neural Network (ANN) block is utilized shown in fig 7. Optimum coefficients for the most efficient fuzzy logic control signal are calculated based on Unit 1 input power P_t.

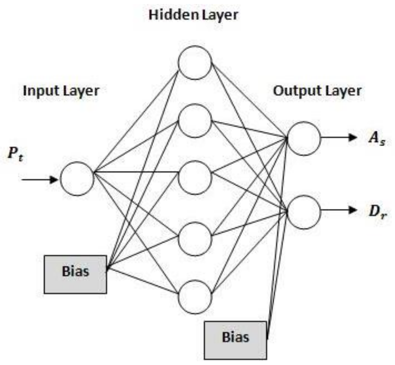

Fig. 7. Configuration of Artificial Neural Network

4. Eigenvalue Based Stability Evaluation Scheme

In eigenvalue stability evaluation method, two signals from the target system are monitored and sampled. By sampling these two signals at a certain sampling interval, required information in order to set up a low-order discrete time model are obtained for the estimation of discrete time eigenvalues. Through the monitoring of input signal $P_I(t)$, and the output signal $P_O(t)$, the parameters of the target system can be identified. Therefore, the stability of the target system can be evaluated from the eigenvalues of the identified study system. After monitoring the output $P_O(t)$ for an input signal $P_I(t)$, the relation between these two signals can be expressed in discrete way as follows:

$$P_0(k) = a_1P_0(k-1) + a_2P_0(k-2) + \cdots + a_nP_0(k-n)$$
$$+b_1P_1(k) + b_2P_1(k-1) + b_nP_1(k-n) \quad (2)$$

After identifying the above model parameters by using the least square method, the discrete time transfer function $H(z^{-1})$ can be derived as follows:

$$H(z^{-1}) = \frac{b_0+b_1z^{-1}+\cdots+b_nz^{-n}}{1-a_1z^{-1}-a_2z^{-2}-\cdots-a_nz^{-n}} \quad (3)$$

By solving the following characteristic equation, the stability of the discrete time system with the transfer function $H(z^{-1})$ can be evaluated

$$1 - a_1z^{-1} - a_2z^{-2} - \cdots - a_nz^{-n} = 0 \quad (4)$$

The discrete time eigenvalues can be easily converted to their corresponding continuous time eigenvalues as follow:

$$z_i = x_i + jy_i \quad (5)$$

$$\alpha_i = \frac{\ln(\sqrt{x_i^2+y_i^2})}{T} \qquad , \beta_i = \frac{\tan^{-1}\left(\frac{y_i}{x_i}\right)}{T} \quad (6)$$

The term α, which is the real part of the calculated eigenvalues, gives the damping coefficient and β gives the calculated frequency of the oscillation modes of the continuous system *F(s)*. Here, it must be noted that the system is stable when the all the damping coefficients α have negative values. In addition T denotes the sampling interval for the discrete time system. In non-linear simulations, sampling interval T is set to 0.5 s. Therefore, only the oscillation modes, related to the dominant low frequency global mode of oscillation and inter-sectional oscillations, are maintained in the identified low order model.

5. Nonlinear Simulation Results

To demonstrate the efficiency of the proposed reactive power control, nonlinear simulations have been performed. The stabilization performance has been investigated when considering the reactive power regulation through ECS. Fig. 8 respectively shows voltage profile of bus 9, power flow of infinite bus, speed deviation of Unit 1 of the system on Fig. 2 without ECS control operation where the output setting of Unit 1 is 0.5 pu. The study system is unstable after the three-phase to ground fault without the reactive power regulation at Bus 9.

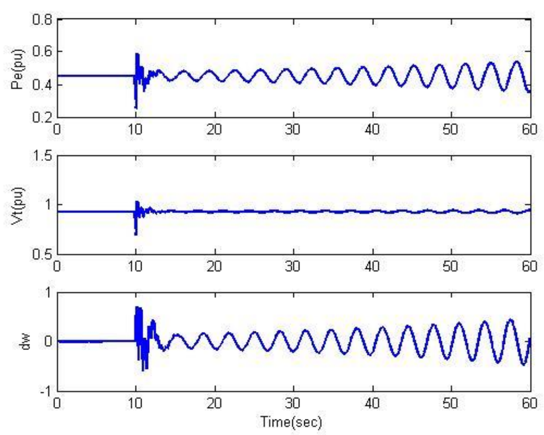

Fig. 8. Voltage profile of bus 9, power flow of infinite bus, speed deviation of Unit 1 of the system on Fig. 2 without

ECS control operation (Setting of Power Output from Unit 1 P_t= 0.5 pu and Q_{smax}=0.05pu MVar).

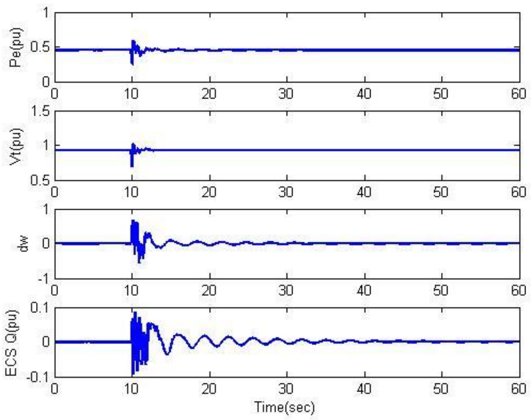

Fig. 9. Voltage profile of bus 9, power flow of infinite bus, speed deviation of Unit 1 of the system on Fig. 2 with ECS control operation (Setting of Power Output from Unit 1 = 0.5 pu and Qsmax=0.05puMVar).

Fig. 9 and 10 show the control performance by the reactive power regulation on fuzzy logic switching controlled ECS. After applying the reactive power regulation, damping of the oscillations of power flow, voltage and speed deviation signal are highly improved. During the operation even when the input power of Unit 1 P_t is increased or decreased, optimum fuzzy logic parameters A_s and D_r are calculated by the ANN block of the study system automatically for any input setting of Unit1. Therefore, the system stays in the stable region even at higher power input values. This can be seen on Fig. 9 and 10.

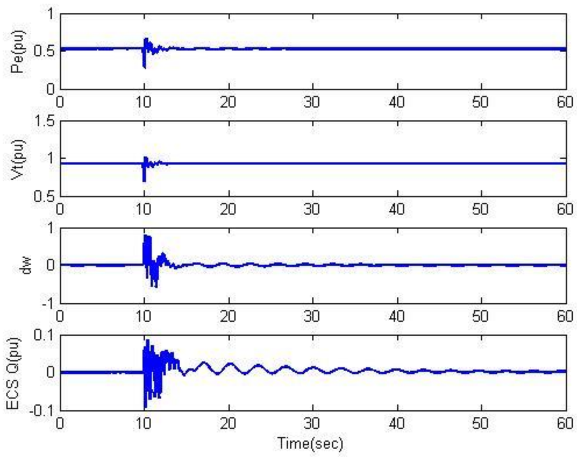

Fig. 10. Voltage profile of bus 9, power flow of infinite bus, speed deviation of Unit 1 of the system on Fig. 2 with ECS control operation (Setting of Power Output from Unit 1 = 0.6 pu and Qsmax=0.05puMVar).

Based on a quadric performance index previously developed, optimum fuzzy logic parameters are obtained experimentally. Afterwards, ANN is trained up to these optimum parameters. Below, some optimum parameters for each possible Unit 1 power input values can be seen on the table 1.

Table 1. Fuzzy logic parameters for some output settings of Unit 1 (ECS is connected to Bus 9)

P_t (pu)	*As*	*Dr*
0.05	105	0.45
0.10	133	0.45
0.15	134	0.45
0.20	202	0.45
0.25	276	0.45
0.30	396	0.45
0.35	390	0.45
0.40	400	0.50
0.45	391	0.70
0.50	394	0.75
0.55	382	0.75
0.60	267	0.75
0.65	195	0.75
0.70	109	0.80

Table 2 shows the critical power output from Unit 1 for the three-phase to ground fault. The critical output power is 0.32 pu without ECS use.The stable region is enlarged by the reactive power regulation at one of the buses. When Bus 11 is selected as the location of ECS, the critical power output of Unit 1 reaches to 0.83 pu. Here it must be noted that the limit of the reactive power regulation is specified as 0.05 pu.

Table 2. Critical power output of Unit 1

Location of ECS	Critical Power Output from Unit 1
None	0.32 pu
Bus 9	0.60 pu
Bus 10	0.82 pu
Bus 11	0.83 pu
Bus 12	0.82 pu

5.1. Eigenvalue Based Stability Evaluation of the Study System

Fig. 11 shows the overview of the simulator PCs used in this study. While one of the PCs is the 4-machine infinity bus model, other one is the eigenvalue stability evaluation monitor. Two PCs are connected to each other through the DSP boards. The Real Time Workshop is also required for its real time operation on the DSP boards. For the dynamic stability evaluation, the real power flow signal on the trunk line to the infinite bus shown in Fig. 1 and the voltage variations of the infinite bus are sampled at every 0.5 s as the output and the input signals for the target system. Therefore, only the oscillation modes under 1 Hz are preserved in the identified low order model including the dominant low frequency global mode of oscillation. The frequency of the dominant eigenvalue is around 0.3 Hz for the low frequency oscillation mode.

The real part α of the eigenvalue is utilized as stability evaluation factor. The system is stable when α has negative values. Fig. 12 shows the eigenvalue based stability graphics of the target system in the case of unit 1 power input is 0.6 pu. Stability of the system measured with and without the ECS is connected to bus 9 separately. As can be seen on the

Fig. 11 and 12, stability margin is enlarged when the ECS is connected to the system.

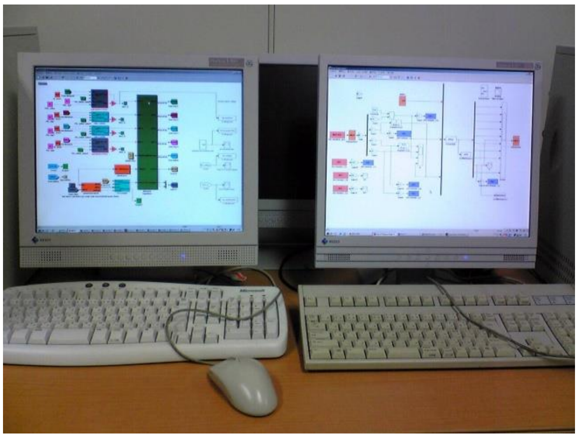

Fig. 11. Overview of Simulator Desk in the Laboratory

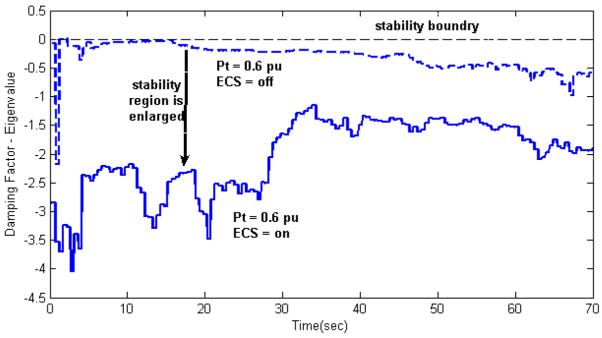

Fig. 12. Eigenvalue based stability evaluation of the study system. (Dashed and solid lines show the cases of ECS is off and on respectively)

6. Conclusion

Reactive power regulation has been presented for the energy capacitor system (ECS). Through the simulation studies, the efficiency of the proposed stability control scheme has been clarified. The stable region is definitely enlarged and voltage profile is straightened by the application of the reactive power regulation on the ECS. In addition, through the non-linear simulations, the efficiency of the proposed eigenvalue based dynamic stability evaluation scheme has been demonstrated. Further studies are ongoing for the development of eigenvalue based dynamic control scheme for the study system.

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