Real Time Transient Stability Simulator of Large Scale Multi-Machine Power System in Matlab/Simulink Environment

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Abstract--A real time power system simulator has been developed in the Matlab/Simulink environment for testing the prototypes of advanced power system stabilizers and also of the other controllers of new types of energy storage devices such as the Energy Capacitor System composed of electrical double-layer capacitors. The real time transient stability simulations are available on the proposed simulator for multi-machine power systems. The model of the study multi-machine system has been developed in the Matlab/Simulink environment. The efficiency of the developed real time power system simulator has been demonstrated through the real time simulations to investigate the stabilization control performance on the Energy Capacitor System for a study multi-machine power system.

Keywords: Real time power system simulator, transient stability analysis, multi-machine power system, stabilization control, energy storage device, Energy Capacitor System.

I. INTRODUCTION

A real time power system simulator[1] has been developed in the Matlab/Simulink environment for testing the prototypes of advanced power system stabilizers and also of the other controllers of new types of energy storage devices such as the Energy Capacitor System composed of electrical double-layer capacitors.[8-10] The real time transient stability simulations are available on the proposed simulator for multi-machine power systems.

The model of the study multi-machine system has been developed in the Matlab/Simulink environment. The initial condition of the study system is specified through the power flow calculation described in the Matlab language. Through the numerical integration, additional non-linear equations should be solved to determine the *d-q* components of both the terminal voltages and the currents for generators and other control devices including energy storage devices. The developed Simulink block includes these equations as a *S*-function block.

Typical excitation control systems and also typical speed governing control systems are ready to be utilized as basic components of the developed simulator. Users can easily modify or replace the generating units to alternative ones. The graphical interfaces are also prepared. Therefore, users can easily examine the simulation results on the display in real time.

To demonstrate the efficiency of the developed simulator, the stabilization control performance of a new type of energy storage device have been experimentally evaluated for a longitudinal four-machine study system on the developed real time power system simulator.

II. BASIC CONFIGURATION OF REAL TIME SIMULATOR

A typical set up of the proposed real time simulator is shown in Fig. 1 to investigate the stabilization control performance on the energy storage device. The proposed real time simulator is set up by a personal computer with a DSP board having AD and DA conversion interfaces.[1]

An external control device such as the Energy Capacitor System, evaluated on the real time simulator, is also set up in the same configuration by using another personal computer as shown in Fig. 1. In this case, the real power flow signal *P* and the *D-Q* components of the bus voltage, at the location of the external control device, are the signals sent to the external control device through AD and DA conversion interfaces. The *D-Q* components of the injected current from the control device are sent from the external control device to the power system simulator.

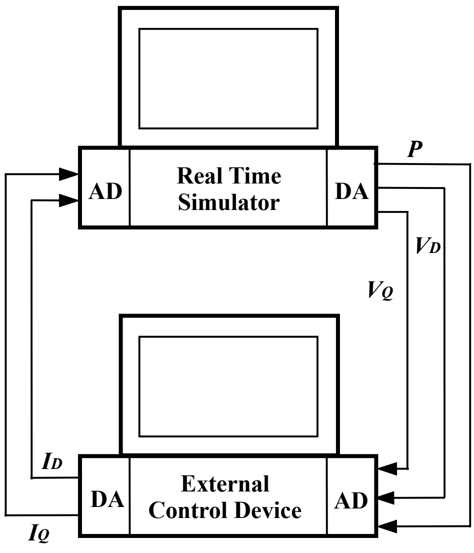

Fig. 1. Basic configuration of proposed real time power system simulator

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III. MODELING OF ENERGY CAPACITOR SYSTEM

In this paper, an innovative stabilization control scheme has been tested on the proposed real time simulator. A new energy storage device, the electrical double-layer Energy Capacitor System (ECS) has been considered as the external control device[2, 3].

Switching control of braking resistors is one of the most effective means to enhance the overall stability of electric power system. In the case of the braking resistors, only the absorption of active power is available whenever the braking resistors are switched in; however, the injection of active power is impossible. On the other hand, both the absorption and the injection of the active power and/or the reactive power are possible on the Energy Capacitor System (ECS) composed of electrical double-layer capacitors [4-6] through the PWM type switching control for the AC/DC conversion unit. This paper presents a coordinated scheme for the active and the reactive power regulation on a small sized ECS. The ECS is a newly developed high power energy storage device. Its response is quite fast compared with that of the conventional lead acid batteries.

The basic configuration of the mathematical model for ECS is given in Fig. 2.[7]

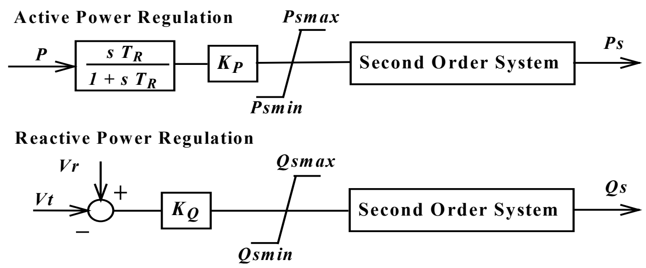


Fig. 2. Basic configuration of mathematical model for ECS

On the ECS, the injected current is regulated at the AC side by using the PWM type inverter to satisfy the required active power absorption or injection and/or 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. 2, the term *P* gives the measured active power at the location of the ECS, and the terms *Vt* and *Vr* denote the voltage measured at the location of the ECS and its reference, respectively. The output *Ps* and *Qs* gives the active power and the reactive power from the ECS to the transmission network. The terms *Psmax* and *Psmin* denote the maximum and minimum active power output from ECS, respectively. In addition, 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.

$$
\begin{aligned}
Ps\,min &= -\,Ps\,max \\
Qs\,min &= -\,Qs\,max
\end{aligned}
\qquad (1)
$$

When considering the coordinated control on a single ECS, the maximum active power *Psmax* and the maximum reactive power *Qsmax* are restricted by the *Wmax* as follows:

$$\sqrt{Ps\,max^2 + Qs\,max^2} \le Ws\,max \qquad (2)$$

In addition, when considering the active power control and the reactive power control separately on different ECSs, both the *Psmax* and the *Qsmax* are equal to *Wsmax*.

To solve the network equation, the injected currents I_D and I_Q from the ECS should be determined as follows:

$$\begin{bmatrix} I_D \\ I_Q \end{bmatrix} = \frac{1}{V_D^2 + V_Q^2} \begin{bmatrix} V_D & V_Q \\ V_Q & -V_D \end{bmatrix} \begin{bmatrix} P_S \\ Q_S \end{bmatrix} \qquad (3)$$

Here, it must be noted that I_D gives the D-axis component and I_Q gives the Q-axis component of the injected current in the common reference frame.

The solution of the network equation is obtained at each interval of simulations by using these currents together with the other essential quantities such as the induced voltages and the phase angles of the generators.

IV. CONFIGURATION OF STUDY 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 shown in Fig. 3.

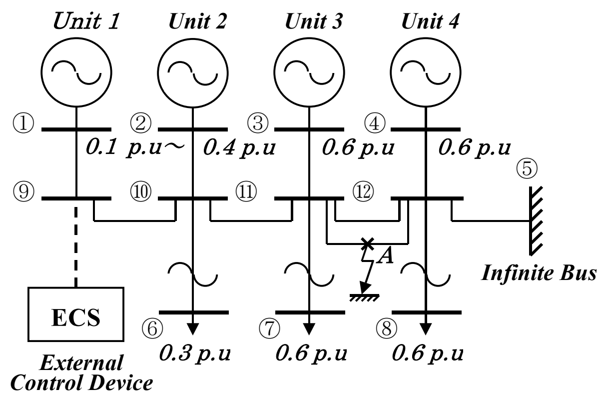
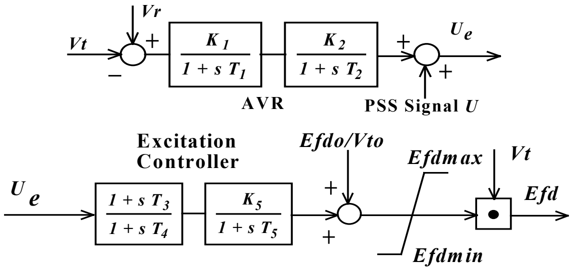


Fig. 3. Longitudinal four-machine infinite bus system (ECS is set on a selected bus from Bus 9 to 10.)

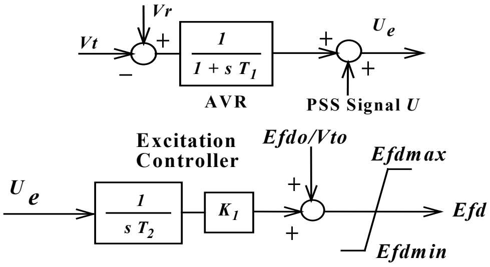
Each unit is a thermal unit, and Units 1 and 4 have a self-excited excitation control system, and Units 2 and 3 have a separately excited excitation control system. Each unit has a full set of governor-turbine system: governor, steam valve servo-system, high-pressure turbine, intermediate-pressure turbine, and low-pressure turbine. The configurations of the excitation systems are shown in Fig. 4 and in Fig. 5. The configuration of the conventional power system stabilizer (PSS) is illustrated in Fig. 6. The conventional speed governor is shown in Fig. 7. The detailed block diagram of the turbine system is also illustrated including the high-pressure, intermediate-pressure, and low-pressure turbines in Fig. 8.

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



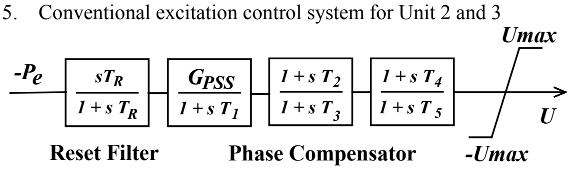
$K_1 = 1.0$, $T_1 = 0.013$ s, $K_2 = 10.0$, $T_2 = 0.013$ s,
$T_3 = 3.0$ s, $T_4 = 10.0$ s, $K_5 = 6.48$, $T_5 = 0.2$ s,
Efdmax = 7.6, *Efdmin* = -5.2

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



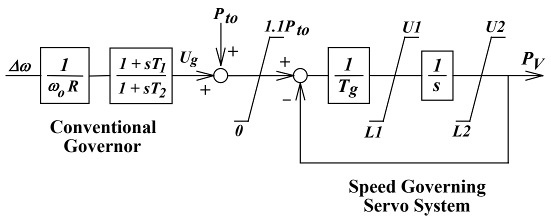
$K_1 = 1.0$, $T_1 = 0.01$ s, $T_2 = 1.56$ s
Efdmax = 7.6, *Efdmin* = -5.2

Fig. 5. Conventional excitation control system for Unit 2 and 3



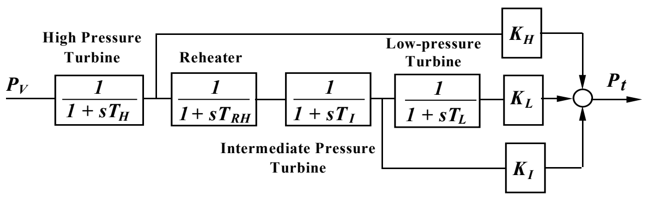
$T_R = 4.0$ s, *Gpss* =10.0, $T_1 = 0..025$ s, *Umax* = 1.0 pu

Fig. 6. Conventional power system stabilizer (PSS)



Tg = 0.2 s, $U_1 = 0.2$, $L_1 = -1000$, $U_2 = 1.5$, $L_2 = 0.0$

Fig. 7. Conventional speed governing system



$T_H = 0.44$ s, $T_{RH} = 10.0$ s, $T_I = 0.08$ s, $T_L = 0.58$, $K_H = 0.31$,
$K_I = 0.24$, $K_L = 0.45$

Fig. 8. Detailed turbine system including HP, IP, and LP turbines

In the real time transient stability simulations, a three-phase to ground fault is considered as a disturbance at the location *A* in the study system. The faulted line is isolated from the system after 0.07s. To investigate the critical power flow to the infinite bus, the active power output is increased on Unit 1 from 0.1pu to its critical power output. However, the setting of the active power output from the other units is fixed to the values shown in Fig. 3.

TABLE I
GENERATOR CONSTANTS (1000MVA BASE)

Unit No.	*M* *[sec]*	*Xd* *[pu]*	*Xd'* *[pu]*	*Xq* *[pu]*	*X'q* *[pu]*	*Td'* *[sec]*	*Tq'* *[sec]*
1	8.05	1.860	0.440	1.350	0.332	0.733	0.08730
2	7.00	1.490	0.252	0.822	0.243	1.500	0.12700
3	6.00	1.485	0.509	1.420	0.463	1.550	0.26752
4	8.05	1.860	0.440	1.350	0.332	0.733	0.08730

TABLE II
LINE CONSTANTS (1000MVA BASE)

Line No.	Bus-Bus	*R[pu]*	*X[pu]*	*S[pu]*
1	1-9	0.02700	0.1304	0.0
2	2-10	0.07000	0.1701	0.0
3	3-11	0.04400	0.1718	0.0
4	4-12	0.02700	0.1288	0.0
5	10-6	0.02770	0.2238	0.0
6	11-7	0.04000	0.1718	0.0
7	12-8	0.06130	0.2535	0.0
8	9-10	0.01101	0.0829	0.0246
9	10-11	0.01101	0.0829	0.0246
10	11-12	0.01468	0.1105	0.0328
11	12-5	0.12480	0.9085	0.1640

The generator parameters are shown in TABLE I, where the term *M* gives the inertia constant. The damping coefficient of each generator is fixed to 0.01. The line parameters are also shown in TABLE II, where the terms *R, X*, and *S* denote the line resistance, the line reactance, and the line susceptance in per unit, respectively.

The real time nonlinear simulations have been performed on the proposed power system simulator together with the personal computer(PC) based external control device, i.e., the Energy Capacitor System(ECS) in the Matlab/Simulink environment. The Simulink main block is illustrated in Fig. 9.

The essential quantities, from Unit 1 to 4, from the infinite bus, and from the PC based ECS module, are passed to the network equation block to determine the bus voltages and the line currents in the study system. To specify the initial condition, i.e., to solve the power flow equation, and also to solve the network equations at each time interval during the real time simulation, computer programs have been developed, by using the Matlab language and the C language, respectively.

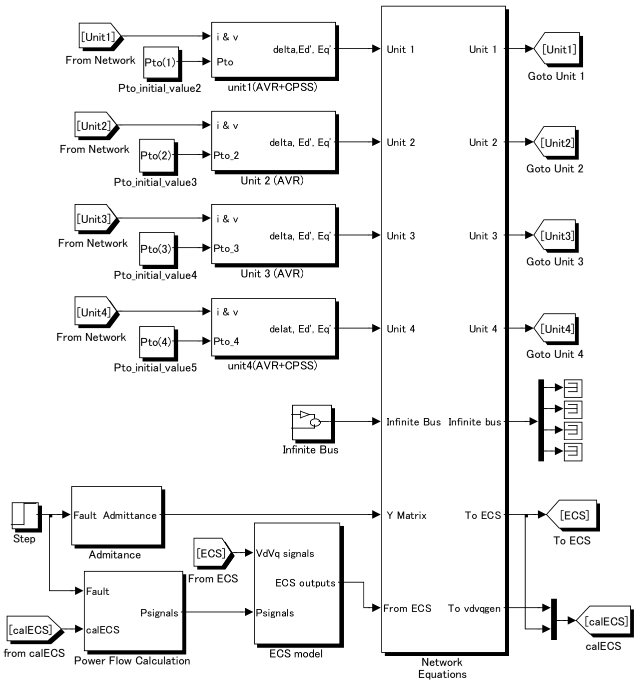


Fig. 9. Simulink main block for study system

V. REAL TIME SIMULATION RESULTS

To demonstrate the efficiency of the proposed real time simulator, the stabilization performance has been investigated for the coordinated active and reactive power control on the Energy Capacitor System. Namely, nonlinear real time simulations have been performed on the developed power system simulator.

A. Stabilization by Reactive Power Regulation

Here, the stabilization performance has been investigated considering only the reactive power regulation on the ECS. TABLE III shows the critical power output from Unit 1 for the three-phase to ground fault at the location *A* in the study system. The critical power output is 0.37pu to 0.42pu following the setting of PSS without the ECS control, where the conventional PSS are installed on Unit 1 and/or Unit 4.

As show in the table, the stable region is enlarged by the reactive power regulation on the ECS located at one of the buses from Bus 9 to 12. When Bus 12 is selected as the location of ECS, the critical power output of Unit 1 reaches to 0.85pu, where Unit 1 and Unit 4 are equipped with the PSS. Here, it must be noted that the limit of the reactive power regulation is specified as follows: *Wsmax* = *Qsmax* = 0.05pu.

B. Stabilization by Real Power Regulation

The stabilization performance has also been investigated for the active power regulation on the ECS. The limit of the active power regulation is given by *Wsmax* = *Psmax* = 0.05pu. TABLE IV indicates the critical power output from Unit 1, where the location of the ECS is selected at one of the buses from 9 to 12. The critical power output reaches to 0.91pu as shown in the table at location of Bus 11, where the conventional PSS is installed on both Unit 1 and Unit 4.

TABLE IV
CRITICAL POWER OUTPUT OF UNIT 1
REAL POWER CONTROL ON ECS

Location of ECS	Critical Power Output PSS on Unit 1	Critical Power Output PSS on Unit 4	Critical Power Output PSSs on Unit 1 & 4
none	0.37 pu	0.41 pu	0.42 pu
Bus 9	0.65pu	0.60 pu	0.60 pu
Bus 10	0.77 pu	0.75 pu	0.74 pu
Bus 11	0.85 pu	0.83 pu	0.91 pu
Bus 12	0.87 pu	0.86 pu	0.88 pu

Psmax = 0.05puMW

C. Coordination of Active and Reactive Power Control

In this case, the coordination of active and reactive power regulation is considered on the ECS. The limit of total regulation is *Wsmax*, and *Wsmax* is set to 0.05pu, then the limits for the active power regulation and the limit of the reactive power regulation should satisfy the relation given by eqn.2.

The critical power output from Unit 1 is shown in TABLE V. The critical power output reaches to 0.92pu at the location of Bus 11, where conventional PSS is installed on both Unit 1 and Unit 4.

TABLE III
CRITICAL POWER OUTPUT OF UNIT 1
REACTIVE POWER CONTROL ON ECS

Location of ECS	Critical Power Output PSS on Unit 1	Critical Power Output PSS on Unit 4	Critical Power Output PSSs on Unit 1 & 4
none	0.37 pu	0.41 pu	0.42 pu
Bus 9	0.68 pu	0.52 pu	0.68 pu
Bus 10	0.67 pu	0.61 pu	0.67 pu
Bus 11	0.75 pu	0.78 pu	0.75 pu
Bus 12	0.76 pu	0.79 pu	0.85 pu

Qsmax = 0.05puMVar

TABLE V
CRITICAL POWER OUTPUT OF UNIT 1
REAL AND REACTIVE POWER CONTROL ON ECS

Location of ECS	Critical Power Output PSS on Unit 1	Critical Power Output PSS on Unit 4	Critical Power Output PSSs on Unit 1 & 4
none	0.37 pu	0.41 pu	0.42 pu
Bus 9	0.78 pu	0.61 pu	0.82 pu
Bus 10	0.83 pu	0.76 pu	0.85 pu
Bus 11	0.88 pu	0.83 pu	0.92 pu
Bus 12	0.89 pu	0.87 pu	0.91 pu

Wsmax = 0.05puMW

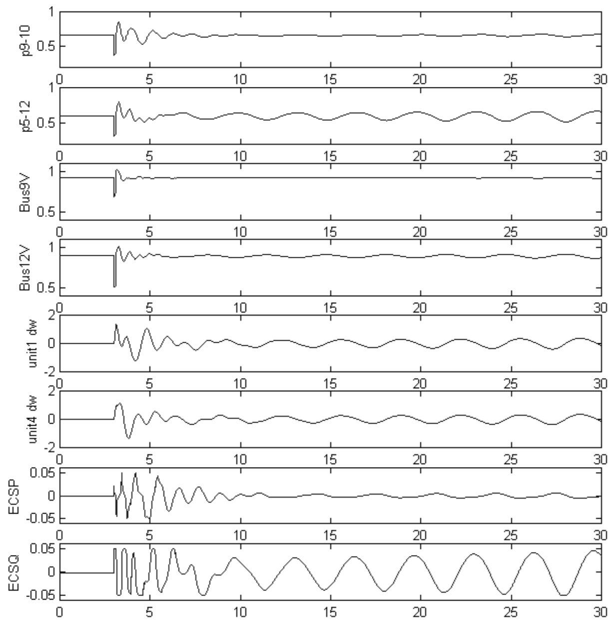


Fig. 10. Stabilization control performance by active and reactive Power regulation on ECS at Bus 9, where output setting from Unit 1 is 0.70pu (Unit 4 with PSS)

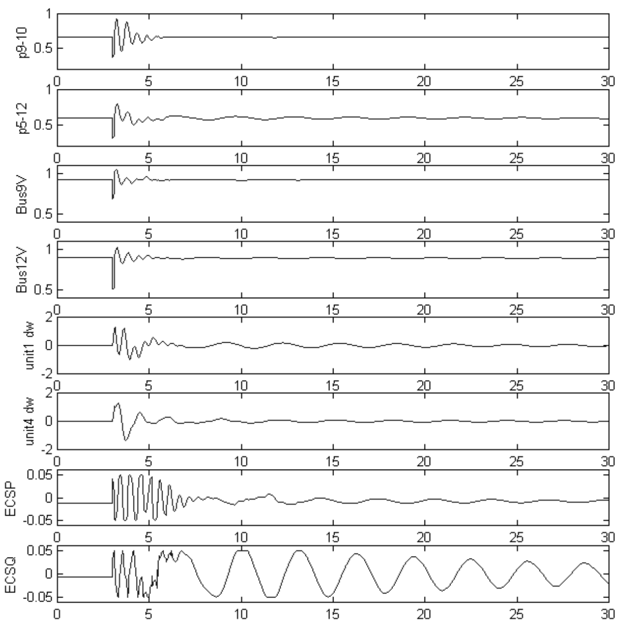


Fig. 11. Stabilization control performance by active and reactive Power regulation on ECS at Bus 9, where output setting from Unit 1 is 0.70pu (Unit 1 and Unit 4 with PSS)

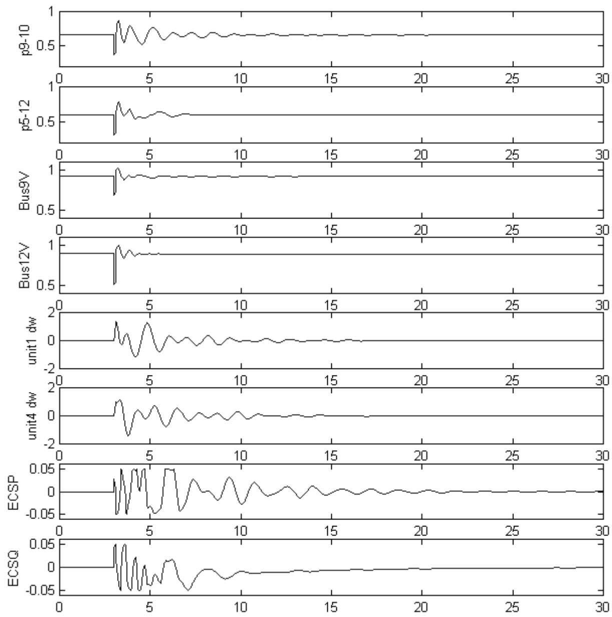


Fig. 12. Stabilization control performance by active and reactive Power regulation on ECS at Bus 12, where output setting from Unit 1 is 0.70pu (Unit 4 with PSS)

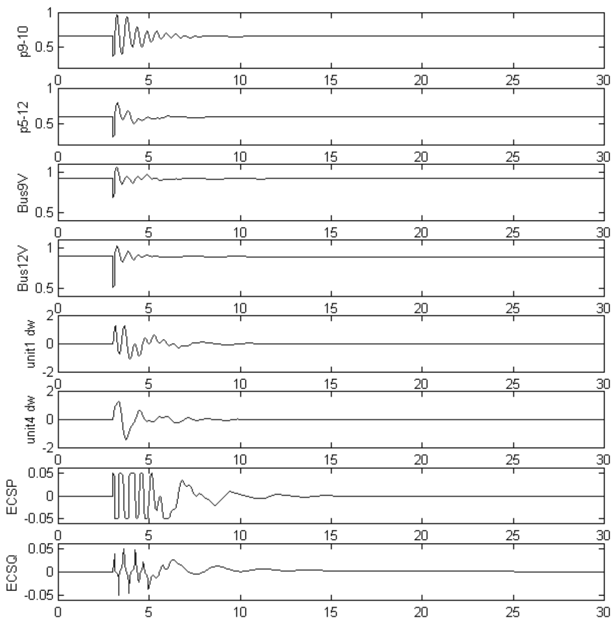


Fig. 13. Stabilization control performance by active and reactive Power regulation on ECS at Bus 12, where output setting from Unit 1 is 0.70pu (Unit 1 and Unit 4 with PSS)

Typical simulation results are shown in Fig. 10 to Fig. 13. In these figures, the real power flow from Bus 9 to Bus 10, the real power flow from Bus 12 to Bus 5, the voltage at Bus 9, the voltage at Bus 12, the speed deviation of Unit 1, the speed deviation of Unit 4, the active power from ECS, and the reactive power from ECS are illustrated from the top to the bottom.

In Figs. 10 and 11, the location of the ECS is Bus 9. In Figs. 12 and 13, the location of the ECS is Bus 12. In addition, the output setting of Unit 1 is 0.70pu in all the cases shown in these figures. The better damping is achieved at the location of Bus 12 as clearly indicated in these figures.

As shown in the simulation results, the proposed coordination has brought a significant effect to widen the stable region. In this study, the maximum power level is *Wsmax*, and *Wsmax* is set to 0.05pu. Then, the rated power of the ECS is 50MVA in the actual scale. The required capacity of the ECS is 2 to 3kWh based on the ratio between the power and capacity for the experimental units of ECS. The required capacity is relatively small to have significant control performance in the study four-machine infinite bus system. That is a quite encouraging result for the further studies on the Energy Capacitor System composed of the electrically double layer capacitors.

In addition, the coordination with the conventional PSS is also successfully achieved as clearly illustrated in these figures. In the case shown in Fig. 10, the study system becomes unstable. However, by adding additional PSS on Unit 1, the study system can be stabilized as shown in Fig. 11.

VI. Conclusion

A coordinated active and reactive power regulation has been presented for the energy capacitor system (ECS). Through the simulation studies on the developed real time power system simulator, the efficiency of the coordination has been demonstrated. The stable region is definitely enlarged by the application of the proposed regulation. Further studies are now ongoing for a ten-machine infinite bus West Japan Standard Model System on the proposed real time power system simulator.

VII. References

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VIII. Biographies

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