

Multi-Agent Based Operation and Control of Electric Power Systems

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Intelligent Systems Application to Power Systems

- 1. Expert System (Rule Base System)**
- 2. Fuzzy Inference & Fuzzy Reasoning**
- 3. Artificial Neural Network**
- 4. Heuristic Approach (Genetic Algorithm, Tabu Search, SA)**
- 5. Multi-Agent System (Intelligent Agent)**

International Conferences

ESAP(Expert System Application to Power Systems)

ANNPS(Application of Neural Network to Power Systems)

Now, ISAP(Intelligent Systems Application to Power Systems)

Research Topics

1. Real Time Wide Area Stability Monitoring System
2. Real Time Stability Margin Control of Electric Power Systems
3. Operation, Control and Management of Dispersed Power Sources including Renewable Energy Power Sources and Energy Storage Device
4. Artificial Neural Network Based Identification of Fault Location
5. Application of Energy Capacitor System to Power System Control
6. Multi-Agent Based Wide Area Operation, Control and Management of Electric Power Systems
7. Multi-Agent Based Hierarchical Stabilization Control of Power Systems
8. Multi-Agent Based AGC for Isolated Power Systems including Renewable Energy Power Sources and Energy Storage Device
9. Rule Based Voltage and Power Flow Management
10. Remote Tuning of Power System Controllers through Computer Network
11. Artificial Neural Network Based Estimation of Power Demand and Electricity Cost
12. Artificial Neural Network Based Diagnosis of Induction Machines
13. Development of Real Time PV System Simulator and MPPT Control under Partially Shaded Condition

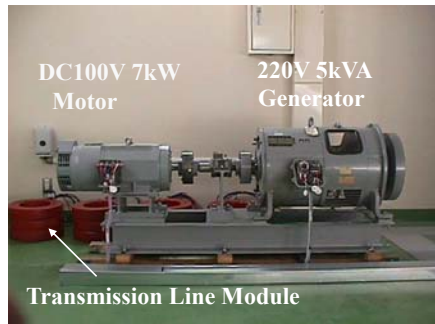
Facilities for Experimental Studies

1. **5kVA Laboratory One Machine Power System:**
5kVA Synchronous Generator
7kW DC Motor
Transmission Line Modules
Load Modules
2. **70Wh New Energy Storage Device(ECS):**
Electrical Double Layer Capacitors
Maximum Charging/Discharging Power: 7kW
3. **AC/DC Conversion Unit for Real Power Control**
4. **AC/DC Conversion Unit:**
Active/Reactive Power Control
5. **Wind Turbine Generators: 600W**
6. **PV System: 400W**
7. **VPN: Virtual Private Network**

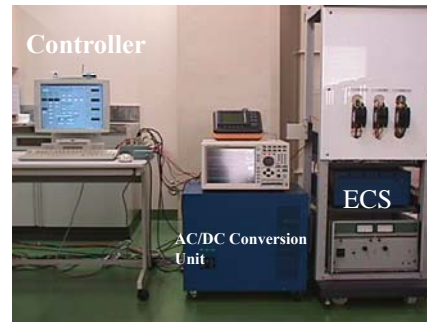
**Analog Power System Simulator at the Research
Laboratory of Kyushu Electric Power Co. for Joint
Research Projects: 10 to 14 weeks a year**

Experimental Facilities (1)

MG Set



ECS and AC/DC Conversion Unit



**ECS: Energy Capacitor System
Electrical Double-Layer Capacitors**

We have several AC/DC conversion units for PV and WTG system and also for different control purposes.

Experimental Facilities (2)



**Small Sized Wind Turbine
Generating Units**



**Photo-Voltaic Generating
Units**

Analog Power System Simulator at the Research Laboratory of Kyushu Electric Power Co. (10 to 15 weeks per year)

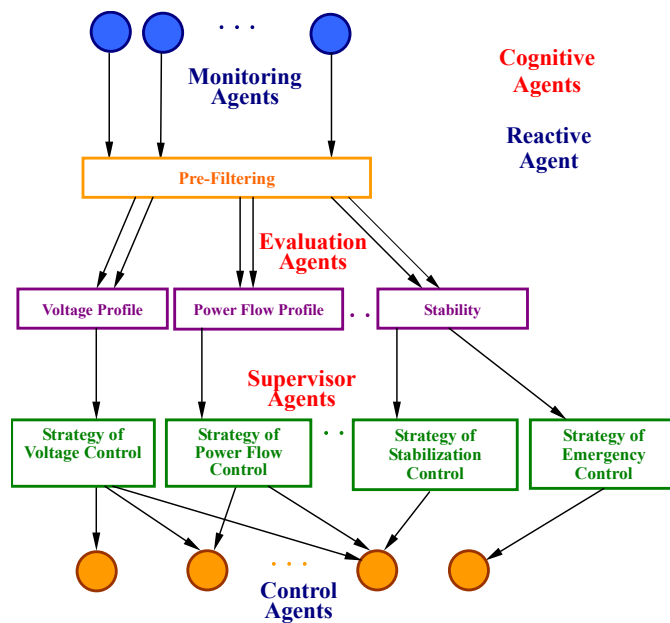


Preparation of Simulator Test

Overview of Analog Power System Simulator

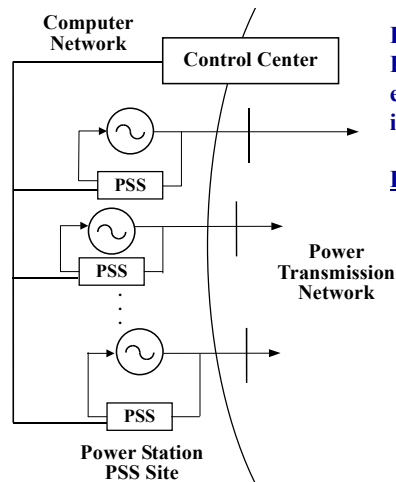


Multi-Agent Based Control System for Electric Power Systems



Intelligent Agent Based Remote Tuning of Power System Stabilizer through Computer Network

Configuration of Intelligent Agent Based Remote Tuning System



For the remote tuning of each PSS, the PSS standard tests should be activated and evaluated regularly at the PSS sites by the intelligent agent from the control center.

Evaluation of Control Performance:

$$J = \sum \Delta T^2 \Delta P_e^2$$

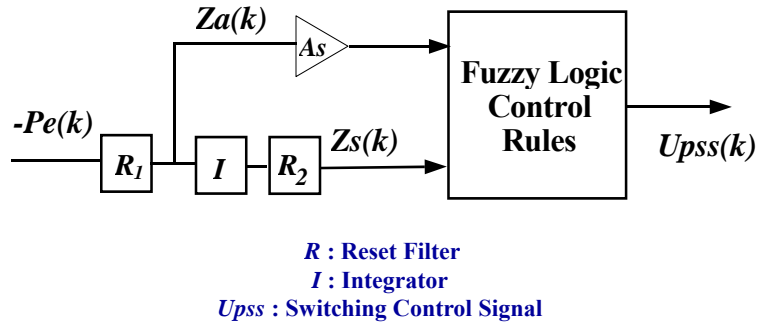
ΔP_e : generator real power deviation

ΔT : sampling interval of the PSS.

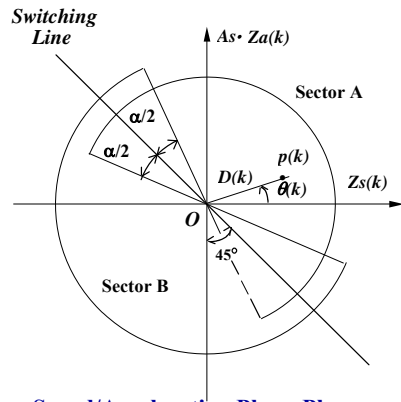
Here, it must be noted that the proposed remote tuning system utilizes the virtual private network(VPN) among different network groups and also for the security reasons.

Basic Configuration of Fuzzy Logic PSS

Pre-Filtering for Acceleration and Speed Deviation Signals



Membership Functions and Control Signal

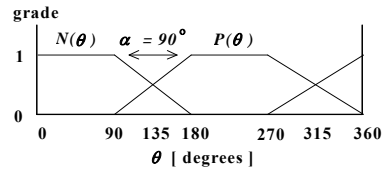


Speed/Acceleration Phase Plane

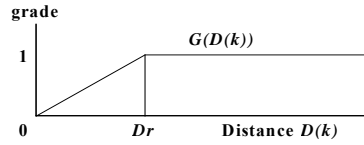
$$D(k) = \sqrt{Z_s(k)^2 + (A_s \cdot Z_a(k))^2}$$

$$\theta(k) = \tan^{-1}(A_s \cdot Z_a(k) / Z_s(k))$$

Angle Membership Functions



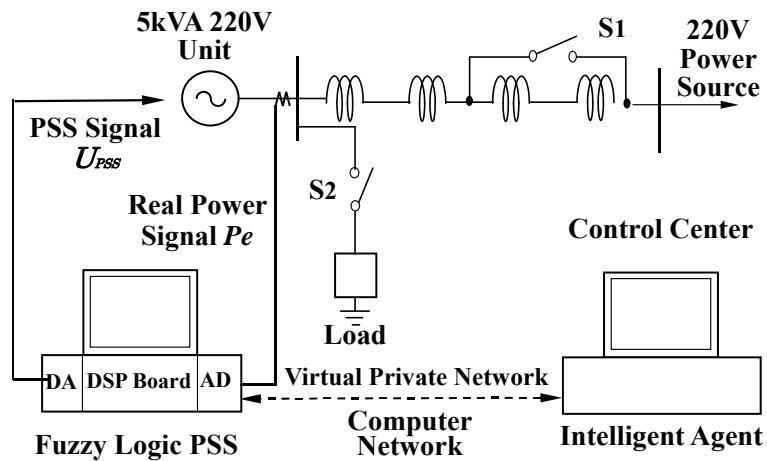
Radius Membership Function



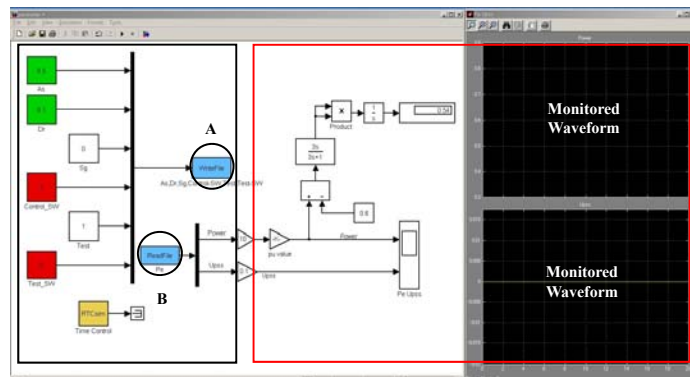
$$Upss(k) = \frac{N(\theta(k)) - P(\theta(k))}{N(\theta(k)) + P(\theta(k))} \cdot G(D(k)) \cdot U_{max}$$

$$= [1 - 2P(\theta(k))] \cdot G(D(k)) \cdot U_{max}$$

Configuration of Laboratory System



Computer Display on PC Based Intelligent Agent at Control Center



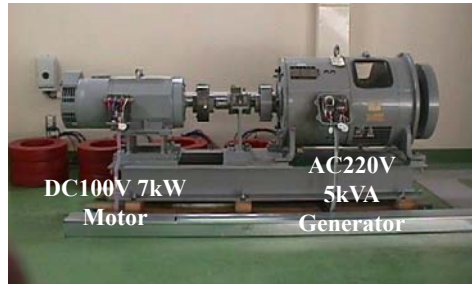
Tuning & Testing Block

Evaluation Block

A: Block to send commands from control center to PSS site

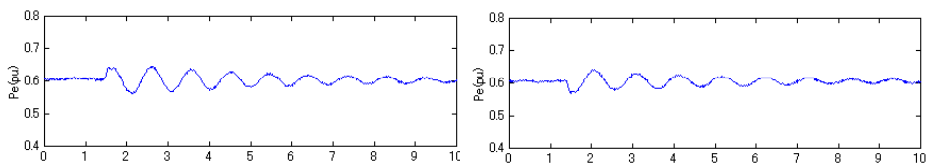
B: Block to receive monitored results from PSS site

Overview of Laboratory System

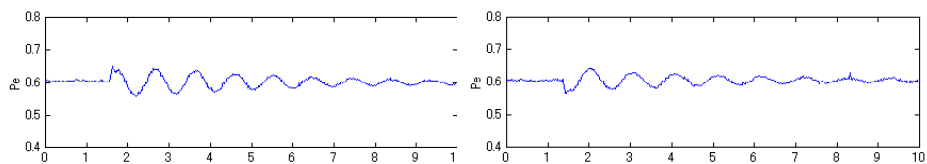


Experimental Results –I (Remote Monitoring)

(a) Monitored at Generator Site



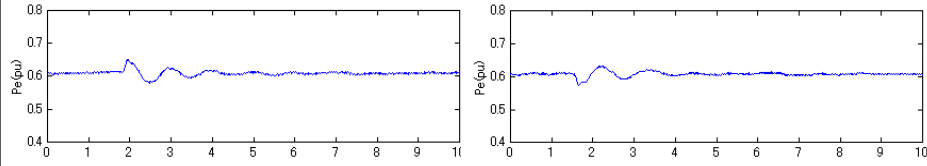
(b) Monitored at Control Center



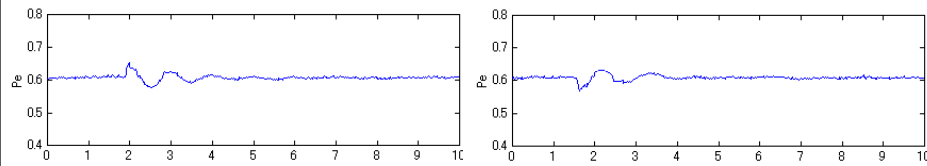
The power oscillations without PSS following the step increase and decrease of the AVR reference voltage, are illustrated, respectively.

Experimental Results –II (Initial Parameter Setting)

(a) Monitored at Generator Site



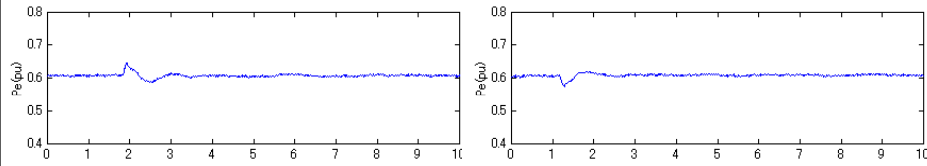
(b) Monitored at Control Center



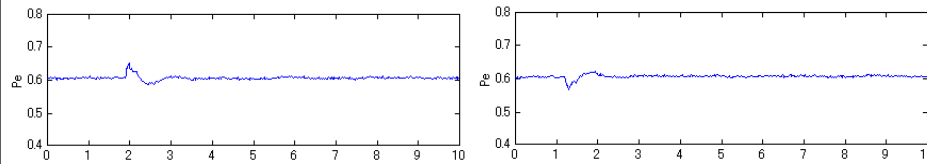
with FLPSS ($A_s = 0.5$ and $D_r = 0.1$)

Experimental Results –III (Final Parameter Setting)

(a) Monitored at Generator Site



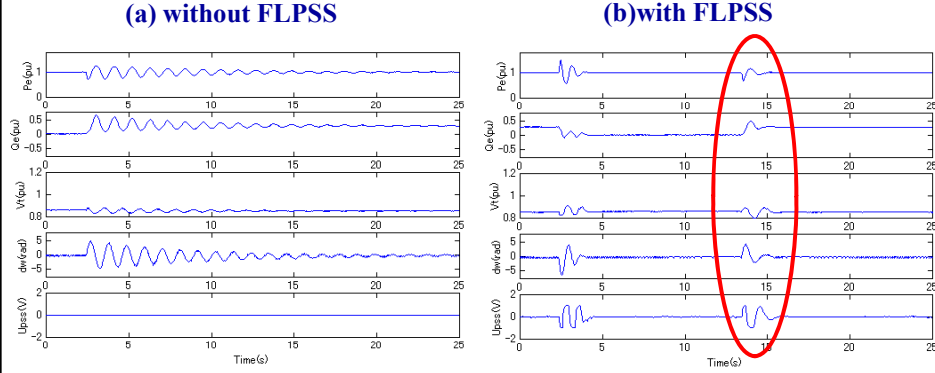
(b) Monitored at Control Center



with FLPSS ($A_s = 1.3$ and $D_r = 0.1$)

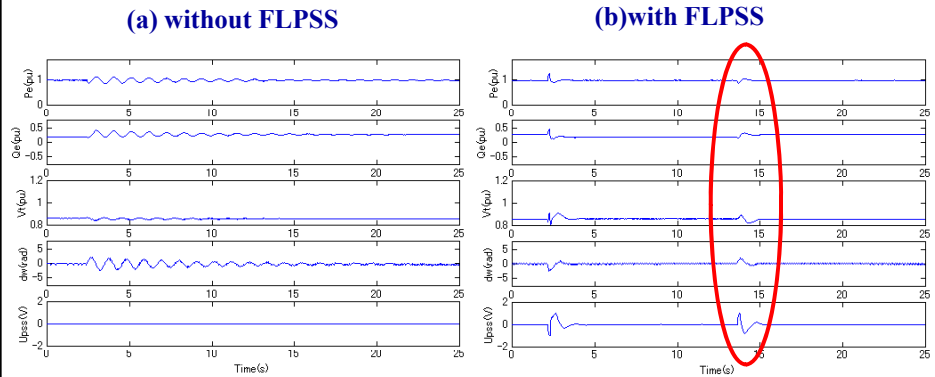
From comparisons between the initial setting and the final setting of the FLPSS parameters, the PSS performance is significantly improved by the modification of the FLPSS parameters. Regular tuning of the PSS parameters definitely provides more reliable generator operation.

Experimental Results –IV (Large Disturbance Test by $S1$)



After finishing the remote tuning of the PSS parameters through the standard tests, disturbance tests have been performed on the switching disturbances for the switches $S1$ and $S2$.

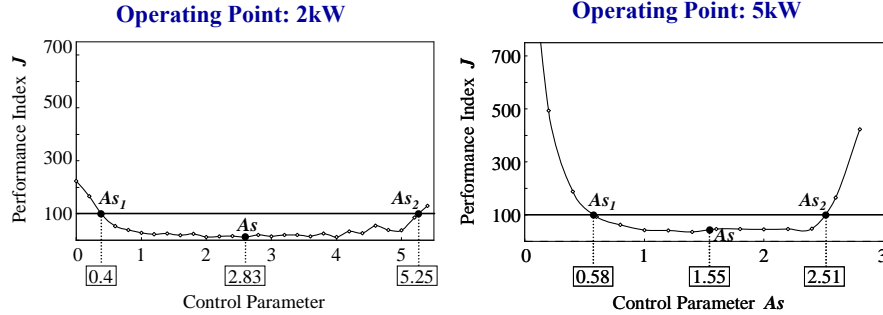
Experimental Results –V (Large Disturbance Test by $S2$)



The PSS standard tests and the following tuning of the PSS parameters have been successfully performed at the control center apart from the generator site. Namely, mobile agents have been utilized for the proposed remote tuning system through the computer network.

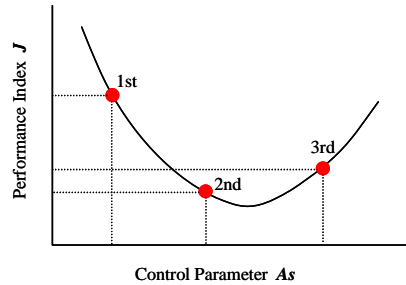
The mobile agent based automatic remote tuning of PSS parameters is readily available at the control center to ensure more reliable generator operation.

Experimental Results: Detailed Tuning of PSS Parameters at Site



1. The performance index J has a quite wide bottom within a certain range of the parameter As . Therefore, the robustness of the fuzzy logic PSS is clearly recognized from the results.
2. At the middle points of the bottom, the parameter As are found as 2.83 and 1.55 for the output setting of 2kW and 5kW, respectively. These two values might be considered as the optimal setting of As at those two different generator operating points.

Experimental Results: Intelligent Agent Based Remote Tuning



For the optimization of the parameter As , the standard tests have been activated by the intelligent agent from the control center.

To determine the optimal value for the parameter As , the quadratic approximation has been utilized as shown in the figure.

(a) Generator operating point: 2kW

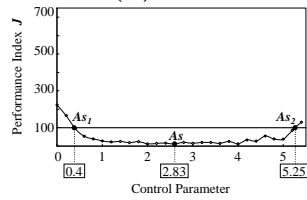
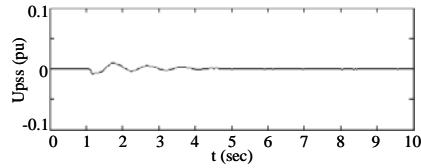
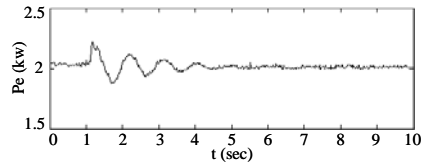
No. of Standard Test	As	Index J (x 100)
1	0.3	151
2	0.35	137.2
3	0.45	105.9
4	0.65	68.3
5	1.05	38.6
6	1.85	20.1
7	3.45	23.9
Optimal Setting	2.54	19.7

(b) Generator operating point: 5 kW

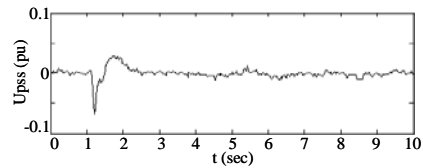
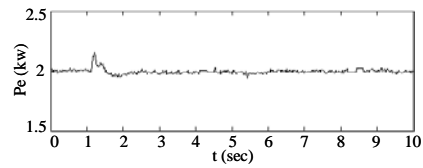
No. of Standard Test	As	Index J (x100)
1	0.3	315.6
2	0.35	276.1
3	0.45	172.4
4	0.65	110.7
5	1.05	31
6	1.85	26.2
7	3.45	850.5
Optimal Setting	1.46	25.3

Control Performance at Generator Operating Point of 2kW

Initial Setting of As : 0.30



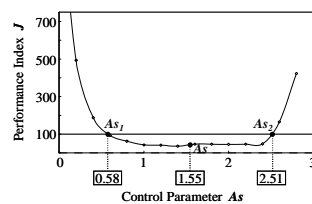
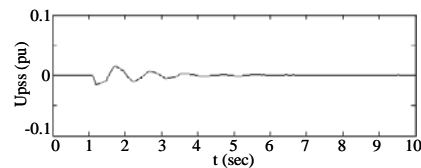
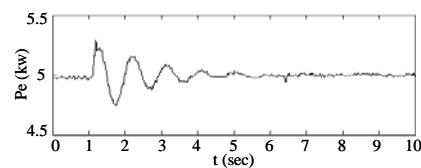
Optimal Setting of As : 2.54



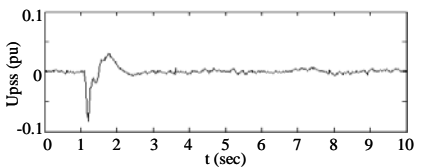
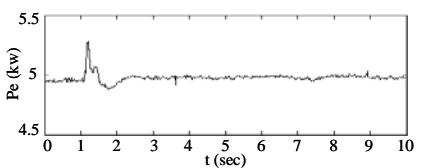
Optimal Setting of As at Site: 2.83

Control Performance at Generator Operating Point of 5kW

Initial Setting of As : 0.30

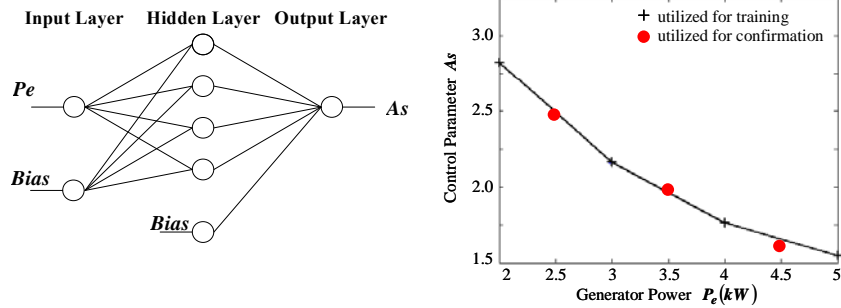


Optimal Setting of As : 1.46



Optimal Setting of As at Site: 1.55

Artificial Neural Network Base Real Time Tuning



The training of the neural network is performed by the intelligent agent at the control center after having enough data for the training.

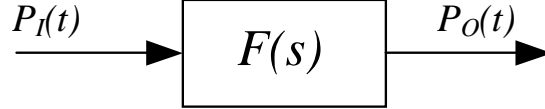
Whenever the retraining is required, the retrained result is transferred to the corresponding adaptive fuzzy logic PSS for its renewal.

Eigenvalue-based Wide Area Stability Monitoring of Power Systems

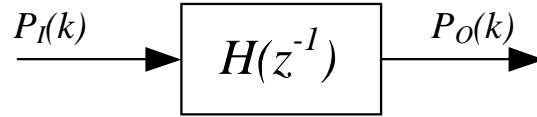
Journal of Control Engineering Practice 13 (2005) 1515-1523

Real Time Stability Evaluation - 1

(a) Continuous Time Transfer Function



(b) Discrete Time Transfer Function



Through the monitoring of the input signal $P_I(t)$, and the output signal $P_O(t)$, the parameters of the target system can be easily identified. Therefore, the stability of the target system can be evaluated from the eigenvalues of the identified transfer function.

Real Time Stability Evaluation - 2

After monitoring the output $P_O(t)$ for an input signal $P_I(t)$, the relation between the input $P_I(t)$ and the output $P_O(t)$ can be expressed in a discrete manner as follows:

$$P_O(k) = a_1 P_O(k-1) + a_2 P_O(k-2) + \dots + a_n P_O(k-n) + b_0 P_I(k) + b_1 P_I(k-1) + \dots + b_n P_I(k-n)$$

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:

$$H(z^{-1}) = \frac{b_0 + b_1 z^{-1} + \dots + b_n z^{-n}}{1 - a_1 z^{-1} - a_2 z^{-2} - \dots - a_n z^{-n}}$$

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

$$1 - a_1 z^{-1} - a_2 z^{-2} - \dots - a_n z^{-n} = 0$$

Real Time Stability Evaluation - 3

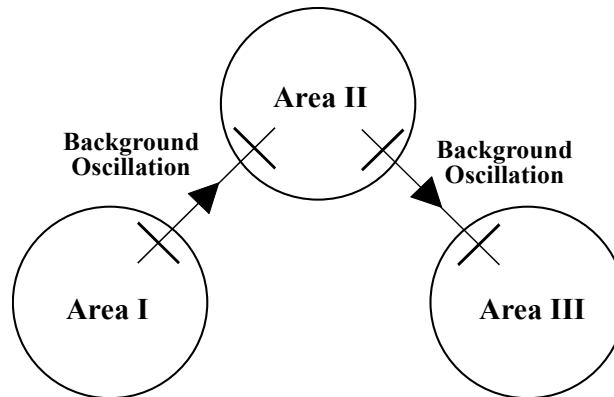
The discrete time eigenvalues can be easily converted to their corresponding continuous time eigenvalues as follow:

$$z_i = x_i + j y_i$$

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

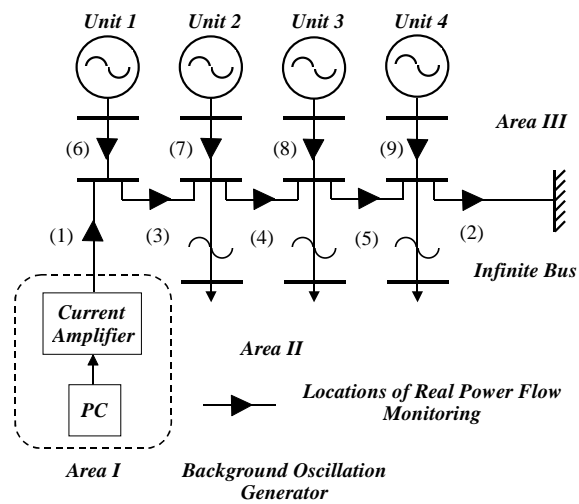
where α is the estimated damping coefficient and β gives the estimated frequency of the oscillation modes of the continuous study system $F(s)$. Here, it must be noted that the system is stable when all the damping coefficients α have negative values. In addition, T denotes the sampling interval for the discrete time system.

Study System

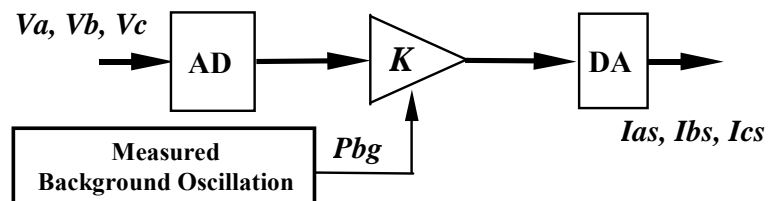


Background oscillations are measured at the locations between Area I and Area II, and also between Area II and Area III. The stability of the study system is evaluated based on those measured background oscillations.

Longitudinal Four-Machine Infinite Bus System

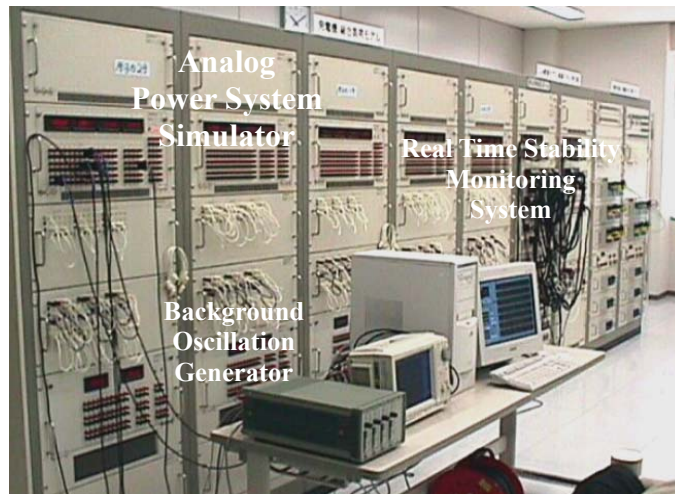


Basic Configuration of Background Oscillation Generator



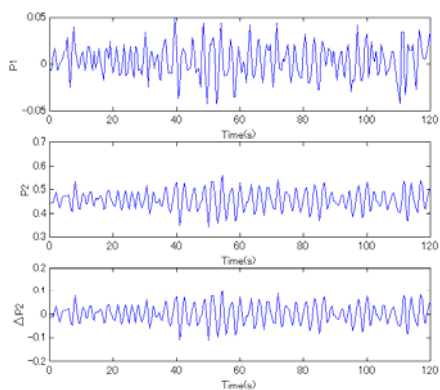
To generate background oscillations, real power flow actually measured on a 500kV trunk line were utilized.

Overview of Analog Power System Simulator

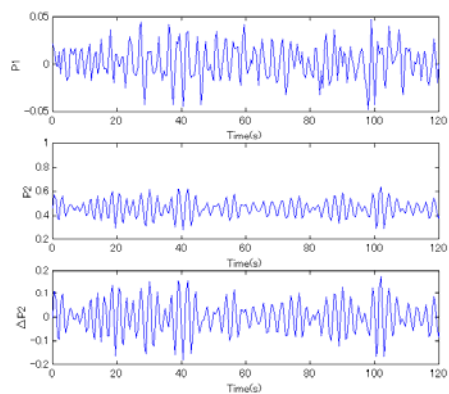


Propagation of Background Oscillations - 1

Case 1: Unit 1 and Unit 4 are equipped with CPSS.

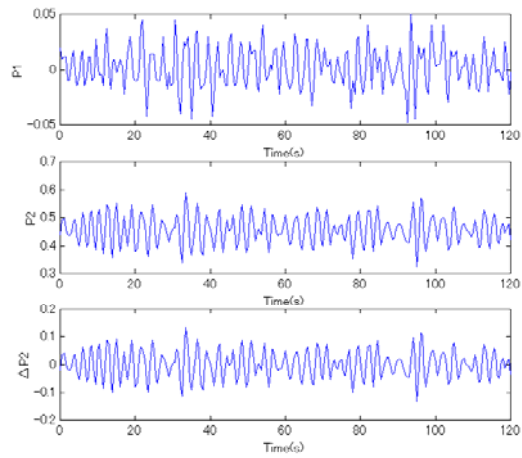


Case 2: Unit 1 is equipped with CPSS.



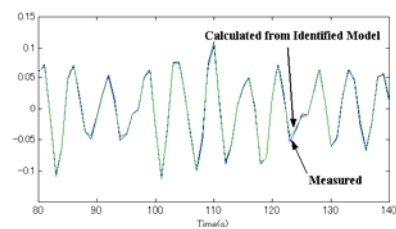
Propagation of Background Oscillations - 2

Case 3: Unit 4 is equipped with CPSS.

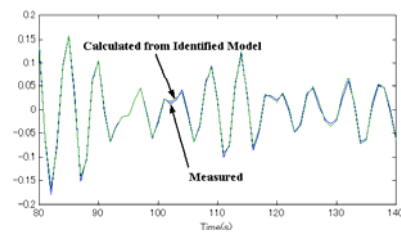


Stability Evaluation – Identification of Discrete Time Model

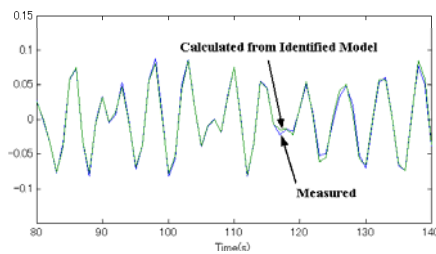
Case 1: Unit 1 and Unit 4 are equipped with CPSS.



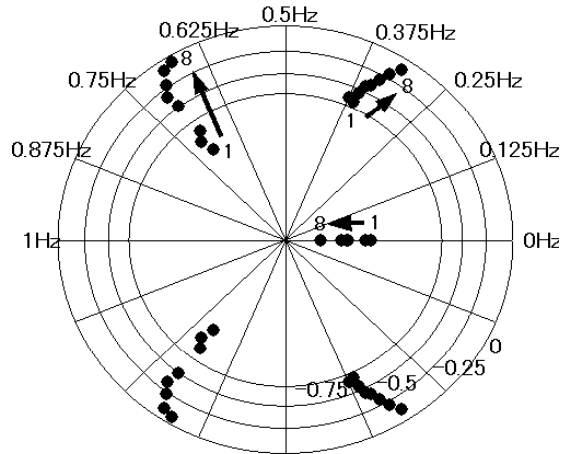
Case 2: Unit 1 is equipped with CPSS.



Case 3: Unit 4 is equipped with CPSS.



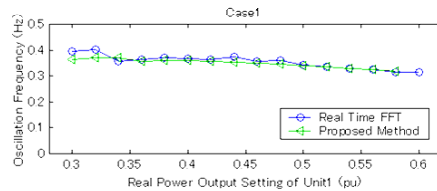
Stability Evaluation – Eigenvalues on z-Plane



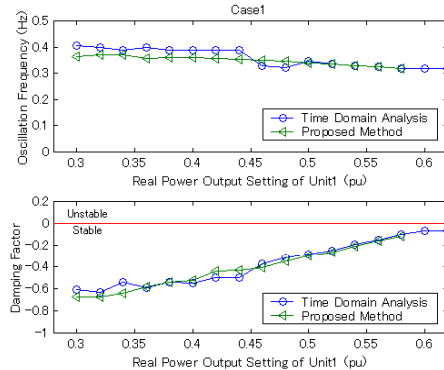
Real Power Setting of Unit 1: 0.30 pu at Point 1 to 0.58 pu at Point 8.

Stability Evaluation - Comparisons of Identified Global Mode of Oscillation

Frequency Domain Analysis: Real Time FFT

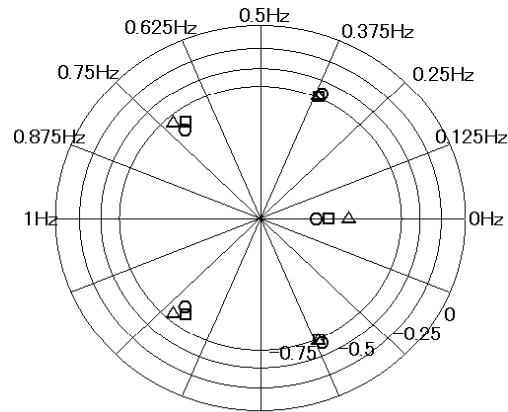


Time Domain Analysis



Stability Evaluation

- Effect of Time Difference between Two Measurement Sites

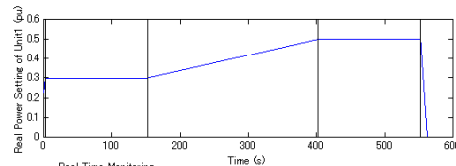


Time Difference
1: without time difference(synchronous)
2: with time difference of 5 samples (0.1 s)
3: with time difference of 10 samples (0.2 s)

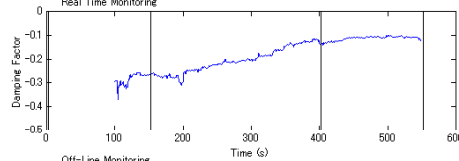
Real Time Stability Evaluation

- Real Time Evaluation of Damping Factor

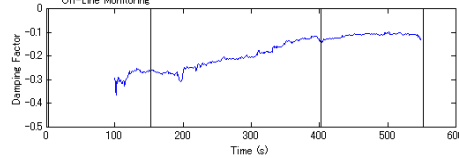
Output Setting of Unit 1



Real Time Evaluation

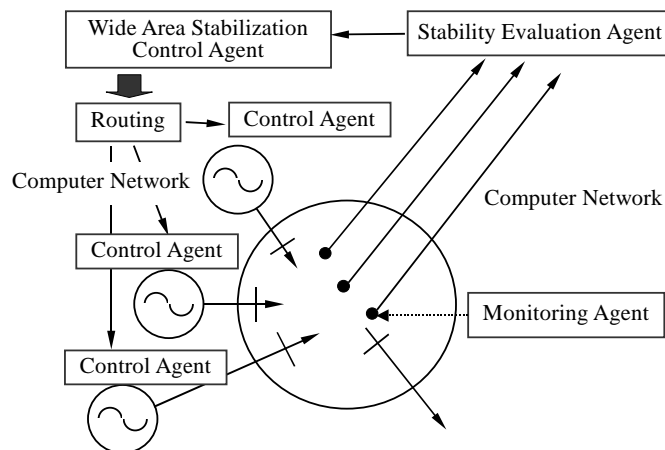


Off Line Evaluation



Multi-Agent Based Wide Area Stabilization Control of Electric Power Systems

Configuration of Multi-Agent Based Wide Area Stabilization Control System



Three different types of intelligent agents:

Monitoring agents for the distribution of required information through the computer network

Control agents for the actual emergency control on a selected unit

Wide area stabilization control agent as the supervisor of the entire system

Selection of Target Unit for Emergency Control

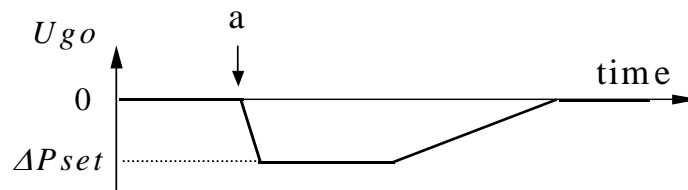
Following performance index has been utilized to evaluate the stability of each generating unit. The unit with the lowest stability level is selected as the target unit for the proposed emergency control.

$$J_i = \sum \Delta\omega_i^2$$

$\Delta\omega_i$: speed deviation of the i -th unit

Emergency Control after Detecting Instability on Selected Unit - 1

The emergency controller on the selected unit shifts its operating point to its new stable equilibrium by modifying the real power output setting in the corresponding speed governing control system.



Instability is detected at $t = a$.

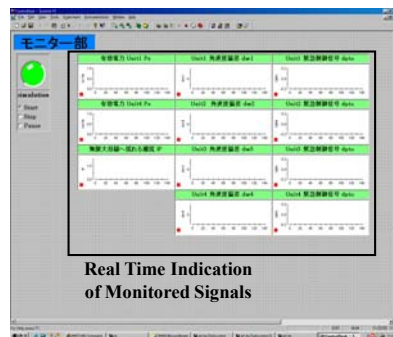
PC Based Wide Area Stabilization Control System for Analog Simulator Tests



A DSP board with AD/DA conversion interfaces has been installed on the PC based Monitoring & Control Agent as the interfaces to and from the Analog Power System Simulator.

The computer network has been utilized as the interfaces between these two personal computers.

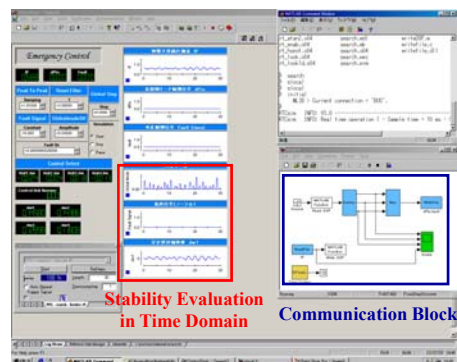
Computer Display on Each Agent



Real Time Indication
of Monitored Signals

Computer Display on Monitoring & Control
Agent

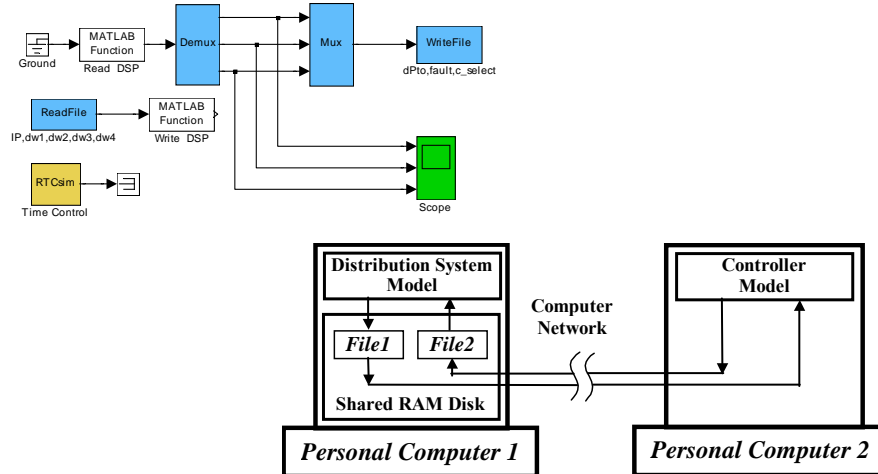
Computer Display on Wide Area
Stabilization Control Agent
Including Stability Evaluation Agents



Stability Evaluation
in Time Domain

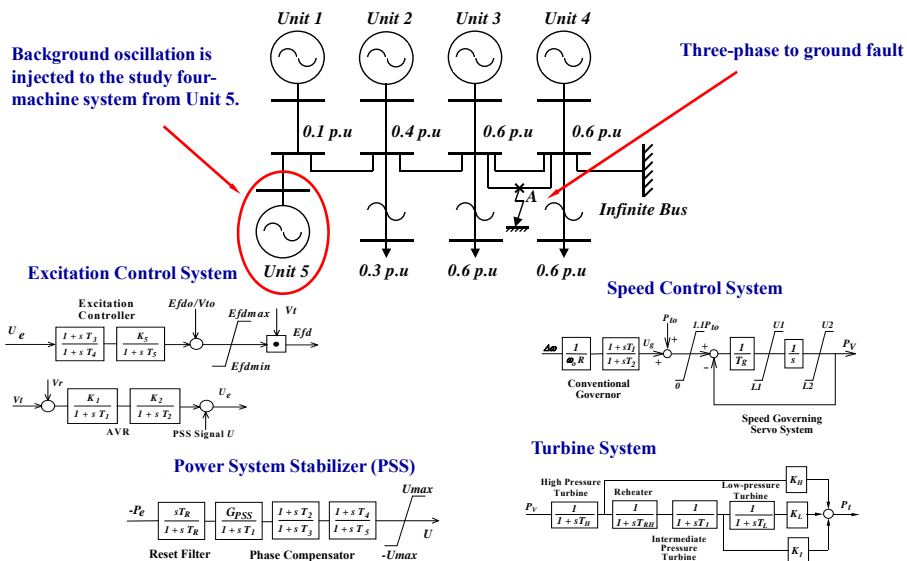
Communication Block

Communication System between Two PC Based Agent System



The Communication system between two PC based Agents has been developed in the Matlab/Simulink environment.

Longitudinal Five-Machine Study System



Result of Analog Simulator Test - 1

Real Power from Unit 1

Real Power from Unit 4

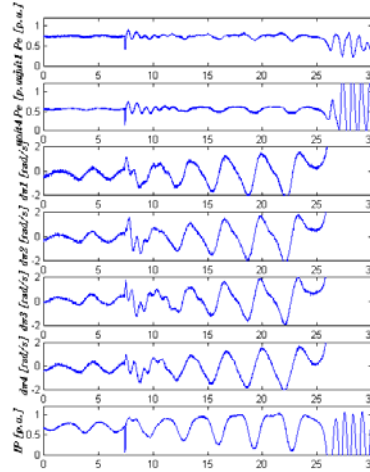
Speed Deviation on Unit 1

Speed Deviation on Unit 2

Speed Deviation on Unit 3

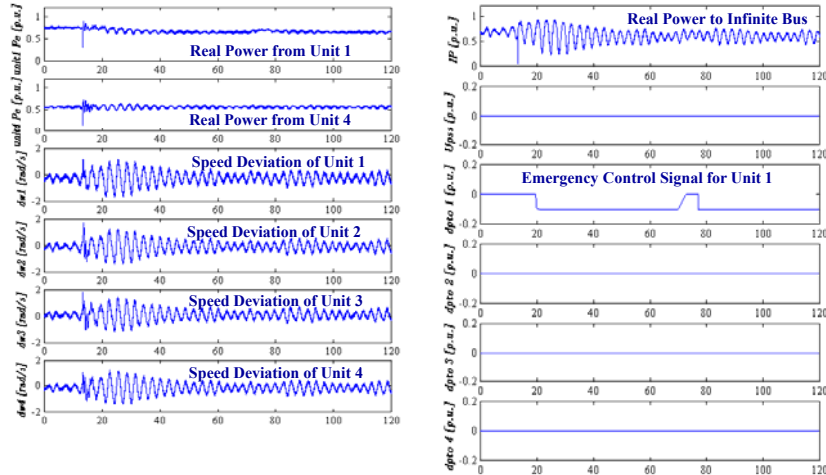
Speed Deviation on Unit 4

Real Power to Infinite Bus



In this case, the stabilization control is not applied to the study system, therefore, the study system is going out of the step about 20seconds after applying the fault. As clearly shown in this figure, the system instability is observed in the global mode of oscillation around 0.3Hz.

Analog Simulator Test - 2



One of the typical stabilized cases after applying the proposed wide area stabilization control system: the permanent emergency control is applied on Unit 1 to stabilize the study system in this case.

Multi-Agent Based Operation and Control of Distribution Systems with Dispersed Power Sources

- With Renewable Energy Power Sources & Energy Storage Device

Introduction

Renewable Energy Power Sources:

Photo-Voltaic Generation & Wind Turbine Generation

Conventional Power Sources:

Diesel Generation & Gas Turbine Generation

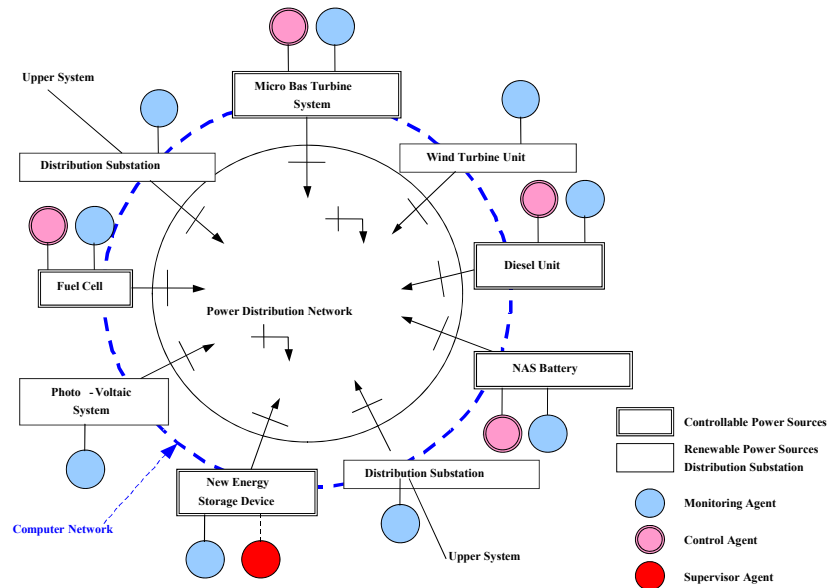
Energy Storage Devices:

Energy Capacitor System (Electrical Double Layer Capacitors)

A number of new distributed power generation technologies are currently available to offer integrated performance and flexibility for the power consumers.



Multi-Agent Based Coordinated Operation of Dispersed Power Sources



Multi-Agent System

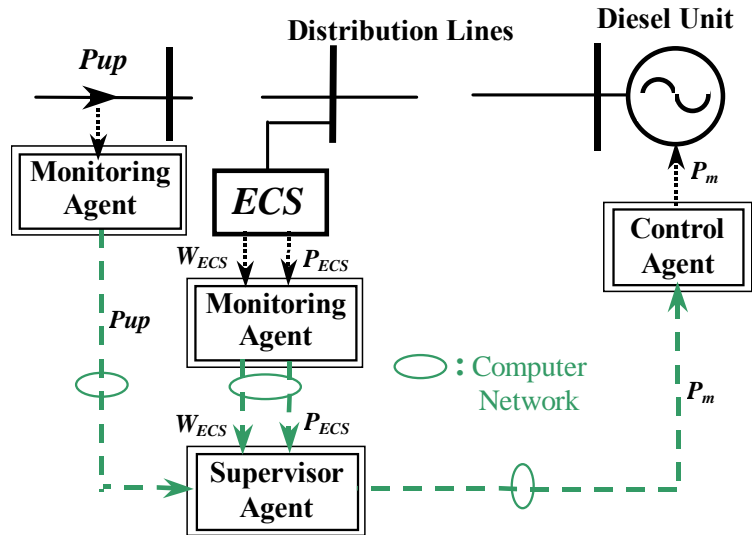
Three Types of Agents:

Monitoring Agents for the distribution of required information through the computer network (Reactive Agent)

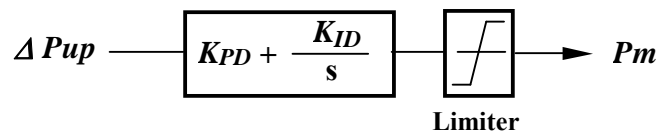
Control Agents for the charging/discharging operation on the ECS and also for the power regulation on the diesel units (Reactive Agent)

Supervisor Agent for the coordination between the ECS and the diesel units (Cognitive Agent)

Multi-Agent Based Load Leveling of Distribution System

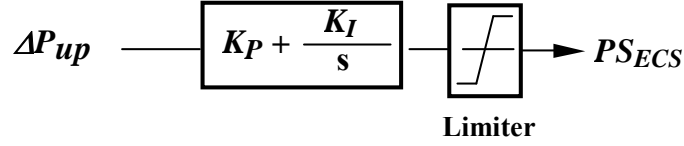


Conventional Load Leveling Control on Diesel Unit



ΔP_{up} : Deviation of Power Flow from Upper System
 P_m : Output Setting of Diesel Unit

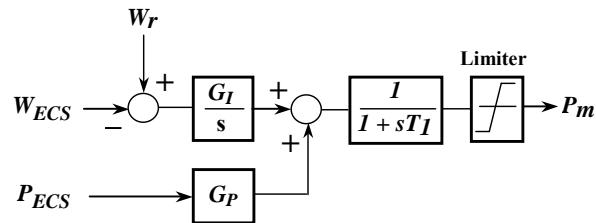
Proposed Load Leveling Control (Supervisor Agent)



ΔP_{up} : Power Flow Deviation from Upper System
 P_{SECS} : Output Setting of ECS

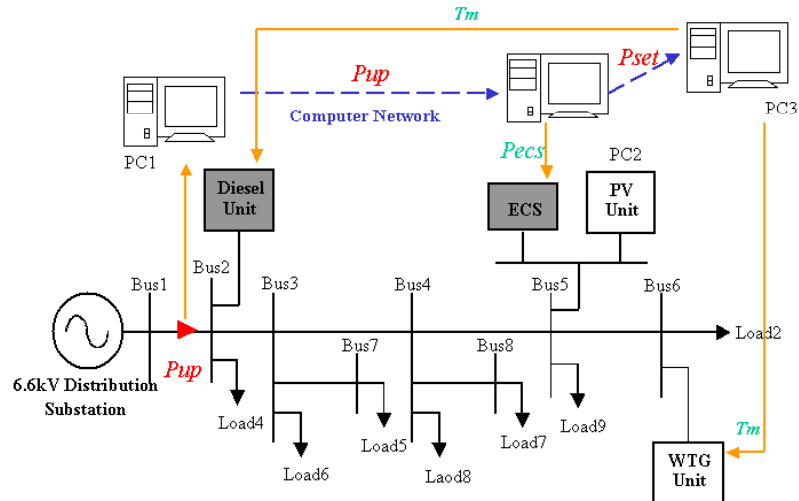
Coordination between ECS and Diesel Unit (Supervisor Agent)

1. A small sized ECS is considered in this study, therefore, the regulation of the output from the diesel unit is required to keep the stored energy level of the ECS in a proper range.
2. The ECS provides the main function of load leveling control and the diesel unit provides its supplementary function to support the load leveling control on the ECS.

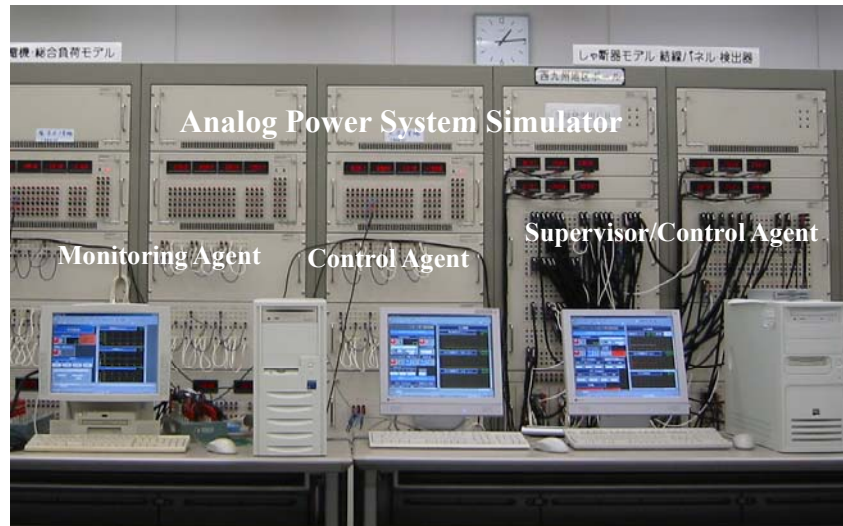


W_r : Target Stored Energy, W_{ECS} : Current Stored Energy
 P_{ECS} : Power from ECS
 P_m : Power Regulation on Diesel Unit for Coordination with ECS

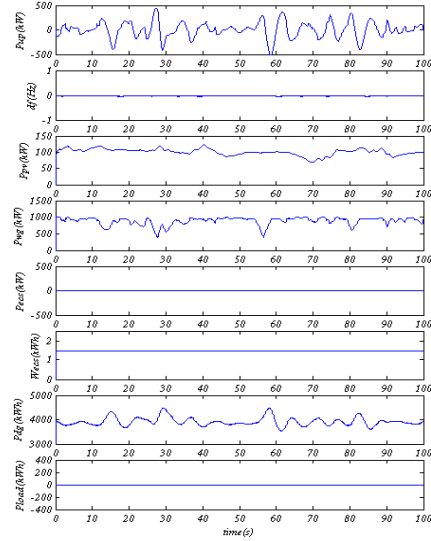
6.6kV Distribution System on Analog Power System Simulator



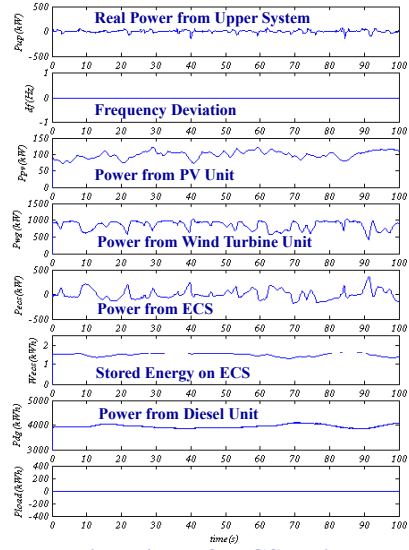
Overview of Analog Power System Simulator at the Research Laboratory of Kyushu Electric Power Co.



Load Leveling Control (Fixed Load)

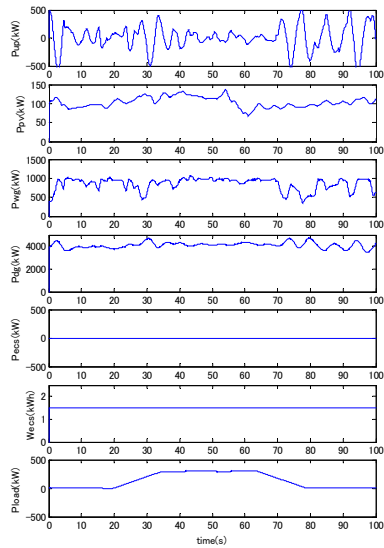


With Diesel Unit

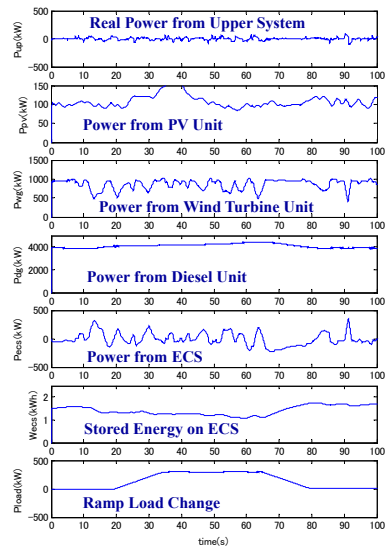


With Diesel & ECS Units

Load Leveling Control (Ramp Load Change)

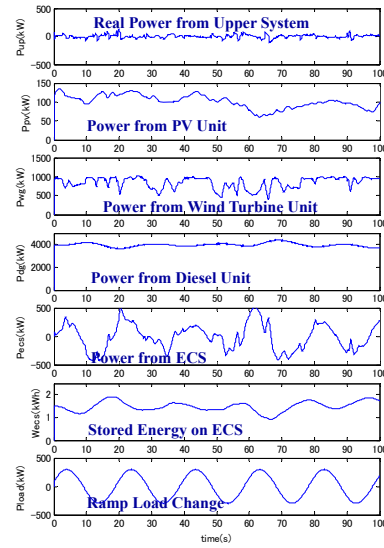
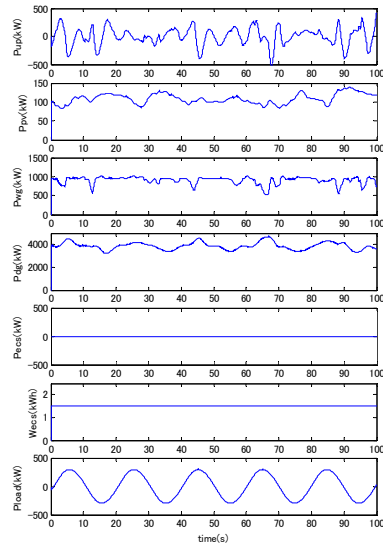


With Diesel Unit

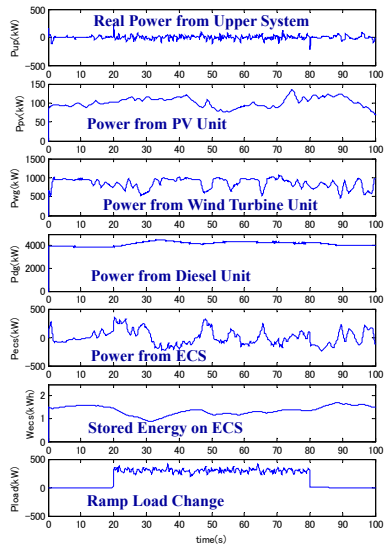
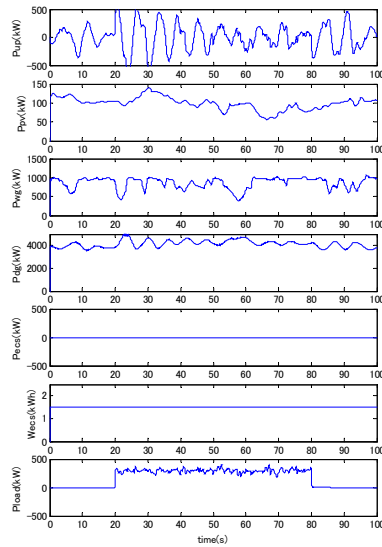


With Diesel & ECS Units

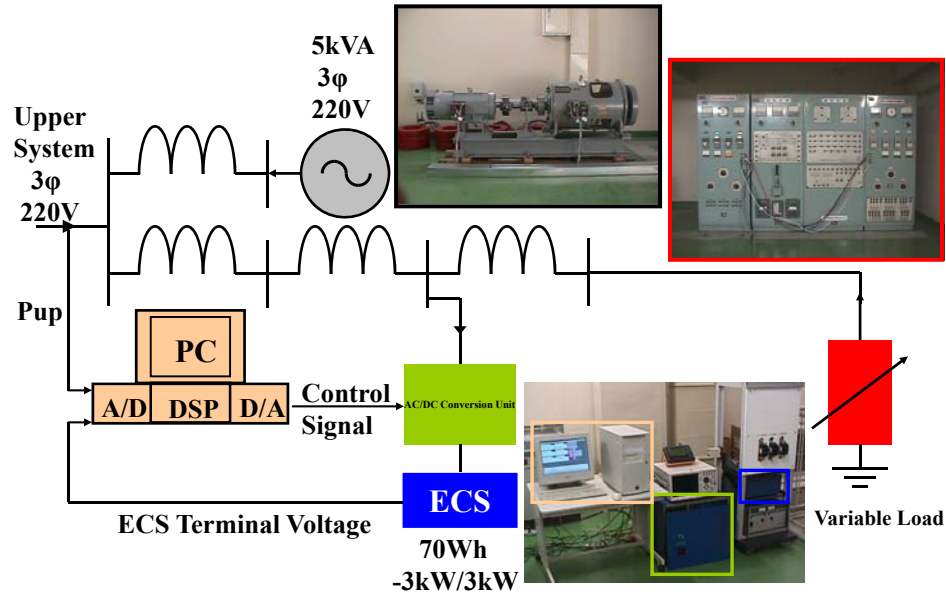
Load Leveling Control (Periodical Load)



Load Leveling Control (Step & Random Load Change)



Laboratory System for Load Leveling Control



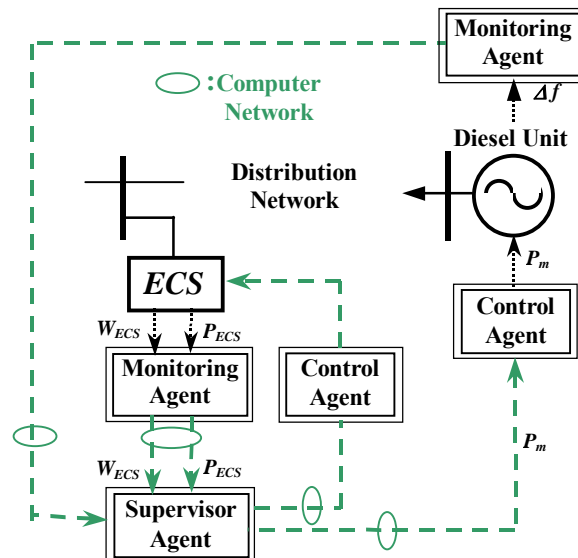
Conclusion

A multi-agent based load leveling control scheme has been proposed for distribution systems.

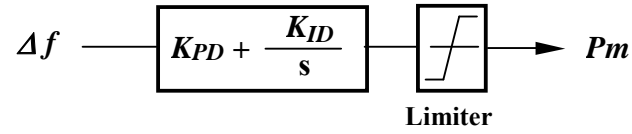
The real time simulation results, performed on the Analog Power System Simulator at the Research Laboratory of Kyushu Electric Power Co., clearly indicate the advantages of the proposed multi-agent based load leveling control scheme even in the existence of the communication delay to a certain level.

Further studies are now ongoing for the compensation of the long communication delay.

Journal of Engineering Intelligent Systems, Vol. 13, No. 2 (2005)

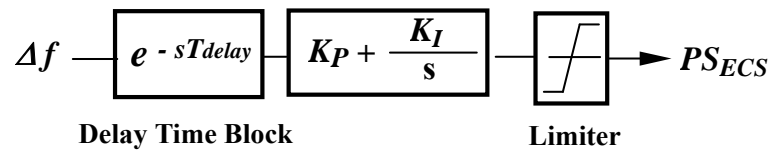


Conventional AGC on Diesel Unit



Δf : Frequency Deviation on Diesel Unit
 P_m : Output Setting of Diesel Unit

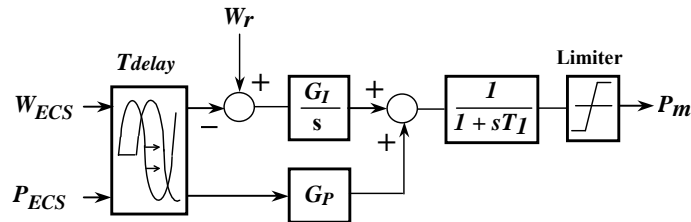
Proposed AGC (Supervisor Agent)



Δf : Frequency Deviation of Diesel Unit
 PS_{ECS} : Output Setting of ECS
 T_{delay} : Communication Delay Time

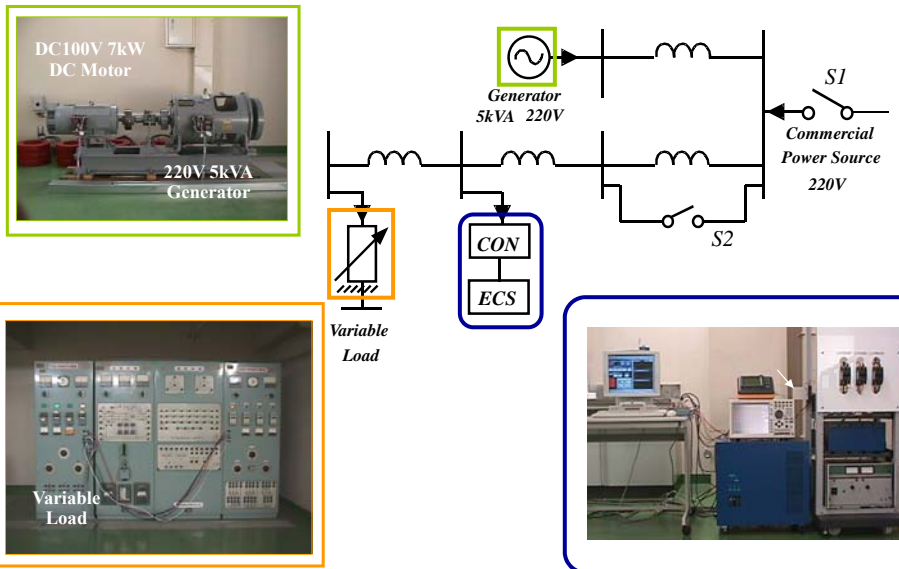
Coordination between ECS and Diesel Unit (Supervisor Agent)

1. A small sized ECS is considered in this study, therefore, the regulation of the output from the diesel unit is required to keep the stored energy level of the ECS in a proper range.
2. The ECS provides the main function of AGC and the diesel unit provides a supplementary function to support the AGC on the ECS.

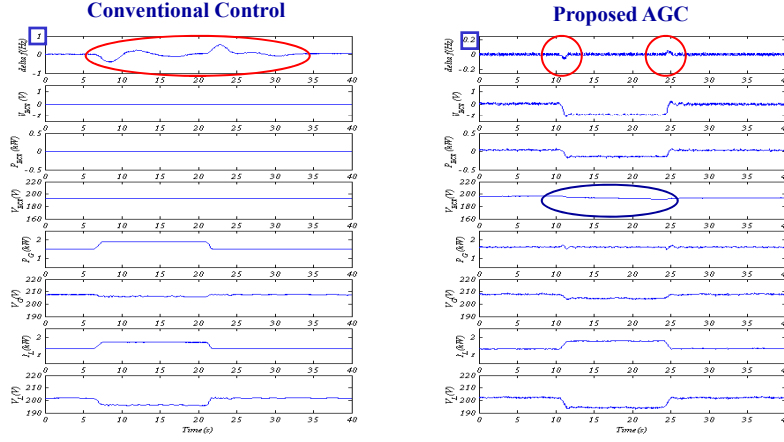


W_r : Target Stored Energy, W_{ECS} : Current Stored Energy
 P_{ECS} : Power from ECS
 P_m : Power Regulation on Diesel Unit for Coordination with ECS
 T_{delay} : Communication Delay Time

Laboratory System for AGC

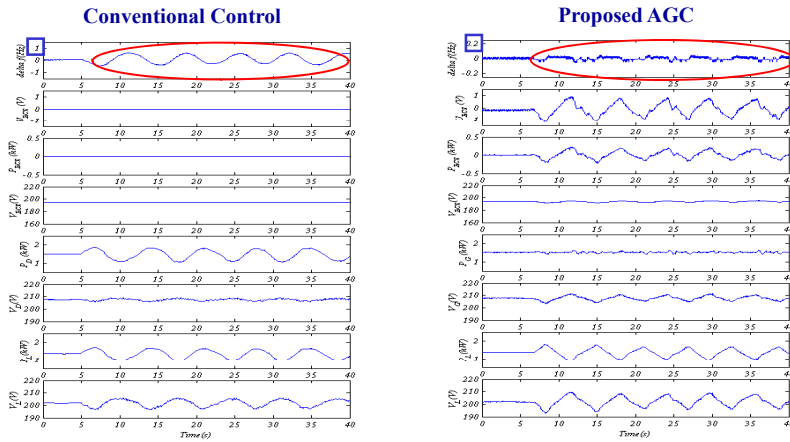


AGC for Step Load Change 1



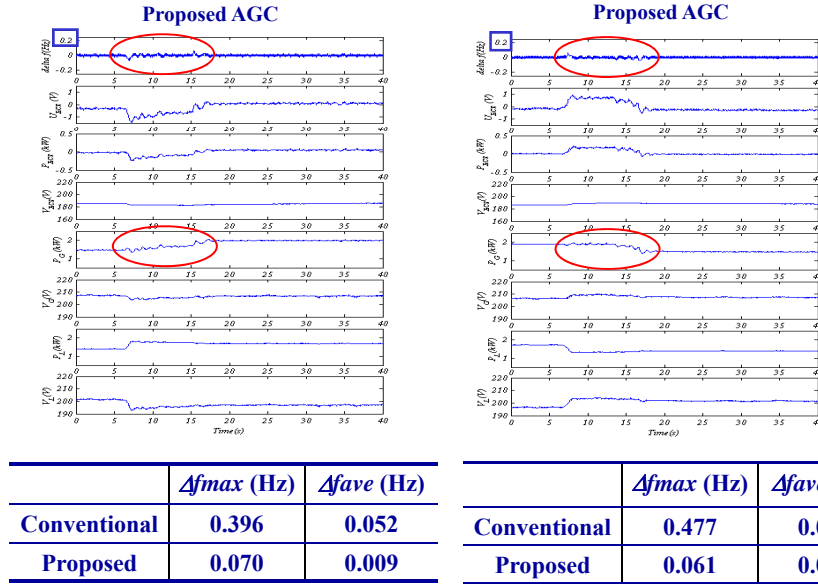
	Δf_{max}	Δf_{ave}
Conventional	0.802	0.263
Proposed	0.068	0.011

AGC for Periodic Load Change

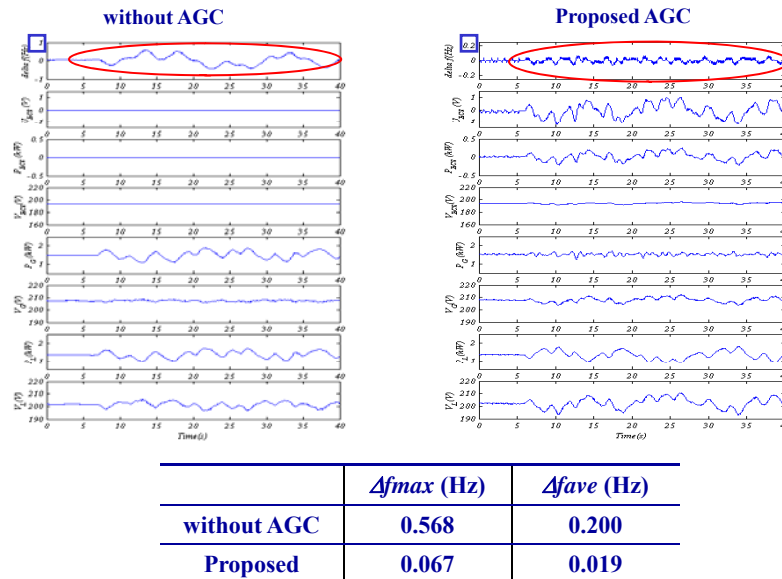


	Δf_{max} (Hz)	Δf_{ave} (Hz)
Conventional	0.702	0.257
Proposed	0.056	0.016

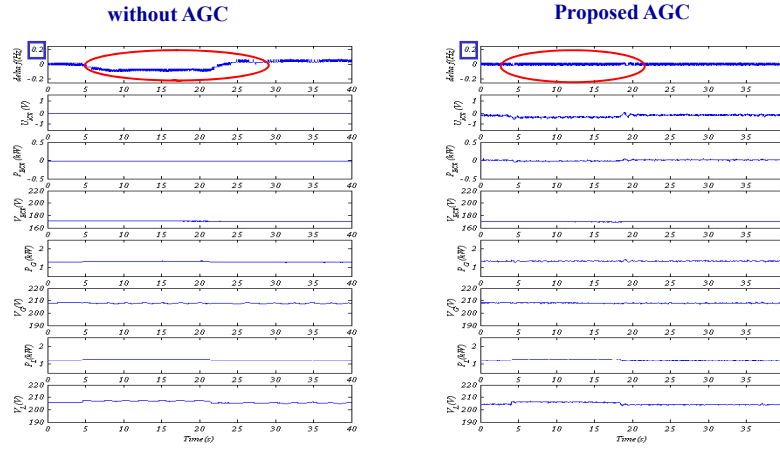
AGC for Step Load Change 2 & 3



AGC for Random Load Change



AGC under Large Disturbance



	Δf_{max} (Hz)	Δf_{ave} (Hz)
without AGC	0.101	0.050
Proposed	0.028	0.009

Conclusion

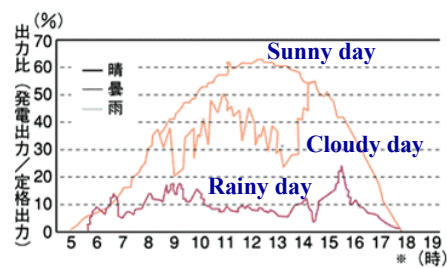
A multi-agent based AGC scheme has been proposed for isolated power systems. The experimental results, performed on the laboratory system, clearly indicate the advantages of the proposed multi-agent based AGC scheme even in the existence of the communication delay to a certain level.

Further studies are now ongoing for the development of hierarchical control where the multi-agent based control system performs its upper level control and the local control system performs its lower level control.

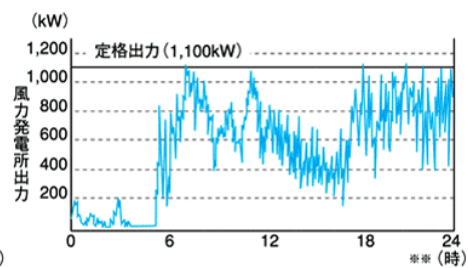
Operation and Control for Hybrid Power Source Including Renewable Power Sources - Rule-based Regulation & PI-type Regulation

Fluctuation of Power Output

Output from PV System

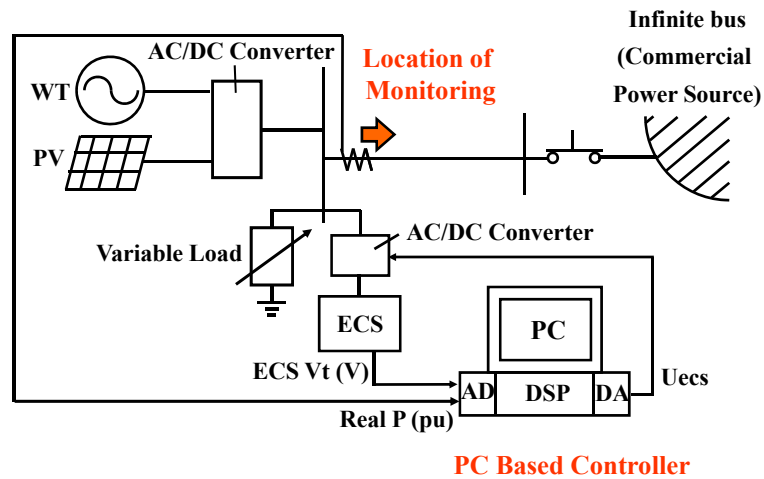


Output from Wind Generation System



出典：※第3回総合エネルギー調査会 新エネルギー部会資料
※※北海道電力ほりかつ発電所

Configuration of Laboratory System



Estimation of Stored Energy

Stored Energy in Wh

$$Wh = \frac{1}{2} CV^2 * \frac{1}{3600}$$

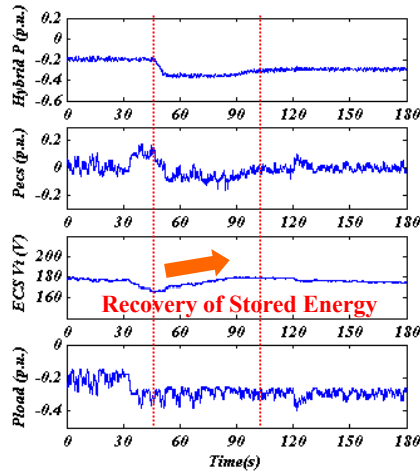
C : Capacitance (F)

V : DC side terminal voltage **Monitoring of DC side voltage**

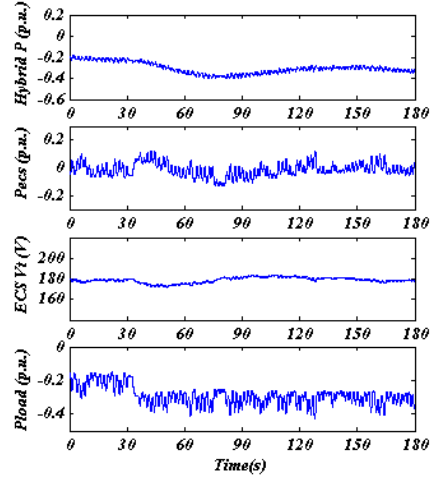


Experimental Results (1)

Rule-based Regulation

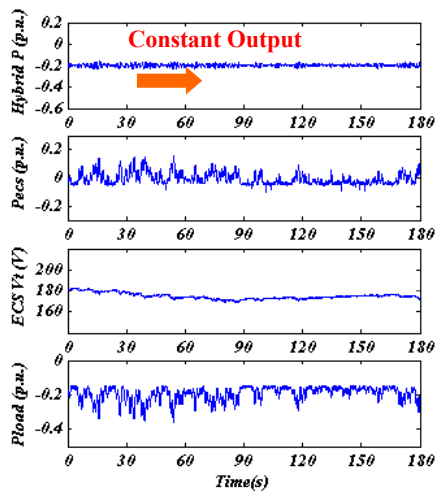


PI-type Regulation

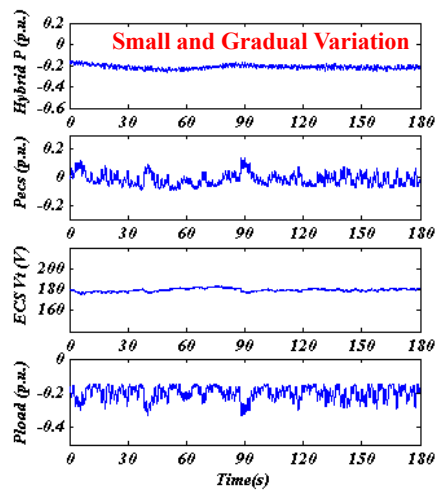


Experimental Results (2)

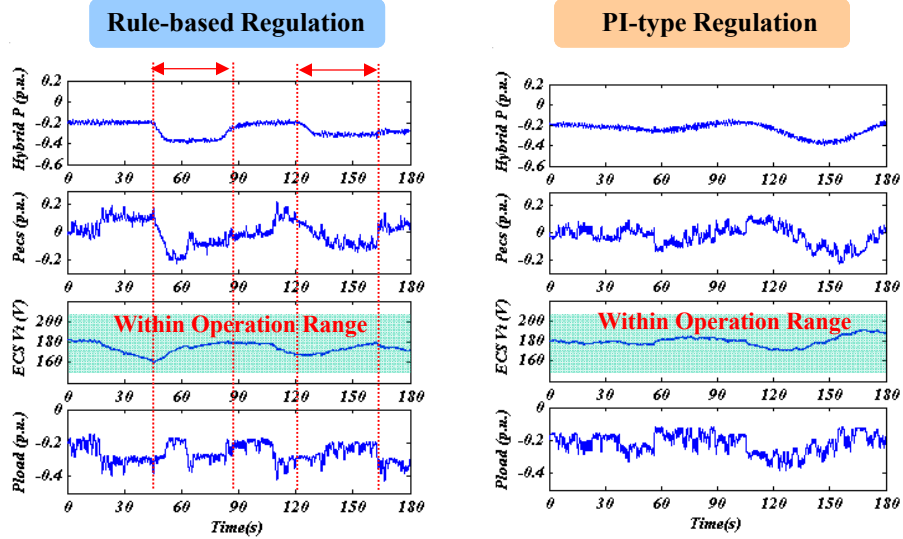
Rule-based Regulation



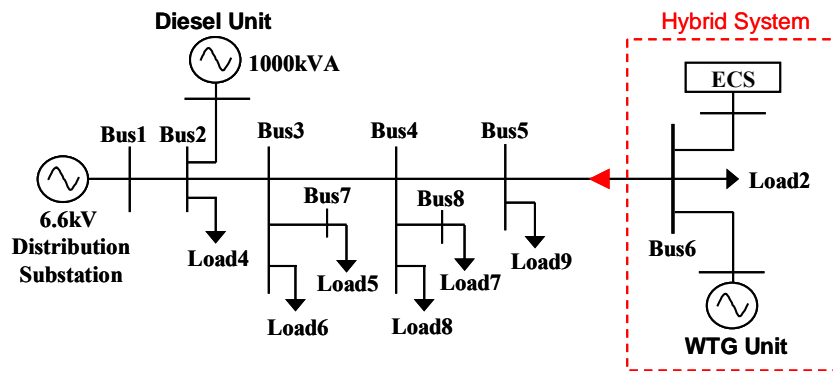
PI-type Regulation



Experimental Results (3)

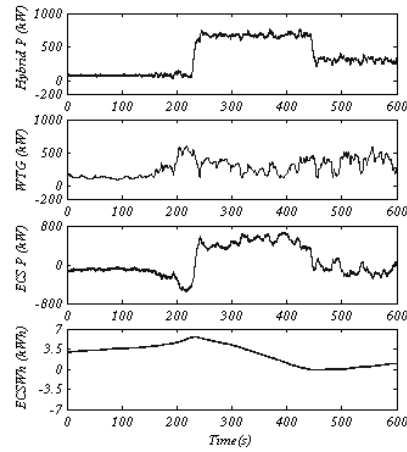


Analog Simulator Tests

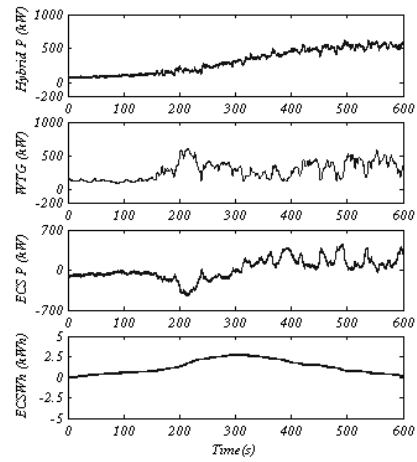


Typical Results in Analog Simulator Test

Rule-based Regulation

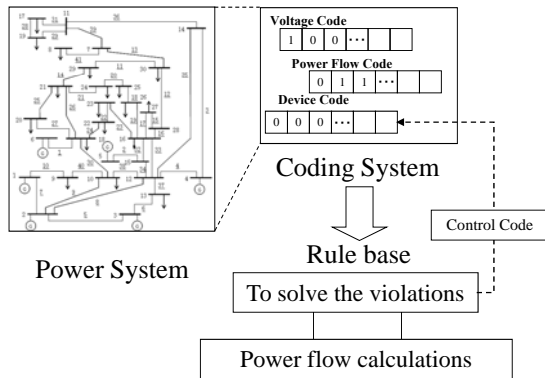


PI-type Regulation



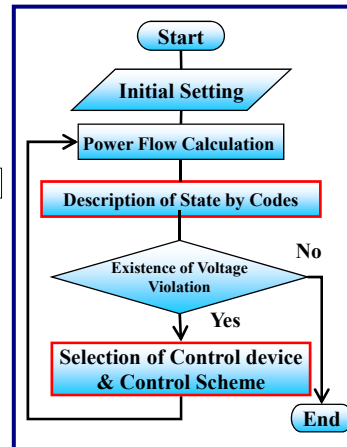
Rule-Based Voltage Control of Power Systems

Proposed Control Scheme for Voltage Regulation



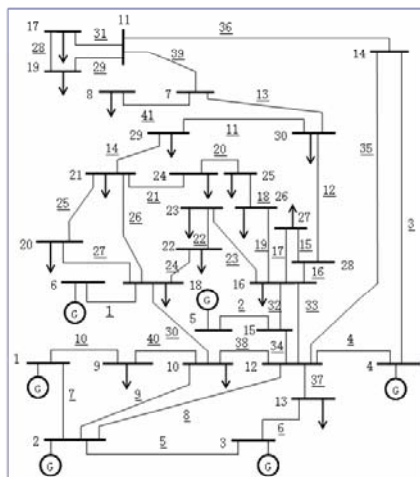
- Code Based Description of System State
- Rule Based Control Scheme

Flow Chart



IEEE 30 Bus System

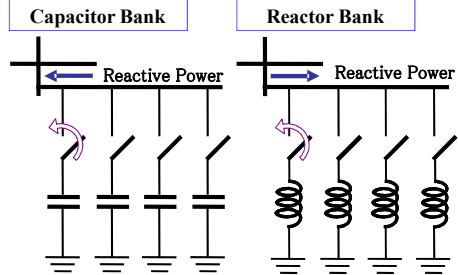
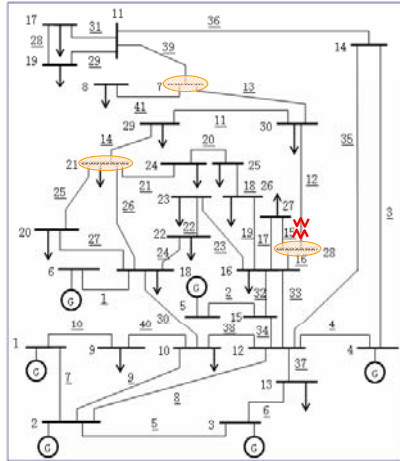
Configuration



Operating Condition

Node	P_G	V_G	P_L	Q_L
1	0.3278	1	0	0
2	0.3278	1	0	0
3	0.3278	1	0	0
4	0.3278	1	0	0
5	0.3278	1	0	0
6	slack node	1	0	0
7	0	0	0	0
8	0	0	0.1032	0.0288
9	0	0	0.1431	0.0563
10	0	0	0.1834	0.0774
11	0	0	0	0
12	0	0	0	0
13	0	0	0.241	0.1163
14	0	0	0	0
15	0	0	0	0
16	0	0	0.1112	0.0518
17	0	0	0.1024	0.294
18	0	0	0.1291	0.0367
19	0	0	0.1041	0.0421
20	0	0	0.1235	0.0467
21	0	0	0.0812	0.0255
22	0	0	0.0731	0.0475
23	0	0	0.1122	0.0475
24	0	0	0.1122	0.0475
25	0	0	0.0612	0.0172
26	0	0	0.1432	0.0573
27	0	0	0.0552	0.0552
28	0	0	0	0
29	0	0	0.0923	0.0342
30	0	0	0.0782	0.0232

Voltage Control Devices



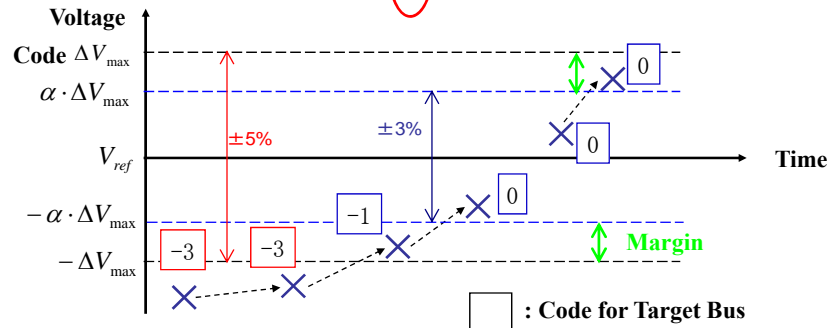
Control Device	Bus Number	Specification
Capacitor bank	Bus 7, 21 & 28	4 unit (0.05pu/unit)
Tap Changer	Bus 28	$\pm 10\%$
Generator Voltage	1,2,3,4,5	$\pm 3\%$

Transition of Code through Voltage Regulation

Voltage Profile

Target bus \Rightarrow Bus 17

7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
-2	-2	0	0	-2	0	0	0	0	0	-3	0	-2	0	-2	0	0	-2	-2	0	0	0	-2	-2



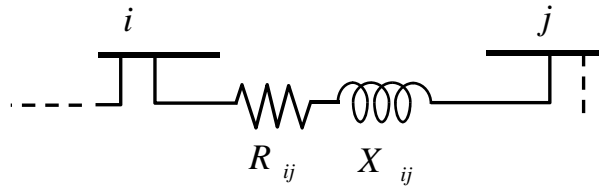
Selection of Control device – Measure of Electrical Distance

The controlled device is selected by using the distance measure.

The distance L_{ij} of the line between Bus i and Bus j is defined as follows:

$$L_{ij} = \sqrt{R_{ij}^2 + X_{ij}^2}$$

where the terms R_{ij} and X_{ij} give the resistance and the reactance of the line between Bus i and Bus j . The minimum distance for any pair of Bus i and Bus j can be calculated by using the Dijkstra Method.

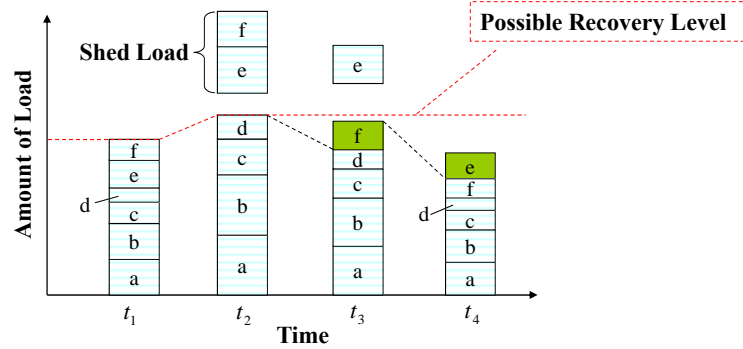


Process to Solve Voltage Violation

Violated Node	Ranking of Nearest Voltage Control Distances
17	7, 28, 21, 4, 5, 2, 1, 3

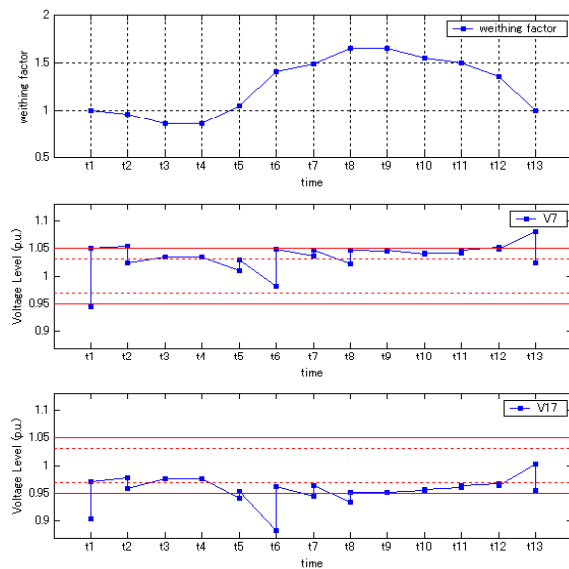
	Cap. Bank			Generator	Trans.	Code V																														
	7	21	28			7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30							
	0	0	0	0	1	-2	-2	0	0	-2	0	0	0	0	0	-3	0	-2	0	-2	0	0	-2	-2	0	0	0	-2	-2							
1	1	0	0	0	1	0	-2	0	0	-2	0	0	0	0	0	-3	0	-2	0	0	0	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	
2	2	0	0	0	1	0	-2	0	0	0	0	0	0	0	0	-3	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
3	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	-3	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
4	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	-3	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
5	4	0	0	0	1.01	0	0	0	0	0	0	0	0	0	0	-3	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
6	4	0	0	0	1.02	0	0	0	0	0	0	0	0	0	0	-3	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
7	4	0	0	0	1.03	0	0	0	0	0	0	0	0	0	0	-3	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
8	4	0	0	0	1.04	0	0	0	0	0	0	0	0	0	0	-3	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9	4	0	0	0	1.05	0	0	0	0	0	0	0	0	0	0	-3	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
10	4	0	0	0	1.06	0	0	0	0	0	0	0	0	0	0	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
11	4	0	0	0	1.07	0	0	0	0	0	0	0	0	0	0	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
12	4	0	0	0	1.08	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
13	4	0	0	0	1.09	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
14	4	0	0	0	1.1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
15	4	0	1	0	1.1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
16	4	0	2	0	1.1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
17	4	0	3	0	1.1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
18	4	0	4	0	1.1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
19	4	1	4	0	1.1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
20	4	2	4	0	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Load Scheduling



Shed loads are recovered following the level of current power demand.

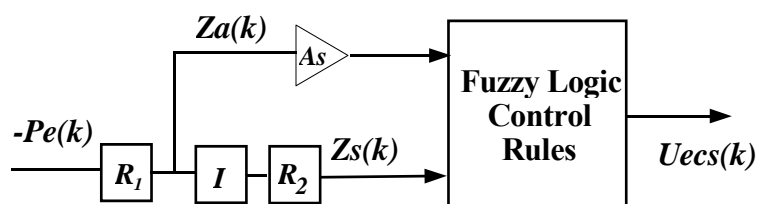
Transition of Bus Voltage on Node 7 and Node 17



Multi-Agent Based Stabilization Control using Energy Capacitor System

Fuzzy Logic Control Scheme – Pre-Filtering

Pre-Filtering for Acceleration and Speed Deviation Signals



R : Reset Filter
 I : Integrator
 U_{ecs} : Switching Control Signal

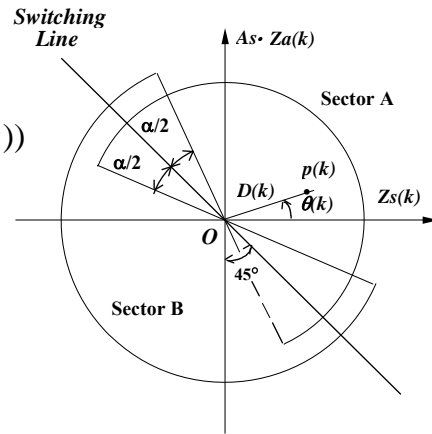
Fuzzy Logic Control Scheme - Operating Point

Operating Point on Polar Coordinates

$$p(k) = [Z_s(k) \quad A_s Z_a(k)]$$

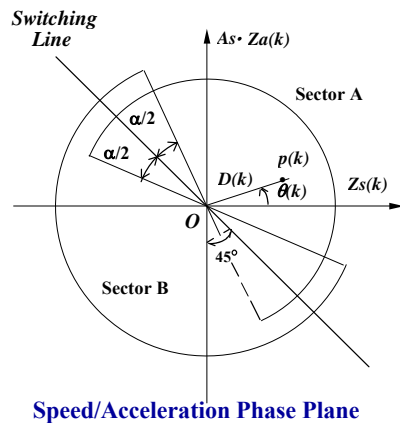
$$D(k) = \sqrt{Z_s(k)^2 + (A_s \cdot Z_a(k))^2}$$

$$\theta(k) = \tan^{-1}(A_s \cdot Z_a(k) / Z_s(k))$$



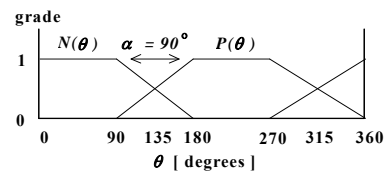
Speed/Acceleration Phase Plane

Membership Functions and Control Signal

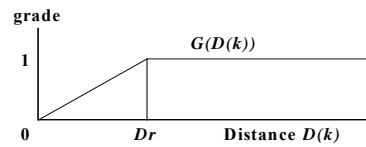


Speed/Acceleration Phase Plane

Angle Membership Functions



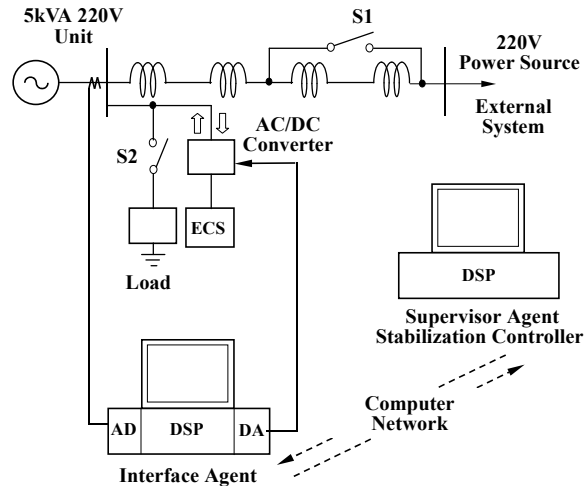
Radius Membership Function



$$U_{ecs}(k) = \frac{N(\theta(k)) - P(\theta(k))}{N(\theta(k)) + P(\theta(k))} \cdot G(D(k)) \cdot U_{max}$$

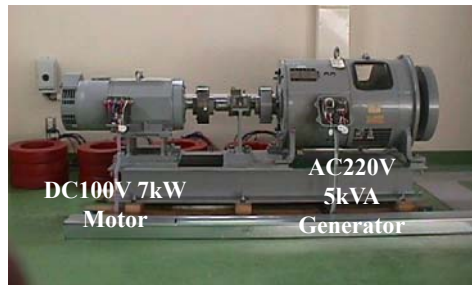
$$= [1 - 2P(\theta(k))] \cdot G(D(k)) \cdot U_{max}$$

Configuration of Laboratory System



To demonstrate the efficiency of the multi-agent based stabilization control scheme, experimental studies have been performed on a 5kVA one-machine infinite-bus laboratory system

Overview of Laboratory System



ECS: Energy Capacitor System

Electrical Double Layer Capacitors

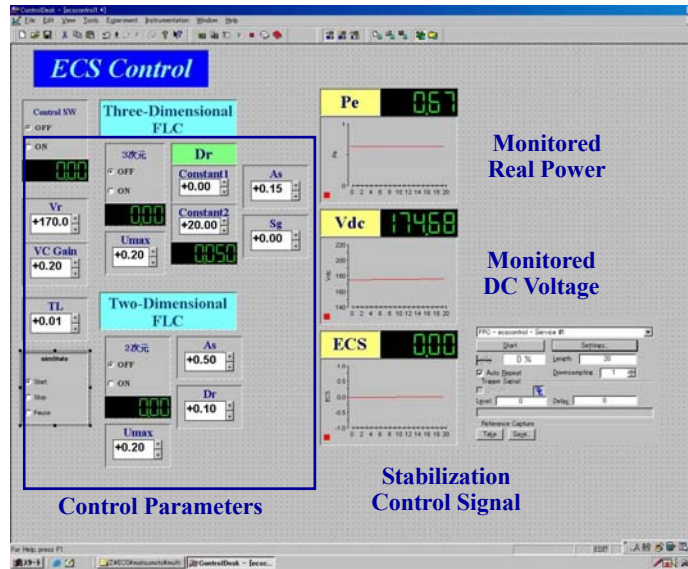
Capacity of ECS : 70 Wh (250kJ)

Maximum Charging Power: 3 kW

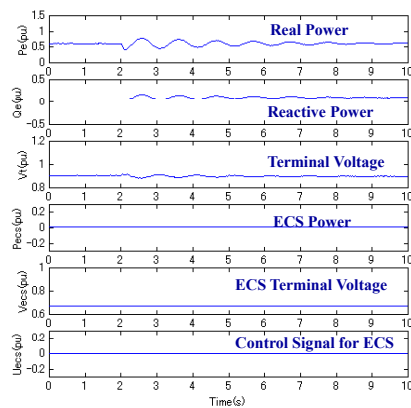
Maximum Discharging Power : 3 kW



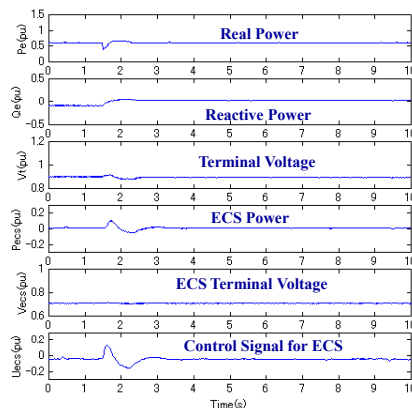
Computer Display on Supervisor Agent



Performance of Direct Control for Switching of $S1$

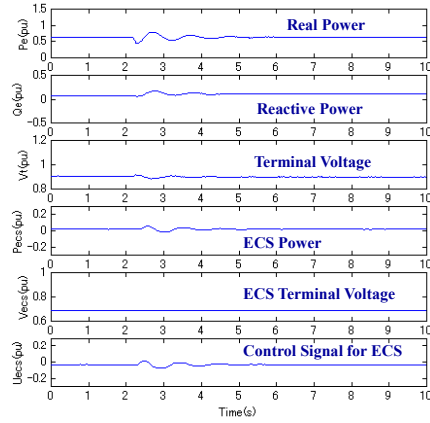


Without Control
Setting of Generator Output : 0.6 pu
Switching of $S1$

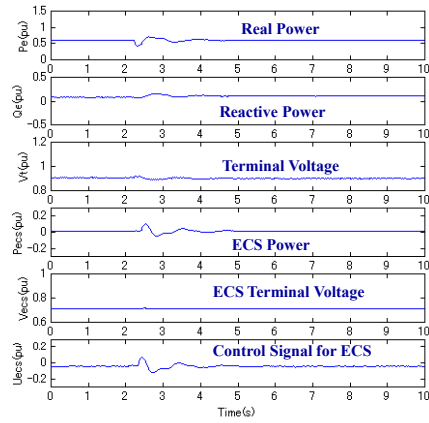


With Direct Control
Setting of Generator Output : 0.6 pu
Switching of $S1$

Performance of Multi-Agent Based Control for Switching of S1

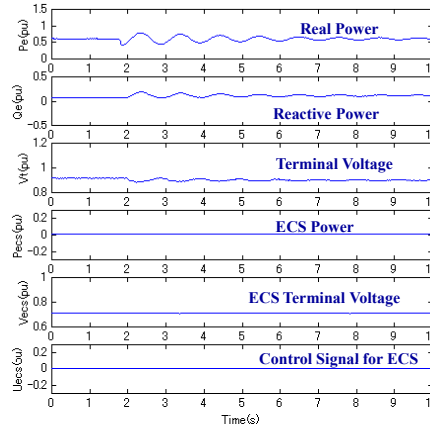


With Multi-Agent Based Control
Setting of Generator Output : 0.6 pu
Switching of S1

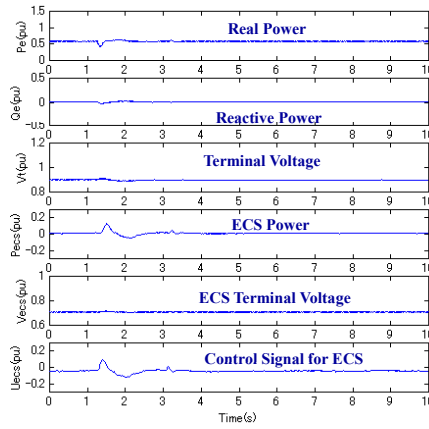


With Retuned Multi-Agent based Control
Setting of Generator Output : 0.6 pu
Switching of S1

Performance of Direct Control for Switching of S2

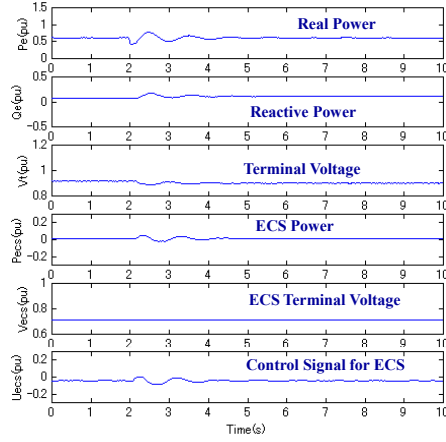


Without Control
Setting of Generator Output : 0.6 pu
Switching of S2

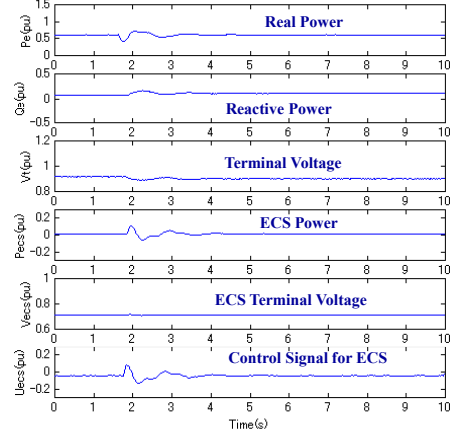


With Direct Control
Setting of Generator Output : 0.6 pu
Switching of S2

Performance of Multi-Agent Based Control for Switching of S2

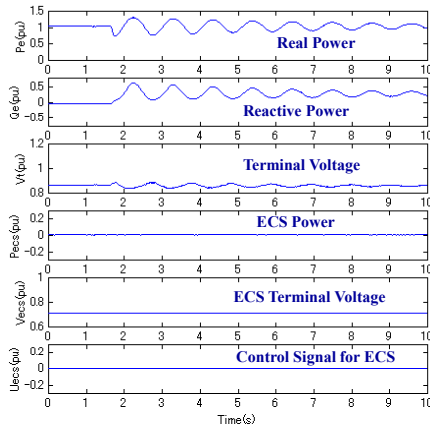


With Multi-Agent Based Control
Setting of Generator Output : 0.6 pu
Switching of S2

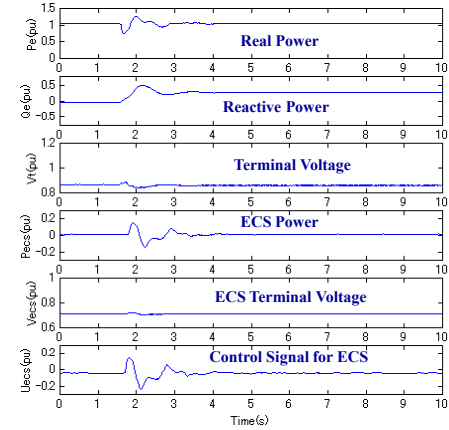


With Retuned Multi-Agent based Control
Setting of Generator Output : 0.6 pu
Switching of S2

Control Performance under Large Disturbance



Without Control
Setting of Generator Output : 1.0 pu
Switching of S1



With Retuned Multi-Agent based Control
Setting of Generator Output : 1.0 pu
Switching of S1

