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Decentralized Control of Smart Grid by using Overlapping Information

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Abstract: This paper deals with a decentralized control of smart grid by using overlapping information for load frequency of power networks introducing distributed power generations. The control objective is to minimize the cost function of load frequency control problem. We expand the state space of the system of power networks and propose a decentralized state feedback control of subsystems for the expanded system. Then we contract the decentralized feedback law to match the original system. Finally, we show the effectiveness of the load frequency control by using the proposed decentralized control method through the simulation result of decentralized large scale power network systems.

Keywords: Decentralized Control, Distributed Generations, Load Frequency, Overlapping Decomposition, Smart Grid.

1. INTRODUCTION

The decision making problems for using different information concerning underlying uncertainties has been studied since the 1950's. Some of typical problems in these fields are called as game problem and team problem and so on. In the 1970's/1980's, relations with the decentralized control and decision making was strengthened and information structured systems that have multiple subsystems getting different information had been actively studied. Also decentralized control methodologies were proposed and discussed such as [1, 2].

In recent years, decentralized control methodologies to apply these systems receive large attention again [3-6]. This is because new environmental and energy technologies for new electric power systems that is called "smart grid" (Fig. 1) where different power generators and power storages cooperate in energetically and environmentally optimal way are required. Energy problems and global warming have become the hottest problems in the world. Therefore distributed generations such as wind power generations, the battery systems, are going to be installed in electric power systems to save energy resources. However, it is difficult to control all of these distributed generations by one operation system and some distributed generations have bad effects on system frequency and fluctuation of voltage. Hence, it is necessary to operate these generations in a decentralized, coordinated and safe way. The number of studies for smart grid is increasing (see [7]), and decentralized control methodologies are also studied extensively. The optimal centralized control of an old electric power system was deeply studied in 1970's[8]. Recently, system frequency control in an new power networks installing wind power generations, battery energy storage system has been studied by [9] and a distributed control methodology for such system is proposed by [10].

In this paper, we propose a decentralized control of smart grid with information structure constraints by using overlapping information for load frequency of power networks introducing distributed power generations. We expand the state space of the system of power networks, propose a decentralized state feedback control of subsystems and contract the decentralized feedback law to match the original system. Then, we simulate decentralized large scale power network systems, and show the effectiveness of the load frequency control using the proposed decentralized control method by the simulation result.

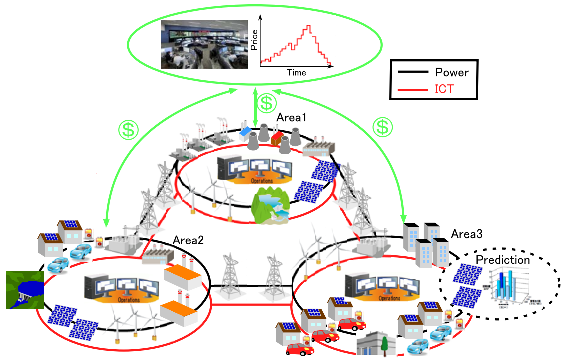


Fig. 1 smart grid

The following notations are used in this paper. $\mathbb{Z}_+$ is the nonnegative integer set, $\mathbb{R}^n$ shows the real space of the n-dimension, $\mathbb{R}^{m\times n}$ shows the real space of the m× n-dimension, X_{ij} shows the (i, j)th sub-matrix of a matrix X, I_n shows the unit matrix of the n× n-dimension, E is an expectation operator, and $Ric(A, B, Q, R, P, K)$ is a set of matrices related to discrete-time algebraic Riccati equation.

2. PROBLEM FORMULATION

We consider electric power networks S with two subsystems. The overall dynamics of electric power networks is given by the

$$S : x(k + 1) = Ax(k) + Bu(k) + Hw(k) \tag{1}$$

where $k \in \mathbb{Z}_+$, $x \in \mathbb{R}^n$ is the state, $u \in \mathbb{R}^m$ is the input, $w \in \mathbb{R}^l$ is the white noise with variance W. x consists of $x_1 \in \mathbb{R}^{n1}$, $x_2 \in \mathbb{R}^{n2}$, $x_3 \in \mathbb{R}^{n3}$, u is composed of $u_1 \in \mathbb{R}^{m_1}$, $u_2 \in \mathbb{R}^{m_2}$, w consists of $w_1 \in \mathbb{R}^{l1}$, $w_2 \in$

$\mathbb{R}^{l2}$. Relation of these is represented as

$$x = [x_1^T, x_2^T, x_3^T]^T, \ n = n_1 + n_2 + n_3, \quad (2)$$
$$u = [u_1^T, u_2^T]^T, \ m = m_1 + m_2, \quad (3)$$
$$w = [w_1^T, w_2^T]^T, \ l = l_1 + l_2. \quad (4)$$

In this assumption, the state of power subsystem 1 is x_1, the state of power subsystem 2 is x_3, and the interaction state between two subsystems is x_2. u_1 is the input for subsystem 1, and u_2 is the input for subsystem 2.

The matrices, $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times m}$, and $H \in \mathbb{R}^{n \times l}$ are represented as

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix},$$

$$B = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \\ B_{31} & B_{32} \end{bmatrix}, H = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \\ H_{31} & H_{32} \end{bmatrix}. \quad (5)$$

We assume the situation like Fig. 2 where power subsystem 1 can measure state x_1, x_2, and power subsystem 2 can measure state x_1, x_2, x_3. For this system, we consider a decentralized feedback control law where subsystem 1 decides the input u_1 from x_1, x_2 and subsystem 2 decides the input u_2 from x_1, x_2, x_3.

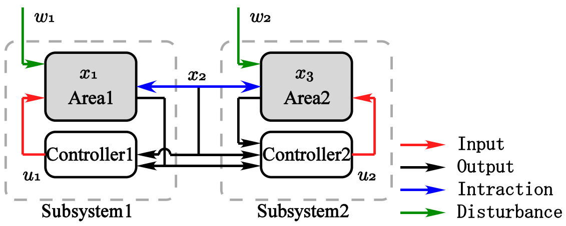


Fig. 2 Electric Power System

The part of the input dealing with the state directly, $u_x(k)$ has the following structure.

$$u_x(k) = -K \begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \end{bmatrix}, \quad (6)$$

where K is shown as Eq. (7).

$$K = \begin{bmatrix} K_{11} & K_{12} & 0 \\ K_{21} & K_{22} & K_{23} \end{bmatrix} \quad (7)$$

Here, the following performance index is defined as

$$J(x_0, u) = E[\sum_{k=0}^{\infty}(x^T Q x + u^T R u)], \quad (8)$$

where x_0 is the initial state of the system S, $Q \in \mathbb{R}^{n \times n}$ is a constant positive-semidefinite matrix, and $R \in \mathbb{R}^{m \times m}$ is a constant positive-definite matrix. Q and R are expressed by using $Q_1 \in \mathbb{R}^{n1 \times n1}$, $Q_2 \in \mathbb{R}^{n2 \times n2}$, $Q_3 \in \mathbb{R}^{n3 \times n3}$, $R_1 \in \mathbb{R}^{m1 \times m1}$, $R_2 \in \mathbb{R}^{m2 \times m2}$ as

$$Q = \mathrm{diag}\{Q_1, Q_2, Q_3\}, \quad R = \mathrm{diag}\{R_1, R_2\}. \quad (9)$$

We consider a feedback control to minimize Eq. (8) in this situation.

3. PROPOSED DECENTRALIZED CONTROL

3.1 Expansion of the state space of the system

To set up a decentralized feedback control law, we decompose the state x into two overlapping components, and expand the system S.

$$\tilde{S} : \tilde{x}(k+1) = \tilde{A}\tilde{x}(k) + \tilde{B}u(k) + \tilde{H}w(k) \quad (10)$$

where $\tilde{x} \in \mathbb{R}^{\tilde{n}}$ is composed of $\tilde{x}_1 = [x_1^T, x_2^T]^T$ and $\tilde{x}_2 = [x_2^T, x_3^T]^T$, $\tilde{x}_0$ is the initial state of the system $\tilde{S}$, $\tilde{A} \in \mathbb{R}^{\tilde{n} \times \tilde{n}}$, $\tilde{B} \in \mathbb{R}^{\tilde{n} \times m}$, $\tilde{H} \in \mathbb{R}^{\tilde{n} \times l}$ are constant matrices, and $\tilde{n}$ satisfies $\tilde{n} = n_1 + 2n_2 + n_3$.
We also expand performance index J as follows.

$$\tilde{J}(\tilde{x}_0, u) = E[\sum_{k=0}^{\infty}(\tilde{x}^T \tilde{Q}\tilde{x} + u^T \tilde{R} u)] \quad (11)$$

where $\tilde{x}_0$ is the initial state of the system $\tilde{S}$, $\tilde{Q} \in \mathbb{R}^{\tilde{n} \times \tilde{n}}$ is a constant positive-semidefinite matrix, and $\tilde{R} \in \mathbb{R}^{m \times m}$ is a constant positive-definite matrix. $\tilde{Q}$ and $\tilde{R}$ are expressed by using $\tilde{Q}_1 \in \mathbb{R}^{(n1+n2) \times (n1+n2)}$, $\tilde{Q}_2 \in \mathbb{R}^{(n2+n3) \times (n2+n3)}$, $\tilde{R}_1 \in \mathbb{R}^{m1 \times m1}$, $\tilde{R}_2 \in \mathbb{R}^{m2 \times m2}$ as

$$\tilde{Q} = \mathrm{diag}\{\tilde{Q}_1, \tilde{Q}_2\}, \quad \tilde{R} = \mathrm{diag}\{\tilde{R}_1, \tilde{R}_2\}. \quad (12)$$

Here, we introduce a linear transformation V and U.

$$V : \mathbb{R}^n \to \mathbb{R}^{\tilde{n}}, \ rank(V) = n \quad (13)$$
$$U : \mathbb{R}^{\tilde{n}} \to \mathbb{R}^n, \ rank(U) = n \quad (14)$$

These matrices satisfy $UV = I_n$. We relate (S, J) and $(\tilde{S}, \tilde{J})$ by the following definition.

Definition 1: The pair $(\tilde{S}, \tilde{J})$ includes the pair (S, J) if there exists a matrix V such that $\tilde{x}_0 = V x_0$ and following two equations are satisfied for any input $u(t)$.

$$x(k; x_0, u) = U\tilde{x}(k; \tilde{x}_0, u), \text{ for all } k \geq 0 \quad (15)$$
$$J(x_0, u) = \tilde{J}(x_0, u) \quad (16)$$

If $(\tilde{S}, \tilde{J})$ includes (S, J), then we say that $(\tilde{S}, \tilde{J})$ is an expansion of (S, J), and (S, J) is a contraction of $(\tilde{S}, \tilde{J})$.

We relate the matrices of $(\tilde{S}, \tilde{J})$ and (S, J) by using proper dimensions matrices M, N, N_H, M_Q, N_R as $\tilde{A} = VAU + M, \tilde{B} = VB + N, \tilde{H} = VH + N_H, \tilde{Q} = U^T QU + M_Q, \tilde{R} = R + N_R$. With this representation, the condition for the inclusion is given by the following theorem.

Theorem 1: The pair $(\tilde{S}, \tilde{J})$ includes The pair (S, J) if either
(i)

$$MV = 0, \ N = 0, \ N_H = 0, \quad (17)$$
$$V^T M_Q V = 0, \ N_R = 0 \quad (18)$$

or
(ii) for $i = 1, 2, \cdots, \tilde{n}$

$$UM^i V = 0, \ UM^{i-1}N = 0, \ UM^{i-1}N_H = 0, \quad (19)$$
$$M_Q M^{i-1} V = 0, M_Q M^{i-1} N = 0, \ N_R = 0. \quad (20)$$

Proof: The theorem can be proven based on [2]. ■
We choose matrices which satisfies (i) of this theorem as

$$V = \begin{bmatrix} I_{n1} & 0 & 0 \\ 0 & I_{n2} & 0 \\ 0 & I_{n2} & 0 \\ 0 & 0 & I_{n3} \end{bmatrix}, U = \begin{bmatrix} I_{n1} & 0 & 0 & 0 \\ 0 & \frac{1}{2}I_{n2} & \frac{1}{2}I_{n2} & 0 \\ 0 & 0 & 0 & I_{n3} \end{bmatrix},$$

$$N=0,\ N_H=0,\ M=\begin{bmatrix} 0 & \frac{1}{2}A_{12} & -\frac{1}{2}A_{12} & 0 \\ 0 & \frac{1}{2}A_{22} & -\frac{1}{2}A_{22} & 0 \\ 0 & -\frac{1}{2}A_{22} & \frac{1}{2}A_{22} & 0 \\ 0 & -\frac{1}{2}A_{32} & \frac{1}{2}A_{32} & 0 \end{bmatrix},$$

$$N_R=0,\ M_Q=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{1}{4}Q_2 & -\frac{1}{4}Q_2 & 0 \\ 0 & -\frac{1}{4}Q_2 & \frac{1}{4}Q_2 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}. \quad (21)$$

With this choice, the system S can be expanded to $\tilde{S}$ and the matrices $\tilde{A}$, $\tilde{B}$ and $\tilde{H}$ are described as

$$\tilde{A}=\left[\begin{array}{c|c} \tilde{A}_{11} & \tilde{A}_{12} \\ \hline \tilde{A}_{21} & \tilde{A}_{22} \end{array}\right]=\left[\begin{array}{cc|cc} A_{11} & A_{12} & 0 & A_{13} \\ A_{21} & A_{22} & 0 & A_{23} \\ \hline A_{21} & 0 & A_{22} & A_{23} \\ A_{31} & 0 & A_{32} & A_{33} \end{array}\right],$$

$$\tilde{B}=\left[\begin{array}{c|c} \tilde{B}_{11} & \tilde{B}_{12} \\ \hline \tilde{B}_{21} & \tilde{B}_{22} \end{array}\right]=\left[\begin{array}{c|c} B_{11} & B_{12} \\ B_{21} & B_{22} \\ \hline B_{21} & B_{22} \\ B_{31} & B_{32} \end{array}\right],$$

$$\tilde{H}=\left[\begin{array}{c|c} \tilde{H}_{11} & \tilde{H}_{12} \\ \hline \tilde{H}_{21} & \tilde{H}_{22} \end{array}\right]=\left[\begin{array}{c|c} H_{11} & H_{12} \\ H_{21} & H_{22} \\ \hline H_{21} & H_{22} \\ H_{31} & H_{32} \end{array}\right]. \quad (22)$$

3.2 Decentralized Control of Two Subsystems for the expanded system

Then, we consider the new system $\tilde{S}_D$ corresponding to the system $\tilde{S}$. $\tilde{S}_D$ is expressed as follows.

$$\tilde{S}_D : \tilde{x}(k+1)=\tilde{A}_D\tilde{x}(k)+\tilde{B}_Du(k)+\tilde{H}_Dw(k) \quad (23)$$

where $\tilde{A}_D, \tilde{B}_D$ and $\tilde{H}_D$ are block lower triangular matrices of $\tilde{A}, \tilde{B}$ and $\tilde{H}$ described as

$$\tilde{A}_D=\left[\begin{array}{c|c} \tilde{A}_{11} & 0 \\ \hline \tilde{A}_{21} & \tilde{A}_{22} \end{array}\right], \tilde{B}_D=\left[\begin{array}{c|c} \tilde{B}_{11} & 0 \\ \hline \tilde{B}_{21} & \tilde{B}_{22} \end{array}\right],$$

$$\tilde{H}_D=\left[\begin{array}{c|c} \tilde{H}_{11} & 0 \\ \hline \tilde{H}_{21} & \tilde{H}_{22} \end{array}\right]. \quad (24)$$

The performance index of the system $\tilde{S}_D$ is the same as Eq. (16).

For the system $\tilde{S}_D$ which has an information structure the decentralized feedback control to minimize Eq. (8) is shown as follows.

Theorem 2: [5] For the system $\tilde{S}_D$ with the information structure where subsystem 1 can measure state $\tilde{x}_1$, and subsystem 2 can measure state $\tilde{x}_1, \tilde{x}_2$, the decentralized feedback control to minimize Eq. (8) is shown below.

$$u_1(k)= -(\tilde{K}_p)_{11}\tilde{x}_1(k)-(\tilde{K}_p)_{12}\tilde{\eta}_2(k) \quad (25)$$

$$u_2(k)= -(\tilde{K}_p)_{21}\tilde{x}_1(k)-\tilde{J}\tilde{x}_2(k) -((\tilde{K}_p)_{22}-\tilde{J})\tilde{\eta}_2(k) \quad (26)$$

$$\tilde{\eta}_2(k+1)=(A_K)_{21}\tilde{x}_1(k)+(A_K)_{22}\tilde{\eta}_2(k) \quad (27)$$

where $A_K=\tilde{A}_D-\tilde{B}_D\tilde{K}$, $Ric(\tilde{A}_D, \tilde{B}_D, \tilde{Q}, \tilde{R}, P_1, \tilde{K}_p)$, and $Ric((\tilde{A}_D)_{22}, (\tilde{B}_D)_{22}, \tilde{Q}_2, \tilde{R}_2, P_2, \tilde{J})$. $\tilde{\eta}_2(k)$ is the estimation of $\tilde{x}_2(k)$ calculated from $\tilde{x}_1$.

Proof: Omitted. see [5]. ■

3.3 Contraction of State Feedback Law

The control law expressed above can be represented as $u(k)=u_x(k)+u_\eta(k)=-\tilde{K}\tilde{x}(k)-\tilde{K}_e\tilde{\eta}(k)$ where $\tilde{\eta}(k)$ is the estimation of $\tilde{x}(k)$. We use this control method into the system $\tilde{S}$ and contract the method to match the system S. We assume $\eta(k)$ for the system S corresponding to $\tilde{\eta}(k)$ for the system $\tilde{S}$ and $u(k)=-\tilde{K}\tilde{x}-\tilde{K}_e\tilde{\eta}(k)$ can contract to $u(k)=-Kx(k)-K_e\eta(k)$. To find condition of contractability, we define contractability of the estimation and control input.

Definition 2: $\tilde{\eta}(k)$ is contractible to $\eta(k)$ if

$$\eta(k;x_0,u)=U\tilde{\eta}(k;\tilde{x}_0,u), \text{ for all } k\geq 0. \quad (28)$$

Definition 3: We regard $u(k)=-\tilde{K}\tilde{x}-\tilde{K}_e\tilde{\eta}(k)$ as the control input of the system $\tilde{S}$ and $u(k)=-Kx(k)-K_e\eta(k)$ as the control input of the system S. $u(k)=-\tilde{K}\tilde{x}-\tilde{K}_e\tilde{\eta}(k)$ is contractible to $u(k)=-Kx(k)-K_e\eta(k)$ if following two equations are satisfied for any input $u(t)$.

$$Kx(k;x_0,u)=\tilde{K}\tilde{x}(k;\tilde{x}_0,u), \text{ for all } k\geq 0 \quad (29)$$

$$K_e\eta(k;x_0,u)=\tilde{K}_e\tilde{\eta}(k;\tilde{x}_0,u), \text{ for all } k\geq 0 \quad (30)$$

We relate matrices such as $\tilde{K}=KU+F, \tilde{K}_e=K_eU+F_e$, then the condition for the contractability is given by the following Theorem. This is a main result in this paper.

Theorem 3: $-\tilde{K}\tilde{x}-\tilde{K}_e\tilde{\eta}(k)$ is contractible to $-Kx(k)-K_e\eta(k)$ if $\tilde{\eta}$ can contract to η and for $i=1,2,\cdots,\tilde{n}$

$$FM^iV=0,\ FM^{i-1}N=0,$$
$$FM^{i-1}N_H=0, F_e=0. \quad (31)$$

Proof: $Kx(k;x_0,u)$ and $\tilde{K}x(k;\tilde{x}_0,u)$ are expressed as follows.

$$Kx(k;x_0,u)=$$
$$KA^kx_0+\sum_{i=0}^{k}\{KA^{k-i}Bu(i)+KA^{k-i}Hw(i)\} \quad (32)$$

$$\tilde{K}x(k;\tilde{x}_0,u)=$$
$$\tilde{K}\tilde{A}^k\tilde{x}_0+\sum_{i=0}^{k}\{\tilde{K}\tilde{A}^{k-i}\tilde{B}u(i)+\tilde{K}\tilde{A}^{k-i}\tilde{H}w(i)\} \quad (33)$$

It can be said that Eqs. (29) and (30) are equal as follows from these Eqs. and Definition 2.

$$KA^k=\tilde{K}\tilde{A}^kV, KA^{k-i}B=\tilde{K}\tilde{A}^{k-i}\tilde{B} \quad (34)$$

$$KA^{k-i}H=\tilde{K}\tilde{A}^{k-i}\tilde{H}, K_eU=\tilde{K}_e \quad (35)$$

We substitute Eqs. defined previous subsections and use Eqs. in Theorem 1 for Eqs. (34) and (35). By comparing right-hand side and left-hand side of Eqs. (34) and (35), Eq. (31) is derived. ■

We choose matrices which satisfies this Theorem as

$$F_e=0. \quad (36)$$

Then, we get the decentralized control law of smart grid. The control input is shown below.

$$\left[\begin{array}{c} u_1(k) \\ \hline u_2(k) \end{array}\right]=-\left[\begin{array}{cc|c} (\tilde{K}_{11})_1 & (\tilde{K}_{11})_2 & 0 \\ \hline (\tilde{K}_{21})_1 & (\tilde{K}_{21})_2+\tilde{J}_1 & \tilde{J}_2 \end{array}\right]\begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \end{bmatrix} -\left[\begin{array}{c} \tilde{K}_{12} \\ \hline \tilde{K}_{22}-\tilde{J} \end{array}\right]\begin{bmatrix} \eta_2(k) \\ \eta_3(k) \end{bmatrix} \quad (37)$$

$$\begin{bmatrix} \eta_2(k+1) \\ \eta_3(k+1) \end{bmatrix}=(A_K)_{21}\begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix}+(A_K)_{22}\begin{bmatrix} \eta_2(k) \\ \eta_3(k) \end{bmatrix} \quad (38)$$

4. APPLICATION FOR SMART GRID CONTROL

4.1 Electric Power System

We consider electric power network shown in Fig.3. It focuses on Load frequency and is composed of two power systems. There are a thermal power plant and a wind power plant in Area 1 and there are a battery system and micro gas turbine generators in Area 2 and the power supply is done to the electric power demand with these power generations. The detail and dynamics of the electric power network is shown below.

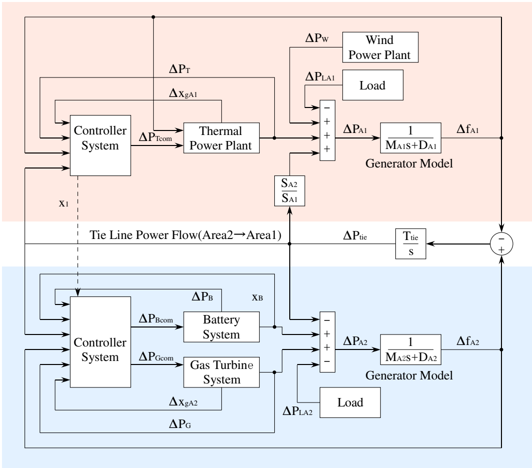


Fig. 3 Power Network Model

4.1.1 Relationships of demand and supply

Relationships between electric demand and supply is shown in Eq. (39).

$$M\frac{d\Delta f(t)}{dt} = \Delta P_m(t) - \Delta P_e(t) \tag{39}$$

$\Delta P_m(t)$ is mechanical input of generator, $\Delta P_e(t)$ is an electric output of generator, M is a inertia constant of generator, and $\Delta f(t)$ is a deviation of rotating velocity of generator. System frequency changing, rotation frequency of rotating load power consumption shift. This is described as follows.

$$\Delta P_e(t) = \Delta P_L(t) + D\Delta f(t) \tag{40}$$

$\Delta P_L(t)$ is a load deviation and D is a damping constant. In addition, when it is assumed that all generators in one system are completely synchronous driving, system can be expressed as one equivalent model like Fig 4. M_{eq} is a inertia constant of equivalent generator.

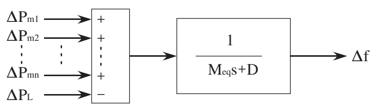


Fig. 4 Equivalent Generator Model

4.1.2 Tie-Line Power Flow

By DC method, the tie-line power flow from Area 2 to Area 1 $P_{tie}(t)$ is expressed like Eq. (41).

$$P_{tie}(t) = \frac{1}{X_T}(\delta_{A2}(t) - \delta_{A1}(t)) \tag{41}$$

X_T is the reactance of the interconnected line between Area 1 and Area 2 and $\delta_{A1}(t)$, $\delta_{A2}(t)$ are phase angles of each system. Using Frequency deviations of each system $\Delta f_{A1}(t)$, $\Delta f_{A2}(t)$, $\Delta P_{tie}(t)$, the deviation of $P_{tie}(t)$, is represented as Eq. (42).

$$\Delta P_{tie}(t) = \frac{T_{tie}}{s}(\Delta f_{A2}(t) - \Delta f_{A1}(t)) \tag{42}$$

T_{tie} is a synchronizing coefficient. If there is 50Hz area, then $T_{tie} = 100\pi/X_T$.

4.1.3 Thermal Power Plant and Micro Gas Turbine Generator

In this paper, thermal power plant is assumed that all generators in the thermal power plant are completely synchronous driving and can be expressed as one equivalent model like Fig 5.

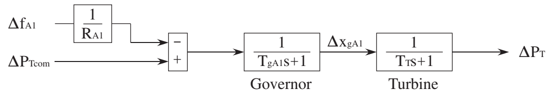


Fig. 5 Thermal Power Plant Model

$\Delta P_{Tcom}(t)$ is a change command of production of electricity, R_{A1} is a regulation constant, T_{gA1} is a governor time constant, and T_T is a gas turbine constant. Micro gas turbine generator also can be expressed as one equivalent model like Fig 5 but it is assumed that micro gas turbine generator operates without governor free. $\Delta P_{Gcom}(t)$ is a change command of production of electricity, T_{gA2} is a governor time constant, and T_G is a gas turbine constant. Micro gas turbine generator moves more quickly than thermal power plant, which means T_G is smaller than T_T.

4.1.4 Battery system

It is assumed that Battery system has a delay in response of inverters and this is expressed with first-order lag like Eq. (43). $\Delta P_{Bcom}(t)$ is a change command of discharge and charge of electricity, T_B is an inverter time constant. The state of discharge and charge $x_B(t)$ is expressed with discharge and charge amount $\Delta P_B(t)$ and discharge and charge efficient value K_B like Eq. (44).

$$\Delta P_B(t) = -\frac{1}{T_B}\Delta P_B(t) + \frac{1}{T_B}\Delta P_{Bcom}(t) \tag{43}$$

$$\dot{x}_B(t) = -K_B\Delta P_B(t) \tag{44}$$

4.1.5 Controller

It is assumed that each controller system calculates integration of AR, $U_{A1}(t)$ and $U_{A2}(t)$. While the controller system of Area 1 calculates by FFC method, the controller system of Area 2 calculates by TBC method.

$$\dot{U}_{A1}(t) = -K_{A1}f\Delta f_{A1}(t) \tag{45}$$

$$\dot{U}_{A2}(t) = -K_{A2}f\Delta f_{A2}(t) - \Delta P_{tie}(t) \tag{46}$$

K_{A1}, K_{A2} are system constants, f is a standard frequency, and $\Delta f_{A1}(t)$, $\Delta f_{A2}(t)$ are deviations of frequencies of each area.

The controller system of Area 2 decides a command of production of electricity $\Delta P_{A2com}(t)$ and divides it into

$\Delta P_{Gcom}(t)$ and $\Delta P_{Bcom}(t)$ with the ratio of each rated capacity.

$$\Delta P_{Gcom}(t) = \frac{S_G}{S_G + S_B} \Delta P_{A2com}(t) \tag{47}$$

$$\Delta P_{Bcom}(t) = \frac{S_B}{S_G + S_B} \Delta P_{A2com}(t) \tag{48}$$

We regard load fluctuation and wind power fluctuation as disturbances made by reference to actual fluctuation.

4.2 Expression of State Space on Smart Grid

By preceding section, we can represent the smart grid shown in Fig.3 the state space as in Eq. (49).

$$\dot{x}(t) = A_c x(t) + B_c u(t) + H_c w(t) \tag{49}$$

$$x(t) = \begin{bmatrix} x_1(t) \\ \hline x_2(t) \\ \hline x_3(t) \end{bmatrix} = \begin{bmatrix} \Delta f_{A1}(t) \\ \Delta P_T(t) \\ \Delta x_{gA1}(t) \\ U_{A1}(t) \\ \hline \Delta P_{tie}(t) \\ \hline \Delta f_{A2}(t) \\ \Delta P_G(t) \\ \Delta x_{gA2}(t) \\ x_B(t) \\ \Delta P_B(t) \\ U_{A2}(t) \end{bmatrix} \tag{50}$$

$$u(t) = \begin{bmatrix} u_{A1}(t) \\ \hline u_{A2}(t) \end{bmatrix} = \begin{bmatrix} \Delta P_{Tcom}(t) \\ \hline \Delta P_{A2com}(t) \end{bmatrix} \tag{51}$$

$$w(t) = \begin{bmatrix} w_{A1}(t) \\ \hline w_{A2}(t) \end{bmatrix} = \begin{bmatrix} \Delta P_W(t) - P_{LA1}(t) \\ \hline \Delta - P_{LA2}(t) \end{bmatrix} \tag{52}$$

$$A_c = \begin{bmatrix} A_{c11} & A_{c12} & A_{c13} \\ A_{c21} & A_{c22} & A_{c23} \\ A_{31} & A_{c32} & A_{c33} \end{bmatrix} =$$

$$\begin{bmatrix} -\frac{D_{A1}}{M_{A1}} & \frac{1}{M_{A1}} & 0 & 0 & \frac{S_{A2}}{M_{A1}S_{A1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{T_T} & \frac{1}{T_T} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{T_{gA1}R_{A1}} & 0 & -\frac{1}{T_{gA1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -K_{A1}f & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -T_{tie} & 0 & 0 & 0 & 0 & T_{tie} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{M_{A2}} & -\frac{D_{A2}}{M_{A2}} & \frac{1}{M_{A2}} & 0 & 0 & \frac{1}{M_{A2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_G} & \frac{1}{T_G} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{gA2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -K_B & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_B} & 0 \\ 0 & 0 & 0 & 0 & -1 & -K_{A2}f & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{53}$$

$$B_c = \begin{bmatrix} B_{c11} & B_{c12} \\ B_{c21} & B_{c22} \\ B_{c31} & B_{c32} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{T_{gA1}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{S_G}{T_{gA2}(S_G+S_B)} \\ 0 & 0 \\ 0 & \frac{S_B}{T_B(S_G+S_B)} \\ 0 & 0 \end{bmatrix} \tag{54}$$

$$H_c = \begin{bmatrix} H_{c11} & H_{c12} \\ H_{c21} & H_{c22} \\ H_{c31} & H_{c32} \end{bmatrix} = \begin{bmatrix} \frac{1}{M_{A1}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{1}{M_{A2}} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{55}$$

To treat this system as discrete system, it is converted by the sampling time T.

$$x(k+1) = Ax(k) + Bu(k) + Hw(k) \tag{56}$$

The control object is to minimize the following cost function (57) and we assume the situation that the controller system of Area 1 decides $\Delta P_{Tcom}(t)$ by $x_1(t), x_2(t)$ and the controller system of Area 2 determines $\Delta P_{A2com}(t)$ by $x_1(t), x_2(t), x_3(t)$. the parameters of the cost function are made $Q = \text{diag}\{100\ 0\ 0\ 10\ 10\ 100\ 0\ 0\ 10\ 0\ 10\}$, $R = 5I_2$.

$$J(x_0, u) = E[\sum_{k=0}^{\infty}(x^T Q x + u^T R u)] \tag{57}$$

To apply the decentralized control of two subsystems with overlapping information in preceding chapter, we expand the system (56), then, we get the expanded system (58) and the new cost function (59) by using matrices in Eq. (21).

$$\tilde{x}(k+1) = \tilde{A}\tilde{x}(k) + \tilde{B}u(k) + \tilde{H}w(k) \tag{58}$$

$$\tilde{J}(\tilde{x}_0, u) = E[\sum_{k=0}^{\infty}(\tilde{x}^T \tilde{Q} \tilde{x} + u^T \tilde{R} u)] \tag{59}$$

We consider the new system $\tilde{S}_D$ corresponding to the system $\tilde{S}$, derive a decentralized control of two subsystems, and contract this decentralized control law. We verify power fluctuations and frequency deviations and compare the proposed decentralized control, a centralized control, and other decentralized controls. The parameters of power network are shown below.

Table 1 Simulation Parameters

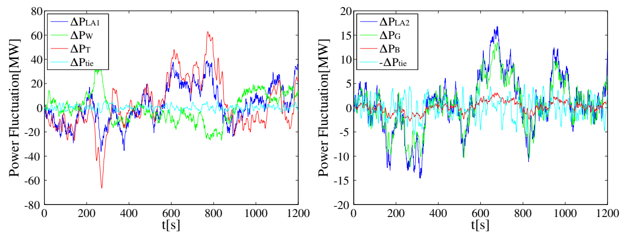
standard frequency f[Hz]	50
Area1 system capacity S_{A1}[MW]	3000
Area1 inertia constant M_{A1}[s]	10
Area1 damping constant D_{A1}[p.u.]	1
Area1 system constant K_{A1}[% MW]	0.1
Area1 gas turbine constant T_T[s]	9
Area1 governor time constant T_{gA1}[s]	0.25
Area1 regulation constant R_{A1}[s]	0.05
Area2 system capacity S_{A2}[MW]	900
Area2 inertia constant M_{A2}[s]	10
Area2 damping constant D_{A2}[p.u.]	2
Area2 system constant K_{A2}[% MW]	0.1
Area2 gas turbine constant T_G[s]	1
Area2 governor time constant T_{gA2}[s]	1
Area2 inverter time constant T_B[s]	1
Area2 gas turbine rated capacity S_G[MW]	900
Area2 battery rated capacity S_B[MW]	200
Area2 discharge and charge efficient value K_B	0.94
synchronizing coefficient T_{tie}[s]	2.0
sampling time T[s]	1

4.3 Simulation Results

We simulates the effectiveness of the proposed method by using Matlab R2011a.

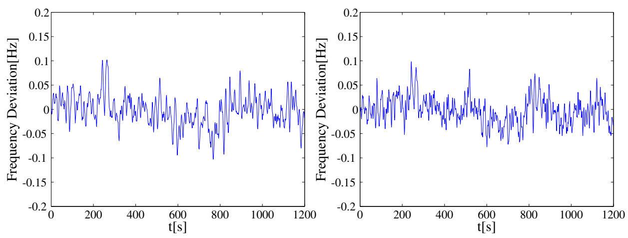
4.3.1 Power Fluctuation and Frequency Deviation

When applying the proposed method, power fluctuations and frequency deviations in each area are shown in Fig 6 and Fig 7. In Fig 6 (a), the blue line is the load fluctuation of area 1 $P_{LA1}(t)$, the greenish yellow line is the wind power fluctuation $P_W(t)$, the red line is fluctuation of the output of the thermal power plant $P_T(t)$, and the light blue line is fluctuation of the tie-line power flow between area 1 and area 2 $P_{tie}(t)$. In Fig 6 (b), the blue line is the load fluctuation of area 2 $P_{LA2}(t)$, the greenish yellow line is fluctuation of the output of the micro gas turbine generator $P_G(t)$, the red line is fluctuation of the output of the battery system $P_B(t)$, and the light blue line is fluctuation of the tie-line power flow between area 1 and area 2 -$P_{tie}(t)$. From Fig 6, we can see the outputs of controllable generators (thermal power plant, micro gas turbine generator and battery system) change to adapt fluctuations of load and wind power. That means these generators correct imbalances between electric demand and supply and stabilize power networks. In addition, we can also see stabilization of frequency deviations in Fig 7, which range within ± 0.2[Hz].



(a)Area 1 (b)Area 2

Fig. 6 Power Fluctuation



(a)Area 1 (b)Area 2

Fig. 7 Frequency Deviation

4.3.2 Comparison of Cost Function Value

Cost function value of k=800[s] is shown in Fig 8. Here, in Fig 8, C is the proposed decentralized control method, Cc is the centralized control method, and Co is the decentralized control method of [2]. From Fig 8, the cost value of the proposed method is second lower after the centralized control method and lowest among the decentralized control methods.

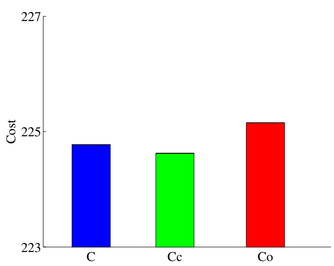


Fig. 8 Comparison of Cost (k=800)

5. CONCLUSION

In this paper, we applied the decentralized control of smart grid by using overlapping information to control of load frequency of power networks that installed distributed generations. We expanded the state space of the system ,got a decentralized feedback law for the expanded system and contract the decentralized feedback law to match the original system. Then, we simulated decentralized large scale power network systems, and showed the effectiveness of the load frequency control by using the proposed decentralized control method by verifying power fluctuation and frequency deviation and comparison between the proposed method and other methods.

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