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A Method to Determine the Distributed Control Setting of Looping Devices for Active Distribution Systems

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***Abstract*--To improve operational flexibility, we proposed the loop or mesh structure for distribution systems using looping device called loop power flow controller (LPC) at the opened switch which can connect the adjoining feeder as an active distribution system. LPC is able to optimally control distribution systems in the points of reducing voltage rise, voltage fluctuation and loss minimum power flow control, and so on, with acquisition of state of distribution systems.**

Adapting to the area that cannot use communication system, points of view at the power quality for the transition phenomena, as assistance to the central control, we also required the distributed control using local voltage information for the LPC control.

The purposes of this paper are the application of the proposed determination method for control coefficients using optimal operation pattern of LPC and local voltage information to two LPC and the confirmation of its validity by simulation. The distributed control using these control coefficients was verified by two 6.6kV 100kVA BTB (back to back) type LPC and distribution system testing facility in CRIEPI.

***Index Terms*—loop power flow controller, voltage control, power flow control, distributed control, optimal coefficients setting, active distribution systems**

I. Introduction

THE uncertainty on power distribution systems needs more operational flexibility. For example, it's able to think that active distribution systems are one of the measures for large introduction of renewable energy resource into the distribution systems. A looping device improves controllability on distribution systems and its relocate ability is a promising solution for operational flexibility. We proposed loop or mesh structure for the distribution systems using looping device called loop power flow controller (LPC) at the opened switch which can connect the adjoining feeder as an active distribution system. LPC is able to optimally control distribution systems in the points of reducing voltage rise, voltage fluctuation and loss minimum power flow control, and so on, with acquisition of state of distribution systems. Adapting to the area that cannot use communication system, points of view at the power quality for the transition phenomena, as assistance to the central control, it's also required the distributed control using local voltage information for the LPC control [1]. In this paper, a method to determine coefficients of the distributed control is verified by simulation and experiment with two LPC.

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II. Control Model of Active Distribution Systems

A. Approximation to optimal operation

In approximation to the optimal operation by using distributed control, the problem is how to choose the control coefficients A which is shown in the Fig. 1. We use optimal data sets (Y^O, X^O) that were calculated in advance. And distributed control coefficient A is solved by the least squares method with the optimal data sets.

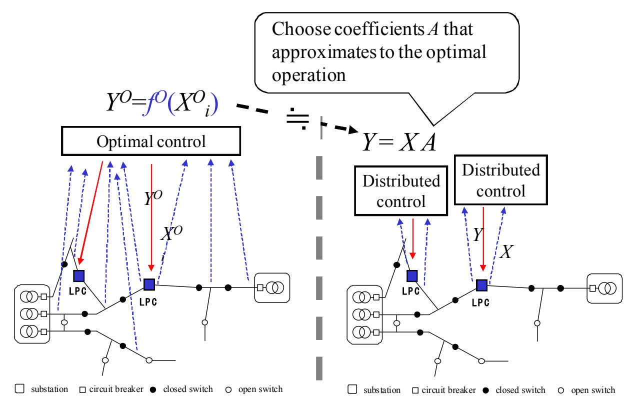


Fig. 1. A general idea of distributed control that approximates to the optimal operation

B. Distributed Control

When a LPC is installed in a normally open switch, the voltage of the two feeders is obtained as local information. Therefore, as shown in Fig. 2, the voltage V_i, V_j of the two feeders and the phase difference θ_{ij} between the two feeders are obtained. The sending voltage V_{si}, V_{sj} of feeders is managed by the voltage control of on load tap changer at transformers located in the distribution substation. If a difference of the loads and the DGs of the two feeders can be observed as a voltage difference at the normally open switch, the LPC can control the loop power flow using the local voltage information. Theoretically, the voltage of the power system is controlled by reactive power. Here however we would like to focus on the line resistance (R) close to the line inductive reactance (X) for Japanese 6.6kV overhead distribution lines. Furthermore line resistance higher than inductive reactance for distribution cable lines.

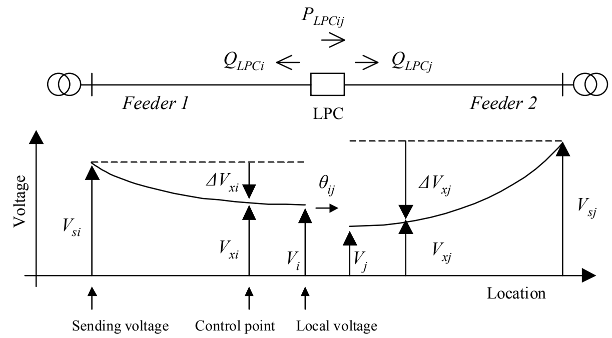


Fig. 2. Connection of two feeders with looping device

The case where the installation point of the LPC and control points (V_{xi}, V_{xj}) are separated is discussed in the Fig. 2. The voltage of the control point is presumed as following.

$$V_{xi} = v_x\left(V_i, P_{LPCij}, Q_{LPCi}, R_i, X_i\right) \tag{1}$$

$$V_{xj} = v_x\left(V_j, -P_{LPCij}, Q_{LPCj}, R_j, X_j\right) \tag{2}$$

The impedances ((R_i, X_i), (R_j, X_j)) of the line are from the LPC of feeder 1 and feeder 2 to the control points (V_{xi}, V_{xj}), P_{LPCij} is power flow of LPC, Q_{LPCi} and Q_{LPCj} are reactive power of LPC, V_i and V_j are the local voltage of LPC.

Here, $v_x(.)$ is

$$v_x\left(v,p,q,r,x\right) = \sqrt{\left(v + \frac{pr - qx}{v}\right)^2 + \left(\frac{qr + px}{v}\right)^2} \ . \tag{3}$$

The following shows a simple method of power flow control using terminal voltages:

$$P_{LPCij} = G_{pij}\left(V_{xi} - V_{xj}\right) + P_{cij} \tag{4}$$

where, V_{xi} and V_{xj} are the voltages of control points shown in Fig. 2. G_{pij} is the loop power flow gain based on the voltage difference. P_{LPCij} is loop power flow controlled by LPC. P_{cij} is constant of the P_{LPCij}.

Similarly, a method of controlling the reactive power is shown in the following equations.

$$Q_{LPCi} = G_{qi}\left(V_{xi} - V_{ri}\right) \tag{5}$$

$$Q_{LPCj} = G_{qj}\left(V_{xj} - V_{rj}\right) \tag{6}$$

Here, G_{qi} and G_{qj} are the gain of the reactive power control. V_{ri} and V_{rj} are reference voltages of the feeders. Q_{LPCi} and Q_{LPCj} are the reactive power of both terminals.

C. Optimal Control

We use a combination of minimization of power transmission loss and minimization of square of the voltage error as the objective function. The optimum power-flow (OPF) problem [2] of time sections t using this objective function is shown by the following equation.

$$\left.\begin{array}{l} \text{minimize} \quad f\left(x\left(t\right)\right) \\ \text{subject to} \quad h\left(x\left(t\right)\right) = 0, \underline{g} \le g\left(x\left(t\right)\right) \le \overline{g} \end{array}\right\} \tag{7}$$

Here, $f(x(t))$ is the objective function. $h(x(t))$ is the power equation. $\underline{g} \le g(x(t)) \le \overline{g}$ is the constrained condition.

D. Determination of Coefficients

In order to obtain optimum operation and local voltage of the LPC, results of the OPF problem are used as optimal operations. The power demand $P_{Li}(t)$, $Q_{Li}(t)$ and the generator output $P_{Gi}(t)$, $Q_{Gi}(t)$ are given to (7), and the optimum operation $P^O{}_{LPCij}(t)$, $Q^O{}_{LPCi}(t)$, $Q^O{}_{LPCj}(t)$ of LPC and the voltage $V^O{}_i(t)$ of each node obtained in each time section t.

The optimum operation $P^O{}_{LPCij}(t)$, $Q^O{}_{LPCi}(t)$, $Q^O{}_{LPCj}(t)$ of the LPC and the relation of local voltage $V^O{}_i(t)$ are approximated by the relational expression of the distributed control shown in (4)~(6). Here, the least-squares method is used for the determination of coefficients (G_{pij}, G_{qi}, G_{qj}, V_{ri}, V_{rj} and P_{cij}) in the relational expression of distributed control.

The determination of the coefficient of a distributed control rule is formulized as the least-squares method problem.

$$Y = XA \tag{8}$$

Here, the optimum operation of the LPC is Y. The local voltage is X. The control coefficient is A. The control coefficient A of distributed control can be found as follows by the least-squares method.

$$A = (X^TX)^{-1}X^TY \tag{9}$$

The equation (4) is arranged as following.

$$\begin{array}{l} P^O_{LPCij}\left(t\right) = G_{pij}\Delta V^O_{xij}\left(t\right) + P_{cij}, \\ \Delta V^O_{xij}\left(t\right) = V^O_{xi}\left(t\right) - V^O_{xj}\left(t\right) \end{array} \tag{10}$$

The optimum operation Y, the local voltage X, and the control coefficient A of the LPC are

$$Y = \begin{bmatrix} P^O_{LPCij}(1) \\ P^O_{LPCij}(2) \\ \vdots \\ P^O_{LPCij}(t) \end{bmatrix}, X = \begin{bmatrix} \Delta V^O_{xij}(1) & 1 \\ \Delta V^O_{xij}(2) & 1 \\ \vdots & \vdots \\ \Delta V^O_{xij}(t) & 1 \end{bmatrix}, A = \begin{bmatrix} G_{pij} \\ P_{cij} \end{bmatrix} \ . \tag{11}$$

These are substituted for (9), and the control coefficients G_{pij} and P_{cij} can be found.

To determine the control coefficients of reactive power, (5) is arranged and set to following.

$$Q^O_{LPCi}\left(t\right) = G_{qi}V^O_{xi}\left(t\right) - G_{qi}V_{ri} \tag{12}$$

The optimum operation Y, the local voltage X, and the control coefficient A of the LPC are

$$Y = \begin{bmatrix} Q^O_{LPCi}(1) \\ Q^O_{LPCi}(2) \\ \vdots \\ Q^O_{LPCi}(t) \end{bmatrix}, X = \begin{bmatrix} V^O_{xi}(1) & 1 \\ V^O_{xi}(2) & 1 \\ \vdots & \vdots \\ V^O_{xi}(t) & 1 \end{bmatrix}, A = \begin{bmatrix} G_{qi} \\ -G_{qi}V_{ri} \end{bmatrix} \ . \tag{13}$$

These are substituted for (9) and the control coefficients G_{qi} and V_{ri} can be found. Similarly, the control coefficient G_{qj} and V_{rj} can be found from (6).

III. Simulation

A. Model

A simulation model of active distribution system with LPC is shown in Fig. 3. The model is based on full-scale simulated distribution system in Akagi testing center of CRIEPI. Two transformers are installed in the distribution substation. The rated voltage and capacity of each transformer are

66kV/6.6kV and 2MVA respectively. And cable feeders, overhead feeders and simulated feeders are installed in the testing field. The branch impedance of the simulation model is listed in table I. Two looping devices (LPC) which are able to control loop power flow and reactive power are installed in node n7-n26 and n11-n23. And these LPC are designed based on BTB (back to back) converter technology [3]. Load and DG (distributed generation) were located in node n7 and n11.

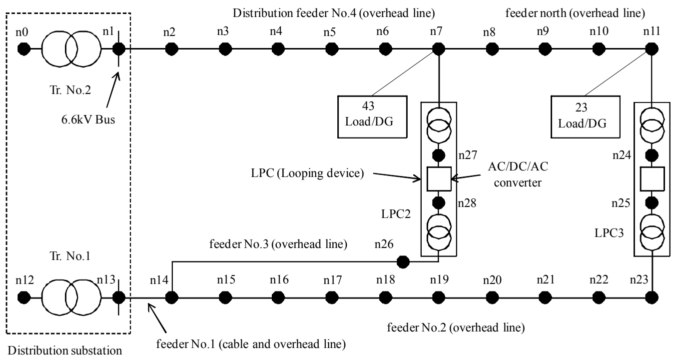


Fig. 3. A simulation model of active distribution system with LPC based on distribution system in Akagi testing center of CRIEPI

TABLE I
INCIDENCE MATRIX AND IMPEDANCE OF BRANCH

Branch	Node A	Node B	R(Ω)	X(Ω)	Attribute
b0	n0	n1	0	1.25	Tr. No. 2
b1	n1	n2	0.3783	1.045	Feeder No. 4
b2	n2	n3	0.3783	1.045	Feeder No. 4
b3	n3	n4	0.3783	1.045	Feeder No. 4
b4	n4	n5	0.7767	1.11	Feeder No. 4
b5	n5	n6	0.7767	1.11	Feeder No. 4
b6	n6	n7	0.7767	1.11	Feeder No. 4
b7	n7	n8	0.756	0.756	Feeder north
b8	n8	n9	0.756	0.756	Feeder north
b9	n9	n10	0.756	0.756	Feeder north
b10	n10	n11	0.756	0.756	Feeder north
b11	n12	n13	0	1.22	Tr. No. 1
b12	n13	n14	0.0787	0.065	Feeder No. 1
b13	n14	n15	0.695	1.028	Feeder No. 2
b14	n15	n16	0.695	1.028	Feeder No. 2
b15	n16	n17	0.695	1.028	Feeder No. 2
b16	n17	n18	0.695	1.028	Feeder No. 2
b17	n18	n19	0.695	1.028	Feeder No. 2
b18	n19	n20	0.695	1.028	Feeder No. 2
b19	n20	n21	0.695	1.028	Feeder No. 2
b20	n21	n22	0.695	1.028	Feeder No. 2
b21	n22	n23	0.695	1.028	Feeder No. 2
b22	n11	n24	4	7.46	LPC-3 Tr. A
b23	n23	n25	4	7.46	LPC-3 Tr. B
b24	n14	n26	0.3	0.3	Feeder No. 3
b25	n7	n27	4	7.46	LPC-2 Tr. A
b26	n26	n28	4	7.46	LPC-2 Tr. B

In this simulation, we used 21 cases of load consumption and DG output combinations. The sets of bus voltage at on load tap changer and active and reactive power at load and DG bus are shown in table II. Here, the primary voltage of Tr. No.1 and 2 is converted into the secondary voltage 6.6kV and the on load tap changer is simulated with the voltage of node n0 and n12.

TABLE II
SETS OF BUS VOLTAGE AT ON LOAD TAP CHANGER AND ACTIVE AND REACTIVE POWER AT LOAD AND DG BUS

Case	On load tap changer		43 Load and DG		23 Load and DG	
	V0 (V)	V12 (V)	P7 (kW)	Q7 (kVar)	P11 (kW)	Q11 (kVar)
1	6600	6600	0	0	0	0
2	6600	6600	20	10	20	10
3	6600	6600	30	20	30	20
4	6600	6600	50	30	50	30
5	6720	6600	70	40	70	40
6	6720	6600	80	50	80	50
7	6720	6600	100	60	100	60
8	6600	6600	-75	0	-60	0
9	6600	6600	-55	10	-40	10
10	6600	6600	-45	20	-30	20
11	6600	6600	-25	30	-10	30
12	6720	6600	-5	40	10	40
13	6720	6600	5	50	20	50
14	6720	6600	25	60	40	60
15	6600	6600	-150	0	-120	0
16	6600	6600	-130	10	-100	10
17	6600	6600	-120	20	-90	20
18	6600	6600	-100	30	-70	30
19	6720	6600	-80	40	-50	40
20	6720	6600	-70	50	-40	50
21	6720	6600	-50	60	-20	60

B. *Setting of control point*

The control points of the distributed control are set at around the connection point of LPC. For example, n7, n26 and n11, n23 are connection points of LPC2 and LPC3 respectively. Table III shows R and X setting for voltage estimation of control point. The voltage sensor of this LPC is located on between the convertor and the transformer. Therefore these R and X include the impedance of the transformer for the interconnection.

TABLE III
R AND *X* FOR ESTIMATING CONTROL POINTS

Item	LPC2	LPC3
$R1$	7	7
$X1$	11	11
$R2$	7	7
$X2$	11	11

C. *Objective function*

We used a objective function $f(x(t))$ for a time section t.

$$f\left(x(t)\right)=\sum_{i=0}^{m}a_i G_{jk}\left\{\left(e_j(t)-e_k(t)\right)^2+\left(f_j(t)-f_k(t)\right)^2\right\} +\sum_{i=0}^{n}b_i\left\{\sqrt{e_i^2(t)+f_i^2(t)}-V_{refi}\right\}^2 \quad (14)$$

$$(\, j=brA(i),\ k=brB(i)\,)$$

a_i is a coefficient of power transmission loss. G_{jk} is a real part of the admittance between node j and k. $e_i(t)$ and $f_i(t)$ are real and imaginary part of a node i voltage on a time section t, respectively. $j=brA(i)$ and $k=brB(i)$ are node numbers for a branch i, which is shown in Table I. m is the number of branches. b_i is a coefficient of the square of voltage error on a node i. V_{refi} is a reference voltage of node i. n is the number of nodes.

The weighting factor and reference voltage using in this paper are shown in table IV.

TABLE IV
WEIGHTING FACTOR AND REFERENCE VOLTAGE OF OBJECTIVE FUNCTION

Branch	a_i	Node	b_i	V_{refi}
b0	0	n0	0	0
b1	1	n1	0	0
b2	1	n2	0	0
b3	1	n3	0	0
b4	1	n4	0.03	6600
b5	1	n5	0.03	6600
b6	1	n6	0.03	6600
b7	1	n7	0.03	6600
b8	1	n8	0.03	6600
b9	1	n9	0.03	6600
b10	1	n10	0.03	6600
b11	0	n11	0.03	6600
b12	1	n12	0	0
b13	1	n13	0	0
b14	1	n14	0	0
b15	1	n15	0	0
b16	1	n16	0	0
b17	1	n17	0	0
b18	1	n18	0	0
b19	1	n19	0	0
b20	1	n20	0	0
b21	1	n21	0	0
b22	1	n22	0	0
b23	1	n23	0	0
b24	1	n24	0	0
b25	1	n25	0	0
		n26	0	0
		n27	0	0
		n28	0	0

D. Control coefficient

The control coefficients are determined with (9), (11), (13) and the result of optimal operation on (7). Table V shows control coefficients which are determined by using case 2~7 of on load tap changer, load and DG conditions shown in table II.

TABLE V
SETTING OF CONTROL COEFFICIENTS, SETTING A

Item	LPC2	LPC3
G_p	319.32	768.72
P_c	-16861	-374.20
G_{q1}	-648.44	-632.38
V_{r1}	6611.1	6598.4
G_{q2}	39.836	-42.130
V_{r2}	6605.0	6594.2

Figure 4 shows the comparison of distributed and optimal control for the case 1~21. Here, the case number in table II means the time section t which is described in (7). Evaluated value shown in Fig. 4 are normalized for the sum of optimal controlled case 1~21.

The distributed control of the case 1~7 are good agreement with optimal control. However, the evaluated value of distributed control on the case 8~21 are a little bigger than the optimal control.

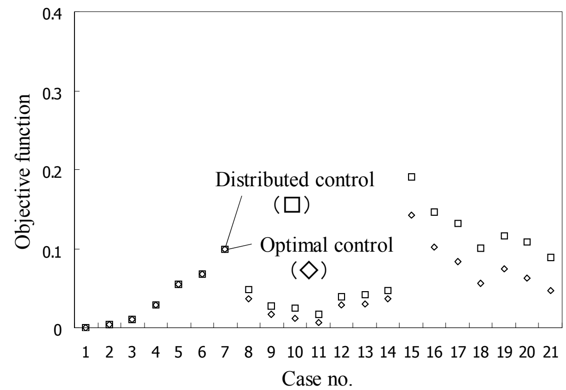


Fig. 4. Objective function for each case, setting A

Figure 5 shows a numerical verification of the coefficients setting. The objective functions are increase with tiny variation of coefficients G_p and G_{q1}, which means these coefficients optimal setting. The optimality of the other coefficients was similarly checked from each tiny variation.

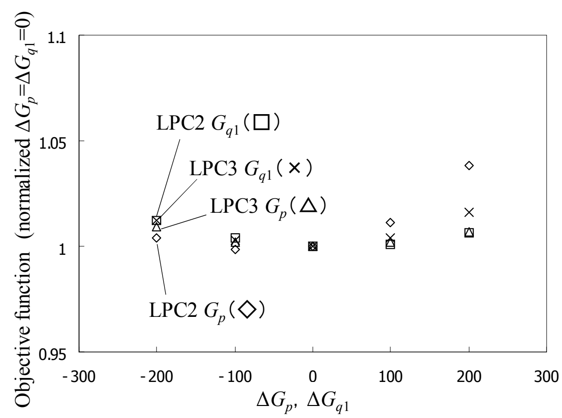


Fig. 5. Numerical verification of coefficients setting

Table VI shows the control coefficients which are determined by using case 1~21. The coefficients on table VI are utilized for the following distributed control.

The comparison of evaluated value for the each case is shown in Fig. 6. As contrasted with Fig. 4, the distributed control of the case 1~21 are good agreement with the optimal control. In this condition, the distributed control realize to the optimal operation for all the case from objective functional point of view.

TABLE VI
SETTING OF CONTROL COEFFICIENTS, SETTING B

Item	LPC2	LPC3
G_p	713.17	1044.4
P_c	-829.91	11015
G_{q1}	-446.49	-373.59
V_{r1}	6628.9	6634.7
G_{q2}	-13.042	11.542
V_{r2}	6616.8	6577.1

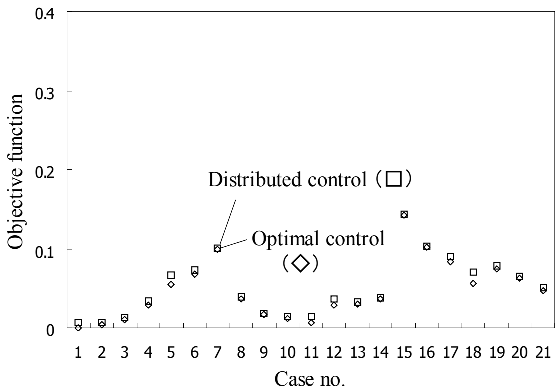
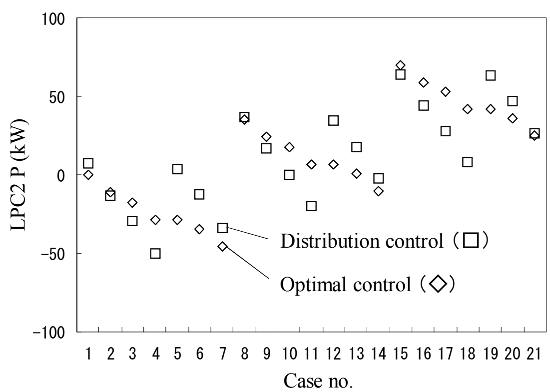


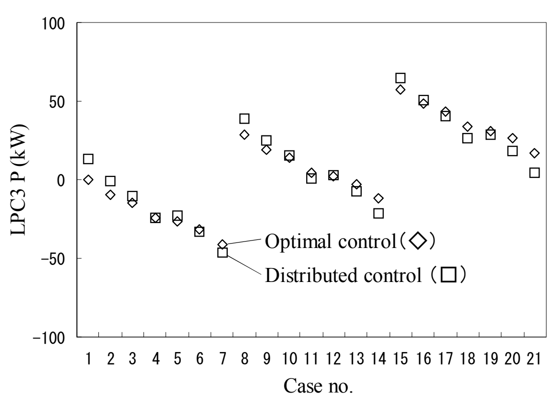
Fig. 6. Objective function for each case, setting B

E. Operation of LPC

Figure 7 shows a comparison of LPC operation for optimal control and distributed control. In case of LPC2, shown in (a), the tendency of the distributed operation is similar to optimal operation. However, at the case 4, 5, 11, 12, 18 and 19, there are a difference between them. It is considered that these differences are because of linear approximation on distributed control in contrast with nonlinear on optimal control. In case of LPC3, shown in (b), the distributed control has good approximations to the optimal control.



(a) LPC2

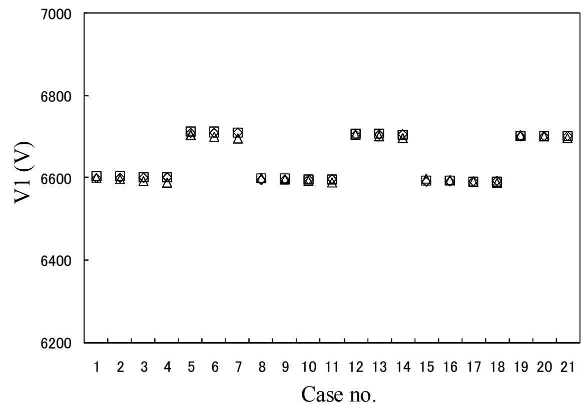


(b) LPC3

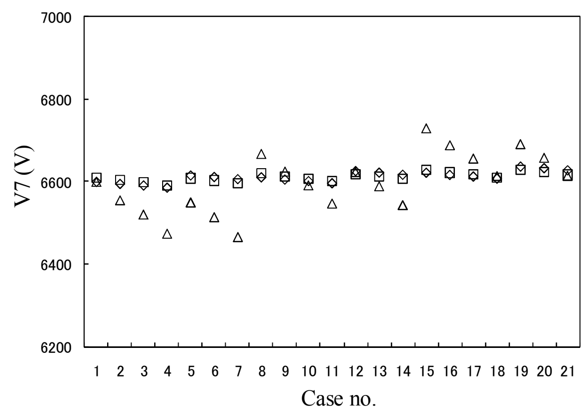
Fig. 7. Comparison of LPC operation

F. Feeder voltage

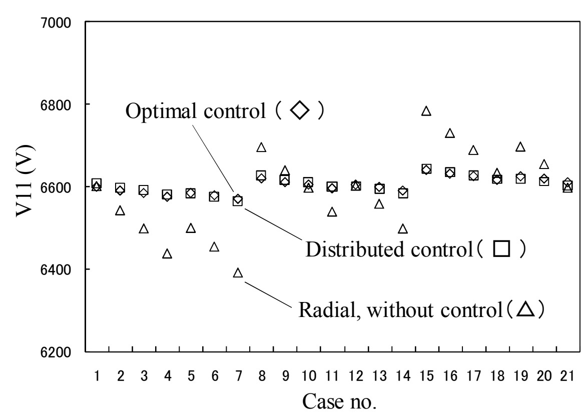
The feeder voltage of node n1, n7 and n11 are shown in Fig. 8 (a), (b) and (c) respectively. The results of the radial (without control), the distributed control and the optimal control were plotted in these Figures. In (a), the voltage of these results is alike because the node n1 voltage is controlled by on load tap changer on the Tr. No.2. Focus on (b) and (c), the voltage of the distributed control is equal to the optimal control. And the variation of these voltages is smaller than the radial.



(a) Node n1



(b) Node n7



(c) Node n11

Fig. 8. Feeder voltage

G. Evaluated value

The total evaluated value of objective function is shown in Fig. 9. The evaluated value is normalized for the optimal control. The value for the case 8~14 is smaller than for the case 1~7 and the case15~21 because the case 8~14 is balanced between the load consumption and DG power more than the other case. The total value of the distributed control is 1.09 which is very close to the optimal value.

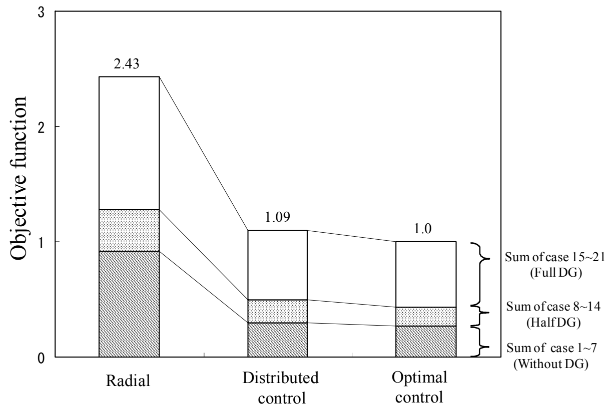


Fig. 9. Total evaluated value of objective function

H. Influence of distribution

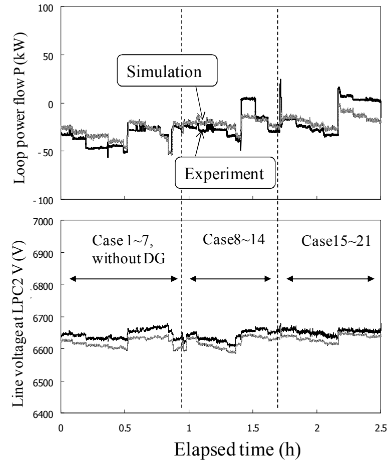
To confirm influence of load and DG distribution, new four load and DG locations are simulated here. The new locations are node n5, n7, n9 and n11. Each node is given sum of 43 and 23 load and DG pattern shown in table II. The evaluated values of the node n5, n7, n9 and n11 are 1.10, 1.07, 1.09 and 1.11 for each optimal value respectively. These values are in the same range.

IV. Experiment

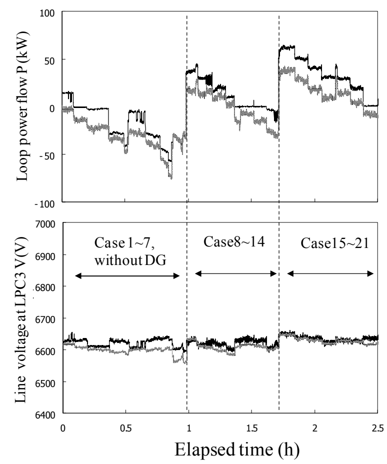
An experimental test has been done by using real scale distribution system in Akagi testing center of CRIEPI. Figure 10 shows the testing result of LPC operation and the feeder voltage for the 1~21 cases of load and DG combinations with elapsed time. The simulation curve shows simulation result of the distributed control by using measured load and DG operation as input data. The experiment agrees with the simulation.

V. Conclusion

This paper describes an application of determination method for control coefficients using optimal operation pattern of LPC and local voltage information to two LPC. And the confirmation of its validity is based on simulation. Furthermore, a distributed control using these control coefficients which were determined by proposed method was verified by two 6.6kV 100kVA BTB (back to back) type LPC and distribution system testing facility in CRIEPI.



(a) LPC2



(b) LPC3

Fig. 10. A testing result of LPC operation

VI. References

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VII. Biographies

Naotaka Okada (M'06) was born in Saitama, Japan, on Jan 5, 1967. He received his B.E. and M.E. degrees in Electrical Engineering from Seikei University, Tokyo, Japan in 1990 and 1992, respectively. In 1992, He joined the Central Research Institute of Electric Power Industry. And he received his Dr. Eng. degree in Electronic and Information Engineering from Tokyo University of Agriculture and Technology, Tokyo, Japan in 2005. He was a visiting researcher in Technische Universität Dortmund, Dortmund, Germany from 2008 through 2009. He has been involved with the analysis and control of distribution systems including power electronics.