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Autonomous Decentralized Voltage Profile Control Method in Future Distribution Network using Distributed Generators

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1. Introduction

To realize the sustainable energy society, it is of prime importance to introduce the renewable energy, such as Photovoltaics (PV) and Wind Turbine generators, or Co-generation systems which can utilize the exhaust heat energy. These generators are called "Distributed Generator (DG)" and they are introduced to the distribution network mainly as shown in fig.1. However, in the distribution network with a large number of DGs, the voltage profile maintenance becomes important issue due to the reverse power flow caused by DGs.

Conventionally, the voltage profile is controlled within the allowable range by the use of load-tap-changing substation transformer (LTC) or Static Capacitor (SC) in order to compensate the voltage drop caused by the demand-directional power flow. There are a lot of studies in which the voltage profile is maintained by the effective utilization of those facilities when a large number of DGs are introduced. For example, the optimization technology based on the global information of distribution network is utilized to determine the control actions of voltage control equipments. However, it should be difficult to control the high-speed voltage change by LTC or SC because those equipments work by switching. Although the utilization of SVC (Static Var Compensator) is one of effective approach to realize the high-speed voltage control, it should not be desirable from a viewpoint of increase in cost.

To realize the high-speed and flexible voltage maintenance control with reducing capital investments, it should be effective to utilize the reactive power control of DGs. Supposing that a large number of DGs are introduced, it should be difficult to manage the all information of whole system and to control all DGs. Hence, the much attention is paid to the autonomous decentralized control method, for example, by P. N. Vovos or P. M. S. Carvalho. However, the cooperative work among multiple DGs is not considered in their papers because only the information of the connection node is utilized. Although Mesut E. Baran et al studied the cooperative work among DGs based on the multi-agent system, the

method is not autonomous decentralized one because the specific control signal is generated by the optimization based on the global information.
On the other hand, the authors have developed autonomous decentralized voltage control method so far using reactive power control of DGs. Specifically, voltage profile maintenance is realized by the reactive power control of inverter based on the multi-agent system. In those papers, it is supposed the agent program is installed to each DG. The agents determine their proper control actions based on the local information exchange among neighboring agents. Where, the feedback control based on integral logic is applied. The proposed method is composed by three control methods whose control purposes are different. It is possible not only to maintain the voltage profile but also to decrease the excessive reactive power. Additionally, in our other paper, the proposed method is enhanced to realize the effective utilization of free capacity.
In this chapter, we will describe the outline of the voltage profile control method proposed in our previous work. First, the concept of the reactive power control of DG and voltage profile control method are described in section 2. Next, the basic and enhanced method of autonomous decentralized control are shown in section 3 and 4, respectively. Finally, a conclusion is provided in section 5.

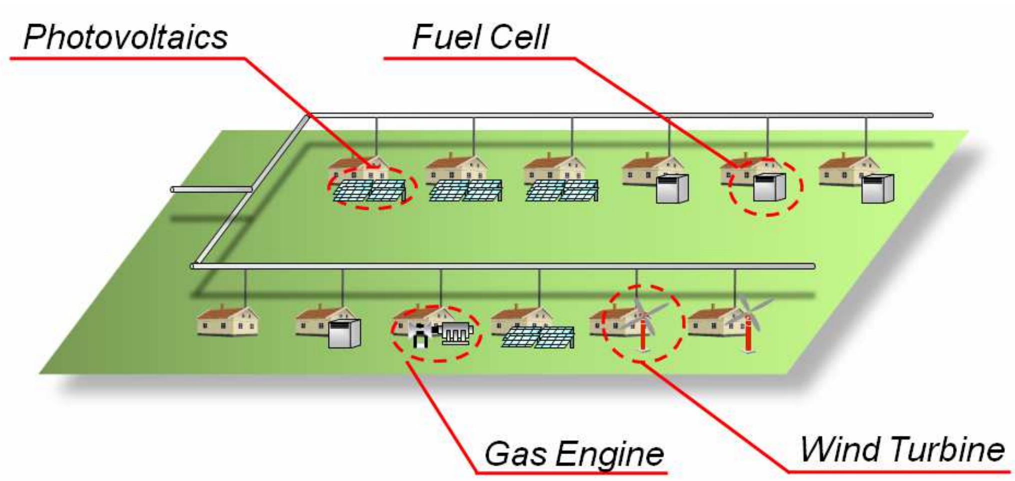


Fig. 1. Distribution network with distributed generators.

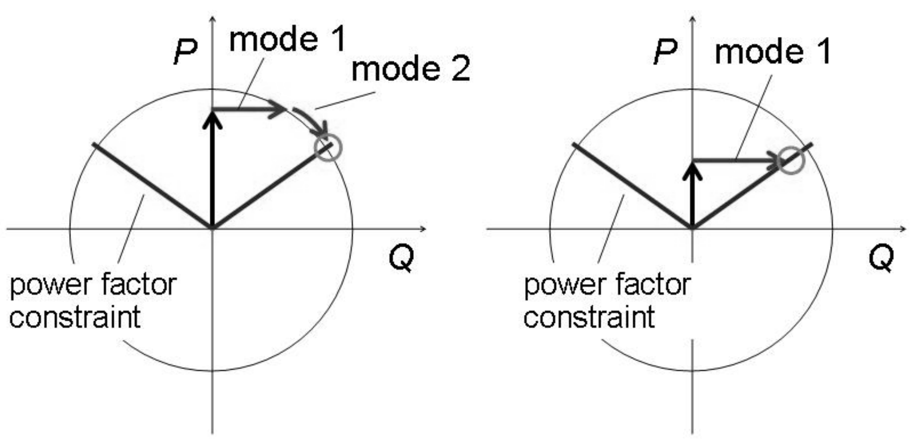
2. Concept of voltage profile control method

2.1 Reactive power control of inverter

There are various types of DGs. AC generator such as Gas Engine is connected to a distribution network directly and it can control its reactive power. On the other hand, the inverter is required as for the DC generator such as PV or Fuel Cell and so on. The self-excited inverter can control its reactive power in the case it has a “free capacity”. In this paper, the voltage profile control method is developed supposing a large number of inverter-connected DGs are introduced to the distribution network.
If a DG is connected to the distribution system with a self-excited inverter, it can change its power factor. At this time, the inverter capacity, active power output and reactive power output must satisfy the following equation.

$$\sqrt{P_{DGi}^2 + Q_{DGi}^2} \leq S_{INVi} \tag{1}$$

P_{DGi}, Q_{DGi} : active and reactive power output of DG i
S_{INVi} : inverter capacity of DG i
It is supposed the active power output is determined by DG owner because the DG owner control their DGs so freely in the framework of electricity liberalization. In the case the left part is smaller than the right part, it is defined that the inverter has a "free capacity". When the inverter has a free capacity, it can control its reactive power without decreasing its active power. Oppositely, when the inverter does not have a free capacity, it is required to decrease the active power to increase the reactive power. The reactive power control is classified into following two modes according to the free capacity.
mode 1: reactive power control without decreasing its active power when the inverter has a free capacity.
mode 2: reactive power control with decreasing its active power when the inverter has no free capacity.
The concept of the both control modes are shown in fig.2. Because the power factor constraint is considered in this study, there are two cases as shown in fig.2(a) and (b) according to the amount of active power output. When the active power output is large enough, the reactive power control is classified into two phases as shown in fig.2(a). First, only the reactive power is controlled using free capacity (mode 1). After the operating point reaches the inverter capacity constraint, the reactive power is increased with decreasing its active power (mode 2). On the other hand, when the active power output is not large, only mode 1 has a control capacity because lower limit of power factor becomes dominant constraint as shown in fig.2(b).
The power factor constraint is set up in order to avoid that adverse affect is caused by the excessive reactive power control by DGs. Therefore, in the case we have an assumption that the reactive power control of DG is effectively utilized for voltage profile maintenance, the power factor constraint does not seem to be required. Although the power factor constraint is considered in this study according to the conventional system requirement in Japan, the revalidation will be required in the future work.



(a) active power : large (b) active power : small

Fig. 2. Control mode.

The control capacities of both control modes are defined as follows according to the active power output as shown in fig.3. The dominant constraint to determine the control capacity of mode 1 depends on the amount of active power. In the case the active power is larger than the point "a" in fig.3, the capacity of mode 1 and mode 2 are determined by the inverter capacity and the power factor constraint, respectively. In the case the active power is smaller than the point "a", the capacity of mode 1 is determined by the power factor constraint and the mode 2 control is not available.

As above, the control capacities of both modes and the active power changes associated with the reactive power control are described as Eq.(2)-(5). In addition, in the case that the control capacity of either mode becomes zero, the capacity of the mode is defined as a sufficient small value, ε, because a problem is caused in the work of Q-Coop method which is described in section 3.2

- $if\ P_{original,i} > S_{INVi}\cos\varphi_{\max}$ (section A)

$$\begin{cases} Q_{\max 1,i} = \sqrt{S_{INVi}^2 - P_{original,i}^2} \\ Q_{\max 2,i} = S_{INVi}\sin\varphi_{\max} - Q_{\max 1,i} \end{cases} \tag{2}$$

$$P_{DGi} = \begin{cases} P_{original,i} & (-Q_{\max 1,i} < Q_{DGi} < Q_{\max 1,i}) \\ \sqrt{S_{INVi}^2 - Q_{DGi}^2} & (Q_{DGi} < -Q_{\max 1,i}\ or\ Q_{\max 1,i} < Q_{DGi}) \end{cases} \tag{3}$$

- $else\ if\ P_{original,i} < S_{INVi}\cos\varphi_{\max}$ (section B)

$$\begin{cases} Q_{\max 1,i} = P_{original,i} \times \tan\varphi_{\max} \\ Q_{\max 2,i} = 0 \end{cases} \tag{4}$$

$$P_{DGi} = P_{original,i} \tag{5}$$

$P_{original,i}$: active power of DG i determined by DG owner originally
$\varphi_{\max}$: upper limit of power factor angle [rad]
$Q_{\max1,i}$: mode 1 capacity of DG i
$Q_{\max2,i}$: mode 2 capacity of DG i

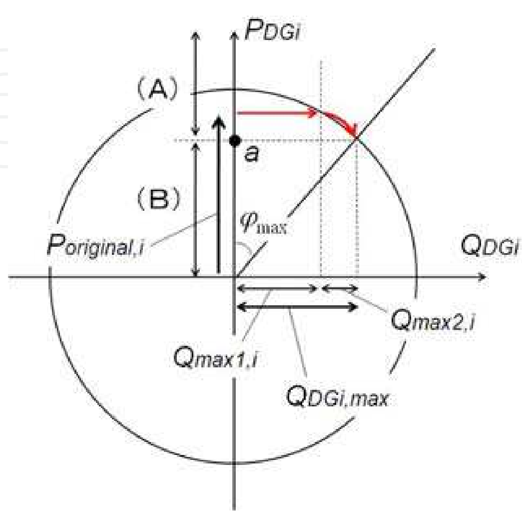


Fig. 3. Reactive power control capacity of each mode.

2.2 Voltage profile control method using inverter

In the proposed method, power factor control of all DGs are defined as control objects. However, since the DGs are demand side facilities, customers have no responsibilities to maintain system voltage. So, it is assumed that proper incentives are given to DG owners to realize the proposed method.
Although the inverter control is effective, the reactive power control of one or two inverter is not enough to realize the proper voltage maintenance. Hence, it is desirable that multiple DGs work as a group cooperatively. In order to realize such a cooperative work, a centralized or autonomous decentralized approach should be available. The concept of those approaches are described below.

(a) centralized control method

The ideal cooperative control should be achieved by determining the control signal based on the optimization using all information of whole system. Because the reduction of active power output is required to maintain the voltage profile, the maximization of total active power generated by DGs is treated as an object function. Specific formulation is as follows.
<object function>

$$\text{Maximize} \quad \sum_{i=1}^{m} P_{DGi} \tag{6}$$

<constraints>

$$P_{DGi} - P_{Li} - V_i \sum_{k=i}^{n} V_k \left\{ G_{ik} \cos(\theta_i - \theta_k) + B_{ik} \sin(\theta_i - \theta_k) \right\} = 0 \tag{7}$$

$$Q_{DGi} - Q_{Li} - V_i \sum_{k=i}^{n} V_k \left\{ G_{ik} \sin(\theta_i - \theta_k) - B_{ik} \cos(\theta_i - \theta_k) \right\} = 0 \tag{8}$$

$$\cos \varphi_{\max} \le \frac{P_{DGi}}{\sqrt{P_{DGi}^2 + Q_{DGi}^2}} \tag{9}$$

$$V_{\min} \le V_i \le V_{\max} \tag{10}$$

$$\sqrt{P_{DGi}^2 + Q_{DGi}^2} \le S_{INVi} \tag{11}$$

m : total number of DGs
n : total number of nodes
P_{Li}, Q_{Li} : active and reactive power of load i
V_i, θ_i : voltage and phase angle of node i
G_{ik}, B_{ik} : conductance and susceptance of branch i-k
$V_{\min}$, $V_{\max}$: lower and upper limit of voltage
Theoretically, the optimal control efficiency is realized using the centralized control method. However, there are following issues.

- The information and communication infrastructures should be required to gather all information of whole system.

- It is difficult to compensate the high-speed change of load and DG output because a long time is necessary to calculate the optimization.

(b) autonomous decentralized control method

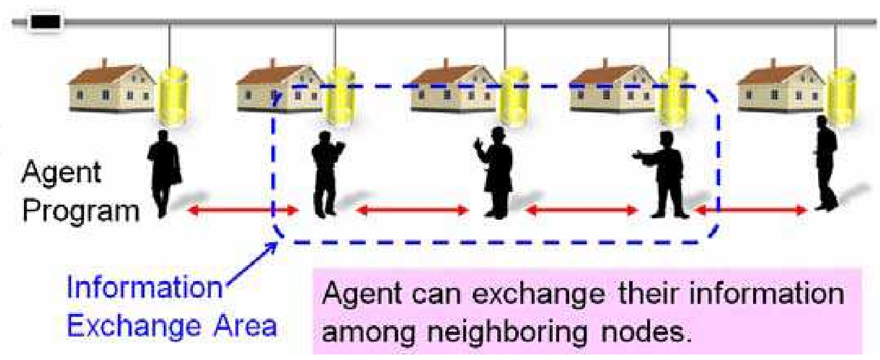


Fig. 4. Concept of multi-agent system in distribution network.

In this paper, we try to develop a voltage profile control method from a viewpoint of autonomous decentralized approach because it should be difficult to realize the centralized control method as described in the previous subsection. Distribution system operator installs the agent program into each DG as shown in fig.4. The agent sends a control signal to its DG in place of the distribution system operator. The agent of each DG determines the control action of its DG autonomously based on the local information exchange.
The class and amount of available information are extremely important for autonomous decentralized control. In this paper, we define the area where the agent can exchange information as "Information Exchange Area (IEA)". IEA is represented by a node number on system model. In the proposed method, IEA is defined as 1 in order to develop a control method which can work even in the case only the local information is available. Which means that each DG is controlled using information of self-node and neighboring nodes. Time delay related to communication is ignored and it is supposed that real-time communication is available. The detailed explanation will be provided after the next section.

3. Autonomous decentralized voltage profile control method -Basic method-

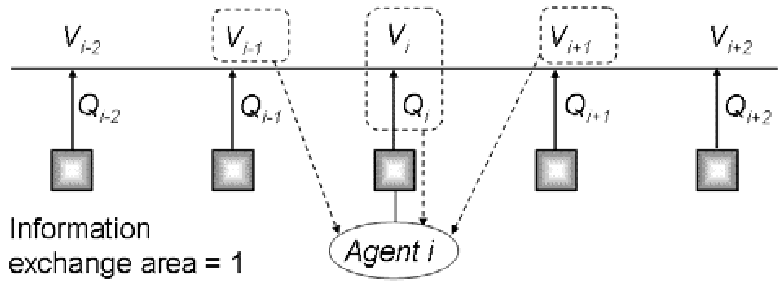
3.1 Concept of basic control method

The basic method of autonomous decentralized voltage control is described in this section. To simplify the problem, only the control mode 2 is treated supposing all DG has no free capacity. Basic control method is composed by following three methods: "Voltage reference method (V-Ref method)", "Reactive Power Saving method (Q-Save method)"and "Reactive Power Cooperation method (Q-Coop method)". In the V-Ref and Q-Save method, each agent requires the information about voltage profile within IEA and the amount of reactive power of its DG as shown in fig.5(a). On the other hand, each agent needs the information about the amount of reactive power of DGs within IEA additionally as shown in fig.5(b). The detail of each method is described as follows.

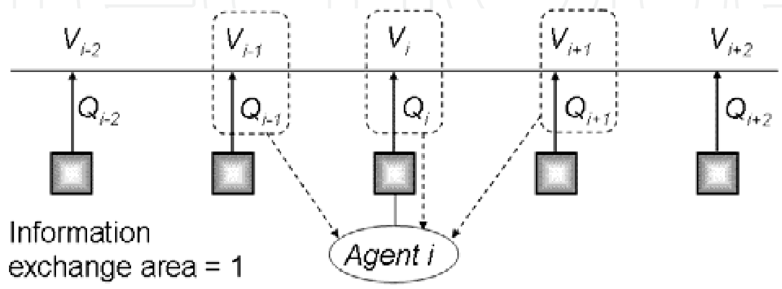
3.2 The combination of three control methods

(a) Voltage Reference method (V-Ref method)

Each agent gathers the voltage information of self-node and neighboring (Fig.5 (a)). When the voltage at any node within IEA deviates from the proper range, each agent coordinates its



(a) Information exchange of V-Ref and Q-Save method



(b) Information exchange of Q-Coop method

Fig. 5. The definition of information exchange area.

reactive power output in order to reduce the total amount of voltage deviation from reference value according to Eq.(11). Although it is important to control voltage profile close to reference value, we assume that the necessity of voltage control is lower within the proper range. Which means that the control object is achieved when the voltage profile is maintained within the proper range at least. Therefore, this V-Ref method does not work when the voltage profile within IEA is maintained properly. In addition, (t) is added to the time-variant variables and it is supposed that the real-time communication is realized without considering the time-delay.

$$\text{if} \quad V_k(t) < V_{lo} \quad \text{or} \quad V_{hi} < V_k(t)$$

$$T_\alpha \dot{Q}_i(t) = K_\alpha (V_{ref,i} - V_k(t)) \tag{11}$$

where,
V_{lo}, V_{hi} : lower and upper limit of voltage constraint (proper range)
T_α : time constant of V-Ref method [sec] , K_α : control gain of V-Ref method
$V_{ref,i}$: reference value of voltage control at node i
(it is defined as 1.0[p.u.] at all nodes in this paper)
$V_k(t)$: voltage at node k where the voltage deviation value becomes maximum within IEA

(b) Reactive Power Saving method (Q-Save method)

When the voltage profile within IEA does not deviate from the proper range, it is desirable that the reduction of power factor is recovered by saving the excessive reactive power output. Such a control is realized using Eq.(12), where $Q_{ref,i}$ is the reference value of reactive power output and it is set to 0 (p.f.=1.0) usually. Because the priority of this control method is lower than Q-Coop method, the dead band Δ is set as shown in fig.6. When the reduction of reactive power causes the voltage deviation again, Q-Save method should be stopped at the time. Such a control is realized with combination of three methods as described later. The concept of information exchange of this method is shown in fig.5(a).

$$\text{if} \quad V_{lo} + \Delta < V_k(t) < V_{hi} - \Delta$$

$$T_\beta \dot{Q}_i(t) = K_\beta (Q_{ref,i} - Q_i(t)) \tag{12}$$

where,
T_β : time constant of Q-Save method [sec], K_β : control gain of Q-Save method
$Q_{ref,i}$: reference value of Q-Save method at DG i (in this paper, 0.00[p.u.])

(c) Reactive Power Cooperation method (Q-Coop method)

In the autonomous decentralized method, the information about the voltage deviation is not detected from the agents at distant nodes over IEA. Therefore, we propose Q-Coop method which does not use voltage information directly. In this method, the power factors of DGs are controlled to be equalized within IEA. The concept of information exchange is shown in fig.5(b) and this method is formulated as Eq.(13)-(15).

$$\text{if} \quad V_{lo} < V_k(t) < V_{hi}$$

$$T_\gamma \dot{Q}_i(t) = K_\gamma (Q^*_{ref,i}(t) - Q_i(t)) \tag{13}$$

$$Q^*_{ref,i}(t) = S_i \sin\theta^*_{ref,i}(t) \tag{14}$$

$$\sin\theta^*_{ref,i}(t) = \frac{\sum \sin\theta_j(t)}{M_i + 1} \tag{15}$$

where,
T_γ : time constant of Q-Coop method [sec], K_γ : control gain of Q-Coop method
$\theta_j(t)$: power factor angle of DG j
$Q^*_{ref,i}(t)$: reference value of Q-Coop method of DG i
M_i : total node number included in IEA of DG i
S_i : inverter capacity of DG i
$\theta^*_{ref,i}(t)$: an average value of θ_i within the IEA.
Following merits are obtained by local equalization of the power factors.

- The chain of Control Action

When a certain DG increases its reactive power output, other DGs which locate on neighborhood also increase their outputs in order to equalize their power factors. This control action leads to a chain reaction. As a result, the distant DGs also increase their reactive power outputs. From the standpoint of whole system, which seems that the distant DGs help the voltage control of distant area by changing their reactive power outputs. This control action is interpreted as a cooperative control.

- Equalization of Power Factor

When a control load gathers to a certain DG, the power factor of the DG decreases greatly. Lower the power factor decreases, the more active power of the DG decreases to generate the same amount of reactive power because reactive power (Q) and active power (P) must satisfy Eq.(1). At this time, generating efficiency greatly decreases. Therefore, the economic efficiency will be improved with an equalization of the reactive power outputs.

(d) Operating condition of each control method

Each DG switches its control method using voltage information within IEA, as shown in fig.6. When there exists a voltage deviation node within IEA, V-Ref method works to improve the voltage profile directly. V-Ref method stops and both Q-Save and Q-Coop methods work when the voltages of all nodes within IEA are improved to the proper range. At this time, the dead zone is set not to cause a chattering between V-Ref and Q-Save method. We can see from the same figure that the control area of Q-Save method and Q-Coop method is almost the same. Then, we encounter the difficulties that the proper control method must be selected depending on the situation. To decide the proper control method is not easy from a viewpoint of autonomous decentralized control. In the proposed method, both control methods are executed simultaneously and a flexible control is realized according to the following logic.

When we apply the both Q-Save and Q-Coop methods, the proper setting of control parameters is needed. Q-Save method works to decrease the reactive power output to improve the efficiency, and Q-Coop method works to increase the reactive power output to improve the voltage profile. The stationary voltage profile is determined by control gain of both methods. The mechanism is represented as fig.7 when both methods are applied. Assume that all voltages are within a target range as shown in fig.7(a), the difference of reactive power outputs between DG i and j disappears due to the work of Q-Coop method first. Once reactive power outputs are equalized, only the control effect of Q-Save method remains and reactive power outputs decrease gradually. On the other hand, when there exists a voltage deviation node, V-Ref method works preferentially at the node. As shown in fig.7(b), the reactive power output of the DG is stack to a maximum value, and reactive power output of next node is determined to a value where the product of the error between the reactive power and its reference value and Q-Save gain is equal to that of the error and Q-Coop gain. Therefore, if K_γ is large enough, the effect of Q-Coop method is also large. If voltage profile is within the proper range, Q-Save method works effectively without

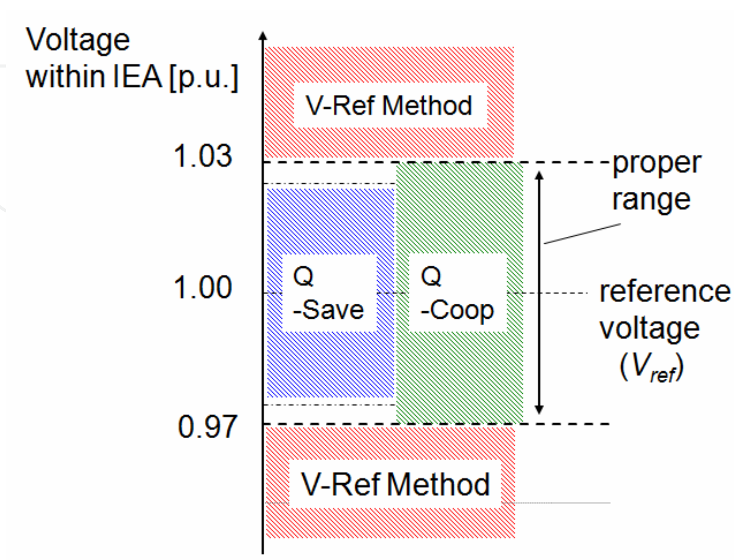
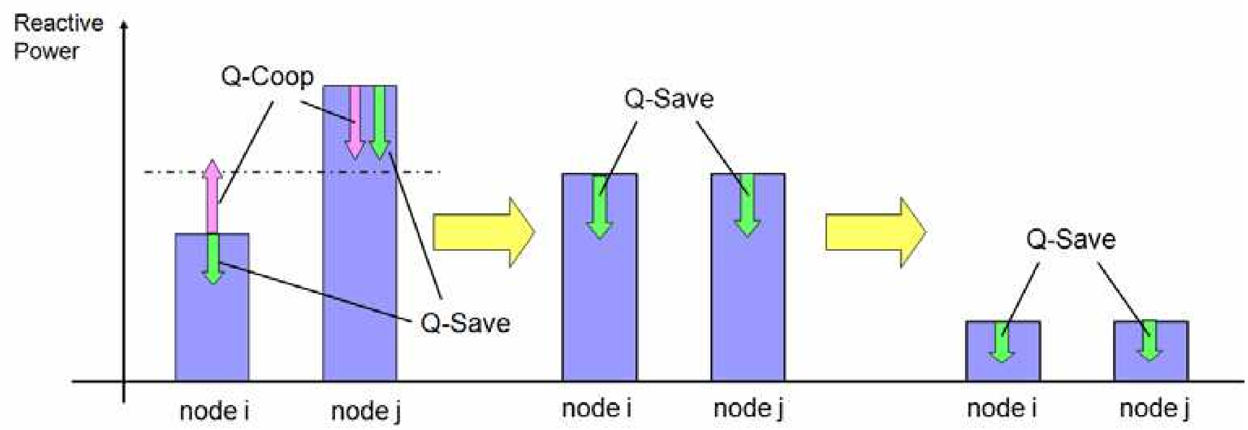
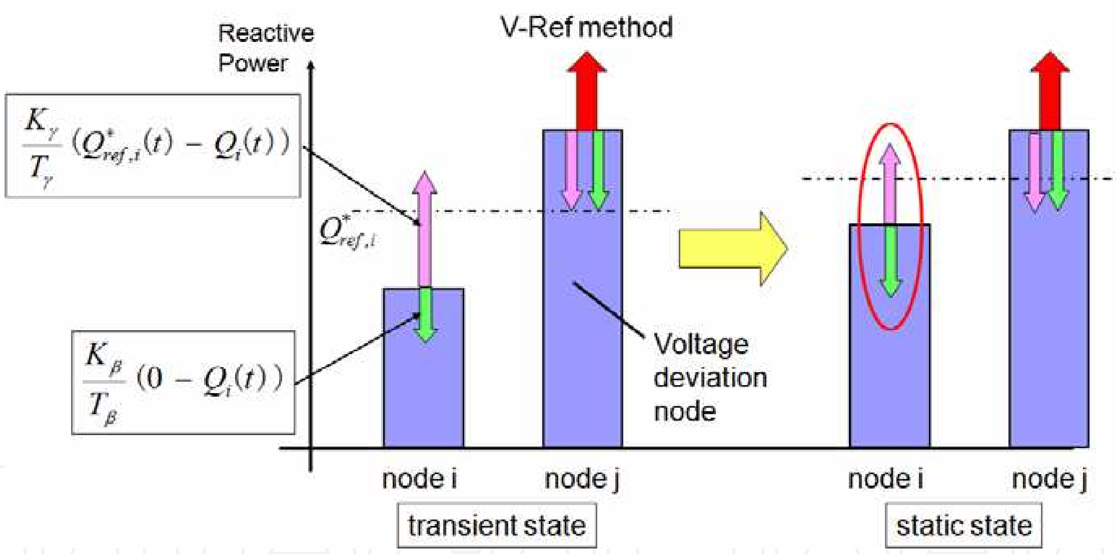


Fig. 6. Operating conditions of each method.

relation to the Q-Coop gain since Q-Save method starts to work after the equalization control has finished. Hence, the large value of K_γ does not influence to the performance of Q-Save method.
Thus, K_γ should be set to a large number. However, the gain constant must be set carefully since too large gain causes an unstable control when the time-delay is considered.



(a) In the case the voltage profile is within the target range



(b) In the case there exist a voltage deviation node

Fig. 7. Cooperative work of Q saving method and Q cooperation method.

3.3 Simulation results by 4-node model system

(a) Model system

The proposed method is tested in 4-node model system shown in fig.8. Both DGs and loads are connected to all nodes and the load changes discontinuously as shown in fig.9. Before time=0 [sec], all loads are light and the voltage profile is within the proper range without using reactive power control of DGs. The control parameters are determined by trial and error according to following guidelines as shown in table 1.

- K_α is set to 1.00 because V-Ref method is defined as a basic control.

- The priority of Q-Save method is low because its main purpose is the improvement of economical efficiency. Therefore, K_β is set to half of K_α (0.50) in order that it works gradually.
- K_γ is set to 8.00 because it must be sufficient large value compared with K_β.
- Supposing that the gradual control, time constants of all control methods are set to 4.00 [sec].

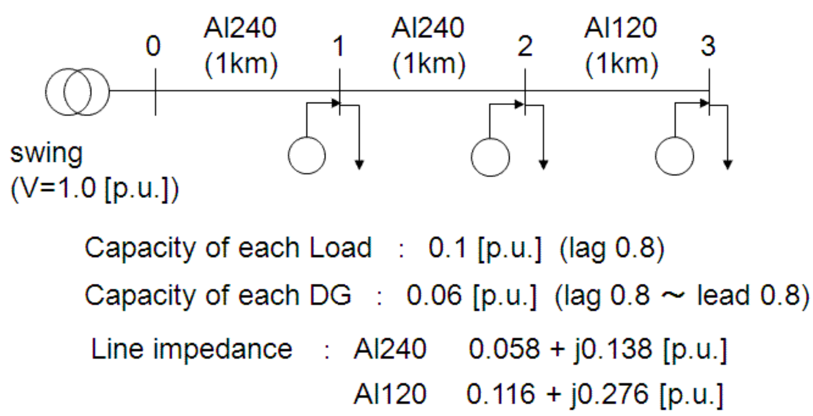


Fig. 8. 4-node model system.

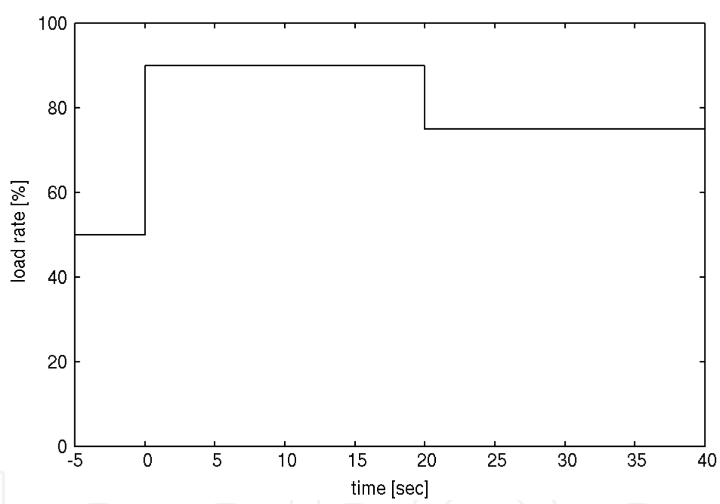


Fig. 9. Load change pattern.

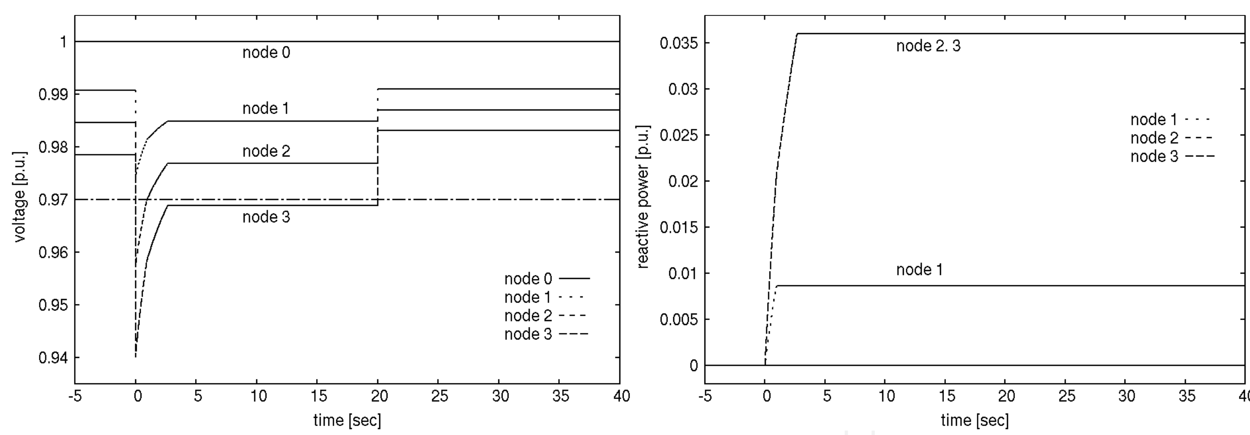
T_α	4.00 [sec]	T_β	4.00 [sec]	T_γ	4.00 [sec]
K_α	1.00	K_β	0.50	K_γ	8.00

Table 1. Control parameters.

(b) Simulation Results

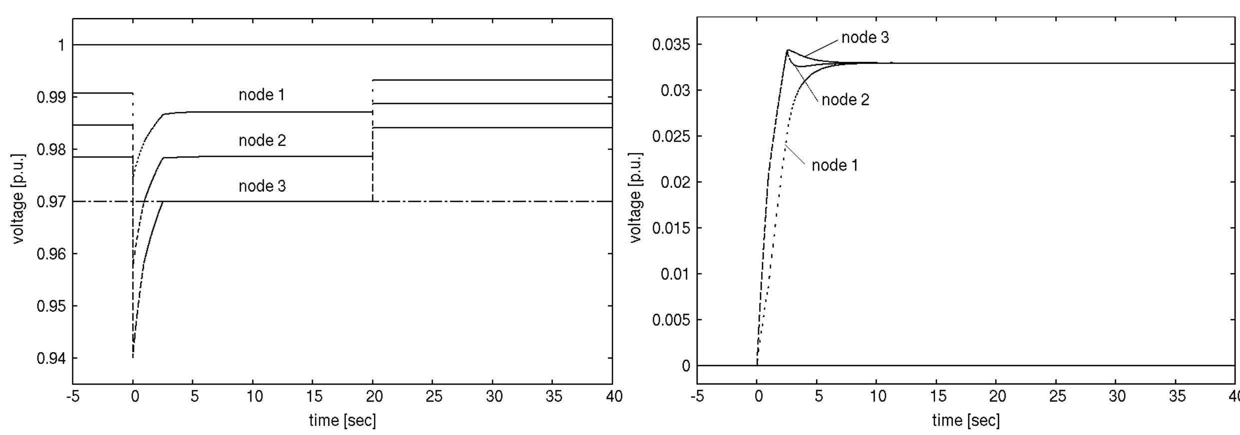
Figure 10 shows the simulation results in the case only V-Ref method is applied. At this time, each DG works to improve the voltage profile only using local information about voltage within IEA. We can see from these results that there are two problems as below.

- voltage at node 3 is not within the proper range.
- after time=20 [sec], the power factor of each DG remains to be decreased.



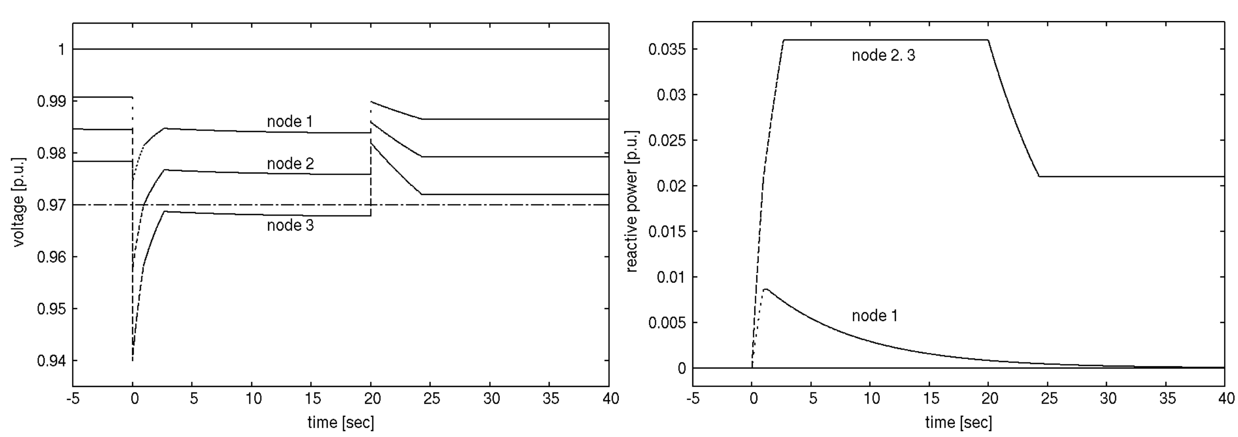
(a) Voltage change of each node (b) Reactive power change of each DG

Fig. 10. V-Ref method.



(a) Voltage change of each node (b) Reactive power change of each DG

Fig. 11. V-Ref method and Q-Coop method.



(a) Voltage change of each node (b) Reactive power change of each DG

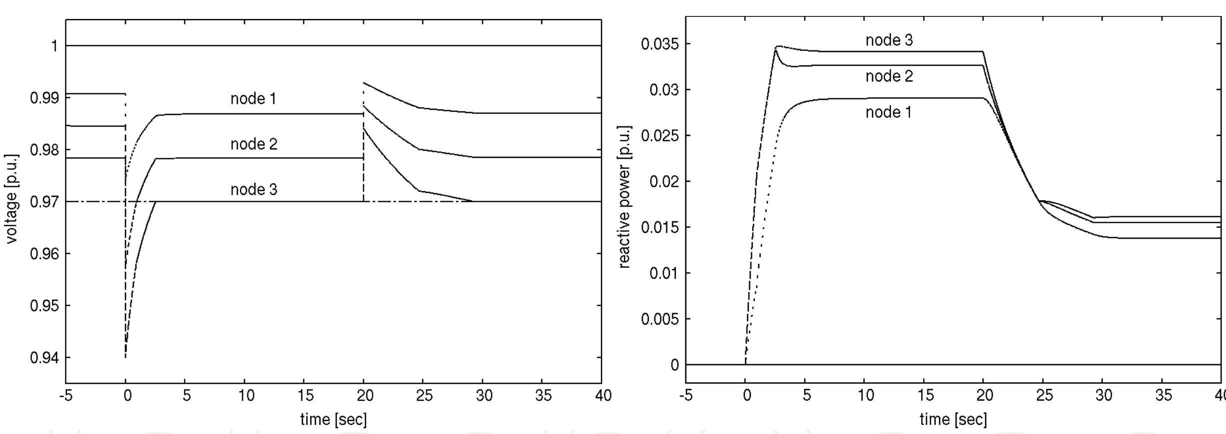
Fig. 12. V-Ref method and Q-Save method.

The first problem is the result from that the reactive power control of DG2 and DG3 which can observe the voltage at node 3 directly reaches the maximum value. At this time, it is possible to improve the voltage at node 3 if the reactive power control of DG1 is available.

However, it is difficult to utilize the reactive power control of DG1 because the voltage profile at node 1 and node 2 which DG1 can observe directly remains to be within the proper range. If it is assumed that the information about the reactive power control is exchanged among agents, the agent of DG1 can estimate the voltage deviation occurs at any node because the reactive power of DG2 increases. Figure 11 shows the simulation results with V-Ref and Q-Coop methods. We can see the reactive power of all DGs are equalized at the stationary point due to the work of Q-Coop method and the voltage profile is within the proper range by the cooperative work.

The second problem is the result from that V-Ref method does not work when the voltage profile of all nodes are within the proper range because the dead zone of V-Ref method corresponds with the proper range. Therefore, as a countermeasure of this problem, the simulation result with V-Ref and Q-Save method is shown in fig.12. Since the DGs whose local voltage are within the proper range change their control methods to Q-Save method, the reactive power of each DG decreases after time=20 [sec] before the voltage profile reaches the lower limit, including the dead band, again.

Finally, figure 13 shows the simulation results with three control methods. Both two problems are solved at the same time by the cooperative work of Q-Save and Q-Coop methods described in fig.7. Before time=20 [sec], Q-Coop method works dominantly because the voltage at node 3 reaches the lower limit of proper range. Oppositely, after time=20 [sec], reactive power output of all DGs are equalized immediately by the work of Q-Coop method, and after that, the reactive power output decreases due to the work of Q-Save method.



(a) Voltage change of each node (b) Reactive power change of each DG

Fig. 13. The application of all methods.

Table 2 shows the comparison of the control effects. Table 2(a) and (b) show the comparisons related to "all time period" and "steady solution" based on Eq.(16) and (17), respectively.

$$\int_0^T \sum_i^m Q_{DGi}^2(t)dt \tag{16}$$

$$\sum_{i=1}^m Q_{DGi}^2 \tag{17}$$

T : simulation time [sec]

The control effect is compared with "the control effect without Q-Save method". In table 2(b), it is also compared with "optimal solution". Although the formulation of this optimization is according to the section 2.2, the object function is replaced by Eq.(17). The utilization of Eq.(17) seems to be almost same as Eq.(6) because only the mode 2 control is treated in this section and the voltage – reactive power sensitivity is larger than voltage – active power sensitivity. From table 2(a), we can see the total amount of reactive power is reduced by about 39%. On the other hand, from table 2(b), the difference between the proposed method and optimal solution is approximately from 7 to 19%.
Additionally, the proposed method does not need the information about "voltage –reactive power sensitivity" which is often utilized for voltage profile control in conventional control manner. Hence, it is possible to apply the proposed method to the 4-node model system without considering the difference of distribution lines between node 2 and 3.

	without Q-Save method	with Q-Save method
Eq.(16)	0.1250 (100%)	0.07645 (61.2%)

(a) Comparison of all time period.

	without Q-Save method	with Q-Save method	optimal solution
Eq.(17) t=15[sec]	0.00326 (114%)	0.00308 (107%)	0.00287 (100%)
Eq.(17) t=35[sec]	0.00326 (562%)	0.000689 (119%)	0.000580 (100%)

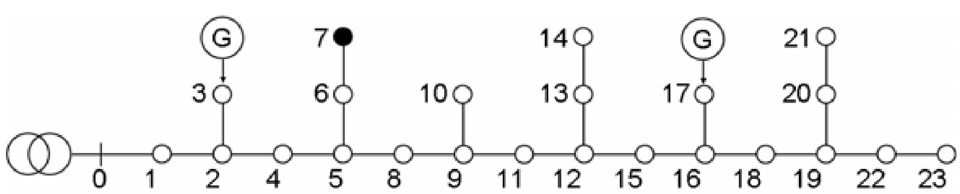
(b) Comparison of steady solution.

Table 2. Comparative table of economical efficiency (4-node model system).

3.4 Simulation results by 24-node model system

(a) Model system

The proposed method is tested using 24-node model system shown in fig.14 to test its effectiveness in the large scale model system. DG whose capacity is small is connected to each node. Although the large capacity DG is connected to node 17, it is uncontrollable and its active power output changes as shown in fig.15. Voltage increases largely at the downstream side of the feeder when the active power output of DG17 increases. However, at that time, voltage drop at the upstream side also becomes problem because the large capacity load is also connected to node 7. Therefore, it is required to maintain voltage profile considering both upper and lower constraints. On the other hand, voltage drop becomes problem in whole system when the active power of DG17 is small.



6.6kV 20MVA base

Fig. 14. 24-node model system.

The detailed settings of model system are listed in table 3. Control parameters are same as table 1 and K_γ is modified to 48 to enhance the work of Q-Coop method.

Demand of each node node 7 Others	 0.075[p.u.] (p.f.lag 0.80) 0.02[p.u.] (p.f. lag 0.80)
DG capacity of each node Additional Generator : node 3 node 17	0.02[p.u.] 0.08[p.u.](p.f.lead 0.80) variable (p.f. lead 0.90)
Power factor control range of controllable DG	lag 0.8～lead 0.8
Proper range of voltage	0.97 ～ 1.03 [p.u]
Line impedance	Al240 (400m/1section) 0.0232+j0.0552 [p.u.]

Table 3. System constant of 24-node model system.

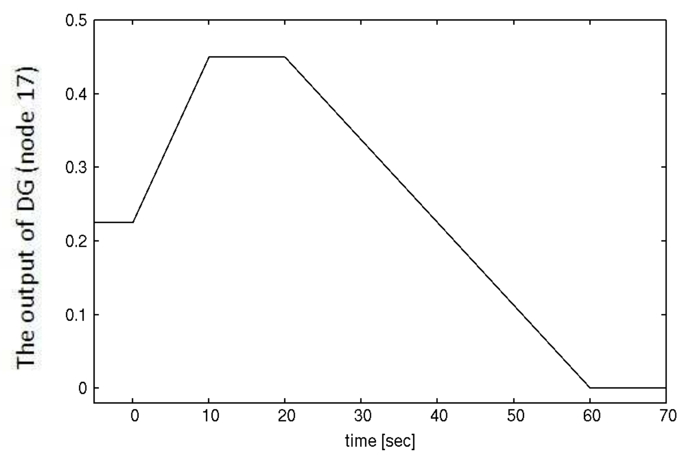
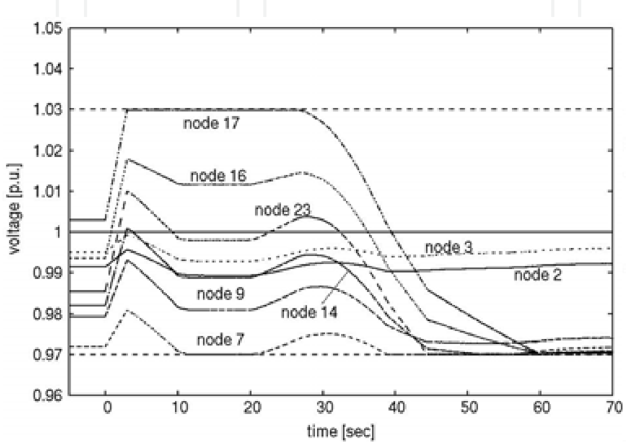
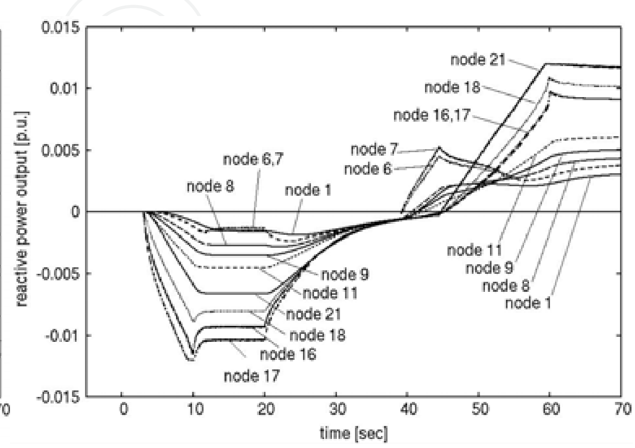


Fig. 15. The active power change of DG (node 17).

(b) Simulation results



(a) Voltage changes of representative points



(b) Reactive power changes of DGs

Fig. 16. Simulation results by proposed method.

The change of voltage profile and reactive power in the case the proposed method is applied are shown in fig.16. By the active power change of DG17 from time=0 [sec], the voltage profile of whole system reaches the upper limit during about 30 seconds. We can see from the figure that the proposed method works well and voltage profile is maintained within the proper range due to the reactive power control of multiple DGs. From time=30 [sec] to 40 [sec], voltage profile is within the proper range originally and each DG decreases its reactive power to improve the power factor. After time=40 [sec], voltage profile is also maintained by the reactive power supply although the voltage profile of whole system becomes lower.
Control effects are compared in Table 4 as shown in the case of 4-node model system. From table 4(a), we can see the evaluation index is improved by approximately 60 percent using Q-Save method. This is due to the difference mainly from 30 [sec] to 40 [sec] when the voltage deviation does not occur. From table 4(b), we can see the proposed method with Q-Save method provides the comparable results with the optimal solution.

	without Q-Save method	With Q-Save method
Eq.(16)	0.08352 (100%)	0.03302 (39.5%)

(a) Comparison of all time period.

	without Q-Save method	with Q-Save method	optimal solution
Eq.(17) t=60[sec]	0.003888 (295%)	0.001331 (101%)	0.001319 (100%)

(b) Comparison of steady solution.

Table 4. Comparative table of economical efficiency (24-node model system).

4. Autonomous decentralized voltage profile control method - Advanced Method -

4.1 Concept of preferential utilization of free capacity

In section 3, it is supposed that inverter has no free capacity. However, it is expected DG has a free capacity except at the peak time because the inverter capacity is determined by the maximum active power output. Reactive power control using the free capacity, which is called "mode 1", does not need the active power decrease. Hence, in this section, mode 1 based on the free capacity of inverter is defined to be "high priority control". The proposed autonomous decentralized control method is enhanced in this section so that it can utilize the high priority control effectively. The control theory in this section should be applied to both the inverter control and SVC control. When the both equipments are included in the distribution network model, the proposed method works to realize their cooperative work. However, to simplify the explanation, only the inverter control is treated in this section.

4.2 Multiplexing of autonomous decentralized control

First, the work of basic control described in the previous section is summarized again. The specific control procedure of basic control is as follows:

Step 1. When the voltage at any node is out of proper range, the DGs which can observe the voltage deviation adjust the reactive power in order to recover the voltage deviation (V-Ref method)

Step 2. The neighboring DGs control their reactive power by the work of Q-Coop method.
Step 3. The control action due to the Q-Coop method travels to the distant nodes like chain reaction.

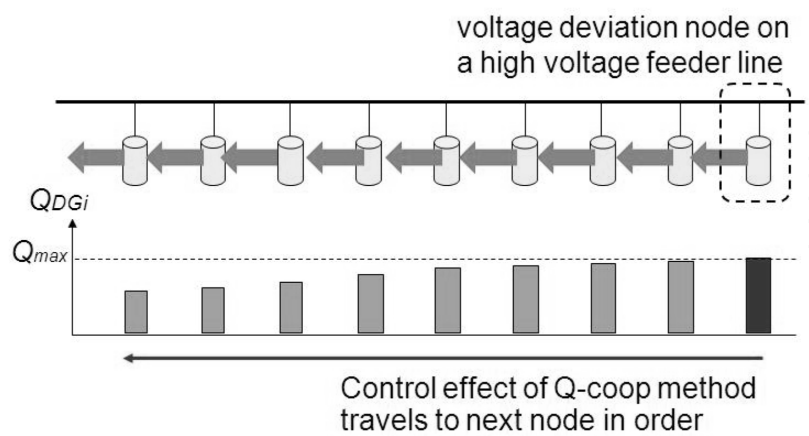
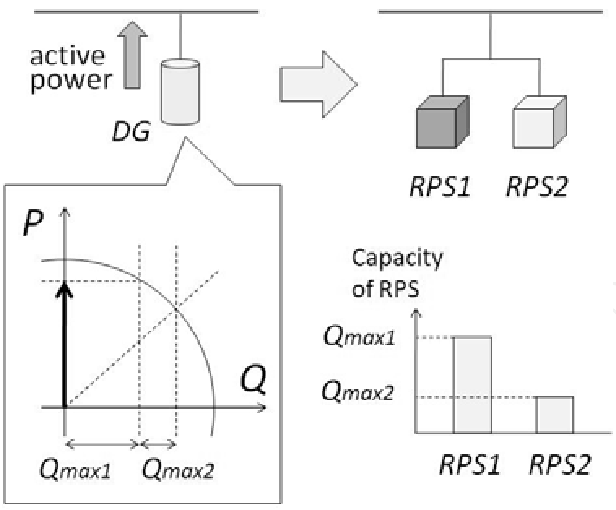


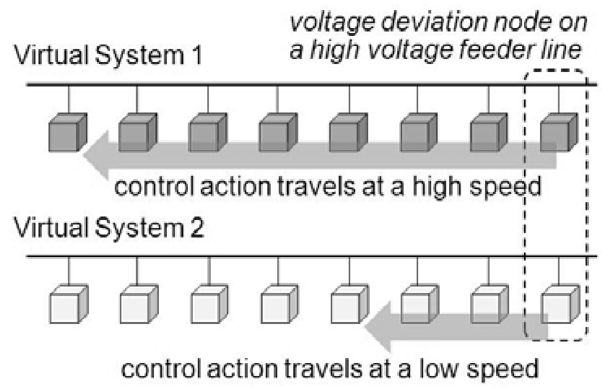
Fig. 17. Concept of Q-Coop method.

According to above procedure, nearer the DG locates, larger the reactive power is controlled as shown in fig.17. Therefore, the amount of reactive power output of each DG depends on the distance between the DG and the voltage deviation node. At this time, the control priority is not considered. Thus, in this section, the distribution network is virtually divided into two systems. One is "Virtual System 1" composed by the control of mode 1, and the other is "Virtual System 2"composed by the control of mode 2. Control speed of Virtual System 1 is set to be higher than that of Virtual System 2. Which enables to utilize the mode 1 control preferentially. Specific procedure is as follows.

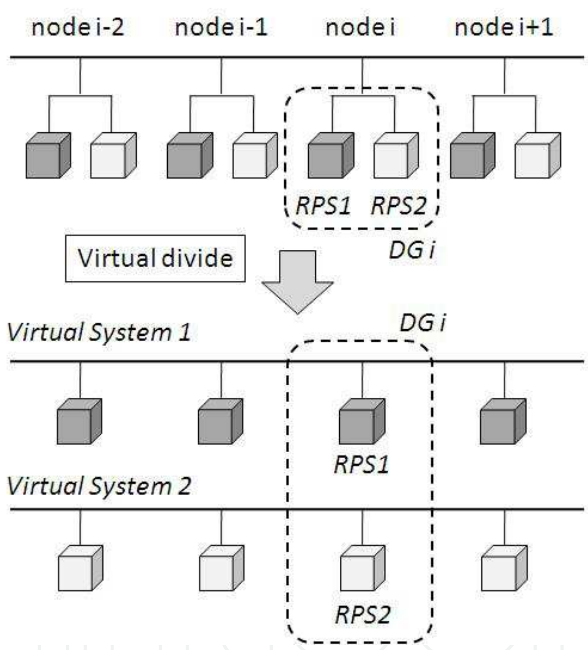
Step 1. The agent of each DG has two Reactive Power Sources (RPS1 and RPS2) virtually. The capacity of RPS1 and RPS2 are defined as same as the capacity of mode 1 and mode 2, respectively. In the case that the capacity of either RPS1 or RPS2 becomes zero, the capacity is defined as ε. The capacity ε needs to be sufficient small value, and in this study, ε is one-twelfth of inverter capacity. As a result, all DGs have capacities of RPS1 and RPS2. (fig.18 (a))
Step 2. The neighboring agents exchange their reactive power output of RPS1 and RPS2. The required information for RPS1 control are "voltage value at self-node and neighboring nodes" and "reactive power output of self-node and RPS1 at neighboring nodes" while the information about RPS2 is not required. Oppositely, the controller of RPS2 does not need the information of RPS1. Hence, it is possible to divide the information exchange system into two systems. They are defined as "Virtual System 1" and "Virtual System 2". (fig.18(b))
Step 3. In each Virtual System, the agent of each DG controls its RPS1 and RPS2 individually using control logic described in 4.3 which is based on the basic method. The control speed of each Virtual System is adjusted so that the Q-Coop method works faster in Virtual System 1 than that in Virtual System 2. (fig.18(c))
Step 4. Virtual reactive power of each RPS1 and RPS2 are summed up by the agent of each DG and it becomes the reference value of each DG. If the reference value is smaller than its capacity of mode 1, the active power decrease is not necessary. (fig.18(d))



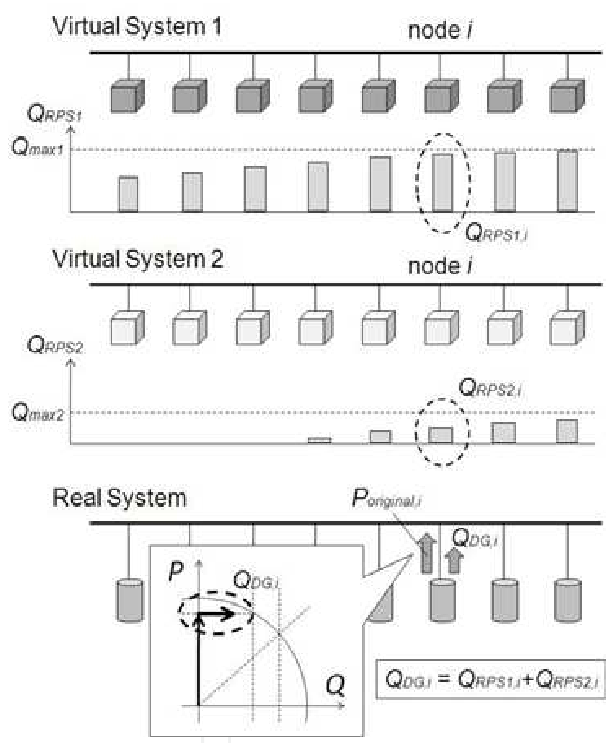
(a) STEP1 : Reactive Power Source.



(c) STEP3 : Autonomous Decentralized Control in each Virtual System.



(b) STEP2 : Virtual System.



(d) STEP4 : Reactive power of each real DG.

Fig. 18. Proposed method by virtually divided system.

The concept of the proposed method is shown in fig.18. Both the high-speed Virtual System 1 and the low-speed Virtual System 2 work in parallel, and chain reaction of Q-Coop method works faster in Virtual System 1. As a result, mode 1 controls of all DGs are utilized preferentially because the reactive power control of RPS1 which is included in Virtual System 1 works faster.

4.3 Autonomous decentralized voltage profile control method in each Virtual System

The reactive power control of each Virtual System is also composed by V-Ref method, Q-Save method and Q-Coop method. The control logic of V-Ref method is same as that in section 3, and it is simply modified to Eq.(18) to realize the multiplexing. Q-Save method and Q-Coop method also need some modifications. The equalization of power factor is main aim of Q-Coop method in the proposed method in section 3.3. However, in the case the inverter has a free capacity, power factor is not proper index for expressing the control efficiency because the reactive power control based on mode 1 does not decrease the control efficiency. Hence, in this section, the ratios of the amount of reactive power to its maximum value are utilized in place of power factor. The ratio is also utilized in Q-Save method. The modified equations are shown in Eq.(19)-(21).

(a) Voltage Reference method (V-Ref method)

$$if \quad V_k(t) < V_{\min} \quad \text{or} \quad V_{\max} < V_k(t)$$

$$\begin{cases} T_{\alpha 1}\dot{Q}_{RPS1,i}(t) = K_{\alpha 1}(V_{ref,i} - V_k(t)) \quad (RPS\,1) \\ T_{\alpha 2}\dot{Q}_{RPS2,i}(t) = K_{\alpha 2}(V_{ref,i} - V_k(t)) \quad (RPS\,2) \end{cases} \tag{18}$$

where,
$Q_{RPS1,i}$, $Q_{RPS2,i}$: reactive power of RPS1 and RPS2 of DG i
$T_{\alpha 1}$, $T_{\alpha 2}$: time constant of V-Ref method in each Virtual System [sec]
$K_{\alpha 1}$, $K_{\alpha 2}$: control gain of V-Ref method in each Virtual System
$V_{ref,i}$: reference voltage at node i (usually defined as 1.00 [p.u.])
$V_k(t)$: voltage at node k where the voltage deviation value becomes maximum within IEA

(b) Q Saving method (Q-Save method)

$$if \quad V_{\min} + \Delta < V_k(t) < V_{\max} - \Delta$$

$$\begin{cases} T_{\beta 1}\dfrac{\dot{Q}_{RPS1,i}(t)}{Q_{\max 1,i}} = K_{\beta 1}(Q_{ref,i} - \dfrac{Q_{RPS1,i}(t)}{Q_{\max 1,i}}) \quad (RPS\,1) \\ T_{\beta 2}\dfrac{\dot{Q}_{RPS2,i}(t)}{Q_{\max 2,i}} = K_{\beta 2}(Q_{ref,i} - \dfrac{Q_{RPS2,i}(t)}{Q_{\max 2,i}}) \quad (RPS\,2) \end{cases} \tag{19}$$

where,
$T_{\beta 1}$, $T_{\beta 2}$: time constant of Q-Save method in each Virtual System [sec]
$K_{\beta 1}$, $K_{\beta 2}$: control gain of Q-Save method in each Virtual System
$Q_{ref,i}$: reference reactive power of Q-Save method (it is set to 0.00 [p.u.] in this section)

(c) Q Cooperation method (Q-Coop method)

$$if \quad V_{\min} < V_k(t) < V_{\max}$$

$$\begin{cases} T_{\gamma 1}\dfrac{\dot{Q}_{RPS1,i}(t)}{Q_{\max 1,i}} = K_{\gamma 1}(Q^*_{RPS1,ref,i}(t) - \dfrac{Q_{RPS1,i}(t)}{Q_{\max 1,i}}) \quad (RPS\,1) \\ T_{\gamma 2}\dfrac{\dot{Q}_{RPS2,i}(t)}{Q_{\max 2,i}} = K_{\gamma 2}(Q^*_{RPS2,ref,i}(t) - \dfrac{Q_{RPS2,i}(t)}{Q_{\max 2,i}}) \quad (RPS\,2) \end{cases} \tag{20}$$

$$\begin{cases} Q^*_{RPS1,ref,i} = \dfrac{1}{M_i} \displaystyle\sum_{j \in G} \dfrac{Q_{RPS1,j}}{Q_{\max 1,j}} \\ Q^*_{RPS2,ref,i} = \dfrac{1}{M_i} \displaystyle\sum_{j \in G} \dfrac{Q_{RPS2,j}}{Q_{\max 2,j}} \end{cases} \tag{21}$$

where,
$T_{\gamma 1}$, $T_{\gamma 2}$: time constant of Q-Coop method in each Virtual System [sec]
$K_{\gamma 1}$, $K_{\gamma 2}$: control gain of Q-Coop method in each Virtual System
$Q^*_{RPS1,ref,i}(t)$, $Q^*_{RPS2,ref,i}(t)$: reference reactive power of Q-Coop method in each Virtual System
M_i : total node number included in IEA
G_i : node group neighboring node i

Above three control methods do not always work, and they are switched by the voltage information within IEA. When the voltage deviation node is included in IEA, reactive power is controlled according to Eq.(18). When the voltage deviation node is not included, the reactive power control is determined as a sum of the Eq.(19) and (20). Control parameters of each Virtual System are determined individually according to following guidelines.

- Time constant of RPS1 is set to a small value in order that control becomes faster in Virtual System 1.
- It is desirable that Q-Save method works faster in Virtual System 2. So the control gain of Q-Save method of RPS2 is set to a larger value.

4.4 Simulation results using 5-node model system

(a) Model system

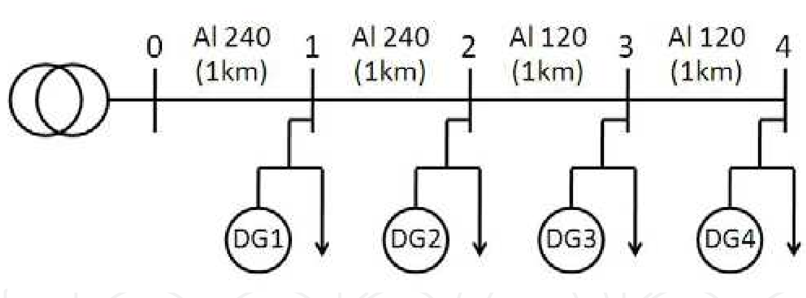


Fig. 19. 5-node model system.

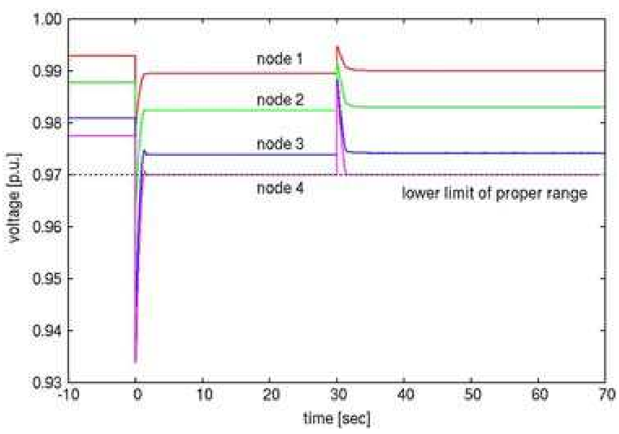
The proposed method is tested using 5-node model system shown in fig.19. Both load and DG are connected to all nodes and load capacity is relatively larger. Then, the voltage drop becomes main issue in this case. The detailed settings of the model system are listed in table 5. Although the active power of all DGs are set to 0.050 [p.u.], inverter capacity of DG1,2 and DG3,4 are different as shown in the table and the DG1 and DG2 have free capacities. Additionally, DG1,2 have only the free capacity as shown in the section (B) in fig.3. Because the DG3,4 have no free capacity, they have only the control capacity of mode 2 oppositely. The amount of each load is set to 50% at initial condition. After that, the loads show the stepwise change from 50% to 90% at time=0[sec], and from 90% to 75% at time=30 [sec], respectively.

Load capacity of each node	0.070[p.u.] (p.f.lag 0.80)
Inverter capacity (active power of DG) : node 1,2	0.080[p.u.] (0.050 [p.u.])
node 3,4	0.050[p.u.] (0.050 [p.u.])
Power factor control range of controllable DG	lag 0.8～lead 0.8
Objective range of voltage	0.97 ～ 1.03 [p.u]
Line impedance Al240 (1km/1section)	0.058+j0.138 [p.u.]
Al120 (1km/1section)	0.116+j0.276 [p.u.]

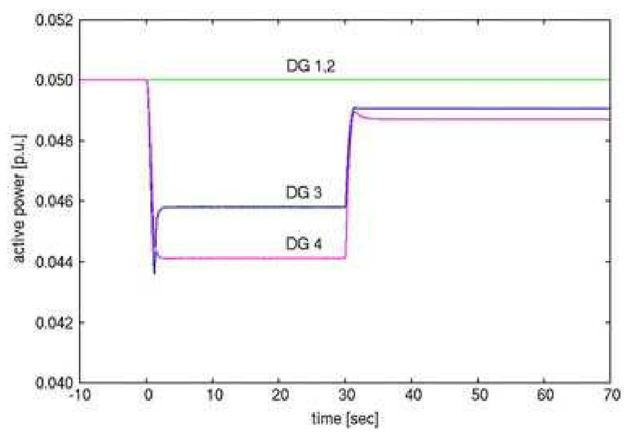
Table 5. System constants of 5-node model system.

(b) Application of basic method (case 1)

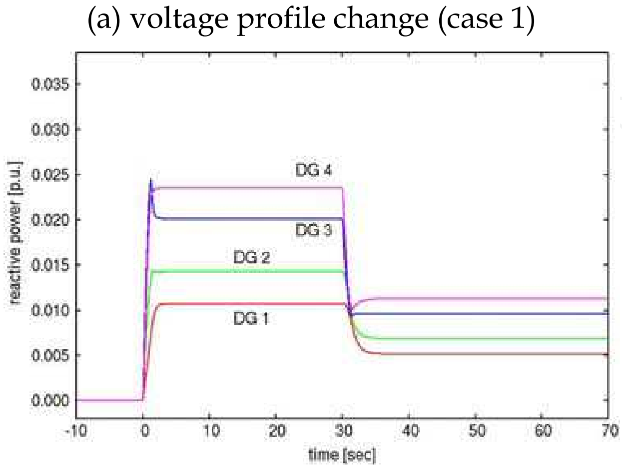
Control parameters are listed in table 6. First, fig.20 shows the simulation results by the basic method proposed in section 3. Figure 20(a)-(d) show the voltage profile change, active and reactive power change, and the ratio of reactive power to its control capacity. Voltage decreases largely by the load change at time=0 [sec]. DG3 and DG4 increase their reactive



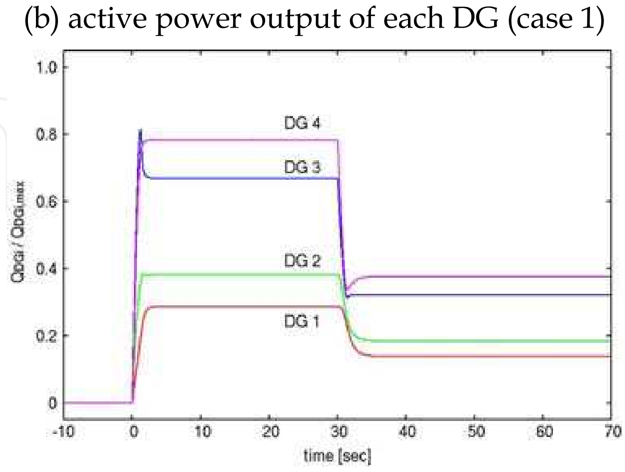
(a) voltage profile change (case 1)



(b) active power output of each DG (case 1)



(c) reactive power output of each DG (case 1)



(d) ratio of reactive power of DG to its capacity (case 1)

Fig. 20. Simulation results in case 1.

power in order to recover the voltage profile at node 3 and node 4. To help the reactive power control at downstream side, the reactive power of DG1 and DG2 are also increased by the work of Q-Coop method. In the case the basic method is applied, the nearer the voltage deviation node, the larger the reactive power is controlled. Therefore, the amount of reactive power control of DG1 and DG2 become smaller relatively. Hence, the reactive power of DG3 and DG4 become larger than that of DG1 and DG2. As a result, the active power of DG3 and DG4 decrease as shown in fig.20(b). Especially from fig.20(d), we can see that DG1 and DG2 are utilized only 30-40[%] of their free capacity while reactive power of DG3 and DG4 are utilized about 70-80[%] of their capacity. As seen above, in the case the control priority is not considered, it is possible the heavy control burden is imposed to the specific DG whose free capacity is small. At this time, it should be possible that large active power reduction occurs at the DG.

T_α	1.00 [sec]	T_β	1.00 [sec]	T_γ	1.00 [sec]
K_α	0.25	K_β	0.50	K_γ	3.00

Table 6. Control parameters. (case 1).

(c) Application of advanced control method (case 2)

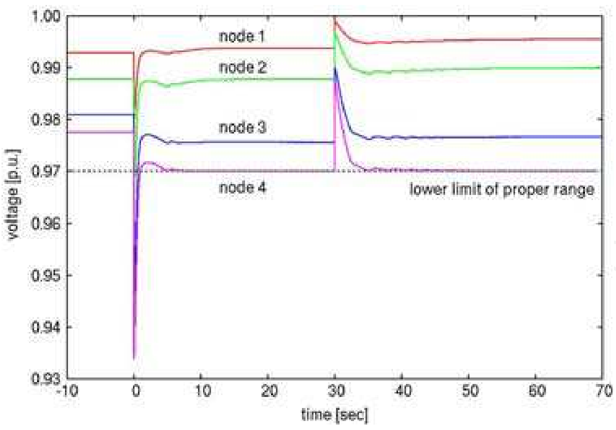
The proposed method is applied to the same 5-node model system. Control parameters are determined as table 7 according to the following guidelines in order to make a fair comparison with the results by previous subsection

- Let the control performance of V-Ref method at mode 2 become same as that of the case 1. Specifically, the control gain and time constant are adjusted to satisfy $K_\alpha / T_\alpha = K_{\alpha 2} / T_{\alpha 2}$.
- Let the control performance of Q-Coop method at mode 1 become same as that of the case 1. Specifically, the control gain and time constant are adjusted to satisfy $K_\gamma / T_\gamma = K_{\gamma 1} / T_{\gamma 1}$.

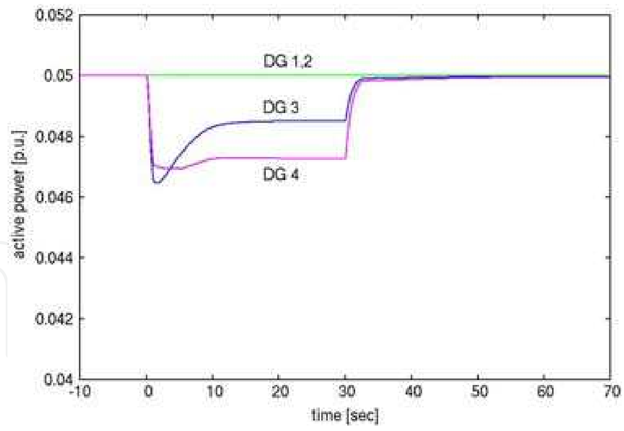
Mode 1	$T_{\alpha 1}$	1.00 [sec]	$T_{\beta 1}$	1.00 [sec]	$T_{\gamma 1}$	1.00 [sec]
	$K_{\alpha 1}$	1.00	$K_{\beta 1}$	0.05	$K_{\gamma 1}$	3.00
Mode 2	$T_{\alpha 2}$	4.00 [sec]	$T_{\beta 2}$	4.00 [sec]	$T_{\gamma 2}$	4.00 [sec]
	$K_{\alpha 2}$	1.00	$K_{\beta 2}$	2.00	$K_{\gamma 2}$	1.00

Table 7. Control parameters. (case 2).

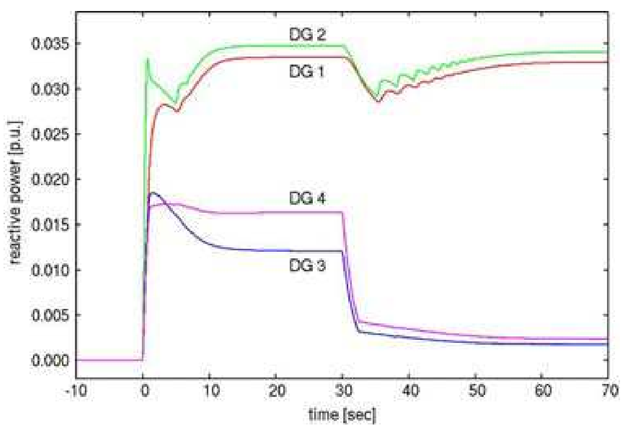
Figure 21 shows the simulation results by the proposed method. Figure 21(a)-(d) show the voltage profile change, active and reactive power change, and the ratio of RPS1 output to its control capacity. Voltage at node 2, 3, 4 become lower than the lower limit of proper range at time=0 [sec] due to the load change at the same time (fig.21(a)). Then, the voltage profile is recovered before time=1[sec] by the work of reactive power control of DGs immediately. Especially, the reactive power of DG1 and DG2 are utilized greatly due to the work of Virtual System 1. Specifically, after the voltage deviation occurs, the proposed autonomous decentralized control starts to work at both Virtual Systems and the reactive power control of Virtual System 1 works faster than that of Virtual System 2. We can see from fig.21(d) that the Q-Coop method works rapidly in Virtual System 1.



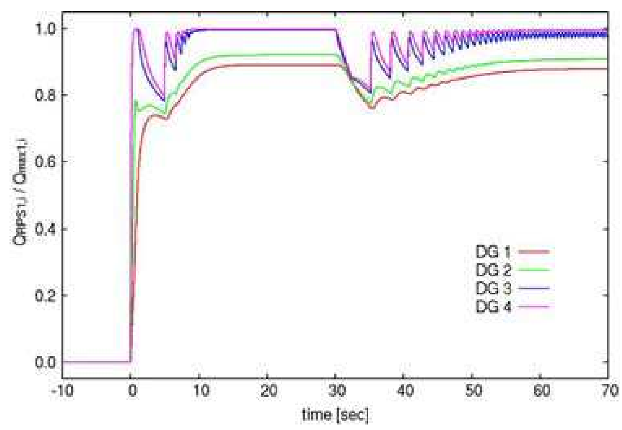
(a) voltage profile change (case 2)



(b) active power output of each DG (case 2)



(c) reactive power output of each DG (case 2)



(d) ratio of reactive power of RPS1 to its capacity (case 2)

Fig. 21. Simulation results in case 2.

It should be noted that the capacities of RPS1 at DG3 and DG4 are defined as ε virtually although the DG3 and DG4 have no free capacity. Utilizing the capacity of mode 1, DG3 and DG4 scarcely increases their ratios of reactive power to the maximum value when the voltage drop occurs. As seen above, even in the case a certain DG has no capacity of either RPS1 or RPS2, it can control its "ratio" using the small control capacity. In addition, because the reactive power by RPS1 of all DGs are not over the capacity of mode 1, only the mode 1 works actually. Therefore, the active power of DG1 and DG2 do not decrease as shown in fig.21(b). Although the reactive power of DG3 and DG4 decrease, the amount of active power reduction becomes smaller compared with case 1.

At the time=30 [sec], the required amount of reactive power for voltage profile maintenance decreases since the load becomes light again. By the work of Q-Save method, the reactive power of RPS2 decreases faster at this time because the control gain of Q-Save method is set to large value in Virtual System 2. Therefore, the reactive power of DG3 and DG4 decrease faster than that of DG1 and DG2. Which results in the rapid recover of active power reduction. The reactive power of DG1, 2 increase again after time=35 [sec]. This is because the reactive power of DG1 and DG2 are required again for voltage profile maintenance according to the reactive power decrease of DG3 and DG4. Then, the Q-Coop method works in both Virtual Systems and the reactive power of multiple DGs increase. Because the Q-Coop method in Virtual System 1 works faster, the reactive power of DG1 and DG2 increase largely. At this time, the required amount of reactive power is supplied by the Virtual System 1. In Virtual System 2, the reactive power do not increase and Q-Save method continues to work. As a result, at the steady solution, control mode 1 is effectively utilized and minimum amount of control mode 2 works properly.

4.5 Simulation results using 24-node model system

(a) Model system

The proposed method is tested using 24-node model system described in section 3.4. Although the overview of the system model is the same, the inverter capacity and active power of DGs are modified as shown in table 8, where the DGs at odd-numbered nodes have free capacity. The active power change of DG17 is modeled as fig.22. Table 9 shows the

Inverter capacity (active power of DG) : node 1,3,5, … , 23 node 2,4,6, … , 22	0.030[p.u.] (0.020 [p.u.]) 0.040[p.u.] (0.040 [p.u.])

Table 8. Modified part of 24-node model system.

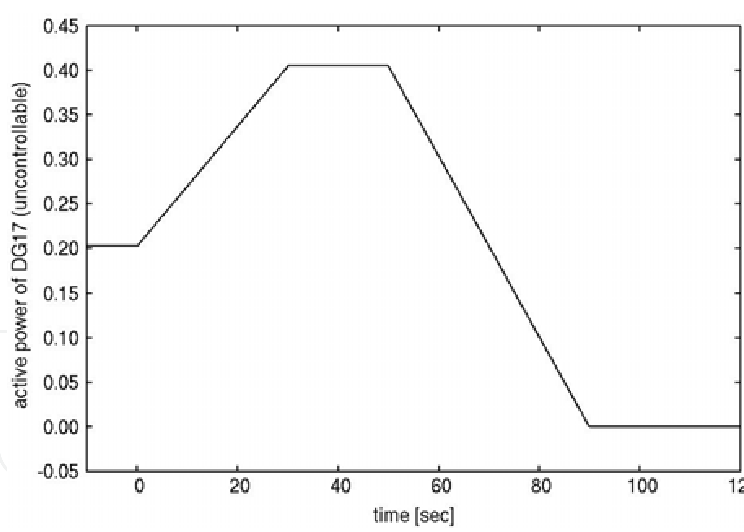
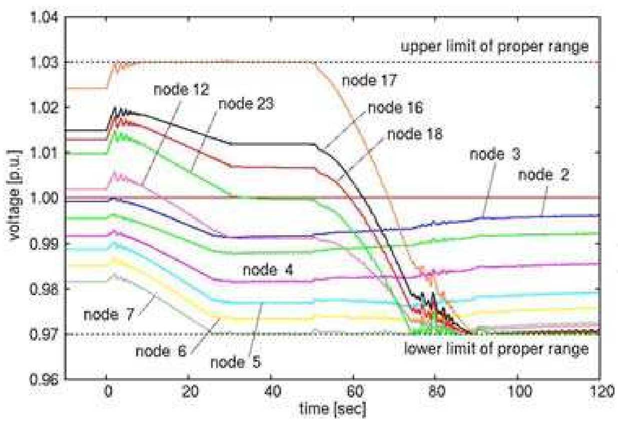


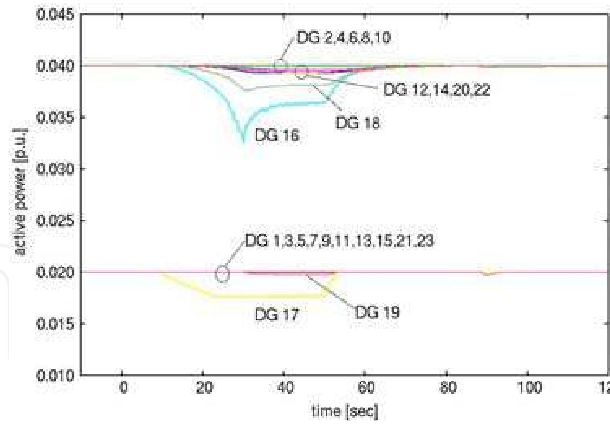
Fig. 22. Active power change of DG17.

Mode 1	$T_{\alpha 1}$	1.00 [sec]	$T_{\beta 1}$	1.00 [sec]	$T_{\gamma 1}$	1.00 [sec]
	$K_{\alpha 1}$	1.00	$K_{\beta 1}$	0.03	$K_{\gamma 1}$	1.00
Mode 2	$T_{\alpha 2}$	10.0 [sec]	$T_{\beta 2}$	10.0 [sec]	$T_{\gamma 2}$	10.0 [sec]
	$K_{\alpha 2}$	1.00	$K_{\beta 2}$	0.50	$K_{\gamma 2}$	1.00

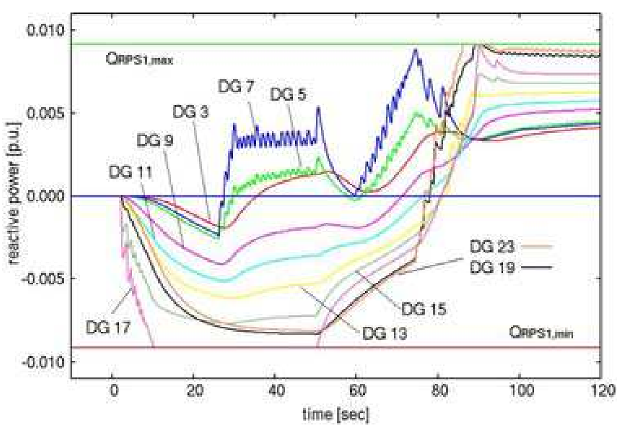
Table 9. Control parameters in 24-node model system.



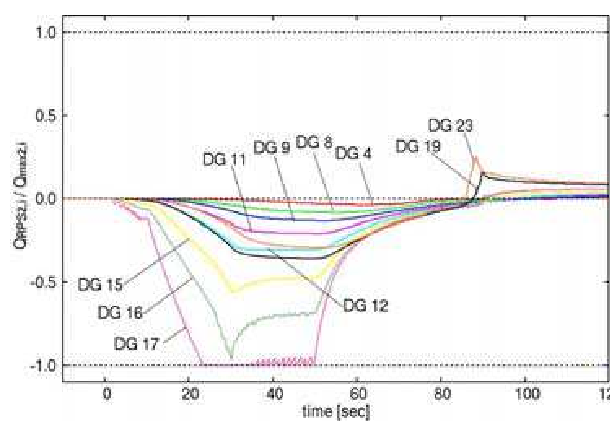
(a) voltage profile change (case 3)



(b) active power output of each DG (case 3)



(c) reactive power output of RPS1 (case 3)



(d) ratio of reactive power output of RPS2 to its capacity (case 3)

Fig. 23. Simulation results in case 3.

control parameters. Each parameter is determined by trial and error considering control stability.

(b) Simulation results (case 3)

Figure 23(c) shows the reactive power of RPS1 injected by DG3, 5 and 7 in order to control the voltage profile, active power of DGs, and the reactive power change of RPS1 and RPS2. As shown in fig.23(a), the voltage at node 17 reaches the upper limit at time=1[sec] by the active power change of DG17.

Before time=50 [sec], the voltage profile at downstream side of the feeder increases and it decreases around node 7 oppositely. Because the high and low voltage areas are included at the same time, the appropriate adjustment of voltage profile is required. Figure 23(c) shows RPS1 of DG3, 5 and 7 inject the reactive power in order to control the voltage profile within the proper range while RPS1 of other DGs absorb the reactive power to avoid the over voltage. As for the RPS2, the reactive power of most DGs are not so large except DG15,16,17 (fig.23(d)). DG16 and DG17 increase their reactive power largely due to V-Ref method because the voltage at node 17 reaches the upper limit of proper range. The reactive power of DG15 also becomes large due to Q-Coop method because DG15 neighbors DG16 whose reactive power is large. The active power of DG15 does not decrease because the sum of the reactive power of RPS1 and RPS2 is lower than the capacity of mode 1 while the active power of DG16,17,18 decrease. In addition, as for other than those above, we can see the active power decrease slightly at even-numbered DGs which have no free capacity due to the reactive power control of RPS2.

After time=70 [sec], it becomes possible for all DGs to supply the reactive power cooperatively since only the lower limit of voltage profile becomes problem. Hence, the reactive power of RPS1 of all DGs are controlled largely and the voltage profile is maintained properly without depending the reactive power control of RPS2.

As above, the proposed method works effectively even in the large scale system model. However, it is likely important to consider the control stability in the case that the proposed method is applied to the relatively large scale system. The decision technique for control parameters considering control stability should be developed in the future work.

5. Conclusion

To solve the energy and environmental issue, the introduction of DGs is one of important technologies. In this paper, we described a new voltage profile control method of a distribution network with a large number of DGs. Specifically, we have developed an autonomous decentralized voltage control method based on a multi-agent system using a reactive power control of inverter. The proposed method is composed by three control methods whose control purposes are different and only the local information exchange is required for flexible voltage control. In addition, as an advanced control method, we have described the voltage profile control method which can utilize a free capacity of inverter preferentially. Both basic and advanced methods are tested using 4-node, 5-node and 24-node model system and their effectiveness are shown. Future works are as follows.

- In our proposed method, the control object is limited to the continuous control such as reactive power control of inverter. However, there exist some discontinuous voltage control facilities such as LRT or SC in the distribution network. The cooperative work among continuous and discontinuous control should be developed.
- The control parameters are determined mainly by trial and error in this paper. However, in the future work, they should be adjusted automatically. Especially, it is expected to utilize the learning function of agents for automatic parameter adjustment considering control dynamics.

6. References

F.A. Viawan and D. Karlsson: “Combined Local and Remote Voltage and Reactive Power Control in the Presence of Induction Machine Distributed Generation”, IEEE Trans. Power Syst., Vol.22, No.4, pp.1002-1012 (2007)

F.A. Viawan and D. Karlsson: “Voltage and Reactive Power Control in Systems with Synchronous Machine-Based Distributed Generation”, IEEE Trans. Power Delivery, Vol.23, No.2, pp.1079-1087 (2008)

T. Senjyu, Y. Miyazato, A. Yona, N. Urasaki and T. Funabashi: “Optimal Distribution Voltage Control and Coordination With Distributed Generation”, IEEE Trans. Power Syst., Vol.23, No.2, pp.1236-1242 (2008)

Naoto Yorino, Takahiro Miki, Yuuki Yamato, Yoshifumi Zoka and Hiroshi Sasaki: “A Time Scale Separation Method for the Coordination of Voltage Controls for SVC and SVR”, IEEJ Trans. PE, Vol. 124, No. 7, pp.913-919 (2004)

Daisuke Iioka, Kuniaki Sakakibara, Yasunobu Yokomizu, Toshiro Matsumura and Norihisa Izuhara: “Distribution Voltage Rise at Dense Photovoltaic Power Generation Area and its Suppression by SVC”, IEEJ Trans. PE, Vol. 126, No. 2, pp.153-158 (2006)

P. N. Vovos, A. E. Kiprakis, A. R. Wallace and G. P. Harrison: “Centralized and Distributed Voltage Control: Impact on Distributed Generation Penetration”, IEEE Trans. Power Syst., Vol.22, No.1, pp.476-483 (2007)

P. M. S. Carvalho, P. F. Correia and L. A. F. M. Ferreira: “Distributed Reactive Power Generation Control for Voltage Rise Mitigation in Distribution Networks”, IEEE Trans. Power Syst., Vol.23, No.2, pp.766-772 (2008)

Shunsuke Tanaka and Hirokazu Suzuki: “A Study on Voltage Compensation Method using Autonomous Decentralized Control of Distributed Generators”, IEEJ Trans. PE, Vol. 129, No. 7, pp.869-879 (2009)

Mesut E. Baran and Ismail M. El-Markabi: “A Multiagent-Based Dispatching Scheme for Distributed Generators for Voltage Support on Distribution Feeders”, IEEE Trans. Power Syst., Vol.22, No.1, pp.52-59 (2007)

Takao Tsuji, Ryoichi Hara, Tsutomu Oyama, and Keiichiro Yasuda: “Autonomous Decentralized Voltage Profile Control of Super Distributed Energy System using Multi-agent Technology”, IEEJ Trans. EIS, Vol.126, No.2, pp.167-176 (2006)

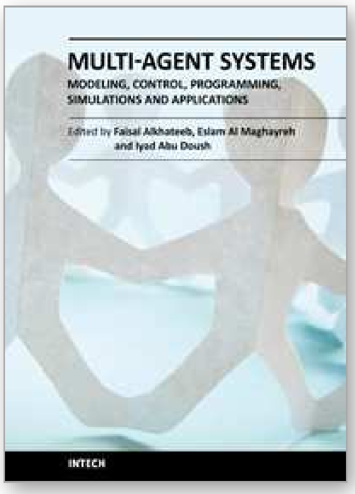
Takao Tsuji, Tadahiro Goda, Kazushige Ikeda and Seiji Tange: “Autonomous Decentralized Voltage Profile Control of Distribution Network considering Time-Delay”, Proceedings of the International Conference on Intelligent System Application to Power System, WA3-2 (2007)

Takao Tsuji, Tadahiro Goda, Kazushige Ikeda and Seiji Tange: “A Study of Autonomous Decentralized Voltage Profile Control of Distribution Network considering Economic Efficiency”, IEEJ Trans. PE, Vol. 128, No. 1, pp.174-185 (2008)

Takao Tsuji, Kohsuke Tomura, Tsutomu Oyama, Takuhei Hashiguchi Tadahiro Goda, Seiji Tange and Toshio Nomura: “A Study of Centralized Voltage Profile Control of Distribution Network considering Dynamics of Distributed Generator”, IEEJ Trans. PE, Vol.129, No.4, pp.507-516 (2009)

Takao Tsuji, Noriyuki Satoh, Takuhei Hashiguchi, Tadahiro Goda, Seiji Tange and Toshio Nomura: “A Study of Economical Incentives for Voltage Profile Control Method in Future Distribution Network”, IEEJ Trans. PE, Vol.129, No.6 (2009)

Takao Tsuji, Takuhei Hashiguchi, Tadahiro Goda, Takao Shinji and Shinsuke Tsujita: "A Study of Autonomous Decentralized Voltage Profile Control Method considering Control Priority in Future Distribution Network", IEEJ Trans. PE, Vol. 129, No. 12, pp.1533-1544 (2009)



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A multi-agent system (MAS) is a system composed of multiple interacting intelligent agents. Multi-agent systems can be used to solve problems which are difficult or impossible for an individual agent or monolithic system to solve. Agent systems are open and extensible systems that allow for the deployment of autonomous and proactive software components. Multi-agent systems have been brought up and used in several application domains.

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