Program for the Development of Autonomous Distributed Voltage Control Technologies for Power Distribution Networks (Optimal Control Technology Demonstration Project for the Next-Generation Power Transmission and Distribution Networks)

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Abstract

Meidensha Corporation took part in an "Optimal Control Technology Demonstration Project for the Next-Generation Power Transmission and Distribution Networks" sponsored by the Agency for Natural Resources and Energy under the Ministry of Economy, Trade and Industry Japan. The grant to this project was given during Fiscal 2010 to Fiscal 2012. We engaged in promoting technical development for advanced voltage control technologies for power distribution networks. Presently, voltage control in power distribution networks is managed by the control functions based on each terminal information level of each voltage control unit. Primarily, these control functions are based on the assumption that power flow is directed to the demand side; therefore, there is indication that there will be some difficulty in voltage control in the event that many photovoltaic power resources are installed extensively on the demand side. Considering such challenges, we have promoted its technical development for effective control parameters which aim to maintain system voltage in the regal range. This is based on the fundamental functions of the said independent distributed resource control.

1 Preface

With the growing demand for the reduction of greenhouse gas emissions, in April 2009 the Japanese Government set up a photovoltaic power generation system introduction target in order to realize 28 GW by fiscal 2020, which is a very challenging goal[(1)]. In March 2011, Japan was hit by The Great East Japan Earthquake causing tremendous damage. As a result, nuclear power stations were forced to shut down plants despite the fact that nuclear energy offers a high effect of reduction of greenhouse gas emissions. In addition, the long duration of nuclear power station shutdown has resulted in repeated power shortage problems. Under such circumstances, it has sparked public awareness regarding energy saving and has invited higher expectation of the use of renewable energy resources.

The photovoltaic power generation system (PV system) is an excellent power resource in terms of zero carbon dioxide emissions during power generation. On the other hand, its energy source is unstable and we cannot expect it to be a reliable energy supply source. In addition, the power output is greatly changed by variations in the solar radiation. Due to the aforementioned characteristics, the PV systems involve some concern affecting the power systems adversely in terms of stable system management. Recently, technologies generally called the "smart grids" are getting attention. The smart grids are expected to solve various grid problems by interconnecting with the increasing number of renewable energy resources such as PV systems.

In such a situation, the "Optimal Control Technology Demonstration Project for the Next-Generation Power Transmission and Distribution Networks" commenced[(2)]. It involves demonstration projects under the grants by the Agency for Natural Resources and Energy under the Ministry of Economy, Trade and Industry during Fiscal 2010 to Fiscal 2012. A total of 28 firms including 9 power utility companies joined the demonstration projects. The target of these demonstration projects was to achieve the most effective balanced use of electrical energy in terms of supply (grids) and the demand (electric users) from the standpoint of both the power supply side and demand side. These demonstration projects are supported by four subsidiary working groups, each having a mission of promoting technical development toward the establishment of basic technologies for the Japanese version of smart grids. We joined this project and worked on the problem of technical development for the advanced voltage control technologies for power distribution networks. This is to solve the challenges at the grid power side. This paper defines the challenges brought by the increasing installations of PV systems, outlines the problem-solving technologies that are being developed in the said demonstration project, and provides an example of the demonstration result.

2 Various Challenges in Voltage Control for Power Distribution Networks

Among the Japanese government's introduction target of 28 GW of PV systems by Fiscal 2020, it is concerned that approximately 70% is related to residential application[(3)]. There are many problems anticipated to arise as a result of mass introduction of PV systems. The following paragraphs will outline such problems incurred in power distribution networks where general power users such as residential uses are interconnected.

2.1 Problem of Voltage Rise

When a large number of PV systems are inter-connected to power distribution networks, an unusual voltage rise is caused by reverse power flows. According to the Electric Utility Industry Law in Japan, the terminal voltage at the receiving end of each electricity user is required to be maintained within the range of 101 ± 6V. In circumstances where many PV systems are not connected, one manages the grid only focusing on the voltage drops against the voltage control allowance range of 12V; however, if many PV systems are under-connected, a voltage rise is caused by reverse power flows and the voltage control allowance is relatively reduced as a result. Fig. 1 shows the challenge of a voltage rise in power distribution networks.

According to the relevant rules for the system interconnection of distributed energy resources, these power sources causing reverse power flows are required to have the power restricting function (voltage rise suppression function) to reduce the power generation output by controlling both active and reactive power whenever the voltage is raised above the preset level[(4)]. Due to the effect of this provision, there is no serious maintenance problem due to the voltage rise. Without the power control of distribution network, we will lose distribution energy resources like PV resources.

2.2 Problem of an Increase in Power Flow Deviation

In the future when the use of heat pumps for air conditioning becomes popular and electric vehicles are widely used, such new demand for energy will take advantage of economical nighttime power in Japan. It produces hot water or charges the power at night. A large-scale cluster of PV systems and the use of more power in the heating and power production will invite the expansion of power flow deviation in the daytime which makes it more difficult to pro-

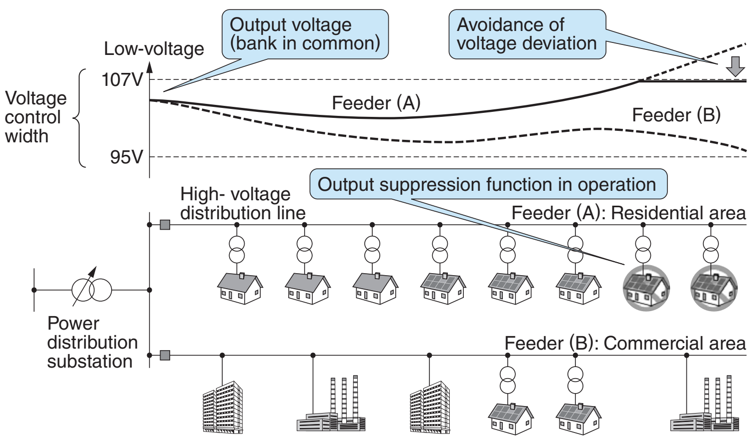

Fig. 1 Problems of Voltage Rise in Distribution Networks

The diagram shows problems in distribution networks anticipated when photovoltaic power systems are introduced in a large quantity.

vide the adequate voltage control. In power distribution networks, electric power is fed through multiple feeders from the same transformer bank. If a power network region with different load characteristics is inter-connected to the same transformer bank, there will be the increase of power flow deviation among the feeders. In such a case, it is anticipated that voltage control becomes difficult to perform if it is attempted only at a substation level. If energy resource and electrical energy modes of use are diversified, we can expect a load leveling effect in the overall power network. There will, however, be some difficulty in voltage control in a local level power distribution system. To meet such needs, it is necessary to grasp the condition of power flows in feeder lines adequately and establish an adequate control approach and suitable allocations of control devices to attain precise control of voltage.

2.3 Problem of Voltage Regulation

In PV systems, the generated power output changes greatly in responding to changes in solar positioning. It is anticipated that frequent power output changes can be relieved to a certain extent by a leveling effect in considering the overall power demand and supply balancing of the grid. On a local level and its distribution line network scale, there is a risk of frequent voltage fluctuations as a result of power output changes.

3 Advancement of Voltage Control Technologies for Power Distribution Networks

3.1 Outline of Present Control Technologies

As shown in **Fig. 2**, major voltage control products used in the power distribution networks (feeder lines) are: on-load tap-changing transformers (LRT: Load Ratio control Transformers) installed in power distribution substations, Step Voltage Regulators (SVRs) installed in the middle of feeder lines, and static synchronous compensators (STATCOMs), etc.[5].

The LRT is capable of regulating the secondary voltage of a distribution transformer in a “step-by step” manner by changing a tap position changer. The control system of the LRT is mainly classified into three categories: the first is the Line Drop Compensation (LDC) system by which the target range voltage is regulated in line with the load current, the second is the program control system for voltage control according to the preset hourly-based patterns, and the third is a combination of the aforementioned two systems. The SVR is used to control the line voltage in the downstream power network system starting from the SVR’s installation point in a “step-by-step” manner. The LDC system is adopted for the SVR control. The STATCOM is equipment that controls reactive power continuously and at a high speed by using a self-excitation type power converter. It is capable of bi-directional control, i.e. up and down of voltage level by phase delaying or advancing direction.

3.2 Program for the Advancement of Voltage Control Technologies

With the wider implementation of PV systems in the future, this demonstration project assumes the scenario to improve the voltage control technologies for power distribution networks so that the present autonomous distributed control system can be upgraded into a higher level. In order to realize this scenario, development, demonstration, and evaluation of a new control system have been covered by multiple firms. **Fig. 3** shows the scenario under the demonstration project.

Presently, the said voltage control equipment is operated under autonomous distributed control based on the self-terminal information and on the fixed pre-set values for control. In the current situation, most power distribution networks are designed to collect telemetry data only at the power-supplying point of each distribution substation. A new system

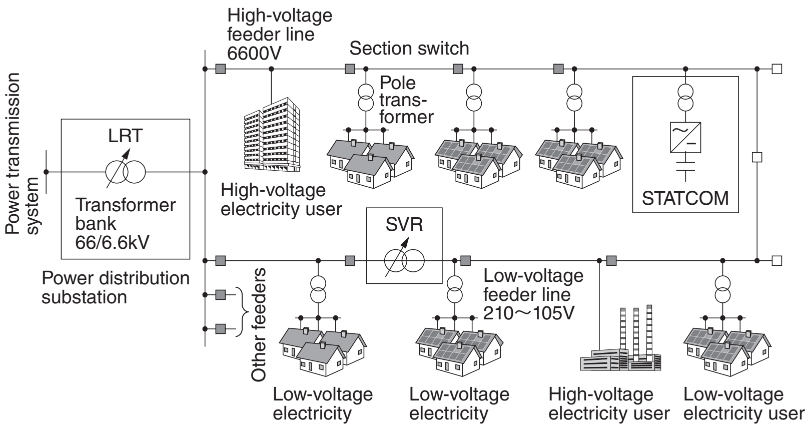

Fig. 2 Configuration of Distribution Networks and Voltage Control Equipment

Voltage control equipment generally used in distribution networks is shown.

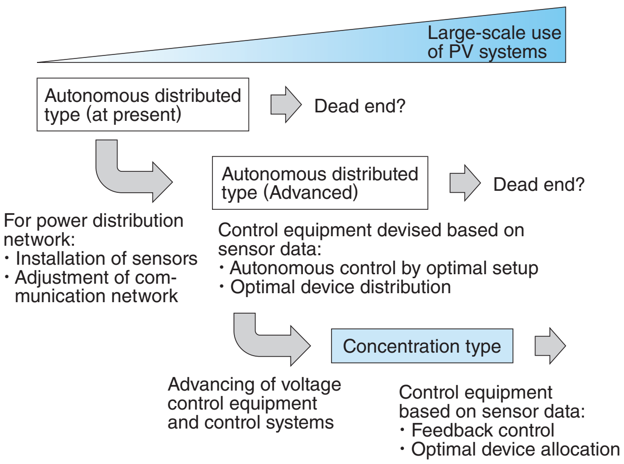

Fig. 3 Scenario under the Demonstration Project

A scenario for the working group is shown, which was established by all participants attending the sub-working group. Each discussed the issues on voltage control technologies for power distribution systems as a part of the programs for the Demonstration Project.

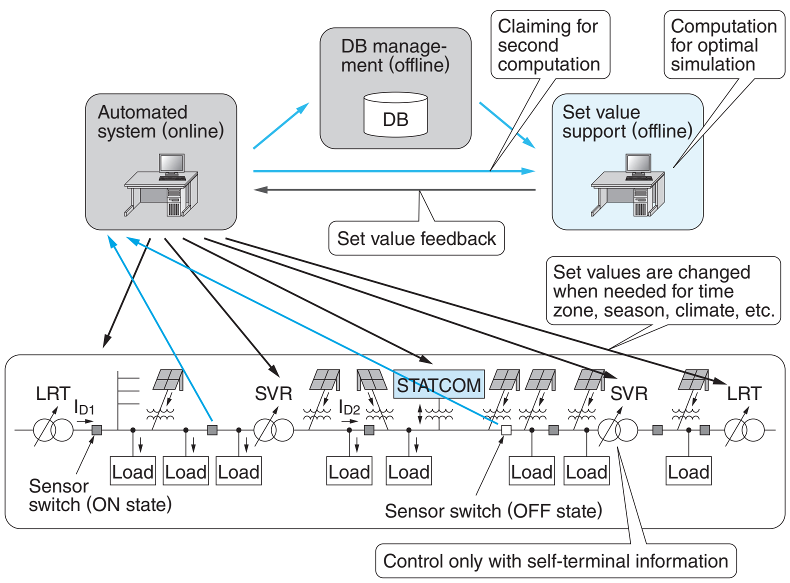

Fig. 4 Advancement Approach (1) for Autonomous Distributed Control

A conceptual diagram of the overall system is shown for approach (1) which is intended to advance the autonomous distributed voltage control. It is assumed that voltage control equipment is made to remain presently in the equivalent situation of autonomous distributed control, but the control parameters are optimized only in conditions where gradual modification is left possible.

to continuously collect the telemetry data by sensors on feeder lines at several places is beginning to be built. This demonstration project is carried on the assumption that such information from the sensor on the feeder line can be acquired. At the initial advancement level, we assume that voltage control equipment is properly arranged and that control parameters of the voltage control equipment for autonomous distributed control are adequately configured. Further, we anticipate the migration scenario in the future be from the autonomous distributed control to a central control system under which the voltage control equipment is operated directly from a remote place. Among such a scenario, we took the program to develop the advanced system for the autonomous distributed control system.

3.3 Advancement of Autonomous Distributed Control Technologies

At an early introductory stage of PV systems, implementation of voltage control is considered possible through new installation and extension of voltage control equipment. When PV systems become more popular, it is anticipated that there will be cases when it is difficult to cope within the given cluster of PV systems so long as conventional autonomous distributed control is carried out. For solutions, we have proposed to improve the situation by easily performing the remote operation control through the adjustment of control parameters of the autonomous distributed control equipment. We believe that it is an effective measure that we take timely control of parameters according to the conditions of season, time range, and weather condition. In this advancement approach (1), the database of past records voltage profiles for feeder lines are being referenced and control parameters of LRT and SVR are optimized using the offline support tools. Fig. 4 shows the advancement approach (1) for autonomous distributed control. When the control parameters are optimized, we can realize the control performance with due consideration to voltage profiles of total feeder lines, even in the case of control logic based on local-terminal information. In addition, by making the obtained control parameters remotely controllable under the given grid situation, we can flexibly manage the power flower change by the increase of PV system cluster or by the seasonal change. In the upgrading approach (1), the feedback control loops do not include any power distribution automation systems; therefore, it does not require either a higher speed information network or advanced redundancy.

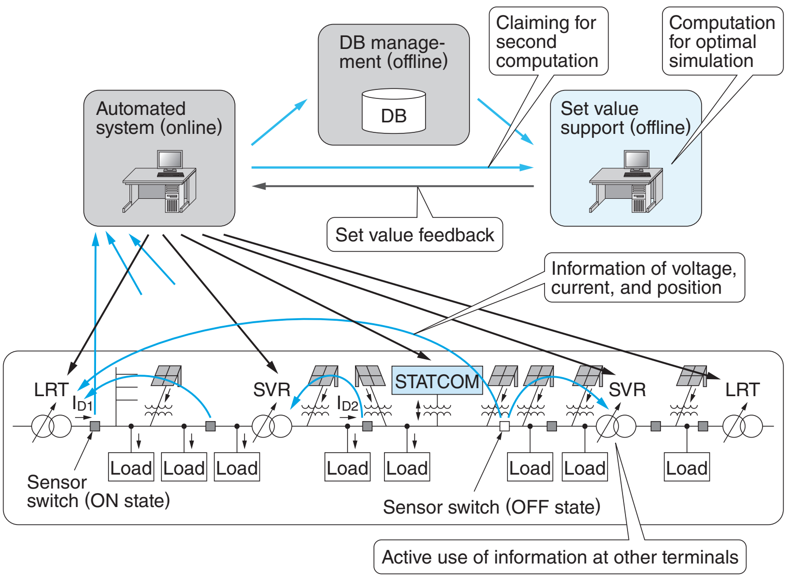

Fig. 5 Advancement Approach (2) for Autonomous Distributed Control

A conceptual diagram of the overall system is shown for approach (2) intended to advance the autonomous distributed voltage control. It is assumed that voltage control equipment is available for the autonomous distributed control, but telemetry values at the self-terminals and on feeder lines can be utilized. Management and control approach are the same for advancement approach (1).

When a PV system cluster is increased, it is assumed that it may be a situation where voltage profiles cannot be precisely grasped by only using self-terminal information. In such a case, it is considered effective to adopt an approach to actively use telemetry data at another point in addition to self-terminal information of voltage control equipment. In the advancement approach (2), normal time voltage control is based on autonomous distributed control. Even in the advancement approach (2), it is assumed that no power distribution automation systems are included in the feedback control loops. Fig. 5 shows the advancement approach (2) for autonomous distributed control.

3.4 Optimization Approach for the Control Parameters

In the case of LDC control adopted for the present LRT and SVR, it is operated within the designated control value of estimated voltage level for the center of the demand area. This control is based on the telemetry values of voltage and current available at the self-terminal. The estimated voltage level is determined based on the line impedance, voltage, and current against the load level target point. Since the control setup value is determined from the line impedance, it requires the understanding of a physical implication. Conversely, the physical implication of the setup value is ignored in the case of an optimal setting. In the case of the latter, simulation is performed for various power flow patterns and the most optimal parameter is determined when the aggregated value of voltage control errors becomes minimized. In so doing, we determined the setting value. There are two(2) optimization approaches: the first approach is a method to solve an exact analytic solution for objective function, and the second is an approximate solution method to determine improved combinations by making the evaluation values of various parameter combinations. In many realistic cases, due to the complexity of the objective function, it is difficult to get the exact analytic solution. As such, a certain method of approximate solution is generally adopted. In the parameter optimization problem covered in this paper, a time-based profile in voltage distribution determined according to a control parameter is deemed as the evaluation value. For this reason, it is necessary to perform time response simulation of the power distribution network in order to define the evaluation value. Since a certain amount of computing time is required for the time response simulation, the number of combinations of trial parameters is extremely limited when determining the most optimal solution (approximate solution) within realistic computing time. As such, selecting what simulation shall be conducted under what combination of the parameters is a vital element for optimization approach. For the method of selecting the best combinations of parameters, there are many proposals in regard to the metaheuristic approach. Fig. 6 shows the operation flow of optimization where both simulation and metaheuristic approach are employed. For operation of optimization, some combinations of proper parameters are initially chosen. Simulation is performed with these combinations in order to obtain an evaluation value. Based on the result, another combination of parameters is newly determined to perform simulation so that a new evaluation value can be obtained. This process is repeated until the operation is completed after reaching a combination of parameters producing the best evaluation value. Such parameter combination is then regarded as

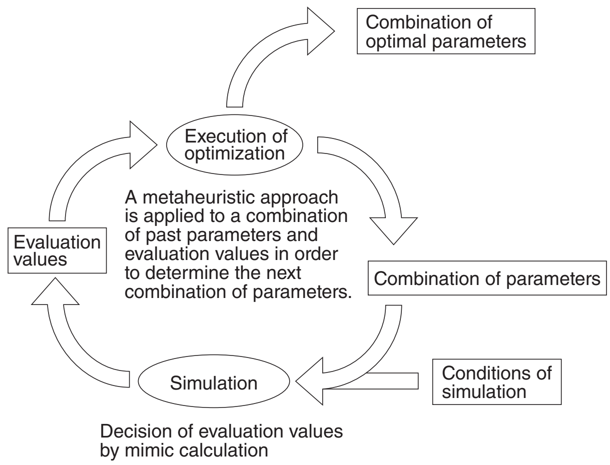

Fig. 6 Operation Flow of Optimization

An operation flow diagram is shown for the optimization of control parameters.

the best solution.

For the solution of optimization problems discussed in this paper, operation for optimization used in the said operation flow is based on the Particle Swarm Optimization (PSO) algorithm and the operation logic[6] developed by Waseda University, Japan. For operation for simulation, the BFS method has been applied and the time-based response power tidal flow calculation program[7] that we developed, is used.

When the control parameters are optimized during autonomous distributed control, it is essential to select the load and the power generating pattern carefully. If optimization is carried out using various demand-supply patterns, the acquired control parameters will have a wide application range; however, the time to conduct optimization operation will become very long and there is a risk that we may not be able to obtain an optimal solution from operation repeated with limited trials. Consequently, patterns should be selected considering demand-supply patterns with as little data as possible. It is vital to seek both the solvability improvement for the optimization operation and the reduction of operation time.

4 Evaluation of Autonomous Distributed Type Voltage Control

In order to evaluate a scenario for advancing voltage control technologies, we verified further to see what level of PV system cluster could be tolerated in the power network system in the event that we applied a specific control technology. In the paragraphs below, we discuss the verification results on our scope of research: the autonomous distributed control (current system) and the autonomous distributed control (advanced system).

4.1 Method of Evaluation

At the beginning of verification, we adopted a feeder line model as shown in Fig. 4. This model is based on the assumption that three different demand areas are covered by a single transformer bank in the model system configuration. The first community is the "commercial area" where demand for electric power is large in the daytime. The second community is the "residential area" where the feeder line span is short and power is assumed to be fed to densely populated area. The third community is the "agricultural area" where the feeder line span is long and electric power is fed to few houses scattered in the area. In the "commercial area," demand for power is large in the daytime while it is small at night. In the "residential area" and the "agricultural area," daytime demand is small, reverse tidal flow from PV systems occurs, and demand is large at night. Accordingly, this model is subject to confronting a situation where a voltage profile between feeders is extremely ununiform and some feeders may have long line length. This model has therefore, been devised in consideration of extreme conditions from a viewpoint of voltage control. This model is a combination of feeder line models also described in a report of the Electric Technology Research Association[8]. Fig. 7 shows the power distribution system model used for the verification project.

For the "commercial area," a load pattern has been assumed where power demand is large in the daytime. For the load patterns and PV power generation patterns in the "residential area" and the "agricultural area," an average household load patterns and telemetry values of sunlight are used. These data were obtained from the demonstration project[9] of the NEDO (New Energy and Industrial Technology Development Organization) implemented in Ohta City, Gunma Prefecture, Japan. The number of houses is assumed to be 2000 for the "residential area" and 1500 for the "agricultural area." We adopted a uniformly distributed model where the number of houses is set up and assigned to each node in proportion to the feeder line length. The capacity of photovoltaic power systems per house is assumed to be 3.5kW. We introduced the

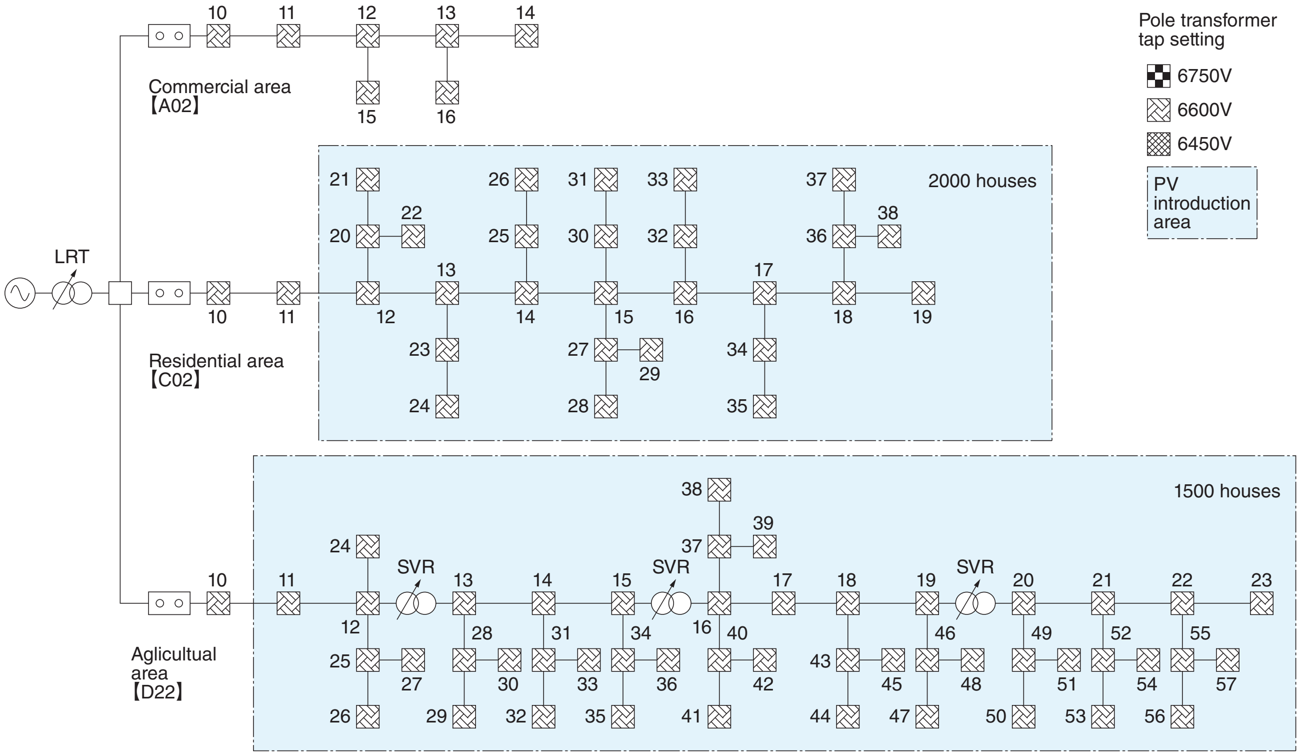

Fig. 7 Power Distribution System Model for Verification

This is an explanatory diagram of a power distribution system model structured for the performance verification of the proposed control approach.

PV systems only by one, starting with a house located at the edge of the feeder line. As far as practically possible, we made a configuration under very distressed power network conditions. It is assumed that the LDC control system is adopted for the LRT control system and the LDC control system of the distributed power resource is adopted for the SVR control system. It is also assumed that three SVR units are installed in the "agricultural area."

In autonomous distributed control using the present system is assumed, the feeder line voltage at the time of 0% PV introduction is configured at a fixed value for optimal setting that can be maintained in a proper range. For autonomous distributed control where the advancement approach (1) is assumed, control parameters are programmed to be modified adequately to an optimal figure in each season along with the rise of PV introduction rate. In any case, if a 30-minute mean value of all node voltages is kept within the adequate range, such a condition is regarded as acceptable. Otherwise, it is regarded not acceptable. The adequate range of voltage mentioned above is 103V to 107V assuming that the high-voltage feeder line voltage is converted into a low-voltage side. When performing optimization of the advancement approach (1), the four types

Table 1 Result of Evaluation

Regarding the autonomous distributed control of the present approach and that of the Advancement Approach (1), the result of evaluation is summed up for the introduction level of photovoltaic power systems obtained from simulation.

PV introduction rate (%)	Present approach (Fixed setup system)		Upgrading Approach (1) [Dynamic setup system]	
	Summer season	Middle season	Summer season	Middle season
10	0	0	0	0
11	0	0		
12	0	0		
13	0	0		
14	0	0		
15	0	2		
16	0	0		
17	0	0		
18	0	4		
19	1	13		
20	8	18	0	0
30			0	1
40			1	16

Note: Figures in the table denote the days when voltage deviation occurs within one month.

: Limit introduction level

: Occurrence of voltage deviation

: No evaluation

Table 2 Assumption of PV Introduction Goal and PV Penetration Rate

The table below provides the summary of goal for the introduction of PV power generation systems in the future that are anticipated by the Demonstration Project.

	PV introduction goal	Rate of diffusion to general homes (No. of houses)
2020	28 GW	Approx. 1/5 (20%)
2030	53 GW	Approx. 1/3 (33%)

of day patterns, a sunny day, cloudy day, and changeable days (two types), are selected as the power generation patterns for the PV systems. At the time of our evaluation, we evaluated load and power generation patterns based on the telemetry data for one month of the summer season and one month of middle season.

As a reference for this demonstration project, the PV introduction rate for general housing is assumed as the values specified in Table 2 when the PV systems saturation will reach as high as 28 GW in Fiscal 2020 and 53 GW in Fiscal 2030. This reference value was set under the assumption that the goal rate of PV introduction for general housing is 70%, the number of houses throughout Japan is 30 million, and a mean PV capacity per home is 3.5kW (28 GW × 0.7 / 3.5kW = 5.6 million homes; 30 million homes / 5.6 million homes ≒ 5.36 ≒ 1/5). Table 2 shows the target PV introduction number and the predicted PV penetration rate.

4.2 Result of Evaluation

The following eight simulation cases were evaluated:

(1) For conventional control system, the LRT control system is assumed to be LDC.

(2) For the advancement approach (1), the LRT control system is assumed to be LDC.

(3) For the advancement approach (1), the LRT control system is assumed to be of program control type.

(4) For the advancement approach (1), the LRT control system is assumed to be of a combination of LDC and program control type.

(5) For the advancement approach (1), the photovoltaic power systems are assumed to be added with reactive power control that lowers voltage.

(6) For conventional control system, the voltage control range is assumed to be 103V to 107V.

(7) For the advancement approach (1), the voltage control range is assumed to be 103V to 106V and STARCOM is added to the residential area.

(8) For the advancement approach (1), the voltage control range is assumed to be 103V to 106V and SVR is added to the residential area.

Fig. 5 shows the result of comparison of PV introduction rates obtained from evaluation. The power distribution network model under study this time is the distressed power network condition where voltage rise and voltage drop occur at the same time. Therefore, the effect of voltage control by LRT is difficult to ascertain. As a result, there is no clear performance difference by the LRT control system.

When we added reactive power control lowering voltage in the PV systems, the PV introduction rate rises as high as 40%.

In the case that voltage control equipment (SVR or STATCOM) is added, control performance is improved substantially, and the addition of SVR is especially effective.

Although not covered in this paper, the advancement approach (2) also produced almost the same level of results. We assume this is due to the distressed power network for the preset conditions of the power distribution network model.

While under the conventional control systems, by using the PV introduction, the rate will stay at around 14%, and the adoption of the advancement approach (1) improved the PV introduction rate up to 30%. Such result confirms that by adopting the advancement approaches, we will be able to reach the introduction target in Fiscal 2020. Fig. 8 shows the demonstration results.

5 Postscript

This paper introduced issues related to voltage control for distribution networks arising out as a result of higher infusion of PV systems in the future. We also showed a scenario leading to the solution of these issues. In regard to the advancement approach for autonomous distributed control which is considered as effective in a process of the scenario, this paper also outlined the approach and showed the simulation results under the said approach. The demonstration project is under the grant by the Agency for Natural Resources and Energy under the Ministry of Economy, Trade and Industry. We received the guidance of Professor Hayashi from Waseda University and support from distribution network-related engineers from power

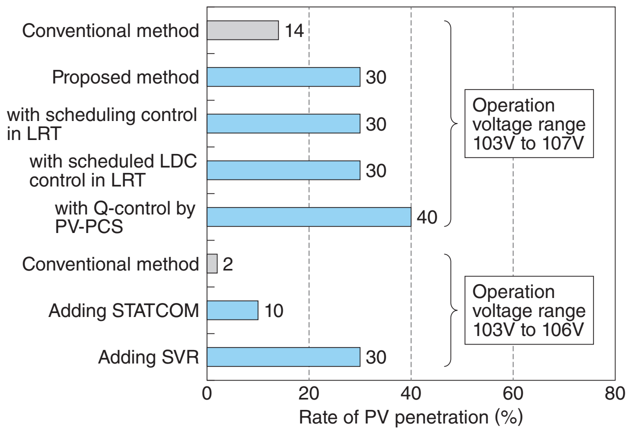

Fig. 8 **Result of Demonstration**

The result of verification is shown in regard to the comparison of present and advancement approaches of LRT control systems, and the effect of other measures (measures by reactive power control in PCS for PV and additional installation of voltage control equipment).

utility companies. We could continue to study with such support. We would like to work on various technical developments to enable us to meet large-scale use of renewable energy resources in the power network.

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