Optimal Operation Plan for Distribution Network Systems Linking with Many Renewable Energy Resources

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Abstract

Recently, the renewable energy resources such as Photovoltaic (PV) power and wind power have been increasingly linked to distribution network systems. As a result, there is concern over the charge to resultant complex power flows from conventional simple ones that were in only one direction power flow. As such, there is a risk that the operation of distribution network systems may cause adverse effects on power supply programs for transmission network systems.

Our research proposes a coordinated control method for controllable loads located on the consumer side and a reactive power control approach with the use of interconnection inverters to be installed between existing voltage control devices (substation LRT and SVR) and PV generation systems. This occurs after the introduction of Battery Energy Storage Systems (BESS) which would be applied to the coupling point between the distribution network system and the transmission network stream. This project is able to maintain appropriate voltage on a distribution network and stabilize power flows at the coupling point.

1 Preface

Recently in Japan, the introduction of distributed energy resource of renewable energy is actively promoted in order to realize a low carbon society. Power generating systems using renewable energy are attracting a great deal of attention because they do not generate any carbon dioxide and they use renewable sources of energy. The power yield, however, tends to be greatly affected by meteorological conditions which make it difficult to maintain the distribution voltage within a proper range if such resources are grid-connected with the distribution network system in a large quantity. Furthermore, existing distribution network systems are being built on the assumption that the power flows run from upstream to downstream. There is no such consideration against a voltage in the end of feeder increase in a distribution network system as a result of an interconnection with distributed energy resources. As a result, the interconnection of a large amount of distributed energy resources can bring about a variety of technical challenges such as the occurrence of reverse power flows toward an upper stream power system(1).

This paper proposes a method of an effective grid power distribution operation planning method with due consideration to battery energy storage systems, interconnection inverters for distributed energy resources, existing voltage control devices, and controllable loads.

2 Grid Power Distribution System Model

Fig. 1 shows a model of the grid power distribution system represented in this paper. The node numbers encircled in the diagram denote that a large number of Photovoltaic (PV) energy resources are presumed to be interconnected with the grid. PV energy resources are anticipated to increase in the future due to the reduction of introduction costs and the concern over the rising power utility charges. Table 1 shows various constants of a distribution network system model. The system capacity and nominal voltage assumed in this table are 5MVA and 5.5kV, respectively.

According to the Electricity Utility Law, the supply voltage is required to be maintained within a

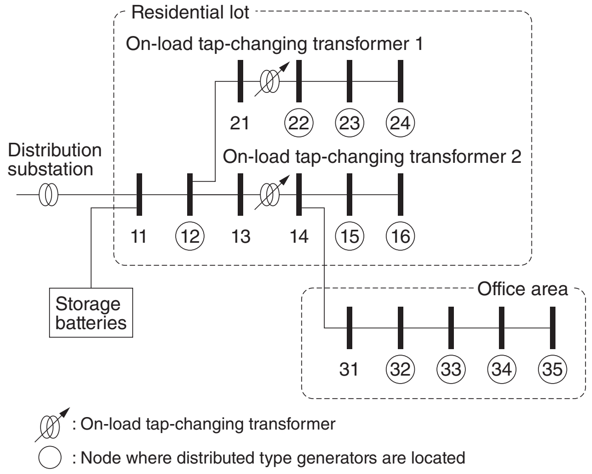

Fig. 1 Grid Power Distribution System Model

A model of the grid power distribution system presumed in this paper is shown. The node numbers encircled in the diagram denote the assumption that PV power systems are interconnected.

Table 1 Various Constants of a Grid Power Distribution System Model

Various constants of a grid power distribution system model used in this paper are defined.

Battery energy storage capacity	4.0pu (20MWh)
Battery inverter capacity	0.3pu (1.5MW)
Impedance of each line	0.04 + j0.04pu
Rated power output of PV generation system	0.08pu (400kW)
Inverter capacity of PV power system	0.08pu (400kW)

range of 202 ±20V or 101 ±6V for low voltage power receiving. In this paper, the range of 101 ±6V for 100V supply is adopted. The voltage range to be maintained in the distribution network system on high-voltage side is assumed to be 6380V (0.967pu) to 6600V (1.0pu)(2).

2.1 PV Power Generation System

In this paper, we propose an adoption of reactive power control for the electricity consumer side. In this case, there are a large number of interconnection inverters of PV power systems that are grid-connected. Fig. 2 shows a conceptual diagram of the PV power system. The reactive power control by the interconnection inverters is assumed to be possible independent of the generated active power output. It is also assumed that the generated active power output is never restricted. By using the optimization approach discussed in the next section, voltage control command values are determined in order to realize reactive power control.

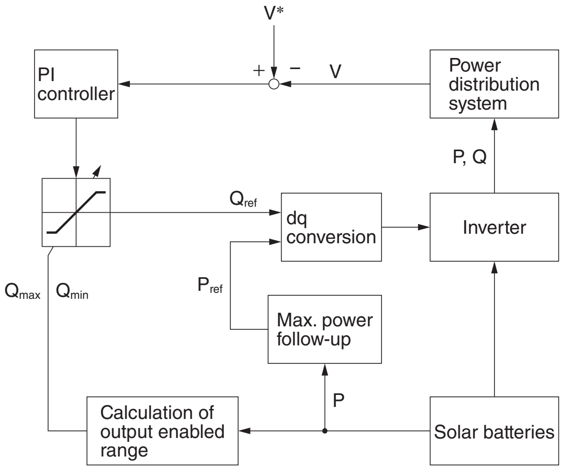

Fig. 2 Reactive Power Control System with Interconnection Inverters of the PV Power System

A conceptual diagram of the reactive power control system is shown. This system employs the interconnection inverters of the PV power system assumed in this paper. Control is carried out according to the control schedule determined on the basis of the optimization calculation.

2.2 Battery Energy Storage System

In this case, a battery energy storage system is introduced and applied to the interconnecting point between the distribution network system and the upper stream grid power system for the leveling of active and reactive power flows at the grid interconnecting point. This system has been established on the assumption that its operation follows up the control command values determined on the basis of optimization calculation in the same manner as for PV power systems.

2.3 Controllable Load

Since the capacity of the battery energy storage system becomes very large in the case of an active power flow control where only batteries are used(3), a cooperated control method is proposed in this paper with the use of controllable loads (which is recently attracting general attention in the field of smart grid technologies). Controllable loads are comparable with electric vehicles, electric hot water dispensers, and such equipment working with electric power consumed on electricity consumer side where control is made flexibly by using information technologies. The controllable load described in this paper assumes that it becomes smaller when power consumption of the grid power system as a whole is larger, and that it becomes larger as power consumption in the overall grid power system is smaller.

3 Decision Approach for Control Command Values

3.1 Formulation of Optimization Subject

As described above, our research aims at the optimal operation of grid power distribution systems such as transformer tap position control by means of existing voltage control devices, reactive power control with the use of connecting inverters available in PV generation systems, control of active and reactive power by using a battery energy storage system installed at the grid interconnecting point, and cooperated control of active and reactive power assuming that controllable loads are located on electricity consumer side. Based on the forecast amount of sunlight and predicted values of power demand for the next day, an optimal schedule is established according to the control command values. The objective function and the constrained conditions for optimization calculation are specified below.

[Objective function]

$$\min: F(P_B, Q_B, P_{CL}, Q_{CL}, Q_G, T_K) = \sum_{l}^{n} \sum_{i}^{x} P_{Li} \cdots\cdots (1)$$

[Constrained conditions]

$$V_{\min} \leq V_i \leq V_{\max} \cdots\cdots (2)$$

$$\sqrt{P_B{}^2 + Q_B{}^2} \leq S_B \cdots\cdots (3)$$

$$C_{B24}{}^{\min} \leq C_{B24} \leq C_{B24}{}^{\max} \cdots\cdots (4)$$

$$C_B{}^{\min} \leq C_B \leq C_B{}^{\max} \cdots\cdots (5)$$

$$\sqrt{P_G{}^2 + Q_G{}^2} \leq S_G \cdots\cdots (6)$$

$$P_f{}^{\min} \leq P_f \leq P_f{}^{\max} \cdots\cdots (7)$$

$$Q_f{}^{\min} \leq Q_f \leq Q_f{}^{\max} \cdots\cdots (8)$$

$$T_{\min} \leq T_k \leq T_{\max} \cdots\cdots (9)$$

$$P_{CL}{}^{\min} \leq P_{CL} \leq P_{CL}{}^{\max} \cdots\cdots (10)$$

$$Q_{CL}{}^{\min} \leq Q_{CL} \leq Q_{CL}{}^{\max} \cdots\cdots (11)$$

$$\Delta W_L \leq \int_0^{24} P_{CL}{}^{up} + \int_0^{24} P_{CL}{}^{down} \leq \Delta W_U \cdots\cdots (12)$$

Where, the respective variables are as follows:

n: Total number of control command switchover actions

x: Total number of lines

P_{Li}: Distribution loss o Line i

V_i: Voltage at i-th node

$V_{\min}$, $V_{\max}$: Upper and lower limits of node voltage

P_f: Tidal flow of active power at grid interconnecting point

$P_f{}^{\min}$: Lower limit of active power flow band width at grid interconnecting point

$P_f{}^{\max}$: Upper limit of active power flow band width at grid interconnecting point

Q_f: Power flow of reactive power at grid interconnecting point

$Q_f{}^{\min}$: Lower limit of reactive power flow band width at grid interconnecting point

$Q_f{}^{\max}$: Upper limit of reactive power flow band width at grid interconnecting point

P_G, Q_G: Active and reactive power output of PV generation systems

S_G: Interconnection inverter capacity of PV power systems

P_B, Q_B: Active and reactive power output from battery energy storage systems

S_B: Interconnection inverter capacity of storage batteries

C_B: Battery energy residual rate

$C_B{}^{\min}$, $C_B{}^{\max}$: Upper and lower limits of battery energy residual rate

C_{B24}: Battery energy residual rate in 24 hours

$C_{B24}{}^{\min}$, $C_{B24}{}^{\max}$: Upper and lower limits of battery energy residual rate in 24 hours

T_K: Tap position of each transformer

$T_{\min}$, $T_{\max}$: Upper and lower limits of tap positions

P_{CL}: Active power consumption in controllable loads

$P_{CL}{}^{\min}$: Lower limit of active power consumption in controllable loads

$P_{CL}{}^{\max}$: Upper limit of active power consumption in controllable loads

Q_{CL}: Reactive power consumption in controllable loads

$Q_{CL}{}^{\min}$: Lower limit of reactive power consumption in controllable loads

$Q_{CL}{}^{\max}$: Upper limit of reactive power consumption in controllable loads

$P_{CL}{}^{up}$: Active power consumption increment in controllable loads

$P_{CL}{}^{down}$: Active power consumption decrement in controllable loads

ΔW_L, ΔW_U: Limits of controllable load increment and decrement

In order to suppress extreme changes in active and reactive power at a grid interconnecting point and establish preferable control flexibility in overall distribution network system, a bandwidth is set up for the power flow at the grid interconnecting point. For our research, the bandwidth for the active power flow is kept constant at average load power ±0.1pu (500kW). The bandwidth for the reactive power flow is set up so that the power factor at the grid interconnecting point can be maintained within the range of 0.8 to unity. As aforementioned, power flow control has been devised to serve controllable loads such as in electric vehicles and all-electric homes. In this case, changes in active and reactive power flows are controlled within the predetermined bandwidth at the system connecting point.

The control command schedule is established for the duration of 24 hours in the increments of one hour. In the state that all restrictive conditions have been satisfied, the objective function is minimized so that power distribution losses can be suppressed throughout the system. There are many restrictive conditions; such as voltage restriction in a grid power distribution system, bandwidth restriction of active and reactive power flows intended to suppress changes in tidal flows at the grid interconnecting point, restriction of interconnection inverter capacity in PV power systems, restriction of interconnection inverter capacity in battery energy storage systems, restriction of battery energy residual rate intended to suppress rapid deterioration of battery energy storage systems ($C_B{}^{min} = 20\%$, $C_B{}^{max} = 80\%$), restriction of battery energy residual rate in 24 hours needed in consideration of operation on next day ($C_{B24}{}^{min} = 40\%$, $C_{B24}{}^{max} = 60\%$), restriction of upper and lower limits for transformer tap-changing, restriction of upper and lower limits for active power consumption in controllable loads, restriction of upper and lower limits for reactive power consumption in controllable loads, and restriction of upper and lower limits in regard to variations in active power consumption throughout 24 hours.

3.2 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a kind of optimization approach developed on the basis of a specific concept: when birds, insects, or a school of fish search for food, and when a particle (individual) discovers an efficient route to acquire it, other particles can follow the discovered route from wherever they are at the moment. This modeling is performed based on a particle swarm having a position and a speed in a multi-dimensional space. According to the retrieval algorism, positional information is exchanged with swarm members and particle position and speed are repeatedly adjusted. Position and speed are updated with the use of the expressions below.

$$V_{k+1}(i) = w \cdot V_k(i) + c_1 \cdot rand_1 \cdot (pbest(i) - S_k(i) + c_2 \cdot rand_2 \cdot (gbest - S_k(i)) \quad \cdots\cdots\cdots (13)$$

$$S_{k+1}(i) = S_k(i) + V_{k+1}(i) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (14)$$

Where, the respective variables are as follows:

$V_{k+1}(i)$: Speed of Particle i at k-th trial

$rand_1$, $rand_2$: Uniform random numbers given within a range of 0 ~ 1

$S_{k+1}(i)$: Retrieval point for Particle i at k-th trial

w: Inertial weight

c_1: Weighting for retrieval to the best particle position

c_2: Weighting for retrieval to the best group position

$pbest$: Best solution obtained in the particle

$gbest$: Best solution obtained in a group

4 Result of Simulation

In order to verify the effectiveness of the proposed method, simulation of power flow calculation has been carried out with a grid power distribution system model shown in **Fig. 1**. For this simulation, an optimal control command schedule is established, using a one-hour mean value of PV generation output in **Fig. 3** as a predicted value for the next day. The results of the simulation conducted under the application of the proposed method are shown

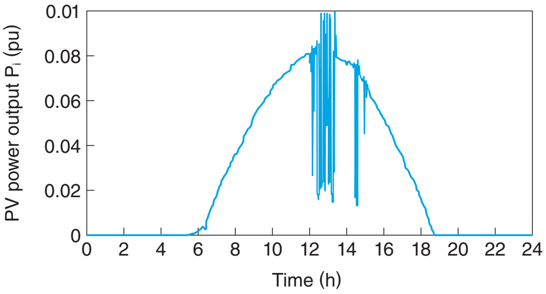

Fig. 3 PV Power Output

A predicted value of PV power output for the next day is shown, which is determined by the simulation described in this paper. A one-hour mean value is defined based on this diagram. It is used as a predicted PV generation output for control command scheduling.

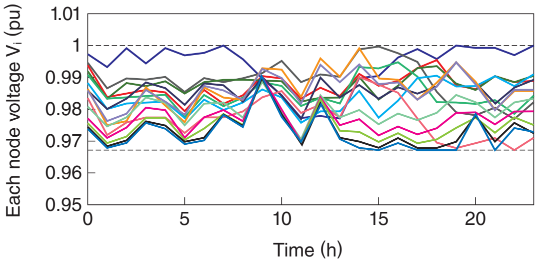

Fig. 4 **Distribution Voltage at Each Node**

The result of the distribution voltage simulation is shown, which is anticipated when the proposed method (cooperated control by controllable loads, battery energy storage systems, interconnection inverters of PV power systems, and existing voltage control devices) is adopted. Voltage restrictions are satisfied.

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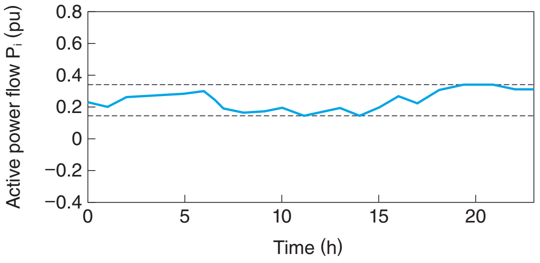

Fig. 5 **Active Power Flow at the Grid Interconnecting Point**

The result of active power flow simulation is shown, conducted at the system connecting point. The restrictive conditions are satisfied by cooperated control with the aid of battery energy storage systems and controllable loads.

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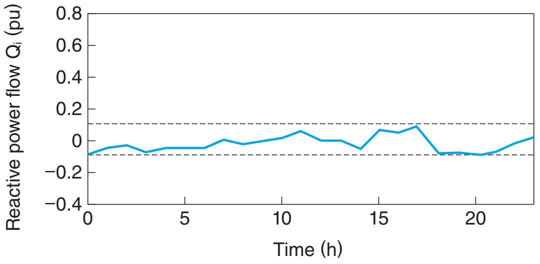

Fig. 6 **Reactive Power Flow at the Grid Interconnecting Point**

The result of reactive power flow simulation is shown, conducted at the grid interconnecting point. The restrictive conditions are satisfied, similar to the active power flows.

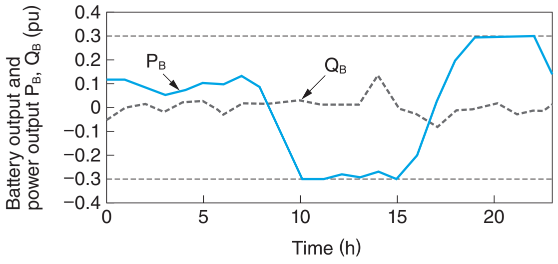

Fig. 7 **Active and Reactive Power Outputs from Battery Energy Storage Systems**

Active and reactive power outputs of battery energy storage systems are shown. It is possible to confirm that batteries are charged in the daytime when reverse power flows take place and are discharged when no PV power output is available.

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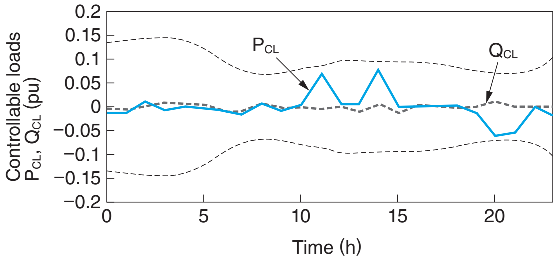

Fig. 8 **Active and Reactive Power Control by Controllable Loads**

The diagram shows the controllable capacity of controllable loads and the control values of active and reactive power. The controllable loads are operated in coordination with the charge/discharge mode of battery energy storage systems.

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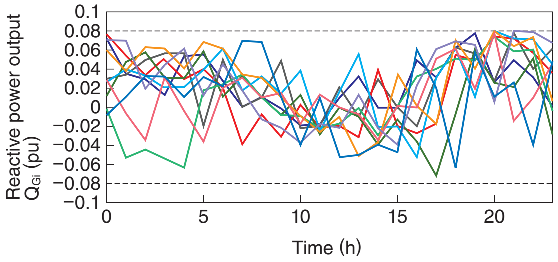

Fig. 9 **Reactive Power Output from Interconnection Inverters of PV Power Systems**

The controllable capacity of interconnection inverters and the capacity of active and reactive power control are shown for the PV power system. It is possible to examine the effect of compensation for reactive power to raise system voltage while no PV power output is available.

in **Figs. 4** to **10**. The respective figures show the distribution voltage at each node under the cooperated control by controllable loads: battery energy storage systems, interconnection inverters of PV power systems and existing voltage control devices, active power flow at the grid interconnecting point, reactive power flow at the system connecting point, active and reactive power output from battery energy storage system, active and reactive power control by controllable loads, reactive power output from connecting inverters of PV power systems, and tap positions of existing voltage control devices, respectively. According to the data, it is possible to confirm that variations in voltage at each node are

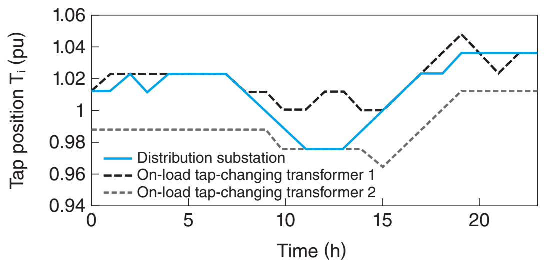

Fig. 10 **Tap Positions of Existing Voltage Control Devices**

The diagram shows the tap positions of substation LRT and SVR. It is possible to confirm that the voltage rise is suppressed in the daytime and the system voltage is raised at any other time.

controlled by tap-position control of existing voltage control devices, by cooperated reactive power control of the respective control devices and that the restrictive conditions are duly satisfied. Leveling of variations in power flows at the system connecting point is attained by active and reactive power control of the battery energy storage system. When controllable loads are adopted, it becomes possible to perform active and reactive power control on the consumer side. This contributes substantially to the reduction of capacities of battery energy storage systems and connecting inverters.

5 Postscript

This paper described our proposal of optimal operation approach for the grid power distribution systems where a large number of renewable energy resources are accommodated. When the proposed method is adopted, it is possible to adequately maintain distribution voltage and level power flows at the grid interconnecting point. Further, we could reduce the capacity of battery energy storage systems by using the controllable loads.

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