Supply and Demand Control System for Power Systems with Distributed Power Supplies

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ABSTRACT

The output of renewable energy sources such as solar and wind power fluctuate frequently. Therefore, it is concerned that maintaining the supply-demand balance in a rural area or an isolated island is difficult. To solve this problem, Fuji Electric has developed a hierarchical supply and demand control system with different control cycles for supply and demand planning, economic load dispatching control and load frequency control. The above functions of the developed system have been verified by digital simulations with promising results.

1. Introduction

Distributed power supplies, which utilize such renewable energy as photovoltaic power generation and wind power generation, are rapidly attracting interest on a global scale; and many countries are promoting efforts to expand the implementation of renewable energy. In Japan, it is pointed out that expanding the implementation of renewable energy is an urgent necessity to achieve the basic principles of the energy conservation policies, or 3Es (energy security, environmental protection from global warming, and efficient energy supply).

The government’s “Basic Energy Plan” revised in June 2010 also set a high goal of increasing the percentage of distributed power supplies using renewable energy to 10% of primary energy supply by 2020. To accomplish this goal, there is a plan to implement 28.00 million kW by photovoltaic power generation and 4.90 million kW by wind power generation in 2020. However, there is a concern that distributed power supplies using renewable energy will cause the frequency of vulnerable electric power systems to fluctuate on isolated islands, resulting in adversely affecting loads because output from distributed power supplies varies every moment with the natural conditions, such as insolation and wind velocity.

As a technological solution to this problem, micro grids come under the spotlight. Especially on isolated islands where there is a concern that fluctuation in frequency may increase by implementing renewable energy, a supply and demand control system using an energy management system (EMS) is expected to come into widespread use at an early stage.

This paper describes an overview of the hierarchi-
plan, with economy taking into account [see Fig. 1 (Layer 1)]. Next, to handle fluctuation for about 60 minutes interval, the dispatching of output is finely adjusted by activating and deactivating the generators and storage batteries whose supply and demand plan was determined by economic dispatching control (EDC) [see Fig. 1 (Layer 2)]. To respond to fluctuation for about 20 minutes interval, output is controlled by load frequency control (LFC) so that the frequencies will fall within the specified range [see Fig. 1 (layer 3)].

Finally, to cope with fast fluctuation for about 1 minute interval, output is controlled by the governor-free operation function provided with the generators and storage batteries.

2.1 Supply and demand plan

The supply and demand plan is formulated as a mixed integer programming problem, which determines the activated and deactivated states of generators and storage batteries and the dispatching of output from them. In this mixed integer programming problem, increase in the number of generators and storage batteries increases their number of combinations enormously. It is, therefore, practically infeasible to evaluate objective functions relative to all combinations of activation and deactivation of the generators. For this reason, processing time is reduced by implementing the following processing to the determination of activation and deactivation patterns of generators and storage batteries:

(a) Relieve constraints to reduce calculation time, and determine the activated and deactivated states of the generators approximately and tentatively by means of quadratic programming.

(b) Apply the preset logic to the activated and deactivated states of the generators tentatively derived in (a) to finally determine the activated and deactivated states of the generators.

(c) Determine the dispatching of output from the generators and storage batteries relative to the activation and deactivation of the generators determined through the processing up to (b) by quadratic programming.

The objective function of this approach is shown below in Equation (1). The target is the minimum economic cost of generator operation and activation costs. The generator operation cost was approximated by the nomic cost of generator operation and activation costs.

\[ \text{Minimize } \sum_{k=1}^{N} (a_{k} P_{k}^{2}(t) + b_{k} P_{k}(t) + c_{k}) + \sum_{k=1}^{N} \Delta u_{k} K_{k} \]  

\[ \text{Subject to: } \text{Constraints are shown below.} \]

**2.2 Economic dispatching control (EDC)**

The dispatching of output from the generators is calculated using economic dispatching control (EDC) based on the activation and deactivation plan worked out in the supply and demand plan. EDC minimizes costs for a future specific period with consideration given to constraints concerning the upper and lower limits of output from the generators. As an approach to realizing it, the quasi-optimization solution applying the equi-incremental fuel cost method is used. The formulation of EDC is shown below.

\[ \text{Obj}_{\text{EDC}} = \sum_{k=1}^{N} (a_{k} P_{k}^{2}(t) + b_{k} P_{k}(t) + c_{k}) \]  

\[ \text{Subject to: } \text{Constraints are shown below.} \]

**2.3 Load frequency control (LFC)**

A block diagram of load frequency control is shown
in Fig. 2. In load frequency control, the input value is different between when the system under control is linked to another system and when it is an independent system. To be specific, the power flow deviation of the point of connection is used as the input value when the system under control is linked to another system, or the deviation of the frequency is used as the input value when it is an independent system; and generator and storage battery output is controlled to minimize the respective deviation. Load frequency control can switch the input value between the case of a linked system and the case of an independent system.

The method of load frequency control is such that the power generation unit with the slowest response shall be set to first undertake control, and those that could not be controlled with it alone are operated by other unit in the order of response. This control method, however, may place a burden on the storage battery with the fastest response and use up remaining electric power of the storage battery when many distributed power supplies are linked to the system under control. To prevent this, a control function was added to allow a slow responding power generation unit with some margin to use its remaining power to bring the state of charge (SOC) of the storage battery closer to the target value. By using this function, the possibility that the remaining electric power of storage batteries to be used up can be reduced even if many distributed power supplies are linked to the system under control.

3. Performance Verification by Simulation

The effectiveness of the hierarchical supply and demand control system must be confirmed by verifying the performance of the system and demand operation plan, the performance of load frequency control and the performance of economic dispatching control[10]. We simulated the developed hierarchical supply and demand control system to verify the supply and demand operation plan and load frequency control. For the performance verification results of economic dispatching control, see Reference (1).

3.1 Performance evaluation of supply and demand plan

To confirm the effectiveness of the proposed approach, a simulation of 48 points a day (planned time interval: 30 minutes) was performed on a model system consisting of generators and storage batteries. We used loads which were reprocessed appropriately for the number of generators based on the value calculated by subtracting the load value of photovoltaic power generation and wind power generation from the load value actually set in the “Kyoto Eco-Energy Project”[2]. A PC equipped with a Pentium4*1 with 3 GHz CPU and 1 GB of memory was used.

(1) Comparison with the exact solution

Figure 3 shows a plan obtained from the developed supply and demand planning function and a supply and demand plan obtained from mixed integer quadratic programming (exact solution), using five generators. For the exact solution, LINGO*2, optimization package software, was used. Table 1 shows a comparison of economic cost (fuel and activation costs of generators) and processing time between the proposed approach and the exact solution. The economic cost is indicated as a relative value with the exact solution as

*1: Pentium4: Trademark or registered trademark of Intel Corporation.
*2: LINGO: Trademark or registered trademark of LINDO SYSTEMS INC.
100%. The economic cost of the proposed approach is only about 0.3% higher than that of the exact solution, although the processing time of the proposed approach is about 1/1000 the exact solution. When comparing the results of the plans, two generators at rest (G1, G2) are activated in the load rise time period to charge the storage batteries with excess electric power in the proposed approach. On the other hand, only one generator (G1) is newly activated in the exact solution. Despite this difference, the results of the plan by the proposed approach meet the constraints, proving that the proposed approach is adequate for practical applications in terms of economic cost and processing time.

(2) Number of generators and processing time

Table 2 shows processing times with different numbers of generators. The processing time is 114 seconds when 15 generators are used, and is considered satisfactory assuming that the supply and demand plan is formulated with a micro grid at intervals of 30 minutes.

3.2 Performance evaluation of load frequency control

To verify the effectiveness of the proposed approach, a system made up of generators, a storage battery, a photovoltaic power generation unit and a load was built on a real-time simulator.

(1) System model

The system model represented a 500 kW system linked to a higher-order system (infinite power supply), and constant control of the power flow was performed at the point of connection. The system model used for the simulation is shown in Fig. 4. The system model consists of two generators, a storage battery, a photovoltaic power generation unit and a load. The supply and demand control system uses the value of the power flow measured at the point of connection as input to control the active power of the generators and the storage battery so that the power flow at the point connection reaches the target value. In this verification, the target value of the power flow at the point of connection was set at 0 kW. Output from the photovoltaic power generation unit and electric power demand used for the verification are shown in Fig. 5. The implementation rate of photovoltaic power generation was assumed to be 30% of the capacity of the system, output from the storage battery to be 30% of output from photovoltaic power generation, and the capacity to be dischargeable for 30 minutes at rated output. In this verification, the model was set to control the SOC of the storage battery to 60%.

(2) Verification results

Using the abovementioned system model, the performance of load frequency control with a function to control the SOC of the storage battery was evaluated on the real-time simulator. The control target of the power flow at the point of connection was set at 3% or less in average error of 5-minute movement. This is slightly stricter than the 30-minutes balancing target where the error is specified as 3% or less between the amount of electric power generated and the amount of load electric power for 30 minutes. Figures 6, 7 and 8 show the verification results. The simulation revealed that the average error of 5-minute movement was up to about 0.1% at the maximum (see Fig. 6) and fulfilled the evaluation target of 3% or less set for control of the
power flow at the point of connection. Next, we will discuss the verification results of the function to control the SOC of the storage battery.

Figure 8 shows that the SOC of the storage battery is controlled to the target value of 60% for the period from 1,800 to 3,000 seconds. The SOC, however, is far from the target value of 60% before 600 seconds and after 3,000 seconds. This is because photovoltaic power generation and the load showed large fluctuation in these time periods and the storage battery carried out its intended function of fluctuation absorption. For the period from 600 to 1,800 seconds, on the other hand, fluctuation in photovoltaic power generation and the load are small, and the generators alone can often deal with these fluctuation. We confirmed that the developed function was effective in bringing the SOC of the storage battery close to 60% while maintaining supply-demand balance on the whole by setting output from the generators higher in this time period and issuing a charge command to the storage battery.

4. Postscript

This paper outlined a hierarchical supply and demand control system for distributed power supply systems, which consists of supply and demand planning, economic dispatching control and load frequency control; and described the verification results of the performance of the system through simulation. We will strive to make this system applicable to actual grid systems.

Reference
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