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Controlling Power Supply Paths in VG Hub Networks Using a Hybrid Type Control Algorithm

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Abstract. Although we have been developing a Virtual Grid (VG) system, where USB-PD-connected devices can alternatively provide and receive electrical power, we have not investigated the desirable power paths in a multiple-VG-Hub network. Our previous study shows that a power loss occurred inside the VG Hub. To minimize the total power loss, the number of used links needs to be minimized; the total power flow in the VG Hub network is minimized. In this paper, we have designed and implemented a cloud-based control system to execute the optimization with preceding local optimization. The experiment result has shown that the proposed hybrid type control algorithm can find the solution in 40% of the computational time on average compared with the algorithm that performs global optimization every time in the network where the solution can be found locally.

Keywords. Microgrids, DC, interconnection

1. Introduction

The power grid we are currently using is a centralized power grid that transmits power to a wide range of consumption areas. The weaknesses of this centralized power grid include transmission loss and widespread impact when a power plant shuts down. Therefore, in recent years, research has been conducted on distributed power grids that generate electricity by combining distributed power sources. As such a decentralized power grid in a small area, we have been developing a Virtual Grid (VG) system [1] using USB-PD [2] to synthesize Direct Current (DC) power from various power sources such as solar cells and storage batteries and distribute it to other loads such as personal computers (PCs). In order to absorb fluctuations in the amount of power generated by solar power generation, it is necessary to achieve a large storage capacity, but the number of batteries that can be handled by one VG Hub is limited. Therefore, the purpose of this study is to examine and compare control algorithms that link multiple VG Hubs.

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Our previous study [3] shows that a power loss occurred inside the VG Hub. Based on the aforementioned background, we develop a system to control the power supply paths in a VG Hub network to minimize the loss occurred in the hubs. In particular, to minimize the total power loss, the number of used links needs to be minimized; the total power flow in the VG Hub network is minimized. In this paper, we have designed and implemented a cloud-based control system to execute the optimization with additional local optimization. The experiment result has shown that the proposed hybrid type control algorithm can find the solution in 40% of the computational time on average compared with the algorithm that performs global optimization every time in the network where the solution can be found locally.

The rest of the paper is organized as follows. Section 2 explains the previous work related to ours. Section 3 describes the details about our system. Section 4 shows an experiment result with our system and Section 5 concludes this study.

2. Related Work

Our VG system is similar to the smart grid [4] which was intended to be used for restructuring old facilities of the power transmission and distribution network. Our system is not exactly identical to the smart grid in that we aim at only low-voltage appliances inside a building or at home. Furthermore, VG systems assume that instead of providers, users themselves construct the power supply network.

The technique we used in this study is based on the minimum-cost flow problem solving algorithms [5] applied in many optimization problems. Arabai *et al.* [6] considered the minimum cost maximum flow problem for a large power grid. They formulated the problem of finding incremental branch exchanges as a minimum cost maximum flow problem. Unlike this work, our system allows a local decision when the optimum solution is obvious i.e., adjacent source nodes can supply sufficient power to a load node.

Solar power generation used as a distributed power source is generated by DC. In addition, terminals such as notebook PCs and smartphones are DC-driven. Therefore, when the power grid is operated with Alternating Current (AC), it becomes necessary to convert the DC generated by the solar cell into AC, and when using electricity at the terminal, it becomes necessary to convert from AC to DC again, and the conversion loss that occurs at this time occurs. Therefore, there is research on the advantages of operating a power grid using renewable energy with DC [7]. While the microgrid, which is a decentralized power transmission network, is expected to be introduced on a city-by-city basis, the virtual grid system is based on the idea of connecting the grids that the users themselves build as a unit.

There are many studies that investigate control methods for micro grids. For instance, Harmon et al. proposed a cloud-based framework for two-step optimization of power distribution in a network with multiple microgrids [8]. In the first step, the proposed algorithm optimizes each microgrid to minimize the generation cost. In the second stage, the algorithm optimizes all microgrids to have the same marginal cost. Although this algorithm optimizes the entire network every time, the algorithm should be improved considering the computation time. In contrast to this study, our system introduces the local decision.

3. System Design

In this section, system architecture and the control algorithm are described.

3.1. Overall Architecture

We base our system on the prototype of the VG Hub. Figure 1 shows the appearance of the prototype. The VG Hub has seven USB Type-C ports that support USB PD and a Raspberry Pi inside. Furthermore, a control library can be used to acquire the status of these ports and control ports. The main functions of the control library are listed in Table 1.

Figure 1. Appearance of VG Hub.

Table 1. Functions of the control library.

Function	Example
Acquiring the status of ports	Connection status, max power value, current, voltage, etc.
Setting a role	Source (From VG Hub to a device) or Sink (From a device to VG Hub)
Setting a max power value	How much power can the port supply or receive

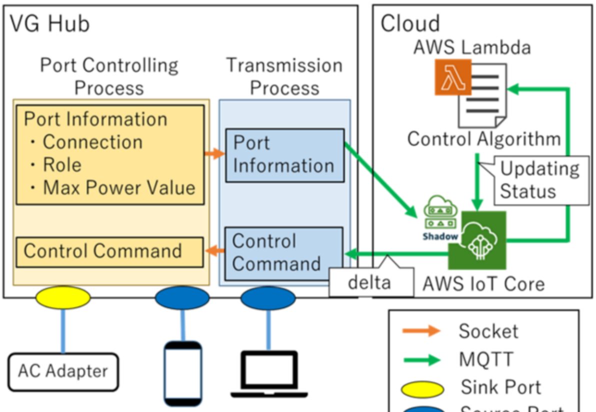

Figure 2. Architecture.

A cloud is introduced as a controller of multiple VG Hubs. The process of the control is as follows: first, the information from each VG Hub is collected to the cloud, then the control algorithm computes new values for ports by using this information, and the result is sent to each VG Hub. Figure 2 shows the overview of the system using AWS of Amazon as the cloud. In the VG Hub, the Port Controlling process and the Transmission process are executed. In the cloud, AWS IoT Core and AWS Lambda are used. AWS IoT Core connects “things,” in this case VG Hub, to the cloud and the control algorithm is deployed in AWS Lambda.

3.2. Hybrid Type Control Algorithm

In this study, we propose a hybrid type control algorithm that combines the method which solves the problem locally before global optimization. The optimization problem is considered as selecting paths and power values to minimize power values supplied between VG Hubs when supplying power from source nodes to load nodes in a network consisting of multiple VG Hubs. One of the methods to solve this optimization problem is to optimize the entire network by adapting a minimum cost flow problem. Although this network is an undirected graph, the network must be a directed graph to apply the minimum cost flow problem to the problem. Therefore, bi-directional edges are adapted between nodes that have edges. Moreover, there is a possibility that the number of source nodes, that are nodes to which powers are connected, and load nodes, that are nodes to which loads are connected, will be more than one in the network. Thus, virtual nodes that bind the source nodes and load nodes respectively are prepared. From the virtual node that binds the source nodes, edges are connected to the source nodes, and from the load nodes, edges are connected to the virtual node that binds the load nodes. The transformation of a graph is shown in Figure 3. By this transformation, the problem can be solved as a minimum cost flow problem.

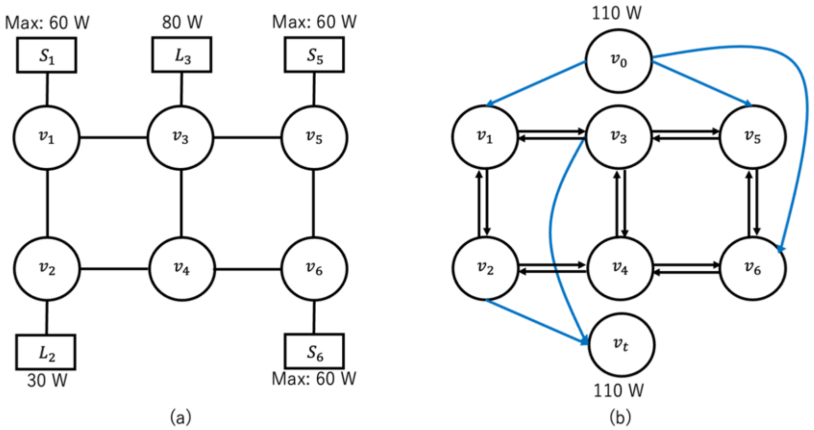

Figure 3. (a) VG Hub network with source and load devices, (b) Directed graph transformed from the graph (a).

The objective function of the optimization problem is as follows:

$$\min \sum\nolimits_{(a_{ij}=1, i\neq j)} p_{ij}, \tag{1}$$

where $A = (a_{ij})$ is the adjacency matrix of the transformed directed graph, v_i is the i-th node, and p_{ij} is the power value supplied from node v_i to node v_j respectively. Eq. (1) means to minimize the sum of power values supplied from node v_i to node v_j when a_{ij} is 1, having edges from node v_i to node v_j, and i and j are not equal, node v_i and node v_j are not the identical nodes. The constraints are as follows:

$$0 \leq p_{0i} \leq S_i, \quad v_i \in V_s \tag{2}$$

$$p_{it} = L_i, \quad v_i \in V_l \tag{3}$$

$$0 \leq p_{ij} \leq p_{ij}^{max}, \quad i \neq 0, a_{ij} = 1 \tag{4}$$

$$\sum\nolimits_{(v_i \in V_l)} L_i = \sum\nolimits_{(v_j \in V_s)} p_{0j}, \quad v_0 \tag{5}$$

$$\sum\nolimits_{(a_{ik}=1, i \neq k)} p_{ik} = \sum\nolimits_{(a_{kj}=1, k \neq j)} p_{kj}, \quad v_k \neq v_0, v_k \notin V_l \tag{6}$$

$$\sum\nolimits_{(a_{ik}=1, i \neq k)} p_{ik} = \sum\nolimits_{(a_{kj}=1, k \neq j)} p_{kj} + L_k, \quad v_k \in V_l \tag{7}$$

where v_0 is a virtual node that binds the source nodes, v_t is a virtual node that binds the load nodes, V_s is the set of source nodes, V_l is the set of load nodes, S_i is the maximum power value supplied by v_i, L_i is the power value required by v_i, and p_{ij}^{max} is the maximum power value over the edge from node v_i to node v_j respectively. Eqs. (2) to (4) are constraints of the flow. Eq. (2) shows that the power value supplied from v_0 to each source node must be equal to or greater than 0 W and equal to or less than the maximum power value that each source node can supply. Eq. (3) shows that the power value supplied from each load node to v_t is equal to the power value required by each load. Eq. (4) is the flow constraint for all edges except for the edges of virtual nodes, which means that the power value supplied from the node v_i to the node v_j must be equal to or greater than 0 W and equal to or less than the maximum power value of each edge. Eqs. (5) to (7) are the conservation law at each node. Eq. (5) is a conservation law on v_0. It means that the sum of power values supplied from v_0 to each source node is equal to the sum of the power values required by the load nodes. Eq. (6) is the conservation law at nodes without v_0 and the load nodes. It shows that the sum of the power values supplied to a node v_k is equal to the sum of the power values supplied by the node v_k. Eq. (7) is the conservation law at the load nodes. The sum of the power values supplied to a load node v_k is equal to the sum of the power values supplied by the load node v_k and the power value required by v_k.

To control multiple VG Hubs, one of the methods is to optimize the entire network as described above. However, the power supply paths and power values are selected locally without global optimization in some networks where adjacent source nodes can supply sufficient power to load nodes. Therefore, we propose a hybrid type control algorithm. When there is a change in the network, such as the connection or disconnection of sources or loads, the algorithm first decides whether it can be solved locally or not. To be more specific, the algorithm focuses on a load node and decides whether adjacent source nodes can supply sufficient power to the load node.

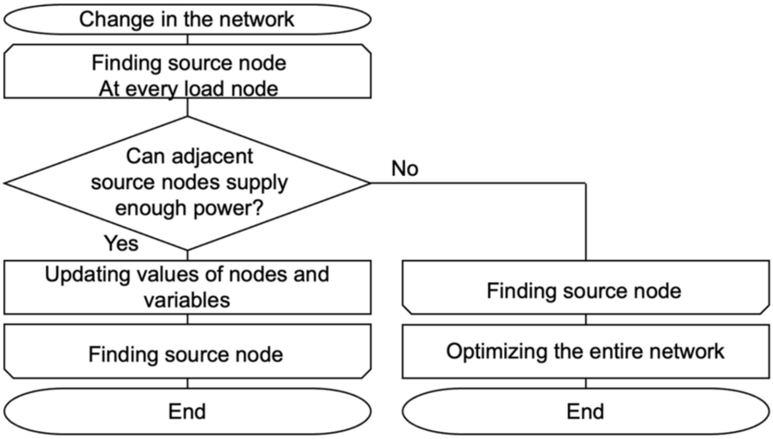

Figure 4. Flowchart of hybrid type control algorithm.

If it is possible, it solves the problem in each part. If the problem cannot be solved locally, then it optimizes the entire network by adapting the minimum cost flow problem. A flowchart of the algorithm is shown in Figure 4.

4. Experiment

In this section we show a preliminary result of an experiment to evaluate our system.

In each experiment, the calculation time was measured for each of the algorithm that performs overall optimization and the hybrid type control algorithm. The network considered here is a straight line of three VG Hubs as shown in Figure 5. The first node has a load of 30 W, the second node and the third node have 60 W of power supply for each. After reflecting the same information on the device shadow of AWS IoT Core, the time taken from obtaining the device shadow information on AWS Lambda to updating was measured using the Python time module. The time was measured 10 times each.

It took 0.15 seconds on average from the acquisition of device shadow information to the update with a control algorithm that performs overall optimization each time. The average time required for the same operation with the hybrid type control algorithm was 0.06 seconds. Figure 6 shows this result, where the error bars are the standard deviation. In a network where solutions can be derived locally from the results, the proposed hybrid type control algorithm calculates the route and flow rate in an average calculation time of 40% compared to the overall optimization. Although the number of nodes in the network were only three, there was a large difference in calculation time between these algorithms. This gap is supposed to be larger when the number of nodes is increased. Therefore, further experiments with larger number of nodes are needed.

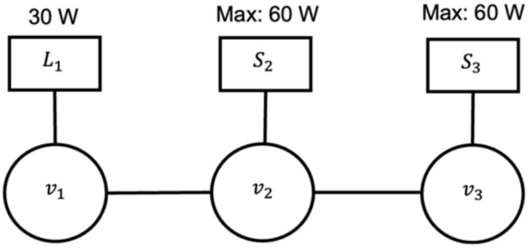

Figure 5. Network for the experiment.

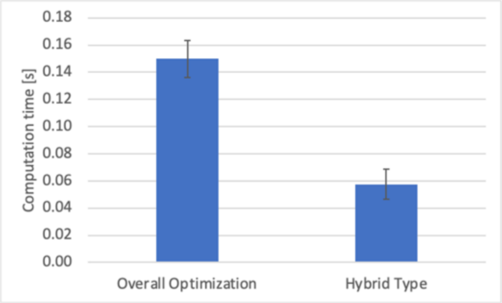

Figure 6. Average of calculation time.

5. Conclusion

In this paper, we proposed a hybrid type control algorithm for selecting the power supply path in the VG Hub network. We compared the calculation time with the control algorithm that performs overall optimization. Our future work includes measuring the calculation time when the number of nodes is increased and examining algorithms for locally deriving solutions.

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