SUPER DECENTRALIZED CONTROL ON THE BASIS OF CENTRALLY OPTIMIZED CONTROL MODEL FOR DISTRIBUTION VOLTAGE REGULATION

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ABSTRACT

Super Decentralized Control system is presented that can achieve semi-optimized voltage control regardless of the state of communications. Previously prepared overall optimized models are used for voltage control when the control devices cannot communicate with the center server. Simulation demonstrated that the proposed system can control voltages almost as well as centralized control in a medium-voltage distribution system.

INTRODUCTION

Next-generation distribution systems optimize the controlled variables of control devices such as step voltage regulators (SVRs) and static VAR (volt ampere reactive) compensators (SVCs) on the basis of measurement data received through information networks. This is because there is a need to control large and dynamic voltage fluctuations produced by photovoltaic (PV) generators and electric vehicles. However, there are not enough information networks in the world, particularly in developing countries, and very robust systems are needed for dealing with network disturbances.

We have developed Super Decentralized Control system that can achieve semi-optimized voltage control regardless of the state of communication. In this system, voltages are controlled autonomously and cooperatively on the basis of limited measurement data, and overall optimized models are created from the results of the centralized control. That is to say, this system transits between centralized mode and decentralized mode depend on the network state.

In this paper we discuss the basic idea, mathematical model, simulation method, and simulation results.

SYSTEM ARCHITECTURE

Overview

Figure 1 shows the main function of the Super Decentralized Control system. This system has two operation modes as follows.

When the center server, control devices, and sensors can communicate, the center server collects the measurement data consisting active power and reactive power of load from the sensors. It optimizes and stores the controlled variables consisting output reactive power of SVCs and tap ratio of SVRs along with the measurement data as training data. When training data are stored enough, the server makes the overall optimized models. The control order consisting the optimal controlled variables and the overall optimized models are sent from the center server to the control devices. The control devices control the voltages in the distribution system in accordance with the control order.

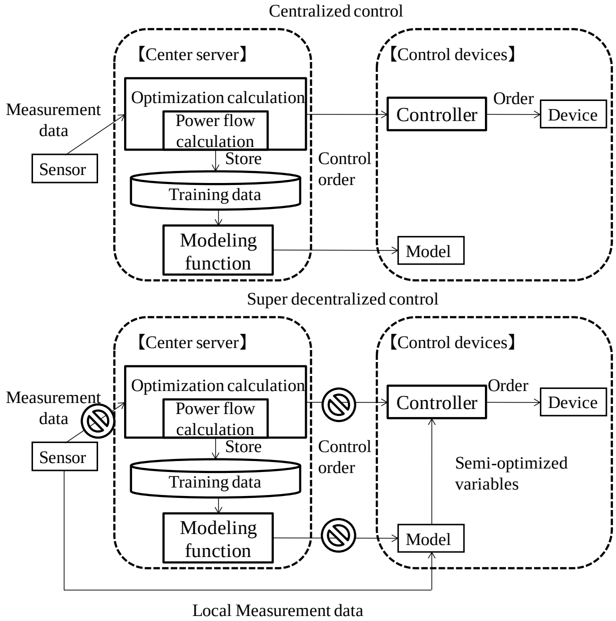

Figure 1. Architecture of Super Decentralized Control system

When they cannot communicate with the center server, the control devices collect local measurement data. They obtain semi-optimized variables instead of the optimal controlled variables by inputting the local measurement data into the overall optimized models and control the voltages in the distribution system in accordance with the semi-optimized variables.

Functions

Three main functions are needed for Super Decentralized Control: optimization, modeling, and variable estimation.

Optimization

The center server optimizes the controlled variables on the basis of the calculated power flow, when it is possible to communicate with the sensors. A non-linear optimization method that minimizes an objective function is used. Some restrictions, e.g. voltage limits and output limits on the control devices, are treated as penalty terms of the objective function in order to perform the calculation as an optimization problem without restriction.

The objective function is the deviation between the node and target voltages.

Modeling

Multiple regression analysis is used to create the overall optimized models. The results of the optimized calculation and measurement data are stored as training data. When sufficient training data have been obtained, the center server executes multiple regression analysis in order to create overall optimized models. The active power P_k and reactive power Q_k of the measurement data are set as explanatory variables and the optimal controlled variables f_i are set as explained variables as shown in equation (1). Suffix *i* represents the number of the control device, and suffix *k* represents the number of the node. This means that the overall optimized models include regression coefficients a_{ik} and b_{ik} and constant value C_i from the regression analysis.

$$f_i = \sum_k a_{ik} P_k + \sum_k b_{ik} Q_k + C_i \qquad (1)$$

Variable estimation

The models are used for control when the control devices cannot communicate with the center server. Each device collects local measurement data P_k and Q_k from neighborhood sensors. These measurement data are input into the models in order to estimate variable f_i. Here, a_{ik}, b_{ik}, and C_i are already-known.

Linear Model

We use linear models for the overall optimized models. This section discusses the validity of linear models. It starts by considering the relationship between the controlled variables and the power of loads on distribution system.

First, we treat a branch part of the distribution system, as shown in Figure 2. Branch part From the power and voltage drop equations, we get equations (2) and (3). [1]

$$P_{k-1,k} + jQ_{k-1,k} = \boldsymbol{V}_k \bar{\boldsymbol{I}}_{k-1,k} \qquad (2)$$

$$\begin{aligned}\boldsymbol{V}_{k-1} - \boldsymbol{V}_k &= \boldsymbol{z}_{k-1,k} \boldsymbol{I}_{k-1,k} \\ &= \frac{(r_{k-1,k} + jx_{k-1,k})(P_{k-1,k} - jQ_{k-1,k})}{\bar{\boldsymbol{V}}_k}\end{aligned} \qquad (3)$$

, where $P_{k-1,k}$ and $Q_{k-1,k}$ are the active and reactive power flows from node *k*-1 to *k*, $\boldsymbol{V_k}$ is the voltage of node *k*, $\bar{\boldsymbol{I}}_{k-1,k}$ is the conjugate current from node *k*-1 to *k*, and $\boldsymbol{z}_{k-1,k}$ is the impedance from node *k*-1 to *k*, which can be separated into resistance $r_{k-1,k}$ and reactance $x_{k-1,k}$. Equation (4) can be derived from equation (3) by setting V_k as a standard vector and taking the absolute value of $\boldsymbol{V}_{k-1}$.

$$V_{k-1} \approx V_k + \frac{r_{k-1,k} P_{k-1,k} + x_{k-1,k} Q_{k-1,k}}{V_k} \qquad (4)$$

If $V_k \approx 1p.u.$, equation (4) can be approximated as equation (5).

$$V_{k-1} \approx V_k + r_{k-1,k} P_{k-1,k} + x_{k-1,k} Q_{k-1,k} \qquad (5)$$

Next, we treat an SVR part of the distribution system, as shown in Figure 3.

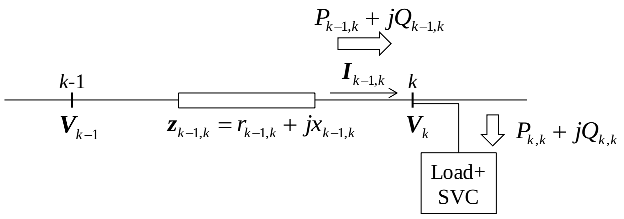

Figure 2. Branch part

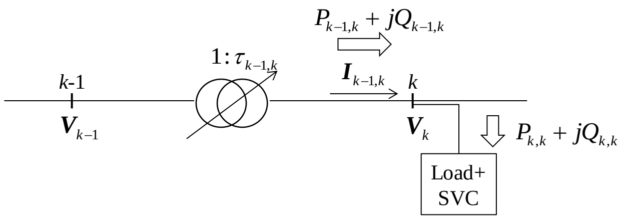

Figure 3. SVR part

We can get equation (6) from the voltage drop equation.

$$\boldsymbol{V}_k = \tau_{k-1,k} \boldsymbol{V}_{k-1} \qquad (6)$$

, where $\tau_{k-1,k}$ is the tap ratio of the SVR.

By generalizing equations (5) and (6), we get equation (7).

$$\begin{aligned}V_k \approx \tau_{k-1,k} V_{k-1} - r_{k-1,k} P_{k-1,k} \\ - x_{k-1,k} Q_{k-1,k}\end{aligned} \qquad (7)$$

If the power supply loss is small, power flow $P_{k-1,k}$ and $Q_{k-1,k}$ can be approximated as the total power of loads $\sum_m^{m\in l(k)} P_{m,m}$ and $\sum_m^{m\in l(k)} Q_{m,m}$, which exist on the downstream side of node k. We can therefore get equation (8). Here, *l(k)* represents the set of nodes existing on the downstream side of node *k*, and $P_{m,m}$ and $Q_{m,m}$ are the active and reactive powers of load connected to node *m*, respectively.

$$\begin{aligned}V_k \approx \tau_{k-1,k} V_{k-1,k} - r_{k-1,k} \sum_m^{m\in l(k)} P_{m,m} \\ - x_{k-1,k} \sum_m^{m\in l(k)} Q_{m,m}\end{aligned} \qquad (8)$$

This equation is derived for each node. We assume that there are only a few SVRs and that the tap ratio of each one nearly equals one. Equation (9) is derived by solving the simultaneous equations constructed by equation (8). Here, the reactive power of the loads and the SVC are expressed separately in order to clear the relationship among the voltages, measurement data and controlled variables.

$$\begin{aligned}V_k \approx \tau_{k-1,k} V_s - \sum a_{k,m} P_{\mathrm{Load},m,m} \\ - \sum b_{k,m} Q_{\mathrm{Load},m,m} \\ - \sum b_{k,m} Q_{\mathrm{SVC},m,m}\end{aligned} \qquad (9)$$

The V_s is the voltage at the swing node. This equation shows that the relationship between the controlled variables and the load power can be approximated as a linear equation.

SIMULATION CONDITIONS AND METHOD

We simulated a medium-voltage distribution system to determine the validity of the proposed method.

Example System

Figure 4 shows an example system used for the simulations. It consists of a main line and eight nodes without branch feeder and loops. There are one SVR, three SVCs(1, 2, and 3), and three loads. Each load can have a PV generator.

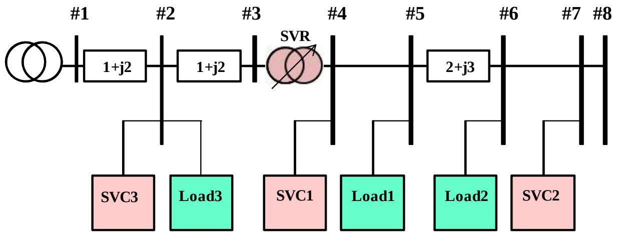

Figure 4. Simulated distribution system

Load Patterns

The load patterns and PV output pattern shown in Figure 5 were used. The loads were an industrial load, a commercial load, and a residential load. The PV output pattern is for photovoltaic generation during the summer. Random number may be multiplied to load patterns in order to simulate fluctuation.

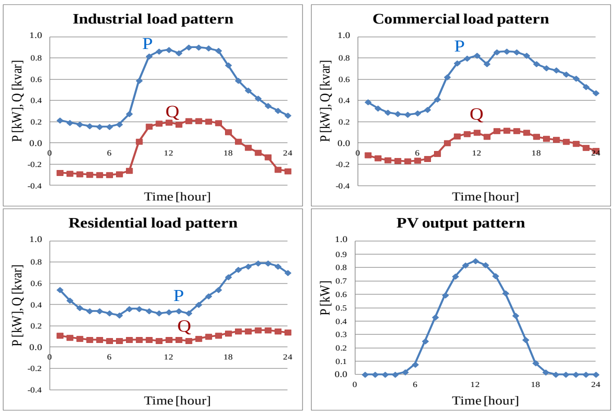

Figure 5. Load & PV Output Patterns

Simulation method

The load was changed in accordance with the time. Voltage control was executed during each time interval. The center server controlled the control devises and stored training data during the first 24 cycles, which is centralized control. At the end of the 24th cycle, the center server created the overall optimized models. They were used by the control devices to control the voltage during the remaining cycles, which is Super Decentralized Control or model control. During Super Decentralized Control, the control devices could not obtain all of measurement data, so they used a static load instead. Model control is for comparison with other control, so it can collect all measurement data.

SIMULATION AND RESULTS

Model accuracy

We investigated errors in the controlled variables and node voltages by comparing the results of model control with those of centralized control to determine whether the linear model was accurate.

Errors depending on volume of distribution system

First, we investigated errors depending on volume of distribution system. The three load patterns used were for residential loads with 40% PV output. The loads were multiplied by random number with a variance of 10% simulate fluctuation. We simulated operation for 24 cycles and then compared the outputs of the control devices and node voltages of centralized control with that of model control. Both control modes used accurate measurement data. Figure 6 shows the results when the system volume was 1.2MVA. The outputs of the control devices and node voltages of centralized control and those of model control were similar well. Figure 7 shows the differences in the output of the control devices and node voltages between model control and centralized control when the system volume ranged from 0.4 to 2.0 MVA. The red line shows the maximum difference and the blue one shows the average difference. The differences increased with the volume. These results indicate that the models can be used to control for volumes up to 1.2MVA under these condition. This is because the difference in the node voltage was smaller than 135V which is only 2% of 6750V. Apparently, the training data that reached the limitation of device output disturbed the linear models, and this caused a large error when the volume exceeded 1.2MVA. A green line and purple line are results with eased limitation, and are lower than red and blue one in Figure 7.

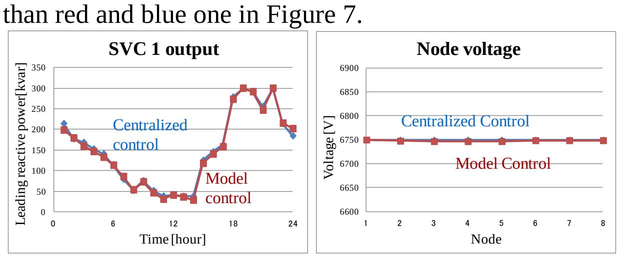

Figure 6. Comparison of centralized control with model control when system volume was 1.2MVA

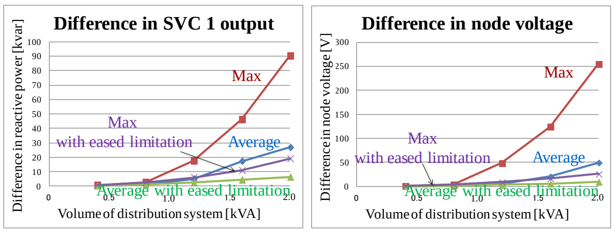

Figure 7. Evaluation of model control

Errors depending on load distribution

We next investigated errors depending on load distribution. The system volume was fixed at 1.2MVA, and the combination of load patterns was varied. The PV output was set for only residential loads and was set to 40% of the total volume of the distribution system. There were 81 load combinations in total. Four representative cases are shown in Table 1. They reflect the deviation and the changes of load between day and night. Figure 8 shows the differences in control device output and node voltage between model control and centralized control for the four cases. The difference in SVC1 output in case 2 was substantially larger than that in the other cases, when SVC1 output reaches to limitation with high frequency. However, the differences in the node voltage were nearly the same regardless of load distribution. This means that the load distribution negligibly cause to the error in the node voltage.

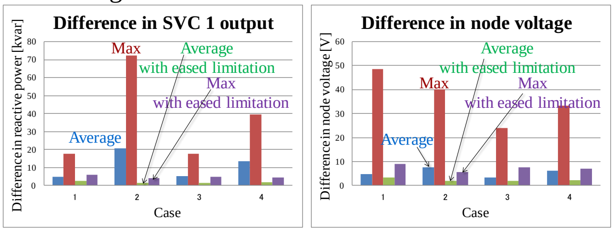

Figure 8. Evaluation of model control

Table 1. Simulation cases

	Load1	Load2	Load3
Case 1	Residential	Residential	Residential
Case 2	Industrial	Residential	Residential
Case 3	Residential	Industrial	Industrial
Case 4	Commercial	Residential	Industrial

Simulation of Super Decentralized Control

Super Decentralized Control is executed when the control devices cannot communicate with the center server. In this situation, the center server cannot operate the control devices, and the control devices cannot obtain all the measurement data. However, the overall optimized models need all of measurement data. So the control devices use static load data instead of lost measurement data. We simulated several cases when the system volume was 1.2MVA. Figure 9 shows the differences depending on variance of a random number that simulated the fluctuations in case 1. The controlled variables and voltage distribution diverged from the optimized ones as the fluctuation increased.

The node voltage distributions for when the difference in the node voltage was the largest are plotted in Figure 10. The left graph shows the voltage distributions with centralized control and Super Decentralized Control. The node voltage distribution diverged more from the centralized one as the fluctuation increased. The right graph shows the voltage distribution with centralized control and model control under the same conditions. The model control used all the measurement data different from Super Decentralized Control. The node voltages were nearly the same. This shows that the performance of Super Decentralized Control is determined mainly by the difference between the static load and the measurement data. However, node voltages are within appropriate voltage range of distribution system when the variance of random number is less than 30%.

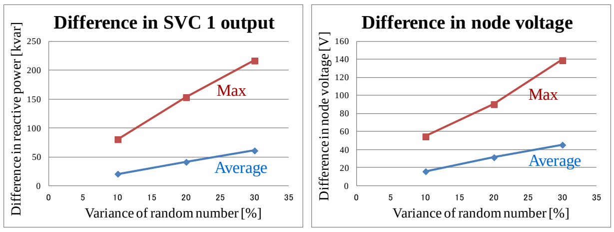

Figure 9. Changes in differences with load fluctuation

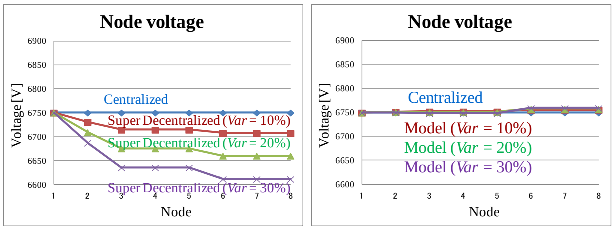

Figure 10. Node voltage variation

SUMMARY

Our proposed Super Decentralized Control system can achieve semi-optimized voltage control regardless of the state of communications. This system uses overall optimized models prepared in advance to control the voltage. Simulation of a medium-voltage distribution system demonstrated the validity of the proposed method. The results showed that the overall optimized models can determine the controlled variables when the volume of the distribution system is up to 1.2MVA under the restriction. Furthermore, the distributions of the loads negligibly contributed to the error in the node voltage. The training data that reaches to the limitation of device output disturb linear models, and it causes the large error when the volume is large.

The performance of Super Decentralized Control depends on the input load data. The control devices cannot obtain all the measurement data when they cannot communicate with the center server. They thus use static load data instead of the measurement data. Simulation showed that Super Decentralized Control can stabilize the voltage when the variance between the static load and actual load data is less than 30%.

Future work includes simulation in other example system, and investigating errors depending on the topology of distribution system.

REFERENCES

[1] Ali Keyhni, Muhammad Marwali, 2012, *Smart Power Grids 2011*, Springer, Berlin, Germany, 308-311.