

Utility and Industrial Perspective in Distribution Systems Under Deregulated Environment

Takamu Genji

Technical Research Center,
Kansai Electric Power Co., Inc.
3-11-20, Nakoji, Amagasaki, Hyogo, 661 Japan

Yoshikazu Fukuyama, member, IEEE

Corporate Technology Development Office
Fuji Electric Co., Ltd.
No. 1, Fuji-machi, Hino-city, Tokyo, 191 Japan

Abstract: This paper presents utility and industrial perspective for distribution systems under deregulated environment. The main concerns under deregulated environment include consideration of distributed generators and increase of utilization rate of distribution equipment. This paper discusses the research items and presents the results of several researches under deregulated environment.

Keywords: Distribution Services, Distributed Generator, Utilization Rate, Distribution Equipment Model, Setting for Voltage Control Equipment, FACTS, Cooperative Control, Long-term Distribution System Planning, Distribution State Estimation

I. INTRODUCTION

Supplying electric power energy to customers keeping reasonable quality of electric power under deregulated environment is the most important task of utilities. Therefore, power utilities have to consider modification of existing services and development of new services in order to realize the required services.

In Japan, only large customers (over 22kV and 2000kW) can select their power supply companies. Namely, deregulation is only opened to non-utility suppliers and the large customers. Therefore, in distribution systems (6.6kV), introduction of distributed generators is the main concerns under deregulated environment. When deregulation is opened more widely to the smaller customers in future, namely, for the next generation of deregulation in Japan, cost down for various tasks in distribution systems is another main concern of power utilities. Namely, at present, consideration of introduction of distributed generators and cost down for various tasks in distribution systems is the main problems.

Especially, for introduction of distributed generators, the following items should be considered:

- Voltage control considering complicated voltage profile
- Consideration of reverse power from distributed generators

For considering the above items, the following questions should be raised:

- What kinds of new phenomena can occur in the target systems? What is the condition for the phenomena?
- How do control and protective devices operate under certain conditions? If we have some problems for the device actions, is it enough to modify the devices or do we have to develop new devices and system operations?
- How do existing services operate under certain

conditions? If we have some problems for the service actions, is it enough to modify the services or do we have to develop new services?

Since the operation and planning of distribution system are becoming complicated and required higher performance than before from above backgrounds, we have to address them by means of applying IT (e.g., highly functional distribution automation system and computer added analysis etc.) and new power electronics equipment.

For cost down, one of the main concerns is improving the utilization rate of equipment in distribution systems. In the past, power utility installed enough equipment in distribution systems considering keeping high quality of electric power. Therefore the utilization rate of distribution equipment is usually not high enough. There should exist a certain utilization rate at which the target distribution systems can keep high quality of electric power. Namely, Addressing various contingencies, we are required to find the economical system configuration considering installation of new customers and natural growth of load capacities.

Considering the above background, the authors have been doing the following researches:

- (a) Studies on impact of installation of distributed generators in distribution systems,
- (b) Improvement of existing devices and development of new devices for voltage control in distribution systems,
- (c) Development of new method for distribution planning and operation.

Concretely, for example, we have the following research items under these researches:

- (1) Development of distribution system equipment models for fast distribution single power flow and three phase unbalanced power flow [1],
- (2) Development of a new setting method for existing voltage control equipment [2],
- (3) Development of new voltage control equipment applied power-electronics and development of cooperative control with existing and new voltage control equipment [3],
- (4) Development of long-term expansion planning method for distribution system [4][5],
- (5) Development of new distribution state estimation method [5][6].

This paper summarizes the above researches under deregulated environment. In this paper, we concentrate on the backgrounds and the main results of each research.

The detailed description of each research can be found in each reference paper.

II. DISTRIBUTION SYSTEM EQUIPMENT MODELS [1]

Background

Electric power in distribution systems has been always flowed from substations to the end of feeders in planning and operation before de-regulation. However, introduction of distribution generators under de-regulated environment causes reverse power flow and complicated voltage profiles in the distribution systems. Therefore, it is required to modify planning and operation methods adjusting to above-mentioned situation.

Since voltage profiles are directly related to power quality and customers' satisfaction, it is of primary concern in power utilities. Conventionally, voltage regulation is realized by LDC functions of transformers in substations, voltage regulators with LDC functions in distribution systems (called Step Voltage Regulator, SVR, in Japan), and so on. Since conventional voltage regulators cannot always handle the reverse power flow and steep and fast voltage fluctuation, new voltage regulation equipment is required. Considering these backgrounds, fast power flow calculation considering various newly introduced equipment models in distribution systems is required in order to utilize the calculation in distribution automation system and routine tasks of utilities.

Various fast backward forward sweep (BFS) type methods have been developed for distribution power flow. Considering introduction of distributed generators and new voltage regulation equipment, practical models for these newly introduced equipment should be developed.

Main results

The following distribution equipment models on ungrounded three line system have been developed:

- (1) Generators
 - a) Synchronous Generator
 - b) Induction Generator
 - c) Inverter Connected Generator (micro turbine ,PV ,fuel cell, etc.)
- (2) Distribution line
- (3) Loads
- (4) Existing Voltage Control Equipment
 - a) Voltage Transformer in S/S with LDC function
 - b) SVR
- (5) New Voltage Control Equipment applied power-electronics
 - a) Series Equipment
 - b) Parallel Equipment such as SVC
 - c) Series and Parallel Equipment such as UPFC
 - d) Phase Shift Equipment

The branch type equipment can be modeled as a variable

impedance branch. The node type equipment can be modeled as a PQ injection node. P and Q values are calculated according to the equipment type. The developed models, and the single and three phase unbalanced load flow using the models can be a basic calculation method for various distribution planning and operation works.

III. A NEW SETTING METHOD FOR EXISTING VOLTAGE CONTROL EQUIPMENT [2]

Background

Distribution system voltage is regulated with SVR, and transformers with automatic tap changer installed in substations. Considering various load changes in practical distribution systems, parameter setting for LDC function at substations and SVR in distribution systems is one of the important tasks in distribution control centers. The parameters for the function include a reference voltage and a dead band value for the reference voltage. The SVR parameters include a reference voltage, a dead band value for the reference voltage, and impedance ($r+jx$) for specifying the target regulated point in the target distribution systems. The setting has been performed using an analytical equation focusing only two situations such as the lightest and heaviest loading conditions in the target distribution system of one direction power flow. Considering deregulation environment and introduction of distributed generation, the conventional setting method is not appropriate any more, because power flow calculation is indispensable for analyzing systems with generators and voltage profiles will be complicated. Consequently, the new setting method should be developed.

Characteristic of optimal setting problem

Fig.1 shows properties and solution methods for the optimal setting problem. Evaluation values in the optimal setting problem are calculated using the voltage profile and the power flow condition as shown in Fig.1. The setting value of the voltage control equipment is related to the

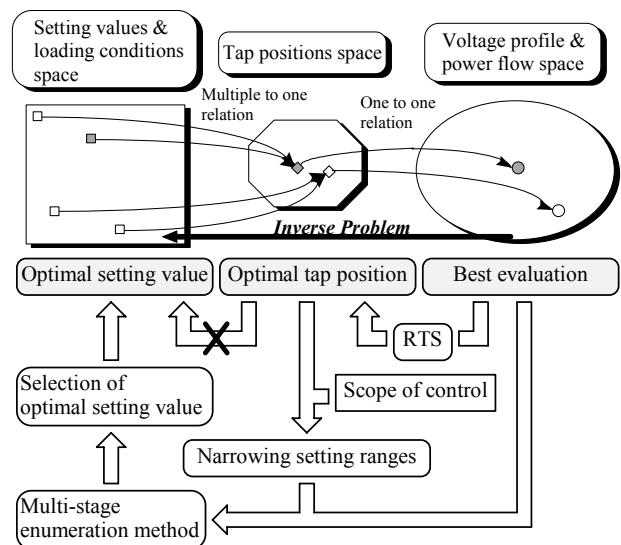


Fig.1 Concept of solutions for the optimal setting problem.

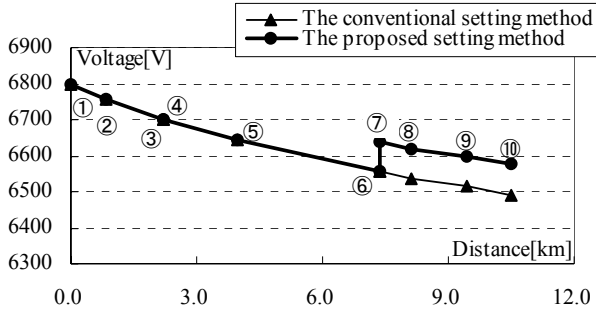


Fig.2 Voltage profiles at maximum loading condition.

evaluation value through the tap position. Using voltage profiles and power flow conditions obtained as a calculation result, setting values of each equipment, which is a cause of the result, has to be determined. Namely, the problem is a kind of inverse problem. Several sets of setting values may have the same evaluation values when a certain section voltage is comprised within the dead band value or SVR tap position cannot be changed because of reverse power flow from distributed generators. Namely, one optimal setting value cannot be calculated using SVR tap position. The enumeration method can obtain a set of the optimal setting values. However, as the number of control equipment increases, the number of solutions (combinations of setting values) increases exponentially. Considering the characteristic of the problem, a new setting method based on a reactive tabu search (RTS) and multi-stage enumeration method has been developed.

Main results

Fig. 2 shows an example of voltage profiles using the optimal setting values calculated by the developed method and the conventional setting values. If the voltage profile is kept near the predetermined reference voltage (6.6kV in this example), the setting values are highly evaluated. The figure indicate that the developed method can modify the voltage profiles more closely to the reference voltage for the target loading conditions than the conventional method, and the practical applicability of the developed method to the optimal setting problem.

IV. COOPERATIVE CONTROL WITH EXISTING AND NEW VOLTAGE CONTROL EQUIPMENT [3]

Background

In recent years, distributed generators (DGs), which may have steep and fast fluctuations of power generation like wind-turbine, have been introduced in distribution systems. Therefore, the introduction of DGs may cause steep and fast voltage fluctuations in distribution systems. SVR has a dead band value for a target control voltage and time delay from a few seconds to a few minutes to avoid frequent tap changing. On the contrary, wind generators may reach full power output from zero output within one

minute, in which SVRs cannot respond because of the time delay. Therefore, it becomes difficult to regulate the line voltage within the prescribed voltage ranges and suppress flicker voltage with only SVRs.

The voltage compensating equipment applying power electronics technology such as SVC and UPFC is effective against steep and fast voltage fluctuations as well as gradual voltage changing, because the equipment can respond quickly to the fluctuations. The equipment includes a series voltage compensating equipment, which can add compensation voltage to line voltage, a parallel voltage compensating equipment such as SVC, and series-parallel voltage compensating equipment utilizing combination of both series and parallel functions such as UPFC. However, SVRs become non-effective if power electronics compensation equipment is connected in the same distribution line because of the difference between their response time. On the other hand, if only the power electronics compensation equipment is installed to regulate line voltage, it requires large capacity to regulate the line voltage. Therefore, cooperative control method using both existing SVR and newly installed voltage compensating equipment applying power electronics technology has been eagerly awaited.

Main Results

The developed method requires little capacity and low cost of the voltage compensating equipment and can be effective to regulate the line voltage with existing SVRs even if power electronics compensating equipment are installed in the same distribution line. The method has features as follows:

- A gradual voltage fluctuation is compensated by SVRs and a steep and fast voltage fluctuation is compensated by UPFC.
- It can select a certain reference voltage value of the series and parallel part of UPFC, which is appropriate to each voltage fluctuation condition. It allows to regulate the line voltage within the prescribed voltage ranges against steep and fast voltage fluctuations by UPFC with minimum capacity.
- It can modify the reference voltage value of the parallel part of UPFC. It allows to regulate the line voltage with SVRs by shifting voltage compensation form UPFC to SVRs.

The cooperative control between SVR and UPFC can be described as follows:

Step. 1 Quick voltage compensation by UPFC

UPFC compensates steep and fast voltage fluctuations by sudden and frequent in short period output changes of various DGs.

Step. 2 Correction of reference voltage of the parallel part of UPFC

The reference voltage value of the parallel part of UPFC, which is changed according to running average

of voltage value, is gradually corrected and the compensation amount by UPFC is gradually decreased. The voltage reference value for the serial part of UPFC is constant.

Step. 3 Constant voltage compensation by SVR

The reference voltage value of SVR goes out from the dead band by the decrease of compensation amount of the parallel part of UPFC. The operated time outside the dead band reaches the SVR's operation time, the tap of SVR is changed.

Step. 4 Standby condition of UPFC

The compensation amount by UPFC changes to the steady state amount by the tap change of SVR. Then, the UPFC becomes the standby condition at which the UPFC can handle the following steep and fast voltage fluctuations.

The feasibility of the developed method is demonstrated on distribution system models by steady-state analysis based on power flow and instantaneous analysis using EMTDC with promising results. The results indicate that the developed method can decrease the voltage compensation amount of series and parallel part of UPFC by tap changing of SVRs. The voltage compensating equipment capacity is different by target distribution systems, target loading conditions, and a distributed generator capacity. According to the result, the UPFC capacity can be decreased by about ten percent in comparison with SVC capacity, especially for a certain model system.

V. LONG-TERM DISTRIBUTION SYSTEM EXPANSION PLANNING METHOD [4][5]

Background

Distribution network expansion planning is one of the important activities in distribution control centers. Several

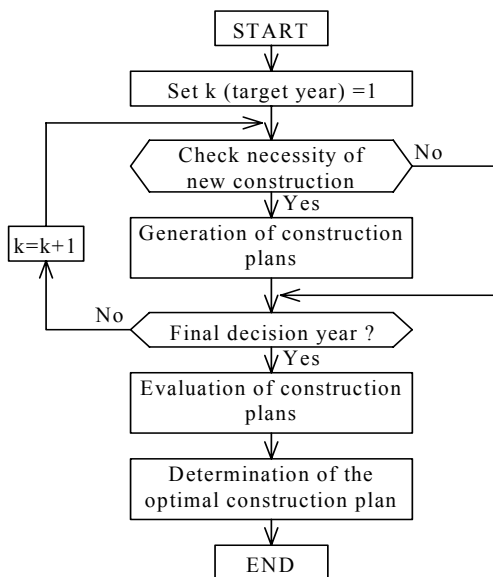


Fig. 3 A general flow chart of the developed method.

objective functions, including new equipment installation cost, equipment utilization rate, reliability of the target distribution system, and loss minimization should be evaluated considering increase of network loads and newly installed loads for each year at the planning. Experienced persons have been performed the planning conventionally. However, only a few cases have been evaluated practically because of limited planning time and it is difficult to evaluate optimality of the generated plans in many points of above-mentioned view. In the conventional evaluation system, it is very difficult to ensure the optimum investment.

In recent years, reduction of costs restraining investment and energy-saving are becoming more important in distribution systems. In this situation, more efficient planning is required. However, there is the limitation to find a high quality system configuration by human planning. Therefore, the practical network expansion planning systems, which can consider exchange of distribution lines to thicker lines, installation of new switches, lines and so on as expansion plan candidates and evaluate many above mentioned objective functions yearly during evaluation term, has not been developed in Japan.

Main Results

The developed distribution network expansion planning method evaluates multiple factors including new equipment installation cost, equipment utilization rate, reliability of the target distribution system, and loss

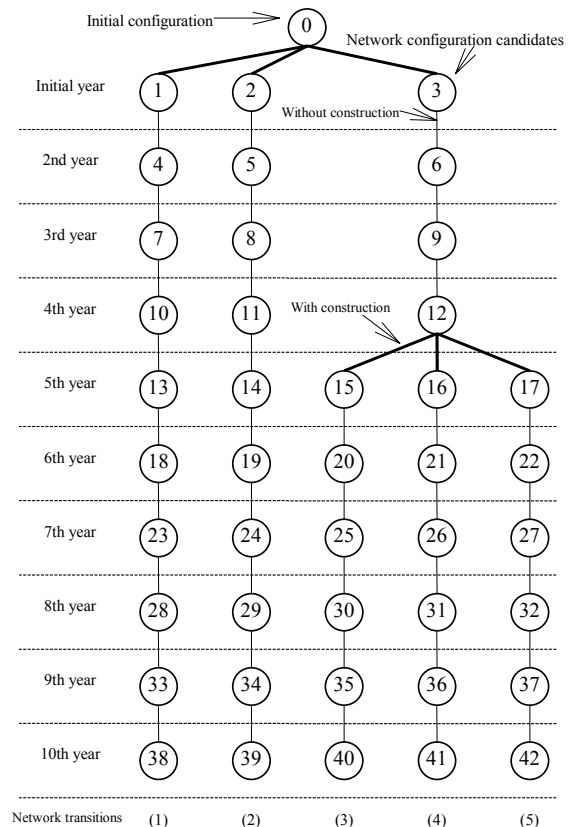


Fig. 4 An example of network configuration transition.

minimization. The developed method generates various construction plans using expert system, RTS, and three phases unbalanced load flow calculation.

The developed method is performed as follows. Firstly, loss minimization and service restoration for various contingencies are performed considering load increase and new load installation plans for the target year, and necessity of additional construction plans is checked. If the method determines to generate new construction plans, the construction plan candidates are generated. The procedure is repeated until the target year reaches the final decision year. Finally, the optimal plan is determined using evaluation of construction cost, loss minimization, service reliability, and equipment utilization rate. Fig. 3 shows a general flow chart of the developed method.

The developed method is verified by comparing construction plans generated by the developed method with the actual plan composed by experienced planning persons in practical distribution systems. The developed method can generate the same plan generated by the experienced persons. Moreover, the method can generate various alternative construction plan candidates. Fig. 4 shows an example of network configuration transition for ten years. The developed system evaluates the five routes to the tenth year and determines the best route for the target distribution system.

VI. NEW DISTRIBUTION STATE ESTIMATION METHOD [5][6].

Background

On-line state estimation is becoming one of the key functions in distribution control centers considering deregulation environment and introduction of distributed generator (DG) in distribution systems as well as automated restoration by distribution automation system. In such a situation, more precise data of system state will be required in order to operate distribution systems adequately against complicated contingency with distributed generators. Distribution state estimation (DSE) is required to consider error and asynchronism of measurement from actual distribution systems. Since measuring points are limited in actual distribution systems, DSE has to realize high accuracy estimation with limited measurement data.

DSE is usually formulated as a weighted least mean square (WLMS) problem. Equipment in distribution systems such as SVC and DG causes nonlinear characteristics of the objective function for DSE. For example, static var compensators (SVCs) have nonlinear output characteristics. Transformers with automatic tap changer have a discrete tap control function. Therefore, target load flow equations may be changed because of automatic tap changing function of voltage controllers during convergence. Output characteristics of induction generators can be described by a nonlinear function expressed by constant impedance, constant current, and constant power (ZIP) load. A number of methods have been

developed as an advanced function of distribution control centers. The methods can be divided into categories: statistical and load adjustment SE formulation. The former methods usually utilize an iterative convergence method such as Quasi-Newton method and the latter methods usually utilize sensitivity analysis. Since conventional distribution state estimation methods belonging to both categories assume that the objective function or equations related to DSE can be differentiable and continuous. However, considering the above-mentioned nonlinear characteristics of the practical equipment in distribution systems, the objective function and the equations cannot be differentiable and continuous, and the conventional methods can not be applied. Therefore, A practical distribution state estimation method has been eagerly awaited considering the practical requirements.

Modern heuristic algorithms are recognized as practical tools for nonlinear optimization problems. The algorithms do not require that the objective function has to be differentiable and continuous. A particle swarm optimization (PSO) is one of the modern heuristic algorithms and can be applied to continuous nonlinear optimization problems such as DSE. It has been developed through simulation of simplified social models. A hybrid PSO (HPSO) adds a selection mechanism of the evolutionary computation (EC) to PSO and it can generate high quality solution within short calculation time. Since the state estimation is one of the on-line functions in distribution control centers, HPSO must be an appropriate method for the target problem.

Main results

A practical distribution state estimation method using a HPSO is developed. The developed method considers practical measurements in actual distribution systems and assumes that absolute values of voltage and current can be measured at the secondary side buses of S/Ss and remote terminal units (RTUs) in distribution systems. The method can handle nonlinear characteristics of the practical equipment in distribution systems. It can estimate load and distributed generation output values at each node by minimizing difference between measured and calculated state variables. The following algorithm is developed for the state estimation:

Step 1 Input data

The following data are input.

- network configuration, line impedance
- contracted load value
- measurement data (S/S, RTU, and DG)

Step 2 Set calculation conditions

(1) Calculation of initial values of state variables

- Using total power input to the target network and ratio of the contracted load value of each load section to the total contracted load values of the target network, initial value of each load is calculated.

- Using average power output of each DG, initial value of each DG is calculated.

Using initial values of state variables, initial load flow calculation by BFS is performed.

(2) Set upper and lower bounds of state variables

- Using the results of initial load flow calculation, upper and lower bounds of each state variable can be calculated.

Step 3 State estimation

Find network condition, which minimizes error between measurement values and calculated values by HPSO.

The feasibility of the developed method is demonstrated and compared with the original PSO on practical distribution system models. Fig. 5 shows a model system. Table 1 shows comparison of the objective function values by both PSO and HPSO. As shown in Table 1, the minimum evaluation values by HPSO and PSO are the same. However, the maximum evaluation value, which has a maximum error between measurement data and calculated value, by HPSO is approximately 59% of that by PSO and average evaluation value by HPSO is approximately 50% of that by PSO. The results indicate HPSO can generate higher quality solutions by PSO without measurement errors.

IV. CONCLUSIONS

Consideration of introduction of distributed generators and cost down for various tasks in distribution systems are the main concerns under the deregulated environment. Considering the background, the authors have been doing the following researches:

- (a) Studies on impact of installation of distributed generators in distribution systems,
- (b) Improvement of existing devices and development of new devices for voltage control in distribution systems,
- (c) Development of new method for distribution planning and operation.

The current researches basically concentrate on introduction of only one DG in the target feeder. Therefore, detailed studies on introduction of plural DGs are one of the next researches. Moreover, after introduction of deregulation environment in the distribution systems (6.6kV), measurement equipment with multi functions should be introduced and development of ancillary services can be one of the primary concerns.

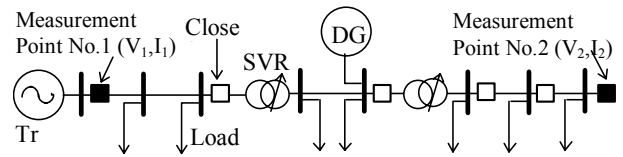


Fig.5 A distribution model system.

Table 1. Comparison of objective function values by PSO and HPSO based methods.

Methods	Max.	Min.	Ave.
HPSO	0.000106	0.000000	0.000015
PSO	0.000180	0.000000	0.000030

REFERENCES

- [1] T. Genji, Y. Fukuyama, et al., "Practical Equipment Models for Fast Distribution Power Flow Considering Interconnection of Distributed Generators", Proc. of IEEE Summer Meeting, July 2011.
- [2] Y. Fukuyama, "State Estimation and Optimal Setting of Voltage Regulator in Distribution Systems", Proc. of IEEE Winter Meeting, January 2001.
- [3] T. Genji, Y. Fukuyama, et al., "Cooperative Control Method for Voltage Control Equipment Considering Interconnection of Distributed Generators", Proc. of ICEE Conference, July 2001.
- [4] Y. Fukuyama, "Reactive Tabu Search for Distribution Load Transfer Operation (panel session on modern heuristics application to power systems)", Proc. of IEEE PES Winter Meeting, Singapore, 2000.
- [5] T. Genji, Y. Fukuyama, et al., "Long-term Distribution Network Expansion Planning Considering Multiple Construction Plans", Proc. of IEEE PowerCon, December 2000.
- [6] T. Genji, Y. Fukuyama, et al., "Practical Distribution State Estimation Using Hybrid Particle Swarm Optimization", Proc. of IEEE Winter Meeting, January 2001.

BIOGRAPHIES

TAKAMU GENJI received B.S. and M.S. degrees in electrical engineering in 1973 and 1975, respectively, from Okayama university, Okayama, Japan. He joined Kansai Electric Power Co. in 1975 and has been working at Technical Research Center from 1985. His research interests include lightning countermeasures in distribution systems and distribution automation. He is a member of IEE of Japan.

YOSHIKAZU FUKUYAMA (M'90) received B.S., M.S., and PhD degrees in electrical engineering in 1985, 1987, and 1997, respectively, from Waseda university, Tokyo, Japan. He has been working at Fuji Electric Co. R&D Japan from 1987. He was a visiting scientist at Cornell University from 1993 to 1994. His research interests include application of intelligent systems such as expert system, neural network, and modern heuristic techniques to power systems, and power system analysis including voltage stability and load flow. He is also interested in applications of modern heuristic techniques to practical and general optimization problems. He is a member of IEEE and IEE of Japan.