Development of Technologies to Simulate Power Flow for Power Grid

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Energy problems are important social ones, and they cause many issues like electricity shortages and environmental impacts. Fujitsu Laboratories has researched and developed technologies to provide "social solutions" to such problems by using information and communications technology (ICT). Our group has been researching some energy management technologies, for example optimization technologies and prediction technologies for energy consumption and generation. In this paper, we introduce our development of a technology to simulate the power flow in a power grid. This simulation requires some special features compared with conventional power flow simulators, because the purpose of the simulation is mainly to carry out real-time monitoring of electricity in a grid. Therefore, we applied an algorithm called the backward-forward sweep method for high-speed processing, which is suitable for the typical Japanese grid model and has good scalability. And we also developed new equipment models (e.g., a distribution model, some transformer models, and a connection model) for this simulator.

1. Introduction

Recently, many measures have been considered to bring about a low-carbon society to prevent global warming and solve power supply shortages in the wake of the Great East Japan Earthquake. Such measures include, for example, installing renewable energy power generation systems represented by photovoltaic (PV) power generation in order to increase power supply and taking energy-saving measures to reduce power consumption. To support these measures, energy management systems (EMSs) are said to be required.

Figure 1 is a schematic diagram of a system that sends power from a power station to consumers. Electric power is generated by large hydraulic, thermal, atomic or other types of power stations often installed in provincial areas, it goes through transmission networks that transmit power at extra-high voltages over long distances from power stations to consumption areas, and is supplied to respective consumers via power grids that transmit power from distribution substations installed in consumption areas. Purposes of power management and control have so far been large-scale power generation and stable management of and reduction of losses in transmission networks, and they have mainly been carried out by utility companies.

However, in future it will be necessary to control the power consumption of consumers in power grids and have power quality stabilization control in order to take the measures mentioned above, and such control is expected to require power management and control of power grids.

As part of its approach to social solutions, Fujitsu Laboratories has been developing energy solutions that make use of information and communications technology (ICT). In particular, it has been energetically working on the development of regional EMS simulation technologies intended for power grid areas including consumers since 2011.[1] Regional EMS simulation technologies consist of various types of ICT including power demand prediction and optimization control technology, social simulation technology and power grid simulation technology.

The power grid simulation technology[2),3)] presented in this paper is used in many different situations as a feature of regional EMS simulation, especially for grasping the voltage state of a power grid. It is

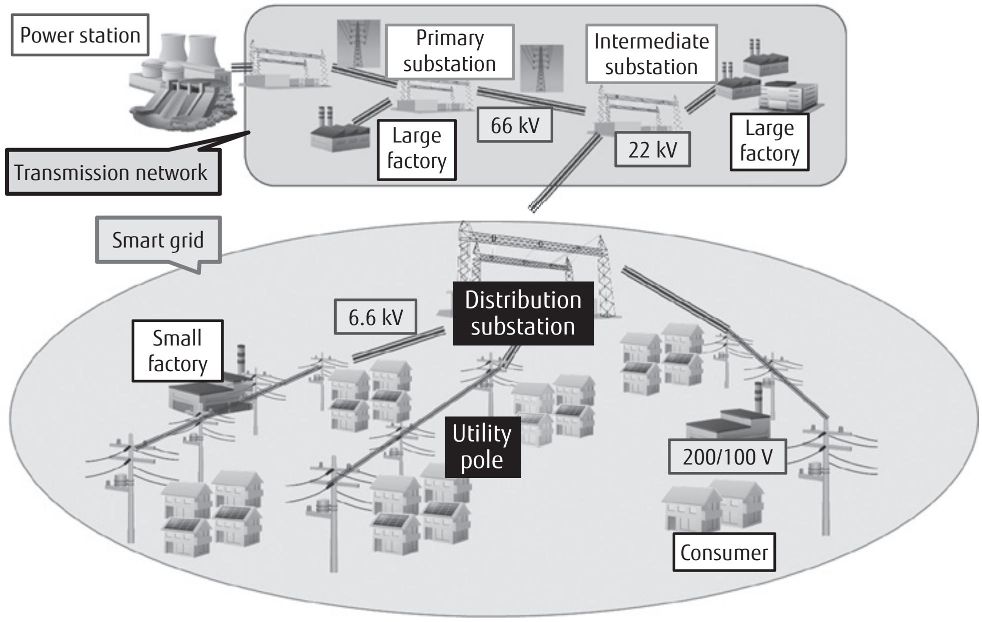


Figure 1
Schematic diagram of power system.

becoming increasingly important to grasp this voltage state along with the recent dissemination of PV power generation to general consumers.

Traditionally, power flow in a power supply system went only in one direction, from a large power station owned by a utility company through transmission and distribution lines to consumers. Meanwhile, a PV power generation system is installed on the roof of a general consumer in a power grid and the surplus power that remains after subtracting the consumer's power consumption from the power generation output is sold as supply power (reverse power flow) from the general consumer to the power grid. This means that, together with the power from the large power generation facilities explained above, the system of supplying power to consumers is bidirectional. PV power generation, which depends largely on the weather conditions, is prone to significant fluctuations and difficult to predict as well. This poses an issue because it is difficult to maintain a balance between power supply and demand.

In addition, a reverse power flow may cause voltage rise in a power grid, which hinders maintenance of supply voltage stabilization. These issues will be obvious as PV power generation becomes widespread in the future and essentially require measures to be taken.

For a regional EMS to address these issues, the first thing that is necessary is to grasp the voltage state in a power grid. The simplest solution is to install electricity sensors (such as voltmeters) in the power grid. However, this requires a large number of electricity sensors to be installed in an extensive power grid, which involves a huge cost. For that reason, a power grid simulator capable of grasping the voltage of a grid with the minimum number of electricity sensors is used.

Part of this power grid simulation technology is applied to the "power grid monitoring solution,"[4] a system to support the advancement of power distribution operations, which is under development by Fujitsu.

2. Purposes of development

Many simulators that can be used to examine power flow are available in different forms including commercial software and free software. However, most of those simulators are intended for transmission networks that assume a one-way power supply as described above and power systems on building and factory sites. In addition, these simulators are used mainly for designing transmission networks and planning power systems. For this reason, it is thought that such simulations require a precision of calculation sufficient for addressing phenomena lasting for less than a second, such as power surges and high-frequency noise, but the number of target nodes is small. In addition, the requirements for processing speed and for visualization of simulation results are not very high.

Meanwhile, power grid simulators are required to determine the voltage state of all consumers in a power grid (approximately 10 000 consumers under the distribution substation) between every few seconds and one or two minutes. Accordingly, the requirement for precise calculations (time interval) is not as high as with conventional simulators but support for a large number of nodes and high-speed processing is essential because they are used for grasping the voltage state almost in real time. Support is also required for modeling of equipment that constitutes a power grid (three-phase three-wire wiring, low-voltage single-phase multi-wire system and several types of transformer connection) where each phase of the voltage, current, and phase, etc. are not equal. Furthermore, a contrivance for visualization to allow users to easily grasp the voltage state of the power grid is important as well.[4)]

For these reasons, conventional simulators are incapable of meeting all of the requirements and so we started to work on the development of an in-house one. **Table 1** shows a comparison of functions between conventional and power grid simulators.

The following sections describe "support for a large number of nodes and high-speed processing technology" and "modeling of a power grid," which characterize the power grid simulator developed.

3. Support for large number of nodes and high-speed processing technology

As shown in Figure 1, a power grid is intended to be used to connect a distribution substation and respective consumers and the distribution line connection has a tree structure (radially-shaped) (connection of a transmission network between the power station and substation is mostly looped). The number of consumers supplied by one distribution substation is about 10 000, which is a large number of nodes.

For the present study, we applied the backward-forward sweep method as the calculation algorithm of the simulator in order to meet the requirements of support for a large number of nodes and high-speed processing.[5)]

The backward-forward sweep method is a numerical calculation method applied to calculation for tree structures. It is an iterative calculation method in which two processes, backward sweep and forward sweep, are repeated until the voltage value of each node converges. Backward sweep uses formulae 1) and 2) to sum up upstream the active power P and reactive power Q and the loss of each node and forward sweep uses formula 3) to calculate the voltage drop V_r based on P and Q obtained by backward sweep (**Figure 2**).

$$P_s = P_r + \frac{R\ (P_r^2 + Q_r^2)}{V_r^2} \qquad 1)$$

Table 1
Comparison of functions between conventional and power grid simulators.

	Conventional simulator	Power grid simulator
Target	Transmission network (power station – substation) On-site power system	Power grid (substation – respective consumers)
No. of nodes	Small (a few tens)	Large (around 10 000)
Requirement for precision of calculation	High (intended for instantaneous values for less than one second)	Medium (intended for effective values for about one second)
Requirement for high-speed calculation	Medium (mainly used for design/planning)	High (ideally real-time)
Requirement for visualization	Medium	High (should give at-a-glance view of simulation result)

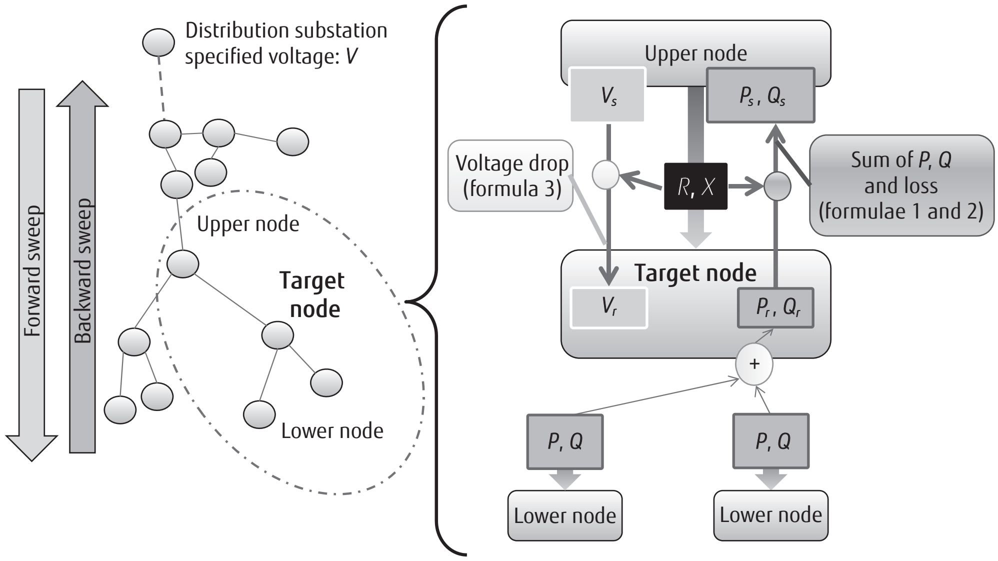


Figure 2
Backward-forward sweep method.

$$Q_s = Q_r + \frac{X\,(P_r^2 + Q_r^2)}{V_r^2} \qquad 2)$$

$$V_r = V_s\left(1 - \frac{P_sR + Q_sX}{V_s^2} + j\,\frac{Q_sR - P_sX}{V_s^2}\right) \qquad 3)$$

where

P_s: active power of the upper node,
Q_s: reactive power of the upper node,
P_r: active power of the target node,
Q_r: reactive power of the target node,
R: resistance of the branch between the target node and upper node and
X: reactance of the branch between the target node and upper node.

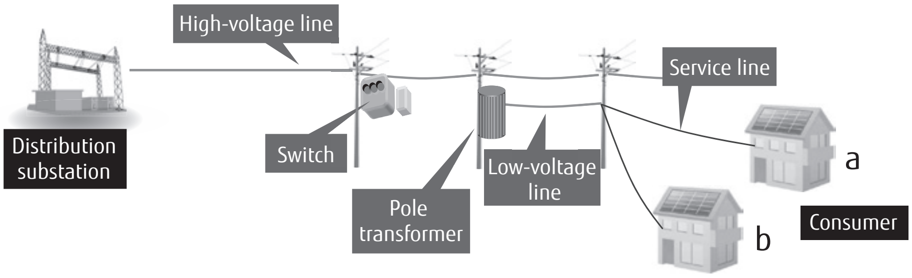
The processing speed is higher than that with the Newton-Raphson method, which is used in many of the conventional simulators (stated as “about eight times” in a comparison paper[6] and the difference is further increased to offer an advantage when a larger number of consumers is involved). The main reason for this is that, while the Newton-Raphson method solves the power equation for each node by calculating an inverse matrix of the Jacobian, the backward-forward sweep method uses a circuit calculation between the respective nodes (Kirchhoff method) and the calculation is simple. In addition, with the Newton-Raphson method, calculation is inclined not to converge as the impedance of the power grid wire increases but the backward-forward sweep method is said to have better convergence than the Newton-Raphson method.

One weakness of the backward-forward sweep is that it can only deal with tree-shaped distribution line connection. However, we used this method because there is a workaround when the number of loops is small[6] and power grids in Japan mostly have a tree structure.

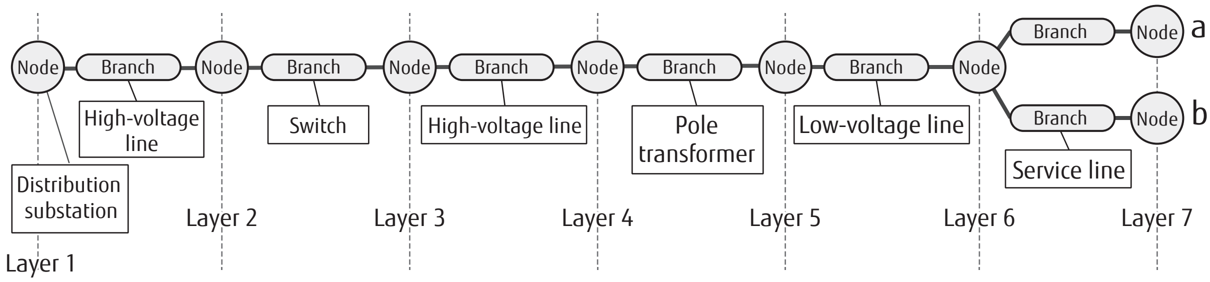
4. Modeling of power grid

4.1 Modeling of power grid connection

To conduct power grid simulation by using the backward-forward sweep method, we modeled a power grid. **Figure 3 (a)** shows a schematic diagram of a basic power grid connection and **Figure 3 (b)** a model of power grid connection. In Figure 3 (a), the power grid is composed of a distribution substation, high-voltage line (voltage: 6.6 kV), low-voltage line (200/100 V), service lines (200/100 V), switch, pole transformer and consumers. The switch has the function of switching the wiring on and off, and the pole transformer is responsible for converting the voltage (6.6 kV to 200/100 V). In an actual power grid, around four high-voltage lines extend from the distribution substation in a tree shape. Many pole transformers are installed on each high-voltage line and the respective transformers supply power to a few to around 10



(a) Schematic diagram of power grid connection



(b) Model of power grid connection

Figure 3
Modeling of smart grid connection.

consumers. Because the total number of consumers supplied by one high-voltage line is approximately 2000, the number of consumers supplied by one distribution substation is approximately 10 000. These values may vary depending on the utility company, installation location, etc.

In the modeled version of this schematic diagram shown in Figure 3 (b), we specified the respective equipment connection points and consumers as nodes, and the lines, switch and pole transformer as branches, in order to simplify program creation as one of the requirements. In addition, we divided the connection by equipment and wire type into layers so that it is easier to manage the input and output data.

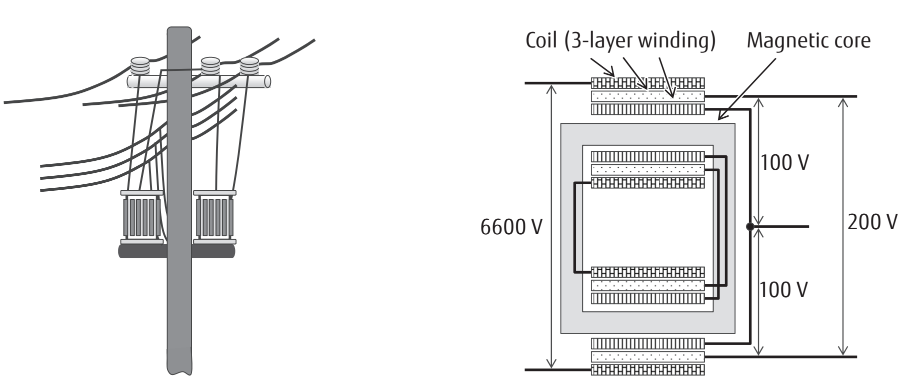
4.2 Modeling of power grid facilities

For conducting simulation, accurate modeling of power grid facilities (creation of an equivalent circuit) is required. Major facilities to be modeled that constitute a power grid are: 1) a three-phase, three-wire, high-voltage power grid, 2) a low-voltage power grid and 3) a transformer that connects them. These models are required to accommodate unbalanced power that flows through each line. Facilities other than those mentioned above include 4) a power grid stabilizer (such as an automatic voltage regulator) but not many of them are installed. The present simulator under development has modeled 1) to 4). Of these, the following describes the modeling of a single-phase, three-wire transformer (**Figure 4**) as the transformer 3).[3)]

Model 1 [**Figure 5 (a)**] is an approximate model with the complexity of the actual transformer eliminated, and it includes two single-phase transformers. Here, Z_{sc} represents the short-circuit impedance, Z_{oc} the open-circuit impedance and r the winding ratio of the transformer.

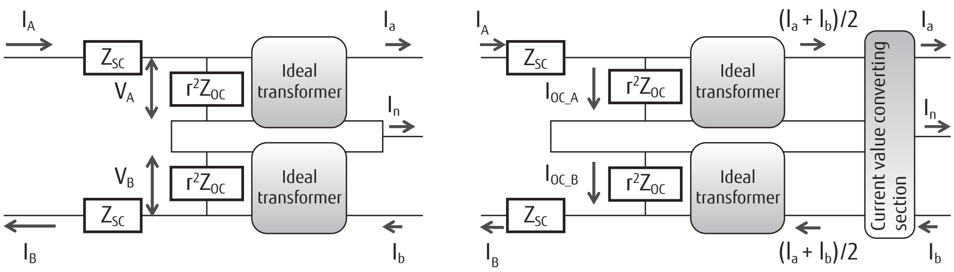
Model 2 [**Figure 5 (b)**] is a detailed model of the function of the actual single-phase, three-wire transformer. A section (current value converting section) that equalizes the values of the currents flowing to the secondary side is provided so that any unbalance between the currents I_a and I_b that flow to the secondary side of the transformer does not cause an unequal effect on the primary side.

The validity of each model was verified by finding the absolute value (ε) of the voltage across Z_{oc} in the transformer obtained by the simulator and the voltage obtained by the current and the impedance at the same transformer/area. This ε is intended to see if the open-circuit impedance Z_{oc} satisfies Ohm's law V =



(a) Pole transformer (b) Schematic diagram of arrangement of coil and magnetic core
(In reality, the secondary winding is divided into two parts for cross connection.)

Figure 4
Single-phase, three-wire pole transformer.



(a) Model 1 (b) Model 2

Figure 5
Model of single-phase, three-wire pole transformer.

ZI and a large value for ε indicates that the solution to the calculation is inappropriate. As a method of verification, we defined parameter k $\{= I_b/(I_a+I_b)\}$ that indicates the degree of unbalance between the currents flowing to the consumer side of each model and examined the relation between values for k and ε. The value for k is between 0 and 1 with k = 0.5 indicating balanced power consumption and deviation from 0.5 indicating unbalance. For k, ranges 0.5 to 1 and 0.5 to 0 are symmetrical and only either needs to be verified. Accordingly the following discusses $0.5 \le k \le 1$. The result of the verification is shown in **Figure 6**. When power consumption is balanced (k = 0.5), the value for ε is almost 0 and both models 1 and 2 satisfy the power equation. With a higher degree of unbalance (larger deviation of k from 0.5), however, model 1 causes the value for ε to be large and fails to satisfy the power equation. With model 2, the value for ε remains approximately 0 regardless of k, which means that the power equation is satisfied and an appropriate solution has been obtained. This has made it clear that, in order to conduct a simulation that takes into account single-phase, three-wire load unbalance, which is possible in reality, model 1, or an approximate model, is inadequate and application of model 2 is essential.

The power grid equipment that has been modeled up to now is only part of the whole and modeling of other types of equipment will be necessary in the future.

5. Verification of simulator

As verification of the present simulator, we compared the simulation result with that obtained by using a conventional simulator. For example, with the calculation of a single-phase, 126-node power grid model,[7] the difference of the voltage of each node with that in a

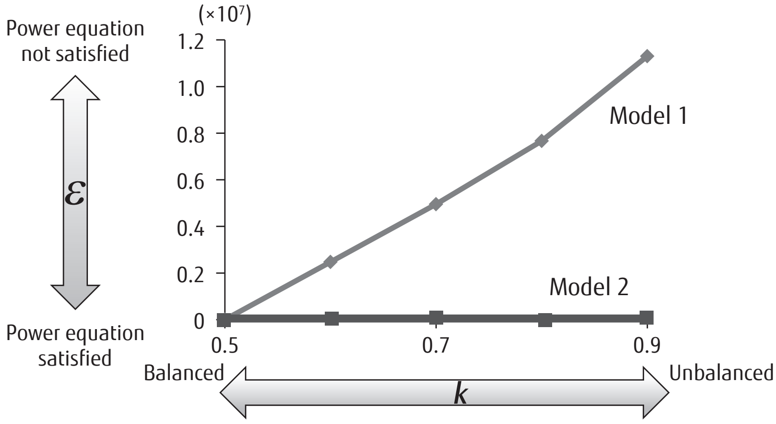


Figure 6
Verification result.

comparison paper was 0.1% or less.[2)]

For verification of the three-phase, three-wire unbalanced and single-phase, multi-wire unbalanced transformer models, we created a verification power grid model with approximately 30 nodes and compared the simulation result with that from a conventional simulator. As a result, the difference between the voltage values obtained with the present simulator and the conventional simulator was 0.1% or less for all nodes. This has led to a conclusion that the results of simulation by the present power grid simulator developed are correct.

In addition, as verification of support for a large number of nodes and high-speed processing, we created a power grid model (three-phase, three-wire for the high-voltage line and single-phase, two-wire for the low-voltage line) with about 2000 consumers and conducted a simulation. The results showed a calculation time of 1 second or less. For the calculation, a commercially available PC (with 4 GB memory and 3 GHz CPU) and C++ as a development language were used.

The verification of the simulator is currently only limited to comparison with other simulation results and verification by field testing is necessary.

6. Conclusion

This paper has presented research and development of power grid simulation technologies. We believe that power grid simulation technologies can help solve wide-ranging issues that are to be targeted by energy solutions. We intend to work on improving the function, accuracy and convenience of the present technologies to develop a power grid simulation that will be put into wide use.

References

1) I. Watanabe and T. Takebayshi: Approach to Social Solutions. *FUJITSU Sci. Tech. J.*, Vol. 48, No. 2, pp. 117–123 (2012).
2) H. Kikuchi et al.: Development of Power Flow Simulator for Regional EMSs (1). Proc. of the National Convention Record, IEE of Japan, 2012, No. 6, pp. 179–180 (in Japanese).
3) Y. Teranishi et al.: Development of Power Flow Simulator for Distribution Systems. Proc. of the National Convention Record, IEE of Japan, 2013, No. 6, pp. 291–292 (in Japanese).
4) K. Nomura et al.: Solution to Utilization of Smart Meter Data. *FUJITSU Sci. Tech. J.*, Vol. 50, No. 2, pp.***–*** (2014).
5) R. D. Zimmerman: Comprehensive Distribution Power Flow; Modeling, Formulation, Solution Algorithms and Analysis. Ph.D. dissertation, Cornell University, 1995.
6) D. Shirmohammadi et al.: A Compensation-Based Power Flow Method For Weakly Meshed Distribution And Transmission Network. *IEEE Transaction on Power System*, Vol. 3, No. 2, pp. 753–762 (1998).
7) H. Yang et al.: Newton-Downhill Algorithm for Distribution Power Flow Analysis. IEEE International Conference on Power and Energy (PECon 08), December 1-3, 2008, pp. 1628–1632.

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