# Power System Analysis for Solving Problems with Expanding Introduction of Renewable Energy Sources

Kazuhiro KURODA*, Toshihiro KUBO, Soichi NAKAJIMA, Norihisa NAGASAKI,
Masaki MURAI and Yoshinori KAWASAKI

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The Great East Japan Earthquake and subsequent electricity crisis, introduction of feed-in tariff (FIT) scheme, and the electricity system reform caused huge changes in the Japanese power system. These changes include the acceleration of installing renewable energy equipment, the enhancement of interconnections among regional power electric utilities, and the increase of the new power suppliers resulting from the full liberalization of retail power sales. This paper introduces Nissin Electric's activities to solve power quality problems caused by the above-mentioned changes, from a viewpoint of the power system analysis.

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Keywords: renewable energy, power system analysis

## 1. Introduction

In Japan, the Great East Japan Earthquake and the subsequent tight power supply, introduction of a feed-in tariff (FIT) scheme, and power system reform have caused dramatic changes in Japan's power systems. These changes led to acceleration in the introduction of solar power and other renewable energies, an increase in the number of the new power suppliers, and reinforcement of interconnections between regional electric power utilities.

This paper introduces the efforts of Nissin Electric Co., Ltd. for solving power quality problems that have been raised in association with the accelerated introduction of renewable energy, from a viewpoint of the power system analysis.

## 2. Nissin Electric's Power System Analysis(1),(2)

Nissin Electric took over the capacitor production business of Sumitomo Electric Industries, Ltd. in 1945. Since then, Nissin Electric has commercialized various types of equipment that can improve power quality, such as shunt capacitors (SCs), series capacitors for use by electric railroad companies and electric power companies, and the world's first static var compensators (SVCs) that reduce arc furnace flicker. Nissin Electric's power system equipment has contributed to expanding the power system in Japan (Table 1).

In particular, Nissin Electric has supplied harmonic filters and SCs to all converter stations for DC interconnections (AC ⇔ DC ⇔ AC) between regional electric power utilities. These harmonic filters are used to reduce harmonics generated from converters, while SCs are used to supply the reactive power consumed by the converters.

Nissin Electric's power system analysis technology is highly effective to preliminarily evaluate the effectiveness of the power system equipment (determination of equipment capacity and selection of equipment control method).

The object of the power system analysis and the analysis tools are shown in Table 2. Nissin Electric has achieved successful results in power system analysis in the time domains of surge (μs range), stability (second range), and load flow analysis (steady state).

Table 1. Nissin Electric's Power Quality Equipment Supply Record and the Contribution of Power System Analysis(1),(2)

| | Nissin Electric's major equipment supply record | Role played by the power system analysis technology |
|---|---|---|
| 1945 | Transfer of power capacitor business from Sumitomo Electric | |
| 1964~ | Series capacitor for use by electric railroad company | Voltage-drop countermeasure: Selection of capacitor compensation degree<br>・Measures to protect the equipment in the event of failure due to short-circuiting<br>・Measures to prevent over-voltage between terminals when reinserting a series capacitor |
| 1973 | Series capacitor for 275 kV-series transmission line of the Kansai Electric Power Co. Inc. (In 1982, expansion in 1984) | |
| 1973 | Static var compensator (SVC) (World's first compensator that prevents arc furnace flicker) | Analysis of arc furnace characteristics when melting scrap steel<br>・Selection of high-speed reactive power detection and control method<br>・Design of optimal harmonic filter |
| 1987 | Increased demand for capacitors and SVCs triggered by the major power outage in the Greater Tokyo Area | Analysis of voltage fluctuation and countermeasure<br>・Selection of SVC control method for voltage stabilization |
| 2000 | Harmonic filter for use in the Kii-Suido DC interconnection between Kansai Electric and Shikoku Electric Power Co., Inc. | Analysis and future prediction of power system harmonics<br>・Selection of the optimal configuration and capacity of the harmonic filter circuit<br>・Transient overvoltage when the filter circuit is switched on/off and evaluation of the countermeasure |

Table 2. Analysis Objects and Analysis Tools

| Analysis object | | | Analysis tool | Time domain |
|---|---|---|---|---|
| 1 | Transients | Lightning surge | Instantaneous value analysis program | 1-100 μs |
| 2 | | Transient overvoltage (Switching, grounding) | | 1-200 ms |
| 3 | Harmonics | | Harmonics analysis program | 20 ms |
| 4 | Fluctuation of power system and its stability degree | | Load flow calculation / stability degree analysis program* | 1-10 s |
| 5 | Load flow analysis | | | Steady |

*A program used to determine the capacities of the phase modifier and SVC that are necessary for bus voltage control

# 3. Problems Associated with Power System and Examples of Analysis

## 3-1 Changes in the environment surrounding power systems and trends in power systems

The recent change in the environment surrounding electricity system and the trends in power systems in Japan are summarized in Fig. 1, in addition with those in India, EU member countries, and China, which has become the world's second largest economic power in terms of GDP. In India and China, in particular, power demand is increasing, while EU countries are increasingly installing renewable energy and promoting the construction of DC grids to unify electric rate structures inside the EU area.

Taking renewable energy power generation as a typical example, the problems associated with interconnections between distributed power sources and those related to business continuity plans of electricity consumers (power outage countermeasures) are described below; in addition, some examples of the analysis of these problems are also provided.

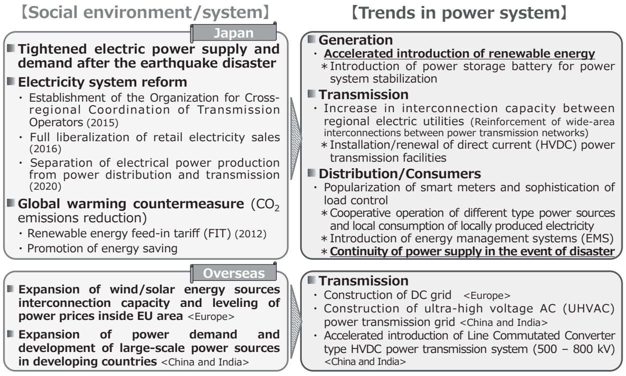


Fig. 1. Changes in Social Environment/System and the Trend of Power System

## 3-2 Problems associated with system interconnections between distributed power sources and examples of problem analysis

The major items to be studied when interconnecting distributed power sources and examples of the measures to be implemented for these items are shown in Table 3. This section describes an example of the analysis of each item.

Figure 2 presents the major problems that will occur when interconnecting massive renewable energy sources. As two typical examples of these problems, the suppression of voltage fluctuation attributable to output fluctuation and the prevention of simultaneous disconnection in the event of a power system disturbance are discussed below.

Table 3. Major Study Items and Solution Examples of Distributed Power Source Interconnection

| Study item | Problem to be solved and example of solution |
|---|---|
| Stability of power system when interconnecting renewable energy sources | 【Problem】Fig. 2 |
| | 【Examples of solution】Constant power factor control of the power conditioning system (voltage fluctuation countermeasure), provision of FRT function, etc. |
| Instantaneous voltage drop when energizing transformer | 【Problems】Instantaneous voltage drop caused by magnetizing inrush current when energizing transformer, malfunction of protective relay |
| | 【Examples of solution】Use of resistor, input phase control, synchronous energization by magnetizing secondary coil |
| Ferroresonance of voltage transformer (VT) used in measuring instrument | 【Problem】VT: Possibility of the occurrence of nonlinear phenomenon (ferroresonance) between inductance *L* of device comprising an iron core and capacitance *C* |
| | 【Examples of solution】Installation of saturable reactor on the secondary side of VT, addition of VT's tertiary load |

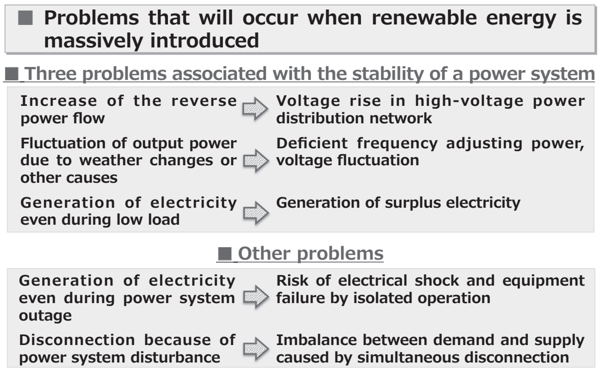


Fig. 2. Power System Problem Associated with Massive Introduction of Renewable Energy

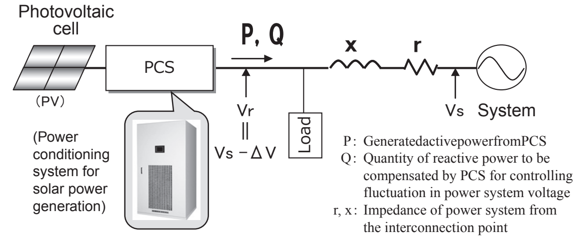


Fig. 3. Power System Diagram for Explaining Voltage Fluctuation Countermeasure(3)

When large-capacity solar power generation systems are installed in a distribution system, it is indispensable to consider that the output voltage may fluctuate in response to the fluctuation of the power they generate. A wind power system is generally equipped with an SVC to control the fluctuation of voltage. In contrast, in a solar power system, it is possible to provide its power conditioning system with an SVC function(3) because the conditioning system itself can generate reactive power. In the power system shown in Fig. 3, the voltage fluctuation $\Delta V$ of the solar power at the point of interconnection can be simply expressed as follows:

$$\Delta V = r \cdot \Delta P - x \cdot \Delta Q$$

where $\Delta P$: Active power fluctuation, $\Delta Q$: Reactive power fluctuation, $r + jx$: Distribution line impedance.

The above equation shows that voltage fluctuation can be suppressed by outputting reactive power, $\Delta Q = (r/x) \cdot \Delta P$, from the power conditioning system.

The effectiveness of the voltage fluctuation countermeasures that were implemented according to the above principles was analyzed using actually acquired solar power data. It was assumed that the reactive power *Q* was feed-forward controlled at its ratio to the generated power *P* (Nissin Electric used this control system in the past as a flicker countermeasure). The analysis results are shown in Fig. 4. The analysis results confirmed that the above countermeasures can suppress voltage fluctuation effectively without limiting the output power of the photovoltaic cells.

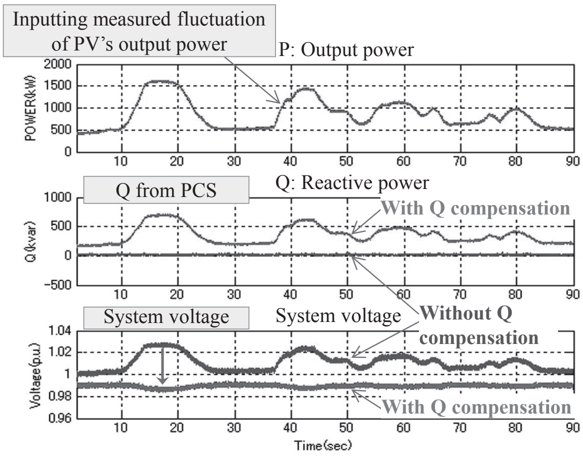
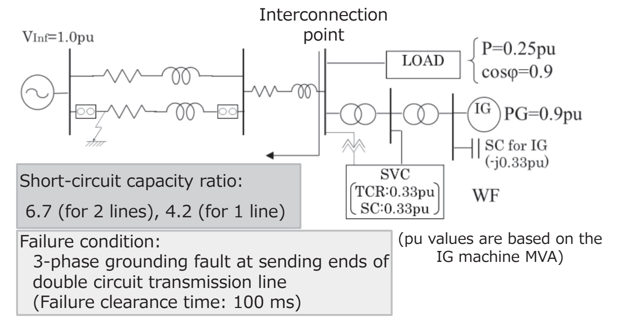


Fig. 4. Analysis Result for Voltage Fluctuation Countermeasure[3]



| Induction Generator Parameters (machine base) | |
|---|---|
| Resistance of stator winding Rs | 0.007 pu |
| Leakage reactance of stator winding Xls | 0.093 pu |
| Resistance of rotor winding Rr | 0.010 pu |
| Leakage reactance of rotor winding Xlr | 0.097 pu |
| Mutual reactance Xm | 3.0 pu |
| Inertia Constant H | 2.0 sec |
| SC for IG (Capacity) | 0.33 pu (L=0%) |

Fig. 5. Configuration of Interconnected Wind Power Systems on a Large Scale and Induction Machine Constant[4]

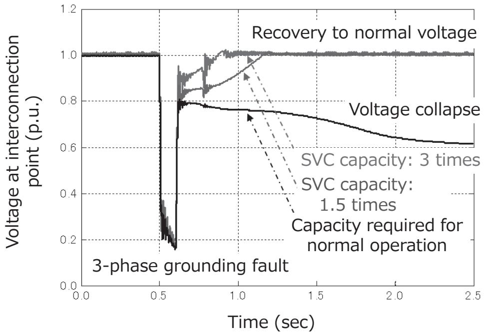


Fig. 6. Analysis Result for Bus Voltage at Interconnection Point in the Event of System Disturbance[4]

Similarly, solar power generation systems and wind power generation systems are also required to continue to operate even in the event of a power system disturbance and thus they contribute to the stable operation of the power system. In a wind turbine generator of direct grid connection type with an induction machine, the rotation speed of the induction machine may drop due to an instantaneous voltage drop. As a result, the generator consumes an increased amount of reactive power and delays the recovery of voltage. Figures 5 and 6 show an analysis[4] of the SVC capacity that would be required for a wind power station equipped with a direct-grid-connection large-capacity induction machine to recover the voltage after an instantaneous voltage drop.

This analysis, which was carried out by accurately simulating the inertia-constant/electric-constant of the induction machine, could simulate the delay in the recovery of voltage due to an increase of the slip of the induction machine. In other words, increasing the capacity of the SVC, which is installed to control the voltage fluctuation, is effective for improving the voltage recovery characteristics of wind power generation systems.

When installing an SVC in a power system, it is necessary to take measures to prevent the voltage drop and the flow of a harmonic current into the SC installed along with the SVC, which are caused by the inrush current subsequent to a no-load energization of the SVC transformer. Figure 7 shows the analysis result when the SVC transformer is energized under the active state of the SC.

The analysis example clarified that the impedance of the SC resonates with that of the power supply system at the third harmonic and, as a result, the third harmonic current component in the magnetizing inrush current expands and flows into the SC. It was also found that magnetizing inrush current from the transformer flows into the power supply system and drops the SVC's bus voltage. The measures for preventing the above phenomena include disconnecting the capacitor before energizing the no-load transformer and shifting the resonance frequency of the main circuit.[5]

The number of offshore wind farm construction plans is increasing, even in Japan. To transmit power from an offshore wind farm to its onshore grid connection point, AC transmission technology is usually used when the distance between the farm and connection point is relatively short. For a relatively long distance transmission, i.e., 30-60 km or longer OF cables, DC transmission technology[6] is usually used.

When transmitting AC power over a long distance, it is important to explore measures against peculiar phenomena

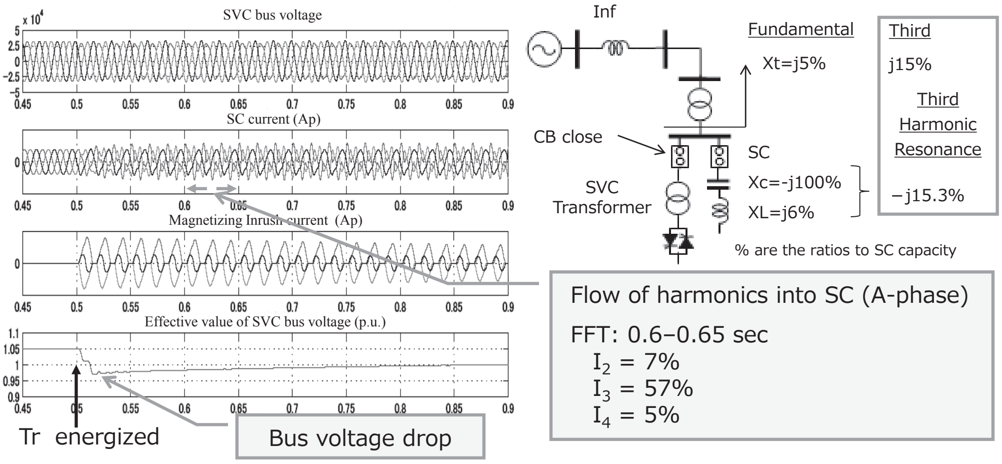


Fig. 7. Analysis Example for SC Overcurrent Caused by No-load Energization of Transformer

that may occur due to the ground capacitance of the transmission cables. Table 4 summarizes the major peculiar phenomena that will occur in the long-distance AC power transmission cables and examples of possible countermeasures. Nissin Electric carries out power system analyses to assess the necessity of implementing countermeasures and provides customers with the equipment specifications when an appropriate countermeasure is essential.

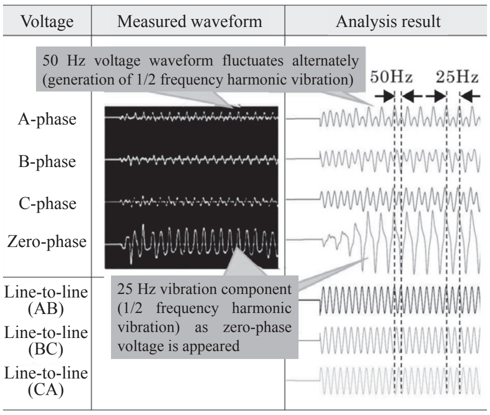
Table 4. Peculiar Phenomena in Long-distance AC Power Transmission Cables and Examples of Countermeasures

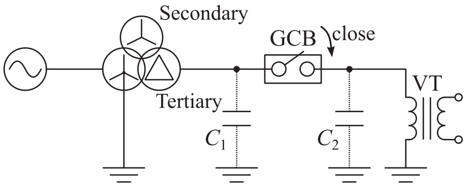
| Phenomenon | Phenomenon of concern and example of countermeasure |
|---|---|
| Residual voltage in cable | Peak voltage remains in the cables when the breaker is turned off. If the breaker is turned on under this condition, overvoltage will occur. As a result, the related equipment and devices may be damaged. |
| | 【Countermeasure】Discharging voltage by installing transmission line VT (after verifying winding tolerance) |
| Harmonic resonance | Large capacitance $C$ of long distance cables reduces the resonance frequency with inductance $L$ of the power system. As a result, particular harmonics expands.<br>Resonance frequency = $1/(2\pi\sqrt{LC})$<br>⇒ Resonance frequency decreases as $C$ increases. |
| | 【Countermeasure】Installation of harmonic filter |
| Current zero miss | When the charge current of cables overlaps the transformer magnetizing inrush current, a time period without current zero occurs. During this time period, it may be impossible to open the CB for transformer when power system fails. |
| | 【Countermeasure】Appropriate operation of power system or energization of transformer by means of breaker mounted with built-in resistor |
| Voltage fluctuation | Voltage fluctuates when power transmission through long-distance cables is turned on/off (voltage rise in particular). |
| | 【Countermeasure】Installation of shunt reactor (ShR) and/or SVC |

In addition, installation of instrument transformers like a voltage transformer (VT) and current transformer (CT) are required when distributed power sources are newly interconnected. It is known that an extraordinary vibration phenomenon, called ferroresonance, rarely continues in a circuit in which capacitance ($C$) coexists with the magnetizing inductance ($L$) of a device equipped with an iron core like a VT. The generation mechanism of ferroresonance is as follows. When $L$ is magnetically saturated temporary by an electrical shock, such as turning on/off of a breaker, energy is transferred between $L$ and $C$. If ferroresonance continues, the related equipment and devices may be damaged due to overheating and the main circuit may cause a grounding fault caused by dielectric breakdown.

An analysis example of the ferroresonance phenomenon(7) is shown in Table 5 and Fig. 8. In the circuit diagram shown in Fig. 8, the tertiary circuit was ungrounded. When the breaker was turned on without load in this power system, zero-phase voltage waveforms (voltage of the same phase

Table 5. Phase Voltages and Line-to-line Voltages of VT and Zero-phase Voltages (measurement and simulation results)(7)





$C_1$: Ground capacitance of transformer's tertiary coil
$C_2$: Ground capacitance of VT + GIS

Fig. 8. Circuit Configuration of GIS Power System for Use in the Tertiary Circuit of Overseas 500 kV Substation

and amount contained in each phase) were measured, as shown in Table 5. It was confirmed from this table that the zero-phase voltage oscillated at a frequency of 25 Hz, which was one-half of the basic frequency (50 Hz), and the same component was superimposed on the voltage of each phase. In the simulation that was carried out to reproduce the zero-phase voltage under practical power system conditions, results of which are shown on the right side of Table 5, a 1/2 frequency harmonic vibration with the same waveforms as those measured was obtained. It was confirmed from the above simulation result that ferroresonance occurs in actual power systems.

The occurrence of the ferroresonance phenomenon depends on the constant of peripheral circuits and the operating conditions of the power system. Based on abundant experiences in this field, Nissin Electric provides customers with the analysis of their power systems and countermeasures.

### 3-3 Analysis example for customer's power system

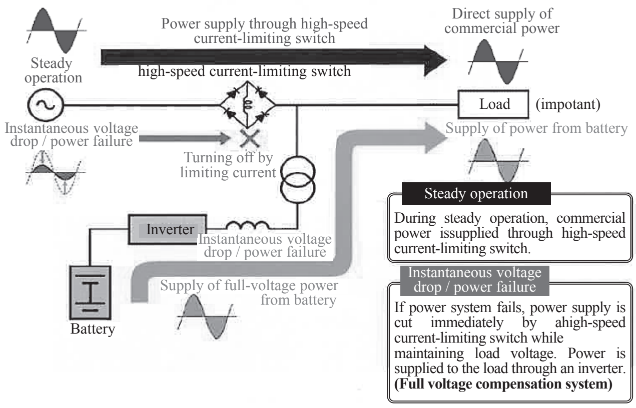
The major items to be studied for the steady operation of customers' power systems and the measures to be implemented to prevent system failures are shown in Table 6. Instantaneous voltage-drop / power-failure prevention techniques will become more important for business continuity given the recent and frequent occurrence of natural disasters and the rising concern about the deterioration of power quality because of the expanded introduction of renewable energy. This section describes and discusses some examples of analyses for instantaneous voltage-drop / power-failure countermeasures.

Nisshin Electric developed various types of equipment that are indispensable for semiconductor production processes in order to prevent instantaneous voltage-drop / power-failure, and supplied them to semiconductor plants. Figure 9 presents an outline of our parallel-type full-voltage compensator "ALLSAFE"(8) that can control instantaneous voltage drop / power failure, while Fig. 10 compares the waveforms that were measured in an in-plant test of this equipment with the waveforms obtained by EMTP, instantaneous value analysis software.

As shown in Fig. 10, by creating analysis models that can accurately reproduce the actual operations of instanta-

Table 6. Major Study Items and Solution Examples to Protect Customers' Power Systems from Failure

| Study item | Problem and example of solution |
|---|---|
| Instantaneous voltage-drop / power-failure countermeasure (Continuous plant operation even in the event of disaster) | 【Problem】Preliminary study of the compensation performance of instantaneous voltage-drop / power-failure prevention equipment: Study of the effect of load device on compensation performance and the torque of rotary machine's output shaft |
| | 【Example of solution】Installation of prevention equipment (e.g., Series/parallel-type compensator and current-limiting circuit breaker) |
| Cooperative control/stable operation of various types of power sources | 【Problem】Verification of the stable operation of a power system during disturbance and compensation for fluctuation of renewable energy supply |
| | 【Example of solution】Installation of power stabilization system (e.g., battery) |
| Voltage fluctuation when power-receiving transformer is energized | 【Problem】Instantaneous voltage drop and malfunction of protective relay that are attributable to magnetizing inrush current generated when transformer is energized |
| | 【Example of solution】Use of resistor, input phase control, and synchronous energization by magnetizing secondary components |
| Generation of harmonics by load device | 【Problem】Expansion of harmonics on customer's power systems |
| | 【Example of solution】Installation of harmonic filter, control of harmonics source (e.g., installation of AC reactor) |



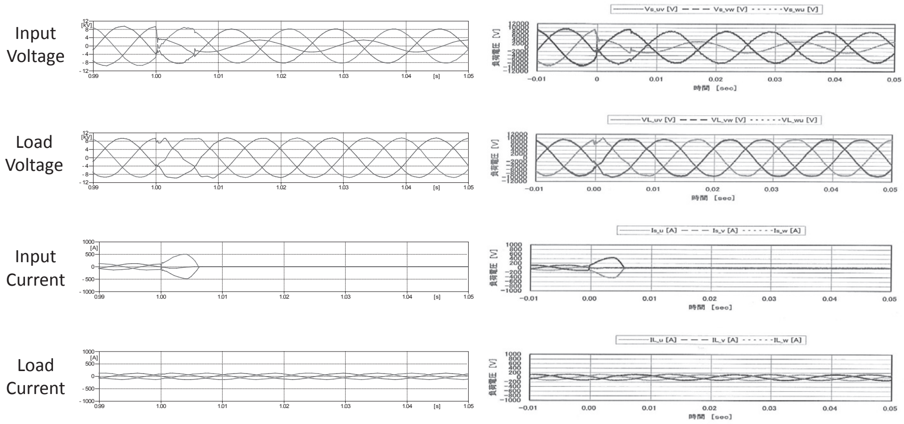
**Steady operation**

During steady operation, commercial power issupplied through high-speed current-limiting switch.

**Instantaneous voltage drop / power failure**

If power system fails, power supply is cut immediately by ahigh-speed current-limiting switch while maintaining load voltage. Power is supplied to the load through an inverter. **(Full voltage compensation system)**

Fig. 9. Outline of the Operation of Instantaneous Voltage Drop / Power Failure Prevention Equipment (ALLSAFE)



【Waveforms simulated by EMTP】　【Measured waveforms】

Fig. 10. Operation Analysis of Instantaneous Voltage Drop / Power Failure Prevention Equipment in In-plant Test

neous voltage-drop / power-failure prevention equipment, Nissin Electric optimized designs for various customers' power system conditions.

It has also commercialized a system that supplies the load power from an emergency power generator in the event of a prolonged power failure.

## 4. Conclusion

Power systems in Japan have been changing dramatically in association with the massive introduction of solar power, electricity system reform, and reinforcement of interconnections between regional electric power utilities. This paper reported Nissin Electric's efforts for solving power system problems that are anticipated to occur in the future, with focus on its original technology for power system analysis. Using its system analysis technology, Nissin Electric will continue to solve various problems and contribute to the development of power systems.

### Technical Terms

∗1 Flicker: Voltage fluctuation in an arc furnace and other facilities that are exposed to load fluctuations. It causes illumination to flicker.
∗2 SVC: Acronym for static var compensator; it comprises a semiconductor device to continuously control the magnitude of reactive power. TCR, which is an acronym for thyristor-controlled reactor, controls lagging power by continuously controlling reactor current by controlling the firing angle of thyristors.
∗3 Harmonic: Voltage or current whose frequency is an integral multiple of the fundamental frequency of the power system (50 Hz in eastern Japan; 60 Hz in western Japan).
∗4 PCS: Acronym for power conditioning system; a device for converting generated power to AC power and delivering it to a power system.

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## Contributors

The lead author is indicated by an asterisk (∗).

**K. KURODA***
• Group Manager, Power Technology Laboratories, Nissin Electric Co., Ltd.

**T. KUBO**
• Power Technology Laboratories, Nissin Electric Co., Ltd.

**S. NAKAJIMA**
• Chief, Instrument Transformer Division, Nissin Electric Co., Ltd.

**N. NAGASAKI**
• Chief Senior Staff, Engineering Department, Capacitor Division, Nissin Electric Co., Ltd.

**M. MURAI**
• Group Manager, System Engineering Division, Nissin Electric Co., Ltd.

**Y. KAWASAKI**
• Chief Senior Staff, Power Technology Laboratories, Nissin Electric Co., Ltd.