

# Technology of Estimating Short Circuit Current and Ground Fault for Direct Current Distribution Systems

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## ABSTRACT

Applications of Direct Current power distribution systems are expanding along with the expansion of renewable energy use, and this has created an urgent need to establish protection technology for their safe operation. Fuji Electric has verified and established short circuit and ground fault estimation technology as protection technology for direct current power distribution systems. We have built an equivalent circuit based on the impedance characteristics of a storage battery to estimate a short circuit fault in the vicinity of a storage battery. We have analyzed the ground fault current waveforms of grounded and ungrounded systems to estimate the ground fault. Moreover, based on the estimation technology, we have built our product line to make it easier for users to select the appropriate protection devices.

## 1. Introduction

Greater use of renewable energy sources and the dissemination of smart grids and electric vehicles have been promoted for the purpose of solving the problems of fossil fuel depletion and global warming. Under these circumstances, power distribution systems using direct current are expanding to use energy efficiently and this has created an urgent need to establish protection technology to ensure their safe operation. To satisfy such a need, Fuji Electric has been working on the development of protection technology and protective devices for direct current distribution systems.

Protection technology for direct current distribution systems is broadly divided into overvoltage protection, overcurrent protection and electric shock protection. The overcurrent protection and electric shock protection have such problems as follows. The peak value and rate-of-rise when a short-circuit fault occurs vary depending on the dispersed power supply to be connected, and the current flowing path and peak value when a ground fault occurs differ depending on whether the converter is an insulated type or non-insulated type.

This paper describes the short-circuit fault and ground fault estimation technologies on which Fuji Electric has been working to solve these problems. It also explains how to select protective devices based on the estimation result.

## 2. Issues in Typical Direct Current Distribution Systems

### (1) Wind power generation system

Since wind conditions change depending on the

season or weather, the output of a wind power generation system greatly fluctuates in the course of a year or a day. Consequently, if a large amount of output is connected directly to a commercial system, the frequency or power flow of the commercial system may be affected by the output fluctuation.

To solve this problem and achieve a stable system connection, there is a method called the DC link system that first converts the output from the generator into a direct current with an AC/DC converter and then converts it into an alternating current with a DC/AC converter (see Fig. 1). This method prevents any fluctuations from influencing the system by charging or discharging the storage battery connected to the direct current section, and thus keeping the output voltage constant.

A lead-acid battery or lithium-ion battery is used as the storage battery. Since their energy density is higher than capacitors or other electricity storage devices, an excessive current may flow continuously when a short-circuit fault occurs. Moreover, in the case of lithium-ion batteries, the internal temperature may rise abruptly due to the short-circuit current, resulting

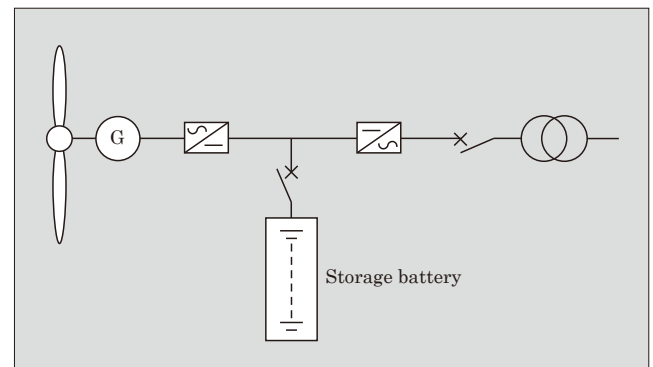


Fig.1 Wind power generation system using DC link system

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in an explosion or fire in the worst case. Consequently, when a short-circuit fault occurs, it is necessary to break the current immediately.

(2) Photovoltaic power generation system

Photovoltaic power generation systems became more popular after the introduction of the “Feed-in Tariff Scheme (FIT)” that encourages the use of renewable energy. As shown in Fig. 2, a photovoltaic power generation system consists of parallel connections of multiple groups (strings) of photovoltaic cell panels connected in series. In order to improve the power generation efficiency, each string is designed to generate power higher than 500 V. Outside Japan, an increasing number of systems are designed to generate around 1,000 V. When a short-circuit fault occurs in a photovoltaic cell panel, a typical increase of the current is about 10 to 20% of the rated current. As a result, a protective device is required to provide a breaking performance and insulation ability to deal with 120% of the rated current of such high voltage systems.

(3) Direct current supply system

In data centers, direct current supply has been proposed instead of conventional alternating current supply in order to reduce power loss in the entire system and ensure energy saving<sup>(1)</sup>. As shown in Fig. 3, the system supplies power by using an AC/DC converter to convert AC power into a direct current and then using a DC/DC converter to convert it into DC voltage in accordance with the device connected to the DC bus. Since a storage battery for backup can be connected directly, the loss caused by voltage conversion can be reduced compared with conventional AC power supply. Since DC voltage of 300 to 400 V is supplied, this system is characterized by having the DC bus grounded at the center tapped grounding on high impedance in order to lessen the influence on the human body in the event of electric shock accidents.

When a storage battery is connected, immediate breaking is required because an excessive short-circuit current may flow due to a short-circuit fault as is the case with the wind power generation system described

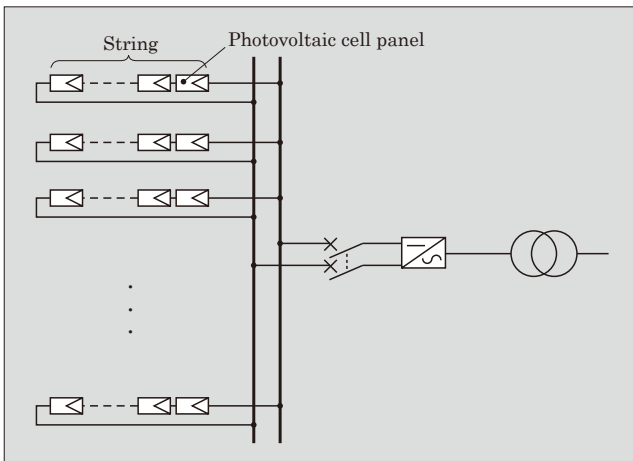


Fig.2 Configuration of photovoltaic power generation system

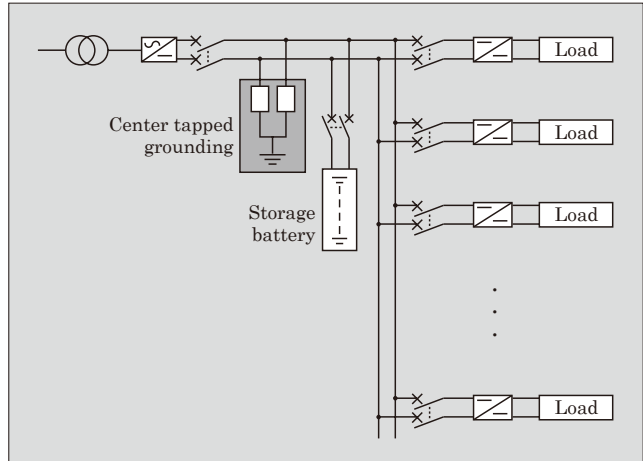


Fig.3 Direct current supply system in data center

above.

3. Short-Circuit Fault Estimation Technology

A short-circuit current flowing in a photovoltaic power panel is about 110 to 120% of the rating. Since storage batteries used in direct current supply systems or wind power generation systems have high energy density, a short-circuit current flows continuously in the event of a short-circuit fault. In addition, when a short-circuit fault occurs between the DC/DC converter and storage battery, a short-circuit current from the storage battery and a current from the capacitor in the AC/DC converter flow into the short-circuit point. In order to isolate the short-circuit fault point to prevent such accidents, it is necessary to know the amount of the short-circuit current flowing from the storage battery and AC/DC converter at the system design stage and select an appropriate protective device.

3.1 Short-circuit fault in the vicinity of storage battery

The current discharged from storage battery due to short-circuiting is determined by the electromotive force of the storage battery, the internal impedance of the storage battery and the line impedance to the short-circuit point. Figure 4 shows an equivalent circuit of a storage battery. This equivalent circuit consists of resistors (R1 to R3) and capacitors (C1 and C2). The parallel circuits of the resistors and capacitors represent the positive or negative poles of the storage battery and the resistor connected in series represents

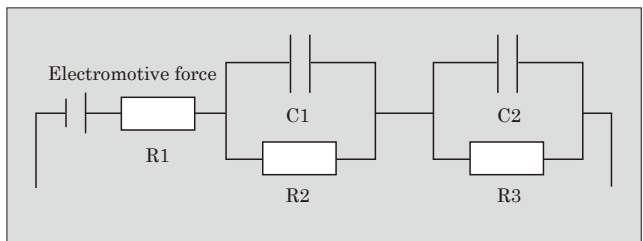


Fig.4 Equivalent circuit of storage battery

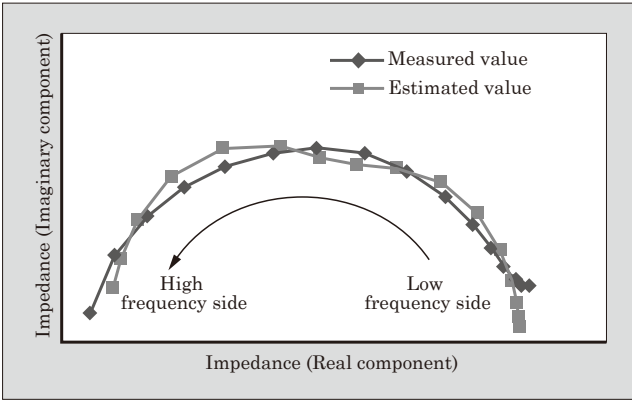


Fig.5 Impedance characteristics of storage battery

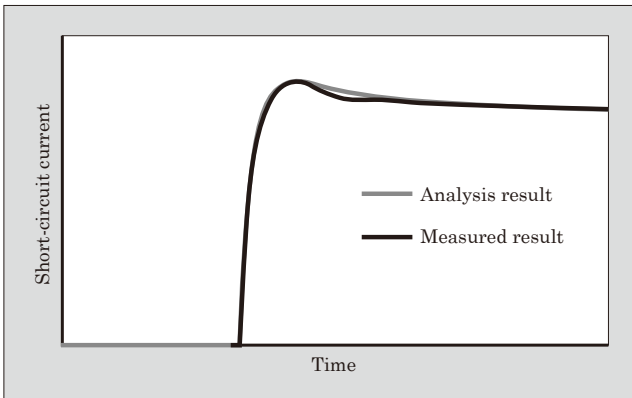


Fig.6 Short-circuit current waveform at short-circuit fault in the vicinity of storage battery

ion conductance. By applying an impedance up to the short-circuit fault point on the equivalent circuit and creating a shorted circuit line, it becomes possible to estimate the value of the short-circuit current.

Figure 5 shows a comparison of the impedance characteristics between the equivalent circuit of a storage battery cell and actual measurement. The impedance characteristics of the equivalent circuit are in good agreement with the measurement across the ranges from low to high frequencies. Consequently, we confirmed that an equivalent circuit consisting of resistors and capacitors can be used to simulate a storage battery. As shown in Fig. 6, the estimated value of the short-circuit current in the equivalent circuit is in good agreement with the measurement, indicating that it is possible to estimate a short-circuit current. In this way, we can easily estimate the value of a short-circuit current by establishing an equivalent circuit based on the impedance characteristics of a storage battery.

### 3.2 Short-circuit fault in the vicinity of converter

A converter has a capacitor connected to its output terminal to suppress the voltage fluctuation in the DC bus. When a short-circuit fault occurs in the system, an electric charge flows from this capacitor to the fault point. Figure 7 shows the short-circuit current waveform when a short-circuit fault occurs in the vicinity of

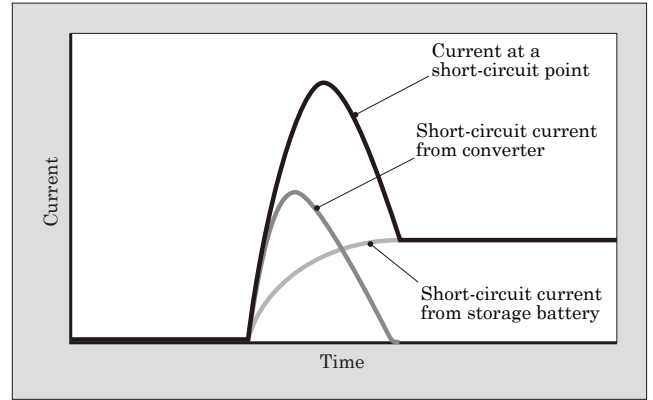


Fig.7 Short-circuit current waveform at short-circuit fault in the vicinity of converter

a DC/DC converter in the DC bus of a direct current supply system.

## 4. Ground Fault Estimation Technology

In some direct current supply systems used for data centers, etc., center tapped grounding is applied to the DC bus. The phenomenon of a ground fault depends on whether the system is grounded or not.

### 4.1 Ground fault in grounded system

This section describes the ground-fault current when center tapped grounding is provided in a direct current supply system for data centers, etc. As shown in Fig. 3, center tapped grounding is established by connecting  $k\Omega$ -level resistors to the positive and negative poles as ground-fault resistance. Figure 8 shows the ground-fault current waveform in the DC bus with center tapped grounding. The ground fault condition assumes contact with a human body and the  $k\Omega$ -level resistor is used to simulate a ground fault. As the figure shows, the measured value of the ground-fault current (solid line) is in good agreement with the calculated value. This indicates that the ground-fault current in a grounded system can be obtained from the voltage and ground-fault resistance of the DC bus.

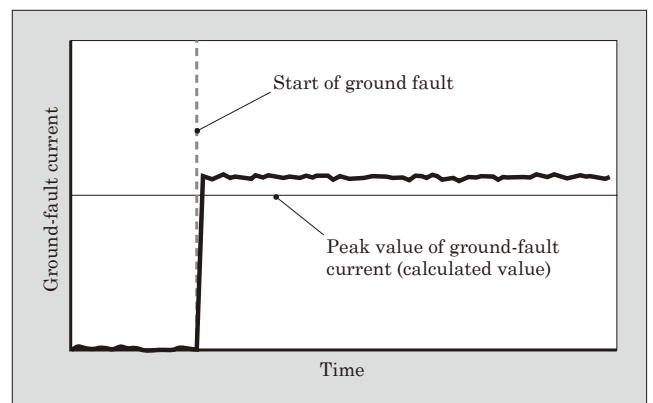


Fig.8 Ground-fault current waveform at ground fault in grounded system

#### 4.2 Ground fault in ungrounded system

In an ungrounded system, when a ground fault occurs in the system, a ground-fault current does not flow as long as there is only one ground fault point, because a path for current flow is not formed. As shown

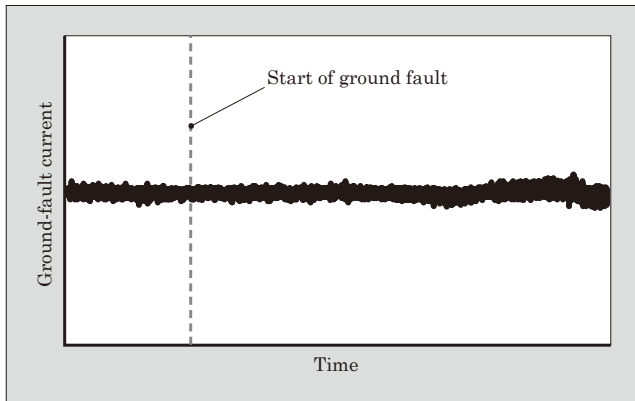


Fig.9 Ground-fault current at ground fault in ungrounded system

in Fig. 9, we simulated the case of a ground fault and confirmed that the ground-fault current flowing to the ground fault point does not change before and after the ground fault event.

#### 5. Selection of an Appropriate Protective Device for the Fault Mode

The characteristics of the fault current in a short-circuit fault depend on the configuration of the dispersed power source. For a storage battery, in particular, immediate breaking is required because a short-circuit current flows continuously. It is therefore effective to obtain the value of a short-circuit current beforehand by using the short-circuit fault estimation technology for storage batteries described in Chapter 3. Table 1 lists the lineup of DC circuit breakers offered by Fuji Electric. You can select a suitable DC circuit breaker by knowing the voltage of the system, the current flowing in steady state and the current value of a short-circuit fault described above at the system design

Table 1 Lineup of DC circuit breakers (400 to 1,000 V DC)

Rated voltage DC (V)	Model	Series name	Connection	Rated current (A)																Breaking capacity $I_{cu}$ (kA)									
				0.1	1	5	10	15/16	30/32	40	50	63	80	100	125	160	200	250	300		350	400	500	630	700	800	1,000	2,000	4,000
400	MCCB	G-TWIN	3-pole (Series connection)	EW32□G-3P C4 to BW100□G-3P C4																2.5 to 5									
500	MCB	Acti9	2 poles	C60H-DC																6									
			4-pole (Series connection)	C120N																10									
				C120H																15									
	MCCB	G-TWIN	3-pole (Series connection)	BW50□G-3P LV=500 V-02015 to BW100□G-3P LV=500 V-02015																2.5									
				BW125□G-3P C5- BW250□G-3P C5																10 to 40									
				BW400□G-3P to BW800□G-3P																20 to 40									
MCCB	DC only																											SD1003B to SD4003B	40
ACB	Master pact	2-pole (Series connection)																										NW10DC to NW40DC	25 to 100
600	MCCB	G-TWIN	3-pole (Series connection)	BW50SBSG-3P C6, BW63SBSG-3P C6																10									
				BW125JAG-3P CP, BW250JAG-3P CP																3									
			4-pole (Series connection)	BW125□G-4P C6 to BW2580□G-4P C6																25 to 40									
				BW400□G-4P to BW800□G-4P																40									
	MCCB	DC only	3-pole (Series connection)																										SD1003B to SD4003B
650	MCB	Acti9	2-pole (Series connection)	C60PV-DC		Up to 25 A rating														1.5									
750	MCCB	Compact	3-pole or 4-pole	NS100DC to 630DC																Up to 550 A rating	100								
	MCCB	G-TWIN	3-pole (Series connection)	BW400RAG to BW800RAG																10									
900	ACB	Master pact	3-pole or 4-pole (Series connection)																									NW10DC to NW40DC	25 to 85
1,000	MCCB	G-TWIN	4-pole (Series connection)	BW400RAG to BW800RAG																5									

stage and checking the values against the lineup table.

The characteristics of a ground-fault current depend on the grounding type in the system. The value of the ground-fault current in the system with center tapped grounding can be estimated from the voltage, grounding resistance and ground fault resistance of the DC wiring for which a ground fault is assumed. The sensitive current setting for the earth leakage circuit breaker must be determined based on both of the possible current flowing range when a ground fault occurs and the protection target. For example, it is several hundreds of mA to mainly protect equipment and around 30 mA to protect a human body.

A ground-fault current is not generated in an ungrounded system. If, however, a first ground fault is overlooked and then a second ground fault occurs, a current close to a short-circuit level may flow. One method to detect a ground fault in an ungrounded system is to monitor the insulation resistance in the

system and detect a drop in the insulation resistance caused by a ground fault. This makes it possible to detect a ground fault even when a ground-fault current is not generated.

Table 2 shows ground fault protection methods according to the grounding type of system. As the table indicates, the method of detecting a ground fault depends on the grounding type of the system. It is necessary to select a device suitable for the detection method. Moreover, when an earth leakage circuit breaker is used, it can be selected based on the sensitive current judged from the estimated ground-fault current value and protection target.

## 6. Postscript

This paper describes the short-circuit fault and ground fault estimation technologies on which Fuji Electric has been working. These technologies relate to direct current distribution systems that are expected to continue expanding in the future. We also explained the way to protect against these faults. Fuji Electric offers various protective device products designed for a short-circuit fault and a ground fault. We will continue with technological development for more user-friendly products.

## References

- (1) Nozaki, Y. Development of Higher-voltage Direct Current Power Feeding System for ICT Equipment. NTT Technology Review. 2009, vol.7, no.10.

Table 2 Ground fault protection method corresponding to each grounding system

Grounding type	Ground fault detection method
Ungrounded system	○ Detection with an insulation monitoring device (Fuji Electric's "Vigilohm")
High resistance grounding (Center tapped grounding)	○ Detection with an earth leakage circuit breaker (High sensitivity model: The sensitive current should be set according to the protection target.) ○ Detection based on the fluctuation in the middle electric potential
Low resistance grounding (Negative grounding)	○ Detection with an earth leakage circuit breaker





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