DC Distribution System for Improved Power System Resilience with Renewable Energy

Kazuhiro KURODA*, Masashi OGURA, Hiroaki MAEJI, Minoru OE, Genki TOYODA, and Nobuhiro KURIO

With the expanding introduction of renewable energy sources and advances in semiconductor and energy storage technologies, direct current (DC) distribution systems that combine renewable energy sources and storage batteries have attracted attention as economical and environment-friendly next-generation power supply systems. These systems are also expected to help improve power system resilience and business continuity planning (BCP). This paper introduces the background of our study and the details of the DC distribution demonstration system built at the Nissin Academy Training Center.

Keywords: DC distribution, DC solid-state circuit breaker, bi-directional isolated DC-DC converter, storage battery, renewable energy source

1. Introduction

Renewable energies, such as photovoltaics (PV) and wind power generations, will be the world's main source of power due to their reduced greenhouse gas emissions, as measures to mitigate the effects of global warming.(1) However, the behaviors of these sources are subject to the dynamism of the weather and climate. Therefore, storage batteries are of importance to balance between supply and demand of electricity, as well as between power generation, distribution, and consumption.

We have embarked on the development of a DC distribution system. This system combines renewable energy sources and storage batteries to make the optimal use of the DC characteristics for self-consumption of renewable energy and for improved power system resilience.

This paper presents the features and configuration (principal components) of the DC distribution system and shows the result of a demonstrative test to evaluate its performance.

2. Application of DC Technology in Next-Generation Systems

The DC technology has been drawing attention in providing environmentally conscious products and services with reduced carbon dioxide (CO_2) emissions, reducing fuel costs in remote islands, and developing systems that improve resilience of power systems for business continuity planning (BCP).

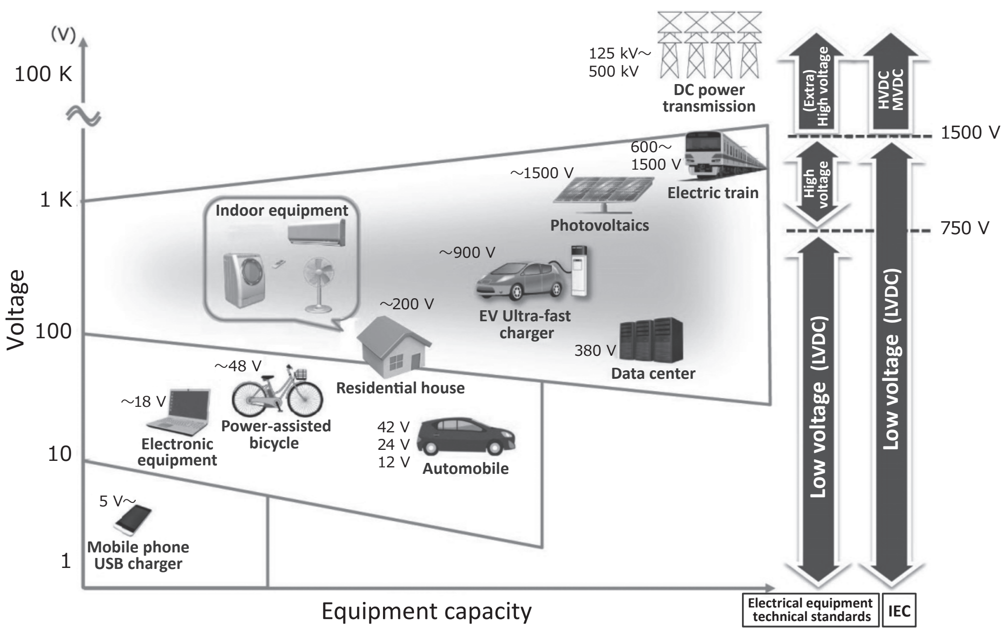

Fig. 1. DC-powered equipment (sort by voltage class)

DC distribution network operates standalone in an accident of the commercial power side, while interchanging surplus renewable power efficiently between consumers (communities) by means of DC technology. By enabling these features, DC distribution network can continue stable power supply despite voltage dips and power outages (BCP measures). Consequently, it can provide as a next-generation power supply system.

Today's renewable energy sources and appliances actually favor DC, with the proliferation of PV, storage batteries, and consumer electronics, which all natively produce and consume DC in their internal components. Figure 1 shows some of these typical equipment. With increasing penetration of DC distribution systems, it is expected that the reduced energy losses with DC power to be a major driver for the use of DC equipment (DC loads).

In the future, it is expected that the DC distribution system will coexist with the alternating current (AC) distribution system along with customer needs. Meanwhile, major challenges for the widespread usage of DC distribution systems are the development of key components, such as semiconductor devices, with higher power capacity and their cost reduction.

3. Features of DC Distribution System

It is commonly known that DC has no current zero point. This characteristic poses difficulties in current interruption, voltage transformation, and insulation as compared to AC. With the recent improvement in the performance of semiconductor devices, the development of DC equipment that overcomes these disadvantages has progressed, and it has become possible to construct DC power supply systems with safety and reliability.

Table 1 shows the main features of the DC distribution system compared to the existing AC distribution system.

Table 1. Features of DC distribution system

Energy conservation	Renewable energy sources combined with storage batteries reduce commercial power consumption and contribute to CO_2 emissions reduction.
Compatibility	Renewable energy sources, storage batteries, and DC loads can be directly connected using DC distribution lines. It is possible to control power balance by voltage control only, because of the absence of frequency.
Robustness	DC distribution systems have been identified for its stable power supply despite disturbances such as voltage dips and power outages in AC power systems. Moreover, standalone operation mode facilitates BCP measures and disaster control.
Compact	Power electronics (high-frequency inverters and transformers) has been used to achieve voltage conversion and insulation. High power density (= conversion capacity per mass unit) of the equipment enables total downsizing and weight reduction.
Power system measures	DC distribution systems have the ability to control fluctuations and peaks in power demand by flattening the duck curve phenomenon*1 and reducing fluctuations in high loads such as electric vehicle (EV) quick chargers.

4. DC Distribution System for Demonstrative Test

In order to clarify the technical and safety issues of the DC power distribution system for practical use, a demonstration system has been installed as part of the power distribution system at the training center (Fig. 2). The demonstrative test started in July 2019.

Our system has adopted two voltage classes: (1) 1500 V DC as the maximum voltage in the low-voltage DC (LVDC) category of the International Electrotechnical Commission (IEC) standards and (2) 600 V DC in compliance with the low-voltage DC category of domestic standards (Technical Standards for Electric Appliances and Materials); this aims to provide several voltage-class solutions suited to customer needs.

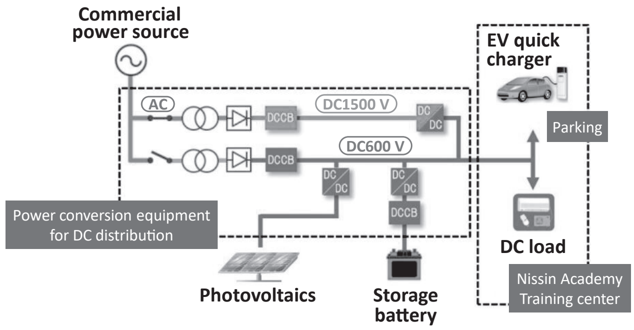

Fig. 2. DC distribution system for demonstrative test

<< Constituent Components >>

- ■ DC solid-state circuit breaker (DCCB)
- ■ Bi-directional isolated DC-DC converter
- ■ Photovoltaics panel (PV)
- ■ Storage battery (lithium-ion)
- ■ EV quick charger (DC input)

Assuming self-consumption of PV power by customers, the demonstration system uses diode rectifiers to connect to the commercial power system so as to simplify the control in comparison with bi-directional inverter interconnection and reduce equipment costs. Since reverse power flow does not occur in this system configuration, then considerations of constraints of the fault ride through (FRT) requirements*2 are not necessary. Consequently, it ensures great flexibility for equipment installation.

Moreover, a storage battery monitor is also installed. This newly developed tool diagnoses battery condition on time and real time without system interruption. Thus, a demonstrative test is concurrently conducted in order to assist in high-efficiency, long-life operation.

The following sections describe the principal components and control functions.

4-1 DC solid-state circuit breaker (DCCB)(2)

A DC distribution system requires the DC circuit breaker to interrupt fault currents immediately coming with no zero current point. One major challenge identified in handling a direct current is failure or degradation caused by DC arc current at electrodes inside the circuit breaker, which comes into be action when a short-circuit or ground fault occurs.

For the demonstration system, we developed the DC solid-state circuit breaker (DCCB) capable of interrupting fault currents immediately at the leading edge. The problem of surge voltage occurring between terminals when interrupting the current was solved using an active clamper.*3

(1) Specifications

Table 2 shows the specifications of DCCBs for 750 V DC and 1500 V DC circuits. Photo 1 and Fig. 3 show the appearance of a DCCB and its internal circuit diagram.

Table 2. Specifications of DCCB

Parameter	Specification	
Rated voltage	750 V DC	1500 V DC
Rated current	135 A	
Rated breaking capacity	2 kA	
Breaking time	Within 2 ms	
Breaking direction	Unidirectional (bi-directional for current passage)	
Number of poles	2	

Photo 1. DCCB for 750 V circuits

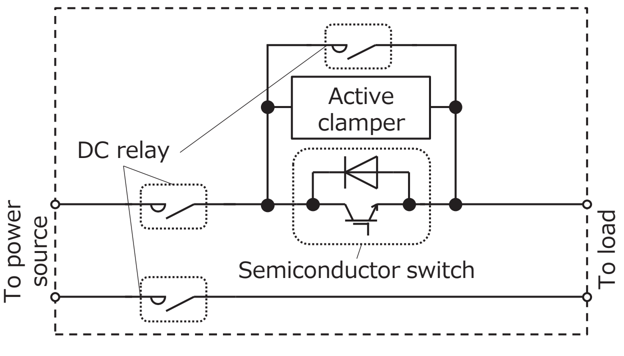

Fig. 3. DCCB circuit configuration diagram

(2) Protective function

(a) Controlling breaking time by microcontroller

To prevent the semiconductor device from being heated by transient currents, DCCBs have achieved both fault current and overload protection, with the control appropriately changing the breaking time by overflow current.

(b) Surge energy absorption by active clamper

When rapidly interrupting a short-circuit current in an accident, a surge voltage occurs due to the counter electromotive force due to the wiring's inductance component. As a counter measure, active clamp circuit is applied to the DCCB to control the overvoltage between the semiconductor switch terminals to an appropriate level.

4-2 Bi-directional isolated DC-DC converter[3]

A DC-DC converter, which is intended to step up/down DC voltages, is required to come with an isolation capability to prevent ground faults and other accidents from affecting the distribution system and its peripheral devices, along with a bi-directional power conversion capability.

A bi-directional isolated DC-DC converter (DAB) based on a dual active bridge topology with a compact size using fast-switching silicon carbide (SiC) devices, and a high-frequency transformer has been developed in the demonstration system. This converter achieved a power conversion efficiency of 96.0% at rated output and a maximum efficiency of 98.8%.

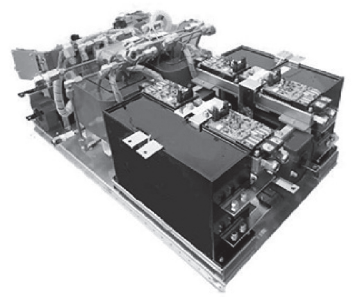

Photo 2. DAB converter

(1) Specifications

Table 3 shows the specifications of the newly developed DAB converter. A DC distribution system with a feeder load capacity of 500 kW, configured with three DAB converters in parallel, was designed with a specification of 167 kW per unit, the highest level in the industry.

In the DAB converter configuration, full-bridge AC-DC converters were placed on both right and left sides of a high-frequency transformer (Fig. 4).

For bi-directional power conversion, the voltage phase between the right and left bridges was adjusted in order to ensure smooth control. Moreover, the isolation function of the high-frequency transformer enables series/parallel connection of a DAB converter, therefore large-capacity conversion is available.

Table 3. Specifications of DAB converter

Parameter		Specification
Rated capacity		167 kW
Rated voltage	High-voltage side	1500 V DC
	Low-voltage side	600 V DC
Rated current	High-voltage side	111 A
	Low-voltage side	278 A
Circuit configuration		High-frequency isolated system (DAB)
Semiconductor module	High-voltage side	Full SiC-MOSFET 1200 V, 400 A (Series connection)
	Low-voltage side	Full SiC-MOSFET 1200 V, 800 A
Switching frequency		20 kHz
Cooling system		Liquid cooling
Volume		72 ℓ

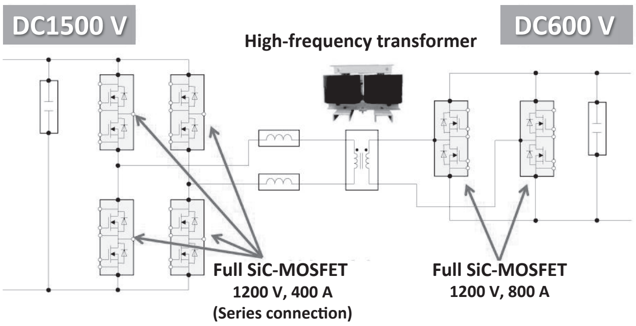

Fig. 4. DAB converter circuit configuration diagram

(2) Downsizing

Increasing the converter switching frequency using the DAB enables downsizing of wire-wound devices such as the transformer and reactor in the DC-DC converter. However, since losses in the semiconductor devices and wire-wound devices tend to increase, loss reduction and improvements in cooling performance emerge as major challenges.

(a) High-frequency switching by a SiC device
(b) Utilize a liquid-cooled system
(c) High-frequency transformer designed with small-size and large-capacity

Table 4 shows the specifications of the newly developed high-frequency transformer. The design dedicated for providing isolation against switching surge voltages and liquid cooling performance enabled downsizing of the device to a power density level of 12 kW/ℓ or higher.

4-3 Protection and control[4]

Overvoltage, overcurrent, and ground fault protections have been identified as important factors for ensuring safety of the DC distribution system. In order to allow transitioning to a standalone operation in the event of a voltage dip or power outage in the commercial power system, and to the peak demand shaving and so on, the integrated control is required to properly coordinate between renewable energy sources, storage batteries and DC loads.

In the demonstration system, each DAB converter for the storage battery and PV constantly monitors the voltage conditions of the DC feeder and autonomously determines the operation.

Table 4. Specifications of high-frequency transformer

Parameter		Specification
Rated capacity		167 kW
Isolation class		Class F
Transformation ratio		2.5 : 1
Voltage	High-voltage side	1500 V DC ±10%
	Low-voltage side	600 V DC ±10%
Frequency		20 kHz
Voltage waveform		Rectangular
Cooling system		Liquid cooling

5. Demonstrative Test

As an example of the demonstrative test, Fig. 5 shows the verification results of transition from peak demand shaving operation during EV quick charging to standalone operation triggered by a commercial power outage (simulated power outage).

Power was supplied from the commercial power source to the DC circuits at the beginning of the test. Subsequently, at T = 10 s, EV quick charge started.

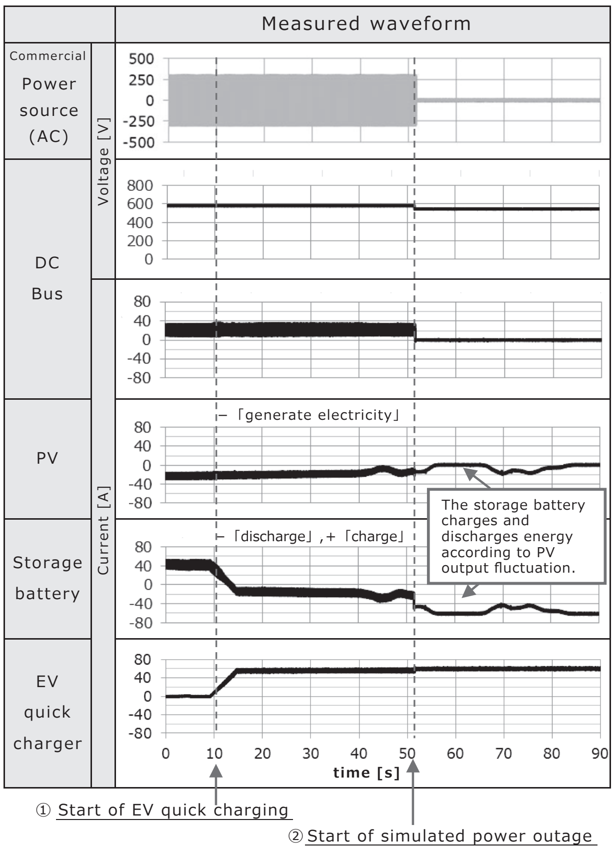

Fig. 5. Waveforms during transition from peak demand shaving operation to standalone operation

The waveform shows that when the current increased due to EV quick charging, a DAB converter for the storage battery detected current fluctuation at the connection point, and then started discharging to control power supplied from the commercial power source to a suitable level, while suitably responding to the PV output. Thus, the measurements have proved the storage battery's favorable operation for commercial power peak demand shaving during EV quick charging.

Moreover, at T = 52 s, the AC circuit breaker at the connection point to the commercial power source was opened to simulate a power outage.

When the power outage occurred, a DAB converter for the storage battery detected the DC voltage drop in the DC feeder, and smoothly transitioned to standalone operation mode. In addition, the storage battery suppressed PV output fluctuations by charging and discharging, and continuously supplied power to the DC load (EV quick charger). Incidentally, even in the event of a voltage drop in the commercial power side, no reverse current from the DC side to the commercial system side was observed. Thus, smooth transitioning to standalone operation has been identified as a feature of this system.

6. Future Deployment

6-1 EV quick charging station

With the increase in the number of EVs, more EV quick chargers need to be installed in service stations or shopping malls. DC networks comprising PVs and storage batteries can control power consumption peaks due to EV quick chargers. Thus, CO_2 emissions can be reduced, while optimizing the overall system capacity (Fig. 6).

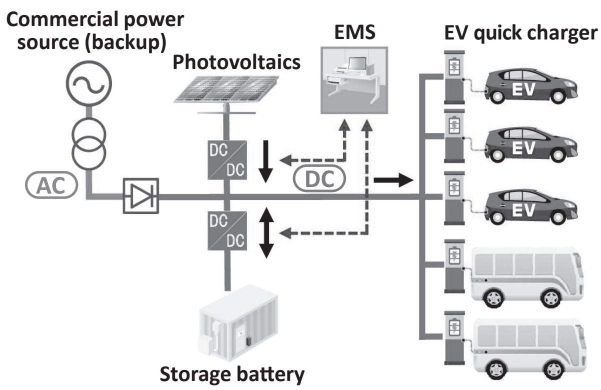

Fig. 6. EV quick charging station

6-2 Services for BCP

DC distribution systems operating as a backup capability alongside the existing commercial power systems enables the provision of services for BCP in the event of a commercial power system blackout. Moreover, DC interconnection between multiple community grids will allow a wider implementation of BCP measures. Figure 7 shows a power interchange system, using renewable energy sources and local generators, which is able to continue power supply in the event of disaster such as a power outage (resilience) for communities.

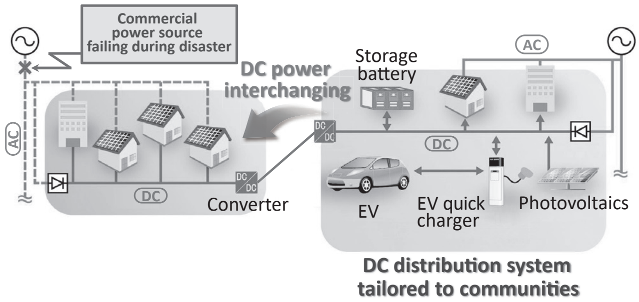

Fig. 7. Intercommunity DC power interchange system

7. Conclusion

This paper presented the DC distribution system of the 600 V DC and 1500 V DC. Today, there are few cases of such demonstrative tests conducted in the world. We intend to construct these systems with overseas deployment in mind and take on challenges of providing optimal solutions to increasingly diverse customer needs.

• DCCB is a trademark or registered trademark of Nissin Electric Co., Ltd.

Technical Terms

*1 Duck curve phenomenon: The phenomenon observed with a power system, in which electricity demand decreases during morning to daytime hours, followed by sharp increases during late afternoon to sunset hours, as a result, among others, of the heavy proliferation of photovoltaics.

*2 Fault ride through (FRT) requirements: Requirements regarding the operation continuation performance of decentralized power sources against system disturbances. This is necessary to ensure the quality of electricity.

*3 Active clamper: A circuit capable of automatically absorbing energy upon the application of surge voltages so as to avoid voltage amplitudes exceeding a certain suitable level.

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Contributors

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

K. KURODA*
• Chief Senior Staff, Nissin Electric Co., Ltd.

M. OGURA
• Chief Research Engineer, Nissin Electric Co., Ltd.

H. MAEJI
• Nissin Electric Co., Ltd.

M. OE
• Nissin Electric Co., Ltd.

G. TOYODA
• Nissin Electric Co., Ltd.

N. KURIO
• Chief Senior Staff, Nissin Electric Co., Ltd.