Abstract—Microgrid is one of the new conceptual power systems for smooth installation of many distributed generations (DGs). While most of the microgrids adopt ac distribution as well as conventional power systems, dc microgrids are proposed and researched for the good connection with dc output type sources such as photovoltaic (PV) system, fuel cell, and secondary battery. Moreover, if loads in the system are supplied with dc power, the conversion losses from sources to loads are reduced compared with ac microgrid. As one of the dc microgrids, we propose “low-voltage bipolar-type dc microgrid,” which can supply super high quality power with three-wire dc distribution line. In this paper, one system for a residential complex is presented as an instance of the dc microgrid. In this system, each house has a cogeneration system (CGS) such as gas engine and fuel cell. The output electric power is shared among the houses, and the total power can be controlled by changing the running number of CGSs. Super capacitors are chosen as main energy storage. To confirm the fundamental characteristics and system operations, we experimented with a laboratory scale system. The results showed that the proposed system could supply high-quality power under several conditions.

Index Terms—DC microgrid, distributed generation (DG), high-quality power, intentional islanding, three-wire dc distribution.

I. INTRODUCTION

Energy and environmental problems are remarkably concerned in recent years, such as greenhouse gas, growth of energy demand, and depletion of energy resources. Against the background of these problems, a large number of distributed generations (DGs) are being installed into power systems. It is well known that if many DGs are installed into a utility grid, they can cause problems such as voltage rise and protection problem. To solve these problems, new conceptual electric power systems were proposed. As one of the concepts, microgrids are especially researched all over the world [1]–[10]. For example, in Japan, microgrid projects are promoted by several private companies and The New Energy and Industrial Technology Development Organization (NEDO). Four popular NEDO’s projects (Aichi Expo, Kyotango, Hachinohe, and Sendai) were undertaken from FY2003 to FY2007 (Sendai: FY2004–FY2007), and the details are reported in [9] and [10]. NEDO also promoted other microgrid projects in Asian countries to research under several conditions.

Including those projects, most microgrids adopt ac distribution as well as conventional power systems. In this case, dc output type sources, such as photovoltaic (PV) system, fuel cell, and energy storages (e.g., Li-ion secondary battery and super capacitor) need inverters. In addition, some gas engine cogenerations (GECs) and wind turbines also need inverters because the output voltages and the frequencies are different from those of the utility grids. Therefore, dc distribution-type microgrids (dc microgrids) were also proposed and researched in order to reduce conversion losses from the sources to loads [11]–[15].

The advantages of dc microgrids are summarized as follows.

1) The system efficiency becomes higher because of the reduction of conversion losses of inverters between dc output sources and loads [15].

2) There is no need to consider about synchronization with the utility grid and reactive power.

3) When a blackout or voltage sag occurs in the utility grid, it does not affect the dc bus voltage of dc microgrid directly due to the stored energy of the dc capacitor and the voltage control of ac/dc converter. Therefore, DGs in dc system are not easy to trip against these disturbances. In other words, dc microgrid already has fault-ride-through capability of its own.

On the other hand, there are some drawbacks to put dc microgrid to practical use as follows.

1) It is needed to construct private dc distribution lines for dc microgrid.

2) The protection in dc system is more difficult than that of the ac system because there is no zero cross point of voltage in dc system.

3) The loads adapted for dc power supply are required for high system efficiency.

As an instance of dc microgrids, the system described in [14] adopted dc 380 V as dc bus voltage. The system has PV systems (2 × 10 kW), wind generator systems (10 kW ± 2 kW), and storage battery (97 kW), but there are no controllable DGs such as gas engine or fuel cell. The system is normally operated in islanding mode. When the storage energy becomes low, the system is supplied power from the utility grid, and charges the battery. It is also unique that the system can be changed into ac microgrid by the switches in order to compare dc system with ac system.

On the other hand, high-quality power is essential for some customers such as banks, hospitals, and semiconductor factories because the downtime related to voltage sag or blackout becomes a great concern. Besides, high-quality power is also requested in our dependable society. Security of electric power is becoming more important in our daily life.
To satisfy high efficiency and high-quality power supply, we proposed “low-voltage bipolar-type dc microgrid” [16]. In this system, dc power is distributed through three-wire lines, and it is converted to required ac or dc voltages by load-side converters. When blackout or voltage sag occurs in the utility grid, the dc microgrid can supply high-quality power stably, while inverters of DGs in ac microgrids should be tripped unless they have fault-ride-through capability.

In this paper, a dc microgrid for a residential complex is presented based on the dc microgrid concept [17]. Each house has a cogeneration system (CGS) such as gas engine or fuel cell. The electric power from CGSs is shared among the houses with dc distribution line, and the total power can be controlled by changing the number of the running CGSs. As main energy storage, super capacitors can be chosen in spite of its low energy density. To confirm the fundamental characteristics and system operation, we did some experiments with a laboratory scale system. The results show that the proposed system could supply high-quality power under several situations. Additionally, smooth disconnection and reconnection with the utility grid were also demonstrated.

The composition of this paper is as follows. Section II describes the configuration and features of low-voltage bipolar-type dc microgrid. Section III shows a concrete configuration of the dc microgrid for a residential complex, and explains the characteristics and operation methods. Section IV explains the circuit and parameters of the experimental system. Section V shows the experimental results that demonstrated the high-quality power supply of our proposed system. Finally, we summarize the outcomes in Section VI.

II. LOW-VOLTAGE BIPOLAR-TYPE DC MICROGRID

Fig. 1 shows a concept of the low-voltage bipolar-type dc microgrid. The utility grid voltage 6.6 kV is converted into dc 340 V by a transformer and a rectifier. It is the characteristic of the system to adopt three-wire dc distribution that consists of +170 V line, neutral line, and −170 V line. The three-wire composition contributes that the voltage to ground becomes low, and one of the single-phase 100-V output lines becomes a grounded neutral line as well as Japanese standard. In addition, load-side dc/dc converters can choose the source voltage from 340 V, +170 V, or −170 V. Moreover, if one wire snaps out, it is possible that the power is supplied by the other two lines and an auxiliary converter.

When there are dc/dc converters for loads, and the source voltages of them are either +170 V or −170 V, dc voltage balance control is essential [18]. Hence, a voltage balancer is placed near a rectifier to balance positive and negative voltages. It is also possible the voltage balancer is placed near load side.

As energy storages, a secondary battery and a super capacitor [electric double-layer capacitor, (EDLC)] are connected to dc distribution line. A PV system and a GEC are also connected through dc/dc converter and ac/dc converter, respectively. At the load side, dc power is converted into required ac or dc voltages by each converter. Characteristics of the system are summarized as follows.
1) Three-wire bipolar dc distribution contributes to lower the distribution voltage to ground. In addition, it allows dc/dc converters in load side choose source voltage from 340 V, +170 V, or −170 V.

2) The distribution of the load-side converters contributes to provide a super high quality power supplying. For instance, even if a short circuit occurs at one load side, it does not affect other loads.

3) Various forms of electric power like single-phase 100 V, three-phase 200 V, dc 48 V can be obtained. These converters are transformerless, therefore, it contributes to the downsizing and high efficiency.

4) DC distribution system is suitable for dc output type DGs and energy storages. If dc power can be supplied to loads directly or through dc/dc converters, the system efficiency becomes high.

5) When an accident occurs in a utility grid, this system can be disconnected from the utility grid seamlessly and supply electric power continuously. The reconnection to the utility grid is also smooth.

6) When a temporary overload occurs at a single-phase load, electric power can be shared between load-side converters by using additional electric power lines.

It is also possible to form dc loop configuration at dc distribution part [19] and share power between other dc microgrid systems.

III. DC MICROGRID FOR RESIDENTIAL COMPLEX

A. System Configuration

As a concrete system, we propose a dc microgrid for a residential complex shown in Fig. 2. There are around 50–100 houses in the system, and each house has a CGS (gas engine or a fuel cell). The CGSs are connected to dc distribution line (three-wire, ±170 V), and the electric power is shared among houses. From this configuration, it is expected that the total CGSs operation period increases and it leads to effective utilization of primary energy [20]. In order to keep high efficiency, these CGSs should not be operated by a partial load condition, but operated by a start/stop control. Cogenerated hot water is used in each house or shared with next houses. This system connects to the utility grid by a rectifier. At load side, various forms of electric power (ac 100 V, dc 48 V, etc) can be obtained by the converters. Despite of low energy density, EDLCs are used as main energy storage because of the fast response, the safeness (especially compared with Li-ion battery), the easy measurement of the stored energy, and no toxicity of the inner materials.

B. System Operation

The total generated power is controlled by changing the number of running CGSs. When the system connects to the utility grid, the deficient power is compensated from the utility grid, as shown in Fig. 3. We call this state interconnected operation. In this operation, the supervisor computer changes the number of the running CGSs so that the generated power from CGSs does not flow to the utility grid in the interconnected operation.

When the system disconnects from the utility grid, the surplus or deficient power is compensated by the EDLC, as shown in Fig. 4. We call this state as intentional islanding operation. In this operation, the converter of the EDLC controls the dc distribution voltage, and the number of the running CGSs is determined by not only the load consumption, but also the stored energy of EDLCs. When the stored energy becomes over a maximum limit, the system stops one of the operating CGSs. Then, the total output of CGSs becomes less than the load consumption, and the EDLC discharges until the stored energy becomes less than the minimum limit. On the contrary, when the stored energy becomes under the minimum limit, the system starts a CGSs. Then, the total output of CGSs becomes more than the load consumption, and the EDLC charges until the stored energy becomes more than the maximum limit. These two modes are repeated alternately in the intentional islanding operation.

This system should choose the CGSs that can start up for a few minutes, so that energy storage does not need a large capacity. Therefore, EDLC can be used as main energy storage in this system. The output capacity of EDLC and its converter are...
designed to compensate the assumed maximum load variation. However, if larger load variation occurs in the system, the output of EDLC could reach the maximum charge or discharge level. If the charge is limited, the supervisor computer stops the required number of CGSs. If the discharge is limited, the supervisor computer stops power supplying to specific loads that do not need high-quality power, and runs CGSs to make the output of EDLC become within the limits.

C. Voltage Clamp Control

When the system is in the interconnected operation, the EDLC does not charge or discharge unless the dc distribution voltage exceeds a limited range. We propose a voltage clamp control by the EDLC. When the dc distribution voltage increases over the upper limit (360 V), the dc/dc converter of the EDLC is operated to clamp the dc voltage at the level. This clamp control contributes to prevent overvoltage of the devices connected to the dc line. The converter of the EDLC is also operated to clamp the at the lower limit (320 V) when the dc voltage decreases to the lower limit, e.g., the current from the utility grid is limited by the capacity of the rectifier. In addition, this clamp control assists the disconnection and reconnection process, as described in the following section.

D. Disconnection and Reconnection With Utility Grid

We propose disconnection and reconnection procedures with the voltage clamp control. Fig. 5(a) shows the flowchart of the disconnection procedure. When a problem of the utility grid is detected, the system stops the grid interface rectifier. Then, the dc distribution voltage decreases, and the converter of the EDLC clamps the voltage at the lower limit (320 V). After this, the converter of the EDLC changes its operation from clamp control to voltage control, and the voltage reference is gradually changed from the lower clamping limit to the nominal dc distribution voltage (340 V).

Without the clamp control, the voltage control has to be immediately moved from the rectifier to the converter of the EDLC. However, there should be some delay in the communication network. Therefore, this clamp control plays an important role to complete the disconnection certainly.

Fig. 5(b) shows the flowchart of the reconnection procedure, which is opposite to the disconnection process. After the utility grid is recovered, the controller of the rectifier detects the phase of the utility grid by phased-lock loop (PLL). Then, the system changes the operation of EDLC from voltage control to clamp control, and dc distribution voltage decreases to the lower limit (320 V). After this, the system starts the rectifier, and the voltage reference is changed gradually from the lower clamping limit to the nominal voltage.

In the experiment described later, it is judged by the voltage drop level and the period whether the problem occurs in the system or not. If the voltage decreases less than 30%, the system judges there is a problem in the utility grid. If the voltage drop is between 30% and 80%, and the period is more than 1 s, the system also judges that the utility grid has a problem. In this case, this system does not disconnect from the utility grid if voltage sag occurs, because the period of the most voltage sag is usually within 0.5 s.
E. Evaluation of System Stability

It is well known that negative incremental impedance of converters can cause stability problems in dc power supply system [21]–[23], because these converters are operated like constant power load. Fig. 6 shows a $V$–$I$ curve of constant power load. The negative incremental impedance $r'$ can cause a voltage oscillation on the distribution line. Fig. 7 shows a simplified dc distribution circuit. In case that the source voltage is instantaneously changed, the current and voltage dynamics can be represented by the following equations

$$
\Delta v = r' \Delta i
$$

(1)

$$
\Delta V_s = R \Delta i_L + L \frac{d\Delta i_L}{dt} + \Delta v
$$

(2)

$$
\Delta i_L = C \frac{d\Delta v}{dt} + \Delta i
$$

(3)

where $\Delta V_s$, $\Delta i_L$, and $\Delta v$ are the instantaneous variations of source voltage, inductor current, and load voltage, respectively.
Using (1)–(3), we obtain the following state equation

\[
\frac{d}{dt} \begin{bmatrix} \Delta v \\ \Delta i \end{bmatrix} = \begin{bmatrix} \frac{P}{C} & -\frac{1}{L} \\ -\frac{1}{C} & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} \Delta v \\ \Delta i \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \Delta V_s. \tag{4}
\]

From (4), the stability condition can be calculated by Hurwitz criterion. For example, when the parameters are set to be \( L = 0.1 \) (mH) and \( C = 10 \) (mF), and \( V_s = 340 (= 170 + 170) \) (V), the stability condition can be drawn, as shown in Fig. 8. The stable condition is in the shaded area. There are two unstable areas. The upper one is an area, where the power cannot be supplied to the load because of the voltage drop of resistance \( R \). The lower one is an area, where the resonance is caused by inductance \( L \) and a smoothing capacitor \( C \). The oscillation in an upper unstable area does not happen in a practical system because proper sectional size conductor will be selected based on the system capacity. On the other hand, there is a possibility that the oscillation in a lower unstable region happens when the resistance \( R \) or the capacitance \( C \) is small, or the inductance \( L \) is large. Therefore, the stability of proposed dc microgrid was examined by the computer simulation (MATLAB/Simulink).

Fig. 9 shows the target model. It is an apartment of ten floors with two houses per one floor. The rectifier is controlled to keep the distribution voltage constant (dc 340 V). Fig. 10 shows the simulation circuit. The main parameters are shown in Table I. The line resistances and line inductances are calculated based on the impedance of unit length (1 km) of the CV cable. Each house that includes inverter and CGS was assumed to be a constant power load. Fig. 11 shows the circuit and control block of the rectifier. The rectifier was represented by a current source and a smoothing capacitor. The current minor loop of the control block was simulated as a first-order delay. The time constant \( T_{im} \) was set to be 2 ms.

From the simulation results, voltage oscillation did not occur even when the line resistances were set to be smaller than 1/200 of the original value shown in Table I. From the economical point of view, it is not practical the line resistances are so small. In addition, it was confirmed that the oscillation did not occur under considerable situations such, as the looped distribution line, power sharing among houses \((P \) was set to be less than 0 at some houses\), etc.

### IV. Experimental System

To examine the fundamental characteristics and the proposed system operations, we constructed a laboratory scale experimental system. The circuit and main parameters are shown in Fig. 12 and Table II. It is assumed that there are three households, and each house has a GEC. Fig. 13 shows the system appearance, and Fig. 14 shows a GEC used in house 1. We use a commercial GEC with the rated capacity of 1 kW. Fig. 15 shows the inside configuration of the GEC. The generator outputs AC 340 V, 307.5 Hz, and the ac power is converted into dc 390–400 V by...
a thyristor-diode rectifier. Normally, the dc power is converted to single-phase AC 200 V and flown to the utility grid, but we modified to take the dc power directly. In the other two houses, we substitute dc power supply for the real GEC, which output dc 400 V constantly.

Buck choppers are connected between GECs and dc distribution lines because the voltage of the gas engine (400 V) is different from the distribution voltage (340 V). We designed the circuit to be symmetry against the neutral line, because this converter is supposed to be worked as a voltage balancer under an appropriate control. For switching devices of this converter, we adopted super junction MOSFETs (SPW16N50C3, Infineon) with due regard to the converter efficiency. The output power is changed gradually from 0 to 1 kW or from 1 to 0 kW for 1 s.

In house 1, dc power is converted into single-phase 100 V by a half-bridge inverter, and voltage feedback control with a current minor loop is adopted. In houses 2 and 3, dc power is supplied to each electronic load directly, which substituted for an inverter and loads.

The rectifier connected to the utility grid is controlled to keep the dc voltage constant (340 V) in the interconnected operation. The circuit is a conventional two-level voltage source converter, and current control based on $d-q$ decoupling control is adopted. The current reference is calculated from the dc voltage reference and the feedback value. The control time constant of the voltage control was set to be 15 ms. To balance positive voltage (+170 V) and negative voltage (−170 V), a voltage balancer is connected at the dc side of the rectifier, as shown in Fig. 6.

As energy storage, EDLC is connected through dc/dc converter. The rated voltage is 160 V, and the capacitance of one EDLC is 4.5 F. Four EDLCs are connected directly in parallel without any additional circuits, so the total capacitance is 18 F.

We use two digital controllers (PE-Expert2, Myway Plus) for this system. The sampling frequency is 10 kHz. One of the controllers is for rectifier, dc voltage balancer, single-phase inverter, and converter of EDLC. Another controller is for three dc/dc converters for GEC. Those controllers can communicate each other.

It is assumed that the distance between the rectifier and two houses is 100 m, and single conductor cable (5.5 mm$^2$) is used.

### Table II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{b1}$</td>
<td>9400 μF</td>
</tr>
<tr>
<td>$C_{b2}$</td>
<td>220 μF</td>
</tr>
<tr>
<td>$L_{1b}$</td>
<td>4 mH</td>
</tr>
<tr>
<td>$R_{b1}$</td>
<td>0.5 Ω</td>
</tr>
<tr>
<td>$L_{4b}$</td>
<td>30 μH</td>
</tr>
<tr>
<td>$L_{5b}$</td>
<td>30 μH</td>
</tr>
<tr>
<td>$L_{6b}$</td>
<td>5 mH</td>
</tr>
</tbody>
</table>

**Digital Controller**

- PE-Expert2 (Myway Plus)
- MWINV-4R222 (Myway Plus)
- MWINV-9R122A (Myway Plus)
- G8081-50C-1 (Meidensha)
Fig. 16. Experimental results of voltage sag (50%, 0.5 s).

V. EXPERIMENTAL RESULTS

Various experiments were carried out with the experiment system such as load variation, GEC operation, short circuit at a load, and etc [6]. In this paper, we show three kinds of experimental results: voltage sag of the utility grid; disconnection procedure; and reconnection procedure. Table III shows the loads and GECs conditions in each experiment.

A. Voltage Sag of the Utility Grid

The experimental results of the voltage sag in the utility grid are shown in Fig. 16. The voltage sag was simulated by a multipurpose power supply, and the voltage sag was programmed to decrease 50% for 0.5 s. When the voltage sag occurred, the dc voltage was controlled constant by the rectifier, and the current on the ac side of the rectifier increased to keep the power from the utility grid. As a result, it was confirmed that the dc voltage fluctuation was almost negligible, and the power supplied to all loads stably. There were the voltage drops by the line resistances, but the line resistances and inductances did not affect the system operation.

B. Disconnection From the Utility Grid

Fig. 17 shows the experimental results of the disconnection procedure. At the initial condition, the system was in the interconnected operation. When the system detected that the voltage of the utility grid was lower than the 30% of the nominal voltage, the rectifier was stopped. Then, the dc distribution voltage decreased, and the converter of EDLC clamped it at the lower limit (320 V). After this, the converter control was changed from the clamp control to the dc voltage control. Finally, the voltage increased to 340 V gradually for 1 s, and the system was in the intentional islanding operation. In this period, the rms value of the single-phase inverter voltage, which was shown as “house 1 inverter output voltage (rms),” was not affected, and the smooth disconnection was confirmed from the results. It was also confirmed the line resistances and inductances did not affect the disconnection process.

C. Reconnection With the Utility Grid

Fig. 18 shows the experimental results of the reconnection procedure. When the system detected the utility grid was recovered from a problem, the controller of the rectifier detects the
phase of the utility grid by PLL. Then, the control of EDLC’s
converter was changed from the dc voltage control to the clamp
control. Then, the dc voltage decreased to the lower clamp limit,
and the rectifier started and controlled the dc voltage. Finally,
the voltage gradually increased to 340 V for 1 s, and the system
was in the interconnected operation. In this period, the rms value
of the single-phase inverter voltage was not affected as well, and
the smooth reconnection was also confirmed. In addition, it was
also confirmed that there are no affects by the line resistances
and inductances.

In this paper, we show the disconnection and reconnection
results under the condition that all GEC were turned off so
that all power was supplied from the utility grid. Surely, we
confirmed in the case that some GEC were tuned on, and those
results also showed the smooth disconnection and reconnection.

VI. CONCLUSION

For smooth introduction of a number of DGs, we proposed
“low-voltage bipolar-type dc microgrid” to satisfy high effi-
ciency and high-quality power supply. We presented a system
for residential complex, where each house has a CGS such as
a gas engine, and the power is shared among the houses by
dc distribution. To confirm the fundamental characteristics and
the proposed operations, a laboratory scale experimental system
was constructed. Several kinds of experiments were carried out
such as a sudden load variation, short circuit at a load, inter-
connected operation, intentional islanding operation, supplying
commercial home appliances, etc. As a part of the results, we
showed the results of voltage sag in the utility grid, disconnec-
tion procedure, and reconnection procedure in this paper. These
results demonstrated that the system could supply high-quality
power to loads in those conditions. The mathematical analysis
of the system stability during proposed disconnection or recon-
nection process is a next study.

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