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Premium power quality with DG integrated DC systems

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***Abstract*— The necessity to ensure premium power quality to the sensitive customers and development of distributed generators (DG), have determined the consideration of realizing a low voltage dc distribution system. This low voltage dc distribution system will represent a premium power network that combines the advantages of the equipments used for improving the voltage quality and supply continuity, and uses sustainable power generating units. The paper deals with the energy management and dynamic analysis of the dc system with interconnect distributed generators and storage devices, focusing on guaranteeing high voltage quality levels in case of ac mains disturbances.**

***Index Terms*—premium power quality, dc distribution system, distributed generation**

I. Introduction

THE integration of the distributed generation units within the existing power system affects its traditional principles of operation, the utilization of DG presenting advantages and disadvantages. The existing trend of installing more and more DG units implies the establishment as accurate as possible of the DG impact on power system operation and on the power quality. The question if the present distribution networks are still the most adequate to satisfy the nowadays demands is made. Most of the small power distributed energy resources and storage energy systems located close to the point of consumption of the customer are generating dc power or require a dc intermediate stage. Hence many of these sources can be connected to a dc distribution system [1].

Sensitive equipments that require a high degree of power continuity are installing back-up power, like uninterruptible power supply (UPS), or equipments for the improvement of the voltage quality, like dynamic voltage restorers and active filters. These equipments are anyhow characterized by the presence of a dc stage.

These considerations brought to the possibility to use dc distribution networks, in the presence of sensitive loads and distributed generation [2, 3]. Currently, there are installations using dc power for their operation [4-7]. The low voltage dc system ensures a stable voltage level for the supplied customers, connected at the dc bus through ac/dc or dc/dc converters. The choice of the most suitable equipments, which respond to the requirements of an optimum operation of the entire system, is necessary. For guaranteeing the correct and robust operation of the system is essential to adopt adequate control logic for obtaining the best system performances.

In the present paper the study of the dc system, which guarantees high voltage quality even in the presence of disturbances, is conducted. The proposed energy management system ensures fast intervention and automatic exclusion of the energy sources, and the improvement of the dynamic interconnection between devices and dc network. As one of the main purposes of the dc distribution system is to ensure premium power quality to the loads connected to the dc bus, transitions between the various sources are conducted and analyzed.

II. DG Integrated DC System

The design process of the low voltage dc distribution system requires the selection of the most suitable combination of energy sources, power-conditioning devices, and energy-storage systems for answering the necessities and requirements of the dc low voltage dc distribution system, together with the implementation of an efficient energy dispatch strategy.

In Fig. 1 the layout of the dc distribution network with distributed generators, storage energy systems and sensitive loads, is illustrated.

A. AC/DC interface

The interface between the ac power supply and the low voltage dc distribution system is realized by two voltage source converters (VSC), for improving the reliability of the entire power system. The two voltage source converters, equipped with IGBTs, allow the regulation of the dc network voltage and its maintenance to the desired value. Because of the gate-commutating action of these devices, much higher switching frequencies can be achieved, enabling the possibility for much cleaner output power. The voltage source converter is a PWM current-controlled one, forcing the instantaneous phase current to follow a sinusoidal current reference template, in phase with the input voltage [8].

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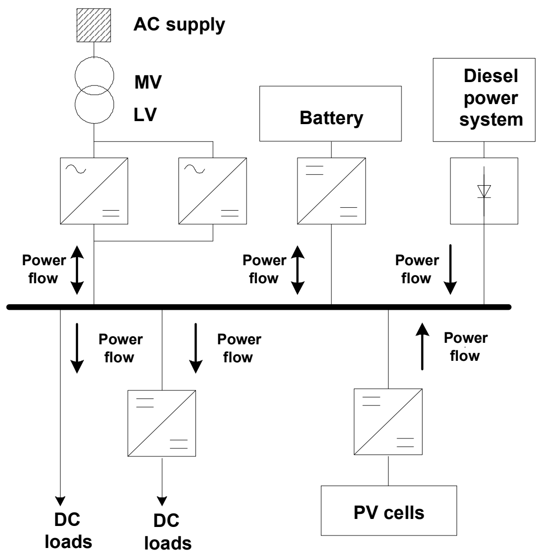

Fig. 1. Layout of the DG integrated dc distribution system

B. DC network devices

1) Battery system

To guarantee the supply continuity of the customers during short-duration interruptions, a storage power system is interconnected to the low voltage dc distribution system with the help of a bidirectional chopper. Storage is requested to satisfy the power balance in case of increase of the load demand without neglecting the quality of other network measures. The bidirectional chopper allows the recharge of the storage system, if it is necessary, when the power is flowing from the ac network to the dc system or when in the dc network an excess energy is available. During the discharge process of the battery, the control system maintains and stabilizes the dc voltage during islanding operation of the dc network.

2) Diesel power system

The Diesel power system is designated to supply the dc system loads during sustained interruptions in the ac network. The diode bridge, of high reliability, has to prevent the power flow through the Diesel power system during the islanding operation of the dc system. In this case, the Diesel power system regulates the voltage of the dc distribution system. The load demand is achieved regulating the output of the Diesel engine.

3) PV system

One of the main purposes of the dc distribution system is to allow a more easily integration of the distributed generators. The distributed generators contribution is to allow the injection in the ac network of the power excess, during light load, and to supply, in parallel with the Diesel power system, the dc distribution system during islanding operation.

4) Loads

The dc loads interconnected to the dc distribution system can be directly supplied, if the loads operation permits, or using a buck converter, when the loads operating voltage is lower than the dc voltage level.

III. Control Strategy

Different reference values of the dc voltages are assigned to the various power electronic converters present in the dc system in conformity with the functioning requirements of the dc grid. At each instant of time, one power system component is predominant with respect to the other devices. In this case, the device is behaving as a voltage source and regulates the dc voltage to the value imposed by the equipment threshold voltage.

The rigorously established voltage thresholds are illustrated in Fig. 2. In Fig. 2 the voltage threshold V_{CONV} is maintained by the interface converter. For variations of the load demand, the control loop of the converter has to maintain the dc voltage at the threshold V_{CONV}. In case of ac faults or outage of both VSC converters, the dc voltage falls below V_{BS} determining the battery intervention. The storage system becomes predominant and regulates the dc voltage, stabilizing it to the value V_{BS}, only if the storage system is fully or partially charged.

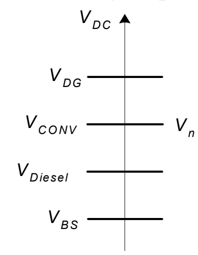

Fig. 2. Voltage thresholds assigned to the power system components.

The Diesel power system is started only during islanding operation of the dc network, in case of sustained interruptions in the ac grid, for covering the load demand. The Diesel power system is turned on after a certain time, regulating the dc voltage and maintaining it at the threshold V_{Diesel}. Because the threshold V_{Diesel} is superior to the value V_{BS}, the storage system is automatically turned off. The choice of a superior Diesel power system threshold is for avoiding the complete discharge of the storage system that shortens the battery's lifetime.

In case of power excess in the dc network, the threshold V_{DG} is reached and the distributed generators will limit their power generated.

IV. VSC Front End Converter

The three reference currents i_{ref} are obtained multiplying the three phase sinusoidal balanced voltages v_1, with a gain G representing the smoothed output of a proportional-integral (PI) controller used for obtaining null steady state error of the dc voltage [3]. These ac voltage components will be generated by applying a conventional algorithm based on abc-dq and dq-abc Park transformations to the measured mains voltages. Therefore the key relation of the control is

$$i_{ref} = G \cdot v_1 \tag{1}$$

A control strategy that generates three sinusoidal and balanced currents even under voltage distortion or unbalance will be adopted. A modulation technique, called Smart Modulation, with constant commutation frequency and high accuracy and dynamics is used [3].

V. CONTROL OF THE DC BUS

The dc voltage controller ensures that v_{DC} has an average value equal to the reference voltage. For sizing the VSC, the mains current vector $\bar{i}$, neglecting the high frequency ripple, may be approximated with $\bar{i}_{ref}$, and as well $\bar{v} = \bar{v}_1$. Provided that the zero-sequence current is nil and neglecting converter losses, based on the principle of power balance, we have

$$p(t) = \mathrm{Re}\left(\bar{i} \cdot \bar{v}_1^{\,*}\right) = v_{DC} \cdot i_{DC} \qquad (2)$$

where "*" denotes the conjugate of a complex quantity (see Fig. 3).

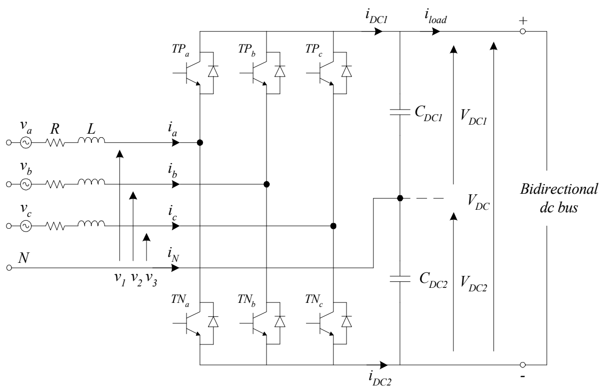

Fig. 3. Schematic diagram of the three phase voltage source converter

Based on (1) and (2), neglecting the ripple, the dc current can be obtained

$$i_{DC} = G \cdot \frac{v_1^2}{v_{DC}} \qquad (3)$$

A non-linear relation between the dc voltage v_{DC}, the control variable G and the current i_{load} is obtained

$$\frac{C}{2} \cdot \frac{dv_{DC}}{dt} = i_{load} - G \cdot \frac{v_1^2}{v_{DC}} \qquad (4)$$

The dc voltage controller is designed as a PI controller, and the control variable G has the following expression:

$$G = \left(k_P + \frac{k_I}{s}\right) \cdot F(s)\left(v_{DC}(s) - v_{DCref}(s)\right) \qquad (5)$$

where k_p and k_i are the PI regulator parameters, F(s) is the transfer function of the dc voltage low pass filter, and v_{DCref} is the reference value of the dc voltage.

Equations (4) and (5) describe the dc bus voltage dynamics. In order to design the PI regulator, (4) must be linearized. Indicating with Δ the increments of the linearized measure, and with capital letters the constant voltage amplitudes, by linearization the expression (4) becomes

$$\frac{C}{2} \cdot \frac{d\Delta v_{DC}}{dt} = -\frac{V_1^2}{V_{DC}} \cdot \Delta G + G \cdot \frac{V_1^2}{V_{DC}^2} \cdot \Delta v_{DC} + \Delta i_{load} \qquad (6)$$

Neglecting in a first approach the low pass filter delays, based on (5) and (6), it is obtained

$$\Delta v_{DC}(s) = \frac{s \cdot \Delta i_{load}}{s^2 \cdot \frac{C}{2} + s \cdot \left(k_P - \frac{G}{V_{DC}}\right) \cdot \frac{V_1^2}{V_{DC}} + k_I \cdot \frac{V_1^2}{V_{DC}}} \qquad (7)$$

In (7), the variable G may assume positive or negative values. Considering the rated power P_r delivered by the converter, based on (2) and (3) it results that $|G| \leq \left(P_r / V_1^2\right)$.

The denominator, considering a damping factor of 0.707, constrains the PI controller parameters to fulfill

$$k_P > \frac{G}{V_{DC}} \quad \text{and} \quad k_I = \left(k_P - \frac{G}{V_{DC}}\right)^2 \cdot \frac{V_1^2}{V_{DC}} \cdot \frac{1}{C} \qquad (8)$$

The sizing of the dc link capacitors is done basing on the dc voltage ripple minimization, on the hold-up time, and the expected power fluctuations on the dc side.

VI. DC NETWORK COMPONENTS

The energy sources, the dc loads and the power electronic devices interconnected to the dc bus are modeled within the ATP/EMTP software package. The control strategies are implemented using the Models subroutine [9].

A. Battery system

The control loop of the storage energy system is illustrated in Fig. 4. The current control loop is effectuated only if the voltage measured at the battery terminals is between the minimum V_{stmin} and the maximum V_{stmax} values, avoiding in this way the overcharge and the excessive discharge.

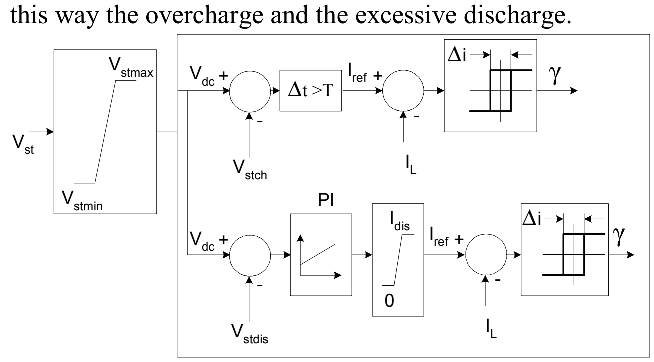

Fig. 4. Control loop of the storage energy system

B. Diesel power system

A second diode bridge is used only for measuring purposes of the voltage beyond the synchronous generator (see Fig. 5). During sustained interruptions in the ac network, the Diesel power system regulates the voltage of the dc distribution system by acting on the synchronous generator excitation system, while the load demand is achieved regulating the output of the Diesel engine.

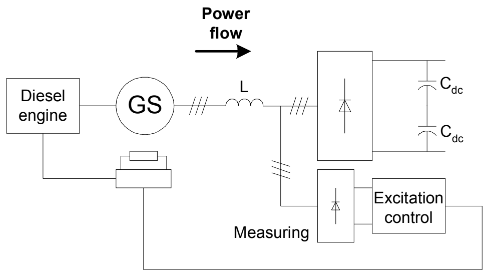

Fig. 5. Diagram of the Diesel power system

C. DC loads

The dc loads are interfaced through a buck converter. The current reference template is generated using a PI regulator. A hysteresis band modulation method is used to produce the PWM pattern for the power valves.

VII. CASE STUDIED

The rated power of the low voltage dc system is 800kW, with a dc voltage equal to 800V. The characteristic data of the current-controlled interface converter are reported in Table I. The dc system has been tested both for showing the correct operation of the VSC control, but also for highlighting the quick intervention and transition between the various energy sources interconnected to the dc bus.

TABLE I
INTERFACE CONVERTER CHARACTERISTIC DATA

P rated power	800kW
L_s VSC input inductance	0.061mH
f_{sw} switching frequency	5kHz
t time step	1μs
C_{dc} dc bus capacitance	0.2F

A. 50% load variation with DG power constant

Fig. 6 shows the behavior of the system in response to a 50% load reduction at time instant t = 0.4 s. The line currents flowing through the converter inductor are illustrated in Fig. 6(a). The proposed control is robust and has a fast response, as Fig. 6(a) shows. The dc-bus voltage behavior during a 50% load reduction is illustrated in Fig. 6(b). The dc-bus voltage is stabilized by the control logic at the reference value of 800 V.

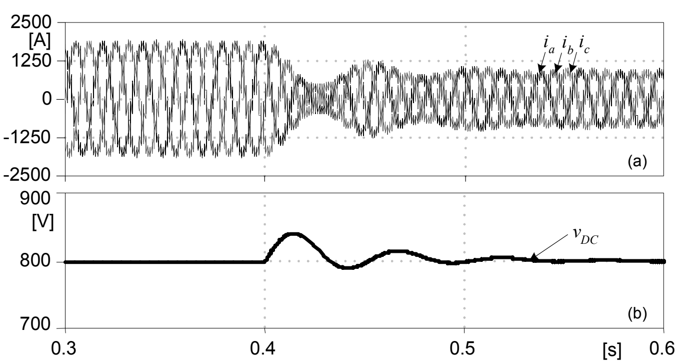

Fig. 6. DC system under 50% load variation; (a) line currents, and (b) dc-bus voltage.

B. Power flow inversion

Fig. 7 illustrates the response of the system subject to a sudden transition at time instant 0.5 s, when the power flow inversion occurs.

In Figs. 7(a) and 7(b), before the transition occurrence the line current and the ac voltage v_a are in phase, and the converter is functioning as rectifier. Subsequent the transition, the current and voltage are 180˚ phase shifted and the power is flowing from the dc network towards the mains supply. Fig. 7(c) illustrates that the dc-bus voltage, subsequent to a power flow inversion, is fast stabilized at its reference value.

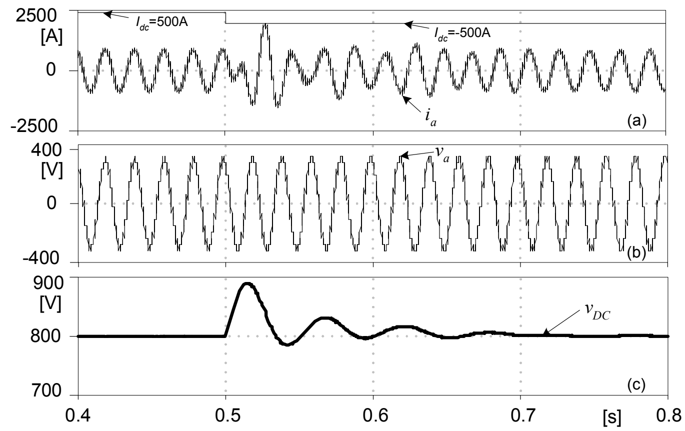

Fig. 7. DC system under power flow inversion; (a) line current and dc current, (b) ac grid voltage, and (c) dc-bus voltage.

C. Three phase ac side fault

A three phase fault occurs at time instant t=0.4 s and it lasts for 250 ms. The dc voltage, maintained before the fault by the interface converter at the nominal value 800 V, will decrease until it reaches the threshold value V_{BS} = 760 V of the storage energy system reference voltage (Fig. 8). This will determine the intervention of battery that comes in and supplies the load demand. In correspondence, the battery current will decrease until becomes zero, as in Fig. 9. After a first transient when the battery is injecting the maximum power for compensating the dc voltage drop, the control regulator of the battery system is stabilizing the dc bus voltage at the reference value V_{BS} and the current injected by the battery will reach the regime value.

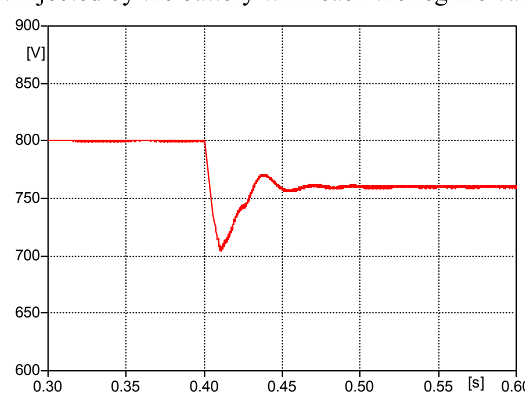

Fig. 8. DC voltage waveform during a three phase fault in the ac grid.

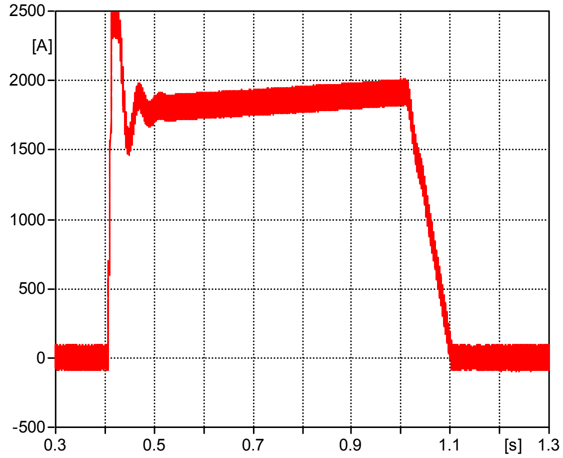

Fig. 9. Waveform of the current flowing through the inductor of the battery chopper.

D. *Mains supply loss*

The behavior of the dc system has been tested during a sustained interruption occurring at time instant 0.4 s in the mains supply. During the period of interruption of 0.6 s, the converter is blocked. The battery comes in and supplies the load demand. At instant t=0.5 s, the Diesel power system is started and the output voltage follows a ramp increase until it reaches the reference value of 770 V (green line in Fig. 10). The transition between the battery system and the Diesel generator is illustrated in Fig. 10.

After the interruption clearance and synchronization of the converter with the mains supply, the VSC is turned on and supplies the load. The current on phase *a* flowing through the VSC inductor, the ac grid voltage and the gain *G* of the dc voltage controller are illustrated in Fig. 11.

The dc voltage, maintained by the Diesel generator at the reference value assigned, is brought by the interface converter to the initial state, respectively 800 V, as depicted in Fig. 12.

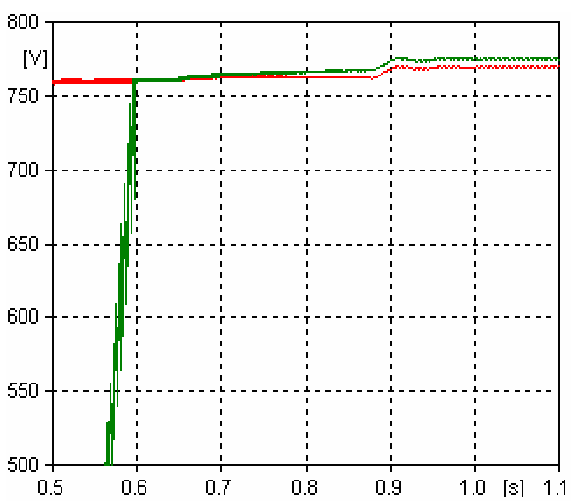

Fig. 10. Transition between battery and Diesel system.

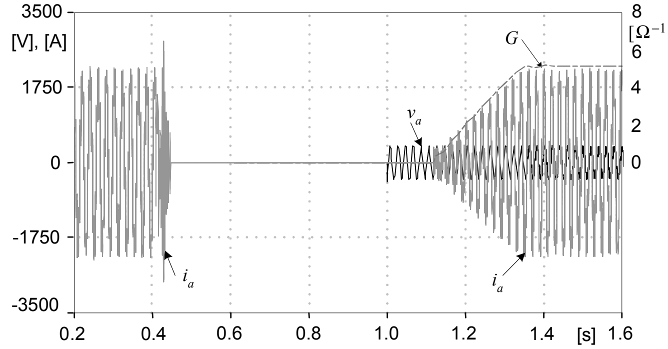

Fig. 11. DC system under mains supply loss.

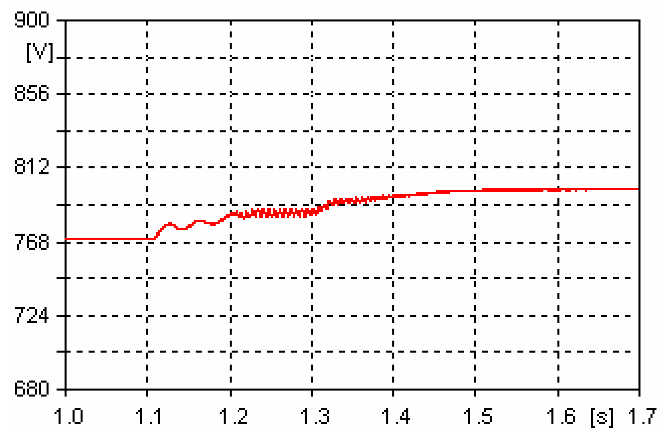

Fig. 12. DC voltage behavior during transition between Diesel group and ac/dc interface converters.

VIII. Conclusions

The paper deals with a low voltage dc distribution system that represents a solution for solving the problems related to ensuring an adequate power quality degree. The sensitive customers are interconnected with the dc grid and can be supplied by the ac main supply, by distributed energy sources or by the storing energy systems.

The design process of the low voltage dc distribution system requires the selection of the most suitable combination of energy sources, power-conditioning devices, and energy-storage systems for responding to the necessities and requirements of the dc low voltage dc distribution system, together with the implementation of an efficient energy dispatch strategy.

The study of the dc power system behavior in case of load variation, power flow inversion and ac faults is required, as the supply continuity of the dc bus loads and the system protection are fundamental.

In case of load variations or power flow inversion, the control operates correctly, is robust and no important transients of the dc voltage are occurring.

In case of a three phase fault the storage energy system supplies the load, without significant transients of the dc voltage. After the fault clearance, a smooth come in of the ac/dc interface converter and a sweet transition between battery and voltage source converter can be observed.

In case of sustained interruptions of the ac grid, the Diesel group comes in for supplying the loads and for avoiding the complete discharge of the battery system. This case study have been conducted to show that the transition between the battery and the Diesel group, but also between the Diesel group and the ac/dc interface converter does not lead to significant transients in the dc grid. The simulations conducted depict the correct operation of the control logic adopted for the dc power system. After the ac grid is restored, the interface converter comes in to supply the load and the Diesel group is excluded.

IX. References

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X. Biographies

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