

DC Distribution for Industrial Systems: Opportunities and Challenges

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Abstract—This paper investigates the opportunities and challenges associated with adopting a dc distribution scheme for industrial power systems. A prototype dc distribution system has been simulated to investigate the issues. One of the issues focused is the interaction between power converters that are used to convert ac to dc and dc to ac. Another challenging issue investigated is the system grounding. These issues become challenging mainly due to the neutral voltage shift associated with the power converters. The paper shows that converter interactions can be minimized with proper filtering and control on the converters. The paper also proposes a grounding scheme and shows that this scheme provides an effective solution by keeping the neutral voltages low under normal conditions and by limiting the fault currents during fault conditions. With these features, dc distribution provides very reliable and high-quality power.

Index Terms—DC systems, power electronics, transient analysis.

I. INTRODUCTION

TODAY'S many industrial plants demand highly reliable supply of power. The loads in these plants have also become very sensitive to power supply disturbances. Recently, dc distribution has been proposed to address some of these challenges [1]–[3]. These new dc systems utilize power electronic based converters to convert ac source(s) to dc and distribute the power using dc lines. The converters convert dc back to ac at the load, when it is needed. For the motor type loads driven by speed drives, this conversion even may not be needed, as the speed drives then can directly be interfaced with the dc. Thus, dc distribution becomes attractive for an industrial park with heavy motor controlled loads and/or sensitive electronic loads [2]. The power converters are the main components of these systems. Their fast response capability facilitates the transfer—or paralleling—of alternate power sources to provide highly reliable supply of power. The converters also provide very effective filtering against power disturbances. The emerging fuel-cell technology is another driver for dc distribution, as the fuel cells produce dc power.

The U.S. Navy is also considering dc distribution for shipboard electric power distribution [1], [3]. The ever-increasing

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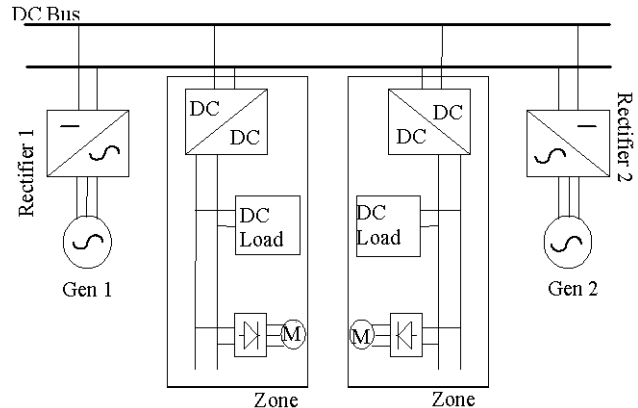


Fig. 1. DC shipboard distribution system.

high-power loads on ships, which need highly reliable and very-high-quality power supply, made conventional ac systems very hard to maintain. The system envisioned by the Navy is illustrated in Fig. 1. Two or more generators supply power to the dc distribution bus through power electronic converters, which rectify ac to dc and regulate the dc-bus voltage. The loads in a given zone are served through a dc–dc converter. The ac loads within the zone are served through the inverters which convert dc to ac. In this system, the dc–dc converters isolate the loads in the zone from the rest of the system, and thus any fault and disturbance within a zone is confined within that zone. The rectifiers, similarly, isolate the ac generators from the system. The rectifiers also eliminate the tight frequency regulation and synchronization requirements on the ac generators. The dc bus itself becomes immune to the ground faults by proper grounding. The dc bus also simplifies the cabling for power distribution, as more power can be transferred on a cable with dc than ac [8]. This is one of the main reasons for the Navy to consider the proposed dc distribution system [3].

The new solid-state power-electronics-based converters employed in the new dc distribution systems help overcome two of the main challenges associated with dc systems: reliable conversion from ac/dc or dc/ac, and interruption of dc current under both normal and fault conditions. The other challenges that need to be addressed in these systems are the confinement of the electric field due to the dc bus and the associated safety issues.

One of the new challenges on the power-electronic-converter-based dc distribution systems turns out to be the system grounding, which is needed to minimize the effects of so-called neutral voltage shift the power electronic converters introduce. Section II introduces this concept and the remedies proposed to mitigate this effect. Feasibility of the proposed scheme is illustrated through system simulation.

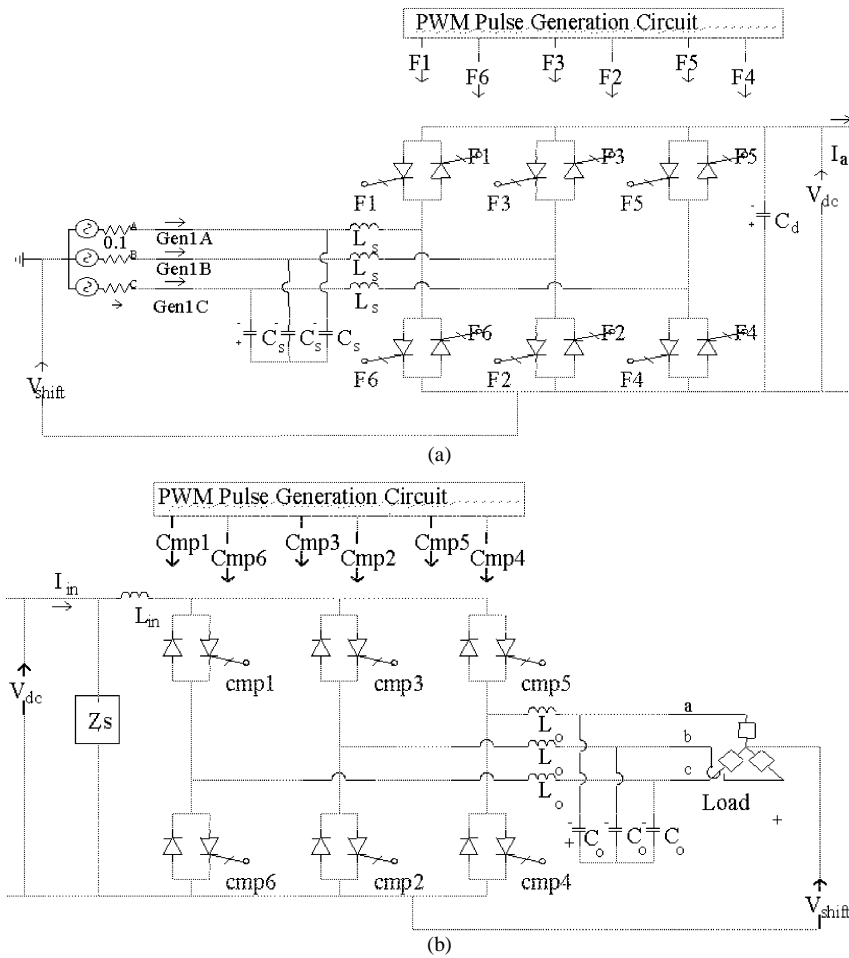


Fig. 2. (a) Rectifier module. (b) Inverter module.

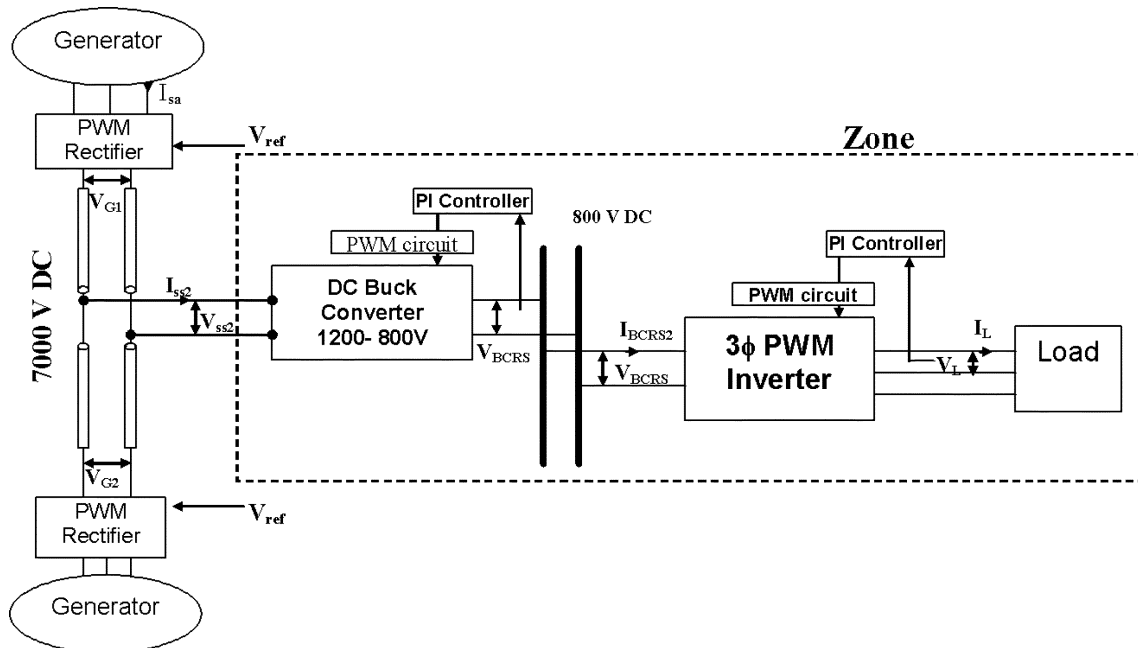


Fig. 3. System block diagram.

II. DC DISTRIBUTION SYSTEM

The main components of a dc distribution system are the power electronics based converters. These converters are of usually bridge type and employ pulsewidth modulation (PWM)

techniques for controlling the switches in order to have more flexibility in control and also to reduce the harmonics. Fig. 2 illustrates the rectifier and inverter modules developed for simulation studies on PSCAD/EMTDC [4].

One of the interesting phenomena associated with these type of rectifiers and inverters is the neutral voltage shift (V_{shift} in Fig. 2); the dc negative bus potential of these devices usually fluctuate with respect to the neutral of the ac side, as Fig. 2 illustrates. The negative dc bus voltage of the rectifier, for example, fluctuates between 0 and $-V_{\text{dc}}$ (dc-bus potential). The negative bus of the inverter, on the other hand, fluctuates with respect to the neutral of its three-phase ac output about the same amount but in opposite direction [5]. These fluctuations create two major challenges. First, they show up at the neutral points of the loads and generators, and thus they contribute to the loop currents between the converters that are connected to the same dc bus in a system. Second, they affect the grounding of the system. Since grounding also affects the loop currents, it becomes one of the main challenges in the design of such systems.

One of the most effective ways for reducing the interactions between the converters is the effective filtering on the converters. This will be illustrated through the simulations. Grounding issues, however, can only be addressed by proper system design.

To illustrate the challenges in grounding, consider the dc shipboard electrical system (SES) illustrated in Fig. 1. To improve continuity of service, it is required that the system be immune to the ground faults. In conventional ac SES this is achieved by not grounding the system. This may not be a good option for the dc SES, as will be illustrated below.

III. PROTOTYPE SYSTEM

A small-scale shipboard system was simulated using PSCAD/ EMTDC. Fig. 3 shows the system, which has two steam turbine generators of 4160 V feeding a dc bus of 7 kV via their rectifiers, and a load zone consisting of one dc load, one three-phase ac load (via a three-phase inverter), and a single-phase ac load (via a single phase inverter). The zone is supplied through the 7000–800-V dc–dc buck converter, which serves as the service converter module for the zone.

The rectifier, buck converter, and the inverter modules all use high-frequency (18 kHz) PWM schemes for switching and have controllers for regulating their output voltages [6].

A. Operation Under Ground Isolation

Consider ground isolating the prototype system, i.e., both the generators and the loads are not grounded, and thus the whole system is ground isolated. Capacitances of 5 nF at the neutral of the generators and the load are used to represent the stray capacitances. Fig. 4 shows the voltage fluctuations on the (–) dc bus due to neutral shift and confirms the predictions made earlier. The neutral voltages of the generator and the load under this condition are given in Fig. 5. These simulations indicate that the neutral potential of the generators and the loads will be quite high—generators neutrals swing up to 5 kV and that of the load is about the half of dc bus (400 V). The variations include relatively high frequency (higher than the switching frequency of 18 kHz), and thus contribute to significant leakage currents. These quite high neutral voltages indicate that maintaining ground isolation and safety in this system will be quite prohibitive. Our investigation, as indicated in [5] also, indicated that the main con-

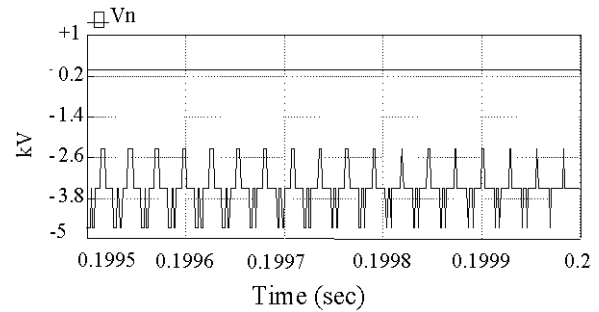
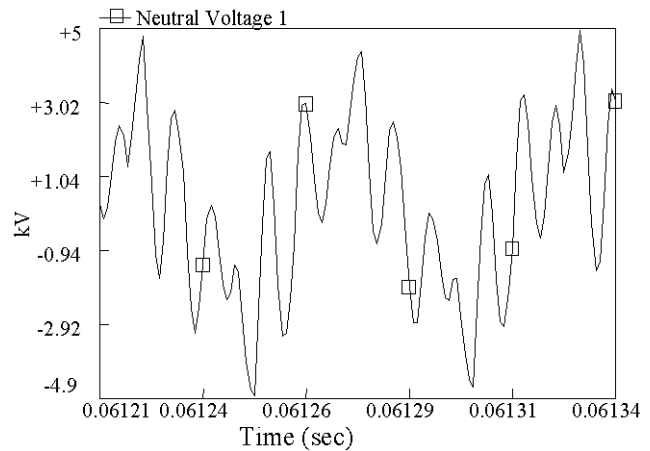
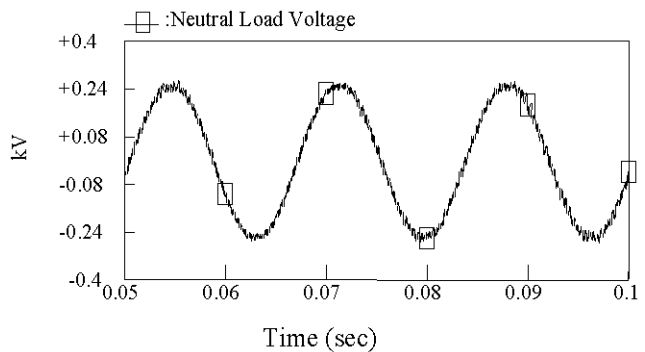


Fig. 4. Voltage fluctuations on negative dc bus.



(a)



(b)

Fig. 5. Neutral voltage under ground isolation. (a) Neutral voltage of the generators. (b) Neutral voltage of the load.

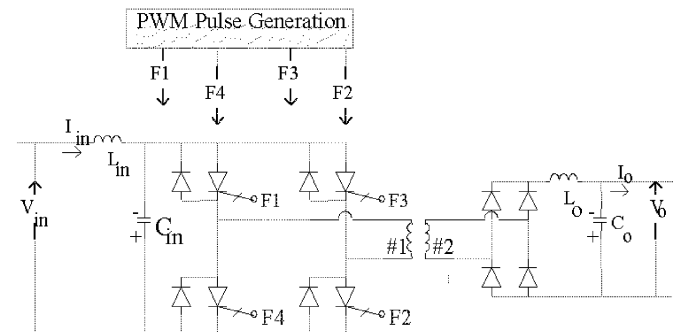


Fig. 6. Buck converter module.

tributor to the high generator neutral voltages is the phase-angle difference between the carrier signals used for the PWM con-

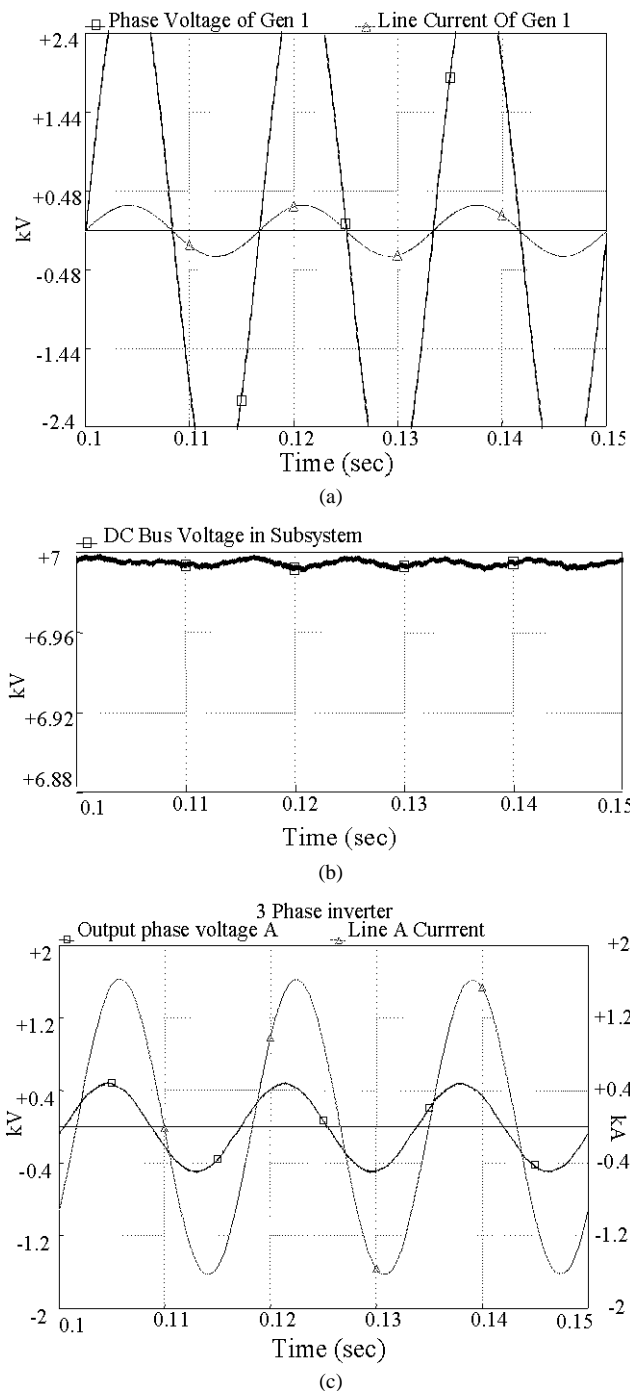


Fig. 7. Performance of the prototype system. (a) G1 Voltage, kV, and current, kA. (b) DC-bus voltage, kV. (c) Inverter output voltage, kV, and current, kA.

trol of the two rectifiers. Thus, by controlling this phase-angle difference, the neutral voltages can be reduced. For example, if the phase angle is reduced to about 5° , the neutral voltages drop to about 1.8 kV. To further control the neutral voltages, we propose to use a high impedance grounding scheme on the generators. This proposed scheme is illustrated next.

B. Operation With High-Impedance Grounding

A grounding scheme we propose involves grounding of the generators through high impedance. This will reduce the neutral voltages at the generators during normal operation, and at the

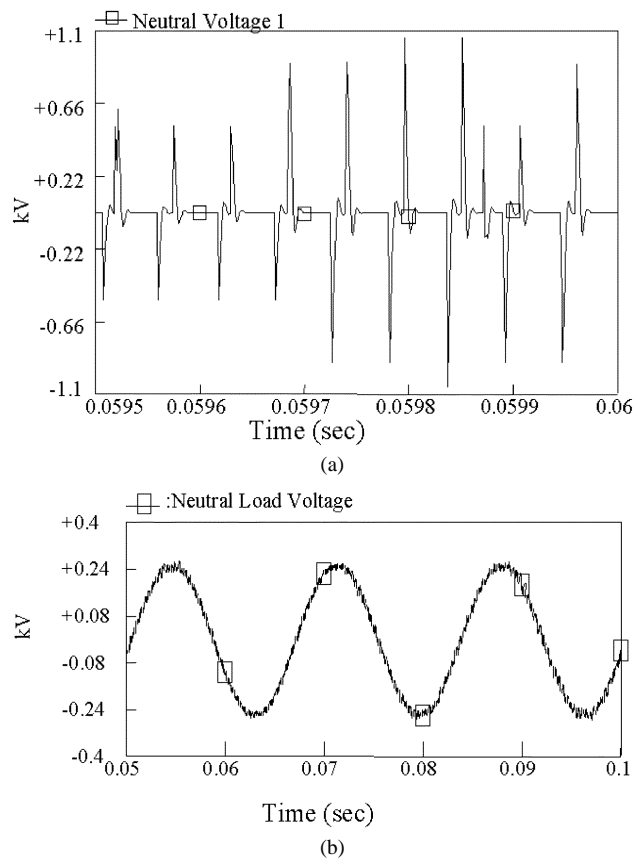


Fig. 8. Neutral voltages under high-impedance grounding. (a) Generator neutral voltages. (b) Load neutral voltage.

same time, limit the ground currents during faults, so that generators could supply power during the fault. Furthermore, we propose to use an isolation transformer (IT) in the dc-dc buck converter, connected between inverter and rectifier stages, as Fig. 6 shows. This IT will isolate the zone from the rest of the system, and thus limit the ground current interactions between the zone and the rest of the system.

The prototype system is modified as described with the two generators grounded through 250-p.u. neutral resistors, and the dc buck converter with an IT. Simulation results for the prototype system operating under normal conditions are given in Fig. 7. Fig. 7(a) shows that the generator current is sinusoidal and of high power factor, as desired. Fig. 7(b) shows the dc-bus voltage (at the source side of the zone buck converter). As the figure indicates, there is only a small ripple of about 10 V ($<0.2\%$). Finally, Fig. 7(c) shows the output phase voltage and current of the three-phase inverter, and indicates that the inverter operates as desired and provides near perfect ac waveforms. These results show that the system provides high-quality power to the loads, i.e., regulated and harmonic-free voltages at the loads. This is mainly attributed to the filtering and control adapted on the converters, as without them the power quality could be quite poor, as illustrated in [7].

Fig. 8(a) shows the neutral voltages of the two generators and the load. The figure confirms that indeed the neutral voltages of generators are lower, about 1.1 kV, and that of the load is about 400 V. Thus proposed grounding scheme reduces the neutral voltage fluctuations considerably compared with ungrounded

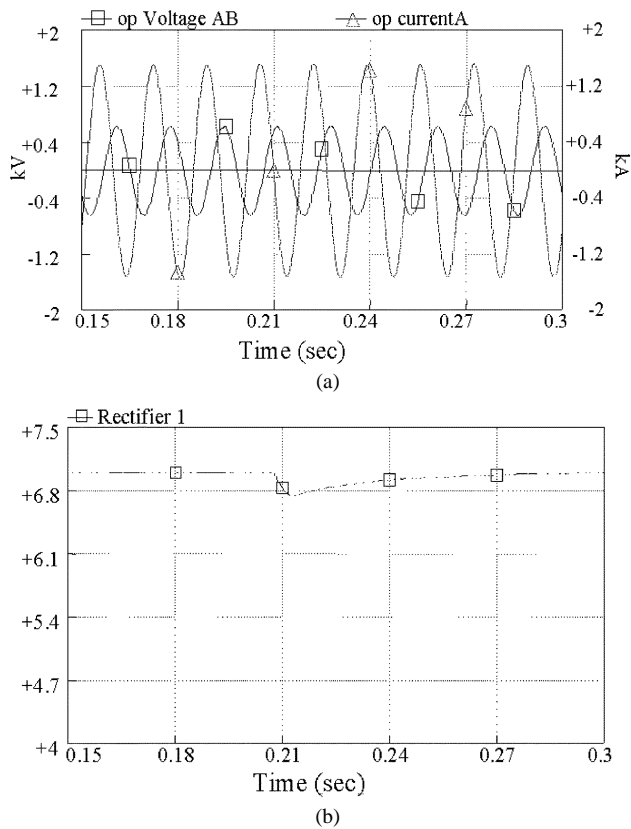


Fig. 9. Operation under generator dropout. (a) Load voltage and current. (b) DC-bus voltage.

case. A fast Fourier transform (FFT) analysis on the generator neutral voltage indicates that the dominant harmonics are 3rd, 9th, 15th, and 30th (switching frequency).

The grounding resistors on the generators, however, increases the total neutral current to about 6 A, which is still below the acceptable limit of 15 A. Thus, selection of grounding resistor should be done to reach a compromise between the acceptable neutral voltage and current levels. For example, if we reduce the grounding impedance on the system to 100 pu., the neutral voltages will be reduced to about 600 V, but the ground currents will increase to about 6.5 A. Therefore, the generators should be grounded with as high resistance as possible to minimize the stray currents, provided that the device insulations are high enough to tolerate the neutral voltage fluctuations.

C. Operation Under Disturbances

To test the performance of the system under varying disturbances the following conditions were simulated.

1) *Generator Dropout*: The reliability of the supply to loads in this system is assured by paralleling the two sources (generators). We simulated the dropout of one generator while the two generators are paralleled to share the load. Fig. 9 illustrates load voltage profiles and the dc-bus voltage during this event. These results confirm that the quality of power does not suffer even under such a large disturbance.

2) *Ground Fault*: One of the main benefits of high-impedance grounding is providing service continuity under ground fault conditions. To check if indeed this is the case for the prototype system, a fault simulation has been performed

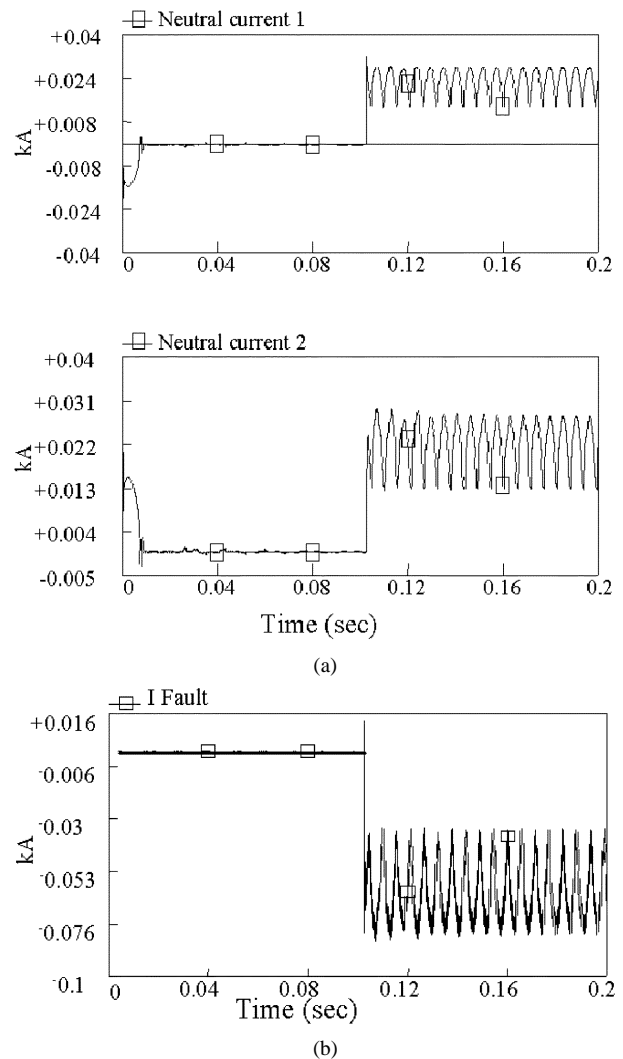


Fig. 10. Fault currents for a ground fault on the dc bus. (a) Generator neutral currents, kA. (b) Fault current, kA.

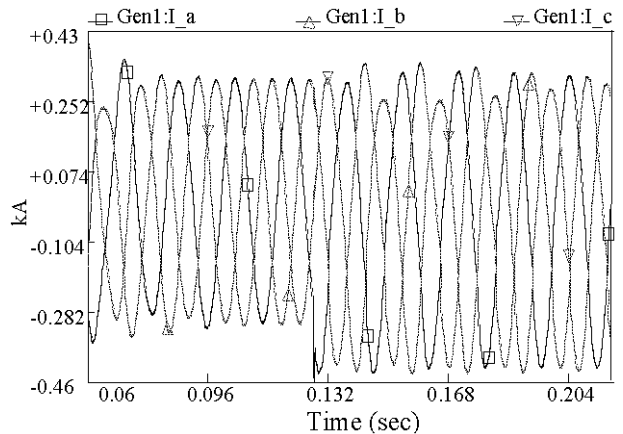


Fig. 11. Generator currents following a fault on the dc bus.

by grounding the negative terminal of the dc bus. Fig. 10(a) shows the resulting fault current, and Fig. 10(b) shows how this fault current circulates through the two generator neutrals (note that the fault is applied at 0.1 s). Generator phase currents under these conditions are given in Fig. 11, which confirms that currents increase only marginally, and thus they do not cause

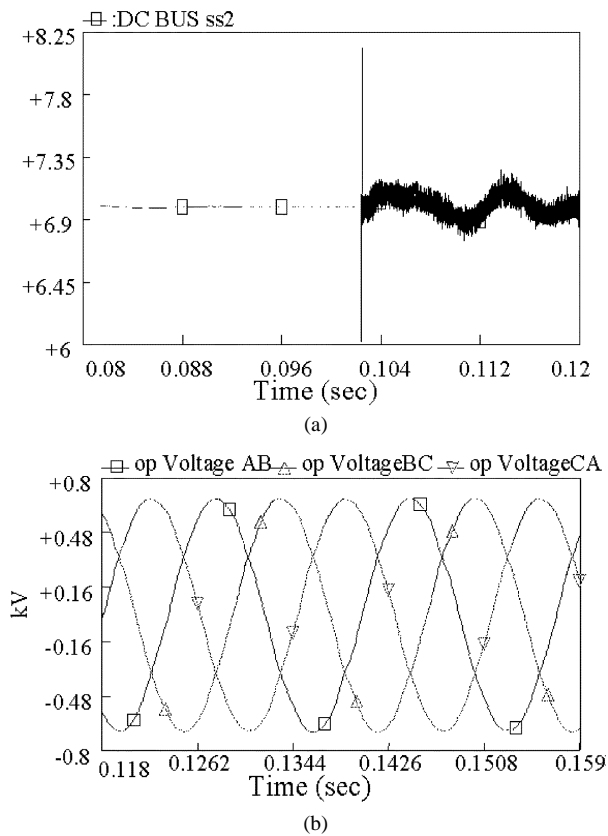


Fig. 12. Ground fault on dc bus. (a) DC-bus voltage under ground fault. (b) Load voltages under ground fault.

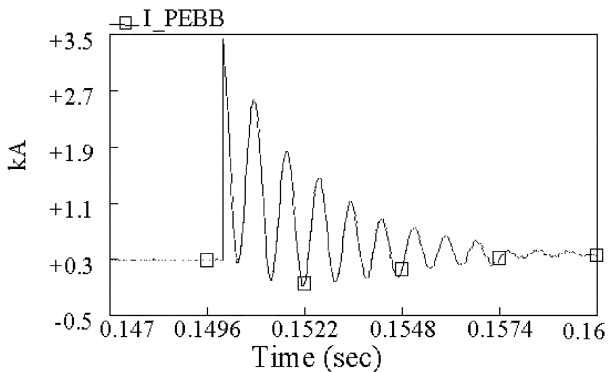


Fig. 13. Short circuit on dc bus.

any significant overload for the generator to trip. Furthermore, Fig. 12(a) shows that the impact of the fault on the dc-bus voltage is marginal, and Fig. 12(b) shows that the load voltages are not affected in any appreciable way by the fault.

3) *Short Circuit on DC Bus:* Fig. 13 illustrates the fault current on the dc bus for a short on the dc bus. The figure confirms that the faults involving the short circuiting the dc-bus terminals will cause high fault current and stress on the system. In order to limit these fault currents, and protect the devices and the converters on the system, we need a fast and effective overcurrent protection system on the system. The power converters again can be tapped for this purpose, as the converters have internal protection against overload and fault conditions. Development of overcurrent schemes by making use of this potential is currently under research.

IV. CONCLUSION

This paper has shown that the challenges associated with the dc distribution can be addressed by proper system design. The results, based on simulations performed on a prototype dc system, clearly show that converter interactions can be minimized with proper filtering and control on the converters. The paper also proposes a grounding scheme and shows that this scheme provides an effective solution by keeping the neutral voltages low under normal conditions and by limiting the fault currents during ground fault conditions. With these features, many advantages of the dc distribution can be utilized for reliable and high-quality power distribution.

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