# Commercial Protection Practices Applied to Naval Power Systems: A Case Study

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***Abstract*—As the U.S. Navy transitions to an all-electric ship, system designers must take great care to ensure that design choices provide highly reliable and safe power system operation and protection during all mission scenarios. Transitioning from low-voltage (450 V) radial configurations to medium-voltage (4160 V) and high-voltage (13800 V) multisource systems requires new naval protection schemes. These new system topologies offer alternate means of supplying power to loads by reconfiguring main distribution paths. However, this flexibility requires advanced protection schemes to reliably protect the power system. This paper describes commercial power system protection techniques that we have applied to the *Makin Island* (LHD 8) power system and new protection features that we have developed specifically for naval ungrounded systems.**

## I. Introduction

The LHD 8 is the eighth ship of the USS Wasp (LHD 1) class. *Makin Island* is a twin-shaft amphibious helicopter/landing craft assault ship approximately 850 feet long and weighing over 40,000 tons that transports U.S. Marines and associated helicopters and landing craft.

Fig. 1. Amphibious Assault Ship (LHD 7 – *Iwo Jima*)

USS *Iwo Jima* (LHD 7, Fig. 1) was the last ship of this class to retain the original steam plant for ship propulsion and auxiliary ship services. The desire of the U.S. Navy not to continue with conventional steam-powered ship designs was in part because of the high life-cycle costs associated with steam plants. The replacement propulsion system developed for LHD 8 is an innovative hybrid propulsion system using both the recently developed General Electric LM2500+ gas turbine (engine rated at 35000 horsepower) for main ship propulsion duty and an electric propulsion system (motor rated at 5000 horsepower) for more economical ship propulsion duty whenever practical, termed the Auxiliary Propulsion System (APS). Also, an increased number of electrical loads were planned for this ship making a 450 Vac design infeasible. The U.S. Navy has developed ships with 4160 Vac power systems, so many components (e.g., switchgear, cables, and other similar equipment) were incorporated in the electric plant design with the exception of modern, multifunction relays.

### *A. LHD 8 AC ZEDS*

Specifically, the LHD 8 generation system consists of six ungrounded 4 MW synchronous generators connected directly to its respective 4160 Vac generator switchboard. The generator neutral is isolated from ground, and each generator switchboard includes a high-impedance grounding transformer. This generator/ground configuration results in a high-impedance grounded system allowing continuous operation during a single-phase-to-ground fault. The distribution system consists of eight 4160 Vac distribution switchboards, each of which connects to a 3.5 MVA $\Delta - \Delta$ 4160/460 Vac distribution transformer. This transformer then connects to a 450 Vac distribution switchboard. Three or four 450 Vac load centers extending from the switchboards in each zone continue the power distribution. While ship power loads are still 450 Vac, distribution remains in their respective zones. This flexibility yielded a new electric plant architecture identified as AC Zonal Electrical Distribution System (AC ZEDS) (Fig. 2) that offers enhanced survivability. The application of AC ZEDS stems from partial- and full-system designs implemented on DDG 51 Flight IIA class destroyers and LPD 17 class amphibious assault ships, respectively. ZEDS architecture is based upon zone-to-zone 4160 Vac primary power distribution and 450 Vac secondary power distribution, in the case of LHD 8, for supplying power to loads within each of the fire/electrical zones.

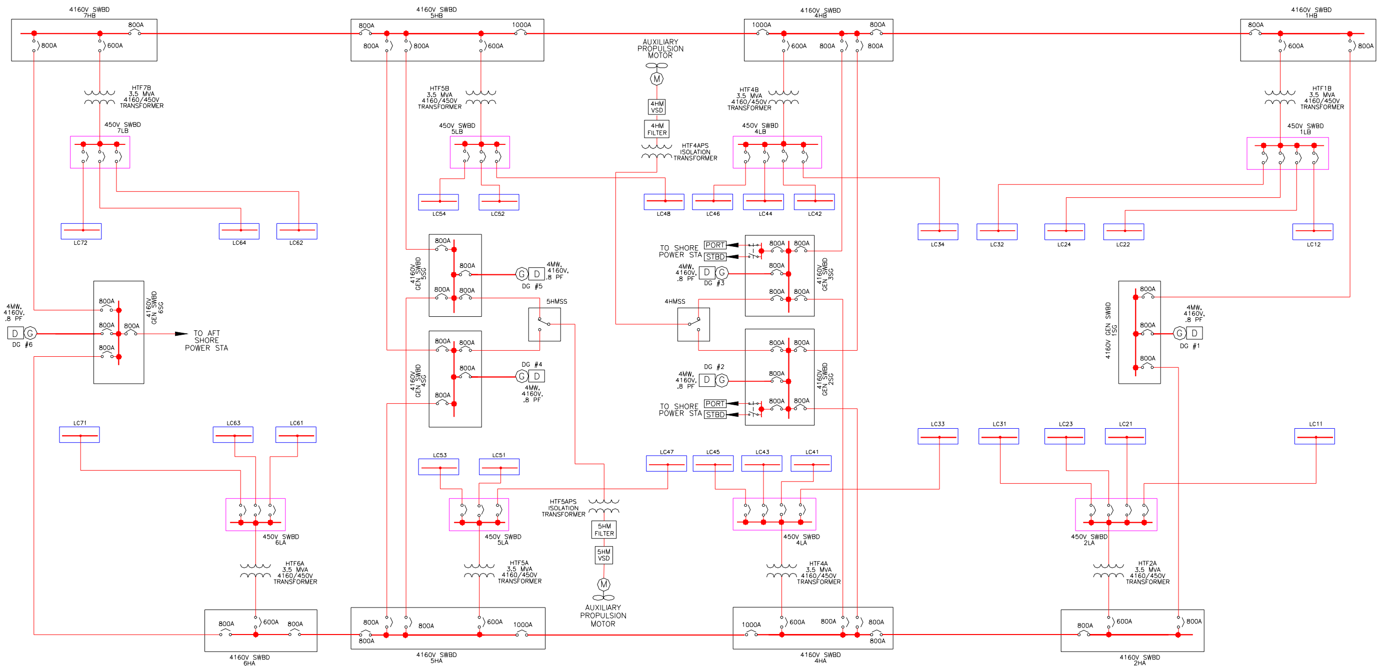



Fig. 2. LHD 8 Electric Plant Single-Line Diagram

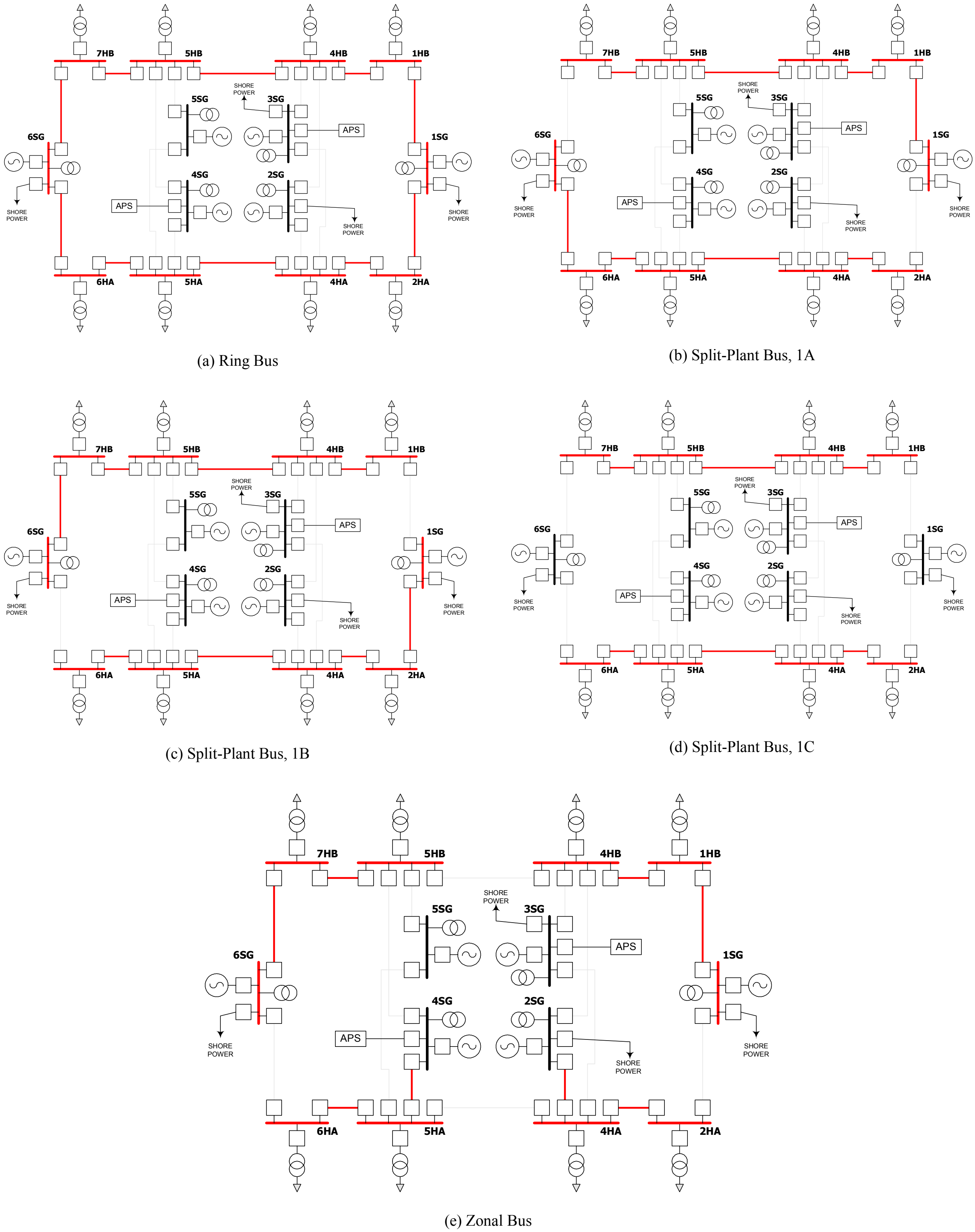
## *B. LHD 8 Standard Bus Configurations*

Fig. 2 shows the LHD 8 electric plant single-line diagram. Note that all generators can connect to either the port or starboard bus via interconnecting cable that run athwartships, designated as cross ties. Double circuit breaker configuration, cross-tie connections, and voltage rating create many advantages for LHD 8 ZEDS design over previous electric plant radial-only designs. These three characteristics enable LHD 8 many configurations via the SCADA system or as referred to on the LHD 8, the Machinery Control System (MCS). LHD 8 has five standard electric plant configurations: one for ring bus, three for split bus, and one for zonal (Fig. 3). Since connection of generators to any bus is possible, combinations are numerous; therefore, a select few are configured automatically. The ability to automatically reconfigure directly results in enhanced survivability, by limiting the electric plant operator's involvement for plant configuration changes. Some nonstandard configurations add to survivability, but require a higher degree of operator interaction.

With the capability to parallel up to five generators, the ring-bus configuration is expected to be the most often used. This configuration allows the electric plant to efficiently operate the six Ships Service Diesel Generator (SSDG) Sets necessary to support the ship's varying electrical load demand. The SSDG Sets are intended to run between 85–90 percent loading as low-load operation can lead to increased maintenance of the diesel engines. A standard automatic split-plant configuration may at times be a more survivable configuration. In the event of excessive damage to the electric plant, a nonstandard manual split-plant configuration may be chosen for survivability purposes.

## *C. LHD 8 Fault Survivability*

The ring-bus configuration provides the best single fault survivability performance on a bus-tie (cable connecting two switchboards). While in ring-bus configuration, a fault event on a bus-tie would put the system into an open ring bus. Open ring bus is a nonstandard configuration; however, in the faulted bus-tie situation it prevents vital load transfer to the alternate bus via automatic bus transfer (ABT) devices. The same basic premise is true upon loss of a 4160 Vac distribution switchboard, sometimes referred to as a longitudinal switchboard. In this case, however, loss of a 4160/450 Vac distribution transformer, which feeds power to a 450 Vac distribution switchboard, can cause load shedding on the electric plant. Similarly, if a problem occurs with a generator, generator interconnecting cable, or generator breaker resulting in a loss of power source to the electric plant, it is less severe in a ring-bus than a split-plant configuration. Under this scenario, Stage One load shedding may occur; however, load shedding may be avoided as the MCS electric plant power management is designed to start a stand-by generator and automatically parallel it to the bus under severe loading conditions. In the event Stage One load shedding occurs, power is still provided to vital loads during the electric plant's reconfiguration process. The ring-bus configuration allows for a more flexible plant reconfiguration than a split-plant configuration. In comparison, while operating in split-plant configuration, the loss of a generator would possibly require both Stage One and Stage Two load-shedding schemes to operate on the affected bus. These actions will produce rolling loads to the unaffected bus, possibly causing the unaffected bus to shed load.




(a) Ring Bus

(b) Split-Plant Bus, 1A

(c) Split-Plant Bus, 1B

(d) Split-Plant Bus, 1C

(e) Zonal Bus

Fig. 3. LHD 8 Standard Electric Plant Configurations

## II. Protection Overview

A design concept using a single relay capable of performing bus-tie, transformer, generator, and shore power protection was implemented to minimize shipboard spares, design complexity, and training requirements. The protection design called for a Multi-Function Monitoring Device (MFMD) that in essence is a multifunction relay found in most modern substations.

Fig. 4. Partial 4160 V Switchboard With MFMD

Fig. 5. 4160 V Control Section View

Each switchboard consists of a control section housing the MFMDs, a Communications Processor (CP) that interfaces with the MFMDs and the SCADA/MCS, and an Uninterruptible Power Supply (UPS). Fiber-optic cables link MFMDs in adjacent switchboards used in the bus-tie differential protection. MFMDs within the same switchboard are hardwired to each other creating a switchboard bus protection scheme based upon directional elements.

Table I shows the MFMD protection elements.

Table I
Element Legend

| Elements | Description |
|---|---|
| 27 | Phase Undervoltage: A-, B-, or C-Phase |
| 59 | Phase Overvoltage: A-, B-, or C-Phase |
| 81 | Under- and Overfrequency |
| 25 | Synchronism Check |
| 27S | VS Analog Input Undervoltage |
| 59S | VS Analog Input Overvoltage |
| 59N | Zero-Sequence Overvoltage |
| 67P | Directional Phase Overcurrent |
| 50P | Nondirectional Phase Overcurrent |
| 32R | Reverse Underpower |
| 32F-1 | Forward Overpower–Stage 1 |
| 32F-2 | Forward Overpower–Stage 2 |
| 87 | Phase Current Differential |
| 87W | Ground Current Differential |
| 67N | Directional Ground Overcurrent |
| 50N | Nondirectional Ground Overcurrent |

Overpower protection is accomplished in two stages of time-delayed load shedding. Reverse power protection uses a time-delayed function to prevent a generator from acting as a motor on the system.

An undervoltage coil in the 4160 Vac switchboard breaker for the 4160/450 Vac distribution transformer helps protect the electric plant upon restoration. The MFMD sees undervoltage as a manual trip. Originally, undervoltage was not an issue or violation of ship specifications. Undervoltage became an issue after modification of the MCS control logic, which latches certain signals inhibiting automatic restoration of the electric plant during a dark ship occurrence. This would be rectified via an undervoltage element in the MFMD that would trip before the breaker undervoltage coil without latching in the MCS.

Because of the new reconfigurable, zonal design of the power system, the synchronism check element, which is generally associated with the generator breaker, became a requirement for all bus-tie breakers. While MCS would perform the synchronization function of paralleling generators, the synchronism element in the MFMD provides added protection by preventing the closing of any breaker and connecting two systems that are out of phase. To allow breaker closing when power is only on one side of the breaker, the MFMD includes a dead-bus feature that bypasses the synchronism check element. Unlike the previously described elements, a line-to-line voltage helps prevent a ground fault from affecting proper synchronism check element operation.

Table II shows protection elements used for protecting each type of apparatus in the power system.

TABLE II
PROTECTION ELEMENTS

| | Bus-Tie | Gen | Transformer | APS | SP |
|---|---|---|---|---|---|
| 27 | | | X | X | X |
| 59 | | X | | | |
| 81 | | X | | | |
| 25 | X | X | | | X |
| 27S | | X | | | |
| 59S | | X | | | |
| 59N | | X | | | |
| 67P | X | X | X | X | X |
| 50P | X | X | X | X | X |
| 32R | | X | | | |
| 32F-1 | | X | | | |
| 32F-2 | | X | | | |
| 87 | X | | | | |
| 87W | X | | | | |
| 67N | X | X | X | X | X |
| 50N | X | X | X | X | X |

The protection system has been designed with multiple levels of protection. The primary protection scheme is referred to as Stage One protection. The two backup or degraded protection schemes are referred to as Stage Two and Stage Three protection. Stage One protection occurs when all communication links are intact and all MFMDs, within a switchboard, are operating normally (i.e., enabled). The MFMDs revert to Stage Two protection in the event of a fiber-optic link loss or MFMD failure (i.e., disabled). Finally, if Stage Two fails to operate within a reasonable timeframe, Stage Three operates.

*A. Bus-Tie Primary Protection*

The primary protection used for bus-tie protection is line current differential. Line current differential protection is ideal for the AC ZEDS because the current differential element zone of protection is the connection between the two MFMDs associated with a bus-tie. Thus, as the system configuration changes, the protection zone stays the same, simplifying the power system operation.

Fig. 6 shows a typical line current differential scheme applied to a bus-tie.

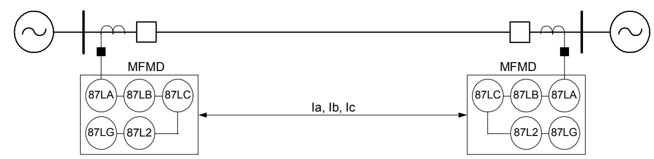



Fig. 6. Typical Line Current Differential Scheme

Each MFMD exchanges time-synchronized $I_a$, $I_b$, and $I_c$ current samples with the other. Current differential elements compare $I_a$, $I_b$, $I_c$, $3I_2$, and $3I_0$ ($I_G$) currents from each line terminal. If a fault condition exists between the two MFMDs, the bus-tie is tripped out.

The MFMD current differential element is based on the Alpha Plane line current protection algorithm. The Alpha Plane maps the complex ratio of remote ($I_R$) to local ($I_L$) currents (see Fig. 7). Through-load current plots at $1\angle -180°$ regardless of magnitude and regardless of angle with respect to the system voltages. An internal fault results in a ratio in the right half plane. For example, on a two-terminal line with equal sources and a mid-line fault, the resulting ratio will be $1\angle\ 0°$. Generally, internal faults result in the right half plane.

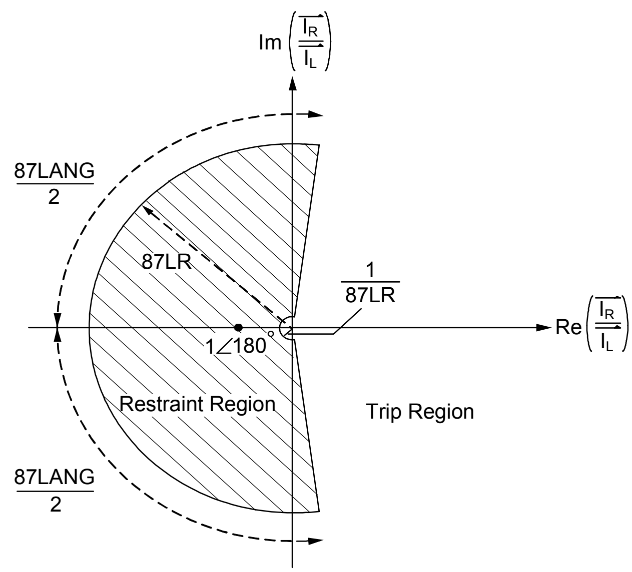



Fig. 7. Alpha Plane

Each phase has an associated Alpha Plane calculation. Each Alpha Plane can determine if a phase is faulted. Therefore, not only does this system provide unit protection for the cable but also for individual cable sections.

The Alpha Plane protection scheme provides fault detection speeds in under a cycle. Fig. 8 shows operating speed as a fault for various fault levels.

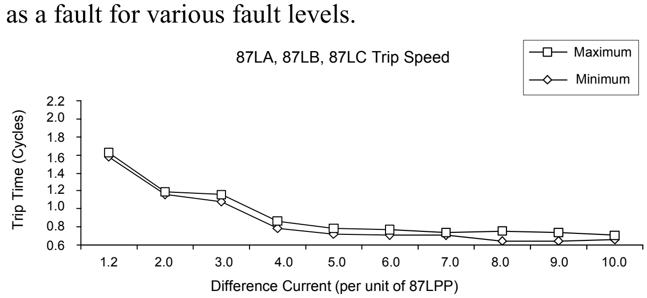



Fig. 8. Operating Speed for Various Fault Levels

### B. Bus-Tie Stage Two Protection

Line current differential elements require a communications channel between the two MFMDs protecting the bus-tie. If the communications channel fails, the line current differential protection is disabled. The communications channel signal integrity checking is an automatic function within each MFMD.

Stage Two is enabled when the communications link fails. In Stage Two, directional overcurrent elements (67) determine if a fault exists on a bus-tie. The 67P element only detects multiphase faults, while the 67N element detects phase-ground faults. Both elements are necessary to detect all fault types because of the difference in pickup and sensitivity levels. The 67P elements operate from phase currents and the 67N elements operate from the current delivered by the core-flux summing current transformers. Note when in Stage Two, the directional overcurrent elements might detect and trip for an out-of-section fault. For example, Stage Two protection detects a fault two switchboards away and trips instead of restraining. Therefore, directional overcurrent elements are only enabled to trip when the current differential communications channel fails.

### C. Bus-Tie Stage Three Protection

The third level of protection for the electric plant is designated as Stage Three. Stage Three protection uses a time-current curve (TCC) characteristic of the circuit breakers. The TCC response of the circuit breakers will not, in most cases, provide selective coordination because fault current measured by circuit breakers will be approximately the same because of the electrically short nature of the ship. To avoid this scenario, while retaining a last level of protection, Stage Three protection generally incorporates a long delay before operation allowing the Primary and Stage Two protection to operate first.

### D. Phase-to-Ground Bus-Tie Fault Protection

Naval power systems are unique relative to most traditional terrestrial power systems because they are designed to operate in an ungrounded configuration. In an ungrounded power system, there is no intentional connection to ground, and loads are connected phase-to-phase.

The advantage of an ungrounded power system is that for a single-phase-to-ground fault, the voltage triangle remains intact and therefore loads can remain in service. When a single-line-to-ground fault occurs, the faulted phase potential decreases to near zero and the healthy phases increase by a factor of 1.73. At the same time, the zero-sequence voltage increases to three times the normal phase-to-neutral voltage. Fig. 9 demonstrates these two conditions. Fig. 9(a) shows an unfaulted, ungrounded system. Fig. 9(b) shows how the voltage triangle shifts relative to ground for an A-to-ground fault.

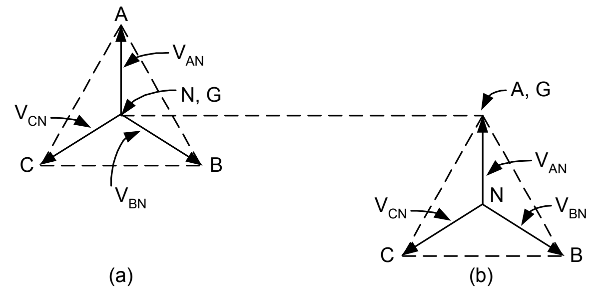


Fig. 9. Voltage Triangle

The traditional method for locating single-phase-to-ground faults was to disconnect a bus-tie feeder and determine if the zero-sequence voltage decreased to its prefault value. If after disconnecting the bus-tie feeder the zero-sequence voltage did return to its prefault value, the operator deduced that this bus-tie was the faulted section.

The MFMD incorporates a doubled-ended, zero-sequence impedance element that vectorially adds the two zero-sequence current measurements, using the communications link between two bus-tie MFMDs, to produce twice the total zero-sequence line current.

To quantify this algorithm we construct Equation 1.

$$z0T = \frac{\mathrm{Re}\left[3V_0 \cdot \left(\left(3I_{NL} + 3I_{NR}\right) \cdot 1\angle ZL_0\_Ang\right)^*\right]}{\left|\left(3I_{NL} + 3I_{NR}\right)\right|^2} \quad (1)$$

where:

$3V_0$ = Summation of phase voltages ($V_A + V_B + V_C$)

$3I_{NL}$ = Zero-sequence current measured by the local MFMD

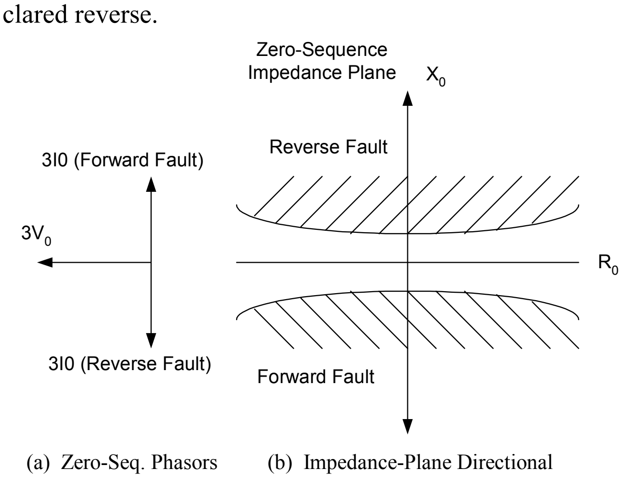
$3I_{NR}$ = Zero-sequence current measured by the remote MFMD.

$ZL_0$_Ang = Zero-sequence line-impedance angle

Re = Real operator

* = Complex conjugate

Fig. 10 produces a forward/reverse fault impedance plane. If the resulting impedance calculation is below the forward threshold (and all of the supervisory conditionals are met), the fault is declared forward. Conversely, if the impedance is above the reverse threshold, the fault is declared reverse.



(a) Zero-Seq. Phasors (b) Impedance-Plane Directional Element Characteristics

Fig. 10. Ground Directional Element Characteristics

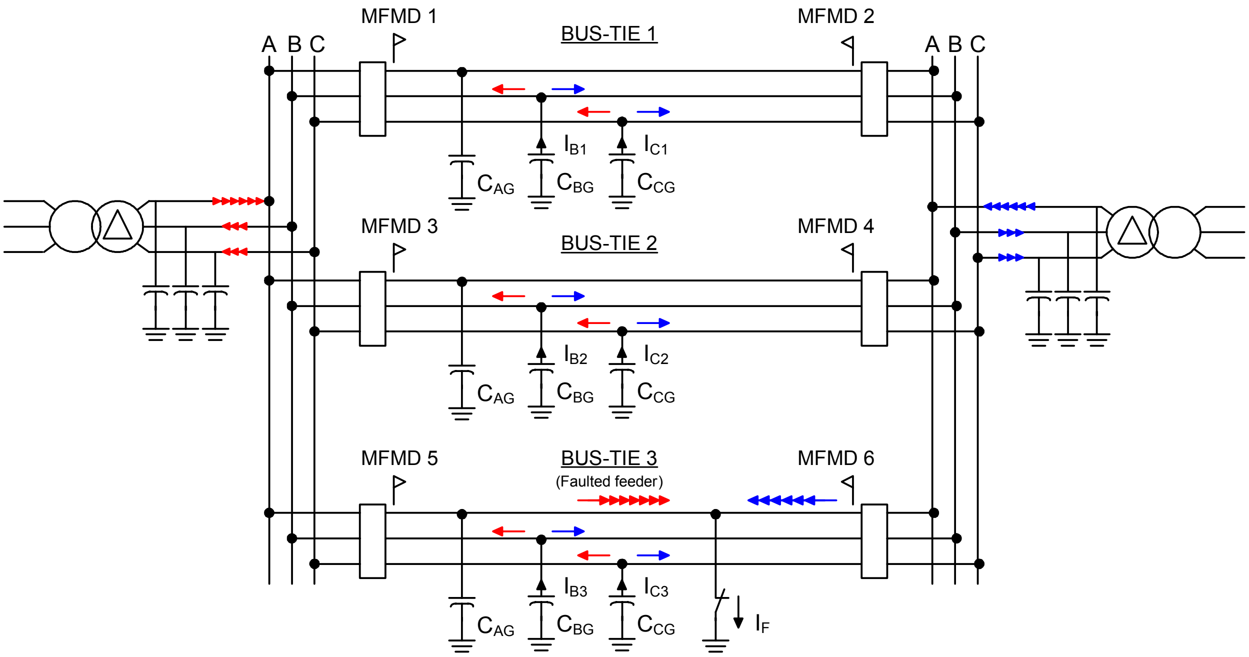



Fig. 11. LHD 8 Ground Transformer Configuration

To examine the relationship of zero-sequence voltage and current for the simple three-line system discussed above, the system is modeled as three, 800-meter long, 400 MCM cables connected to two buses in the ungrounded system shown in Fig. 11.

In this system, the large resistive elements are connected from the power system to ground to provide the simulation program with a ground reference. All transformers shown are connected delta-delta. The generators shown are 1500 Vac and the two 400 MCM cables are operated at 4160 Vac. Table III shows the measurements (secondary) made at the various MFMDs:

TABLE III
MEASUREMENTS AT VARIOUS MFMDS

| MFMD | 3V0 (V) | 3I0_L (mA) | 3I0_R (mA) |
|---|---|---|---|
| MFMD 1 | 207∠180° | 2.5∠-90° | 2.5∠-90° |
| MFMD 2 | 207∠180° | 2.5∠-90° | 2.5∠-90° |
| MFMD 3 | 207∠180° | 2.5∠-90° | 2.5∠-90° |
| MFMD 4 | 207∠180° | 2.5∠-90° | 2.5∠-90° |
| MFMD 5 | 207∠180° | 5∠90° | 5∠90° |
| MFMD 6 | 207∠180° | 5∠90° | 5∠90° |

Assuming a totally capacitive zero-sequence line angle, the resulting total zero-sequence calculation (z0T) for each MFMD is shown in Table IV.

TABLE IV
FAULT IMPEDANCE CALCULATIONS

| MFMD | Z0_Total |
|---|---|
| MFMD 1 | 41,400 Ω |
| MFMD 2 | 41,400 Ω |
| MFMD 3 | 41,400 Ω |
| MFMD 4 | 41,400 Ω |
| MFMD 5 | –20,700 Ω |
| MFMD 6 | –20,700 Ω |

As we can see, MFMDs 5 and 6 would trip out the faulted section while MFMDs 1, 2, 3, and 4 would restrain from tripping.

Now assume the fault is placed closer to MFMD 2, which results in a larger zero-sequence measured by MFMD 1, but a smaller current measured by MFMD 2. In this case, MFMD 2 may not measure enough zero-sequence current to reliably make a fault determination. However, because the zero-sequence currents from each line end are vectorally added, both MFMDs can reliably make a fault determination.

### *E. Bus Fault Protection*

To provide bus protection, we employed a directional comparison scheme within each switchboard. A pair of contact outputs and contact inputs were logical OR'ed together to generate a bus block and bus trip status as shown in Fig. 12.

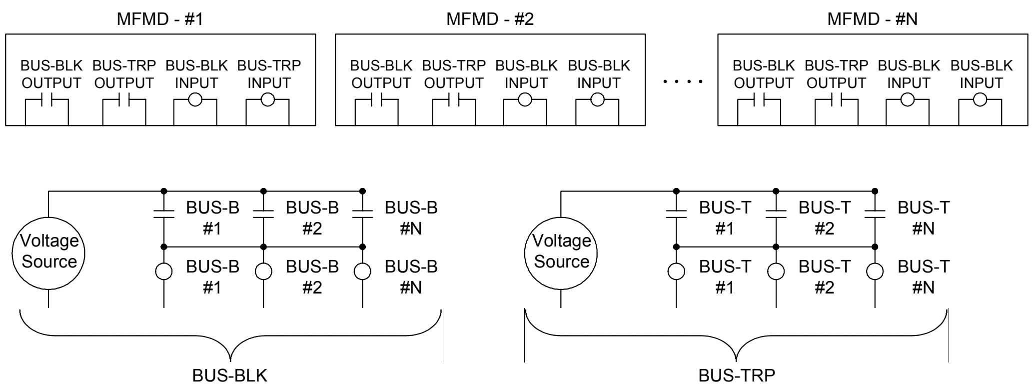



Fig. 12. Bus Block, Bus Trip Wiring Diagram

Conceptually the scheme works as follows:

a. Each MFMD within a switchboard makes a fault direction decision using a directional overcurrent element (67).
b. If the MFMD determines a fault is forward (i.e., outside the bus), a Bus Block contact output is asserted.
c. If the MFMD determines the fault is reverse (i.e., potentially on the bus), the Bus Trip contact output is asserted.
d. The MFMD read the associated Bus Trip and Bus Block contact inputs. If the Bus Trip contact input is asserted and the Bus Block contact input is NOT asserted, the MFMD trips.

## III. Test Results

A computer model of the high-voltage electrical system was developed in order to assess electric plant performance. Generators, transformers, motors, cables, breakers, MFMDs, and other equipment were modeled using Simulink® and the SimPowerSystems toolbox, and multiple fault cases were run to verify protective relay settings.

### *A. Bus-Tie Protection Results*

The bus-tie protection was first tested in a primary protection configuration. Fig. 13 shows the system's response to a phase-to-phase fault on a bus-tie cable. With the system running in a split configuration, the faulted line is tripped within ¾ cycle of fault inception; removing the minimum required portion of the system from service (i.e., only the faulted bus-tie was isolated).

Next, the secondary protection configuration was tested as shown in Fig. 14. In this fault case, a communications channel failure between the 4HB and 5HB switchboards is simulated with a fault placed on the cable between them. Under these conditions a 67-directional element detects and clears the fault without the aid of communications links.

In Fig. 15 we tested the condition of a failed communications link and an out-of-section fault. This condition demonstrates the loss of security that can accompany communication loss and switchover to backup protection. With a channel failure between the 4HB and 5HB switchboards, as before, a fault is placed between the 1HB and 4HB boards. Differential protection quickly clears the faulted line, but the 5HB–4HB MFMDs also see forward faults and trip for the out-of-section fault caused by the inability to coordinate because of the lack of communications.

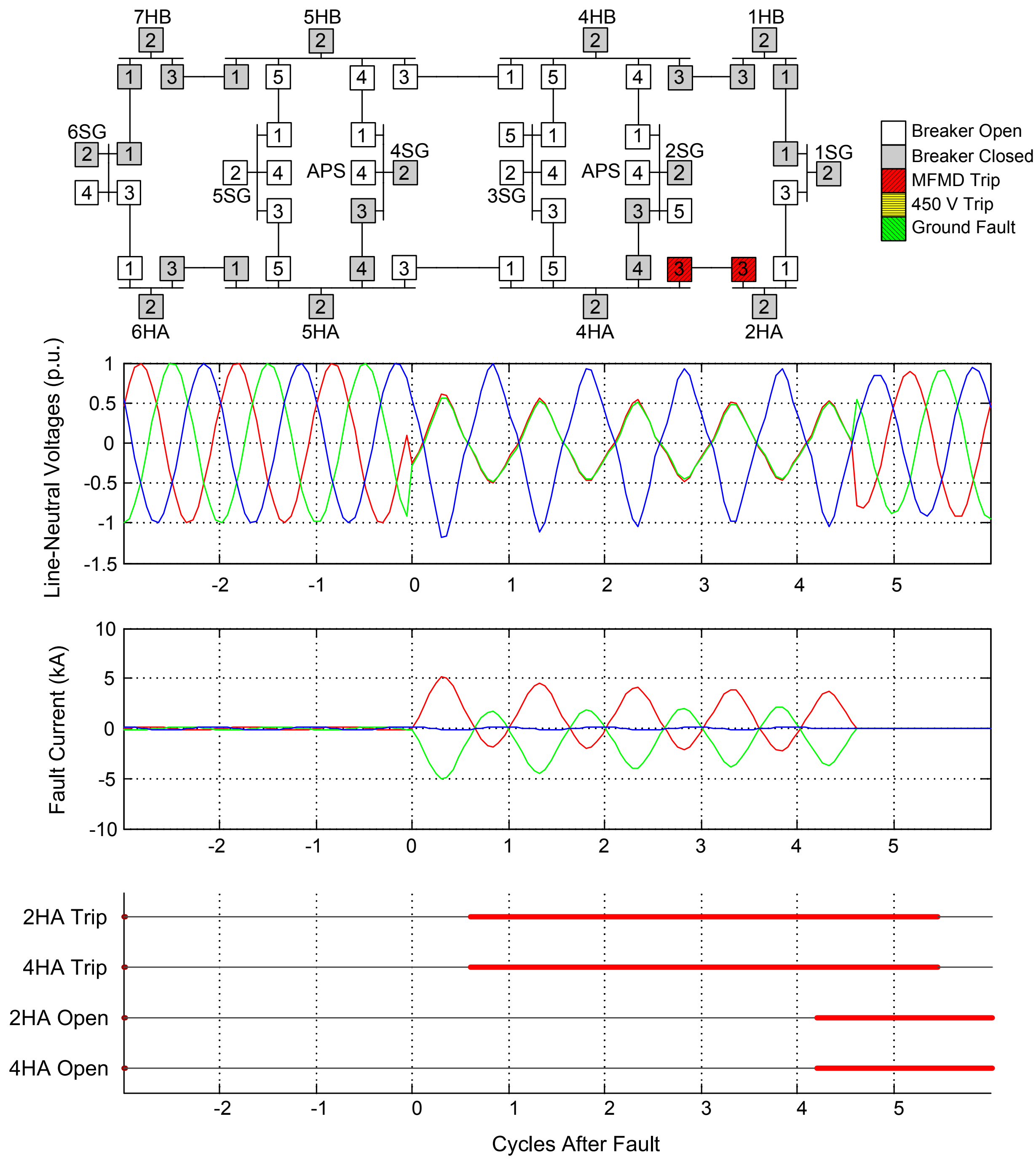



Fig. 13. Isolation of a Phase-to-Phase Fault on a Bus-Tie Cable

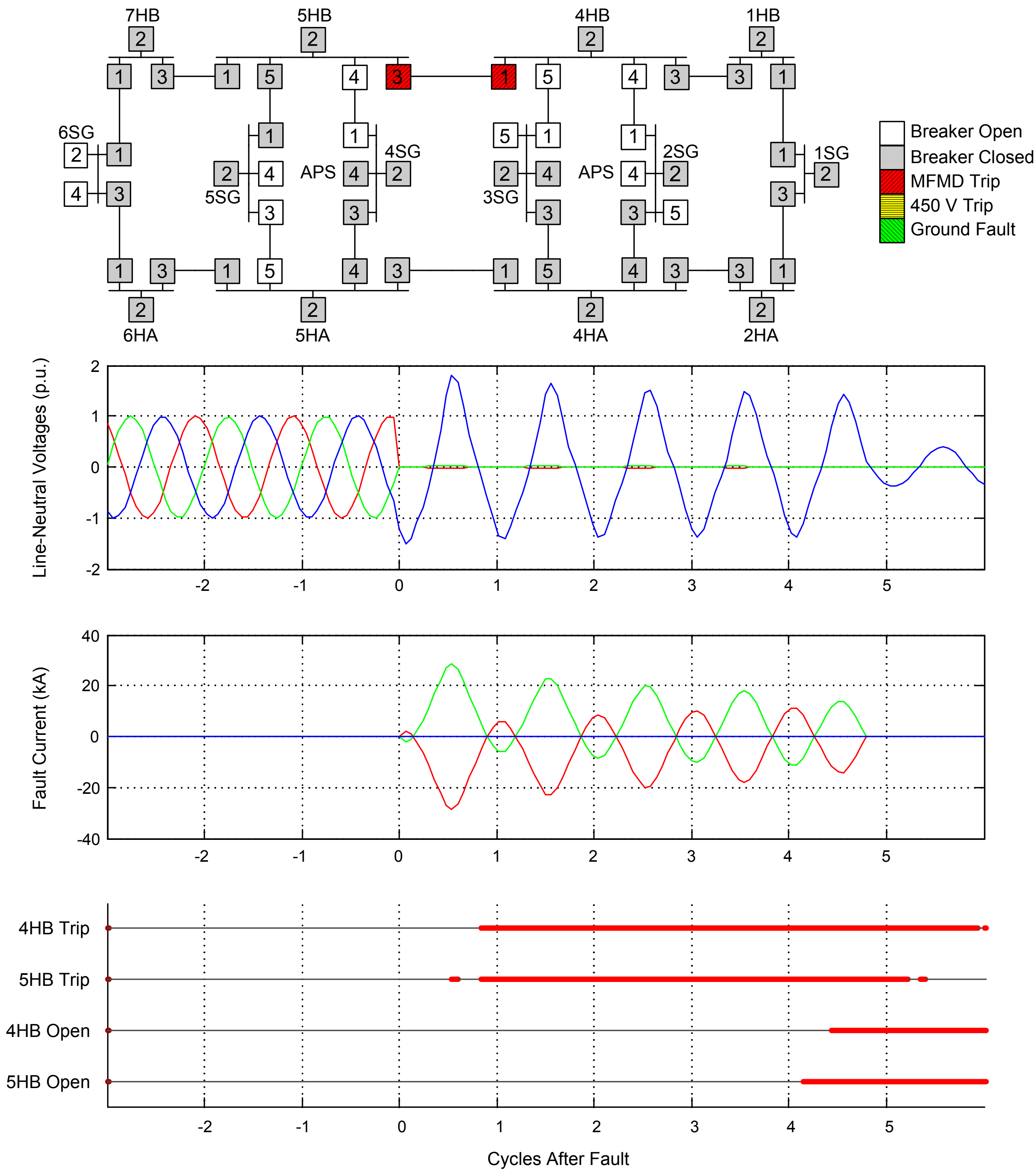



Fig. 14. Backup Protection Clearing a Phase-Phase-to-Ground Bus-Tie Fault

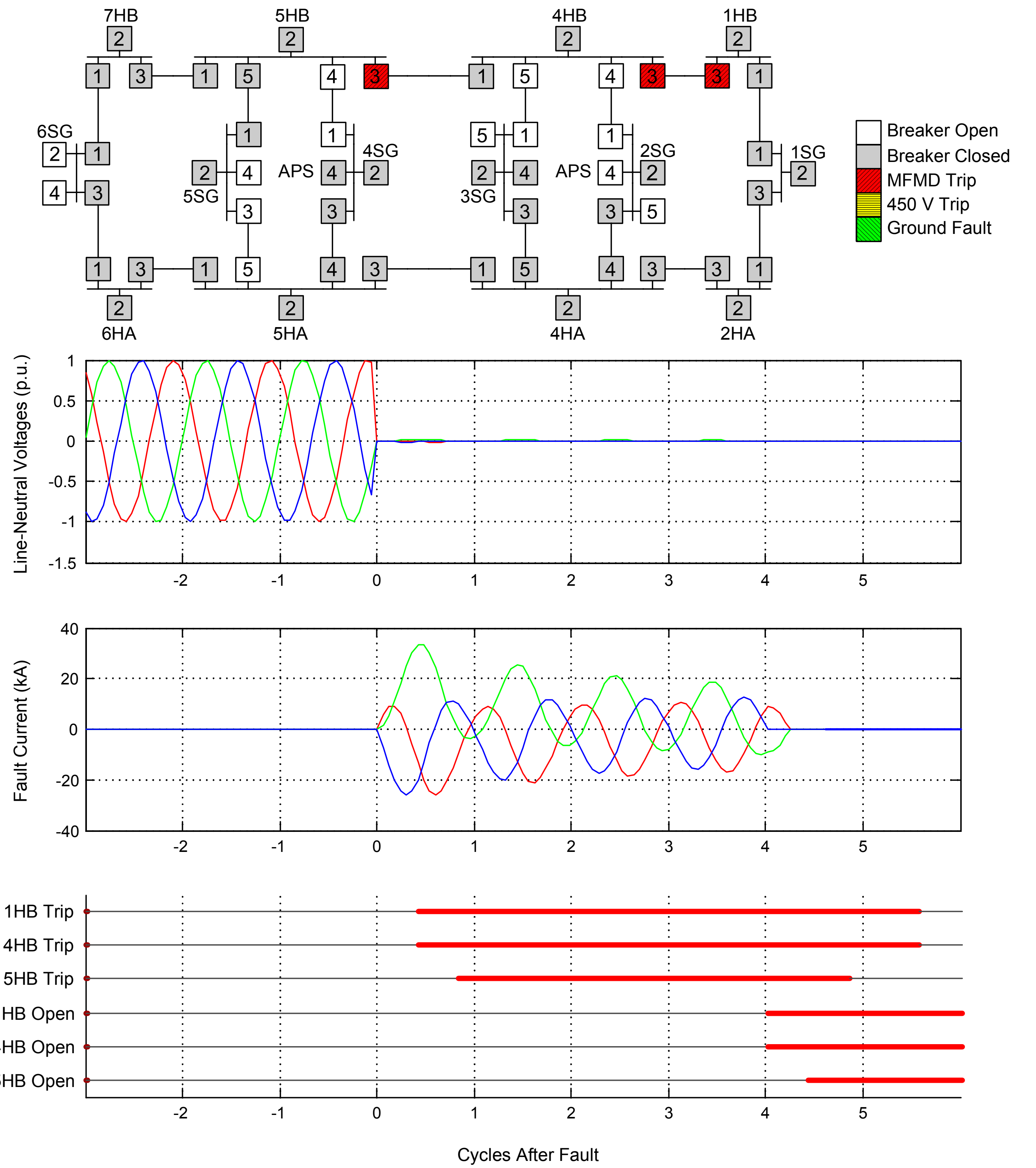



Fig. 15. With Communications Lost, Backup Protection Can Trip for Out-of-Section Faults

## *B. Transformer and Load Protection Results*

Transformer and load center protection is performed primarily via directional elements. Fig. 16 and Fig. 17 show a load center MFMD's coordination with low-voltage protection. A high current fault on the transformer's primary terminals is tripped in less than two cycles, while the 450 V protective equipment is given time to clear a fault on the secondary side.

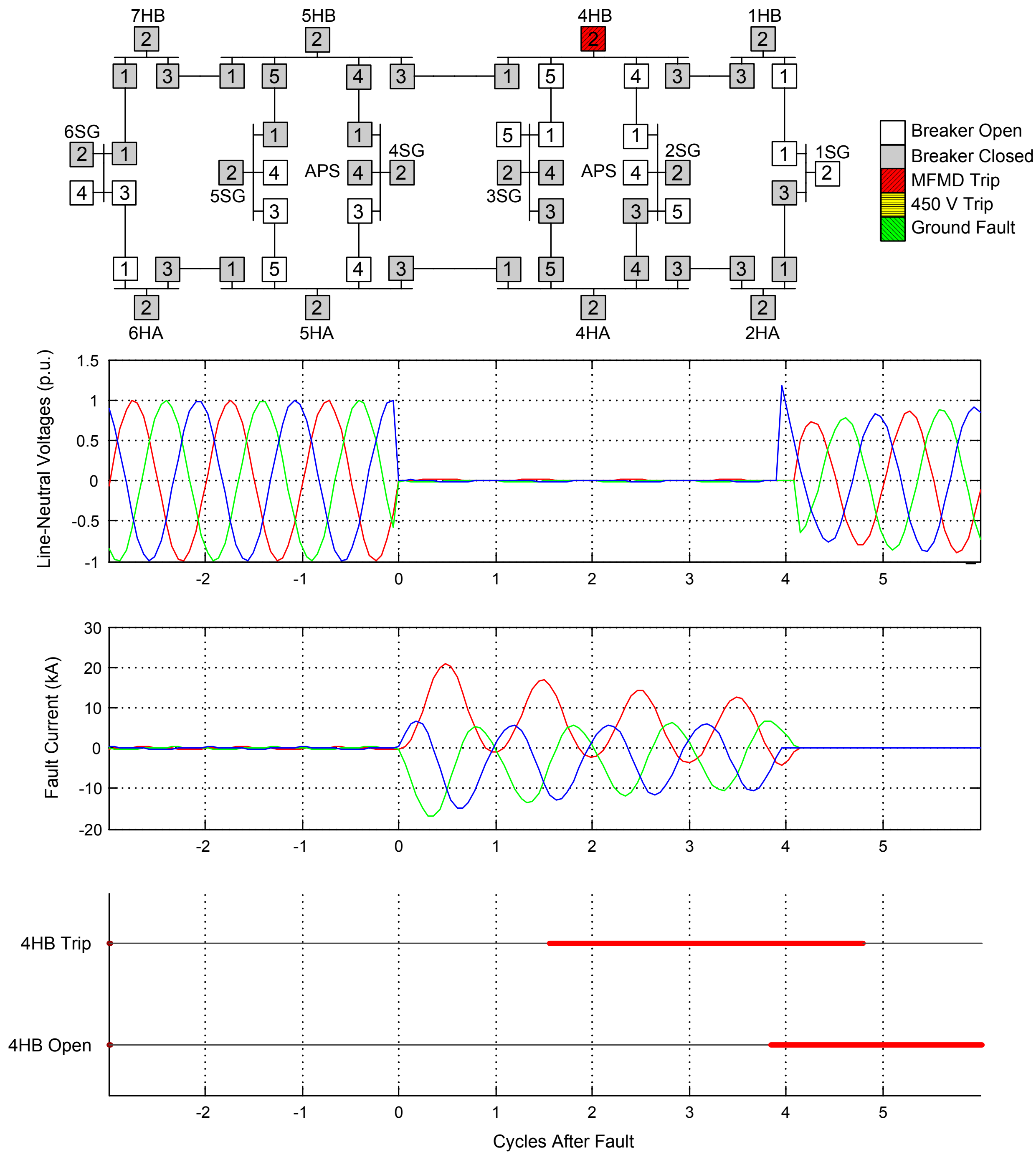



Fig. 16. Clearing a Three-Phase Fault at a Load Center (Primary Side)

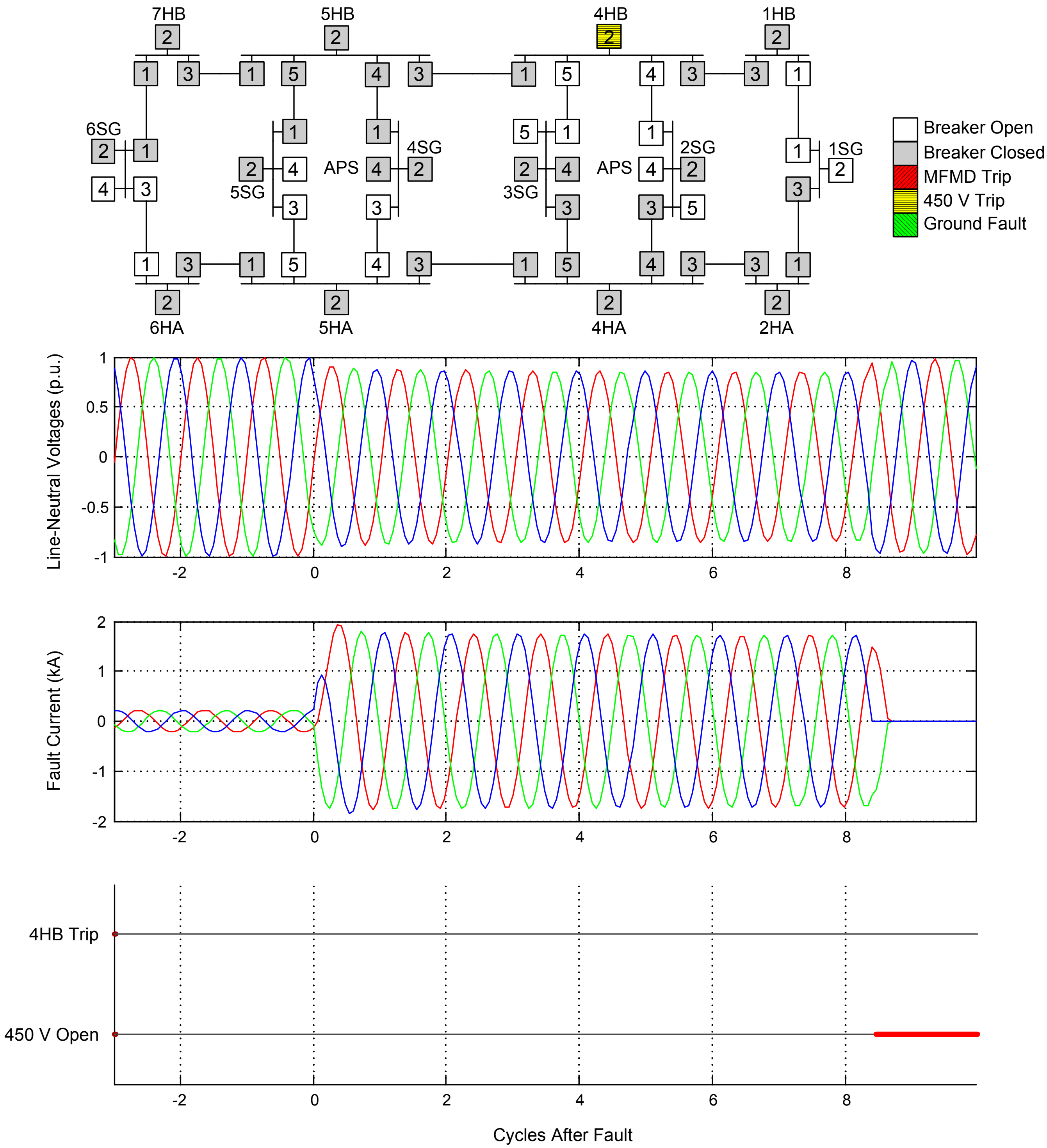



Fig. 17. Low-Voltage Protection Clears a 450 V Fault

## *C. Ground Fault Protection Results*

Fig. 18 and Fig. 19 show selective detection of single-phase-to-ground faults on bus-tie cables and bus bars, respectively. In each case, the MFMDs are able to correctly isolate the fault to a single protected zone without switching breakers or removing any equipment from service.

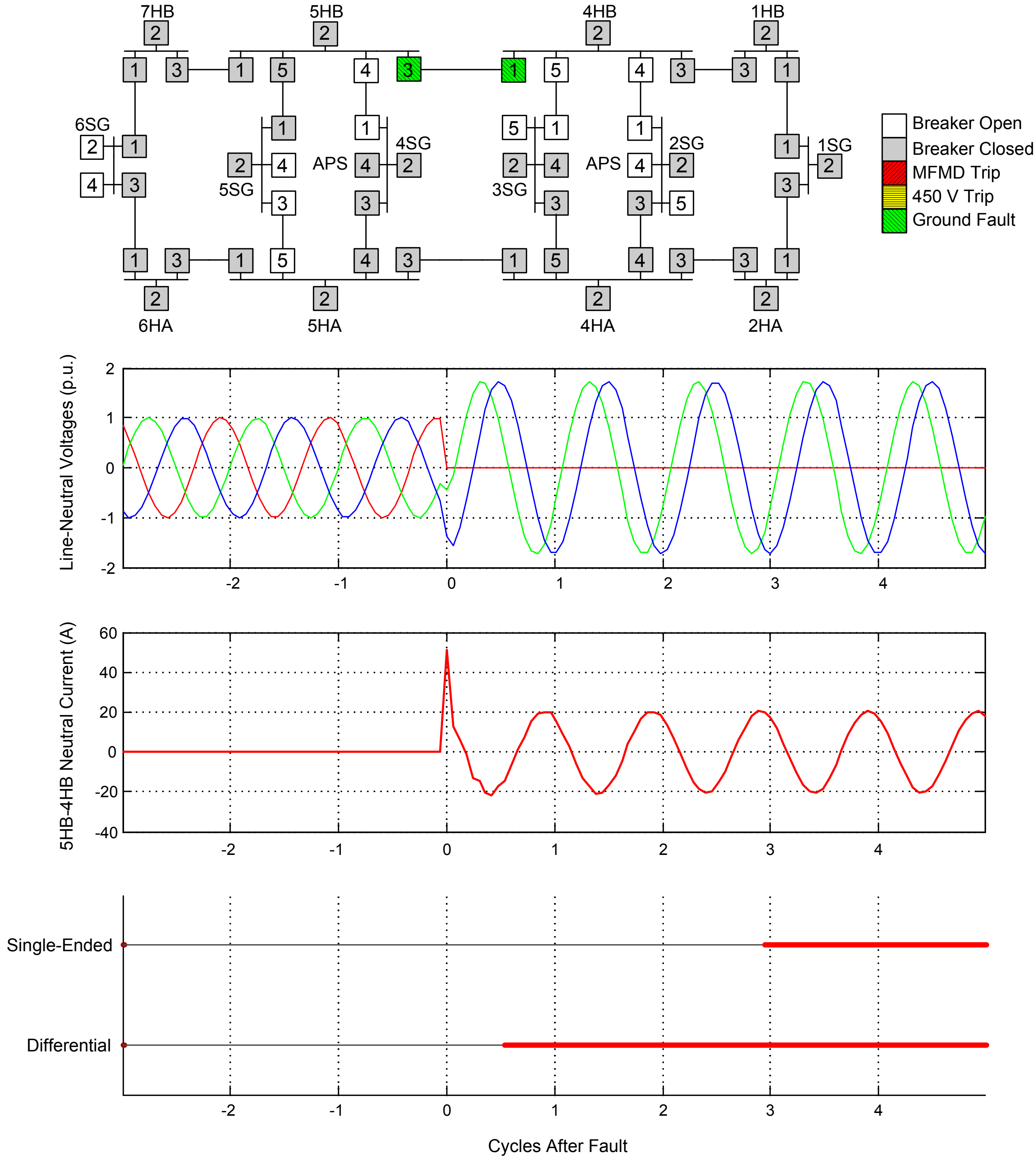



Fig. 18. Differential Detection of a Single-Line-to-Ground Fault

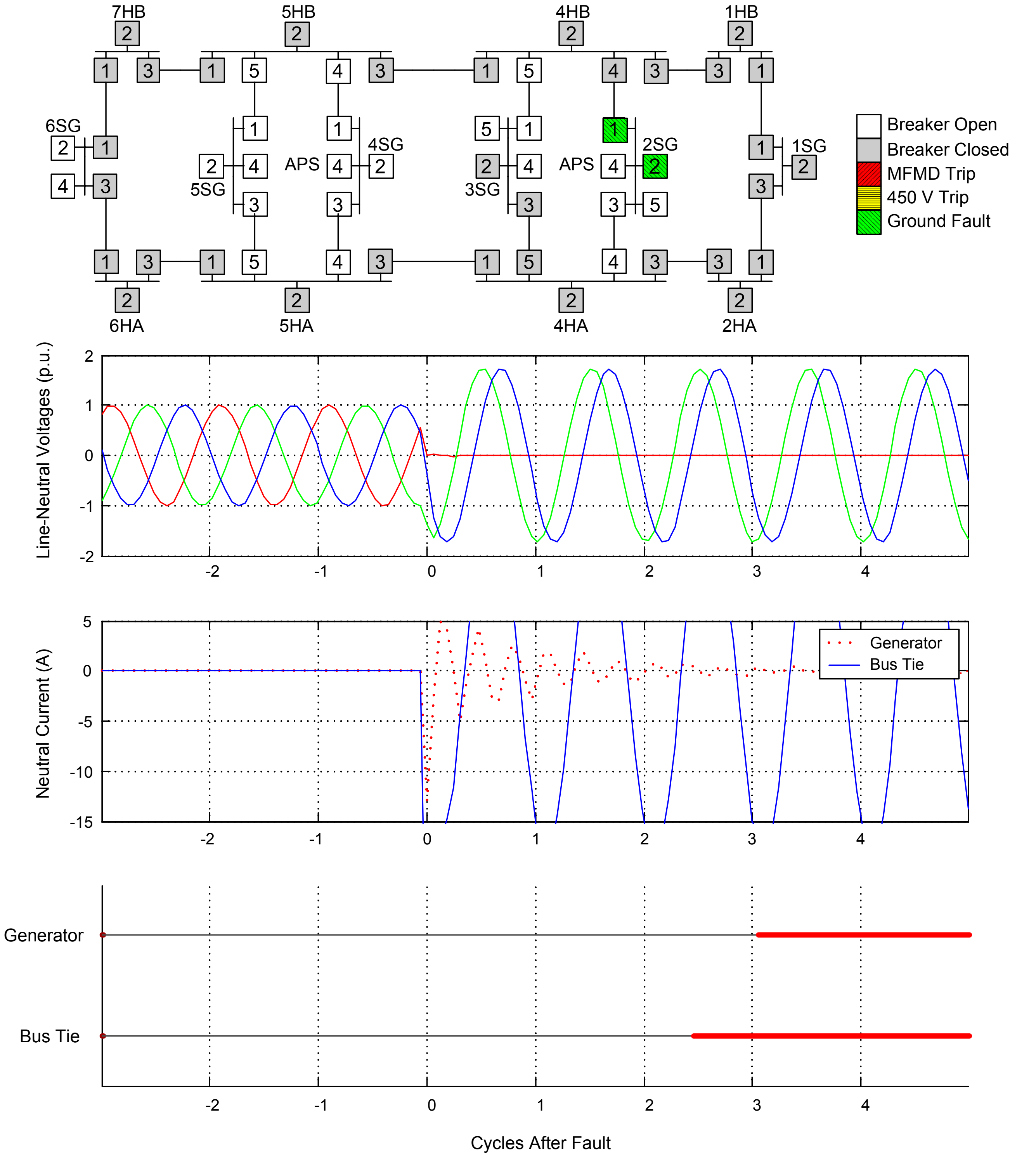



Fig. 19. Cooperative Detection of a Bus Bar Single-Phase-to-Ground Fault

## *D. Bus Fault Protection Results*

Fig. 20 shows the detection and removal of a bus-bar fault without the use of differential bus protection. Both MFMDs involved detect a fault in the reverse direction (toward the bus bar) and each communicates its bus-block and bus-trip signals to the other, tripping its breaker after a short coordinating delay.

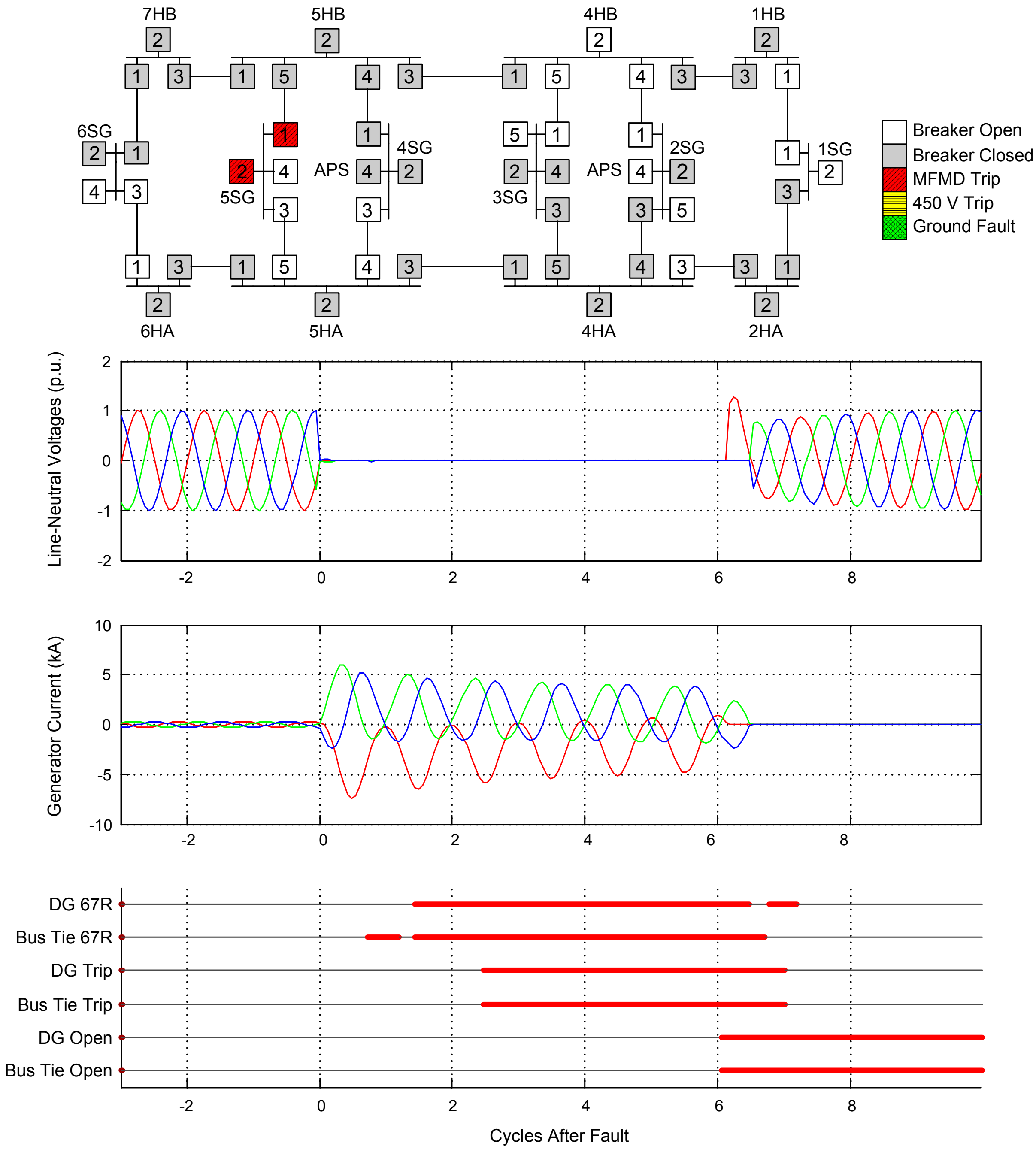



Fig. 20. Detecting a Bus-Bar Fault With Single-Ended Directional Relays

## IV. References

[1] J. Roberts and D. Whitehead, "New Ground Fault Detection Method for Ungrounded Systems," U.S. Patent 6 785 105, Aug. 31, 2004.

## V. Biographies

**Louis V. Dusang Jr., P.E.** (BSEE – Mississippi State University, '88 – Registered Engineer/South Carolina) has been an electrical engineer with NGSS since November 2001. He is the lead engineer for the APS and 4160 V switchboards on LHD 8. He is the specification author of the high-voltage switchboards for the DD(X) program. Prior to joining NGSS, Mr. Dusang worked as both an electrical engineer and controls engineer for Jacobs.

**David E. Whitehead, P.E.** is the Vice President, Research and Development at Schweitzer Engineering Laboratories. Prior to joining SEL, he worked for General Dynamics, Electric Boat Division as a Combat Systems Engineer. He received his BSEE from Washington State University in 1989, his MSEE from Rensselaer Polytechnic Institute in 1994, and is pursuing his PhD at the University of Idaho. He is a registered Professional Engineer in Washington State and Senior Member of the IEEE. Mr. Whitehead holds six patents with several others pending. For the past 12 years at SEL he has been responsible for the design of advanced hardware, embedded firmware, and PC software.

**John Fisher** is a Research Engineer at Schweitzer Engineering Laboratories. He received his BSEE from the University of Idaho in 2000, and his MSEE from the University of Idaho in 2002.