Medium Voltage DC Common Mode Current Control and Grounding

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Abstract

The U.S. Navy anticipates power electronics based Medium Voltage DC (MVDC) power distribution systems will be required to affordably provide power to advanced mission systems. The design of equipment and the system grounding scheme should be designed to limit common mode (CM) currents through the ship's hull. This paper presents a CM model of an MVDC power distribution system and makes recommendations for the design of rotating machines, power electronics, grounding systems, and MVDC bus interfaces to limit CM currents.

Introduction

To counter the anti-access / area denial strategies of potential adversaries, the U.S. Navy is developing high power sensors, high power electronic warfare systems, solid state lasers (SSLs) and electromagnetic railguns (EMRG). MVDC power systems (nominally 6 kV, 12 kV, or 18 kV) are anticipated to affordably power these advanced electric loads with a higher power density than achievable with a.c. systems.

The design of an MVDC power system deviates in a number of ways from contemporary a.c. power system design practices:

1. The MVDC power system will be regulated entirely by power electronic converters,
2. Dielectric and capacitive behavior will differ from a.c. power system practice, and
3. Electric power system dynamics will be faster.

Despite these differences, many of the traditional considerations for grounding shipboard electric power systems are still quite valid. Hence, a subsequent discussion will capture "grounding orthodoxy".

This paper proposes to use the method of Brovont and Pekarek (2015) as a basis for developing recommended practices for limiting common mode (CM) currents and establishing a system ground. Examples of CM models derived from a three phase model of a generator set - motor drive system are provided. This paper expands the discussions of Doerry and Amy (2017).

The CM current is the sum of the instantaneous currents through all of the conductors within a set of power conductors and corresponds to the leakage current that completes the power circuit outside of the set of conductors. Typically the return path is through the ship's hull at the ground potential. The CM current is unintended and different from the intended differential mode (DM) current. Within a set of power conductors, the sum of the instantaneous DM currents add to zero as would be expected in a balanced power circuit without parasitic capacitance connections to ground or an intentional grounding system.

The magnetic fields produced by CM currents in power cables are also sources of electromagnetic interference (EMI). Without CM currents, the DM currents through all the conductors in a cable (or set of cables) sum to zero at every instant in time. The conductors are designed to minimize separation so that the resulting magnetic flux densities cancel each other. With CM currents, the currents in multiple unshielded conductors sum to a non-zero value with the return path of this resulting current conducting through the hull. Inside the ship, the magnetic flux densities of the multiple conductors due to the CM current do not cancel each other, potentially coupling with other systems and causing EMI.

CM voltages applied across CM impedances result in the CM currents. CM voltages, if large enough, can also cause line to ground insulation failures.

MVDC Reference Architecture

A reference MVDC system architecture is depicted in Figure 1 and described in detail by Doerry and Amy (2015A, 2015B, and 2016). The elements of the systems that interact with the MVDC bus are:

- Power Generation Modules
- Propulsion Motor Modules

[1] US. Navy

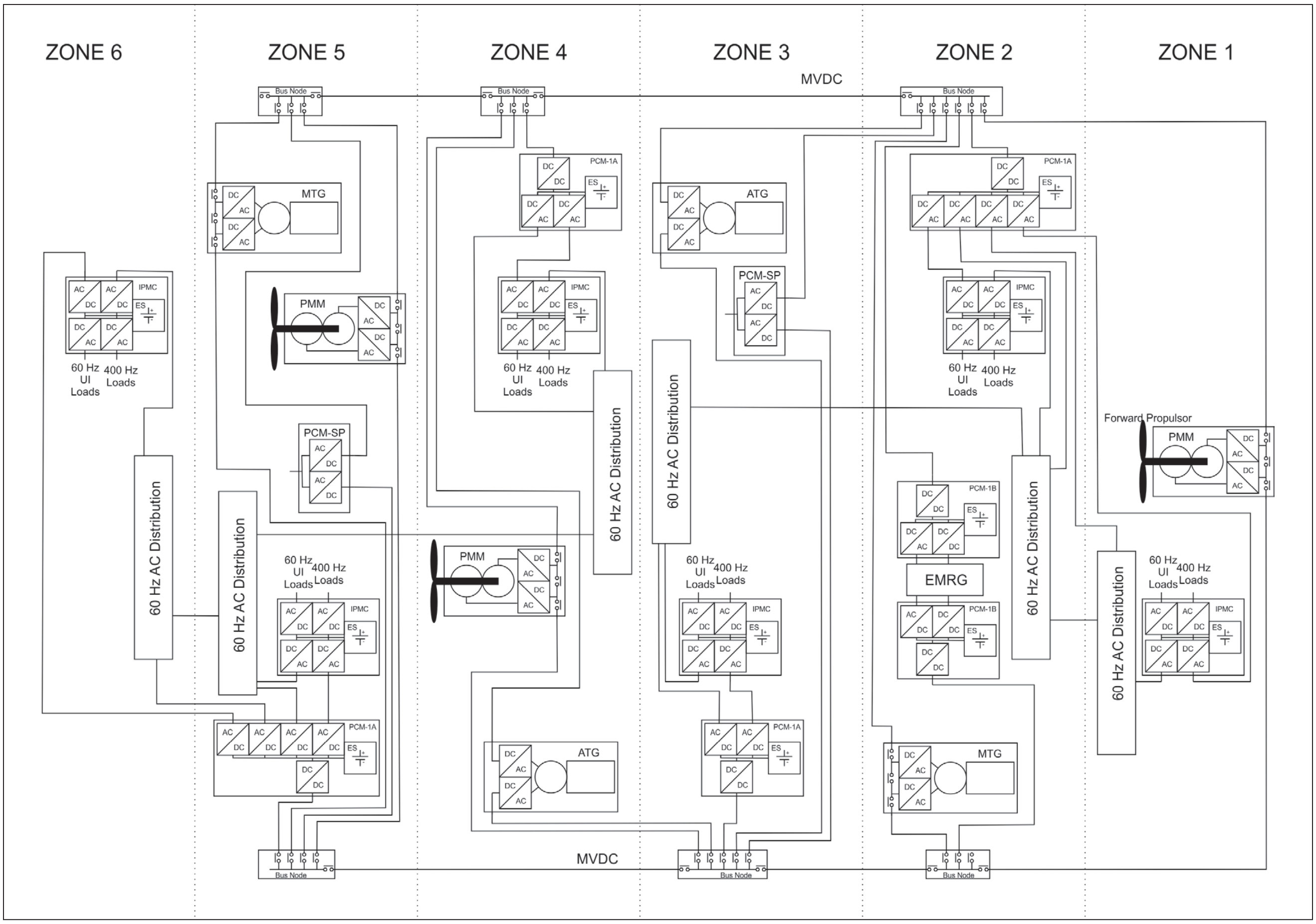

FIGURE 1. Reference MVDC System Architecture

- PCM -1A (AKA Energy Magazine)
- PCM -1B
- PCM - SP (Shore Power interface)
- Bus Nodes
- MVDC Bus
- Controls

The power generation modules consist of a prime mover such as a gas turbine or diesel engine, a generator, and a rectifier. Power generation modules rated for more than about 10 MW are generally labeled as Main Turbine (Diesel) Generators (MTG or MDG). Smaller power generation modules are labeled as Auxiliary Turbine (Diesel) Generators (ATG or ADG). The propulsion motors include the motor and drive. Propulsion motors may be lower power thrusters or main propulsion. The PCM-1A Energy Magazine is used to convert power from MVDC to the type of power required by small and medium sized loads and generally includes energy storage. PCM-1As may either directly power loads via an in-zone distribution system, or may provide conditioned power

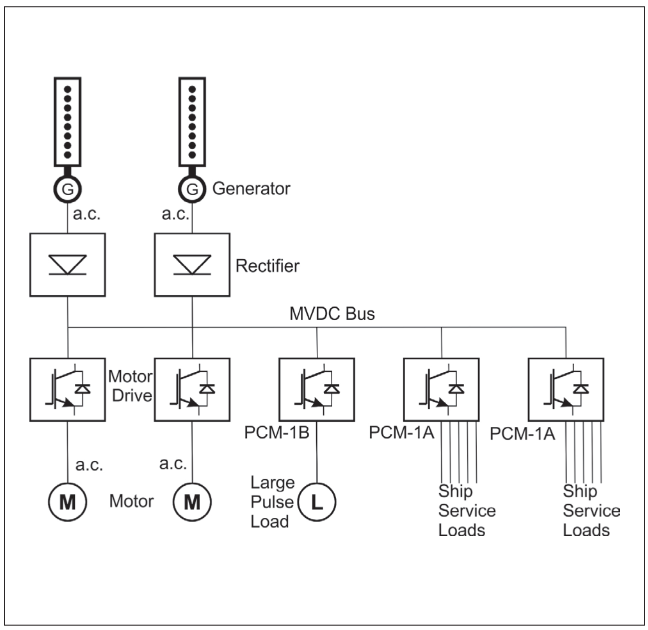

FIGURE 2. Simplified MVDC System

to specific loads via an Integrated Power Management Center (IPMC). The PCM-1B converts power from MVDC to the type of power required by large mission system loads such as the Electromagnetic Railgun (EMRG). PCM-SP converts the type of power provided by shore power to the voltage and power quality required by the MVDC bus. Bus nodes enable isolation of damaged sections of the MVDC bus and specific sources or loads. The MVDC bus may be composed of cable, bus pipe or bus duct. Controls are used to manage power on the MVDC system, manage fault response, etc.

One of the features of the MVDC system is that online PGMs provide power simultaneously and independently to both MVDC buses. This facilitates even loading of the buses while enhancing the tolerance of the system to bus faults. While the two independent MVDC systems are coupled via parasitic capacitances and mutual inductances within the generators, much can be learned initially by assuming the systems are completely independent. The impact of coupling between the two systems will be subsequently discussed. The simplified system is depicted in Figure 2.

Basics of CM Voltages and Currents

For a set of power conductors, a neutral point is the voltage reference where the sum of the conductor voltages with respect to the neutral point is zero. This neutral point may or may not coincide with the voltage of a particular physical object. For d.c. systems the neutral point is the voltage reference midway between the two conductors. In a balanced three phase a.c. system, the neutral point corresponds to the common connection in a set of wye windings. While a neutral point can be defined for any three phase a.c. system, a set of delta windings does not have a physical manifestation of the neutral point. The CM voltage is the voltage difference between the neutral point and the system's reference voltage, typically called "ground." For ship systems, the ground potential is typically assigned to the potential of the ship's hull. In some cases the impedance of the ship's hull may result in the hull not having a common potential. In these cases, a particular point on the ship's hull is established as the ground voltage reference.

For a three phase a.c. power system, the voltage relationships are given by:

$$v_{ag} = v_{an} + v_{ng}$$
$$v_{bg} = v_{bn} + v_{ng}$$
$$v_{cg} = v_{cn} + v_{ng}$$
$$v_{an} + v_{bn} + v_{cn} = 0$$

where:

v_{ag}, v_{bg}, v_{cg} = Phase Voltages with respect to ground

v_{an}, v_{bn}, v_{cn} = Phase Voltages with respect to the neutral point

v_{ng} = CM voltage

The voltages between conductors are DM voltages.

The CM current i_{cm} for the three phase system is given by:

$$i_{cm} = i_A + i_B + i_C$$
$$i_A = i_{pa} + i_a$$
$$i_B = i_{pb} + i_b$$
$$i_C = i_{pc} + i_c$$
$$i_a + i_b + i_c = 0$$

where

i_A, i_B, i_C = Phase currents

i_{pa}, i_{pb}, i_{pc} = Phase leakage current to Ground

i_a, i_b, i_c = Differential mode phase currents

hence

$$i_{cm} = i_{pa} + i_{pb} + i_{pc}$$

For a CM current to exist, a current path must exist external to the power system set of conductors. Typically this current path is via parasitic capacitance to ground within cables and rotating machines. The parasitic capacitance is usually about the same from each conductor of a power system to ground. For a three phase a.c. power system, the CM current i_{cm} due to a set of three balanced parasitic line to ground capacitances C_p is given by:

$$i_{cm} = i_{pa} + i_{pb} + i_{pc} = C_p\left(\frac{dv_{ag}}{dt} + \frac{dv_{bg}}{dt} + \frac{dv_{cg}}{dt}\right)$$

Decompose the conductor voltages into a line to neutral and CM voltage:

$$i_{cm} = i_{pa} + i_{pb} + i_{pc} = C_p\left(\frac{dv_{an}}{dt} + \frac{dv_{bn}}{dt} + \frac{dv_{cn}}{dt} + 3\frac{dv_{ng}}{dt}\right)$$

The line to neutral voltages add to zero, with a zero time derivative:

$$i_{cm} = i_{pa} + i_{pb} + i_{pc} = 3C_p\frac{dv_{ng}}{dt}$$

For a d.c. system with only two conductors and two balanced parasitic line to ground capacitances C_{pdc}, the CM current is given by:

$$i_{cm} = 2C_{pdc}\frac{dv_{ng}}{dt}$$

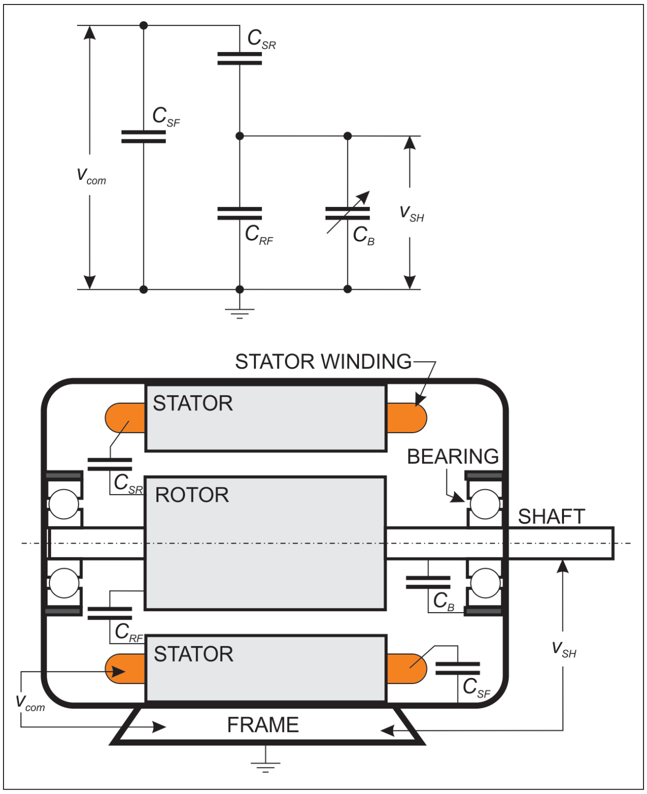

FIGURE 3. CM Model of Parasitic Capacitance of Motor (adapted from Yaskawa Electric America 2008)

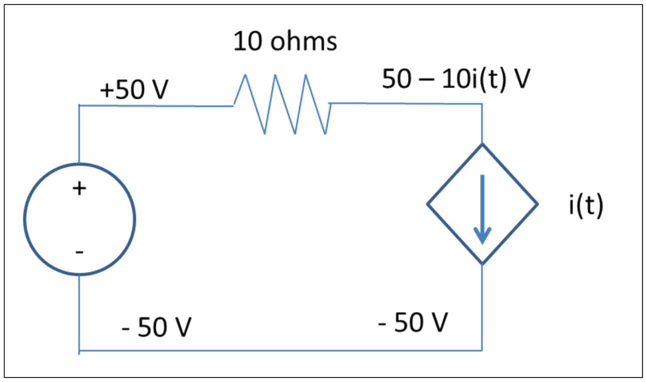

FIGURE 4. CM voltage due to asymmetric circuit

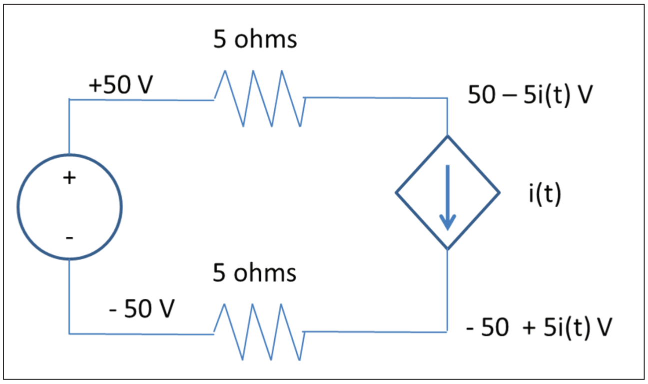

FIGURE 5. Elimination of CM voltage with symmetric circuit

The CM current is therefore shown to be a function only of the parasitic capacitance and the CM voltage.

In the previous paragraphs, a single capacitance represented a rotating machine's parasitic capacitance. An alternate model depicted in Figure 3 represents the capacitance associated with the shaft bearing as a variable capacitance that depends on the rotational speed's impact on oil film thickness.

The method in which a system is grounded impacts CM voltages and currents. An ungrounded system is a power system whereby an intentional current path from the system conductors to ground is not provided. Providing an intentional current path results in a grounded system; this intentional current path results in a reduction in the CM impedance.

Since rotating machines and cables will have parasitic capacitances, reducing the CM voltage applied to these capacitances becomes important in reducing CM current. Within naval power systems, the two major contributors to CM voltages are circuit asymmetry, and power electronic power conversion.

Figure 4 depicts a simple asymmetric d.c. circuit. The asymmetry results from the 10 ohm resistor in the positive conductor path that is not replicated in the negative conductor path. The CM voltage to the left of the resistor is the voltage midway between +50 V and -50 V or 0 V. To the right of the resistor, the CM voltage is -5i(t) volts (midway between 50 – 10i(t) and -50 volts). Hence the "unbalanced" resistor results in a voltage difference between the neutrals of the power systems to the left and right of it. A symmetric circuit is shown in Figure 5. This circuit eliminates the CM voltage to the right of the resistor.

Another source of CM voltage is power conversion between an input and output power system. Based on the design implementation of the converter, a voltage between the neutrals of the input and output power systems can exist. This voltage is the difference between the CM voltages of the input and output power systems.

For example, Figure 6 depicts a three phase uncontrolled rectifier. The input power system is three phase a.c. and the output power system is two conductor d.c. If the three phase rectifier consists of ideal diodes and powered by ideal voltage sources, then Figure 7 depicts the a.c. phase voltages and d.c. conductor voltages with respect to the neutral of the a.c. system. Figure 8 depicts the d.c. waveforms from Figure

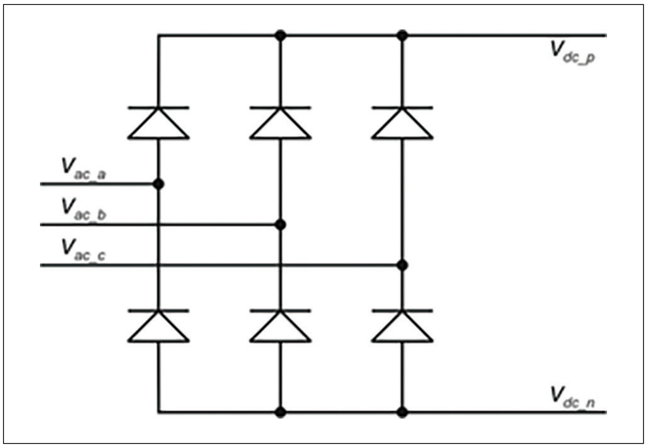

FIGURE 6. Three phase rectifier

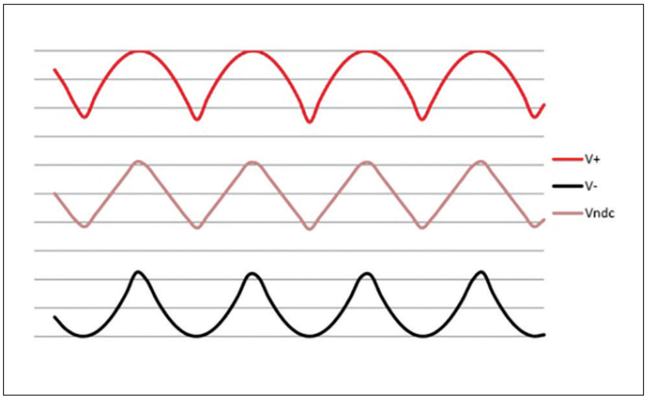

FIGURE 8. D.c. Waveforms and Neutral Offset of d.c. System with Respect to Neutral of a.c. System

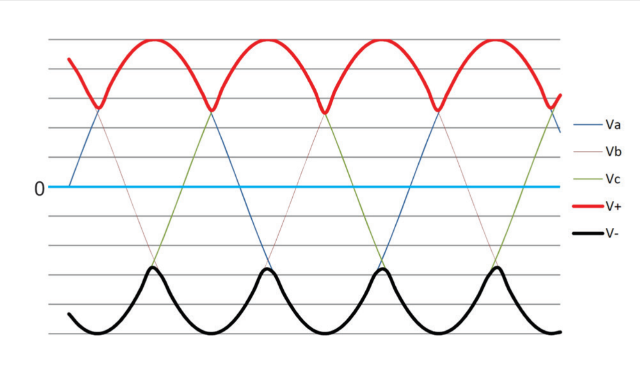

FIGURE 7. Three Phase Uncontrolled Rectifier Voltage Waveforms

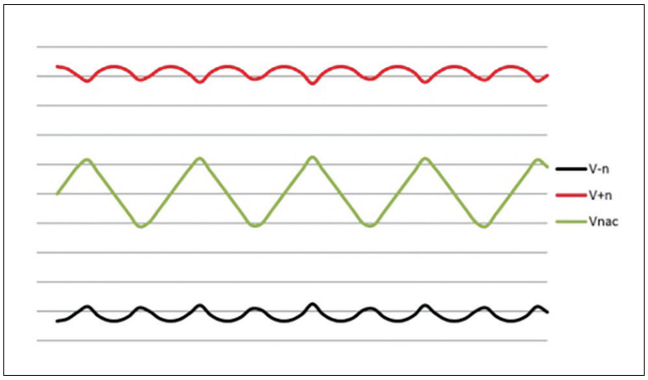

FIGURE 9. D.c. Waveforms and Neutral Offset of a.c. System with Respect to Neutral of d.c. System

7 and the d.c. system neutral voltage with respect to the a.c. system neutral. Figure 9 represents the same data as Figure 8, but with respect to the neutral of the d.c. system.

A Pulse Width Modulation (PWM) voltage source inverter with a d.c. input and a three phase a.c. output will also experience a voltage differential between the neutral points on the d.c. and a.c. sides of the inverter. Each line of the a.c. output is switched between the positive and negative conductors of the d.c. input (±0.50 times the d.c. line to line voltage referenced to the d.c. system neutral). Table 1 lists the voltage of the a.c. system neutral voltage referenced to the d.c. system neutral point (The average of the three phase voltages) for the eight possible combinations of a.c. system phase voltages (referenced to the d.c. system neutral point). The voltage between the a.c. neutral point and the d.c. neutral point will be a.c. with a frequency that depends on the PWM switching frequency. The actual shape of this a.c. waveform depends on the details of the modulation scheme. Figure 10 shows actual measurements for an inverter.

Phase A voltage (ref d.c. neutral)	Phase B Voltage (ref d.c. neutral)	phase C Voltage (ref d.c. neutral)	a.c. neutral Point Voltage (ref d.c. neutral)
-0.5	-0.5	-0.5	-0.50
-0.5	-0.5	0.5	-0.17
-0.5	0.5	-0.5	-0.17
-0.5	0.5	0.5	0.17
0.5	-0.5	-0.5	-0.17
0.5	-0.5	0.5	0.17
0.5	0.5	-0.5	0.17
0.5	0.5	0.5	0.50

TABLE 1. Neutral Point Voltage Difference for Input and Output of PWM inverter.

Figure 11 further simplifies Figure 2 to demonstrate the process of modeling CM circuits. As shown in Figure 11, a voltage source motor drive application generally consists of three connected (non-independent) power subsystems: the

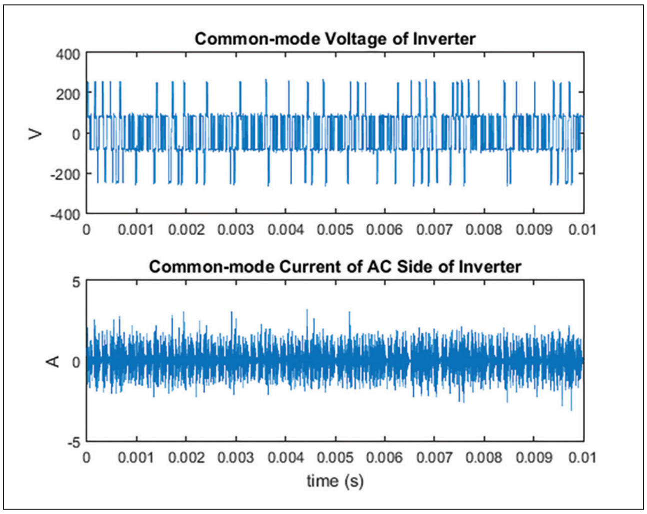

FIGURE 10. CM Voltage and Current of an Inverter (courtesy of Dr. Steve Pekarek)

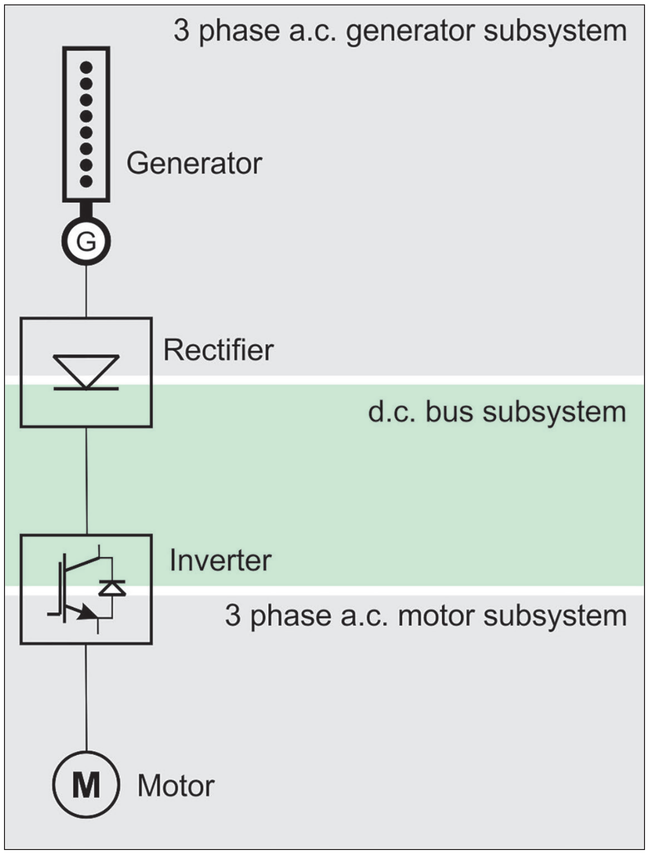

FIGURE 11. Simplified Electric Drive System

a.c. generator subsystem corresponding to the generator (or transformer) output, the d.c. bus subsystem corresponding to the d.c. bus at the rectifier output and inverter input, and the a.c. motor subsystem corresponding to the inverter output and motor input. These three power subsystems will all have voltage differences between their respective neutrals.

The method of grounding establishes the relationship of the various connected power system neutral voltages with respect to ground. Hard grounding a neutral for one of the power systems will eliminate the impact of parasitic capacitances for that power system. However, a voltage difference between power system neutral points will result in CM current to flow in the other power systems back through this hard ground. Impedance grounding a neutral for one of the power systems will result in all of the power systems having CM voltage that depends on the CM current.

A CM model of a power system is derived from a traditional schematic representation with the parasitic capacitances inserted. Figure 12 depicts a traditional multi-phase schematic of the simple power system of Figure 11 where the relationship with ground is established only through parasitic capacitances. The "Rectifier Power Electronics" and "Inverter Power Electronics" contain only power electronic switching elements (such as diodes, controlled rectifiers and transistors) whose switching behavior is determined by a combination (if applicable) of device characteristics and switching scheme. The switching behavior is usually the most significant source of CM voltages within a power system.

The three phase depiction of a power system in Figure 12 demonstrates symmetry that can be exploited to develop the simpler CM circuit also depicted in Figure 12. The impedances for the phases are all combined in parallel. Balanced voltage sources (including the back electromagnetic force in the motor) are eliminated because they do not contribute to CM voltages (The difference in voltage between their wye connection and the neutral of the output of the generator is zero) Although impedances between phases that do not connect with ground are important for differential mode analysis, they can be eliminated in CM analysis if they do not contribute to the CM current (e.g. the d.c. line to line bus capacitance is eliminated). The power electronics are replaced with voltage sources to represent the shift in neutrals between their input power system and output power system. For an uncontrolled rectifier, the CM voltage source for the rectifier will look similar to the middle waveform of Figure 9.

The voltage sources are often represented as a plot in the frequency domain. Since all of the elements in Figure 12 are passive components or voltage sources, the CM current can be calculated by superposition: the CM current from the rectifier can be added to the CM current from the inverter. See Brovont and Pekarek (2015) and Bosworth et al. (2016) for more information on CM modeling.

From a systems perspective, superposition enables examining each CM voltage source independently; other

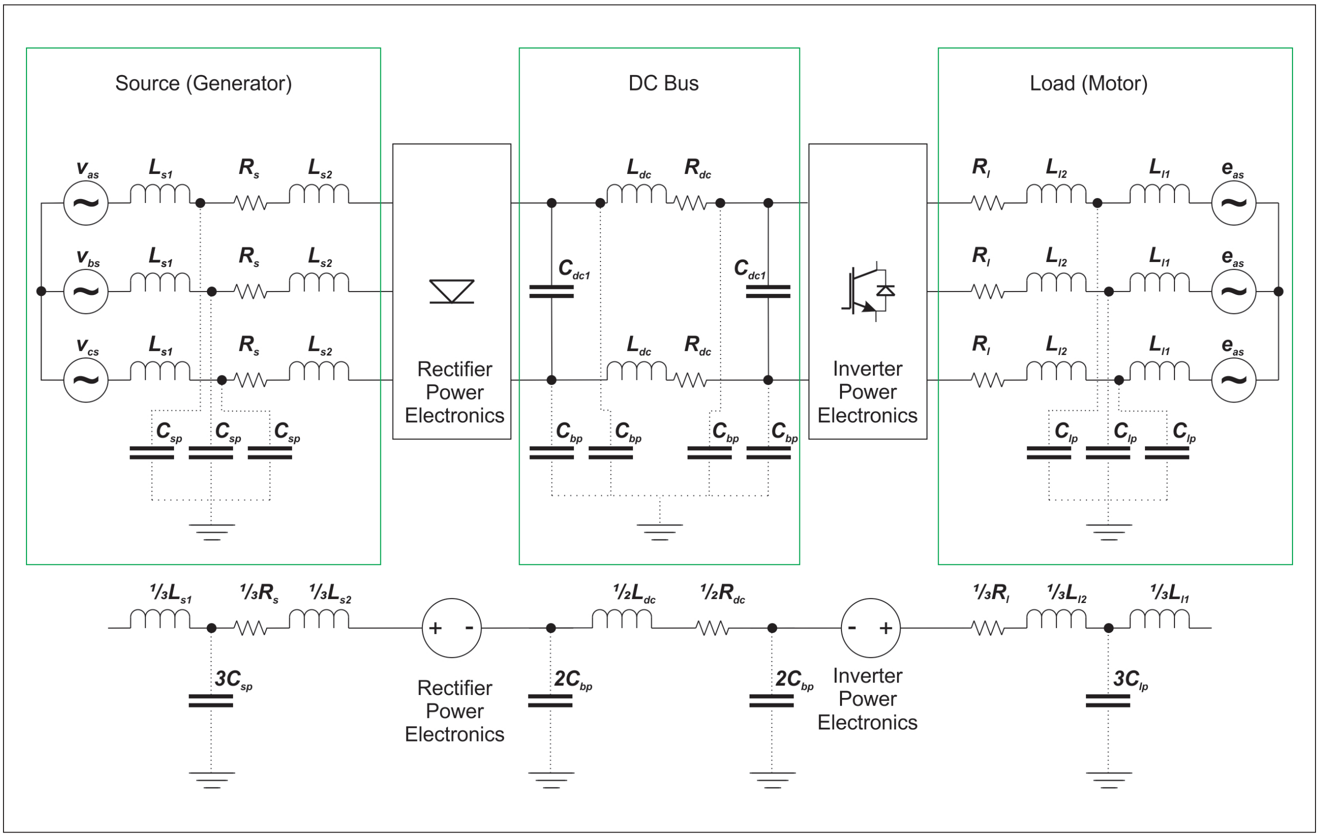

FIGURE 12. Multiphase and CM Depictions of CM Circuit

CM voltage sources are removed in determining the current produced by the CM voltage source under study.

For a given CM voltage source, the CM current it creates in two locations is of greatest interest. First, the CM current through the CM voltage source is generally a lower bound on the total CM current within the equipment. While criteria for the limits of this CM current have not been established, based on analogy to a.c. systems, these currents likely should be kept at less than about 10 amps, perhaps as low as 1 amp. Other CM voltage sources may also contribute to the CM current, but in a well designed power system, this additional current should be much smaller. This current is calculated by dividing the CM voltage by the CM impedance measured at the CM voltage source.

To minimize the impact of a CM voltage source on other power system components, as well as minimizing electromagnetic interference, the CM current in the feeder cable to the equipment caused by the served equipment should be low. While criteria does not exist for this CM current either, keeping the value to under 1A, perhaps under 100 mA, will likely be sufficient to limit EMI as well as minimize the impact of one element of the power system on other elements. For this paper, the ratio of the CM current in the feeder cable to the CM voltage is called the CM transadmittance. Transadmittance is measured in units of siemens (S) or equivalently mhos (the reciprocal of ohms).

The strategy of allowing the current through the CM source to be an order of magnitude larger than the current through the feeder cable enables equipment manufacturers to design their own equipment to operate within the CM environment they themselves create, while minimizing the impact on other equipment.

Using the following values for the common mode circuit depicted at the bottom of Figure 12 results in the frequency response of the CM impedance and transadmittance depicted in Figure 13.

L_{s1}	120 μH
R_s	0.3 Ω
C_{sp}	6.67 nF
L_{s2}	1.3 μH
C_{bp}	58 nF
L_{dc}	19.62 μH
R_{dc}	0.3 m Ω
L_{l2}	1.3 μH
L_{l1}	120 μH
R_l	0.3 Ω
C_{lp}	6.67 nF

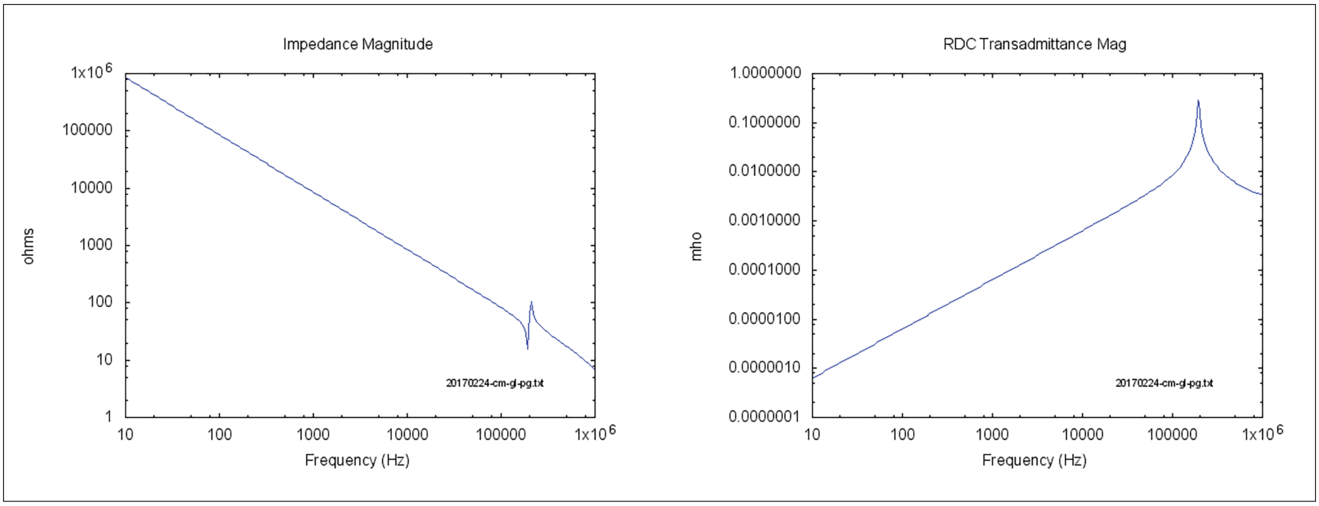

FIGURE 13. CM impedance and CM transadmittance of parasitically grounded system

Since the inductances are small, the frequency response of the impedance is largely due to the parasitic capacitance. For low switching frequencies, the CM impedance is large. For example, a six-pulse rectifier of a 60 Hz. system would have its fundamental at 180 Hz. The CM impedance is about 47kΩ. However, an active rectifier with a switching frequency of about 10 kHz may be needed to provide the requisite power quality and system stability when supplying pulse power loads. For a switching frequency of 10 kHz, the CM impedance at the switching frequency is only 859 Ω. While the magnitude of the CM voltage will depend on the switching scheme employed by the active rectifier power electronics, the CM rms voltage component at the fundamental switching frequency is likely to be less than 25% of the line to neutral voltage. For a 12 kV system (6 kV line to neutral) this implies an upper bound of 1.5 kV for a CM voltage frequency component. Hence the CM current through the CM source is likely to be less than 2 amps at 10 kHz, which may be acceptable. With this system however, the impedance continues to drop as the frequency rises. This implies that high frequency voltage components of the CM voltage must be suppressed to preclude large CM currents at these very high frequencies.

The transadmittance at 180 Hz is very small (less than 10 μS) and thus CM currents at 180 Hz will likely not be in issue with respect to EMI or operation of other equipment. At 10 kHz, the transadmittance is 0.54 mS. Using the same upper bound of 1.5 kV for the CM voltage, the CM current through the feeder cable at 10 kHz will likely be less than 1 amp. Note that the model for the cable is a PI model where the CM current is measured through the resistance. This implies that the CM current through the first parasitic capacitance “leg” of the PI model is ignored. The resonance peak at roughly 100 kHz is due to the interaction of the bus inductance and parasitic capacitance. The bus inductance and parasitic capacitances are a function of cable geometry, possible interaction with ship structure, and cable length. At high frequencies, the validity of the PI model is also questionable.

Note that the CM current is largely determined by the values of the parasitic capacitances. If these capacitances were actually double the assumed values, the CM currents would also be roughly twice as high. The value of the transadmittance at frequencies between 100 kHz and 1 MHz may prove problematic with respect to EMI.

Basics of Shipboard Grounding

Electric power system grounding orthodoxy applied to shipboard systems addresses four principal issues. First, ensure the safety of the crew. Second, mitigate potentially damaging effects of unintended electric currents in the ship’s hull and equipment. Third, enable continued operation of the electric power system while a single ground fault can be detected, localized, isolated, and the power system appropriately reconfigured. Fourth, limit the voltage to which equipment would be exposed during a line to ground fault, which is a major factor in insulation/dielectric design choices. Additional, secondary issues associated with grounding shipboard electric power systems exist and must be considered; however, the principal four are first-order grounding system design drivers.

Ships at sea move, sometimes a lot. At any given time, anywhere onboard a ship, crew may have to reach out and grab the nearest thing – which could be anything - to keep from falling or being thrown. The electric potential of the thing with which they are in contact with one part of their body, let’s say a hand grabbing a corner of an equipment cabinet, must be very, very close (less than a couple tens of volts) to the electric potential of the thing with which they are in contact with a different part of their body, let's say their back pressed up against hull structure, otherwise they may be exposed to a potentially fatal shock. For this reason, all equipment cabinets with electric powered contents must have a solid electrically conducting connection directly to the hull; the interior electric powered contents with potentials greater than local hull potential (local ground) must be electrically isolated from the equipment's exterior cabinet.

The vast majority of ships' hulls are constructed using electrically conductive materials, steel and aluminum. Ships' hulls are largely continuous structures. Hence, if one point of the hull is at a different electric potential than another point in the hull, then an electric current will flow through the hull between those points then back through the circuit which caused the difference in the electric potential of those two points. Given the complexities of hull geometry and the heterogeneous nature of the hull materials, the electric current's path (of least resistance) cannot typically be predicted. Current too great can cause damage to the hull structure through a number of physical effects. Current through equipment made of conductive materials mounted to the hull can cause damage to that equipment. The cause of the difference in potential which leads to the current flow could be the formation of a classic low-resistance conductive path between a powered element to the hull (line-to-ground fault) or the excitation of a capacitive path (ac current flow) between a powered element to the hull (CM current injection). Regardless of the cause, unintended and unconstrained current flow through the hull and equipment is undesirable.

Ground faults can be insidious. Detecting that one exists is usually, although not always, straightforward. Once a ground fault is detected, determining where the ground fault is physically located can require a significant effort, particularly if the ground fault is intermittent. In classic U.S. Navy electric power systems, three phase low voltage 60Hz a.c., ground fault localization had been accomplished by the crew. Hence, it could take at least minutes, probably hours, maybe days – an electric eternity. It is necessary for the ship to continue to operate more or less normally while this ground fault localization is ongoing. This necessity amounted, historically, to a requirement that the electric power system be able to operate continuously in the presence of one line to ground fault. With the move to medium voltage a.c. electric power systems, the potential damage caused by the current flow induced by a single line to ground fault has made continuous operation in the presence of a line to ground fault undesirable. Fast isolation of the portion of the electric power system wherein the line to ground fault manifests itself occurs before precise localization of the fault may have occurred. System redundancies must be relied upon to ameliorate the operational effect of a somewhat broader isolation of power from the fault. A more accurate statement today is that the electric power system must continue to operate long enough to detect, localize, isolate, and reconfigure in response to a line to ground fault; in fact, these steps must be accomplished very rapidly indeed, faster by many orders of magnitude than any crew intervention permits.

The power system ground makes a difference in components' specifications. In an ungrounded (also known as floating or parasitically-grounded) MVDC system, each rail (or line), positive $+\frac{V_{dc}}{2}$ and negative $-\frac{V_{dc}}{2}$ (measured with respect to the MVDC neutural), is isolated from ground (hull potential). In this case, a single rail (line) to ground fault can be tolerated. The faulted rail and the hull will be at the same potential. The voltage of the ungrounded rail will change to $|V_{dc}|$ relative to the hull. When there is no rail to ground fault, the rail to ground voltage is indeterminate; it can 'float' relative to the ground (hull potential). Here, the insulation system for the rails must be specified to accommodate this indeterminacy and transient effect; the insulation system is commonly rated for more than twice nominal voltage $|V_{dc}|$. In a resistance grounded system, the midpoint between the rails is grounded with resistors. When there is no rail (line) to ground fault, the rail to ground voltage is $\left|\frac{V_{dc}}{2}\right|$. When there is a rail (line) to ground fault, the rail to ground voltage is no greater than nominal voltage in the steady-state and transients are damped. Here, the resistance grounded MVDC power system could be specified with lower insulation resistance than an ungrounded MVDC power system.

These considerations influence the three types of grounding techniques found onboard ships. First is equipment grounding. This is to ensure the exteriors of equipment and cabinets are safe to touch. Second is electric power system grounding. This is the intended (constrained) path for ground currents to take during ground fault and CM conditions. Third is signal ground. This is to provide a reference for the detection of electromagnetic phenomenon, particularly for sensors and radio.

IEEE Std 45.1-2017 and IEEE Std 142-2007 articulate what can be taken as a generally accepted approach to shipboard power system grounding, albeit for an MVAC system. MIL-STD-1310 provides standard practices for EMI mitigation, Electromagnetic Pulse (EMP) mitigation, and electrical safety.

Impact of Grounding on CM Currents

The manner in which a power system is grounded has a direct influence on the magnitude and path of CM currents. Solidly grounding the a.c. system at the generator neutral is depicted in Figure 14. This ground inserts the stator inductance into the CM circuit in parallel with the parasitic capacitance. As shown in Figure 15, this lowers the CM impedance, particularly at lower frequencies. At 10 kHz, the CM impedance is only about 60 ohms, likely resulting in very high CM currents. Similarly the transadmittance is about 7.6 mS, implying that the d.c. bus CM current could be in the range of 10 amps. For this reason, grounding the a.c. system at the generator neutral is not recommended.

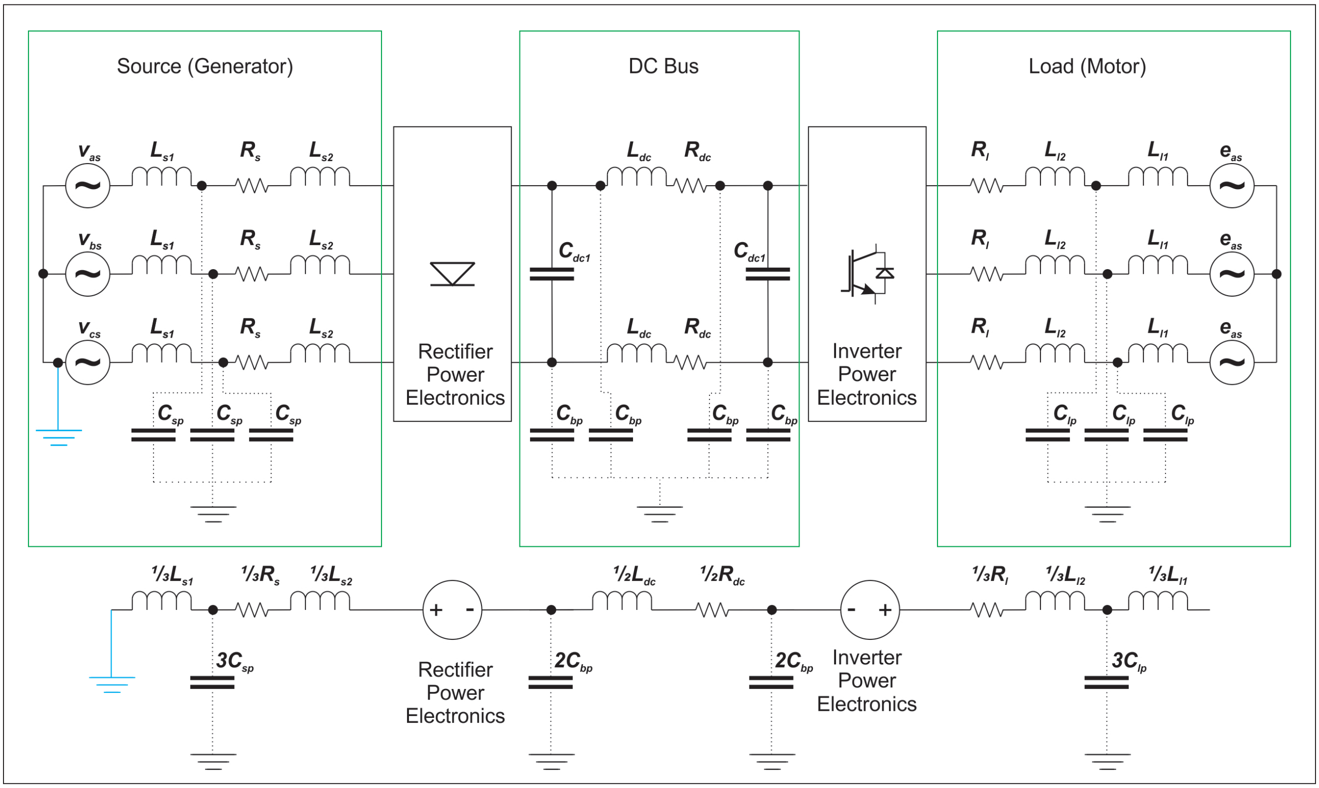

FIGURE 14. CM Circuits for grounding source a.c. system

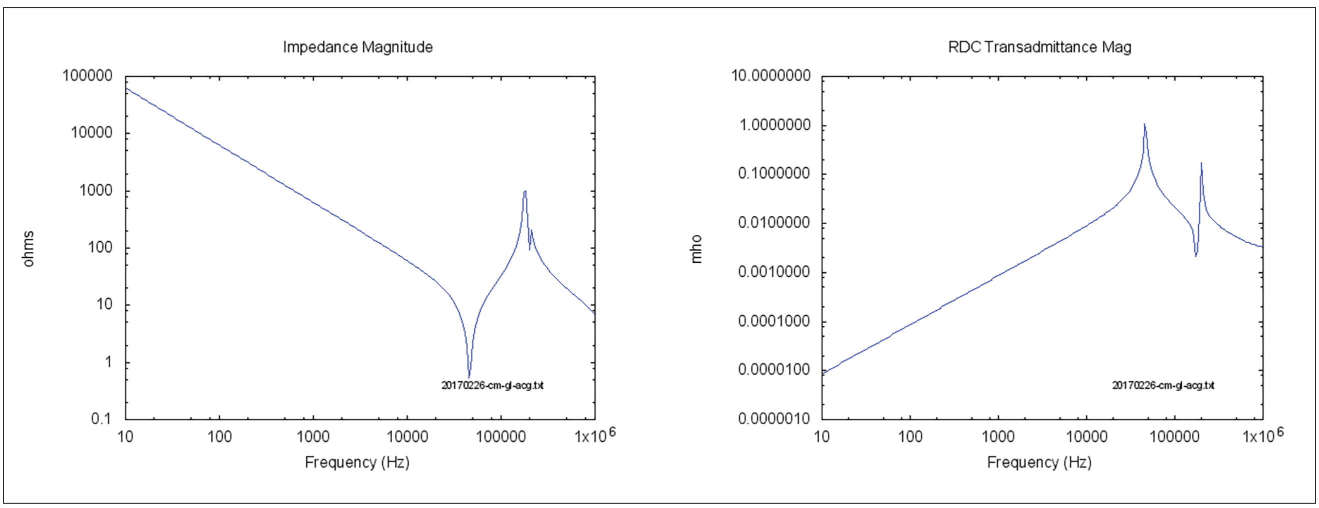

FIGURE 15. CM impedance and CM transadmittance for grounding source a.c. system

Most medium voltage a.c. systems are high resistance grounded at the neutral point as depicted in Figure 16. Figure17 presents the CM impedance and CM transadmittance when using a 1 kΩ grounding resistor. Note that this grounding resistor contributes significantly to the CM impedance between about 1 kHz and 10 kHz. As compared to the parasitically grounded circuit, the impedance is lower at lower frequencies (as expected) and very similar at higher frequencies. From a CM perspective, the grounding resistor does not contribute to managing CM current on the DC bus or CM current through the rectifier. A close examination of Figure 16 reveals that introducing an impedance to ground on the a.c. side of the CM source cannot reduce the transadmittance; focus must be placed on the d.c. side.

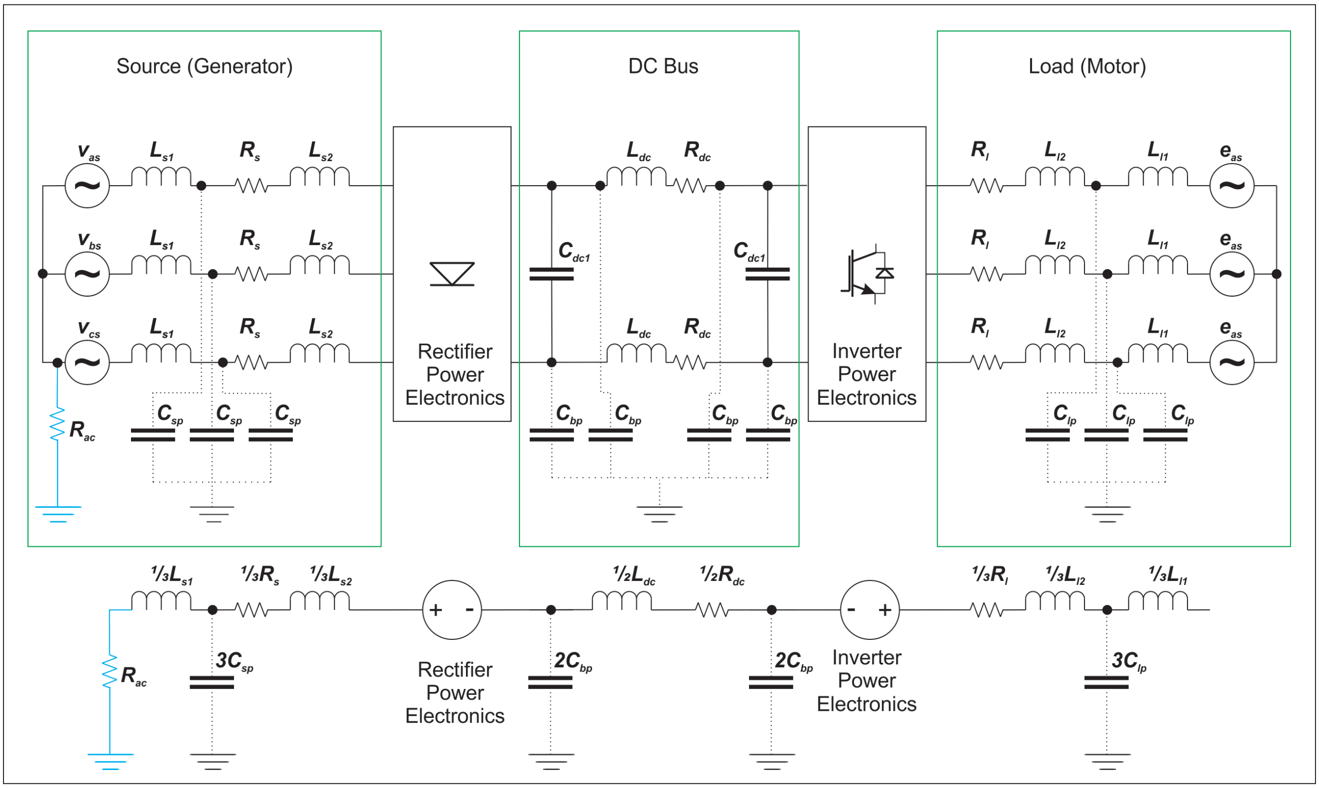

FIGURE 16. CM Circuits for high resistance grounding source a.c. system

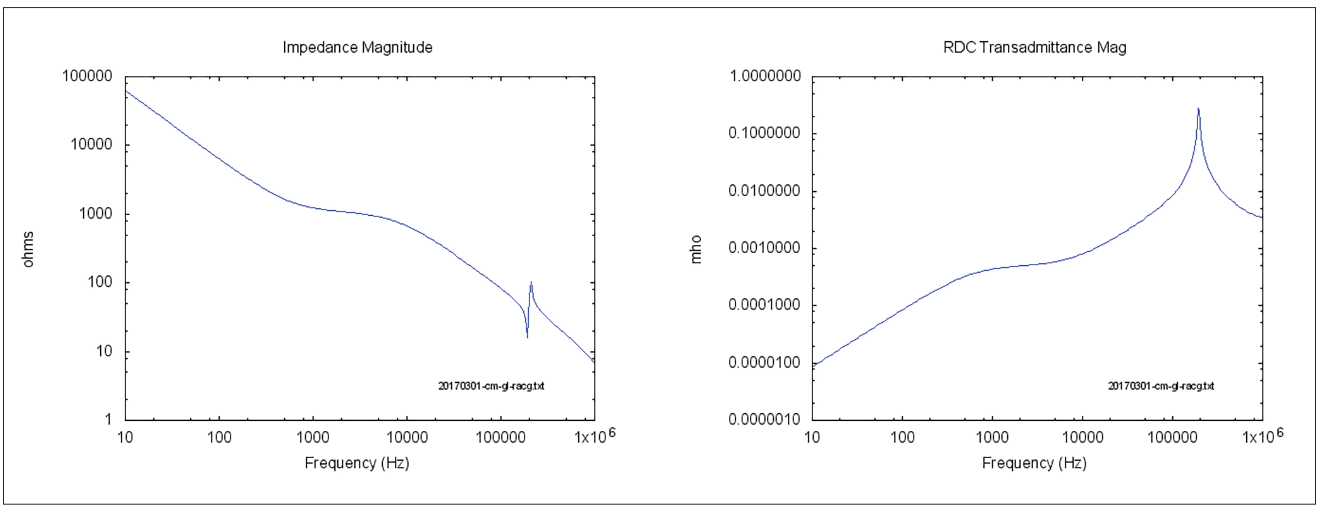

FIGURE 17. CM impedance and CM transadmittance for high resistance grounding source a.c. system

One strategy to reduce the CM current in the d.c. bus, is to shunt the CM current to ground between the CM voltage source and the d.c. bus. This must be done with care. For example, grounding the d.c. system with capacitors as depicted in Figure 18. does not have the intended result. A capacitor divider is used to establish the grounding point on the d.c. side of rectifiers and inverters. If these capacitors provide a suitably low impedance to ground, then little CM current will flow through the d.c. bus; the CM current generated by the rectifier will be shunted to ground by the rectifier capacitor divider and the CM current generated by the inverter will be shunted to ground by its capacitor divider. The capacitor grounding circuit will at high frequencies reduce the CM impedance of the CM sources. If the bus impedance is too low

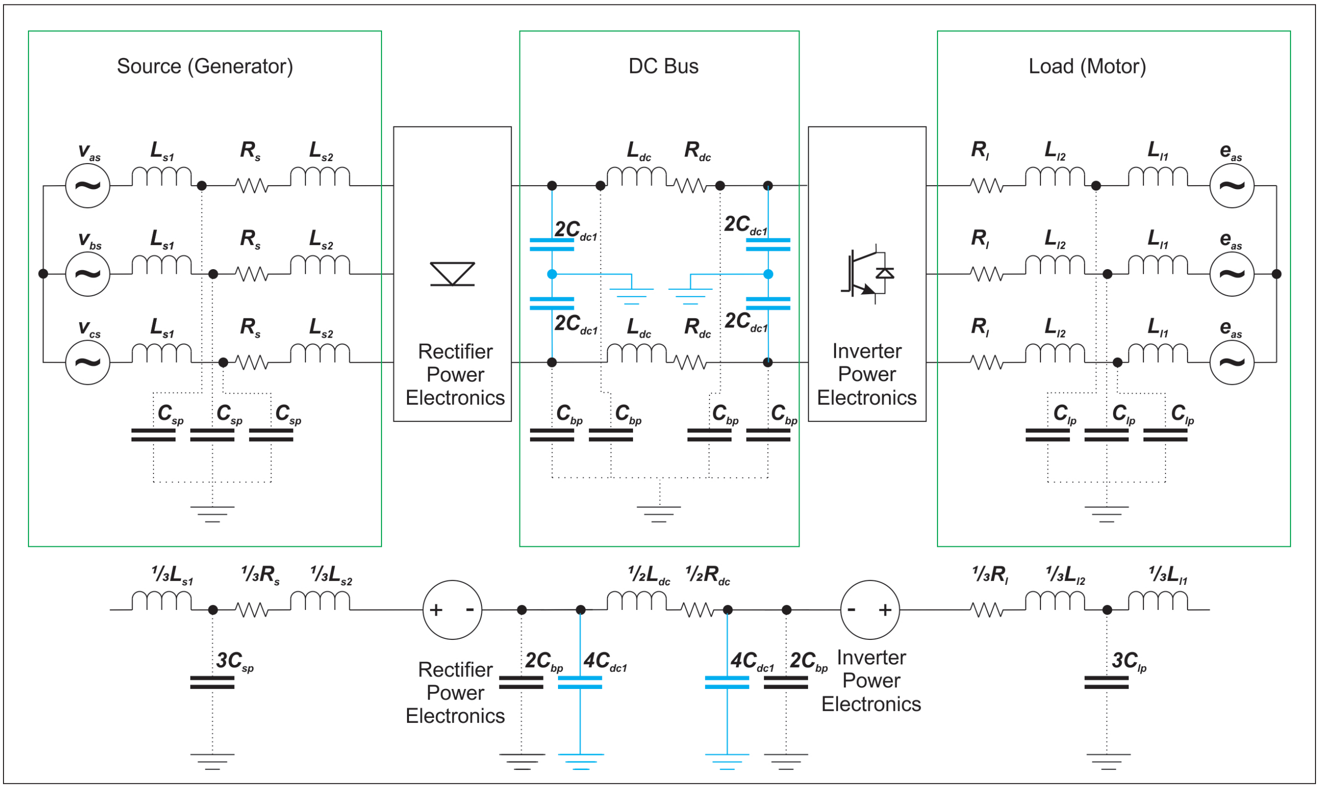

FIGURE 18. CM Circuits for Grounding at d.c. Side of Power Electronics

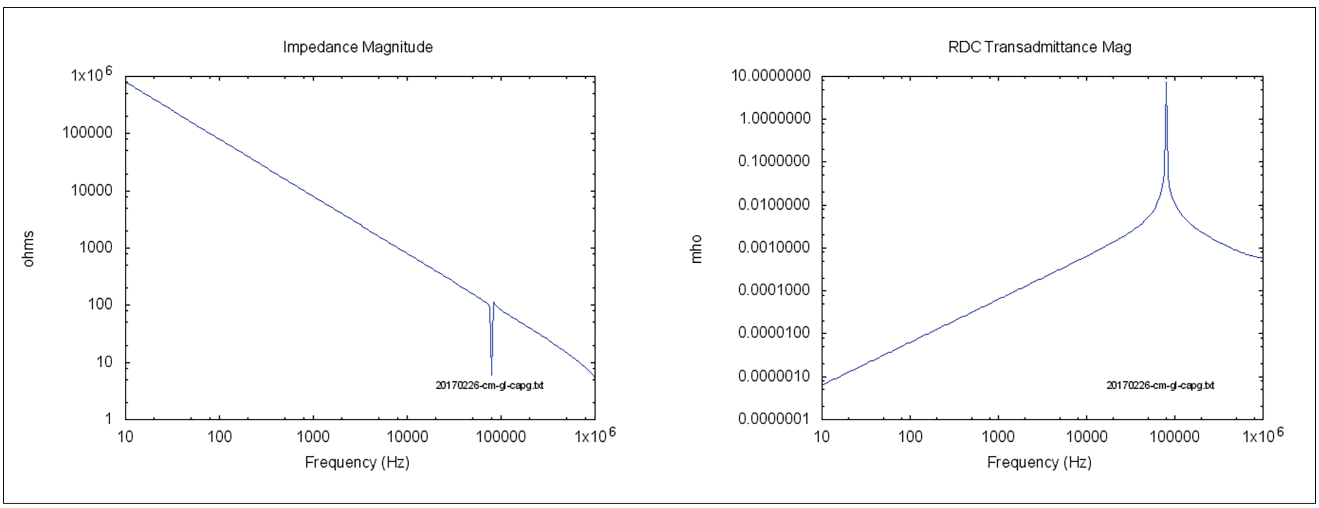

FIGURE 19. CM impedance and CM transadmittance for Grounding at d.c. Side of Power Electronics

however, increasing the line to ground capacitance on both ends of the distribution cable will not significantly change the ratio of current flowing through the d.c. bus and the shunting capacitor. This is demonstrated in Figure19 where $C_{dc1} = 0.17$ μF. A means for increasing the CM impedance of the d.c. bus without increasing the DM impedance is needed.

Increasing the CM impedance without substantially increasing the DM current can be accomplished with a CM choke. A CM choke (Figure 20) presents little impedance to the normal DM currents (currents of equal magnitude with opposite polarity) but a much larger impedance to the CM currents (currents of equal magnitude with the same polarity).

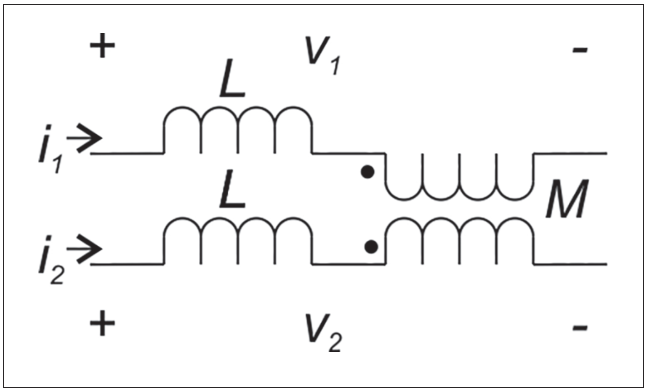

FIGURE 20. CM Choke

The equations for a CM choke are

$$v_1 = L\frac{di_1}{dt} + M\frac{di_2}{dt}$$

$$v_2 = L\frac{di_2}{dt} + M\frac{di_1}{dt}$$

The CM choke is constructed so that $L \approx M$. In a balanced system without the CM current, $i_1 = -i_2$. This implies for v_1

$$v_1 = L\frac{di_1}{dt} + M\frac{di_2}{dt} = (L - M)\ \frac{di_{1cm}}{dt}$$

since $L \approx M$, the voltage drop is very small. For the CM $i_{1cm} \approx i_{2cm}$. This implies for v_{1cm}:

$$v_{1cm} \approx L\frac{di_{1cm}}{dt} + M\frac{di_{1cm}}{dt} = (L + M)\frac{di_{1cm}}{dt}$$

Since L and M are additive, the impedance for the CM currents is generally orders of magnitude higher.

The CM choke is generally inserted on the d.c. side of rectifiers and inverters as depicted in Figure 21. Alternately, an a.c. choke may be inserted on the a.c. side of the inverter. The impedance of the CM choke dominates the other CM impedances, thereby reducing the magnitude of the CM current. Figure 22 depicts the CM impedance and transadmittance for L+M = 50 mH. As expected, the transadmittance decreases with rising frequencies due to the impedance of the choke. The resonant peaks however, are a function of the CM impedance interacting with the parasitic capacitance. Adding grounding capacitors provides the designer with better control for where these resonances reside.

Figure 23 depicts the circuit with both the capacitive ground from Figure 18 and the CM choke from Figure 21. As shown in Figure 24, not only can the transadmittance and CM impedance be controlled, but the frequency of the resonance controlled.

The resonances in Figure 24 can be dampened by introducing a small resistance between the grounding capacitors and ground as shown in Figure 25 and Figure 26. Figure 27 shows the dramatic impact of this resistance (R = 10Ω) on the transadmittance. This resistance also provides a lower bound for the CM impedance at higher frequencies and limits the discharge rate of the capacitance into a ground fault.

Another way to dampen the response is to insert resistances in parallel to the grounding capacitors as depicted in Figure 28 and Figure 29. The CM impedance and transadmittance are shown in Figure 30 for 4kΩ balancing resistors. The balancing resistors have the added benefit of

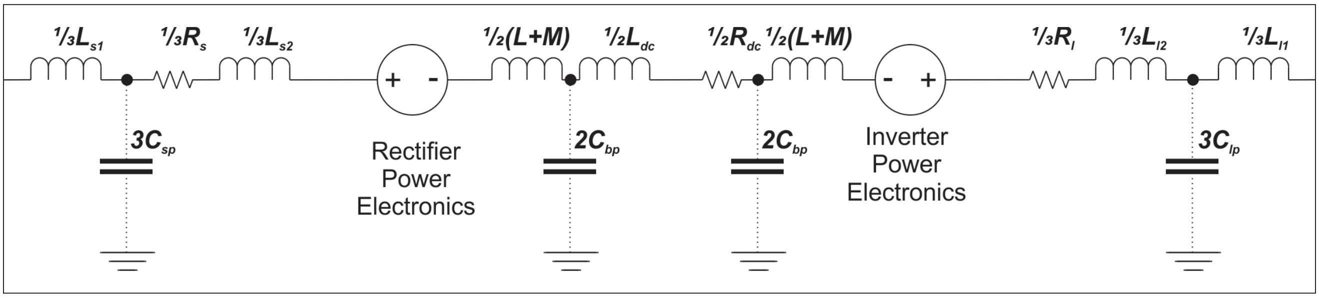

FIGURE 21. CM Circuit with CM Choke

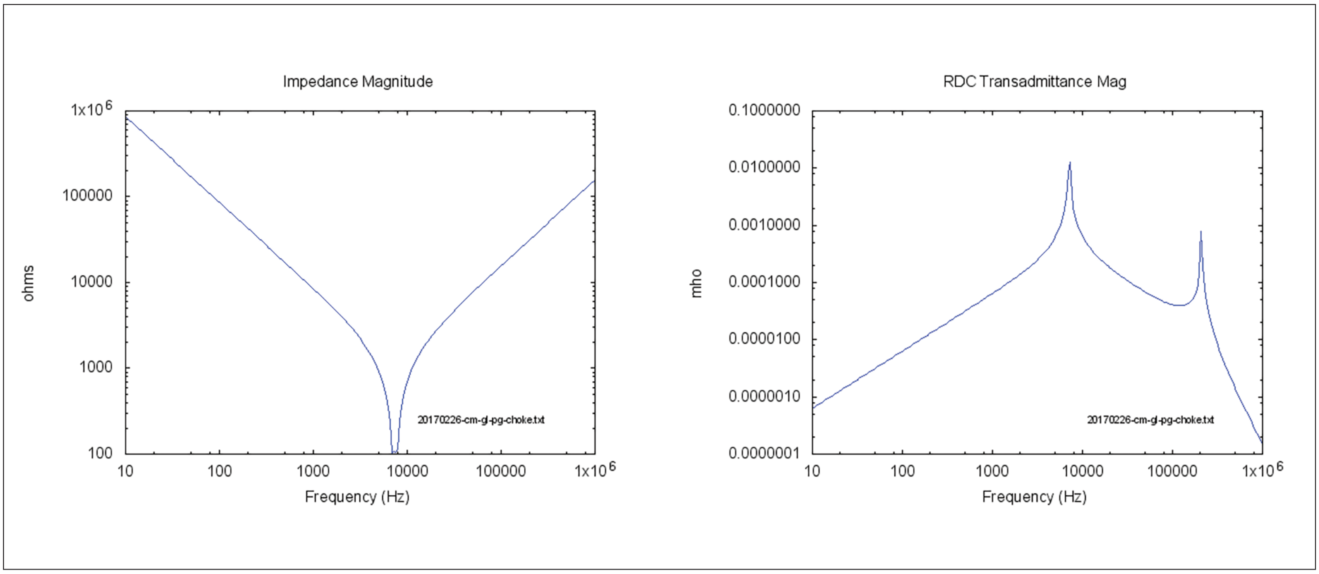

FIGURE 22. CM impedance and CM transadmittance with CM Choke

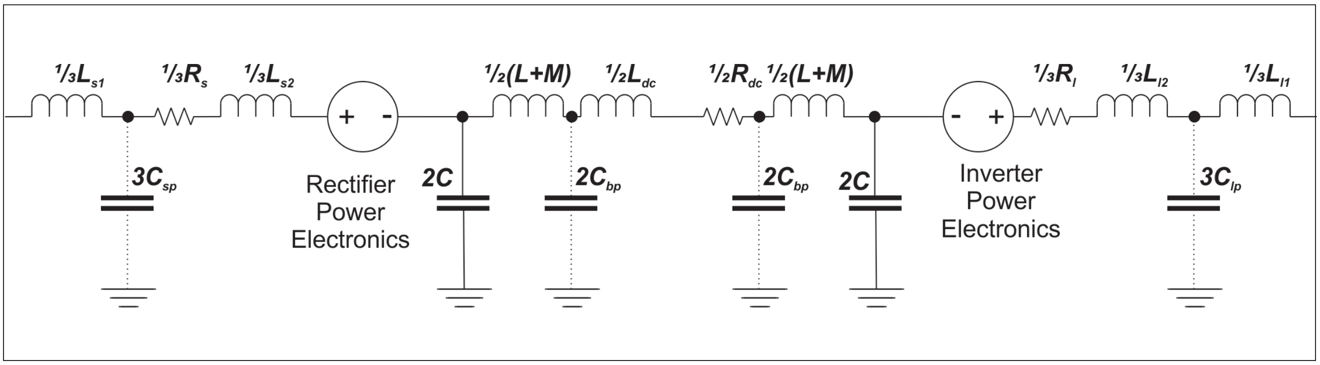

FIGURE 23. CM Circuit with CM Choke and capacitance ground

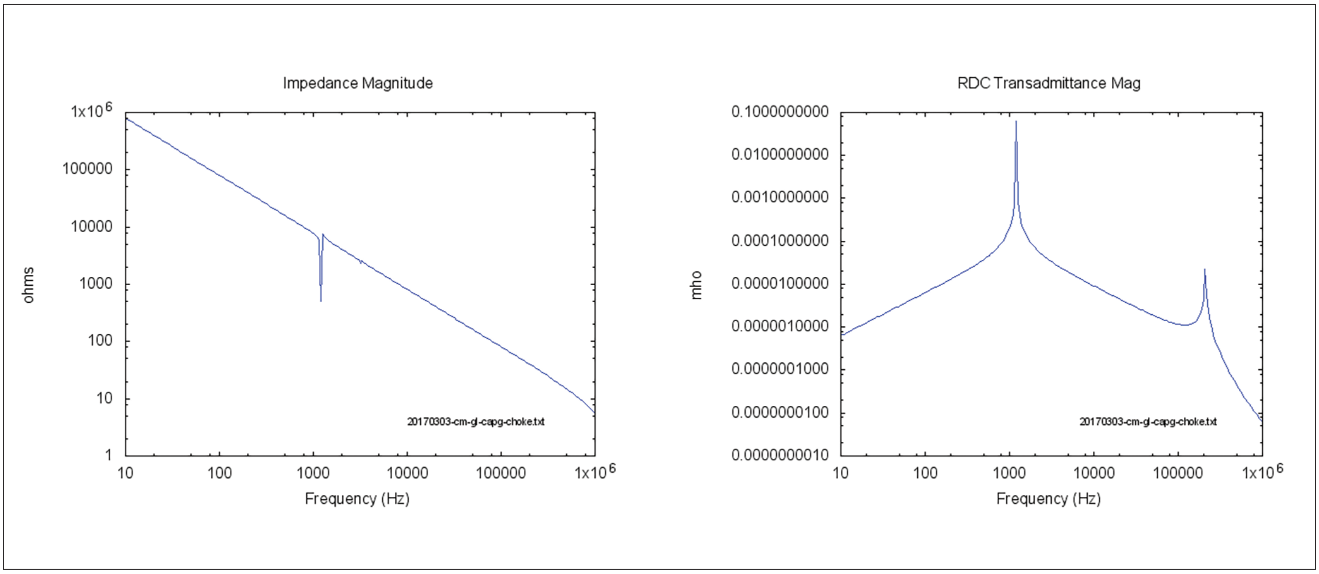

FIGURE 24. CM impedance and CM transadmittance with CM Choke and capacitance ground

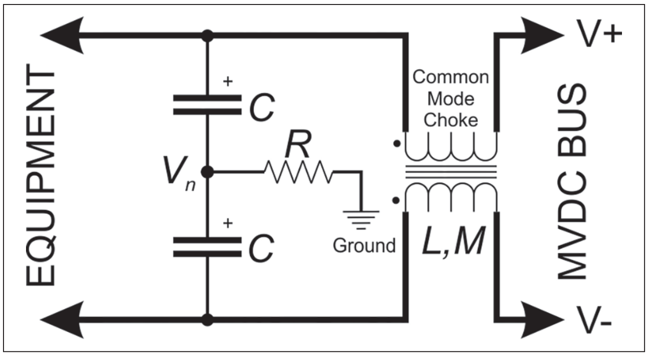

FIGURE 25. CM interface circuit with damping resistor

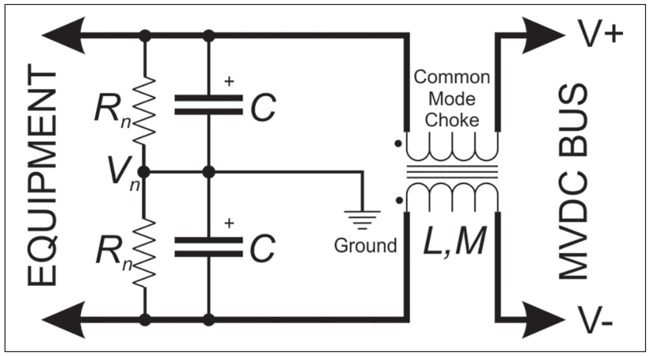

FIGURE 28. CM interface circuit with balancing resistors

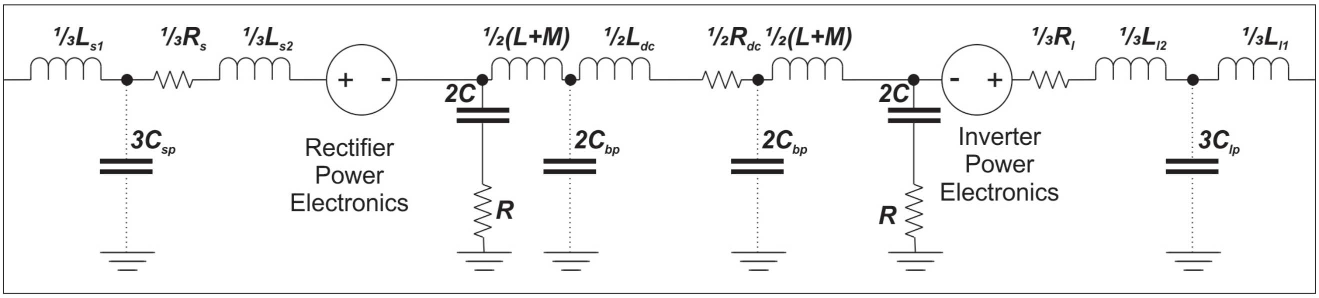

FIGURE 26. CM Circuit with CM interface using damping resistor

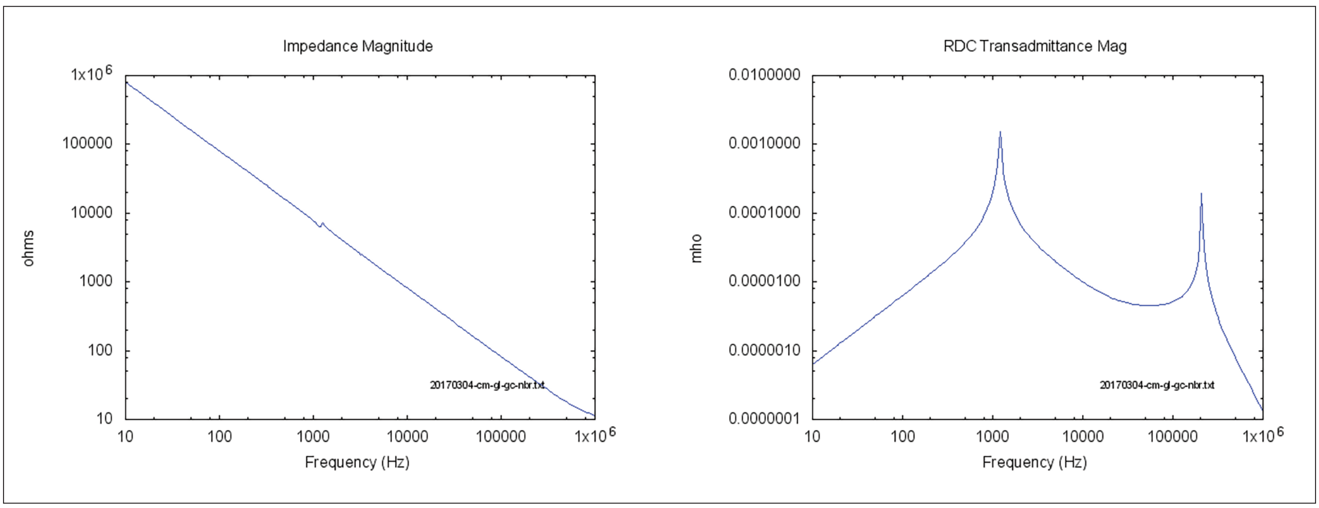

FIGURE 27. CM impedance and CM transadmittance with CM interface with damping resistor

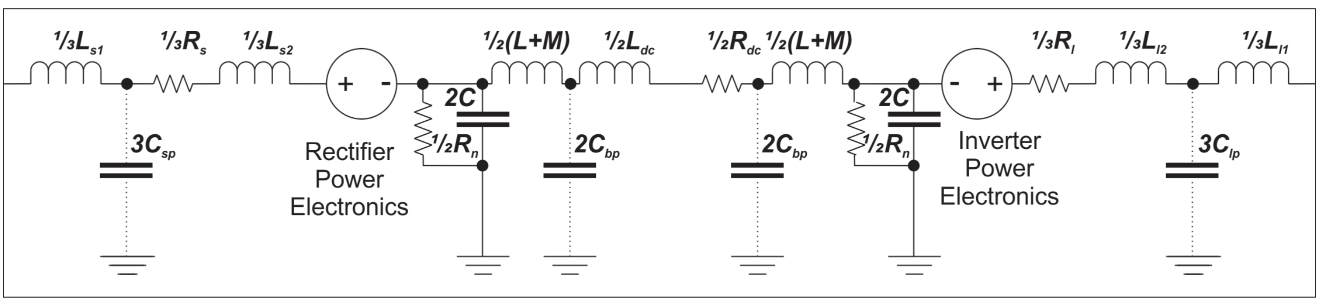

FIGURE 29. CM Circuit with CM interface using balancing resistors

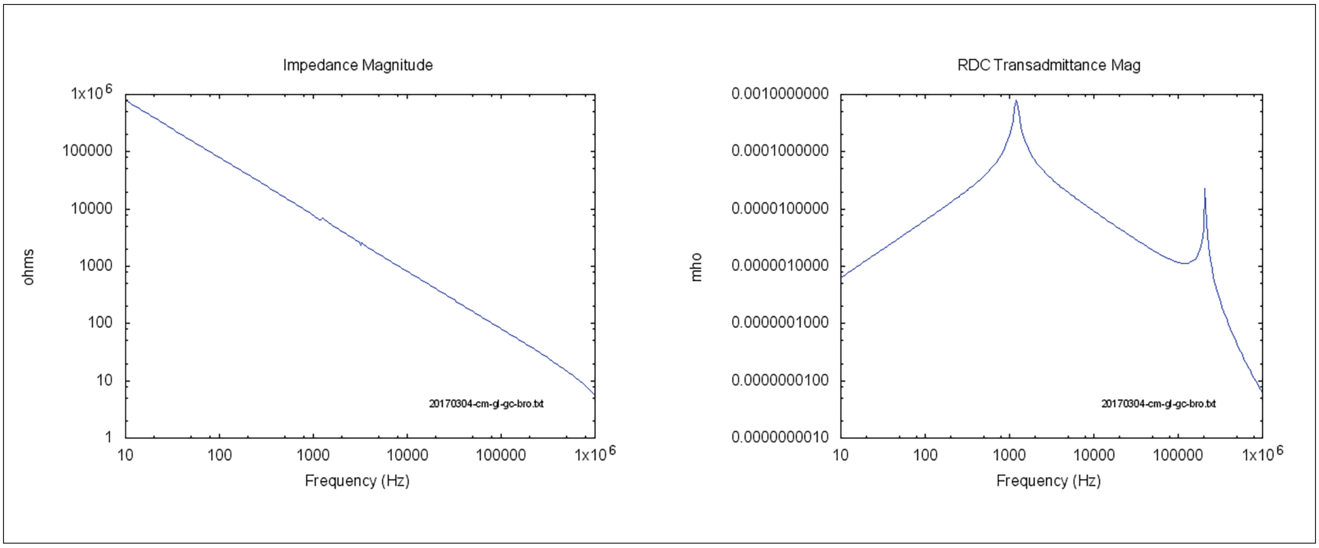

FIGURE 30. CM impedance and CM transadmittance with CM interface with balancing resistors

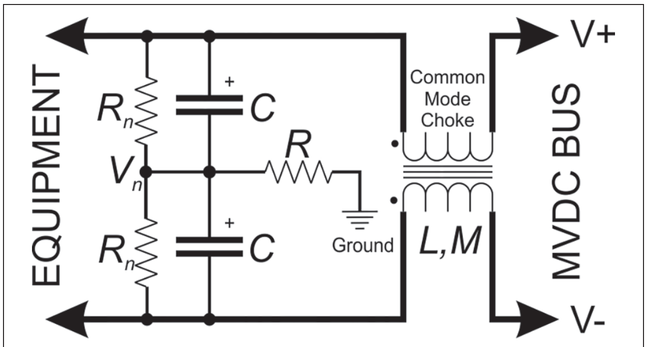

FIGURE 31. CM interface circuit

establishing the d.c. neutral of the d.c. system at the same potential as ground. The balancing resistors are also a differential mode load and will dissipate power at all times, hence keeping their resistance high is important to minimizing steady state losses. Since the d.c. neutral need only be established in one location within one d.c. power system, it is sufficient to provide these balancing resistors only for equipment that may behave as a source.

Adding both the damping resistor and the balancing resistors results in the circuits depicted in Figure 31 and Figure 32. Note that the damping resistor effectively provides a lower bound for the CM impedance. In some cases it may be desirable to insert a small inductance in series with the damping resistor to increase the impedance at high frequencies. The inductance should be chosen to avoid resonances within frequencies of interest.

The plots so far have been limited to a single source and a single load. Figure 34 depicts the CM impedance and transadmittance for a system of two sources and five loads as depicted in Figure 2. Each component has a CM interface circuit as depicted in Figure 31. The distribution cables connecting the various components vary in length. The impedance plot demonstrates that the CM impedance (as compared to Figure 33) is not sensitive to the network of distribution cable and other components in the system. The transadmittance plot is somewhat sensitive to the impedance of the cable network, but the magnitude remains tolerable in the frequencies of interest.

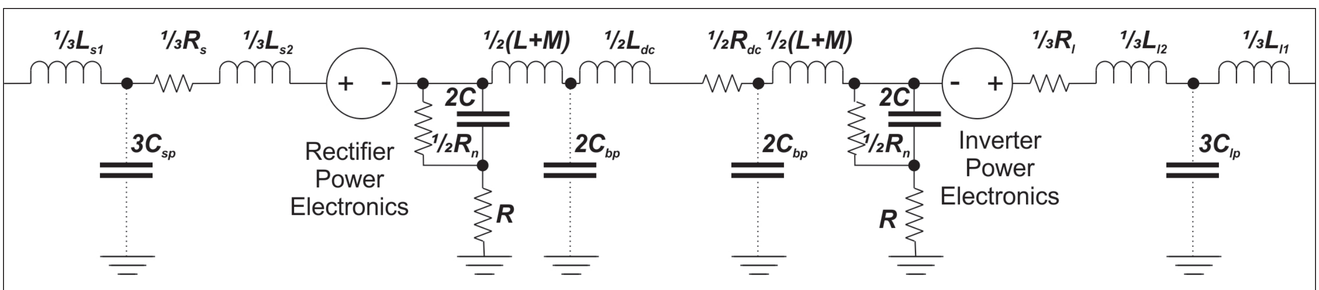

FIGURE 32. CM Circuit with CM interface

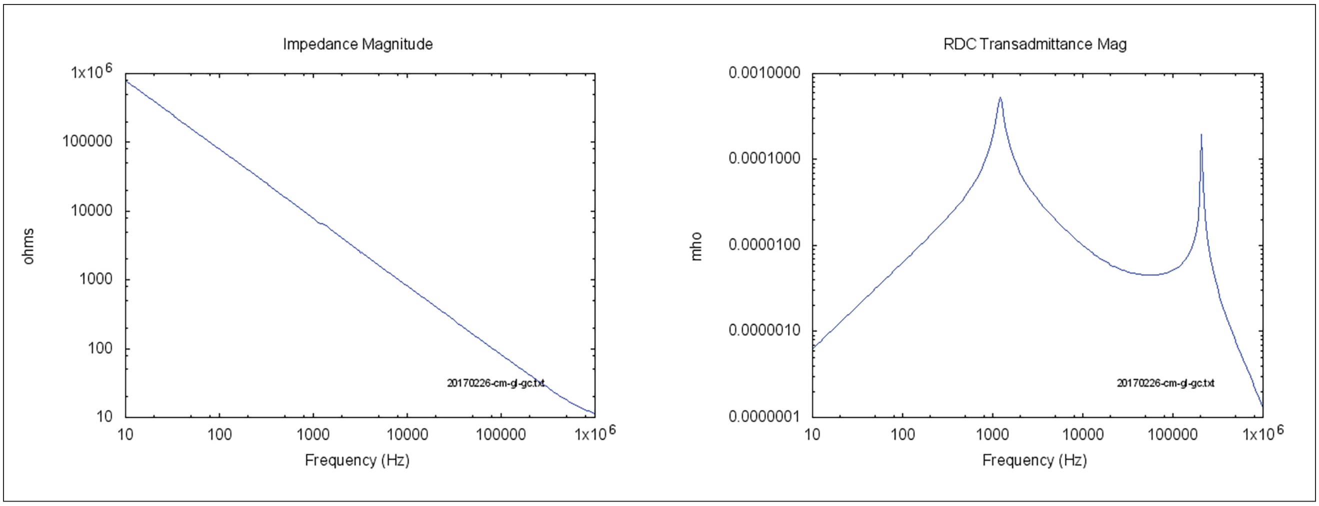

FIGURE 33. CM impedance and CM transadmittance with CM interface

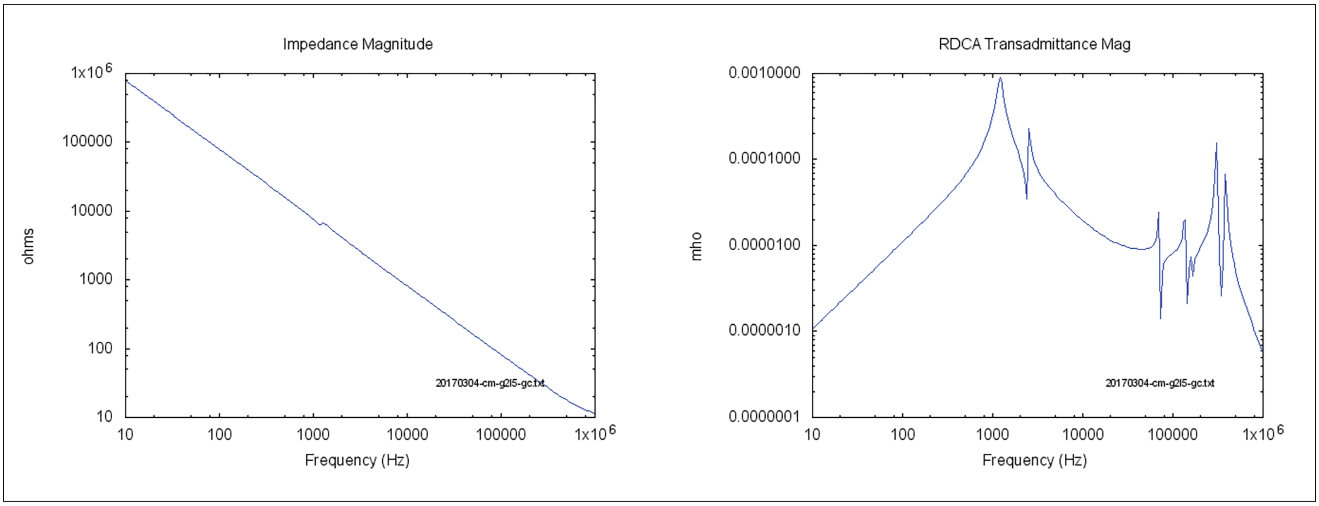

FIGURE 34. CM impedance and CM transadmittance with CM interface for 2 sources and 5 loads

Impact of Ground Faults

Ground faults (line-to-ground, or, rail-to-ground) can be characterized by their impedance. A solid ground fault, or short-circuit to ground fault, is a low-to-no impedance fault. Upon initiation of the ground fault, the grounding capacitors of each source and load will either discharge (if connected to the grounded (faulted) conductor) or charge to the full line to line voltage (if connected to the unfaulted conductor). The red arrows in Figure 35 trace the discharge current from the capacitor highlighted in yellow for a source. Note that this current is a CM current that must pass through the CM choke. The inductance of the choke, the capacitance and the grounding resistances result in a damped oscillatory current. Eventually, the voltage across the lower capacitor will decay to 0 volts unless the line to ground fault clears. The blue arrows depict the possible charging currents for the capacitor connected to the unfaulted bus; it will charge until it achieves a steady state d.c. voltage equal to the bus voltage. If the equipment connected to the grounding capacitor is a local source, the narrow blue arrow is the likely charging path. Note that this charging current is a CM current that also forms a circuit containing the capacitor, grounding resistors, and the CM choke impedance. Another possible source of charging current is a remote source; the charging path is depicted as the thicker blue line. Between the ground fault and the remote source, the charging current is differential mode and between the ground fault and the capacitor being charged, the charging current is CM. The same capacitance, resistance, and CM impedance apply to this charging path.

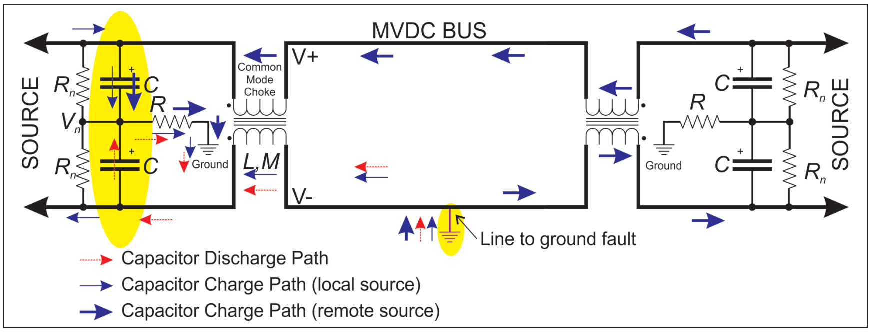

FIGURE 35. Line to ground capacitor charge and discharge paths for ground fault at source

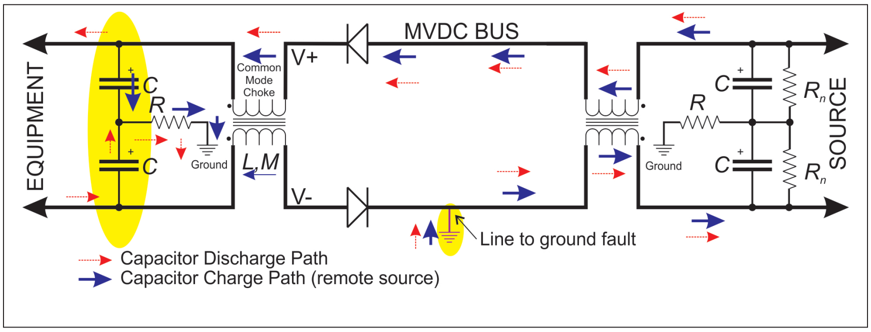

FIGURE 36. Line to ground capacitor charge and discharge paths for ground fault at load equipment

In summary, ground faults initially cause a transient common-mode response as line to ground capacitances charge or discharge to reach a new steady-state d.c. value. In the steady-state, a ground fault produces an asymmetric circuit that results in a d.c. CM voltage. This d.c. CM voltage interacts with the grounding resistors to produce a steady-state CM d.c. current.

One approach for ground fault localization suggested by Pan et al. (2011) is to sense periodically system impedances from selected locations and compare those impedances with reference impedances. A change of impedance observed at an interface at a particular location compared with other contemporaneous observations from other locations may enable localization of a ground fault. Such impedance mapping is wholly within the modeling domain associated with differential- and common-mode modeling discussed above. This emphasizes the usefulness, perhaps the necessity, of adopting CM techniques in power system design and analysis.

The ground fault will also cause a CM d.c. voltage source on the d.c. bus; the bus neutral to ground voltage will be half the line to line voltage. Since the line to ground capacitances are not impacted by a d.c. source in the steady-state, the steady-state CM current from this CM d.c. source will be determined by the grounding resistors.

For load equipment, while blocking diodes as depicted in Figure 36 are effective in preventing discharge of the capacitors into a line to line fault, the diodes do not prevent the capacitor charging and discharging circuits from remote sources as indicated by the red and blue arrows.

A higher (while not being ‘high-impedance’ in an absolute sense) impedance fault, while perhaps not evincing the proximate capacitive discharge fault current of a short-circuit fault, may still lead to damaging transient currents as line to ground capacitances charge and discharge. Intermittent, sometimes arcing faults, can inject current at unusual frequencies; this frequency rich ground fault current would, like the others, move through the lowest impedance path – at that unusual frequency - possibly exciting common-mode resonances. Additionally, again, depending upon location, a ground fault may cause asymmetry in the circuit; so, in addition to altering impedances, asymmetries in the system act as a common-mode source.

Recommended Practices

Designers of shipboard power systems should review IEEE Std. 45.1-2017 and IEEE Std 142-2007. Although these references are mainly concerned with a.c. power systems, aspects also apply to d.c. systems.

Given that a resistance grounded MVDC power system could be specified with lower insulation resistance than a parasitically grounded (“ungrounded”) MVDC power system, a resistance grounded MVDC system is recommended. That, by itself, leaves open the issues of the location of the resistance ground and the magnitude of the resistance. Based upon (1) achieving a symmetric system to minimize that common-mode source which arises from asymmetry, and (2) following the progression through the foregoing discussion of the impact of grounding on common-mode currents, MVDC midpoint grounding using balancing capacitors and resistors in addition to a damping resistor, all associated with a common-mode choke at each source within the MVDC system is recommended (see Figure 31). The corresponding circuit for load equipment should be the same but without the balancing resistors (see Figure 25) The design of each component of this CM interface circuit is very much dependent upon MVDC system design details for both DM and CM circuits. Hence, the magnitude of the resistances and capacitances becomes a design choice within that context; constraining ground fault current magnitude through the CM source argues for 'higher' resistances; this tempered by achieving beneficial common-mode transadmittance which calls for 'lower' resistances and higher CM impedance through the CM choke. The selection of component values should strive to minimize the influence of parasitic capacitances on the CM transadmittance.

The selection of component technologies to implement each of the components in the CM circuit must be done with care. Particularly at higher frequencies, components may have parasitic capacitances and inductances that must be properly modeled and accounted for to ensure adequate performance. The characteristics of these parasitic capacitances and inductances depend on the design, materials, and construction of the components.

Attention should also be placed on reducing the magnitude of the CM voltages, particularly at the frequencies where the power system experiences resonances. Consideration should be given to providing the ability to configure power electronics to have adjustable switching frequencies to avoid system CM resonances. Providing power electronics with frequency bands to avoid (analogous to fire control "cut-outs" for shipboard gun systems) is another way to accomplish this goal.

To minimize the CM voltage source, equipment and systems should be as symmetrical about the ground reference as possible. Passive devices should be incorporated symmetrically as depicted in Figure 5. Additionally, designers should consider rotating machines having an even number of phases with phases 180 electrical degrees apart. Traditional six phase machines are wound with stator windings displaced by 30 electrical degrees to cancel current harmonics; a displacement of 60 electrical degree is identical to a displacement of 180 electrical degrees and enables the power electronics to apply equal and opposite voltages to the stator windings to keep the neutral voltage at ground potential. Whether this recommendation is followed or not, the design of rotating machines (motors and generators) and their associated power electronics should be accomplished synergistically to minimize CM voltages. Designing the rotating machine and the power electronics independently, then integrating them is not recommended.

CM current may flow through the shaft bearings of a rotating machine, if not prevented by some means. These bearing currents may pit and degrade the bearing surfaces. To prevent bearing currents from damaging the bearings, the shaft may be grounded via a grounding brush or the bearing may be insulated from ground.

Reduction gear teeth and reduction gear bearings are also susceptible to damage from CM currents that flow through the motor shaft. These shaft currents may be reduced or prevented by using an insulated coupling or grounding brush.

Conclusion

This paper describes the impact of MVDC grounding system choices on CM current control as well as the response of the system to ground faults. It proposes using the CM impedance presented to each source as well as the transadmittance as useful measures for designing grounding interface circuits. This paper also presented recommendations for limiting CM voltages.

Further work remains to be done in

1. localization of ground faults,
2. coordinating isolation steps between the power electronic converters within the MVDC system and fault protection devices (circuit breakers and disconnects).
3. modeling CM impedances of electromagnetic machines, power converters, and cable systems.
4. determining the high frequency characteristics of resistors, capacitors, and common-mode chokes used in grounding circuits.
5. determining safe limits for CM currents within the boundaries of equipment and within the feeder cables. NEJ

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