MVDC Grounding and Common Mode Current Control

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***Abstract*— The U.S. Navy is exploring the use of power electronics based Medium Voltage Direct Current (MVDC) power distribution systems 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.**

Keywords—common mode; grounding; MVDC

I. Introduction

The U.S. Navy is developing high power sensors, high power electronic warfare systems, solid state lasers (SSLs) and electromagnetic railguns (EMRG) to counter the anti-access / area denial strategies of potential adversaries. Generating and distributing MVDC [1] power promises to enable affordable power systems that can support these advanced electric loads with a higher power density than achievable with AC systems.

An MVDC power system will be different in a number of ways from the AC power systems to which contemporary power system design practice is accustomed. Among these differences are that (1) the MVDC power system will be regulated entirely by power electronic converters, (2) dielectric and capacitive behavior will differ from AC 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.

Common Mode (CM) currents and voltages are aspects of a MVDC system that are greatly impacted by the method of system grounding. 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 current. Within a set of power conductors, the sum of the instantaneous differential mode 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 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 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 common mode 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.

This paper proposes to use CM models as a basis for developing recommended practices for limiting 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.

II. MVDC Reference Architecture

A reference MVDC system architecture is depicted in Fig. 1 and described in detail in [1] [2] and [3]. The elements of the systems that interact with the MVDC bus are:

- Power Generation Modules (PGM)
- Propulsion Motor Modules (PMM)
- Power Conversion Module PCM-1A
- Power Conversion Module PCM -1B
- Power Conversion Module PCM - SP (Shore Power interface)
- Bus Nodes
- MVDC Bus
- Controls

If PGMs of different power ratings are employed, the higher rated PGM is often called a Main Turbine (or Diesel) Generator (MTG or MDG). The smaller rated PGM is called an Auxiliary Turbine (or Diesel) Generator (ATG or ADG).

One of the features of the reference MVDC system is that online PGMs provide power simultaneously and independently to both MVDC buses. This facilitates even

[1] For this paper, MVDC refers to the voltage range from 1 kV to 35 kV in reference to IEEE Std. 1709-2010.

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.

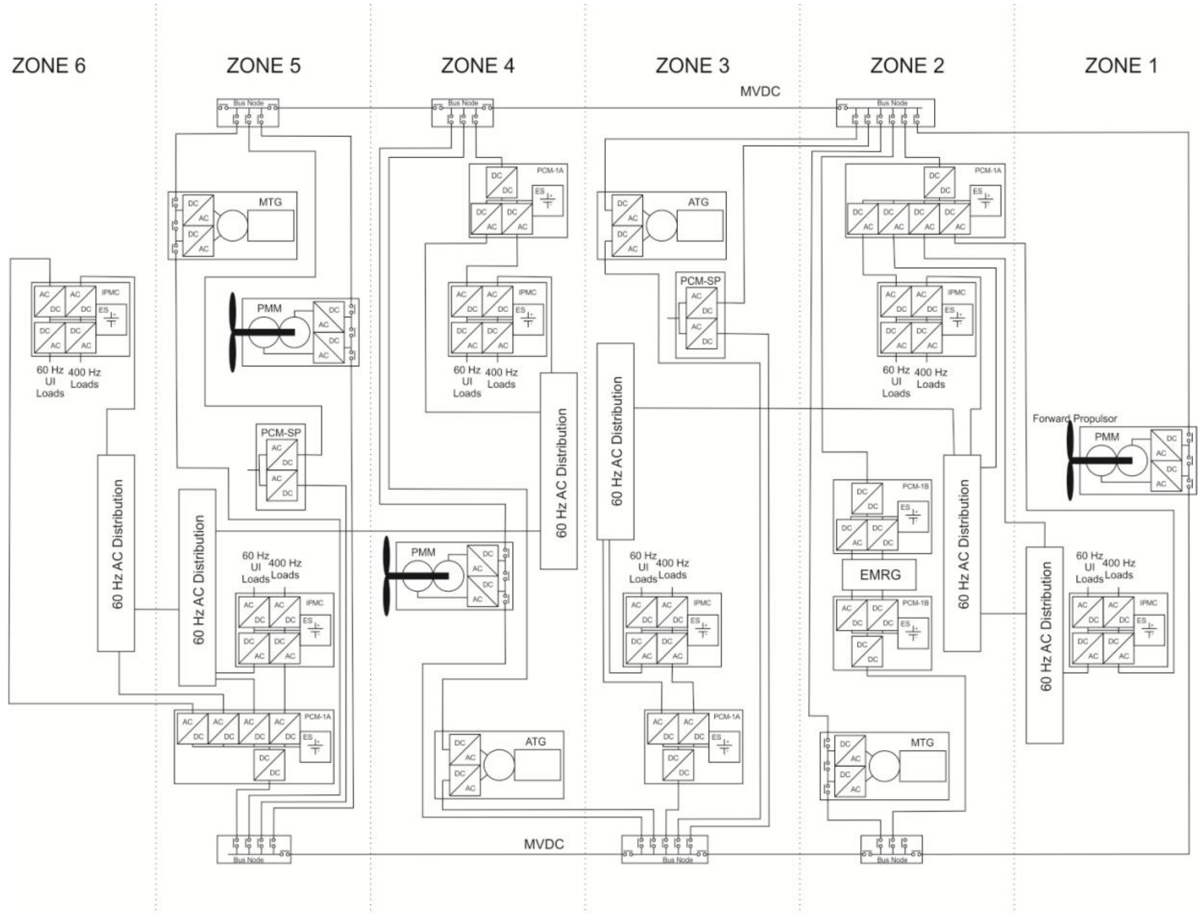

Fig. 1. Reference MVDC System Architecture

III. Common Mode Model

Fig. 2 simplifies Fig. 1 to demonstrate the process of modeling CM circuits. As shown in Fig. 2, a voltage source converter motor drive application generally consists of three connected (non-independent) power subsystems: the a.c. power subsystem corresponding to the generator (or transformer) output, the DC power subsystem corresponding to the DC bus at the rectifier output and inverter input, and the a.c. power 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.

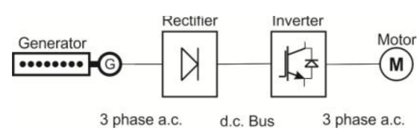

Fig. 2. Simplified Electric Drive System

A common mode model of a power system is derived from a traditional schematic representation with the parasitic capacitances inserted. Fig. 3 depicts a traditional multi-phase schematic of the simple power system of Fig. 2 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 Fig. 3 demonstrates symmetry that can be exploited to develop the simpler CM circuit also depicted in Fig. 3. 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 DC 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.

The voltage sources are often represented as a plot in the frequency domain. Since all of the elements in Fig. 3 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 [4] and [5] for more information on CM modeling.

From a systems perspective, superposition enables examining each CM voltage source independently; other 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, these currents likely should be kept at less than about 10 amps, perhaps as low as 1 amp based on analogy to AC systems. 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.

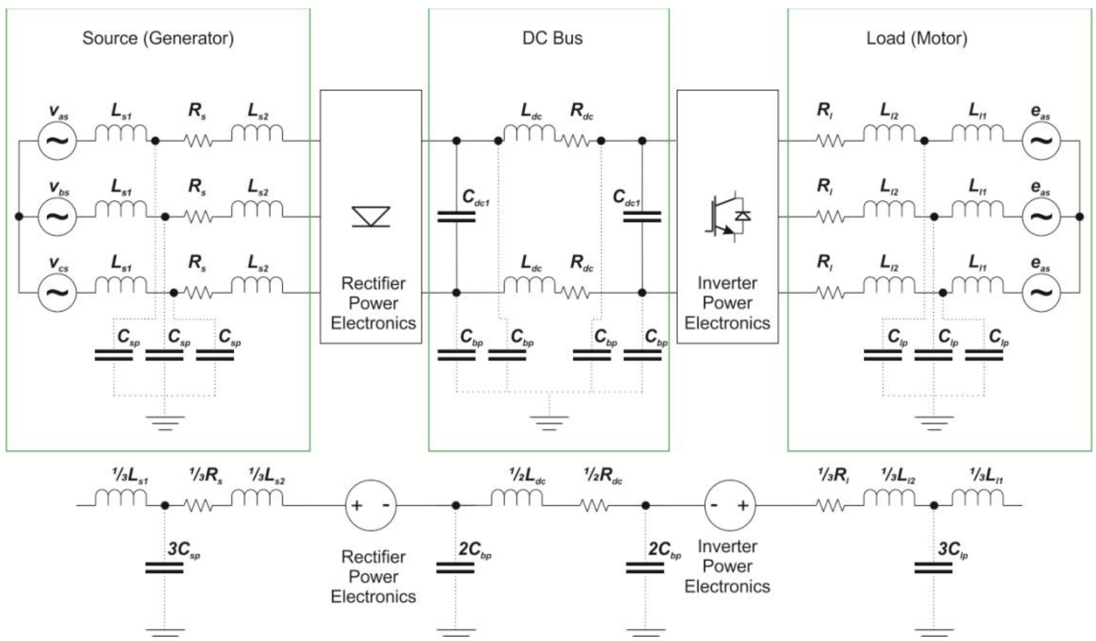

Fig. 3. Multiphase and CM Depictions of CM Circuit

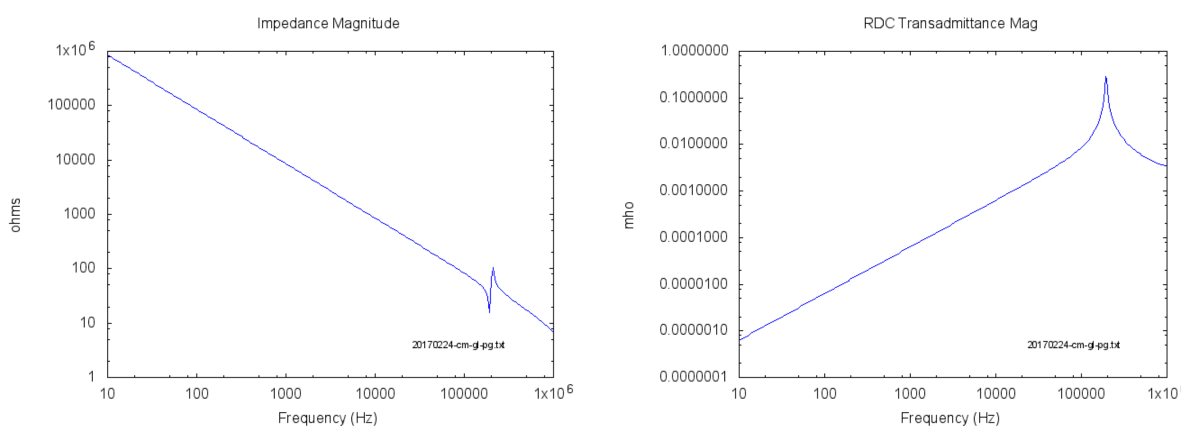

Fig. 4. CM impedance and CM transadmittance of parasitically grounded system

To minimize the impact of a CM voltage source on other power system components, as well as minimizing electromagnetic interference, the common-mode current in the feeder cable to the equipment caused by the served equipment should be low. While criteria does not exist for this common-mode 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 common-mode 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 common-mode 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 common-mode environment they themselves create, while minimizing the impact on other equipment.

Using the following values for the circuit depicted in Fig. 3, results in the frequency response of the CM impedance and transadmittance depicted in Fig. 4.

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

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 47 kΩ. 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 in the model for the cable the CM current is measured through the resistance. This implies that the CM current through the first parasitic capacitance "leg" of the cable 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 this cable model is also questionable.

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.

IV. Impact of Grounding on CM Currents.

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.

Considerable guidance exists for medium voltage a.c. systems (see [6] and [7] for example). Analogous guidance for DC systems is considerably less mature.

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 Fig. 5. This ground inserts the stator inductance into the CM circuit in parallel with the parasitic capacitance. As expected, as shown in Fig. 6, 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 DC 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.

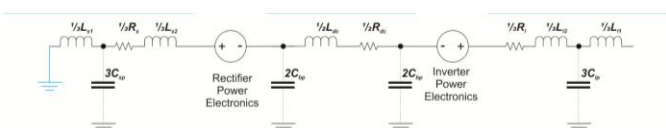

Fig. 5. CM circuit for grounding source a.c. system

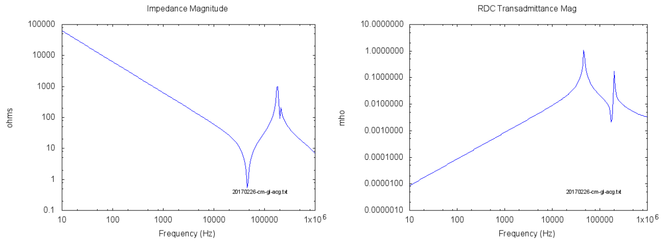

Fig. 6. CM impedance and CM transadmittance for grounding source a.c. system

One strategy to reduce the CM current in the DC bus is to shunt the CM current to ground between the CM voltage source and the DC bus. This must be done with care. For example, grounding the DC system with capacitors as depicted in Fig. 7 does not have the intended result. A capacitor divider is used to establish the grounding point on the DC side of rectifiers and inverters. If these capacitors provide a suitably low impedance to ground, then little CM current will flow through the DC 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 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 DC bus and the shunting capacitor. This is demonstrated in Fig 8 where C_{dc1} = 0.17 µF. A means for increasing the CM impedance of the DC bus without increasing the differential mode impedance is needed.

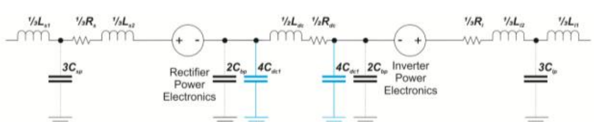

Fig. 7. CM circuit for grounding at DC side of power electronics

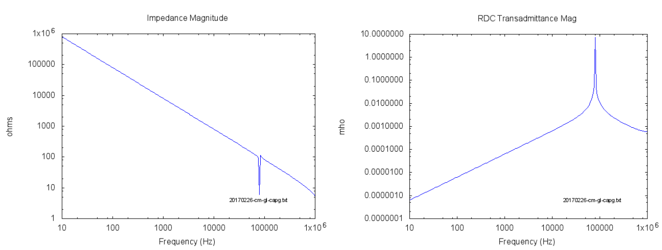

Fig. 8. CM impedance and CM transadmittance for grounding at DC side of power electronics

Increasing the CM impedance without substantially increasing the differential mode current can be accomplished with a CM choke. A CM choke (Fig. 9) presents little impedance to the normal differential 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).

The equations for a CM choke are

$$v_1 = L\frac{di_1}{dt} + M\frac{di_2}{dt} \tag{1}$$

$$v_2 = L\frac{di_2}{dt} + M\frac{di_1}{dt} \tag{2}$$

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

$$v_1 = L\frac{di_1}{dt} - M\frac{di_1}{dt} = (L-M)\frac{di_1}{dt} \tag{3}$$

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

$$v_{1cm} \approx L\frac{di_{1cm}}{dt} + M\frac{di_{1cm}}{dt} = (L+M)\frac{di_{1cm}}{dt} \tag{4}$$

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

The CM choke may be inserted on either the AC or the DC side of rectifiers and inverters. A CM choke inserted on the DC side is depicted in Fig 10. The impedance of the CM choke dominates the other CM impedances, thereby reducing the magnitude of the CM current. Fig. 11 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.

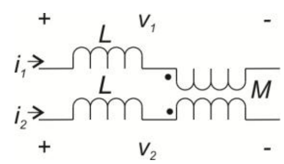

Fig. 9 CM Choke

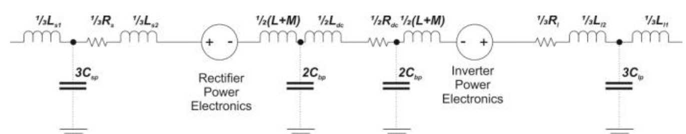

Fig. 10. CM circuit with CM choke

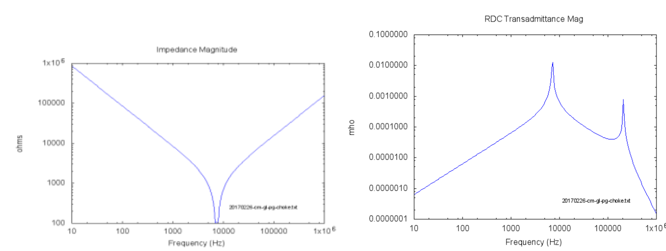

Fig. 11. CM impedance and CM transadmittance with CM choke

Fig. 12 depicts the circuit with both the capacitive ground from Fig. 7 and the CM choke from Fig. 9. As shown in Fig. 13, not only can the transadmittance and CM impedance be controlled, but the frequency of the resonance can also be controlled.

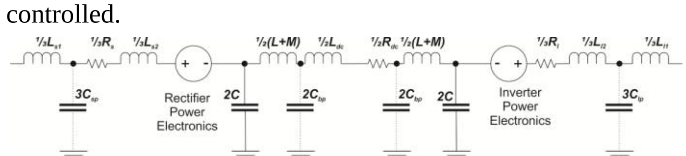

Fig. 12. CM circuit with CM choke and capacitance ground

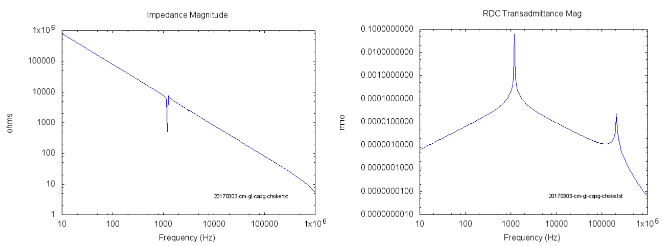

Fig. 13. CM impedance and CM transadmittance with CM choke and capacitance ground

The resonances in Fig. 13 can be dampened by introducing a small resistance between the grounding capacitors and ground as shown in Fig. 14 and Fig. 15. Fig. 16 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.

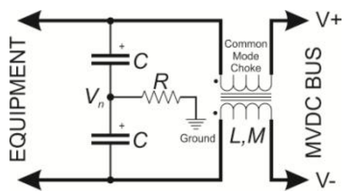

Fig. 14. CM interface circuit with damping resistor

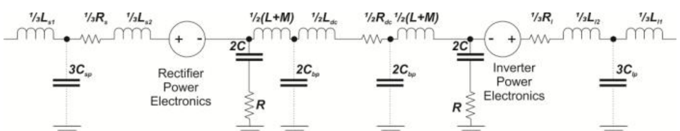

Fig. 15. CM circuit with CM interface using damping resistor

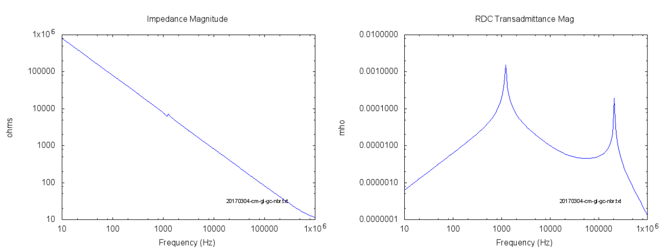

Fig. 16. CM impedance and CM transadmittance with CM interface with damping resistor

Another way to dampen the response is to insert resistances in parallel to the grounding capacitors as depicted in Fig. 17 and Fig. 18. The CM impedance and transadmittance are shown in Fig. 19 for 4 kΩ balancing resistors. The balancing resistors have the added benefit of establishing the DC neutral of the DC 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.

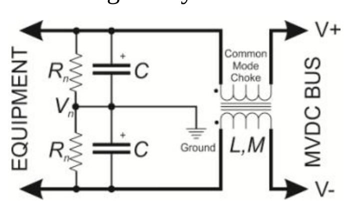

Fig. 17. CM interface circuit with balancing resistors

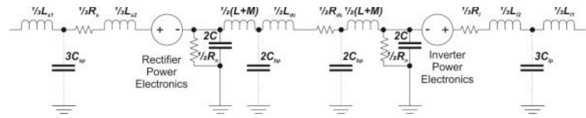

Fig. 18. CM circuit with CM interface using balancing resistors

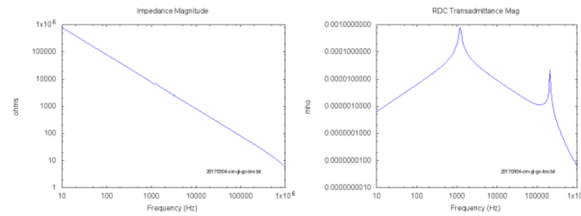

Fig. 19. CM impedance and CM transadmittance with CM interface using balancing resistors

Adding both the damping resistor and the balancing resistors results in the circuits depicted in Fig. 20 and Fig. 21 [8]. The damping resistor effectively provides a lower bound for the CM impedance (Fig. 22). 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.

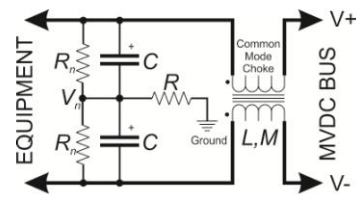

Fig. 20. CM interface circuit

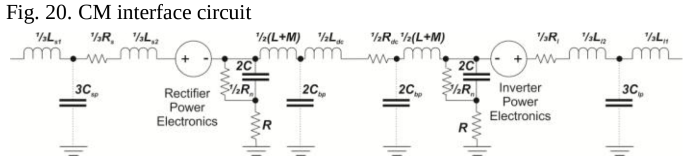

Fig. 21. CM circuit with CM interface

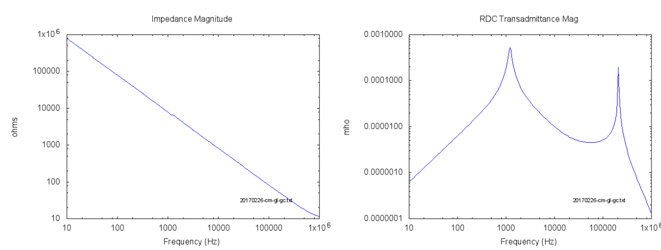

Fig. 22. CM impedance and CM transadmittance with CM interface

V. 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 (Capacitor Discharge Path) in Fig. 23 trace the discharge current from the capacitor highlighted in yellow. 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 (Capacitor Charge Path) depict the possible charging currents for the capacitor connected to the unfaulted bus; it will charge until it achieves a steady state DC 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. If the local equipment is not a source, then the charging current will be provided by 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.

The ground fault will also cause a CM DC voltage source on the DC 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 DC source in the steady-state, the steady-state CM current from this CM DC source will be determined by the grounding resistors.

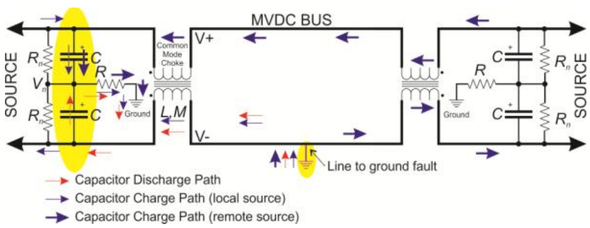

Fig. 23. Line to ground capacitor charge and discharge paths for ground fault

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.

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 DC value. In the steady-state, a ground fault produces an asymmetric circuit that results in a DC CM voltage. This DC CM voltage interacts with the grounding resistors to produce a steady-state CM DC current.

VI. CONCLUSIONS

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.

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