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Fast Reduction of DC Voltage for Half-Bridge MMC HVDC Systems with Symmetrical Monopole during the Non-permanent Pole to Earth DC Fault

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SUMMARY

VSC converters with symmetrical monopole configuration have been successfully applied in many HVDC transmission systems. Based on the location circumstances, it may be desirable and practical for a DC transmission circuit to go underground or underwater, generally with XLPE-DC cables. A symmetrical monopole configuration can have no earth or very high resistance earth on the DC side. Therefore under these circumstances when a DC side line to earth fault occurs, there is almost zero fault current. Moreover, a non-permanent fault like lightning on overhead lines may clear itself. Due to this fact, a significant benefit of the no earth or high resistance earthed symmetrical monopole is that little or no power transfer is lost during the temporary faults, since load current still flows and pole-to-pole voltage stays the same. However, the problem is that the voltage of the un-faulted pole rises to twice rated. This is important for line insulators and converter station clearances but particularly important when the overhead line is connected to cable sections. XCLPE DC cables are type tested (UT) to sustain only about 1.85 pu over voltages as per CIGRE Brochure 496 recommendations. Therefore, means must be found to limit the voltage of the un-faulted pole for a small duration and restore the pole voltages to rated value after the fault clearance as quickly as possible.

A control action can be considered as a possible solution for keeping the voltage of the un-faulted line within the allowable limit for half-bridge MMC HVDC systems with symmetrical monopole. This paper will demonstrate a control method that can reduce the DC voltage immediately. After the fault clearance, the two pole voltages can be balanced again using DC choppers or discharge resistor.

KEYWORDS

Symmetrical monopoles, Half-bridge sub-modules, Non-permanent faults, XLPE-DC cables, DC voltage control

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1. INTRODUCTION

VSC based HVDC transmission systems are expanding rapidly. The modern Modular Multilevel Converters (MMC) with full-bridge and half-bridge modules offer significant benefits compared to previous VSC technologies. Generally both half bridge and full bridge MMC can provide similar performance in normal operation for controlling active and reactive power. One of the major advantages of the full-bridge MMC over half-bridge is their ability to block the DC line fault current. However, for the same voltage rating, the converter losses of full-bridge MMC are greater than the half-bridge MMC. The increased losses are mainly due to additional semiconductors in the current path.

Symmetrical monopoles and bipoles are the two most popular configurations that have been successfully applied in many HVDC transmission systems [1], [2]. Each configuration has specific pros and cons. For example, the symmetrical monopole with two conductors does not require firm earth connection as a conventional bipole requires with three conductors, one of which is the metallic return. A single symmetrical monopole will lose redundancy for a permanent line or cable fault unless there are two independent monopoles with four conductors.

Existing VSC transmission is dominated by underwater and underground cable systems, generally with XLPE-DC cables. As the need for VSC transmission expands, so too will the requirement to minimize transmission costs with overhead transmission where possible. It may not always be likely that VSC transmission can stay overhead. Environmental and agricultural concerns as well as the challenge of obtaining and permitting right-of-way through built-up areas may necessitate reverting to underground and/or underwater cables for a portion of the transmission length. The overhead transmission line portion will be exposed to adverse atmospheric impacts causing line to earth faults which are temporary for the most part which can be cleared and transmission resumed after a period of time.

Phase-to-earth temporary faults for ac transmission may apply circuit breaker reclosing within a second or so with either three phase reclosing or single phase reclosing. HVDC LCC transmission with overhead lines has a controlled arc extinction and restart process for temporary faults that is also accomplished within a second. Fast acting HVDC circuit breakers are being developed to emulate in VSC transmission what circuit breakers accomplish in ac transmission for clearing of line faults and recovery to pre-disturbance transmitted power. It should be considered that some pole-to-earth faults on overhead VSC transmission can be cleared with little or no loss of transmitted power. Taking into account that portion of the transmission line may be underground or underwater cable, control and protection methods have to be investigated in order to prevent any damage on the system [3].

2. SYMMETRICAL MONOPOLE VSC TRANSMISSION

VSC converter with symmetrical monopole configuration is shown in Figure 1. The interface transformers are single, conventional two-winding transformers with the secondary (valve side) windings no earth or high resistance earth. Possible high resistance earth configurations of the VSC converter can be either at secondary winding Y point or a bank of MOV surge arresters connected to the star point. A zig-zag earthing transformer may also be applied to the secondary winding.

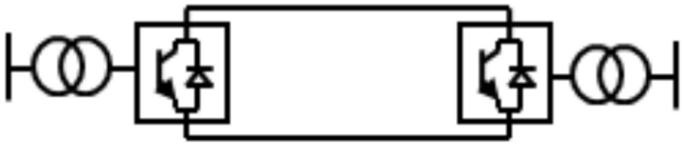


Figure 1 Unearthed, or high resistance earthed, Symmetrical monopole

There are three considerations for selecting the value of the high resistance earth [3]. These are:

1. To keep the DC circuits balanced during normal steady state operation

2. To limit single pole fault current to a level that results in a low enough level that if the fault is from lightning on an overhead line, once the lightning dissipates, the fault arc from the conductor to tower cannot be sustained and will extinguish so that no mechanical switch operation is necessary, just voltage balancing with the DC choppers. In this way, DC power will flow uninterrupted.

3. When a converter is energized and brought on line, or faulted on the overhead line from lightning, that any dc zero sequence current on the ac connection between the converter and the unit transformer is not significant enough to saturate the transformer.

Since a symmetrical monopole configuration can have no earth or very high resistance earthing on the DC side, when a DC side line to earth fault occurs, there is almost zero fault current. Moreover, some non-permanent faults like lightning on overhead lines may clear itself. Due to this fact, a significant benefit of this configuration is that little or no power transfer is lost during the temporary faults, since load current still flows and pole-to-pole voltage stays the same. However, the problem is that the voltage of the un-faulted pole rises to twice rated as shown in Figure 2. No surge of fault current flows through the VSC converters.

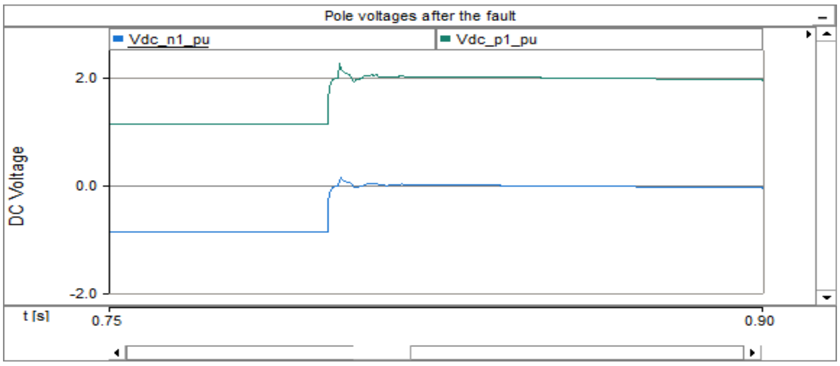


Figure 2 Pole voltages of the dc link during a pole-to-earth fault

The two-per-unit overvoltage on the un-faulted pole is important for line insulators and converter station clearances but particularly important when the overhead line is connected to cable sections. Therefore, means must be found to limit the voltage of the un-faulted pole for a short duration and restore the pole voltages to rated value after the fault clearance as quickly as possible.

3. DC OVERVOLTAGE LIMTAIONS OF DC CABLES

As mentioned before, it would be desirable for the VSC transmission circuit to go underground or underwater in locations where circumstances warrant and is practical to do so. There is one issue still to be resolved and that is for the lighter by weight DC cable, known as XLPE DC cable, to be able to periodically withstand 2.0 pu volts on the un-faulted cable symmetrical monopole for a transient pole fault on an overhead line section for a period for less than a second until the pole voltage is rebalanced. For 320 kV symmetrical monopole transmission lines, a 400 kV or 525 kV XLPE DC cables could be considered to overcome the 2.0 per unit dc voltage problem on a single pole fault. This would allow the rated operating voltage to be increased from 320 kV to 350 kV for a 400 kV cable so that the 2.0 per unit temporary overvoltage to 700 kV would pose no problem in aging a cable type tested to UT = 1.85×400 = 740 kV. 2.0 per unit of a 350 kV rated VSC system would be 700 kV, low enough below the 740 kV type test level to cause no aging problem with the cable for single pole faults to earth from environmental effects such as lightning.
Otherwise for a 320 kV XLPE DC cable if it is qualified strictly to the CIGRE recommendations, the symmetrical monopole could be run at a lower voltage, say ±280 kV which would lower the power transfer of the circuit accordingly unless the symmetrical monopole converters are designed to rapidly lower the DC voltage temporarily from 320 kV to 280 kV [3]. With a 525 kV XLPE DC cable type tested at 1.85 pu, the UT is 970 kV. This allows a ±480 kV high resistance earthed symmetrical monopole to operate

4. ARC MODEL

When a DC side pole to earth fault happens, first the line capacitors are discharged to the fault path with a large current and even though it is a dc fault, the current has zero crossings. In no- or high-resistance earthed symmetrical monopoles, since there is almost no steady state path for the dc fault current, and so after a short time the fault current reduces rapidly to a few tens of Amperes. Self extinction of an arc fault depends on many atmospheric factors such as fault location, wind, arc resistance and current, recovery voltage, etc. Basically the arc will permanently extinguish itself when the arc length is significantly long, and a time of several hundred milliseconds is allowed for the arc path to de-ionize to withstand the recovery overvoltage.

An arc model based on reference [4] is established in PSCAD/EMTDC to test MMC HVDC system behavior during and post dc fault. The arc model has three stages. At the first stage, a single trigger is used to start the primary arc between poles or pole-to-earth. The initial arc length should be given based on the tower configuration and system parameters and initial fault current determined by a test simulation. With the decrease of the current, the arc transits from first stage to second stage. In the ac system with single phase reclosing, the open phase of the ac breaker is used to initiate the second stage of the arc model. In the symmetrical monopole HVDC system, the second stage starts when the fault current to earth has zero crossings from the line and cable discharge oscillations and is low because of the high resistance earthing. The third stage stands for the extinction of the arc. When the current drops below a user settable threshold, the arc length is permitted to grow until the fault off threshold is exceeded [5]. The arc model detects the zero-crossing point and then calculates the rate of change of the voltage to decide whether arc will extinguish.

5. CONTROL METHOD TO REDUCE THE UNFAULTED DC VOLTAGE

The half-bridge multi-modular converter, which is shown in Figure 3, consists of three phase units, each with upper and lower arms. Each arm has a modular structure with a number of n series connected power sub-modules.

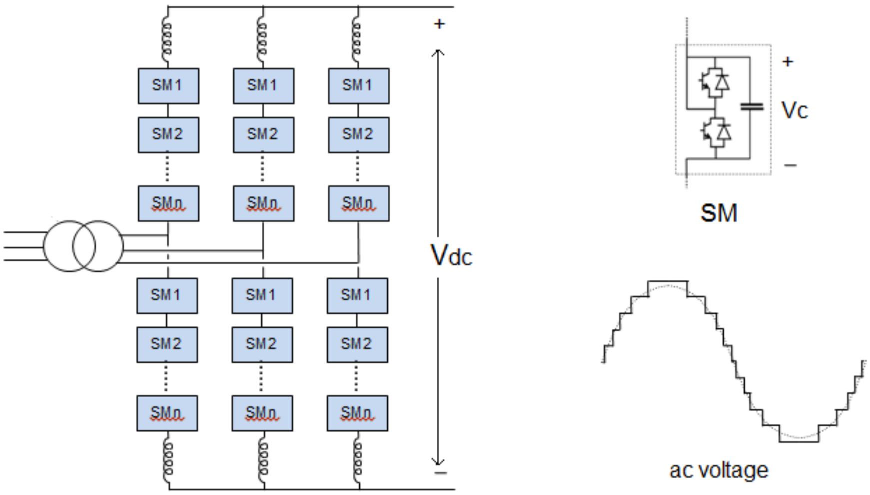


Figure 3 An MMC converter with half bridge sub-modules and the resulting ac voltage wavefrom

Assuming that sub module (SM) capacitor voltage is V_c , the output voltage of each sub-module can take on one of two different voltage levels, zero or V_c, namely 'ON' or 'OFF' states. Each of the sub-modules are individually controlled so that the voltages of each sub-module add up to form a near-sinusoidal stepped voltage waveform at the converter ac terminals as shown in Figure 3. Since at any moment, the sum of the sub-module output voltages of each phase is equal to the dc voltage, the total number of sub-modules with the ON state on the lower and upper arms is constant and equal to n. In other words, if the number of sub-modules with ON state on upper arm is n_{up} , then the number of sub-modules with ON stare on lower arm should be $n - n_{up}$ [6].

As described in section 3, a control action should be considered to keep the voltage of the un-faulted line within the allowable limit for symmetrical monopole. To reduce the DC voltage after the fault occurrence, only reducing the reference value of the controller is not helpful since it will result in reducing the voltage of each sub-module capacitor which based on their time constant will not be fast enough. Therefore reducing the total number of sub-modules of each phase unit with the ON state will drop the dc voltage immediately. To do so, the same number of the sub-modules, less than 10% of the total number, from the upper and lower arms has to be bypassed at the same time. Then the reference value of the voltage controller has to be reduced simultaneously in order to prevent the voltage increase of the other sub module capacitors. The reference power is reduced accordingly in order to prevent over current on the dc line.

After the fault clearance, the overvoltage on the un-faulted pole must be returned to 1.0 pu voltage since un-faulted cable will still retain excessive overvoltage and must be de-energized as quickly as possible. This can be accomplished by switching to the line or cable a discharge resistor or by applying a solid-state switch with a discharge resistor in the form of a dynamic breaking resistor (DBR) or "DC Chopper," The location of a DC chopper is shown in Figure 4.

6. SIMULATION RESULTS

This section shows the system response when the proposed controller is used to reduce the pole voltage of the un-faulted line in a point-to-point HVDC transmission system with a symmetrical monopole. The system is designed to transfer 1000MW power from the AC system1 to AC system 2 through a dc link as shown in Figure 4.

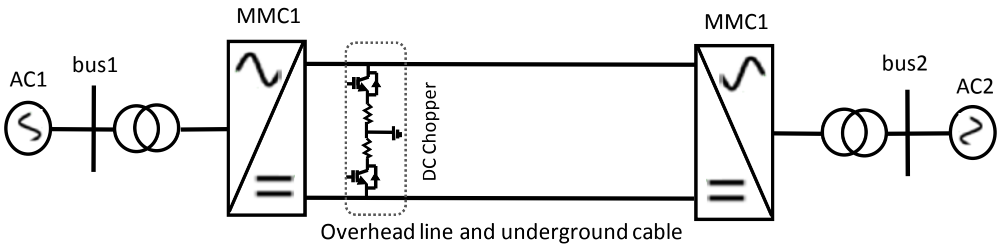


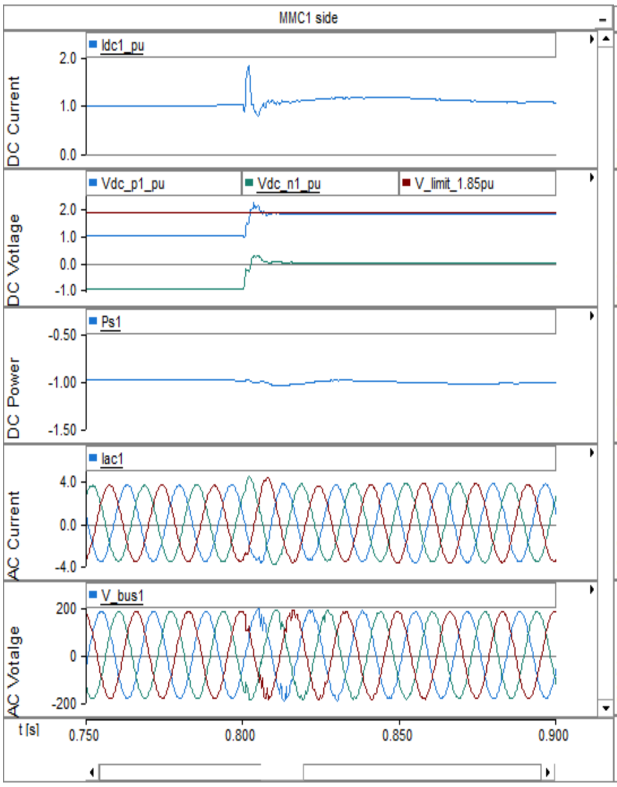
Figure 4 Point to point HVDC test system

The dc line voltage is rated at ±320 kV. MMC1 operates as a rectifier feeding the dc link and is connected to a strong AC system with high short circuit ratio. The receiving-end converter MMC2 operates as an inverter and transfers the dc link power back to AC system 2. The internal controllers of each converter are based on vector control strategy. It is a current control strategy that results in independent control of AC voltage and real power by removing the coupling between the real and the imaginary of the output current [7], [8]. Converter MMC1 is responsible for controlling the DC link voltage and the AC voltage of the bus 1. Converter MMC2 operates in the power control mode to regulate the power transfer and controls the AC voltage of the bus 2. The number of sub-modules was selected based on the converter's dc voltage rating. The system parameters are listed in Table 1.

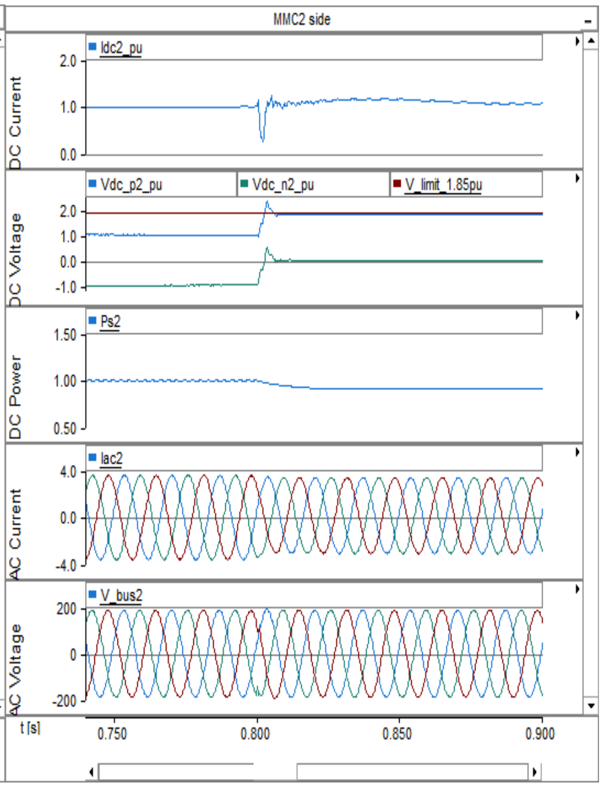
Table 1 System parameters

DC transmission system		**MMCs**	
Rated power	1000 [MW]	Arm inductor	0.02 [H]
DC voltage	640 [kV]	Sub-module capacitance	5500 [uF]
Overhead line	400 [km]	Number of sub-modules per arm	80
Underground cable	50 [km]	Sub-module rated voltage	4 [kV]
AC system 1		**AC system 2**	
AC voltage	230 [kV]	AC voltage	230 [kV]
SCR	$4 \angle 85^0$	SCR	$3 \angle 85^0$
Transformer	230 :380 [kV]	Transformer	230 :380 [kV]
	1200 [MW]		1200 [MW]
	0.1 [pu]		0.1 [pu]

The fault is applied at the midpoint of the overhead line at 0.8s. As soon as the fault is detected, the same number of the sub-modules from top and bottom arms is kept bypassed to reduce the un-faulted pole voltage to 1.85pu during the fault time. The simulation results, which are showing the system response of the ac and dc side of each MMC, are presented in Figure 5.



(a)



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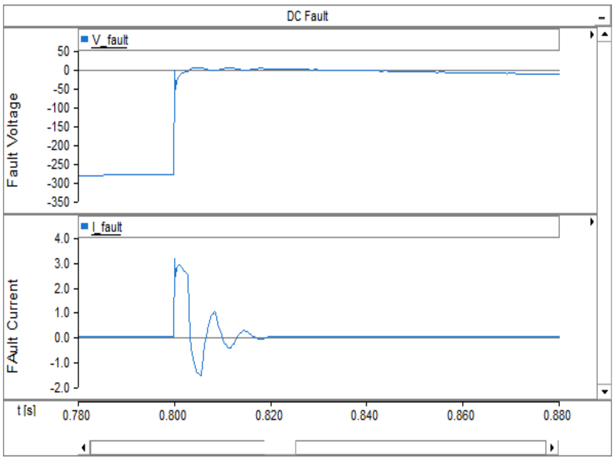

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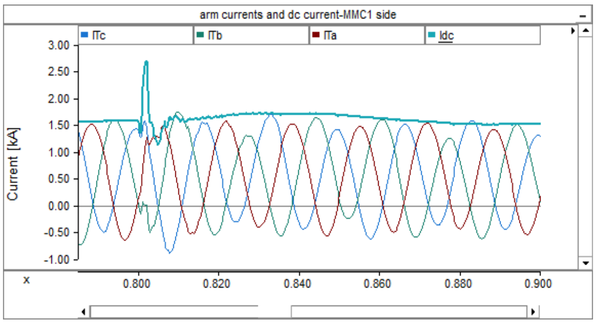

(d)

Figure 5 System response during the pole to earth fault with the proposed control action, (a) AC and DC voltages and currents of side 1, (b) AC and DC voltages and currents of side 2, (c) arc fault current and voltage, (d) arms currents along with the dc current of MMC1

It should be considered that whether the over current on the dc side of MMC1, as shown in Figure 5(a) is causing damage on the IGBTs in each phase units of MMCs. Figure 5 (d) shows the current flowing in each arm of the MMC1 along with the dc current. It is apparent that the distortion of the phase unit currents in each arm results in the dc over current and the arm currents are within the rated range of the converter IGBTs.

7. CONCLUSION

The MMC symmetrical monopole converter with high resistance earthing offers decided advantages in HVDC transmission including little or no loss of transmitted power during non-permanent single pole to earth faults. In order to prevent the voltage of the un-faulted pole to rise to twice rated, this paper proposes a control action to reduce the voltage immediately.

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