SFCL FOR MULTI-TERMINAL DC GRID PROTECTION SYSTEM

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***Abstract*−*During the last decade there has been an increasing interest in the High Voltage DC grids amongst researchers and policy makers. Protection has been identified as a critical component in the realization of these multi-terminal direct current (MTDC) systems. The fault currents in the DC systems are limited by the circuit resistance and inductance and thus are likely to reach very high values. This may also lead to voltage collapse. In order to limit the fault current magnitudes and to prevent voltage collapse use of superconducting fault current limiters (SCFCL) in MTDC system is proposed in this paper. The effectiveness of SCFCL in limiting the fault current along with sizing of SCFCL resistor are explored in this paper. The paper also discusses the effect of initial discharge and critical current setting of SCFCL.*

***Keywords*−** *multi-terminal direct current (MTDC) systems,*

I. INTRODUCTION

There has been a steady increase in electric power demand throughout the world. In addition to this there is more emphasis on use of renewable energy sources especially increasing focus on offshore wind applications. The meshed multi-terminal DC transmission (MTDC) system has become an interesting option due to voltage source converters (VSC). The MTDC systems were envisaged to facilitate the interconnection of various national grids and remote energy resources. There are several challenges that need to be tackled before the MTDC systems are physically realized. A major challenge is the protection of the MTDC systems during faults and current interruption. The protection of MTDC systems during dc faults is a major challenge in realization of the MTDC systems. From the point of view of system operation the dc faults are expected to be interrupted and isolated by equipment on the dc side. Since, if the faults are interrupted by the ac side equipment then entire system will be shut down with possibility of a blackout. It is well-known that dc current interruption is particularly difficult due to no-existence of current zeros.

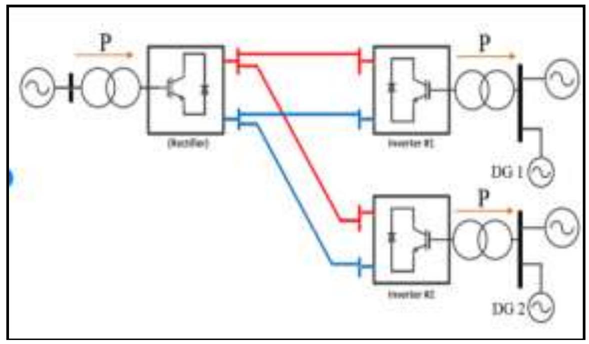


Fig.1- Typical MTDC system

The dc fault current is shown to increase to a large value if the fault persists. A large magnitude initial discharge due to the terminal and cable/ transmission line capacitances is observed in dc fault currents. It is also identified that the dc voltage is likely to collapse rapidly due to low dc resistance values of the cables and transmission lines. The dc circuit breakers are expected to interrupt the fault current and regain full isolation capacities in a very short time to prevent voltage collapse. A typical time duration as reported in the literature is about 35ms. This requirement implies very fast acting circuit breakers which could result in severe breaker design requirements.

A possible solution to arrest the rapid increase in fault current value and prevent voltage collapse of the dc system could be accomplished by the use of resistive fault current limiters (FCL). The use of FCL will limit the fault current and provide additional resistance in the system to delay the voltage collapse. Use of SCFCL for VSC based systems have been studied but focuses on two terminal systems and does not analyze the initial resistance as well as the effect of critical currents on the capacitor discharge.

MULTITERMINAL DC SYSTEMS

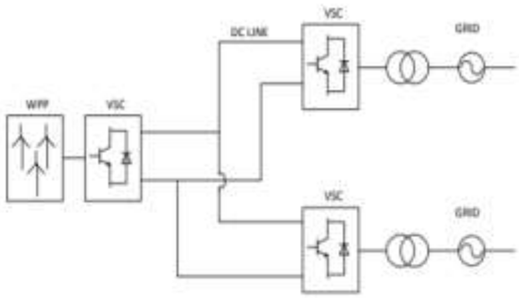


Fig 2- MTDC

The HVDC transmission technology is recognized as an advantageous approach for long-distance bulk-power transmissions with several HVDC applications currently in use for MTDC technologies. Due to its superiority in more efficiently utilizing and integrating renewable energy located in remote areas, MTDC technology has become more attractive in recent years compared to traditional point-to-point HVDCs. The MTDC system can also be reconfigured into different topologies under faults, particularly after a faulted line is isolated, in order to increase the continuity and reliability of the power supply. The regulation of power, the VSC based MTDC system is considered more flexible, particularly in instances where the power flow reversal can be easily achieved by reversing the direction of DC currents rather than the reversal of DC voltages. Based on these characteristics, MTDC applications are being increasingly used in HVDC transmission.

There is a potential risk that one or more branches of a DC grid may become overloaded, while other branches may be underutilized, since more currents will inherently be delivered to the branch of lower resistance. It was found that while the active power of each terminal could be coordinated to a certain extent, the distribution of the DC current on each branch was incapable of being accurately controlled in the meshed grid.

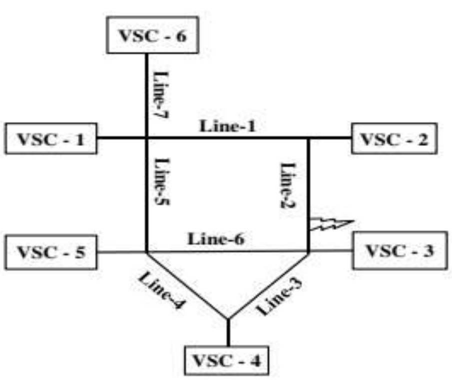


Fig. 3- A six terminals MTDC System [3]

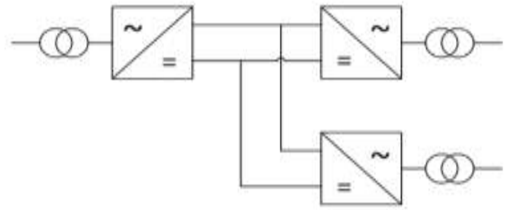


Fig 4- Multi-terminal HVDC system

VSC-HVDC and MTDC System The selected system to get across the energy from offshore to onshore is HVDC. It has several features for carrying out this task. First of all, it is appropriate for long distances, which is perfect to transmit energy from an offshore park to land or from onshore to load centers, for instance. It can use overhead lines and subsea or underground cables, being environmentally friendly.

SUPERCONDUCTING FAULT CURRENT LIMITER

Superconducting fault current limiters exploit the extremely rapid loss of superconductivity above a critical combination of temperature, current density, and magnetic field. In normal operation, current flows through the superconductor without resistance and negligible impedance. If a fault develops, the superconductor quenches, its resistance rises sharply, and current is diverted to a parallel circuit with the desired higher impedance.

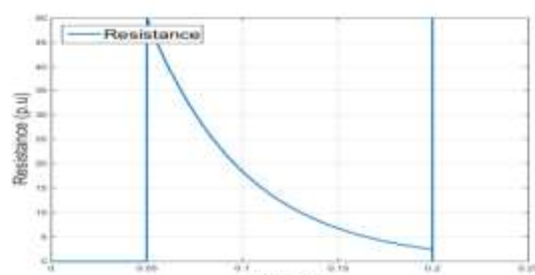


Fig.5- Non-Linear Resistance representation of SCFCL

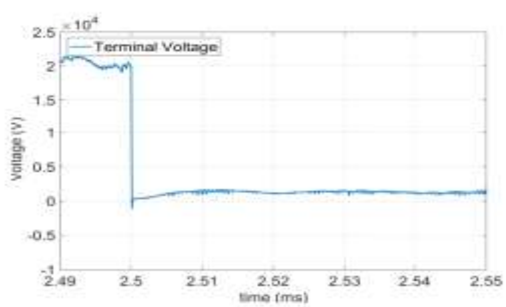


Fig.6- VSC dc Voltage for a terminal fault

In a resistive FCL, the current passes directly through the superconductor. When it quenches, the sharp rise in resistance reduces the fault current. A resistive FCL can be either DC or AC. If it is AC, then there will be a steady power dissipation from AC losses which must be removed by the cryogenic system. Inductive FCLs come in many variants, but the basic concept is a transformer with a resistive FCL as the secondary. In un-faulted operation, there is no resistance in the secondary and so the inductance of the device is low. A fault current quenches the superconductor, the secondary becomes resistive and the inductance of the whole device rises. The advantage of this design is that there is no heat ingress through current leads into the superconductor, and so the cryogenic power load may be lower. For symmetrical three-phase fault, when the capacity of the circuit breaker is less than the transient ($I_s$and steady state fault current (I_{ss}, then the FCL should limit the excesses current. This leads to the constraint on FCL impedance Z_n

$$Z_n > \frac{U_{ph}}{I_{cc}} - Z_{KM}$$

where u_{ph} is phase voltage, Z_{km} impedance of the circuit under fault condition.

Superconductor materials can conduct electricity and carry electrons from one atom to another with no resistance. The current limiting performance initiate with the variation in temperature, current and magnetic field. Superconducting state exists when T < Tc, H < Hc and J < Jc. When superconductor materials cooled down below its critical temperature, resistance immediately drops to zero. At this stage superconductors have the ability to perfectly conduct electrical current.

METHODOLOGY OF SYSTEM

The meshed MTDC systems will invariably be constructed with voltage source converters (VSC) and these can be realized as two level and/or modular multilevel converters (MMC). In case of a dc fault, current rapidly increases being fed by the anti-parallel diode rectifiers and limited only by the system impedance. The dc side voltage for the case of terminal fault. In case of dc fault fast circuit breakers will be required isolate the faulted portion of the dc grid. A fast circuit breaker is required in order to prevent voltage collapse and increase of fault current to high value which is likely to put severe interruption duty on circuit breakers.

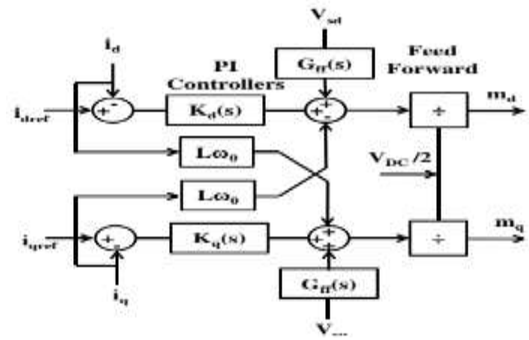


Fig. 7- VSC decoupled d-q axis control

The conventional d-q axis based decoupled converter controller is shown in above. It is used to control the converters. The real power and reactive power can be independently controlled for the voltage source converters. The conventional strategy is to use a synchronously rotating reference frame aligned with ac system to decouple the converter equations and facilitate simple PI controller design.

a) Sizing- Based on the analysis, it can be concluded that fault current is limited by the system and path impedance as well as the fault resistance. During a fault R_f adds to the path impedance thus the fault current magnitude can be limited by proper selection of R_f .Based on the method in the thevenin voltage and impedance of the ac system can be obtained as a function of modulation indices. The value of R_f can then be obtained by the magnitude of the fault current. Equation gives the value of R_f if I_{limit} is defined.

$$Z_{thev} + R_f = \frac{V_{thev}}{I_{limit}}$$

$$R_f = \frac{V_{thev}}{I_{limit}} - Z_{thev}$$

Where, $V_{T\ hev}$ = dc side thevenin voltage , $Z_{T\ hev}$ = Thevenin impedance

SIMULATION AND RESULTS

The simulation model of the six terminal systems is used to study the dc fault currents and the effectiveness of SCFCL. The characteristics of the fault currents are studied and the results are used to define the size of the SCFCL. The SCFCL are assumed to be installed at all the converter stations. The delay in voltage collapse and the reduction in the fault currents are evaluated. The insulated gate bipolar transistors (IGBT) have a limited current handling capacity hence the converter switching is inhibited if the currents above IGBT capability are detected. The anti-parallel diodes provide a path for the fault currents after the switching is stopped. The current path for fault current exists in case of two levels VSC and the modular multilevel VSC (MMC) with half-bridge modules.

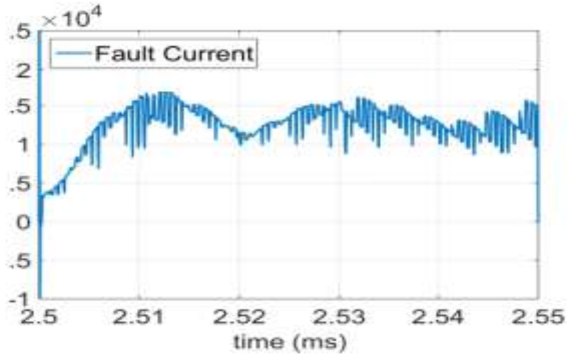
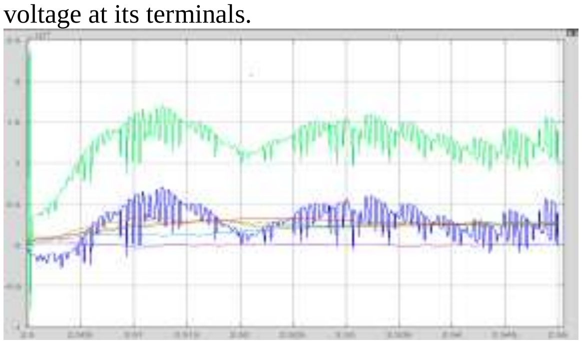


Fig. 8. Fault Currents for VSC terminal fault

The fault current also shows initial discharge of converter and cable or transmission line capacitance. The initial discharge is very fast and magnitude is limited by the resistance between the capacitors and the fault location and fault resistance. The contributions due to the anti-parallel diode rectifier are seen once the IGBT switching is stopped. Fault current contribution is the highest for VSC-1 as the fault is at its terminals. It can be observed that the dc side voltage collapses to zero almost immediately and fault current increases. The terminal voltages of converters electrically far from VSC-1 reduce and depend on the distance from VSC-1. The voltage and currents for a pole-pole fault on Line-2. It can be seen that voltage at VSC-3 approaches zero at about 20ms and farther away a converter is higher the voltage at its terminals.



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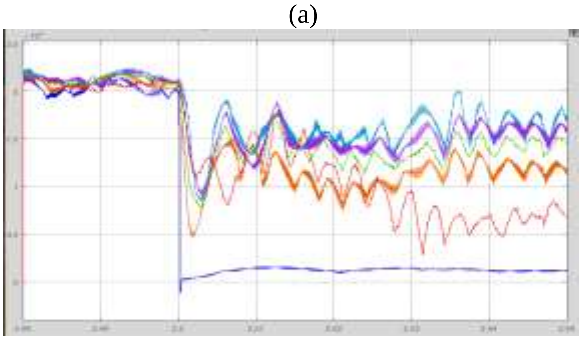

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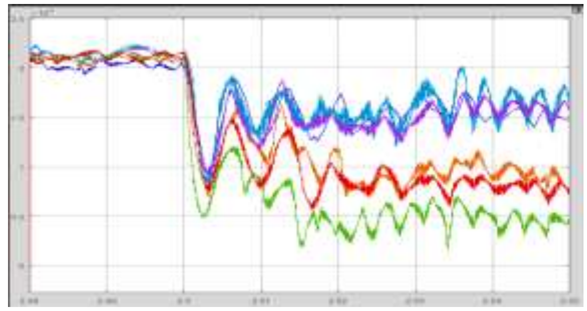
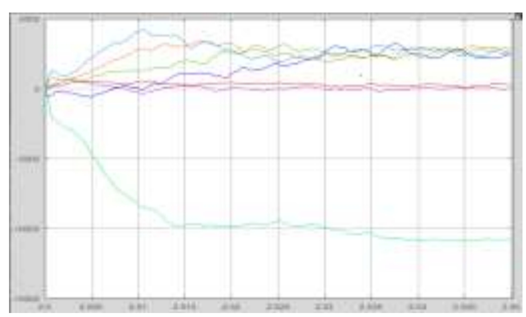


(c)

Figs. 7 - Fault current and voltage for a terminal fault at the VSC1 terminals.

The VSC-1 terminal voltage drops to zero but quickly recovers towards the rated value. A sudden drop in the terminal voltage is observed due to the initial value setting of the SCFCL. The initial value for this simulation was set at 1 mΩ. Hence the terminal capacitors rapidly discharge. It is also observed that the fault current is significantly reduced as compared to current value of approximately 15 kA observed in Fig. 7a. It has to observed that the terminal voltage shows rapid oscillations this could possibly due to ac and dc system interaction. The oscillations need further analysis and can be used for tuning of the converter controls. The voltage at the VSC-1 terminal approaches zero after significant oscillations. These oscillations could possibly be eliminated by proper control action and design of control system. However, these oscillations have to be investigated further from the stability point of view. It was pointed out that the initial resistance of the SCFCL leads to a rapid discharge of the terminal capacitance.



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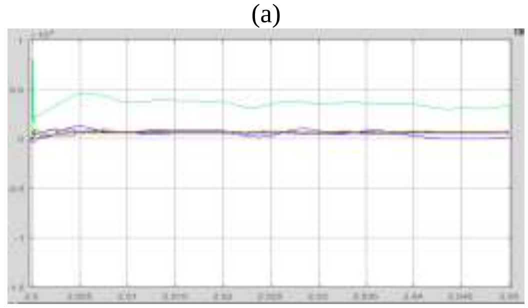

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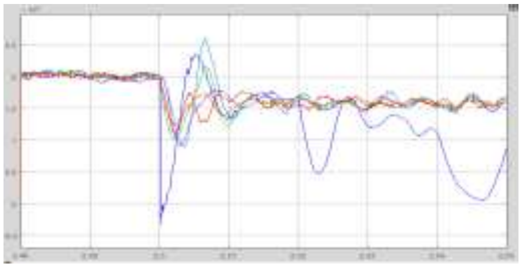

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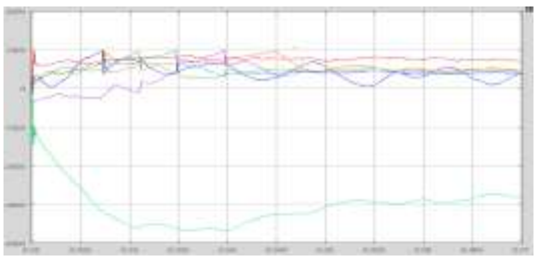
Fig- The fault current and voltages for a terminal fault with SCFCL connected at converter terminals



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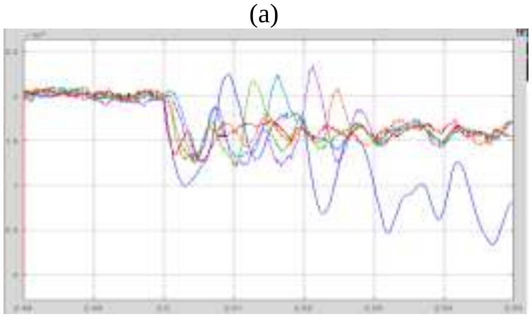

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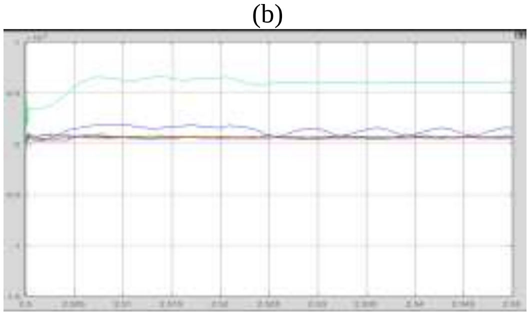

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Figs. 9- The fault current and voltage for line fault with SCFCL connected at all the VSC terminals

The rapid discharge occurs because the of delay in the SCFCL operation. The delay in operation is attributed to the threshold current for actuation of the SCFCL which in the present context is set close to 1000 A. The delay in reaching the threshold current is sufficient to allow a rapid discharge of the terminal capacitance because the resistance of the path is very low leading to very small time constants

CONCLUSIONS

The main contributions are the application of the SCFCL to MTDC systems. The effectiveness of SCFCL in limiting fault current are identified and SCFCL is shown to limit the fault current to low values and arrest rapid drop in the dc grid voltage. The reduction in fault current levels with SCFCL facilitate use of circuit breaker that can operate slower than the stipulated time of about 35ms given in the literature. Thus, leading to reduction in stringent requirements placed on circuit breakers for dc current interruption. The sizing of R_f for values to be used during fault can be done on the basis of thevenin equivalent model and a value of R_f equal to 15 Ω produced a significant fault current reduction along with effectively prevent voltage collapse of the dc grid.

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