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DC fault analysis in voltage source converter based HVDC link

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The use of voltage source converter (VSC) based HVDC transmission for the interconnection of various power networks is increasing day by day. However, VSCs susceptibility to DC faults, particularly the potential damage caused to the converter switches due to overcurrent, is an issue. The fault clearing must be done very rapidly, to limit the effect of the fault on neighboring networks. This paper analyses the two terminal behavior of a VSC- based HVDC system under DC fault condition. In this work, HVDC link is connected between the systems of two different frequencies. Simulations are carried out in RSCAD/RTDS^{TM} software and the performance of the system is analyzed for DC faults and the results are presented.

Keywords: *Voltage source converter, VSC-HVDC, DC fault, DC voltage controller, AC voltage controller, (Neutral Point diode Clamped) NPC converter.*

1.0 INTRODUCTION

The increasing global energy needs and the integration of renewable energy generation have changed the requirements of the electricity grid. Countries are unable to meet their energy demands with their own means and the need for power exchange between neighboring countries has increased. Therefore, power needs to be transmitted over longer distances. On the contrary to the existing AC grids, HVDC is an interesting alternative for future grids.

VSC technology has been the focus of recent HVDC research due to its essential advantages. However, the use of fully-controllable switches is a disadvantage in case of DC contingencies. Till now, opening the AC breakers has been the only way to clear DC faults, by completely de-energizing the system and interrupting the power transfer with significant economic and public consequences. However, DC breakers are necessary to isolate the faulty line from the network under normal operation is recommended. Unlike AC faults; DC faults [1] are always permanent and are caused by failure of cable insulation or damaged cable due to another source, like ship anchors for undersea cables. Cable faults are more common than faults in other parts of the HVDC system. The frequent reason is insulation breakdown. However, there are several others reasons that can lead to the same result, such as electrical stress, environmental conditions, ageing and physical damage. When a DC fault occurs, the current rises significantly and can damage the equipment which is near or close to it.

In the operation of AC grids, AC faults are cleared by means of robust AC breakers, this idea is easily applicable for AC system applications due to the natural zero-crossing of the current, where as it is difficult to be realized in case of DC systems. The DC breaker is required to interrupt high current that do not have a natural zero-crossing

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to dissipate the high amount of energy that is stored in the inductors of the system and also to withstand the voltage created at its terminals after the current interruption [2].

In classical HVDC, Thyristors have the capability to block the AC side from feeding the DC fault. More specifically, by turning them off as soon as a DC fault is detected and by opening AC breakers, in order to de-energize the system. However, this is not applicable in VSC HVDC systems. VSC converter comprises of IGBT/GTO modules with anti-parallel diodes [7], facilitating the two-way exchange of power. Therefore, in case of a DC fault, even if the IGBTs/GTOs are switched off, a large fault current can still flow through the freewheeling diodes.

During fault, the DC link capacitor discharges through the DC cable [8], thus resulting in a large inrush DC current and rapid decrease in the DC voltage effectively shortened by the freewheel diodes. The IGBT/GTOs of the VSC have to be blocked immediately to protect them from the resulting over current. However, as the DC cable current decays, the current at the DC link capacitor becomes negative which effectively recharge the capacitor [3]. In view of the importance of the subject,in this paper DC fault analysis in voltage source converter based HVDC is carried out.

This paper is organized in different sections. Section 2.0 explains the RTDS™ software which is used for simulation purpose. Section 3.0 briefly describes the VSC based HVDC system. Section 4.0 demonstrates the performance of the proposed system. Finally conclusions and future scope of work are discussed at the end of the paper.

2.0 REAL TIME DIGITAL SIMULATOR - RTDS™

The RTDS™ is a special purpose computer designed to study Electromagnetic Transient Phenomena (EMTP) of power systems in real time. The RTDS™ comprises of specially designed hardware and software. RTDS™ hardware is a digital signal processor and Reduced Instruction Set Computer (RISC) based and utilizes advanced parallel processing techniques in order to achieve the computation speeds required to maintain continuous real time operation. RTDS™ software includes accurate power system component models required to represent many of the complex elements which make up physical power systems. The Overall network solution technique employed in the RTDS™ is based on nodal analysis [10].

RTDS™ software includes a powerful and user friendly Graphical User Interface (GUI), referred to as RSCAD™, through which the user is able to construct, run and analyze simulation cases. Unlike analogue simulators, which outputs continuous signals with respect to time, digital simulator compute the state of the power system model only at discrete instants of time. The time between these discrete instants is referred to as the simulation time steps (Δt).

Many hundreds and thousands of calculations must be performed during each time step in order to compute the state of the system at that instant. The temporary transient class of studies for which the RTDS™ is most often used requires (Δt) to be in the order of 50 to 100 μs (frequency response accurate about 3000 Hz). To achieve the real time operation in testing of the controllers, a time step of 50 μs is used to compute the state of the system.

The RTDS is capable of simulating sub-networks containing IGBTs and other GTO devices modeled as ideal switches. For modeling voltage source converters this capability is essential. Each small step time circuit is solved as a sub network that can be interfaced to the main network solution. The main network solution is solved with a nominal step size of about 50 μs, where as small step time circuit is solved with a time step of 1.4 to 2.5 μs.

In order to interface the large and small time step simulations a component called interface transformer is used. Usually interface transformer components are used to transfer power system signals between large and small time step simulations. One side of the interface transformer will have only large time step components connected to it and other side will only be connected to small time step components.

Voltage Source Converter (VSC) based schemes require small timesteps to properly represent high frequency switching and circuit dynamics. To efficiently include such schemes in larger scale simulations, RTDS^{TM} Technologies has developed the small timestep VSC sub network technique. The VSC sub networks operate with timesteps in the range of 1-4 µs and can be interfaced to large scale simulations operating with timesteps in the order of 50 µs. A key feature of VSC subnetworks is that the circuit and valve topology is user configurable. Two- and three-level converters can be freely configured for PWM switching < 2 kHz. A fixed topology two-level converter is also available for operation at PWM switching frequencies in the range of 10 kHz. Multiple VSC subnetworks can be linked together by traveling wave transmission lines or cables to create entire systems running with time steps < 4 µs [11].

3.0 SYSTEM DESCRIPTION

3.1 VSC-HVDC system

Figure 1 shows the system configuration of a two terminal VSC based HVDC system which is connected between the two AC systems of different frequencies. AC system at rectifier and inverter are represented by a thevenin's equivalent of 93 kV and 44 kV. This system involves two stations rectifier and inverter connected by DC cable. The phase reactors smoothens the current and secure the power exchange between AC system and DC link. The capacitors are used for voltage support and harmonic attenuation. The Table 1 below shows the system data. The circuit inside the rectifier box is simulated in small step time simulation and interfaced to the main circuit through interface transformer. The rectifier side circuit of VSC HVDC is shown in Figure 2 consists of interfacing transformer, smoothing reactor, VSC bridge and the DC line. The VSC configuration used is multilevel Neutral Point diode Clamped converter (NPC). The inverter side simulation is the mirror image of this.

TABLE 1		
SYSTEM DATA		
AC system	Rectifier Inverter	93 kV, 60Hz 44 kV, 50Hz
Converter Transformer (Y/Y)	Rectifier	93/44 kV 100 MVA
	Inverter	44/44 kV 100 MVA
VSC HVDC system	DC V: 60 kV POWER:100 MW	
DC cable	100 km	

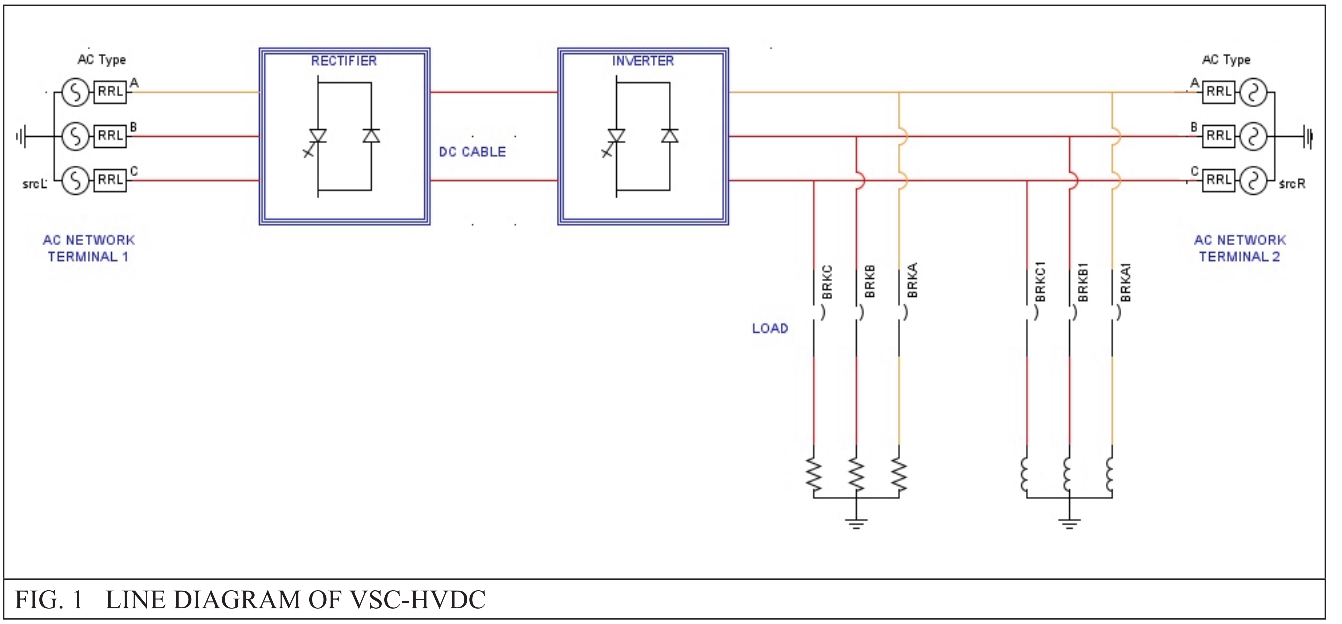

FIG. 1 LINE DIAGRAM OF VSC-HVDC

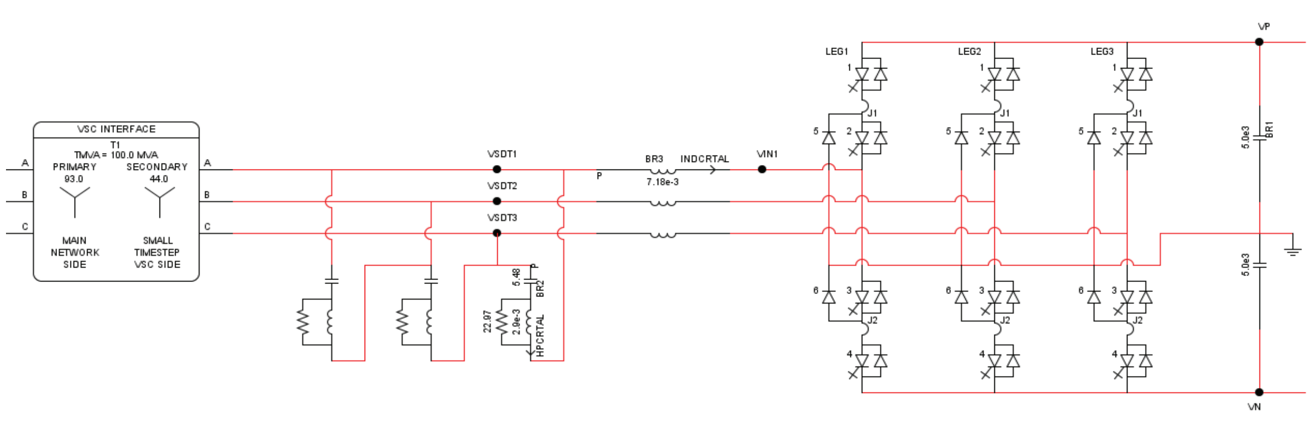

FIG. 2 RECTIFIER CIRCUIT OF VSC-HVDC

3.2 NPC converter

The three-level converter has advantages over the two level converters. Among the multi-level VSC configurations, NPC has been widely accepted for applications of high power. Here DC-link capacitors can be designed only for half the DC-link voltage. The voltage profile is better than the standard two-level converter. The phase potentials can be modulated between three levels, -0.5 V_{dc}, 0, +0.5 V_{dc}. These are used to minimize the operating frequency of the semiconductors inside the VSC and to produce a high-quality sinusoidal voltage waveform with minimum or no filtering requirements [4].

3.3 VSC-HVDC controls

One of the advantages of VSC-HVDC system using PWM technique is that it is possible to independently control the d-axis and q-axis components. In the present topology the rectifier controls the DC voltage of the DC link and AC voltage of the system at the input of the rectifier. Similar control is implemented on the inverter side.

3.3.1 Rectifier and inverter side controls

Figure 3 shows the block diagram of the DC voltage controller and AC voltage controller whose output is given to the inner current control loop. The Direct and Quadrature components of voltage obtained by the inner current controller [6] are used to generate firing pulses for the switches present in rectifier bridge circuit through PWM technique.

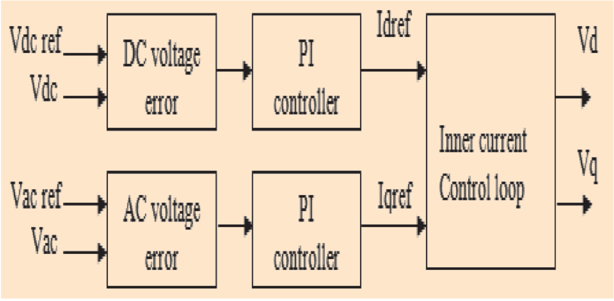

FIG. 3 CONTROLLER BLOCK DIAGRAM

In the DC voltage controller, the actual DC voltage is compared with the reference value and the error is passed through a simple PI controller [5], which gives i_{dref} for the inner current controller. The DC voltage controller adjusts the DC link power such that, the net power exchanged with the DC bus capacitor is kept at zero. In the AC voltage controller, where the actual AC voltage is compared with the reference value and the error is passed through a simple PI controller, which gives i_{qref} for the inner current controller. The function of this controller is to maintain stiff voltage at the AC system.

Figure 4 show the block diagram of the inner current control loop, where the currents derived from the DC voltage controller and AC voltage controller are compared with d-q components of the transformer primary side currents. Then reference d-q component voltages for the modulation index of the control system are derived from this inner current control loop [5].

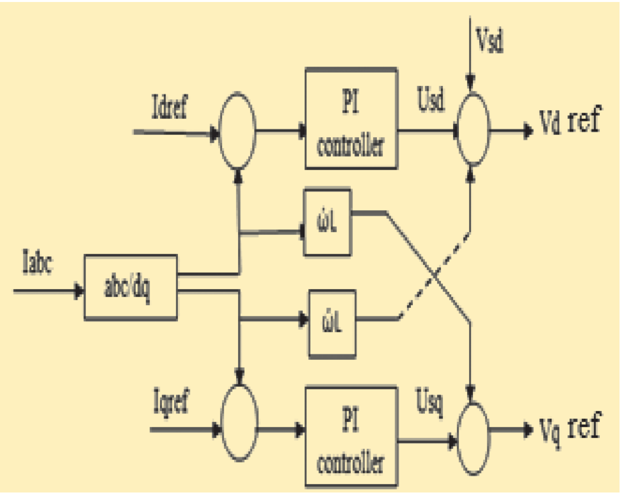

FIG. 4 INNER CURRENT CONTROL LOOP

Firing pulses required for the GTO switches in bridge are generated by the PWM switching strategy as shown in Figure 5. The pulse width modulation technique is sine-triangular pulse width modulation. It involves very fast switching between two fixed voltages to create an AC voltage. The PWM has an advantage of instantaneously controlling the phase and magnitude of the voltage. In order to create this AC voltage, a (sinusoidal) reference control signal at the desired frequency is compared with a (triangular) carrier waveform, as shown in Figure 5. The carrier waveform determines the switching frequency of the devices and its amplitude and frequency are generally kept constant [9].

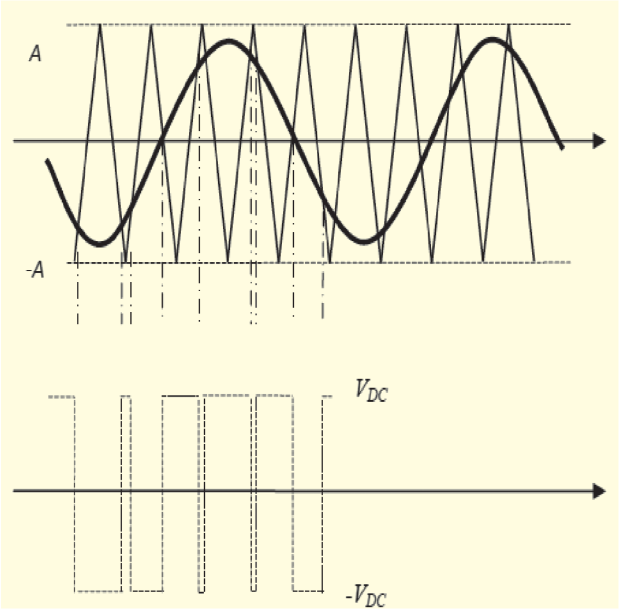

FIG. 5 PWM SWITCHING STRATEGY

4.0 SIMULATION RESULTS

4.1 Steady state simulation

The simulation of VSC-HVDC is studied for steady state condition and DC fault condition. The normal operating condition of VSC-HVDC system is simulated with DC voltage of +/- 60 kV and DC power of 100 MW. Steady state AC voltages of 93 kV and 44 kV are maintained at rectifier and inverter respectively. AC voltage at the sending end is shown in Figure 6 and at the receiving end is shown in Figure 7. Steady state DC voltage is shown in Figure 8.

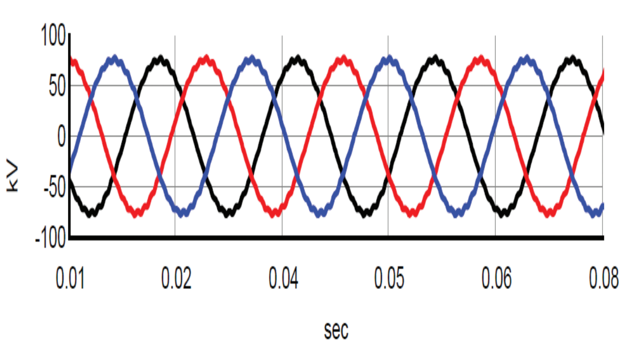

FIG. 6 AC VOLTAGE AT SENDING END

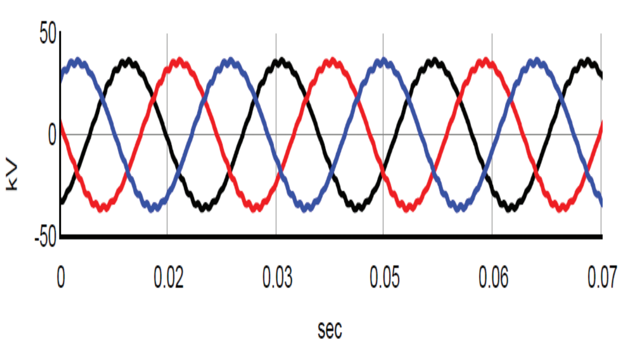

FIG. 7 AC VOLTAGE AT RECEIVING END

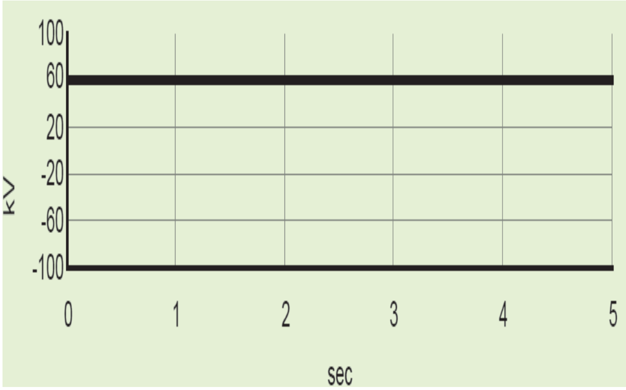

FIG. 8 PRE-FAULT DC VOLTAGE

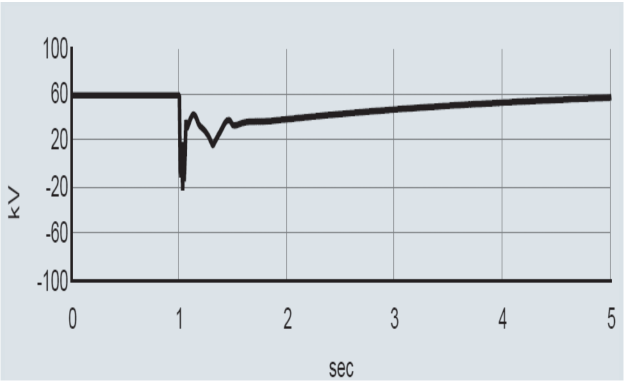

FIG. 9 DURING FAULT DC VOLTAGE

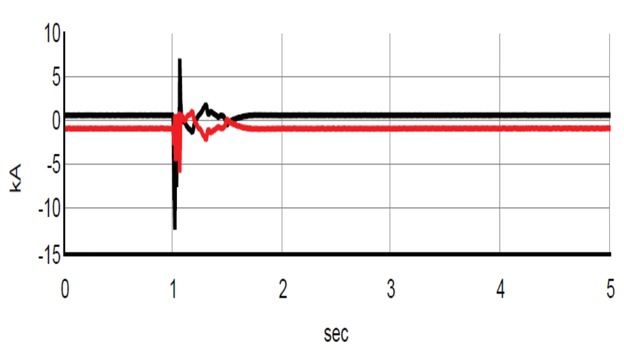

FIG. 10 DC CURRENT

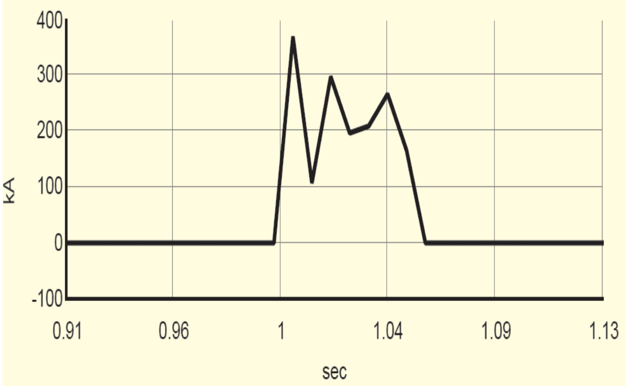

FIG. 11 FAULT CURRENT

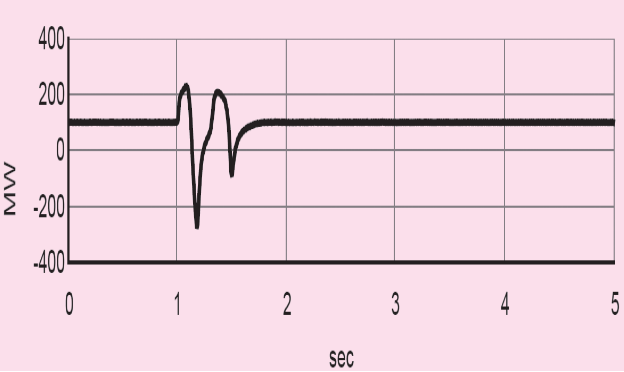

FIG. 12 SENDING END ACTIVE POWER

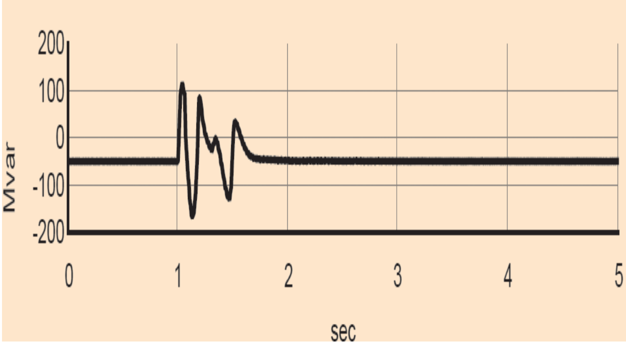

FIG. 13 SENDING END REACTIVE POWER

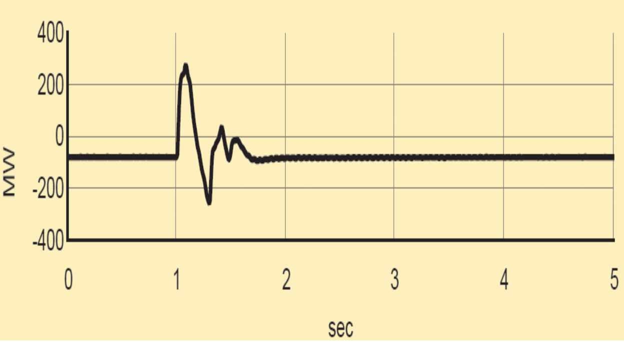

FIG. 14 RECEIVING END ACTIVE POWER

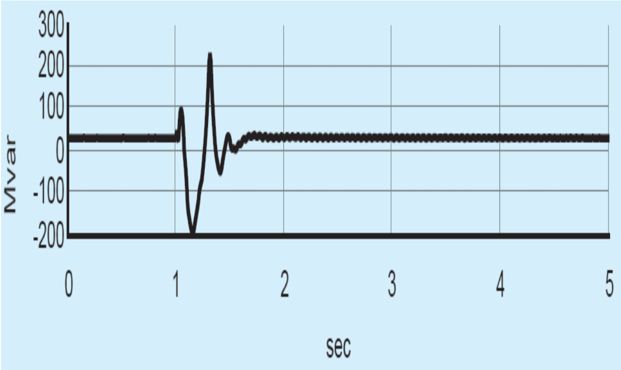

FIG. 15 RECEIVING END REACTIVE POWER

4.2 DC fault simulation

Once the system is reached to this steady state condition after de-blocking the firing pulses, DC fault is created at the positive pole by pushing the fault button for fault duration of 60 msec. During fault, the DC link capacitor discharges as shown in Figure 9. Due to the discharging of capacitor a large inrush of DC current flows through the cable and is shown in Figure 10. The DC inrush current decays by extinguishing the arc through the breaker which is carrying current of 350 kA during fault as shown in Figure 11. Due to the decay of the inrush current the voltage at the capacitor is becoming positive which effectively recharges the capacitor within 3 sec after the fault duration. The active power and reactive power at sending end are shown in Figure 12 and Figure 13. The active and reactive powers at receiving end are shown in Figure 14 and Figure 15.

5.0 CONCLUSION

In this paper design and analysis of the VSC-HVDC system is carried out. DC voltage and AC voltage controllers are implemented at rectifier and inverter. Steady state simulation of VSC-HVDC system is achieved by modeling the detailed system in RSCAD^{TM} software of RTDS^{TM}. DC fault analysis is carried out and the recovery of the system is observed with the modeled controllers and tuned PI controller gains and time constants. The DC breaker extinguishes the fault current without the need of de-energizing the system. This system may be extended for a multi-terminal case with independent active power and reactive power control, DC voltage and AC voltage control.

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