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Review Article

INDEPENDENT CONTROL OF MULTI-TERMINAL VOLTAGE SOURCE CONVERTER-BASED HIGH-VOLTAGE DIRECT CURRENT LINK ANALYZING FOR DIRECT CURRENT FAULTS

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ABSTRACT

The ability to control the active power, reactive power, alternating current (AC) voltage, and direct current (DC) voltage has provided the optimum utilization of the power system. This paper presents the modeling of multi-terminal voltage source converter (VSC)-based high-voltage direct current (HVDC) system. The reactive power by a particular terminal can be maintained constant or controlled. The DC bus voltage and AC voltage are controlled by separate terminal; the active power flow is maintained by another terminal. Each terminal can control up to two parameters depending on the requirement. Each controlled parameter requires tuning of PI controller gains to achieve satisfactory performance. The analysis of VSC-based HVDC is carried out using vector control. The multi-terminal response of a VSC-HVDC system during load changes, power reversal, and line to ground fault on DC cable are analyzed. Simulation is carried out in RSCAD/RTDS software, and the performance of the system is presented.

Keywords: Alternating current voltage controller, Direct current fault, Direct current voltage controller, Multiterminal, Neutral point diode clamped converter, Voltage source converter-high-voltage direct current.

INTRODUCTION

The common direct current (DC) voltage made parallel connections easy to build and control for a multi-terminal voltage source converter (VSC)-based high-voltage direct current (HVDC) system when compared to the current source converter or conventional thyristor-based HVDC systems as shown in Fig. 1.

VSC-based HVDC systems are finding an important place in the transmission systems. Some of the advantages of VSC-HVDC that made this technology more attractive are:
1. Due to its modular, compact, and standardized construction, the converter can be easily and rapidly installed/commissioned at the desired site [1].
2. Commutation with VSCs permits black start [2].
3. VSC technology provides rapid and independent control of active and reactive power [3] without need of extra compensating equipment. The reactive power can be controlled independent of active power [1-4].
4. The VSC-HVDC system connection for a "weak" AC network or to a network where the short circuit level is low, i.e. absence of generation source [4,5].

Due to the advantages, the VSC-based HVDC transmission suits very well in certain applications. The applications are:
1. Remote islands can be supplied by submarine cables using VSC-HVDC transmission. An example of this application is the Gotland Island system.
2. Offshore application using VSC technology is flexible and new units can be easily added if the expansion of the farm is desired.
3. Mainly due to right-of-way and land constraints, the compact VSC-based HVDC technology represents a feasible solution to feed the city centers. Thus, the underground transmission circuits are placed to bring in power as well as to provide voltage support. This process is realized without compromising reliability, and it is an economical way to power supply. Other applications of VSC-based HVDC transmission system is asynchronous interconnection.

The control block diagram shown in Fig. 2 can control four parameters active power, reactive power, DC voltage, and alternating current (AC) voltage. The method of control depends on whether the VSC-HVDC is utilized for unified power flow control (UPFC) or static synchronous compensator (STATCOM). If it is used as a UPFC [6], then to derive the reference quadrature component of current (IQref), AQR in Table 1 is used, and if it is used as an STATCOM, then AC-AVR is used for stiff voltage at that terminal. Both DC-AVR and active power control (APR) are used in case of UPFC or STATCOM for the direct component of current (IDref). To control the active power flow, APR is used [7].

This paper is organized in different sections. Section 2 explains the RTDS software used for simulation purpose. Section 3 briefly describes the VSC-HVDC system and the performance of the proposed system. Finally simulation results are explained in Section 4. Conclusions are discussed at the end of the paper.

REAL TIME DIGITAL SIMULATOR - RTDS

A wide range of studies are possible with the modular fully digital power system simulator RTDS. It is a combination of hardware and software, which permits the simulation of power systems in real time. Simulations performed by the RTDS simulator are of electromagnetic transient's class.

RSCAD
A software package that comprises the graphical user interface used by the RTDS simulator. The functions available are file management, circuit layout, operator's console, and data analysis.

Compiler
The compiler is a software program which takes "picture data" input representing the user-defined circuit from RSCAD and produces the executable code required by the RTDS to perform the simulation of the output.

Giga processor card (GPC)
The GPC is a computational unit which is used for solving the overall network solution. The GPC contains RISC processors. The GPC is used to solve the network solution or various component models. Signal exchange between the GPC cards is accomplished through a common backplane for which all cards within a rack are connected.

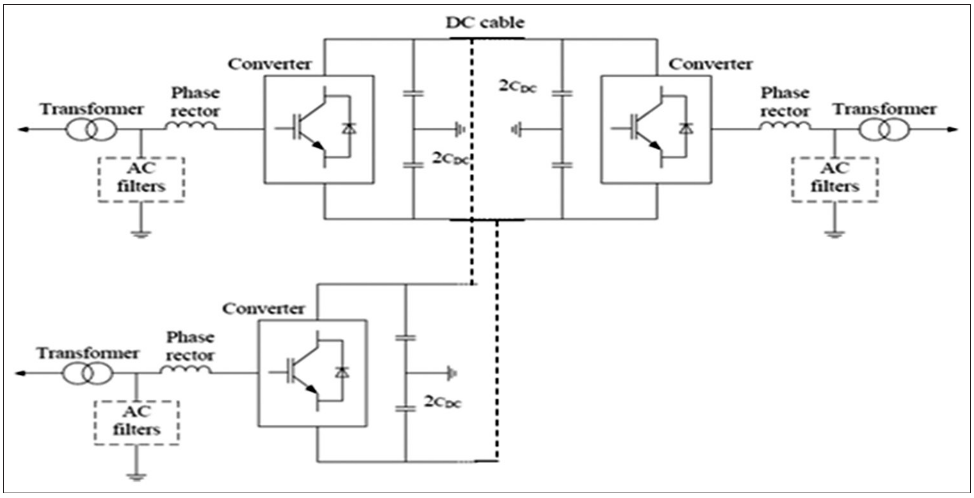

Fig. 1: Multi-terminal voltage source converter-based high-voltage direct current system

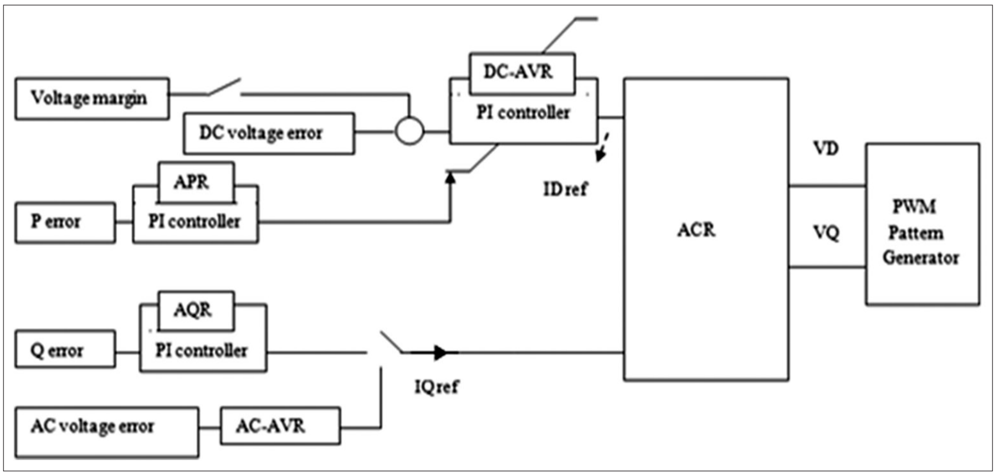

Fig. 2: Block diagram of controllable parameters for an alternating current/direct current converter

Giga bit transceiver workstation interface card (GTWIF)

It is a printed circuit card whose primary function is to handle communication between the rack and the host computer. The communication medium used is a standard Ethernet-based local area network. GTWIF also synchronize the calculations performed by the processor cards within a rack. It also provides inter-rack communication.

RACK

A rack is a basic module of RTDS hardware that includes a card cage and backplane structure to GPC and GTWIF. Larger simulators can be created by connecting multiple racks.

Advantages of RTDS simulator

Expandability, conducting multiple studies simultaneously, interactive runtime interface. Multiple software installations, small time-step subnetwork (<3 μs with which frequencies more than that of processors frequencies can be accurately tested) [8].

SYSTEM DESCRIPTION

VSC-HVDC system

As shown in Fig. 3, the three terminals of VSC-based HVDC system described in Table 2 is connected between three AC systems of two different frequencies. AC systems of rectifier terminal 1 and 3 at inverter terminal 2 are represented by the Venin's equivalent of 93 and 44 kV, respectively. The rectifier and inverter terminals are connected by a DC cable. The phase reactors smoothen the current. The capacitors are used for voltage support and harmonic attenuation. The circuit

Table 1: Terminology for controls

Active power control	APR
Reactive power control	AQR
DC voltage control	DC-AVR
AC voltage control	AC-AVR
AC current control	ACR
Pulse width modulation	PWM
Error	Reference value–Actual value

AC: Alternating current, DC: Direct current

Table 2: System data

AC system		
Terminal 1	Rectifier	93 kV, 60 Hz
Terminal 2	Inverter	44 kV, 50 Hz
Terminal 3	Rectifier	93 kV, 60 Hz
Converter	Rectifier	93/44 kV, 100 MVA
Transformer (Y/Y)	Inverter	44/44 kV, 100 MVA
VSC-HVDC system	DC V: 60 kV, Power: 200 MW	
DC cable	100 km	

AC: Alternating current, DC: Direct current, VSC: Voltage source converter, HVDC: High-voltage direct current inside the rectifier box is simulated in small step time simulation and interfaced to the main circuit through the interface transformer. The rectifier side circuit of VSC-HVDC consists of interfacing transformer, smoothing reactor, VSC Bridge, and the DC line as shown in Fig. 4. The rectifier side of terminal 3 also has a similar configuration. The inverter side configuration is the mirror image of this. The VSC configuration used is having multi-level neutral point diode clamped converter (NPC).

NPC

NPC has been widely accepted among the multi-level converters. The desired output voltage levels can be achieved with a few numbers of capacitors and switches per phase, which is, therefore, more economical and reliable. The size of the capacitor is less since it is designed only for half the DC link voltage. The sinusoidal voltage with minimum or no filtering components can be achieved with optimum frequency of the converter switches [9].

Controls for multi terminals

This paper implements DC-AVR and APR controls for obtaining reference IDref at terminal 1 and to obtain IQref, AC-AVR is used. At terminal 2, DC-AVR is used to obtain IDref and AC-AVR is used to derive IQref. At terminal 3, DC-AVR and AQR are used to obtain IDref and IQref, respectively. This makes the optimum utilization of the power system making two terminals as UPFC and the other terminal as STATCOM.

Voltage margin and power reversal

Voltage margin as shown in Fig. 5 is required for the terminal to supply power [10]. The intersection point of the terminal characteristics and the change in characteristics and intersection point by resetting the voltage margin and the reversal of power flow can be observed as shown in Fig. 6a and b, respectively.

Controls at terminal 1

As shown in Fig. 7, the APR and AC voltage controller output is given to the inner current control loop. The Direct and Quadrature components of voltages obtained by the inner current controller [11] are used to generate firing pulses for the switches present in rectifier bridge circuit through pulse width modulation technique.

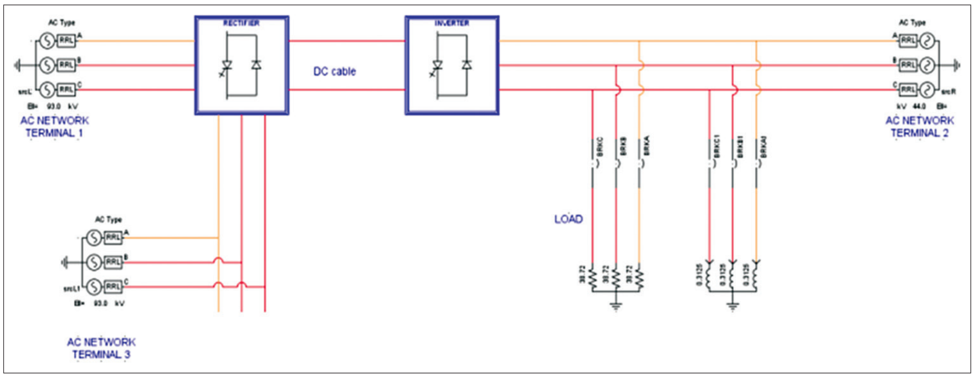

Fig. 3: Line diagram of voltage source converter-based high-voltage direct current

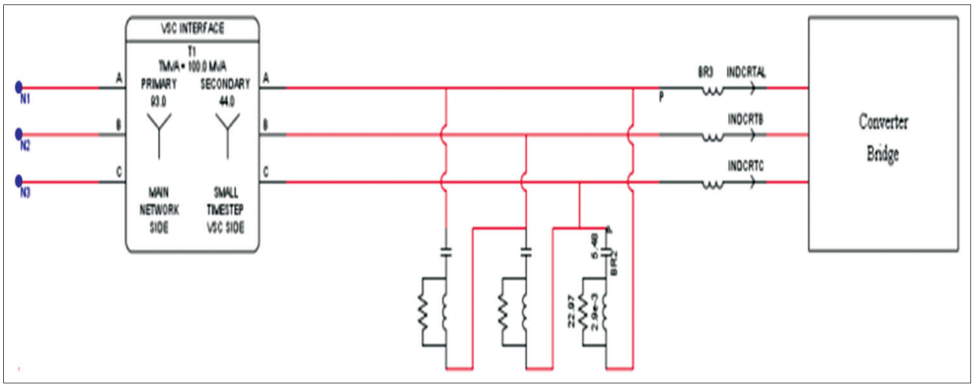

Fig. 4: Rectifier circuit of voltage source converter-based high-voltage direct current

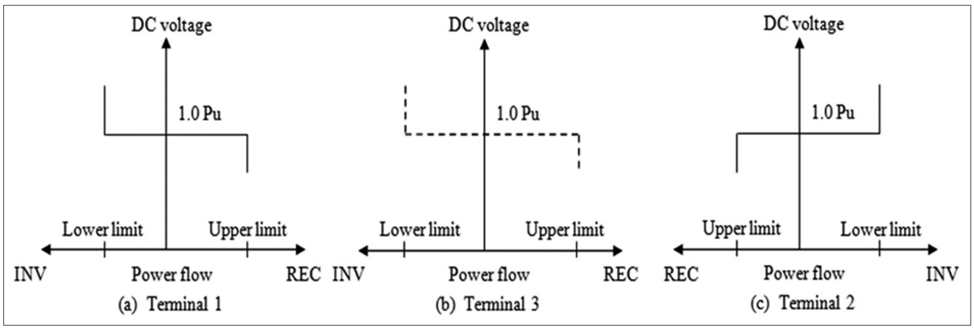

Fig. 5: Power-voltage characteristics of three terminals

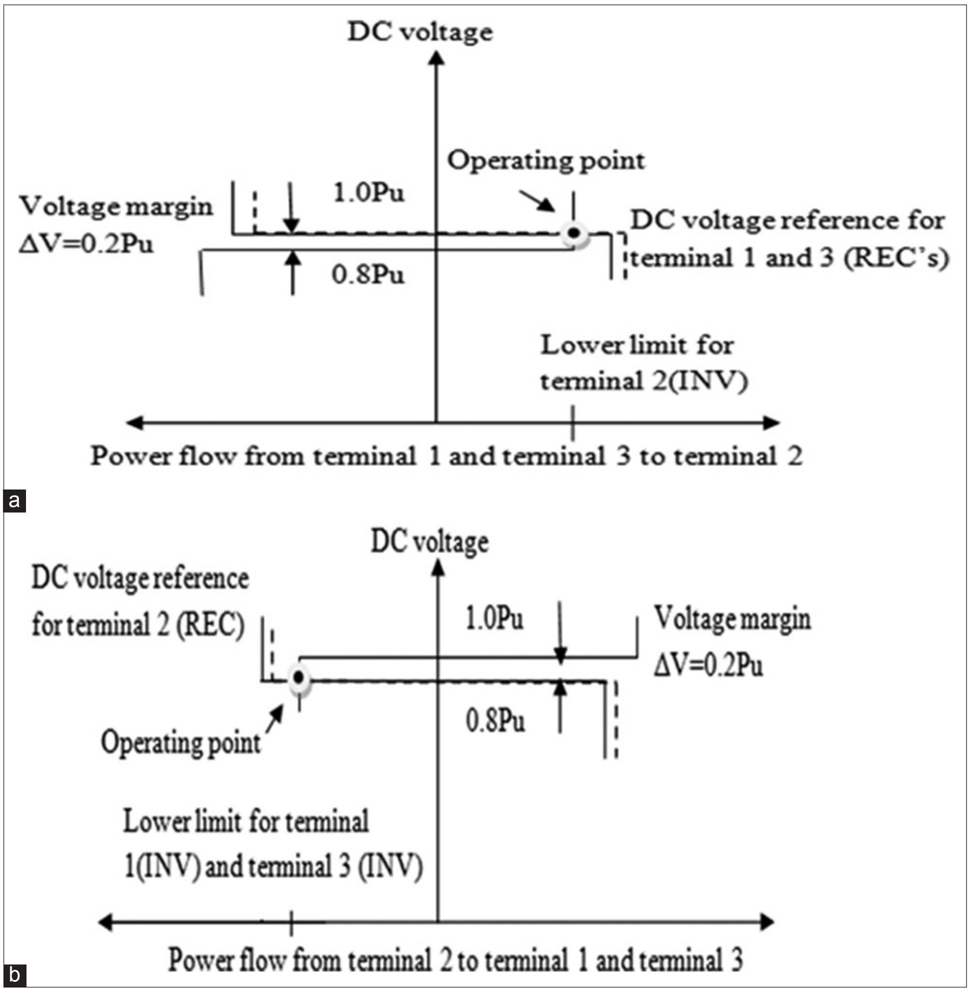

Fig. 6: (a and b) Power flow characteristics of three terminals

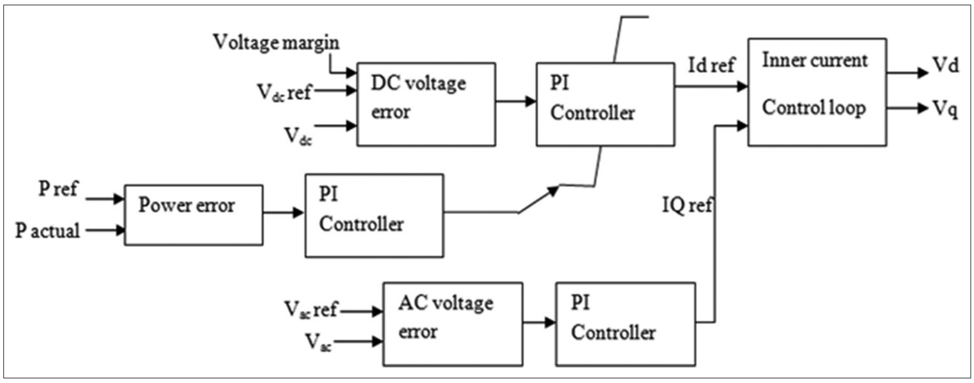

Fig. 7: Block diagram showing control at terminal 1

The actual power is compared with the reference power, and the error is passed through a PI controller which gives the command to the lower limit of the PI controller in DC voltage controller, which controls the active power at the terminal. In the AC voltage controller, the actual AC voltage is compared with reference value and the error is passed through PI controller, which gives IQref for the inner current controller.

Controls at terminal 3

The controls, as shown in Fig. 8 at terminal 3, have the actual reactive power comparison with the reference reactive power, and the error is passed through a PI controller, which gives IQref for the inner current controller. IDref for the inner current loop is similar to the DC voltage controller at terminal 1.

Controls at terminal 2

From Fig. 9, the DC voltage controller and AC voltage controller (Fig. 9) have a combination of controls from terminal 3.

Inner current control loop

The controls discussed above are outer controllers, and the ACR is the inner controller shown in Fig. 10, which is the inner current control loop. Where the currents derived from the PI controllers are compared with the d-q components of the transformer primary side currents.

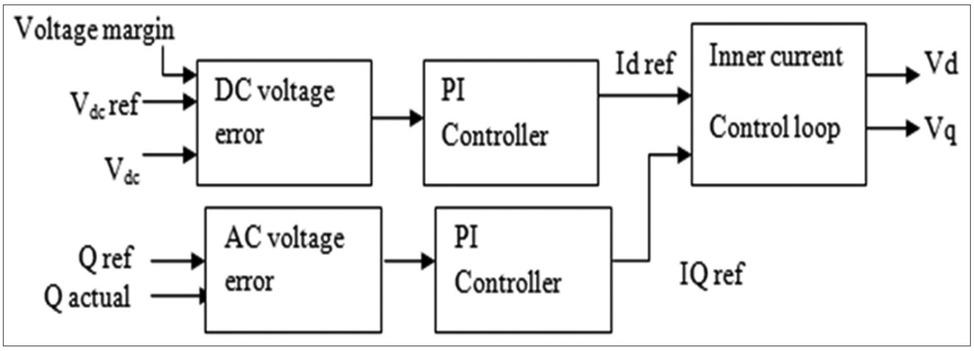

Fig. 8: Block diagram showing controls at terminal 3

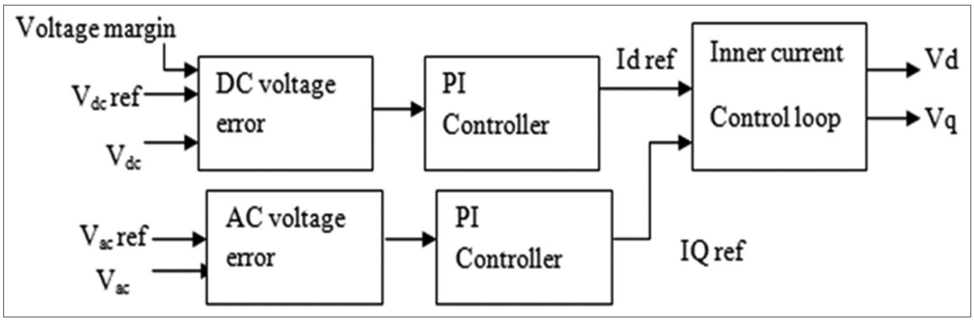

Fig. 9: Block diagram showing controls at terminal 2

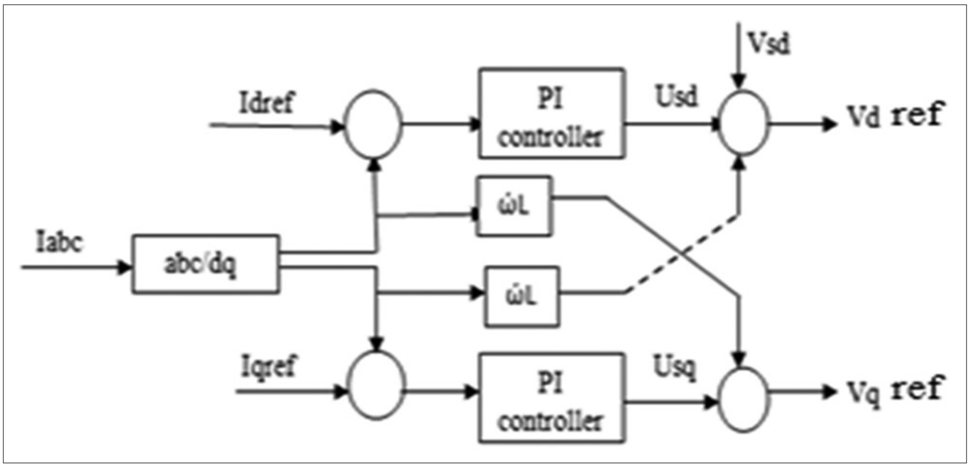

Fig. 10: Inner current control loop

The reference d-q component voltages for the modulation index of the control system are derived from this inner current loop [12].

SIMULATION RESULTS

The simulation of VSC-HVDC is studied for steady state condition, sudden load change without change in reference value and change in reference value, power reversal, and DC fault condition. The normal operating condition of VS-HVDC system is simulated with ±60 kV and 200 MW. Steady state AC voltages of 93 and 44 kV are maintained at rectifiers and inverter, respectively.

Case 1: Load at terminal 2 without change in reference power

A load of 50 MW at 0.95 power factor is added at terminal 2 without the change in reference power at terminal 1, described in Table 3. Since there is no change in power and to maintain the DC link power at 200 MW power at terminal 3 is maintained. The power required by the load is supplied from terminal 2 and this can be observed from Fig. 11. The reactive power controller at terminal 3 is maintained irrespective of load changes since reference reactive power is not changed. The AC and DC voltages are constant during load changes and the change in power is due to change in current and can be observed from Fig. 12.

Table 3: Terminology

PSRCL	Real power at terminal 1
PSRCL1	Real power at terminal 3
PSRCR	Real power at terminal 2
QSRCL	Reactive power at terminal 1
QSRCL1	Reactive power at terminal 3
QSRCR	Reactive power at terminal 2

Case 2: Load at terminal 2 with change in reference power

During this case, the change in reference power at terminal 1 is 50 MW, and now, the DC link power is 150 MW. To maintain the DC link power, the 50 MW power required by the load is supplied by terminal 2. The reactive power at terminal 3 is maintained.

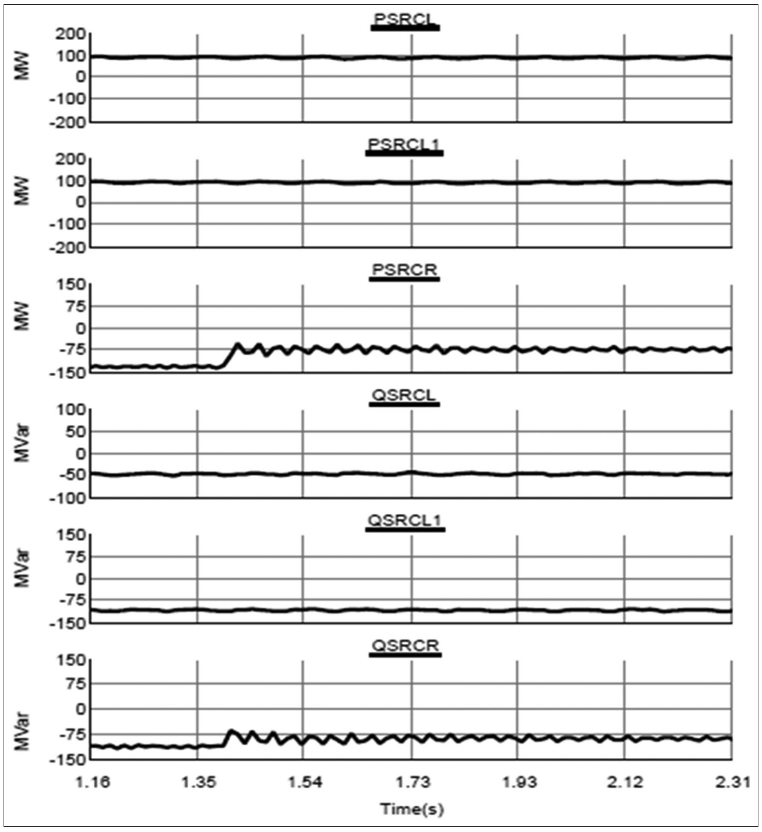

Fig. 11: Powers at terminal 1, 2, and 3 during case 1

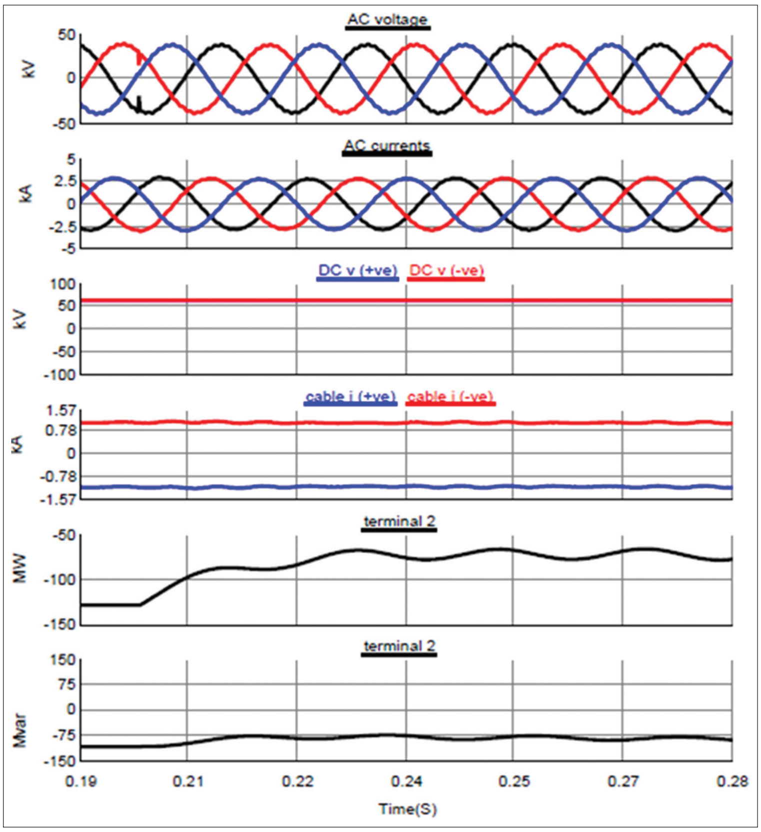

Fig. 12: Terminal 2 voltages, currents, and powers during case 1

These changes can be observed from Fig. 13. To maintain AC and DC voltages by the controllers, the decrease in AC current and DC cable currents can be observed from Fig. 14 for the required amount of power at terminal 2.

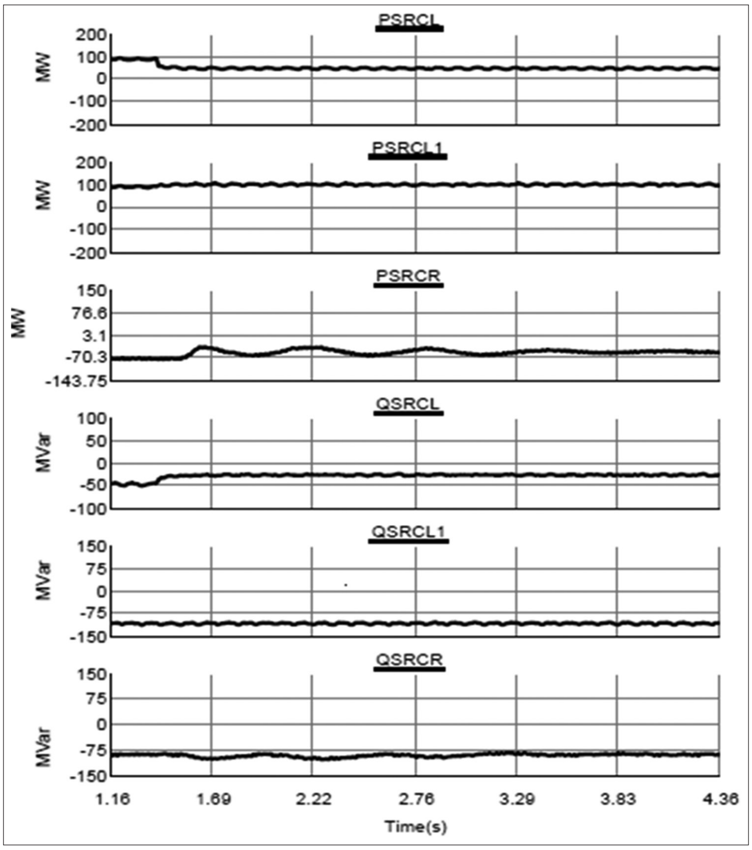

Fig. 13: Powers at terminal 1, 2, and 3 during case 2

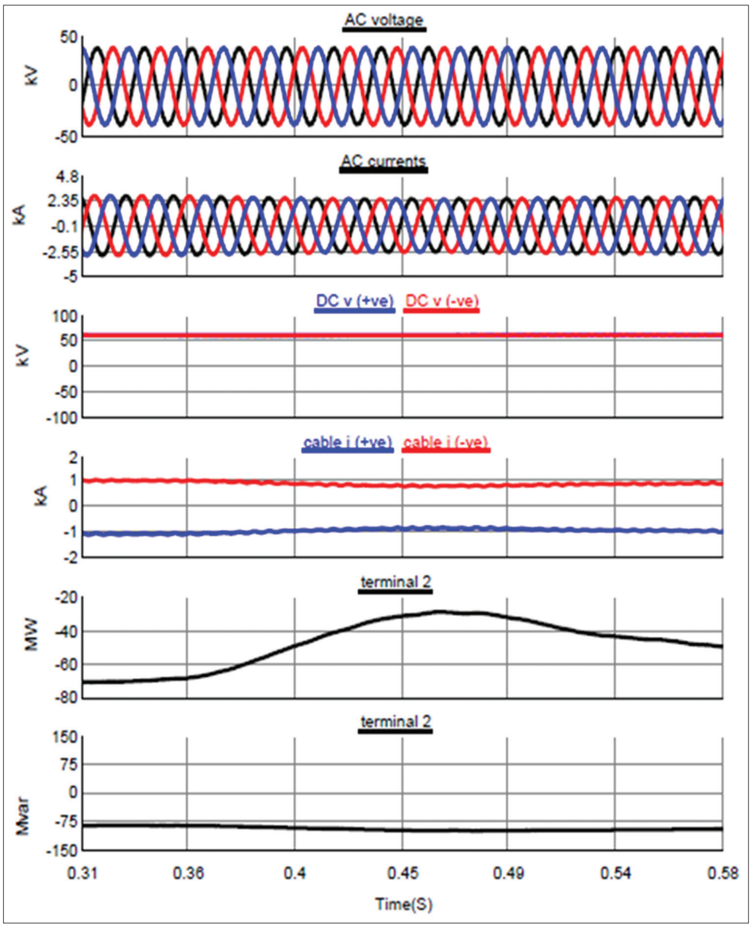

Fig. 14: Voltages, currents, and powers at terminal 2 during case 2

Case 3: Power reversal

Instead of giving voltage reference for terminals 1 and 3, now the DC voltage reference is given to terminal 2 for power reversal case as shown in Fig. 6b. The terminals 1 and 3 are absorbing power, and now, they are inverters and terminal 2 is giving power. The 50 MW of power is absorbed by each inverter side terminal. The reactive

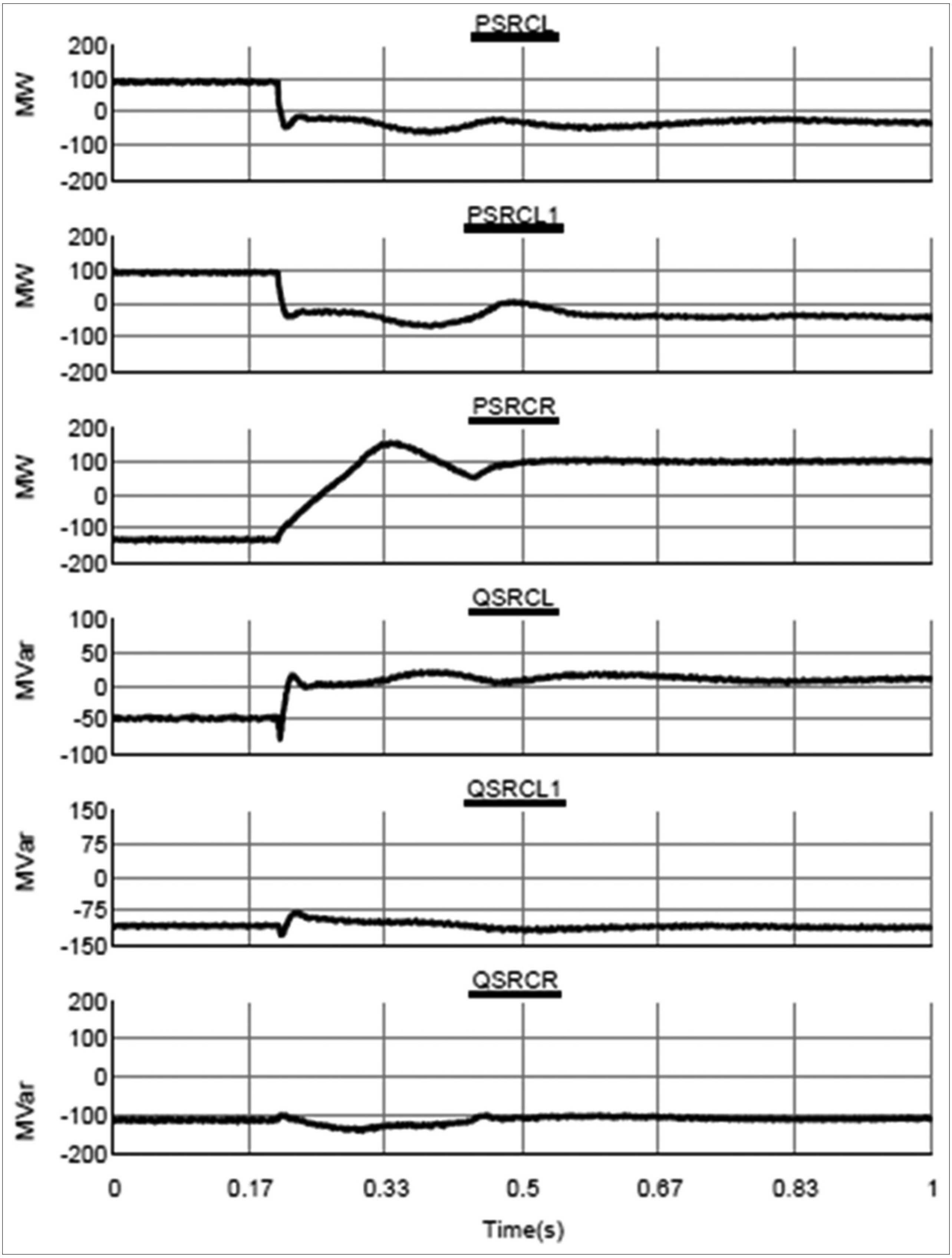

Fig. 15: Powers at terminal 1, 2, and 3 during case 3

power at terminal 3 is maintained by AQR. These can be observed from Fig. 15. During power reversal, the DC and AC voltages are maintained by the respective controllers. The currents through the cable are interchanged from positive to negative and vice versa. The change in AC currents for the change of power can be seen from Fig. 16.

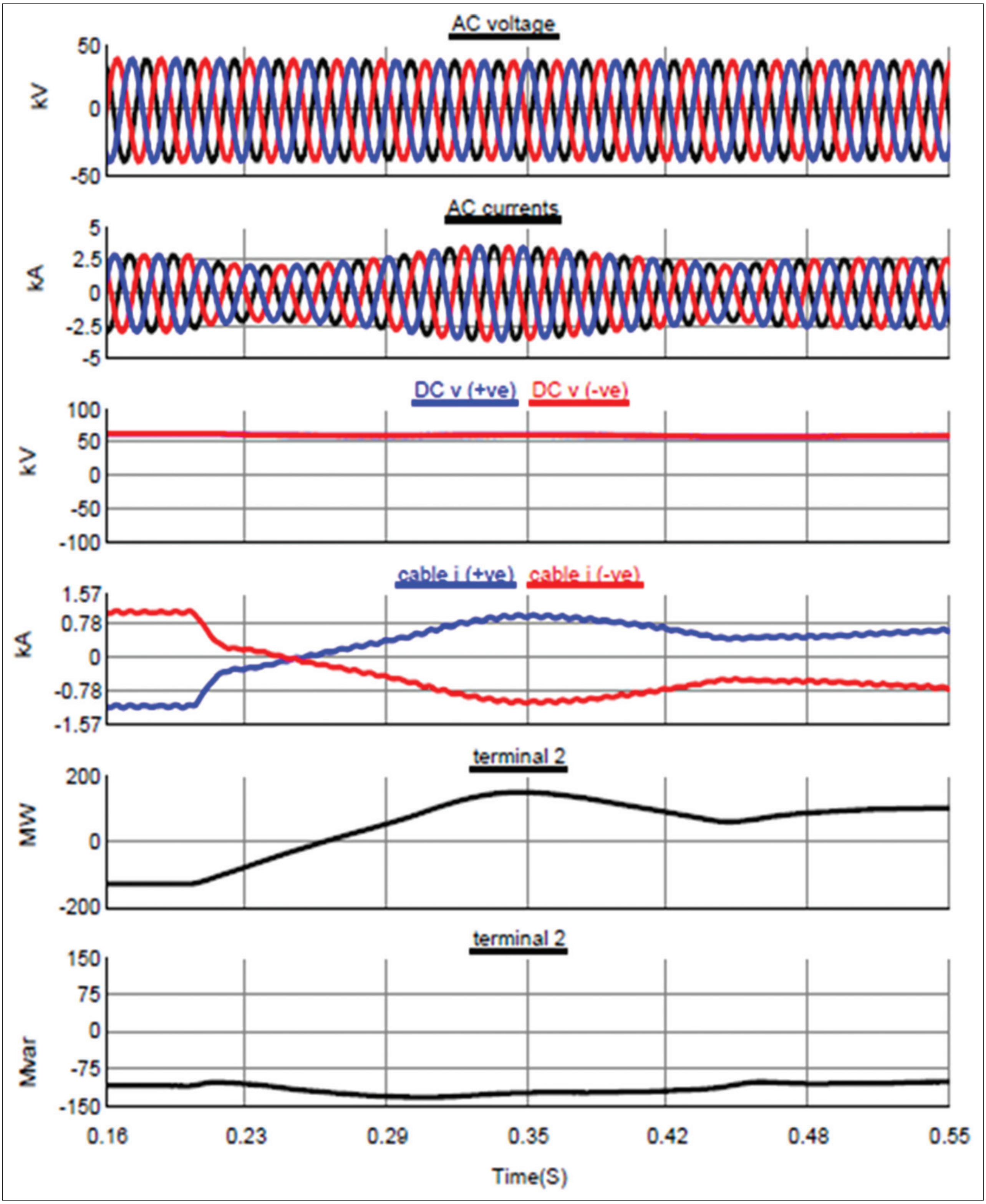

Fig. 16: Voltages, currents, and powers at terminal 2 during case 3

Case 4: Load at terminal 2 during power reversal

DC voltage at terminal 2 gives a DC link power of 100 MW. To maintain this DC link power without the change of reference value at terminal 1, the extra amount of power required by the load is supplied by the terminal 2. Now, the amount of power delivered by the terminal 2 is 150 MW. The reactive power controller at terminal 3 maintains at its

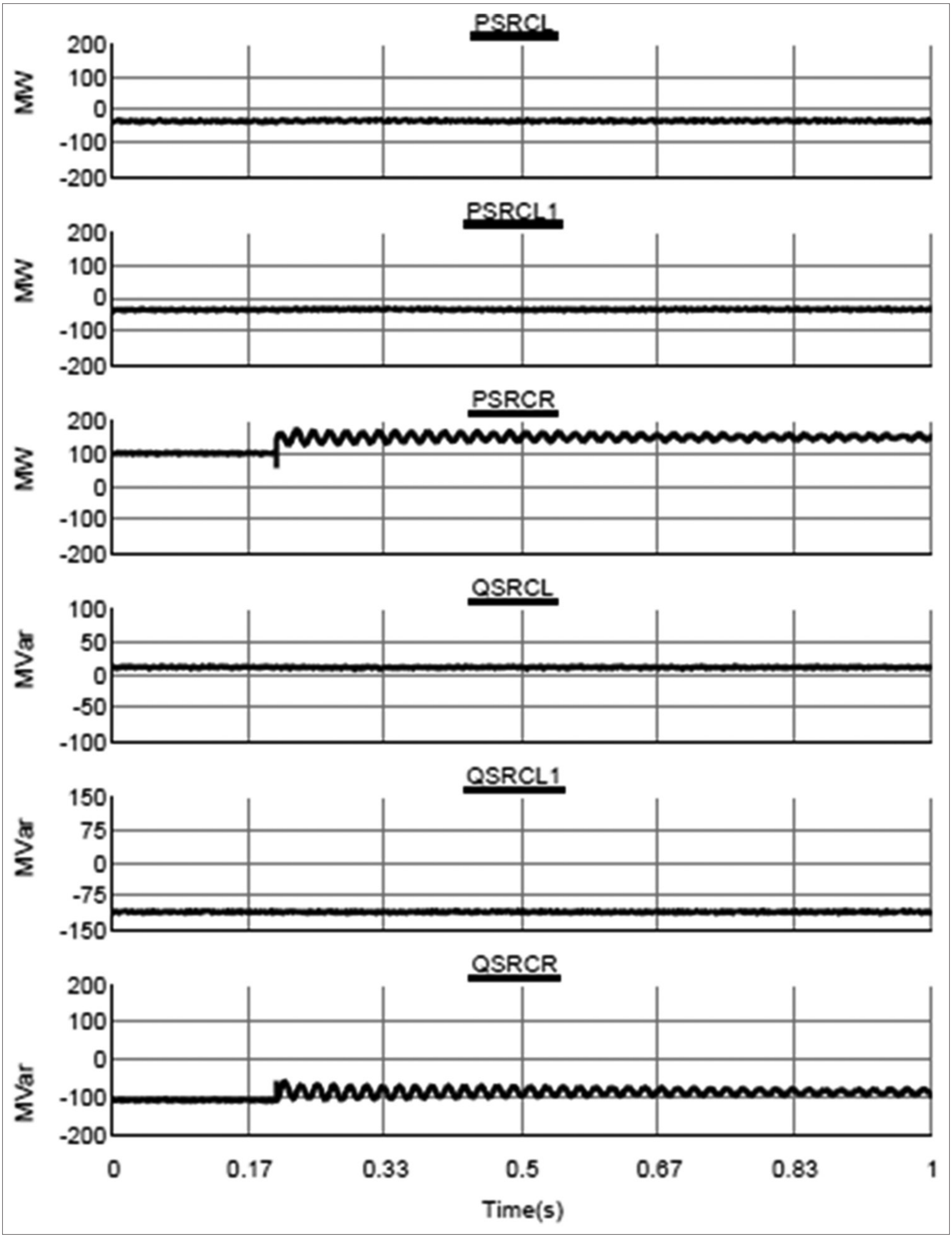

Fig. 17: Powers at terminal 1, 2, and 3 during case 4

value. These changes can be observed from Fig. 17. The required change in AC and DC currents to maintain voltages can be observed from Fig. 18.

Case 5: DC fault condition

Once the system is reached to this steady state condition; DC fault is created at the positive pole by pushing the fault button for fault duration of 60 ms. The DC link capacitors are grounded at the converter.

Capacitor discharging state

Initially, when the fault occurs, the DC link capacitor discharges through the DC cable [13], thus resulting in large inrush of DC current and rapid decrease in DC voltage and a substantial increase in AC current [14,15]. The switches of the VSC have to be blocked immediately to protect them from the resulting over current as shown in Fig. 19.

AC feeding over current stage

When the DC capacitor voltage falls, the large DC current flows through the DC cable and the freewheel diodes effectively shortened. The absence of DC smoothing reactor in the VSC-HVDC results in the generation of large over current. The discharge of voltage results in AC current.

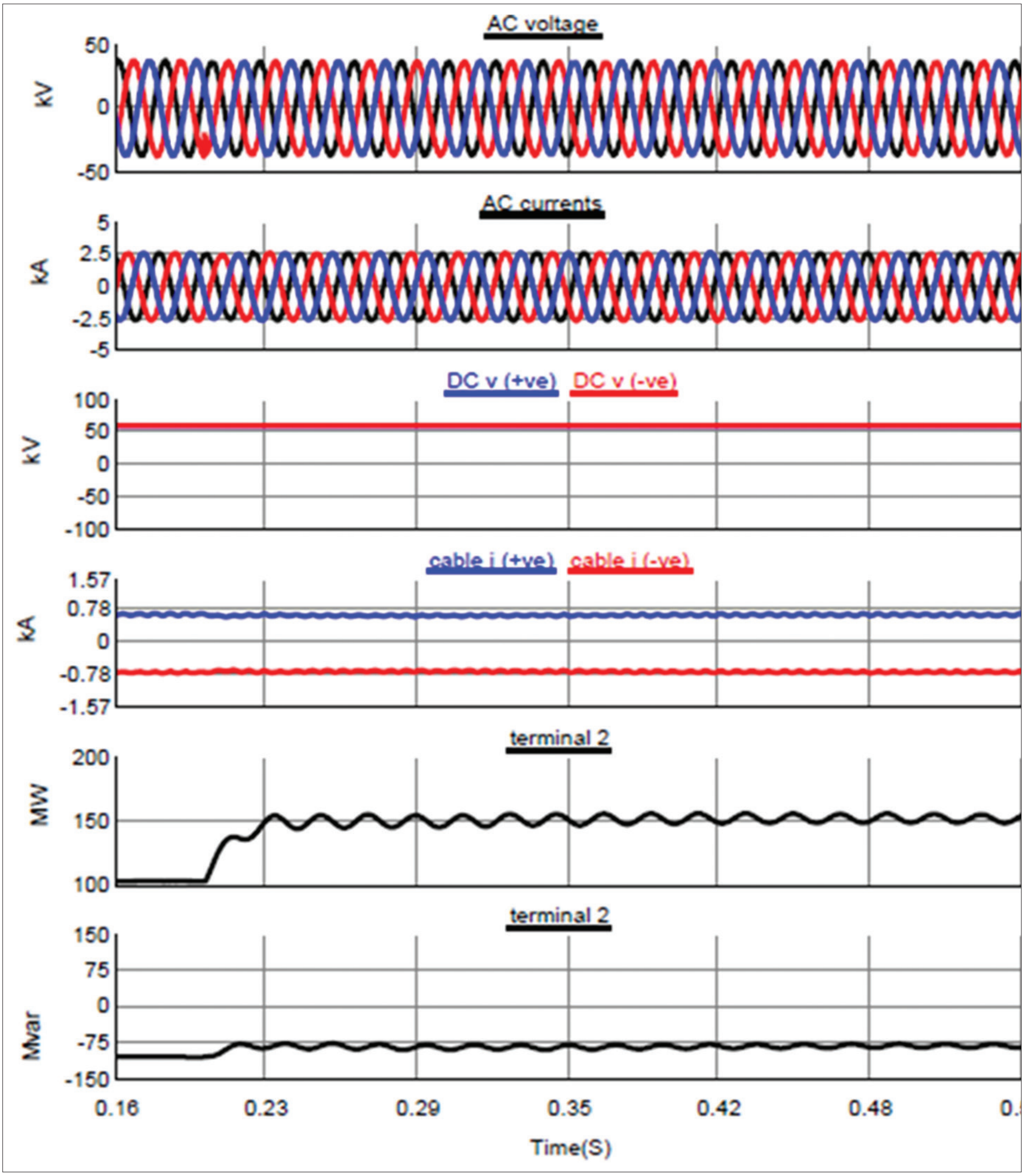

Fig. 18: Voltages, currents, and powers at terminal 2 during case 4

Table 4: PI controller gains and time constants

Terminals	Outer controllers (PI)				Inner controllers (PI)			
	ID axis		IQ axis		ID axis		IQ axis	
	Gain	Time constant	Gain	Time constant	gain	Time constant	Gain	Time constant
1	7.5	0.01	10	0.001	0.18	0.2	0.18	0.2
2	7.5	0.01	10	0.001	0.18	0.2	0.18	0.2
3	7.5	0.01	10	0.001	0.18	0.2	0.18	0.2

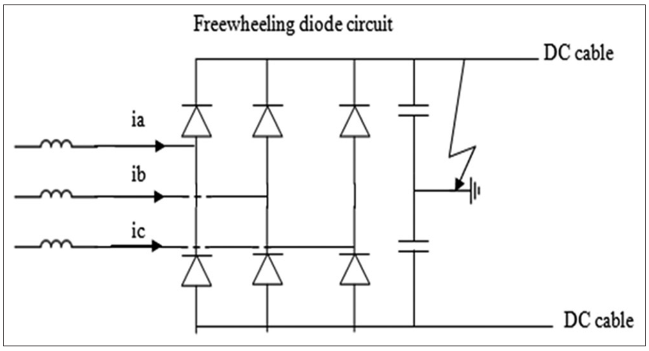

Fig. 19: Single voltage source converter after blocking of switches

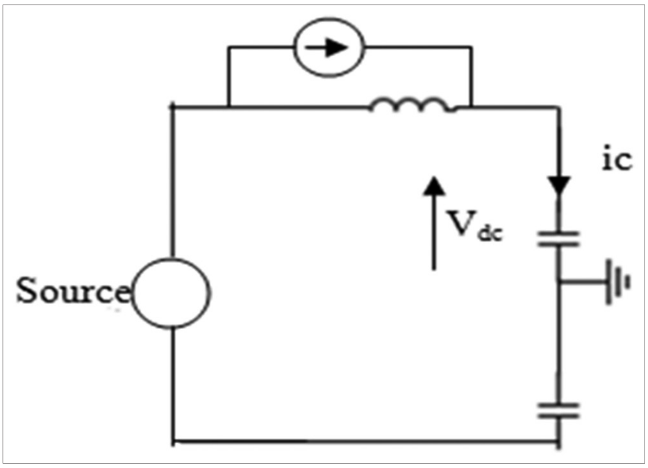

Fig. 20: Capacitor recharging phase

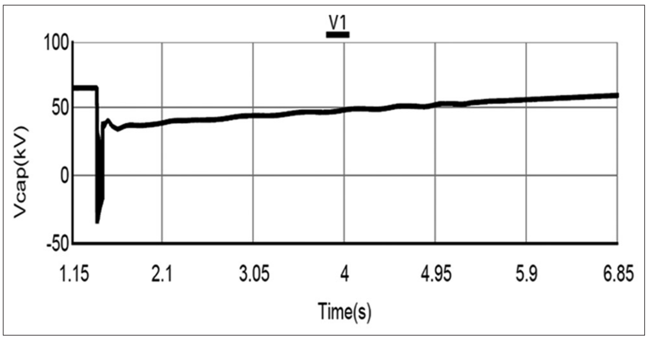

Fig. 21: Voltage across the capacitor

Capacitor recharging stage

As the DC cable current decays, the current in the capacitors changes which effectively recharges the capacitor as shown in Fig. 20.

Capacitor discharging condition, AC overcurrent and cable current, and capacitor current can be observed from the Figs. 21-24, respectively.

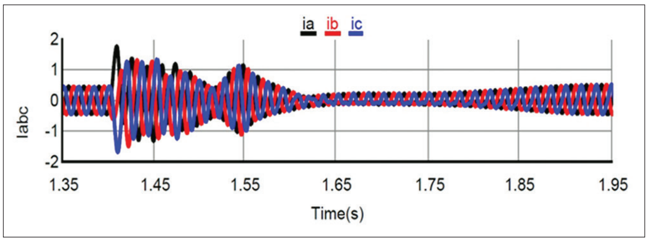

Fig. 22: Alternating current at converter bridge

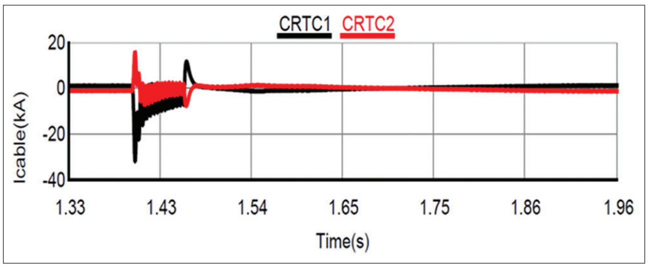

Fig. 23: Direct current cable

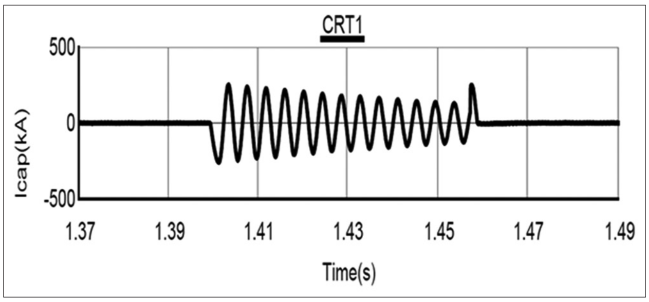

Fig. 24: Current through the capacitor

CONCLUSION

In this paper, design and analysis of the VSC-HVDC system are carried out. Active power, reactive power, DC voltage, and AC voltage controllers are implemented at rectifier and inverter as per requirement. Steady state simulation of VSC-HVDC system is achieved by modeling the detail system in RSCAD/RTDS software. The multi-level NPC converter in this study has reduced large capacitor requirement at the DC link. The high blocking capacity of the switch in the converter protected the system during positive pole to ground fault. The system is observed with the modeled controllers and tuned PI controller gains and time constants as shown in Table 4. This work can be analyzed for larger size wind farms connected to the grid.

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