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Analysis of VSC-HVDC system feeding a passive network

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With the advent of Thyristor technologies, High Voltage Direct Current (HVDC) transmission system is used for transmitting large amount of power over long distance. It is a mature technology and has been playing a vital role in both long distance transmission and in the asynchronous interconnections. VSC-HVDC systems represent recent technology in the area of DC power transmission. One of the limitations in using conventional HVDC system is that it is difficult to connect to a weak network with no local generations nearby. VSCs are based on IGBTs that can be switched on and off by control signals and can be operated at high frequencies. Since VSC, has the capability to control both active and reactive power, it has become a widespread applications in power system. In this paper, the behavior of a VSC-HVDC system when connected to a passive network is studied under the steady state and transient conditions. The simulations are carried out using Real Time Digital Simulator (RTDS) available at CPRI, Bangalore. Simulation results proved that the modeled controller has good steady state and transient response during the faults. Performance of VSC-HVDC is also studied when feeding the loads like motors and found that the system response is satisfactory.

Keywords: *VSC-HVDC, PWM, HVDC, RTDSTM, PI Controller*

1.0 INTROUCTION

Almost in most of the locations, the generating stations are setup far from the load centres owing to the availability of natural resources. At the same time transmission of bulk power over limited transmission corridor becomes a challenging task. Transmission of electrical power can be categorized as High voltage DC transmission system and High voltage AC transmission system. Since HVDC transmission system uses only two conductors for transmission of bulk power over a long distance, the use of HVDC system is most preferred when compared to that of HVAC system.

On the other hand Industrial power systems are characterized by high concentration of loads. Many industrial loads are very sensitive to voltage dips and other disturbances originating from the grid [1, 2]. Equipment mal-operation due to voltage dips and other disturbances can lead to high cost. Therefore, utility electric power systems are faced with the challenge of providing high-quality power to industrial loads.

VSC - HVDC have several advantages over LCC - HVDC viz: VSC-HVDC permits independent control of both active and reactive power outputs [3, 4], it does not require a voltage source for satisfactory operation, no problems of commutation failure, the harmonic filtering required is much simpler as Pulse Width Modulation(PWM) is used, fast communication between the terminals is not required for control purpose and the power reversal in the link does not require voltage reversal, this enables better control during DC system operation. The VSC-

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HVDC, which uses modern semiconductors with self-commuted ability, overcomes the disadvantages of conventional HVDC and is therefore more suitable for a weak ac network or a passive network without any power sources[5]. The use of such DC links provides possible new solution to power-quality related problems in industrial power systems.

2.0 VSC-HVDC SYSTEM

The conventional HVDC uses thyristor devices and is considered to be superior in transmitting maximum bulk power for long distances. Due to several limitations, the use of HVDC systems with Voltage Source Converter(VSC) technology are increasing in recent years especially at power ratings of up to 1000MW due to its controllability, compact modular design, ease of system interface and low environmental impact. Today several commercial projects are already in operation.

2.1 Components of VSC-HVDC

A typical VSC-HVDC system consists of voltage source converters, AC filters, transformers, phase reactors, DC capacitors and DC cables. Mainly two basic configurations of VSCs are used in HVDC transmission system. These are two-level VSC converter and three-level VSC converter. In high power applications the three-level VSC configuration as shown in Figure 1 represents a reliable alternative to the two-level VSC configuration because the phase potentials can be modulated between three levels of -0.5Vdc, 0 and +0.5Vdc. The converters are VSCs employing IGBT power semiconductors one operating as a rectifier and the other as an inverter.

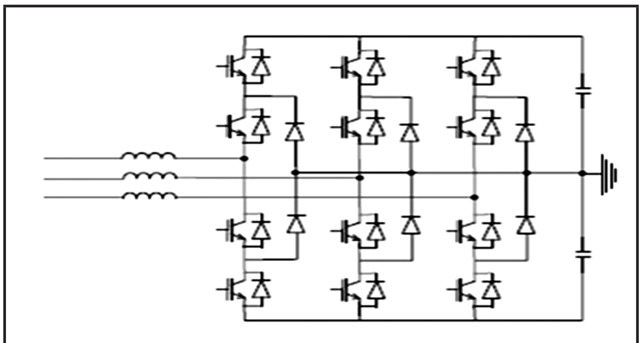

FIG 1 THREE LEVEL VSC CONVERTER

2.2 Operation of VSC-HVDC

The switching strategy is by using Pulse Width Modulation technique which involves a very fast switching between two fixed voltage signals to create an AC voltage. Normal operation modes mean that each station controls its reactive power flow independent of the other station. However, the active power flow into the DC network must be balanced. Any difference means that the DC voltage in the system will rapidly increase or decrease.

3.0 SIMULATION OF VSC-HVDC SYSTEM USING RTDS

3.1 Real Time Digital Simulator

The RTDS [7, 8] is a special purpose computer designed to study Electromagnetic Transient Phenomena in power systems in real time. The RTDS comprises of specially designed hardware and software. RTDS hardware is Digital Signal Processor (DSP) based and utilizes advanced parallel processing techniques in order to achieve the computational speeds required to maintain continuous real-time operation. 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-step(Δt).

Many hundreds of thousands of calculations must be performed during each time-step in order to compute the state of the system at that instant. The temporary transients class of studies for which the RTDS is most often used requires (Δt) to be in the order of 50 to 100µsec (frequency response accurate to about 3000 Hz.). The RTDS Simulator works in continuous, sustained real time. That is, it can solve the power system equations fast enough to continuously produce output conditions that realistically represent conditions in the real network. Because the solution is real time, the simulator can be connected directly to power system control.

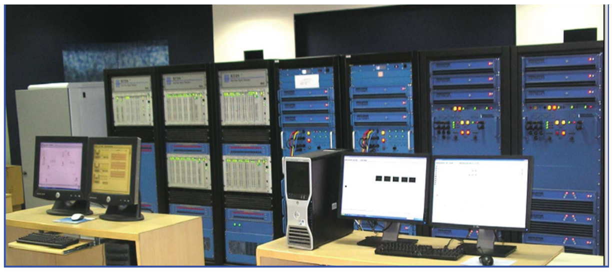

FIG 2. RTDS FACILITY AT CPRI

3.2 Simulation of VSC-HVDC when feeding a passive network using RTDS™

The system considered for simulation is as shown in Figure 3. Three-level VSC's are used for modeling. 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.

The system consists of ac source at the sending end. The source voltage at the sending end is stepped down to the required voltage using converter transformer. Output of converter transformer is connected to three phase VSC PWM rectifier.

Device used for PWM converter is IGBT, a diode is connected in anti-parallel to each IGBT so as to avoid reversal of current. Snubber circuit is connected across switch to protect it from voltage surges. Firing pulses required to turn-on and turn-off the device is generated by control circuit. Direct current from the PWM is transmitted by underground cable. At the receiving end dc is converted to ac using VSC based PWM inverter and stepped to required voltage using transformer, output of the transformer is connected to load.

3.3 Controller Scheme

The objective of the control scheme of a VSC-HVDC system is accurate control of transmitted active and reactive power. The active and reactive power is controlled directly by controlling the phase angle and amplitude of the converter output voltage. The control system generally adopted in VSC-HVDC is Direct control and Vector control methods [5]. The Vector control method is widely used and the same is adopted in this paper. The block diagram is as shown in Figure 4. Vector control system involves simplified representation of three phase systems known as DQ transformations [9]. The transformation into rotating d-q coordinate system leads to the independent control of two current components, id and iq.

The power balance relationship between the ac input and dc output is given as,

$$p = \frac{3}{2}(v_d i_d + v_q i_q) = V_{dc} I_{dc} \quad ...(1)$$

Where Vdc and Idc are dc output voltage and current respectively.

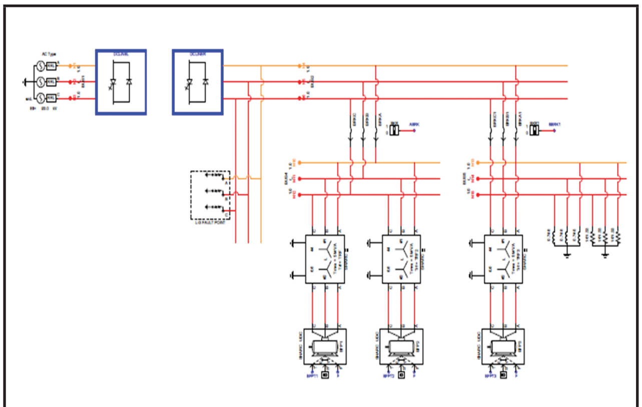

FIG 3. SINGLE LINE DIAGRAM OF VSC-HVDC SYSTEM

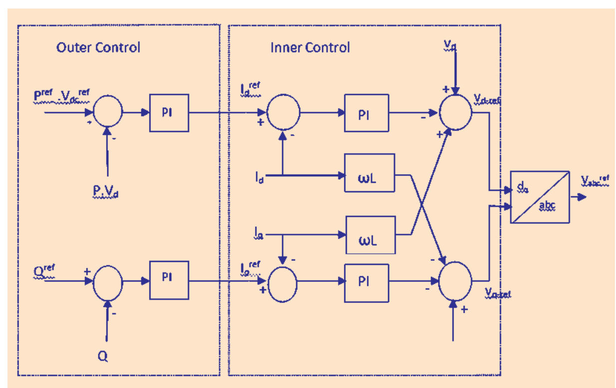

FIG 4. BLOCK DIAGRAM OF THE CONGTROLLER

The grid voltage vector is defined to be along the d-axis direction, and then a virtual grid flux vector assumed to be along the q-axis. With this alignment, vq = 0 and the instantaneous real and reactive power injected into or absorbed from ac system is given by,

$$p = \frac{3}{2} v_d i_d \quad (2)$$

$$q = -\frac{3}{2} v_d i_q \quad (3)$$

In all possible combinations of outer controller [10], the direct voltage controller is always necessary to ensure an active power balance in the system. Active power taken out of the network must equal the active power fed into the network minus the losses in the DC system. The angle between the α-axis of α-β frame and d-axis of the d-q frame is used for transformation between the α-β frame d-q frame. The angular position of the voltage vector is given by,

$$\theta = \tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right) \quad ...(4)$$

Where v_α and v_β are components of voltage in stationary two axis reference frame, α-β. The value of the angle θ is computed by using a synchronization technique, namely, phase lock loop (PLL).

Figure 5 shows the block diagram of the rectifier and inverter side controller where it has DC voltage controller and AC voltage controller whose output is given to the inner current control loop.

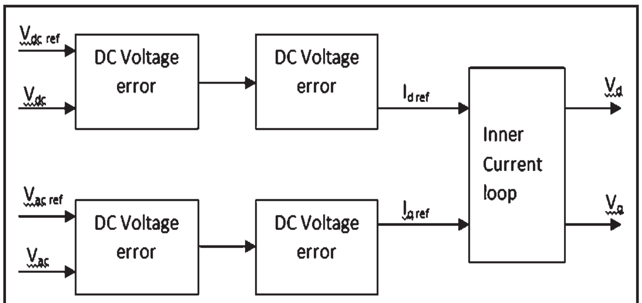

FIG 5. BLOCK DIAGRAM OF RECTIFIER AND INVERTER CONTROL

4.0 SIMULATION RESULTS

The single line diagram of the VSC-HVDC system simulated in RSCAD software of RTDS is as shown in Figure 3. The system details are as given in Appendix-I. As shown in Figure 3, a three phase source of 93kV, 60Hz rating is considered and it is connected to 25MVA, 93/44kV converter transformer. Output of this transformer is rectified through the VSC1 converter bridge. VSC2 is Inverter Bridge, feeding a passive network of RL load and Motor load through a 25MVA transformer. The motors are connected through 5MVA, 44/6.6kV rating transformer. VSC1 and VSC2 are three level converters. VSC1 and VSC2 are interconnected through a DC cable of 100 km length. At inverter side, dc voltage is again converted back to AC.

The performance of the system is simulated for four scenarios, viz.,

(i) Steady state condition

(ii) Single line to ground fault

(iii) Three phase to ground fault

(iv) Load Shedding

4.1 Steady state condition

Steady state simulation of VSC-HVDC system described above is carried out by de-blocking the firing pulses to the switches in bridges VSC1 & VSC2. Once the system has reached the steady state it is observed that the sending end active and reactive power is 24.89-j11.62, the power consumed by the motors M1, M2 is 5.546+j3.811 and the power consumed by M3 and RL load is 14.06+j9.98. The voltage at sending is 0.99pu, while at receiving end is 0.98pu. Total power transmitted through DC line is 23.24MW.

In Figure 6(a) power through DC line1 & line2 are plotted. Figure 6 (b) shows voltage at Bus1, Bus4 and Bus5. Figure 6 (c) shows the Active and reactive power consumed by Motor1 and

Motor2. Similarly, Figure 6 (d) gives the active and reactive power consumed by Motor3.

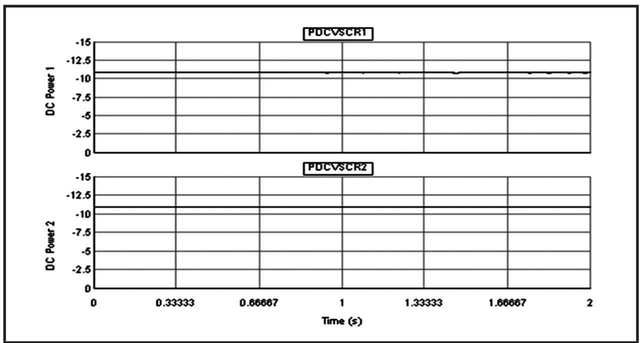

FIG 6 (A). POWER THROUGH DC LINE 1 & 2

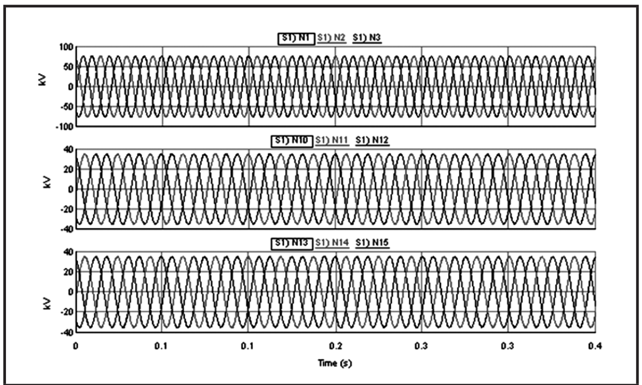

FIG 6 (B). VOLTAGE AT BUS1, BUS4 AND BUS5

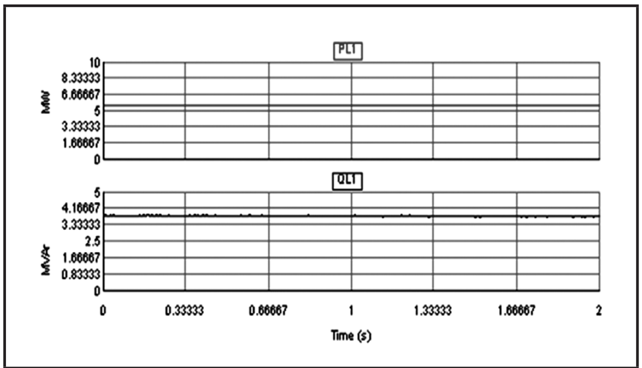

FIG 6 (C). ACTIVE AND REACTIVE POWER OF MOTOR M1 & M2

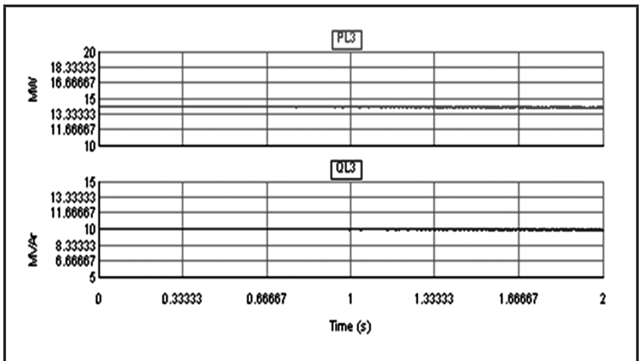

FIG 6 (D). ACTIVE AND REACTIVE POWER AT MOTOR M3

From the simulation results, it is seen that all the parameters in steady state are stable. Simulation results clearly demonstrate the operational feature of VSC-HVDC feeding an entirely passive network.

4.2 Single line to ground fault

In order to investigate the operation of VSC-HVDC under contingencies, simulation of Single line to ground faults at inverter side has been carried out. The fault is created for a duration of 100 msec.

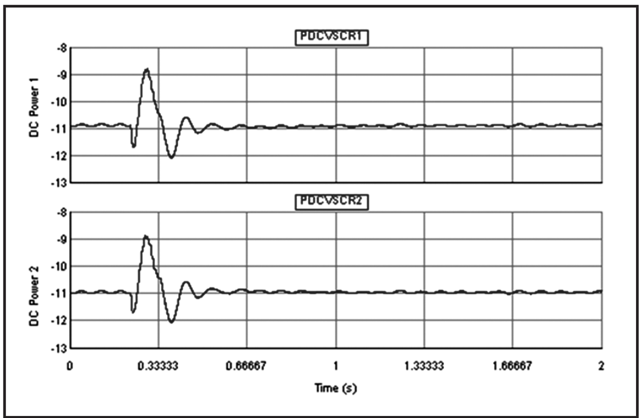

FIG 7 (A). POWER THROUGH DC LINE 1 & 2

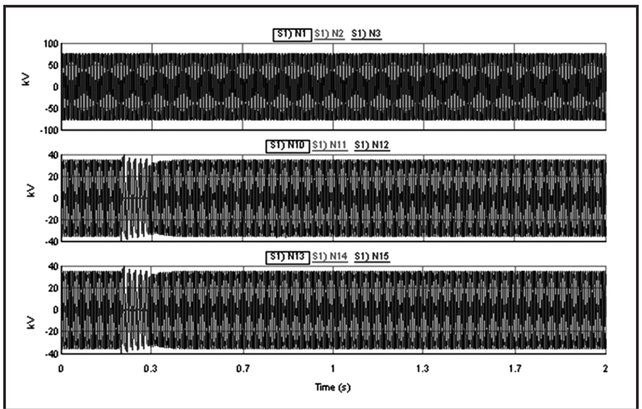

FIG 7 (B). VOLTAGE AT BUS1, BUS4 AND BUS5

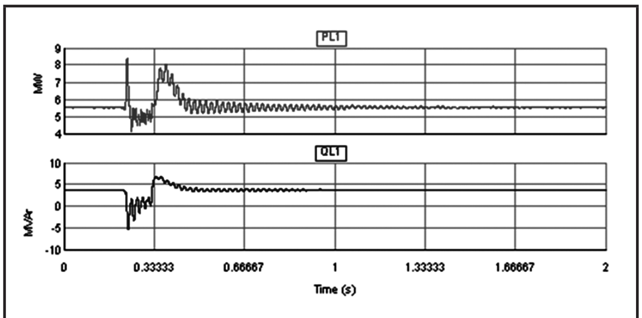

FIG 7 (C). ACTIVE AND REACTIVE POWER OF MOTOR M1 & M2

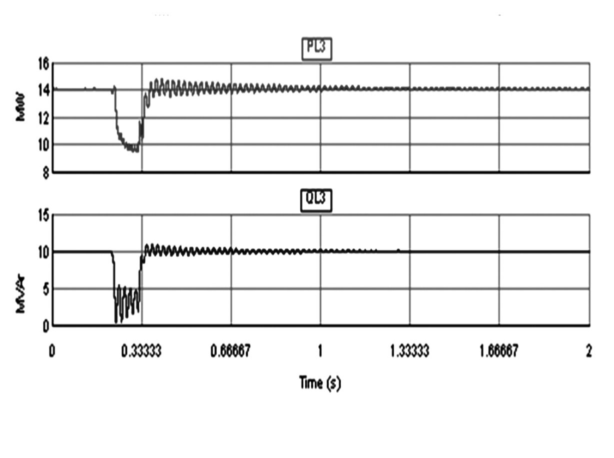

FIG 7 (D). ACTIVE AND REACTIVE POWER OF MOTOR M3

Referring to Figure 7(a), it can be seen that during pre-fault, the active power flow in each of the dc line is 10.91MW and during fault, it varies between 8.91MW to 12.13MW. Once the fault is cleared, it is almost the same as the pre-fault case i.e 10.91MW.

Figure 7 (b) shows the voltage variations at Bus1, Bus4 and Bus5 respectively. In Figure 7 (c) Active power of Motor M1 & M2 varies between 4.42 MW to 7.67MW during the fault and finally settles at a pre-disturbance value of 5.56MW. Even with these disturbances, it is seen that modulation index M1 and M2 responds very quickly. Figure 7 (d) shows the variations of Active and reactive power at Motor M3.

4.3 Three phase to ground fault

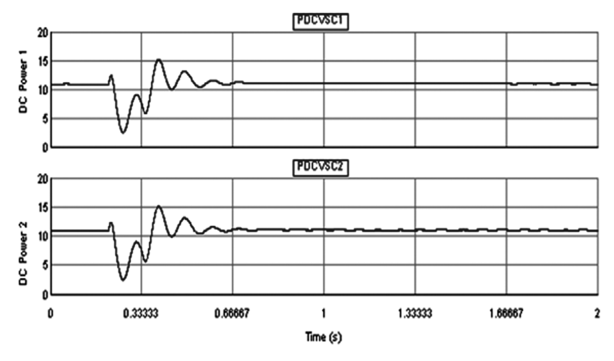

FIG 8 (a). POWER THROUGH DC LINE 1 & 2

In this scenario, three phase to ground fault is applied at receiving end for a duration of 100 ms. The plots of DC line power are shown in Figure 8(a).

Referring to Figure 8(a), it can be seen that the DC power in line1 and line2 varies from 2.76MW to 13.74MW during the fault and finally settles at a pre-disturbance value of 10.93MW.

4.4 Load Shedding

In this scenario, M1 and M2 are connected to BUS4 through a breaker #1 where as M3 and R-L load is connected to BUS5 through a breaker #2.

In order to disconnect the loads connected to breaker #1, at time 't' breaker #1 is opened which will be the general scenario in an industry to feed supply only to essential loads or as another common disturbance. In this case, Induction motors M1 and M2 are disconnected. As a result the sending end voltage increases to 1.126pu while the voltage at BUS5 which was at 35.05kV increases to 40kV as shown in Figure 9(a). The modulation index quickly responds to sudden load change.

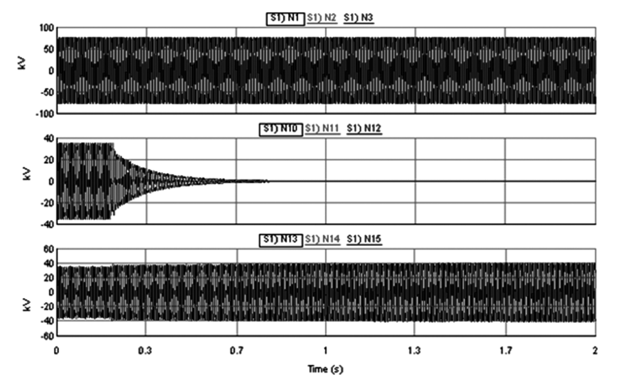

FIG 9 (A). VOLTAGE AT BUS1, BUS4 AND BUS5

5.0 CONCLUSION

The development of high power IGBTs has led to the VSC based HVDC transmission, where it has several advantages that makes it very attractive over conventional HVDC transmission. VSC-

HVDC system feeding a passive network is simulated on RTDS.

The performance of VSC-HVDC for different scenarios is studied. Operation of VSC-HVDC under steady state and transient conditions are investigated. The modeled control has good steady state and transient response during the faults. Performance of VSC-HVDC is also studied when feeding the loads like motors and found that the system response is satisfactory.

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APPENDIX-I

Source parameters	
L-L Voltage	: 93 kV
Resistance Rs	: 1.64 Ω
Inductance Lp	: 9.4 mH
VSC Interface link	
Transformer T1	: 25 MVA
Voltage ratio	: 93 kV/44kV
Leakage reactance	: 0.18 pu
Transformer T2	: 25 MVA
Voltage ratio	: 44 kV/44kV
Leakage reactance	: 0.18 pu
DC Capacitor	: 2 x 5000 µF
DC Line Length	: 100 km
Smoothing Reactor	
Rectifier side	: 0.02874 H
Inverter side	: 0.03451 H
Transformers	: TRF_1, TRF_2, TRF_3
Rating	: 5 MVA
Voltage ratio	: 44 kV/6.6 kV
Leakage inductance	: 0.15 pu
RL Load	
Resistance R	: 0.748 Ω
Inductance L	: 161.33 H
Induction Motors	: M_1, M_2, M_3
Rated Voltage	: 6.6 kV
Rated Current	: 0.359 kA
Stator Resistance	: 0.01509 pu
Stator Leakage reactance	: 0.0909 pu
Magnetizing reactance	: 4.0pu
Rotor resistance	: 0.06 pu
Rotor leakage reactance	: 0.08825 pu
Inertia constant	: 0.2816M Ws/MVA