Generic VSC and Low Level Switching Control Models for Offline Simulation of VSC-HVDC Systems

Luigi Vanfretti, N. A. Khan, Wei Li, Md. Rokibul Hasan, and A. Haider

***Abstract*—This article proposes and implements generic and detailed voltage source converter (VSC) models, and low-level switching control models for simulation of HVDC networks using Modular Multilevel Converters (MMCs) or conventional two-level converters. The low level control approaches for both MMCs and two-level converters are explained. The behavior of the test HVDC networks is analyzed with the detailed model of both types of converter. In addition, high level controls are briefly explained, focusing on their application in DC grids. The simulation results of test networks validate the proposed high level controls and low level switching controls for simulation with detailed models of MMCs and conventional two-level converters.**

***Index Terms*—Voltage Source Converter, Low level controls, Modulation Schemes, HVDC grid test system, controller calibration**

I. Introduction

In the last 20 years the importance of HVDC (High-Voltage Direct Current) long distance interconnections and back-to-back couplings has increased significantly all over the world. Even though the application of point-to-point HVDC links is well known, there are plentiful open questions of the operation of HVDC links within a meshed grid. Unfortunately very few detailed DC grids models, especially multilevel-converter DC grids models, are available for research due to commercial and trade secret reasons. In order to facilitate DC grids research and development, this article proposes generic control models and corresponding DC grids test systems.

This article focuses on the development of a generic VSC (Voltage Source Converter) and low level switching control models, implementation of test networks using these generic models, and provides off-line simulation results. Equipment data and control parameters for each of the model components are provided. The article is written in tutorial fashion, so that the models can be developed in other simulation tools. The simulation models were developed using SimPowerSystems/Simulink and will be made available publically for further development by interested parties. The article reminder of this article is organized as follows. Section II describes generic VSC-HVDC components and control models used for off-line EMT simulation. Next, Section III presents the implementation of the models in Section II using SimPowerSystems/Simulink and test networks of a point-to-point link and a four terminal meshed DC network.

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II. VSC-HVDC Components and Low Level Controls

Two types for VSC are modeled for simulation studies: a) A two-level VSC and b) A Modular Multilevel Converter (MMC).

A. Three Phase Two-Level Voltage Source Converter (VSC)

The first VSC modeled is a two-level voltage source converter. The graphical representation of the VSC is shown in Figure 1. Each phase leg consists of two switches which are switched on/off to control the output voltage. The output is then connected to the midpoint of the phase leg. The switches in the phase legs consist of IGBTs and antiparallel diodes. This configuration makes it suitable for bidirectional power flow.

The modeling of two-level VSC includes: (*i*) Switch Signal generation (Modulation Schemes), (*ii*) DC side capacitor design, and (*iii*) LC filter design.

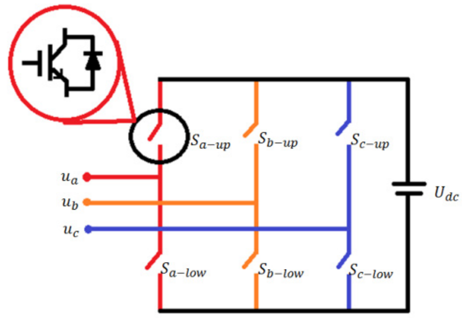


Figure 1: Three Phase Two-Level VSC

1) Switch signal generation- Modulation Schemes

Switch signal generation includes the switching of IGBTs in the phase legs of the converter. There are various control schemes to control the VSC. In this paper the SPWM scheme is used. In SPWM the reference waveform is compared with a carrier waveform to generate the switching signals for IGBTs in each phase leg of the converter. If the reference is greater than carrier then the upper IGBT of the phase leg will be turned i.e. $S_{a-up} = 1$. On the other hand, if the reference is less than carrier then the lower IGBT of the same phase leg will be turned on i.e. $S_{a-low} = 1$. The switch signals of one of the phase legs as a result of comparison process for upper and lower switches are shown in Figure 2.

2) DC side capacitor

The design of DC side capacitor is important to suppress the harmonics in the DC side current which are generated due to PWM operation and result in a ripple in DC side voltage. The ripple of the voltage depends upon the size of the DC side capacitor and switching frequency. Moreover it is also important to design the DC capacitor by keeping in mind not only the steady state but also the transient operation.

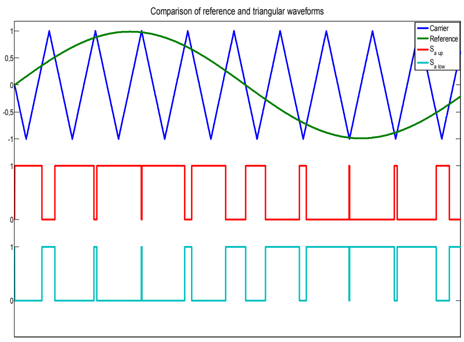


Figure 2: Comparison of triangular and reference waves with switch signals

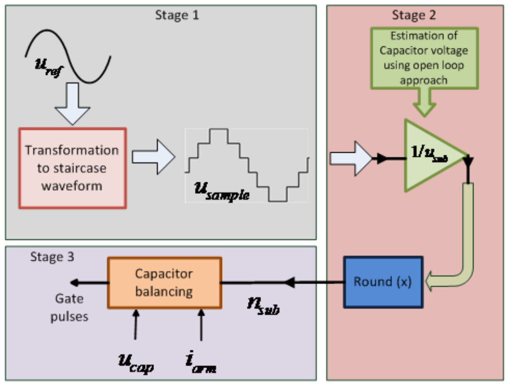


Figure 3: Modulation approach for the Generic MMC

The DC capacitor can be designed by taking into account the time constant that represents the ratio of the rated stored energy at the rated DC voltage and the nominal apparent power of the converter. The time constant can be mathematically defined as [1],

$$\tau = \frac{\frac{1}{2}(C_{dc}U_{dcN}^2)}{S_N} \quad (1)$$

where, S_N is the nominal apparent power, U_{dcN} is the nominal DC link voltage, C_{dc} is the DC link capacitance, and τ is time constant needed to charge the capacitor from zero to U_{dcN}.

The time constant can be selected as $5\,ms$ of the design value to keep the ripple and over voltages suppressed. At the chosen value of the time constant the value of the DC side capacitor can be obtained. A value of $\tau = 5\,ms$ is used to compute the DC side capacitance value used in the next Section.

3) LC filter

The low pass LC filter is used to suppress the voltage and current harmonics produced by the PWM. The reactor in the filter is used to regulate the active and reactive power by controlling the current through it and also suppresses current harmonics. The capacitor in the filter is used to suppress AC side voltage harmonics and to provide reactive power compensation.

The choice of the reactor value depends upon the switching frequency. The value of the reactor in the LC filter is chosen between 0.15 ~ 0.2p.u of the base impedance [1]. The value of the inductor can be varied between this range to get the desired sinusoidal current at the output. A value of 0.15 p.u. is selected and used in the next Section.

While designing the filter capacitor, the value should be chosen in such a way that the ripple in the AC side voltage is suppressed up to the required limit and that it fulfills the reactive power compensation requirements. In this case the value is determined iteratively through simulation. The capacitor value is varied until the sinusoidal wave is obtained at the output with a reduced harmonic content and appropriate power flow between the two ends.

B. Modular Multilevel Converter

The MMC can be controlled with different modulation schemes. Each of them has several advantages and drawbacks. These schemes can be divided into two main categories: (a) High frequency PWM schemes and (b) Low frequency switching schemes.

In (a) multiple carriers, either phase shifted or level shifted are used (see [2] and [3] for details). Category (b) mainly consists of space vector modulation (SVM) with reduced switching frequency, Selective Harmonic Elimination (SHE), Nearest Vector Control (NVC) and Nearest Level Control (NLC). SVM and SHE offer good performance regarding switching losses but for a high number of levels their implementation complexity increases. NLC and NVC are suitable for high number of levels but for lower number of levels and lower modulation indices the total harmonic distortion (THD) increases due to low and variable switching frequency [1]. In this paper a NLC modulation scheme is adopted for switching signal generation. The detailed model of a six-level MMC implemented for simulation is explained in [4]. The modulation approach is illustrated in Figure 3.

III. Implementation of Test VSC-HVDC Systems in

A. VSC SimpowerSystems/Simulink Model Implementation

The detailed model of a VSC is implemented in Simulink by using the SimPowerSystems (SPS) toolbox. The VSC is modeled according to the description given in the Figure 1 and Figure 2. The IGBTs and diodes available in the SPS library are used. Other elements like inductor, capacitor, and voltage sources are also taken from the SPS library in Simulink. The models implemented for both two-level and six-level MMC are shown in Figure 4.

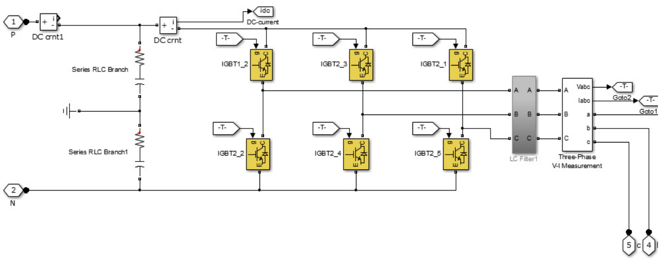
The implemented models are then integrated in HVDC networks in order to assess the operation of active/reactive power controls and DC voltage control.

B. VSC HVDC High Level Controls

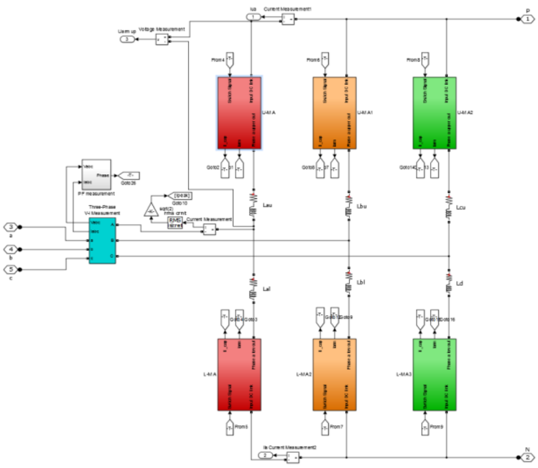
In a VSC HVDC network the transfer of energy from the AC side to the DC side or from the DC side to the AC side can be controlled. The VSC converter is used between two ends and is responsible to control the transfer of energy from one side to the other side and acts as a rectifier or as an inverter. To control the energy transfer additional controllers are required which are known as “high level controllers”. These controls are responsible to control the following parameters: Active power, Reactive power, DC voltage and AC voltage.

Apart from this they are also responsible to control the power flow during the normal and fault conditions. Generally the higher level controls are divided in to two groups which are: Outer control and Inner control.

The graphical representation of these controllers is shown in Figure 5. The outer current controllers use the measured and reference values to generate reference signals for the inner controllers. The inner controllers then use the reference values from outer controllers to produce the reference signals for the converters.



(a) Two-Level VSC



(b) MMC

Figure 4: Implementation of the two-level VSC (a) and MMC (b)

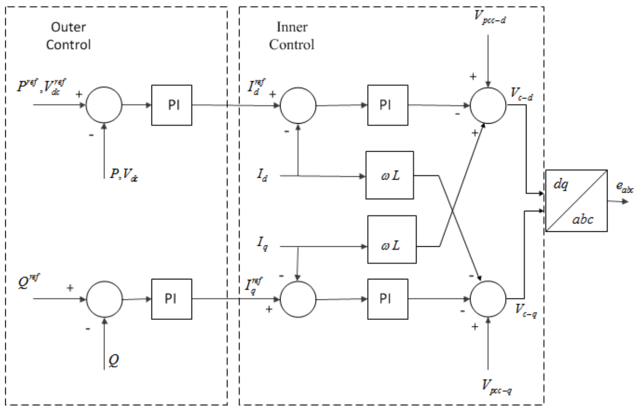


Figure 5: Control structure of the outer and inner controllers

These controllers are based on PI (proportional and integral) blocks and require proper tuning for control operations during normal and fault conditions. The parameters of these PI controllers should be calibrated in such a way that during transient state the overshoots and undershoots of the controls' outputs should not exceed the defined limits. Furthermore the controlled parameters should also reach the steady state in a shortest possible time. More details of these controllers are given in [1] and [5]. A tuning methodology developed by the authors is presented in a companion paper to this article [6].

The controllers that are used in article are: Active power controller, Reactive power controller and DC voltage controller.

C. VSC HVDC Test Networks

Using the implemented models of the two-level VSC and six-level MMC, two test networks are set up for off-line simulation and parameters for simulation are provided. A point-to-point link and four point HVDC network are presented for two-level VSC as well as six-level MMC.

1) Point to Point HVDC Network

In a point to point network one converter station behaves as a rectifier and the other as an inverter. The power flow from one side to the other side is controlled by using the high level controls presented in Section III. The controllers should be used in such a way that one converter station controls the active and reactive powers and the other converter station controls the DC voltage and reactive power. In this way the controlled power can flow from one end to the other and the DC voltage can be controlled.

The one-line diagram of the two point network is shown in Figure 6 and the model implemented in Simulink for simulation is shown in Figure 7. Converter Station A and Converter Station B blocks consist of the detailed model of the converters (two-level VSC and six-level MMC are both considered for simulations), and a transformer as shown in Figure 6. Station A and B are then connected by a DC cable. The sides are configured in such a way that Station A behaves as a rectifier and Station B as an inverter. Station A is assigned with an active power controller and controls the active power. A DC voltage controller is assigned to Station B to control the DC voltage. It should be noted that one station must be in DC voltage control in order to keep the DC voltage within the limits. The reactive power controller is implemented in both stations.

This network is considered as a base for the selection of PI controller parameters for the implemented controllers. The PI control parameters are tuned in order to achieve the design targets for the test point-to-point HVDC network. The same tuned parameters can then be initially assumed for the four point network and can be varied slightly until desired results are obtained. The idea of variation of these parameters according to the design targets is explicitly explained in [6]. The tuning of PI parameters is valid for both two-level VSC and MMC.

The LC filter, is tuned according to the method given in Section II for the two-level VSC only. The capacitance of DC side capacitor is obtained according to (1). The simulation parameters for the test HVDC networks are given in Table 1.

Figure 6: One-line diagram of the point to point network

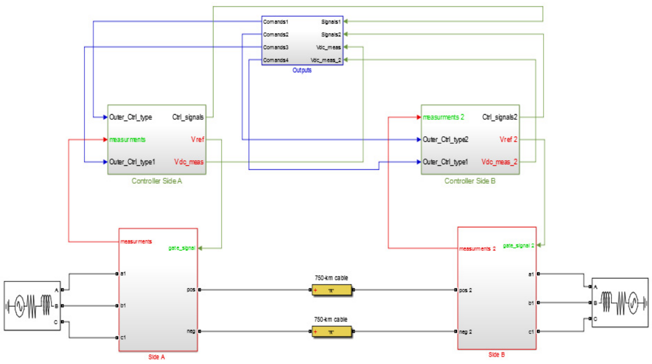


Figure 7: Simulink model of the point to point network

Table 1: Simulation parameters for the point-to-point network

VSC (Two-Level)	Parameter	Value
	DC side capacitor	195 uF
	Reactance of reactor	0.15 pu
	Carrier frequency	1.5 kHz
	Nominal apparent power (Sn)	1000 MVA
	DC voltage	640 kV
	Nominal Line Voltage (rms)	380 kV
Transformer	Reactance of Leakage inductance	0.18 pu
AC source	Voltage (Line to line)	380 kV
	Three phase short circuit level at base voltage	10000 MVA
	X/R	10

Table 2: PI controller parameters for the point to point network

Converter type	PI parameters	DC Voltage controller	Active Power controller	Reactive Power controller
Two-Level VSC	k_p	6	0	0
	k_i	100	30	30
MMC	k_p	6	0	0
	k_i	100	30	30

2) Four Point HVDC network

The one-line diagram of the four point network is shown in Figure 8: One-line diagram of the four point Network The implemented model in Simulink is shown in Figure 9. This configuration is used for both the two-level VSC and MMC for simulation of the HVDC test network.

The parameters for PI controllers are tuned in this case to achieve the desired system performance. For the two-level VSC, the LC filter has also been designed to suppress the voltage and current harmonics.

The converter stations shown in Figure 8 are defined as rectifier and inverter according to the power flow between them. For this purpose different combinations are used. In this case simulations are performed with two different cases: Case A - Stations A and B are used as rectifier whereas Stations C and D are used as inverter, and, Case B - Stations A and C are used as rectifier whereas Stations B and D are used as an inverter. In both cases Stations A, B and C use active power controller whereas Station D uses a DC voltage controller. It should be noted that one station must be in DC voltage control mode to keep the DC voltage of all the converters within the limit.

IV. Simulation Results

This section presents simulation results that validate the performance and calibration of the control systems discussed in Section III. The simulations were carried out off-line with the several test scenarios implemented in both test systems.

A. *Point to Point HVDC Network*

The simulation parameters for the network are given in Table 1. The PI controllers are tuned in order to achieve the desired system response w.r.t. DC voltage, Active power and reactive power controllers. The PI controllers are tuned individually for point to point network with MMC and two-level converters. The tuned parameters are listed in

.

The tuned parameters for both MMC and two-level converter are observed similar in this case. The response of the controllers is also appropriate for both the cases. The simulation results for point to point link with MMC and two-level converters are shown in Figure 10 and Figure 11 respectively.

The converter voltage and current for two-level converter are sinusoidal as compared to MMC. The reason is that it uses LC filter to suppress the harmonics in the voltage and current. For MMC the voltage and currents will be more sinusoidal with least harmonics if the number of levels in the converters output voltage is high. In this case only six level MMC is used therefore the voltage and currents are not completely sinusoidal however if high number of levels are used the voltage and currents will be more sinusoidal.

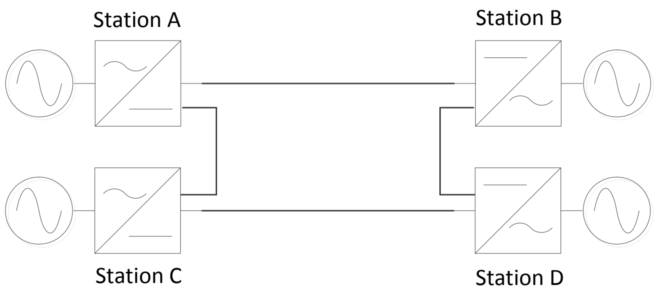


Figure 8: One-line diagram of the four point Network

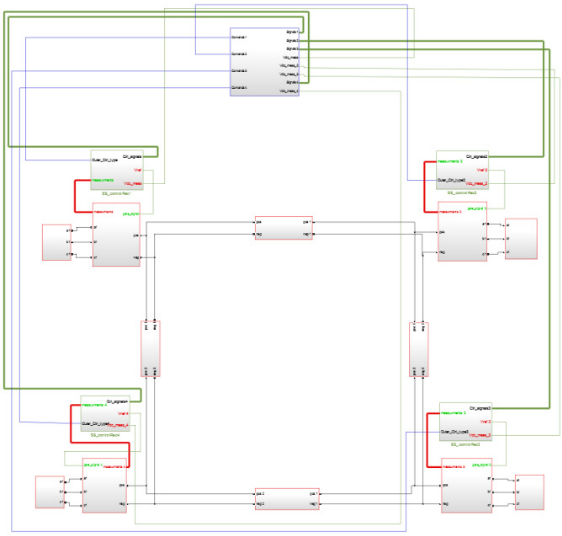


Figure 9: Four point network model in Simulink

Table 3: PI controllers parameters for the four point network

Converter type	PI parameters	DC Voltage controller	Active Power controller	Reactive Power controller
Two-Level VSC	k_p	7	0	0
	k_i	100	30	30
MMC	k_p	40	0	0
	k_i	70	7	30

Table 4: Desired outputs, converter modes and dedicated controllers for Case A

Converter Stations	P	Q	Converter Mode	Control Mode
Station A	0.5 pu	0	Rectifier	Active Power Control
Station B	0.5 pu	0	Rectifier	Active Power Control
Station C	0.5 pu	0	Inverter	Active Power Control
Station D	-	0	Inverter	DC Voltage Control

Table 5: Desired outputs, converter modes and dedicated controllers for Case B

Converter Stations	P	Q	Converter Mode	Control Mode
Station A	0.5 pu	0	Rectifier	Active Power Control
Station B	0.5 pu	0	Inverter	Active Power Control
Station C	0.5 pu	0	Rectifier	Active Power Control
Station D	-	0	Inverter	DC Voltage Control

1) MMC

The simulation results of Station A and Station B are shown inFigure 1 Figure 10. The converters in this case are MMC.

Station A acts as a rectifier and Station B acts as an inverter. The active and reactive powers together with DC voltage and converter output voltages are shown in the Figure 10 for both the stations. The transient stage of the active powers in both the stations has no overshoots and steady state reaches in an appropriate time. The normal overshoot is observed in DC voltage control in the transient stage however due to DC voltage control the voltage reaches steady state in a very short time. The durations of the transient state is important in analyzing the PI controller parameters. The results show that controllers are tuned properly.

2) Two-Level Converter

In Figure 11, the simulation results for point to point network with two-level converter are shown. In this case Station A acts a rectifier and Station B acts as an inverter. The PI controller parameters for two-level converter are found similar to the one used for MMC. However in this case DC voltage has less overshoot as compared to MMC. In this case also the converter stations reach steady state with in appropriate time.

Apart from this the difference between the HVDC network with MMC and two-level converter is observed for active powers at the receiving ends. The active power received for HVDC network with MMC is approximately 0.94 pu whereas with two-level converter is approximately 0.9 pu. This is because MMC offers less power losses as compared to two-level converter which is its major advantage in HVDC transmission.

B. Four point HVDC Network

The simulation results of four point network with MMC and two-level converter are shown in the Figure 12 and

Figure 13. The PI control parameters for all the included controllers for both type of converters are shown in the

Table 3.

In four point network the PI controller parameters for Reactive Power controller are observed similar. In DC voltage controller and Active Power controller however PI controller parameters are found different. However it should be noted that the PI controllers should always be tuned depending upon the type of converter and network configuration. With these tuned controllers the system response is appropriate for MMC as well as two-level converter.

1) Case A

V. In “Case A”, Station A and B behave as a rectifier. These sides use active power controllers. Stations C and D are used as an inverter. Station C uses an active power controller but with negative power as a reference to perform inverter operation. On the other hand, Station D uses a DC voltage controller. One of the Converters in the four point network must be under DC voltage control in order to keep the DC voltage of the interconnection within limits. For network in Figure 8, the mode

Figure 13 the simulation results for “Case B” are shown. In this case only two-level converter is considered. The simulation results for MMC will almost be similar. In “Case B”, Stations A and C are used as rectifier and Stations B and D as an inverter (see Figure 8). With this configuration, power can be transmitted between Stations A and B and also between A and D. The power can also be transmitted between Stations

Figure 13 for the two-level VSC. The desired active powers for Stations A, B and C using active power controllers are obtained. The reactive powers for all the stations were set to zero. Station D behaves as an inverter and uses a DC voltage controller. The DC voltage was set to 1 pu in this case. In addition a fault is introduced on AC side of one of the station to observe the performance of the controllers. It can be seen that during the fault the DC voltage of the interconnection remains at desired level. On the other hand the response of the active and reactive power is quite appropriate. Moreover when the fault is cleared the powers return to desired state within a short time.

The tuning of the PI controllers for both the cases seems appropriate. In four point HVDC network it is again observed that the losses in configuration with MMC are less than for two-level converter. This can be observed by comparing the received powers at Station D for two-level converter and MMC.

VI. Conclusion

The simulation results for a point-to-point and four point DC network depict that the parameters employed for detailed model of VSC and MMC together with higher level controls are appropriate. Also response of the controllers during faults shows that the controllers are properly tuned.

The tuning of high level controllers is also important since they play a major role in keeping the output close to the desired values during fault. It is also observed that the PI controllers depend on the configuration of the network and, should be calibrated according to the network and operational requirement, as the controller parameters change depending on

of each converter, desired powers and the control mode is given in

Table 4.

In Figure 12 the simulation results for “Case A” are shown. This Case is considered only for MMC however similar results will be obtained for two-level converter. The desired active powers for Station A, B and C using active power controllers are obtained. The reactive powers for all the stations were set to zero and the desired results are achieved. Station D behaves as an inverter and uses a DC voltage controller. The DC voltage was set to 1 p.u and was obtained at all stations. With the proper tuning of the active power of converters with active power control reaches steady state with in short time with slight overshoot. However the active power for converter in DC voltage control reaches steady state in slightly longer time. This is because this converter only balances the power from other converters. However the DC voltage reaches steady state within appropriate time. The results show that the PI controller parameters are properly tuned.

1) Case B

In

C and B and Stations C and D. Stations A, B and C use active power controller whereas Station D uses DC voltage controller. The mode of each converter, desired powers and the control mode is summarized in

Table 5.

Simulation results for “Case B” are shown in

these two factors. These aspects are discussed in a companion paper [2]. It can also be observed based on four point network that the controller parameters also depend upon the type of the converter used.

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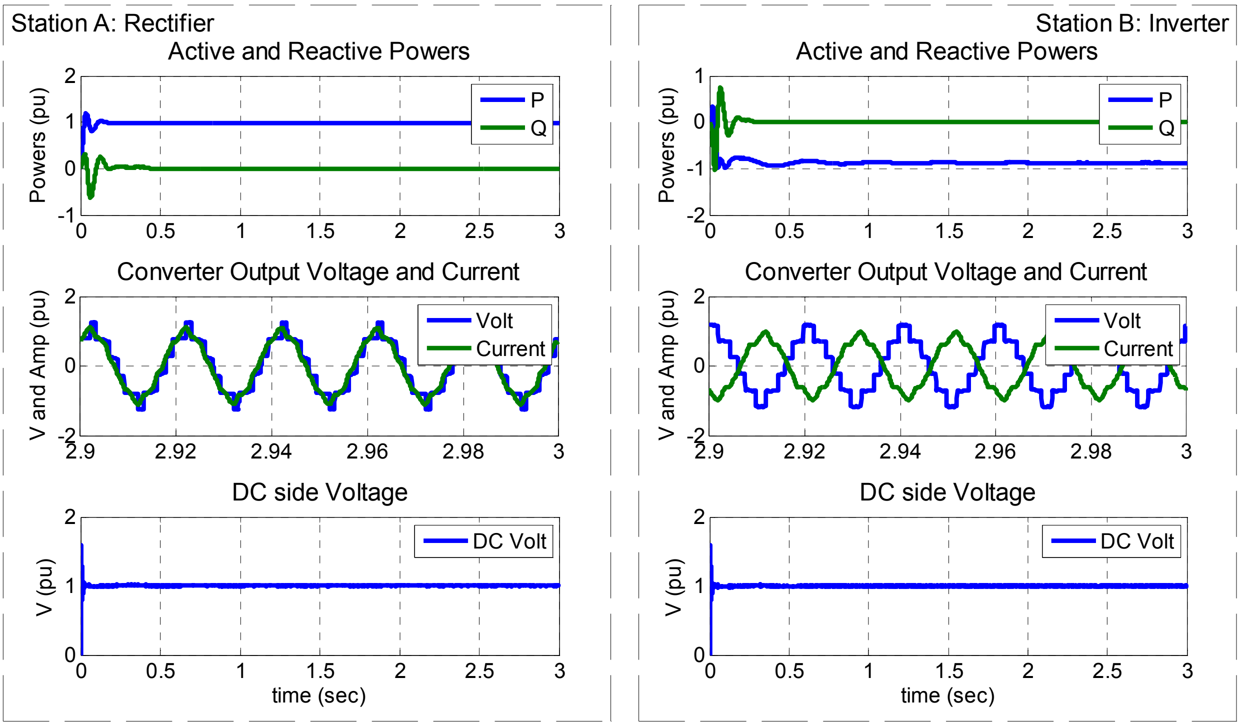

Figure 10: Outputs of Point to Point Network with MMC

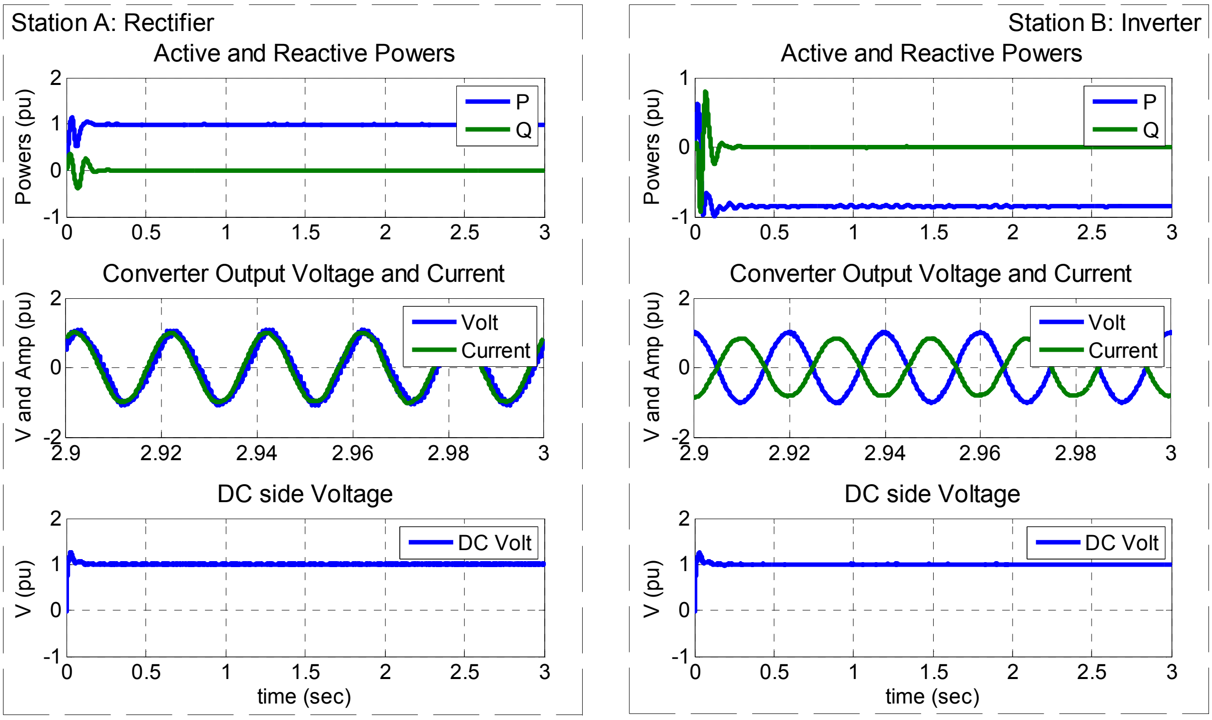

Figure 11: Outputs of Point to Point Network with Two-Level Converter

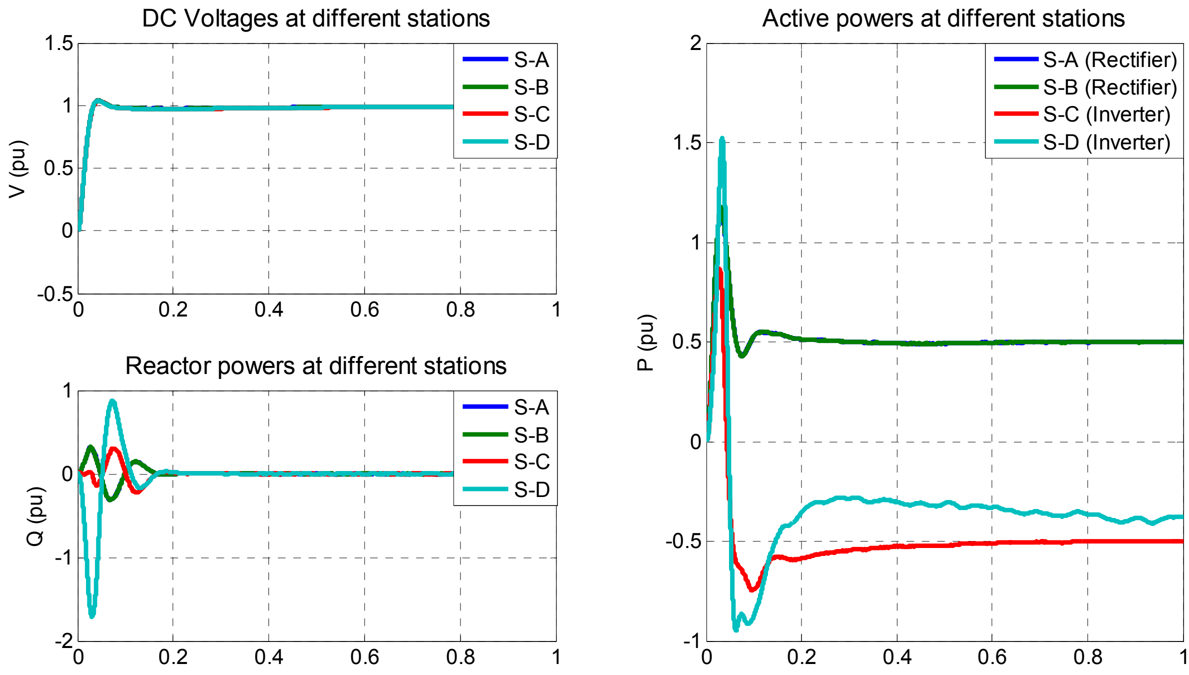

Figure 12: (Case A: MMC) Active, reactive powers and DC voltages for four point network

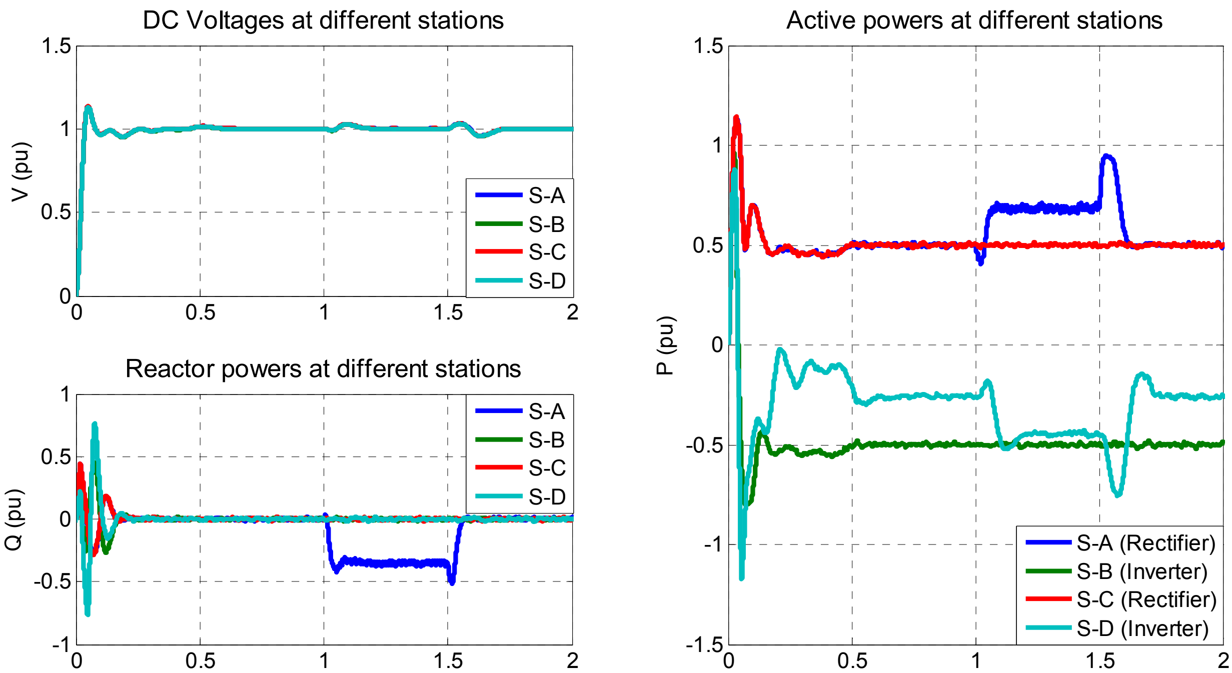

Figure 13: (Case B: Two-Level Converter) Active, reactive powers and DC voltages for four point network