MAATALLAH Elabbes[1], BERBAOUI Brahim[1], ZEMITTE Seddik[1]

University of Adrar, LDDI Laboratory, Algeria (1)

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Performance evaluation of MMC-HVDC Transmission System feeding a passive network during disturbances

Abstract. *The high voltage direct current (HVDC) transmission system has recently been developed due to the high advancement in power electronic devices. The performance and reliability of the MMC-HVDC system feeding a passive network are evaluated in this study. The system model is simulated in MATLAB/Simulink. Several faults are analyzed, including an AC fault on the rectifier side, a pole-to-ground fault on the DC side, and three phase-to-ground faults on the inverter side. The results demonstrate that the control system responds effectively to all fault scenarios.*

Streszczenie. *System przesyłu prądu stałego wysokiego napięcia (HVDC) został ostatnio opracowany ze względu na duży postęp w urządzeniach energoelektronicznych. W tym badaniu oceniono wydajność i niezawodność systemu MMC-HVDC zasilającego sieć pasywną. Model systemu jest symulowany w MATLAB/Simulink. Analizowanych jest kilka usterek, w tym usterka prądu przemiennego po stronie prostownika, usterka biegun-ziemia po stronie prądu stałego oraz trzy usterki faza-ziemia po stronie falownika. Wyniki pokazują, że system sterowania skutecznie reaguje na wszystkie scenariusze awarii. (**Ocena wydajności Systemu Transmisyjnego MMC-HVDC zasilającego sieć pasywną podczas zakłóce**ń)*

Keywords: High Voltage Direct Current (HVDC) - Modular Multi-level Converter (MMC) - Passive Network.
Słowa kluczowe: Wysokonapięciowy prąd stały (HVDC) — modułowa przetwornica wielopoziomowa (MMC) — sieć pasywna.

Introduction

Electricity is usually transmitted by HVAC, but this type of transport as a number of disadvantages, especially when the distance is large, in terms of power losses and the high cost of transmission lines. Due to the development of power electronics, the HVDC electrical transmission system was introduced, which is defined by its flexibility and high level of reliability[1].

High Voltage Direct Current (HVDC) converts AC voltage to DC voltage in the rectifier and transmits DC through a transmission line, then converts DC to AC in the inverter and supplies power. DC transmission has become a major factor due to the rapid development of converters (rectifiers and inverters) at greater voltages and larger currents.

The development of controllable semiconductor components and VSC (Voltage Source Converter) is expanding in HVDC and FACTS type applications. VSC type HVDC links have several advantages over conventional LCC (Line-Commutated Converter) type HVDC links[2]. Applications of VSC-HVDC systems include interconnections of asynchronous systems, grid integration of offshore wind farms, feeding passive or weak grids, and multi-terminal direct current (MTDC) grids[3][4][5]. VSC-HVDC links can independently control active and reactive powers by maintaining a stable voltage and frequency[6], which allows the supply of very weak networks and even passive networks[7]. Different Voltage Source Converter topologies exist, such as two-level converters, multi-level converters with diodes, and multi-level converters with floating capacitors[8]. However, due to control complexity and practical limitations, VSC-HVDC system installations have traditionally been limited to two-level and three-level converters[9].Compared to conventional two-level voltage source converters (VSCs), HVDC systems based on the modular multi-level converter (MMC) offer significant advantages. Given these advantages, simple voltage balancing, the possibility of unbalanced operation, and reduction of harmonic, it has been proven [10] that all future HVDC developments will be based on such devices. This topology, invented by[11], makes it possible to reduce the losses of the converter by using a low chopping frequency. Additionally, filtering requirements are mitigated using many submodules (SM) per phase.

This paper investigates the behavior of the MMC-HVDC in the presence of disturbances. MATLAB/Simulink is used to simulate the selected model, and many fault are addressed and investigated.

Design of MMC-HVDC System

An HVDC link was modeled using the MATLAB/Simulink package (fig.1) based on the point-to-point configuration to analyze the operation of HVDC transport systems. The DC link is used to transmit power of (220MVA) from a 65kV, 50Hz network to a passive 15kV, 50Hz network. The distance between AC systems' receiving and transmitting ends is 120 km. the main components of the system are as follows:

AC system

The AC network rectifier side is an infinite source separated from the switching bus by a simple parallel R-L branch represents the impedance, and next to the inverter is a passive network (resistive, inductive loads). In addition to the rectifier (65kV, 220MVA, 50Hz), the AC system specifications for the inverter are: (15kV, 220MVA, 50Hz).

Transformer

A transformer of type (Yn/Yg, Yn/D) is used at each terminal to achieve the best voltage conversion, moreover guarantee galvanic isolation between the network and the converter station. The parameters adopted (based on nominal AC conditions) are typical for transformers found in HVDC installations[12].

Start up

the starting system includes a circuit breaker in parallel with a resistor of 17Ω placed between the secondary side of the transformer and the converter. The resistor is used when starting the station, in order to avoid very high current draws when charging the capacitors of the MMC. When the station is in normal operation, this resistance is short-circuited by the circuit breaker.

conversion station

Both converter stations include a converter based on a modular multilevel converter (MMC) topology, which consists of several sub-modules connected in series. On the three-phase side, each phase has two half-arms. Reactors in series with each half-arm reduce fault current. This design is better for network applications because it has a low switching loss and an output voltage waveform resembling a sine wave.

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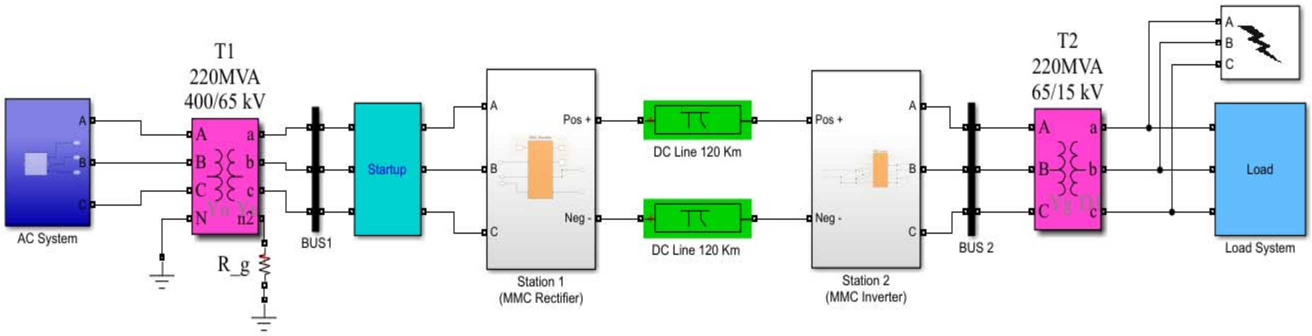


Fig.1. The studied model on MATLAB/Simulink.

DC side of the system

On the DC side of the converter system, each sub-module of rectifier and inverter contain two IGBTs with their antiparallel diodes and a capacitor which serves as an energy accumulator. The control of these IGBTs makes it possible to connect and disconnect the capacitor on the network. The DC line is represented using a PI sections line model

Control Strategies of MMC-HVDC

Several studies have examined VSC-HVDC regulation connected to a passive network using two- or three-level VSC.[13][14]. Nonetheless, only a few studies have examined regulating MMC-HVDC networks that feeding passive networks. In Reference [15], the mathematical model of MMC-HVDC is determined, and a dual-loop controller is built.

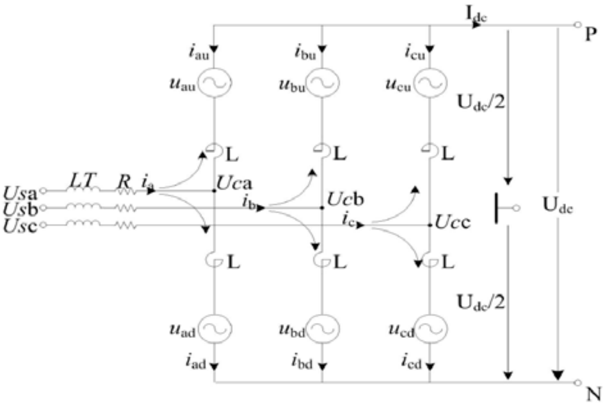


Fig.2. Equivalent circuit of MMC.

From the converter AC side fig.2:

$$L_\Sigma \frac{di_i}{dt} + Ri_i = u_i - v_i \quad (i = a,b,c) \tag{1}$$

where v_i is the output voltage of the MMC, u_i is the system voltage, and $L_\Sigma = L_T + L/2$. If the zero-sequence current is zero, as it is in balanced systems, we obtain the following:

$$\begin{cases} \dfrac{di_d}{dt} = \dfrac{1}{L_\Sigma}(u_d - v_d) - \dfrac{R}{L_\Sigma} i_d - \omega i_q \\ \dfrac{di_q}{dt} = \dfrac{1}{L_\Sigma}(u_q - v_q) - \dfrac{R}{L_\Sigma} i_q + \omega i_d \end{cases} \tag{2}$$

In consideration of the steady state, rephrase (2) as follows:

$$\begin{cases} u_d = Ri_d + \omega L_\Sigma i_q + v_d \\ u_q = Ri_q - \omega L_\Sigma i_d + v_q \end{cases} \tag{3}$$

The following equations determine the instantaneous real and reactive power equation in the d-q reference frame:

$$\begin{cases} P = 1.5(u_d i_d + u_q i_q) \\ Q = 1.5(u_d i_q - u_q i_d) \end{cases} \tag{4}$$

Using the park transformation shows that in a balanced steady-state, the d-axis coincides with the instantaneous voltage vector of the system, therefore:

$$u_q = 0 \tag{5}$$

Then the real and reactive power equations will be:

$$\begin{cases} P = 1.5 u_d i_d \\ Q = 1.5 u_d i_q \end{cases} \tag{6}$$

The rectifier controller must maintain both the continuous voltage and the reactive power, which is often accomplished via a double closed loop.[16], As shown in the figure fig.3.

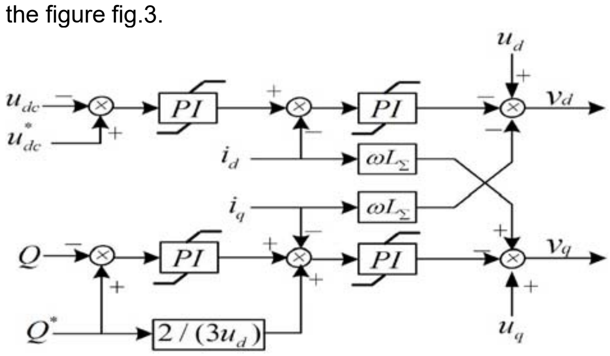


Fig.3. Block diagram of controller at Rectifier[17].

When connecting Inverter Controller to a passive grid, the MMC must supply a stable AC voltage at the passive grid's point of common connection (PCC). The converter must follow the load change as a slack bus while maintaining the AC voltage, unless it is overloaded. Fig.4 requires that the outer loop regulate the d-axis voltage u_d similarly to the q-axis voltage u_q. As shown in the figure fig.4.

Process of HVDC Start-Up and Steady-State Operation

The starting procedure of the converter takes place in several stages where all the capacitors are discharged, and all the SMs are blocked. And then, the circuit breaker is closed to connect the R-start resistor to limit the current flow. Finally, the control systems are enabled to set the control references.

The MMC-HVDC start-up process and the dynamic performances are represented between 0.1s and 1s, as shown in Figs (5, 6). When station 1, which controls constant DC voltage and reactive power, is unlocked at t = 0.1s, the DC voltage rises progressively to 1 p.u fig.5(d). The reactive power flow is zero in station fig.5(c). at the same time, the station 2 converter, which controls the AC voltage, is unlocked at t = 0.5 s fig.6(d). Load switching time, rated load in 0.6s, and full load in 0.7s. So the AC current increase from 0.9 p.u to 1.5 p.u in response to the load demand fig.6(a). At around t=1s, the steady state is reached at both stations.

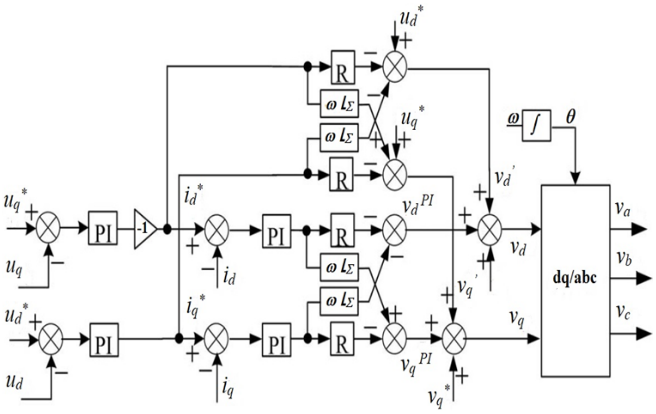


Fig.4. Block diagram of controller at inverter[17].

Faults analysis

In order to investigate the system performance during a disturbance occurs in the normal situation. Three types of faults were tested:

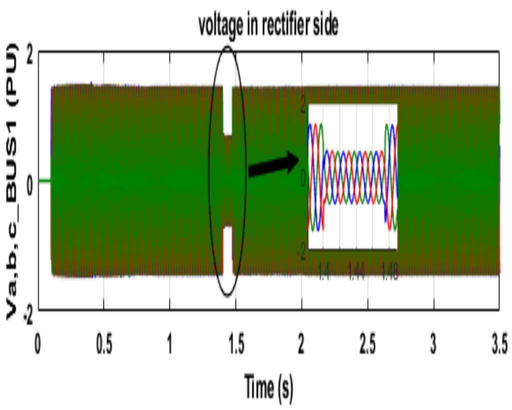
1) AC side fault (rectifier side).
2) Three-phase fault (inverter side).
3) Pole-to-ground fault (DC side).

The sysem retrieval from the disturbances would be fast and stable as explained below :

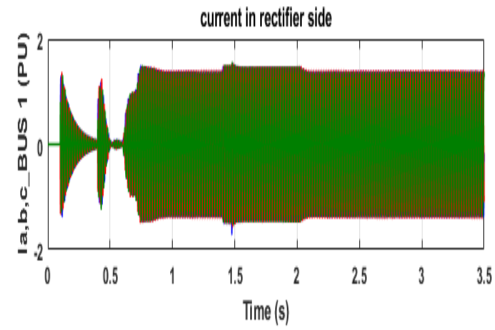
AC side fault (rectifier side)

Figure (5) shows AC fault applied at 1.4s with 5 cycle duration.

The simulation results, during the fault period, the AC voltage increased by (70%) of its nominal value in fig.5(a). On the contrary, the current increases slightly up to 1.6 p.u fig.5(b). The power consumed by the rectifier drops to half 0.5 p.u fig.5(c). Moreover, the DC voltage decreased to 0.8 p.u. It also is noted that after clearing the fault, the voltage immediately returns to normal values. In contrast, the AC current, DC voltage, and active power take around 0.75s to recover to normal values.



(a)



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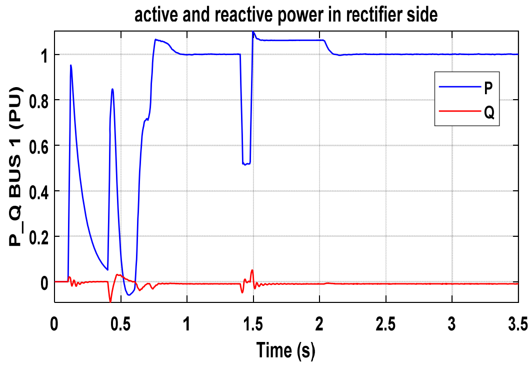
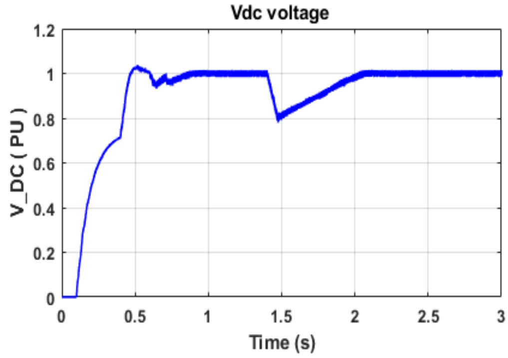




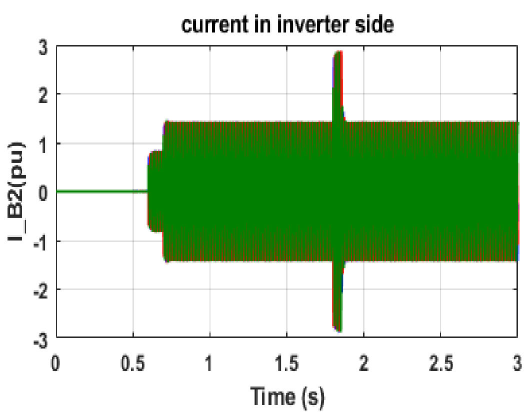
(c)

(d)

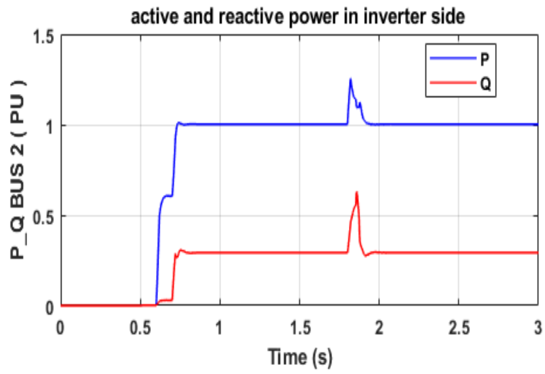
Fig.5. Simulation results of AC fault at rectifier side.

Three-phase fault (inverter side)

From Fig. 6, when the three-phase fault occurs at 1.8s. A peak in the value of the AC current measured at the load terminal Fig.6 (a), which causes a sharp overshot in the values of the active and reactive power Fig.6 (b), and a drop in the AC voltage Fig.6(c), a simple fluctuation shown in DC voltage Fig.6(d), the whole system achieves stable state directly after the fault is cleared.



(a)



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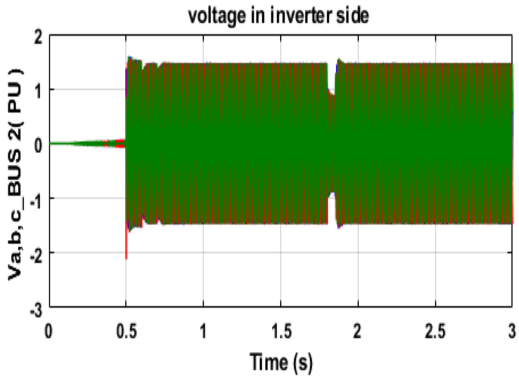
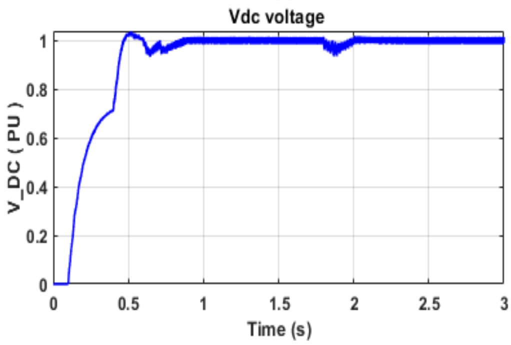




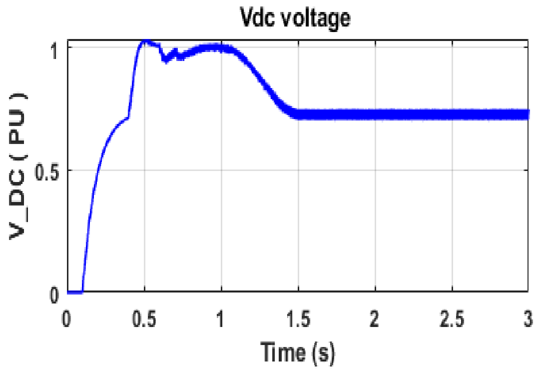
(c)

(d)

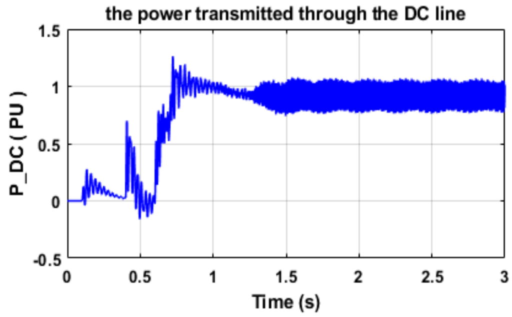
Fig.6. Simulation results of three-phase fault at inverter side.

pole-to-ground fault (DC side)

The results of the pole-to-ground fault on the DC side are shown in (Fig.7). It is noted that the DC voltage decreases progressively to 0.7p.u, Fig.7(a), resulting oscillations of about 5Hz at the power transmitted through the DC link Fig.7(b). Also, the alternating voltage of bus 2 drops at a time (1.4s) and stabilizes at the value of 1.4p. u Fig.7(c), while there is no change in AC voltage on the rectifier side Fig.7(d).



(a)



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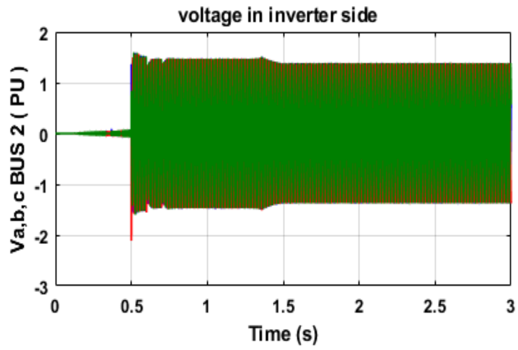

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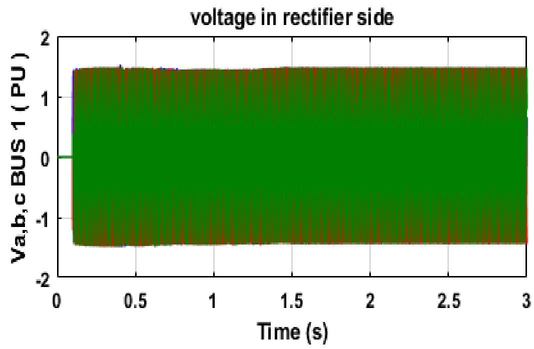

(d)

Fig.7. Simulation results of pole-to-ground fault at DC side.

Conclusion

In this paper, An MMC-HVDC system for supplying a fully passive AC network has been proposed. The principles and model of the MMC-HVDC system are discussed, along with the control strategies that correspond to them.

MATLAB/Simulink demonstrates the dynamic performance of starting when electricity is fed into a passive network. Additionally, different disturbance cases are assessed and analyzed, such as an AC fault on the rectifier side, a pole-to-ground fault on the DC side, and three phase-to-ground faults on the inverter side.

The simulation results demonstrate good dynamic and transient performance. Under fault conditions, the proposed controllers can reliably maintain the AC voltage and respond quickly to load changes in the passive network, also keeping the dc voltage in an acceptable range and stable to continuously supply power to the loads.

***Authors**: PhD Student, MAATALLAH Elabbes,*
E-mail : maatallah_elabbes@univ-adrar.edu.dz
Dr. BERBAOUI Brahim,
E-mail : berbaoui.brahim@gmail.com
PhD Student, ZEMITTE Seddik,
E-mail: sed.zemitte@univ-adrar.edu.dz
Laboratoire de Développement Durable et Informatique (LDDI) , Faculté des Sciences et de la Technologie, Université Ahmed Draïa - Adrar, Algérie.

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