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# A Comparative Study on Capacitor Voltage Balancing using MMC

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***Abstract- The HVDC systems by pointing out the key role that they play in the field of electrical energy transmission. After a chronological description of the penetration of the HVDC system in the transmission grid scenario, the most employed structures are depicted and their advantages/drawbacks are described. A comparison is achieved between the Current Source Converter and Voltage Source Converter based HVDC. Nowadays, regarding economic and technical considerations VSC-HVDC systems are most popular. Then, this work focuses on the topology based on Modular Multilevel Converters (MMCs) which is more and more often chosen for VSC-HVDC power stations.***

***Keywords- HVDC system, hybrid modular converter, modular multilevel converter, dc fault tolerant.***

## I. INTRODUCTION

The world energy consumption is expected to increase by more than 54% every ten years. Moreover, population growth and the development of “new economies” require energy sharing that has to keep in step to guarantee electrical grid voltage stability.

On the other hand, the Kyoto protocol to the United Nations framework convention on climate change defined the ways and the constraints of regulating energy production. Those in attendance at this meeting considered renewable energy sources as a good way to achieve the goal.

Since the beginning of the 21st century, many countries have chosen to deregulate the electricity sector. This has created a more flexible mix of energy sources by encouraging higher efficiencies, particularly with the introduction of private investments in the energy market.

In the scenario of electrical energy transmission growth, HVDC systems seem to best meet the purposes given. As thanks to their inherent power flow control capability and asynchronous feature, HVDC systems associated with flexible AC transmission systems (FACTS) are spreading all over the world.

In the last 40 years, HVDC has played a key role in transmission systems with a series of economic and technical considerations:

As shown in Figure 1.1, compared to AC transmission systems, HVDC transmission systems become more convenient for a distance depending on the line technology (around 800 km for overhead line and 50 km for underground or submarine cables). Despite the fact that HVDC converter stations are expensive, the transmission line requires a reduced number of conductors which approximately leads to a reduction of one third of the cost.

Figure 1.1 Estimation of the coasts for AC and DC transmission

- The ever-increasing improvements in power electronics devices, more particularly in the field of turn-off controlled semiconductors, are at the heart of HVDC technologies.
- HVDC systems allow interconnections between miscellaneous grids which can be asynchronous or with different operating frequencies. They facilitate integration of renewable sources like wind farms or photovoltaic plants.

### The Modular Multilevel Converter

The MMC studied in this work consists of a number of cascaded modules, each one being a half bridge connected to a capacitor. Several modules connected in series with an inductance form a converter arm, according to figure 1.2. Two converter arms form a phase-leg.

Figure 1.2 MMC topology

The structure of the MMC including module capacitors indicates that an inner voltage balancing control for the capacitors’ voltage level is needed. This balancing control includes two parts: the control of the average capacitor voltage in a leg and an individual voltage control for each of the modules in the leg. The dc-link voltage control is assigned to this balancing control. Figure 1.3 provides a general picture of the different controls blocks acting at the MMC.

Figure 1.3 MMC control general overview

## II. SYSTEM MODEL

### *a. Cascaded H-Bridge Multilevel Inverter (CHB-MLI)*

CHB-MLIs formed by the series connection of two or more single-phase H-bridge inverters, hence the name. Each H-bridge corresponds to two voltage source phase legs, where the line–line voltage is the inverter output voltage. Therefore, a single H-bridge converter is able to generate three different voltage levels. Each leg has only two possible switching states, to avoid dc-link capacitor short-circuit. Since there are two legs, four different switching states are possible, although two of them have redundant output voltage. Fig. 1.4 shows the three. Different output voltage levels and their corresponding equivalent circuits. The zero level can be generated connecting the phase outputs to the positive or the negative bars of the inverter.

Fig. 1.4 Three-level CHB-MLI switching states and corresponding output voltage levels

When two or more H- bridges are connected in series, their output voltages can be combined to form different output levels, increasing the total inverter output voltage and also its rated power.

### *b. DC Voltage Controller*

The voltage regulator is incorporated on dc side and is performed by proportional-integral (PI) controller. Inputs to the PI controller are, difference between dc link voltage (Vdc) and reference voltage (Vdc*).

To maintain voltage constant, no real power should be transferred. But due to converter switching, small amount of real power is utilized. To operate APF successfully real power needs to be controlled; this is done by regulation of the first harmonic active current of positive sequence (id+). Further, reactive power flow is controlled by the first harmonic reactive current of positive sequence iq+. On the other hand, considering that primary job of active power filters is just the elimination of the harmonics caused by non-linear loads, current iq+ is set to zero. In fact by controlling both active and reactive positive sequence currents, power flow can be controlled smoothly. To analyze controller performance a step response is presented in next work.

Operation and analysis of the Modular Multilevel Converter the operation and the mathematical analysis of the MMC are presented. For simplification, the initial study is based on the 1-phase model and it can be extended to the 3-phase model. The operation of the 1-phase converter at the inverter mode is explained. The detailed mathematical analysis is presented, as well as the special considerations for this type of power Electronic converter. Finally, the effect of module failure caused by a dc-link short-circuits and its addressing is described.

### c. *APF*

Electrical power is perhaps the most essential raw material used by commerce and industry today. It is an unusual commodity because it is required as a continuous flow. From the consumers’ point of view continuity of supply is an important aspects but in the present days, due to presence of non-linear loads continuity seems to be distractive and it’s all because of power quality problems . It is important to realize that the electrical load is not static. Differences in duty cycles of equipment and variations in working patterns contribute to a constantly changing load pattern.

### *d. Voltage Balancing Control Methods*

The aim of the voltage balancing control is to control the capacitors’ voltage level in the same range and limit the capacitors’ ripple, in order to prevent a module failure or distorted voltage output of the converter. Moreover, the allowed ripple by the balancing control may have an impact on the cost of the capacitors.

*e. Voltage balancing control with phase shifted PWM*

The voltage balancing control with phase shifted PWM consists of two controllers, the averaging control and the balancing contro.

The averaging control in figure 1.5 ensures that the voltage of each capacitor in a leg is close to the average capacitor voltage that is provided as a reference. Summing the measured capacitors' voltages and dividing them by the number of modules per leg the actual average voltage is calculated. The output of the first proportional-integral (PI) controller is the reference for the circulating current controller. The current reference is compared to the actual one that is calculated by measuring the arm currents and applying.

$$i_{circ} = \frac{i_u + i_l}{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(1)$$

The result is sent as an input to a second PI controller. In this way an inner control of the current flowing in the leg is achieved.

Figure 1.5 Voltage balancing control with phase shifted PWM.

The individual balancing control in figure 1.5 is responsible for setting every capacitor's voltage to its reference value. It uses a proportional (P) controller acting only dynamically in the balancing process in every switching period. In order to keep the voltage limited, the output of the controller is multiplied by 1, if the current's direction is to charge the capacitor or by -1, if it is to discharge the capacitor.

The next step is to form the proper voltage reference for each module and send it to the modulator. The outputs of the two controllers are summed together and are added, in the case of the lower arm, or subtracted, in the case of the upper arm, by the sinusoidal reference voltage for each module. This reference is equal to the phase voltage reference divided by the number of modules per arm. Subsequently, an offset is added to the reference to make it positive and the result is divided by the average capacitor voltage to limit the reference between 0 and 1. Phase-shifted PWM is used and every capacitor's reference is now compared to its corresponding triangular carrier.

*f. Closed-loop control*

The idea in this method is the control of the energy stored per leg and not of the average voltage as in the previous method and, also, of the stored energy difference between the two phase arms. Two PI controllers are used. The energy per arm and the total leg energy are estimated by measuring the voltage of each capacitor. A characteristic of this method is that no current is measured and, therefore, no direct current control is implemented. The modulation used is based on the active selection process.

*g. Open-loop control*

An evolution of the closed loop control is the open loop. The voltage of each capacitor is still measured but only for the ranking made in the modulator's active selection process. The upper and lower arms' energy values are used and they are estimated now using the load current. The transferred data to the controller for the arm energy estimation is reduced, which is important especially in the case that a high number of modules are used. In this way the demanded communicational and computational resources are reduced.

## III. LITERATURE REVIEW

| SR.NO. | TITLE | AUTHORS | YEAR | METHODOLOGY |
|---|---|---|---|---|
| 1 | "A New H-Bridge Hybrid Modular Converter (HBHMC) for HVDC Application: Operating Modes, Control and Voltage Balancing," | M. B. Ghat and A. Shukla | 2017 | The operating modes of HBHMC, novel modulation strategies |
| 2 | "France-Spain HVDC transmission system with hybrid modular multilevel converter and alternate-arm converter," | M. A. Abdel-Moamen, S. A. Shaaban and F. Jurado, | 2017 | A novel model of the VSC using hybrid Modular M2C and A2C |
| 3 | "Control of hybrid modular multilevel converter based HVDC | Shahu, T. Bandaru, T. Bhattacharya | 2017 | The control aspects of hybrid MMC with the objective of limiting DC fault |

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| | system under DC short circuit faults," | and D. Chatterjee | | current |
| 4 | "Zero DC voltage ride through of a hybrid modular multilevel converter in HVDC systems," | M. Lu, J. Hu, L. Lin and K. Xu, | 2017 | A comprehensive analysis and a suppression method of sub-modules' (SMs') |
| 5 | "Analysis and control of hybrid modular multilevel converter with scheduled DC voltage reducing in a HVDC system," | K. Xu, J. Hu and M. Miao, | 2016 | The control method of the HVDC systems based on hybrid MMC |
| 6 | "Hybrid modular multilevel converter with reduced three-level cells in HVDC transmission system," | Rui Li, Jing Wu, Liangzhong Yao, Yan Li and B. Williams, | 2016 | A hybrid MMC with reduced three-level (TL) cells |
| 7 | "Hybrid Cascaded Modular Multilevel Converter With DC Fault Ride-Through Capability for the HVDC Transmission System," | R. Li, G. P. Adam, D. Holliday, J. E. Fletcher and B. W. Williams, | 2015 | A new hybrid cascaded modular multilevel converter for the high-voltage dc transmission system |
| 8 | "A Zero-Sequence Voltage Injection-Based Control Strategy for a Parallel Hybrid Modular Multilevel HVDC Converter System," | J. Qin and M. Saeedifard, | 2015 | A zero-sequence voltage injection (ZSVI)-based model predictive control (MPC) strategy |

M. B. Ghat and A. Shukla, [1] An H-bridge hybrid modular converter (HBHMC) is reported for HVDC applications. It uses a wave-shaping circuit (WSC) consisting of series-connected full-bridge submodules (FBSMs) at the output of the main H-bridge converter (MHBC). For a three-phase system, three HBHMCs are connected either in series (series-HBHMC) or in parallel (parallel-HBHMC) across the dc-link. The operating modes of HBHMC, novel modulation strategies for voltage balancing of FBSMs, and control of HBHMC based HVDC system are presented in this work. A detailed comparison between HBHMC and other hybrid topologies is performed on the basis of required number of switches and capacitors. The HBHMC has the features of dc fault blocking capability, lower footprint structure and extra degree of freedom for submodules capacitor voltage balancing. The efficacy of the HBHMC based HVDC system for three-phase balanced and unbalanced grid conditions and its fault tolerant capability are validated using PSCAD simulation studies. Further, the feasibility of reported converter under normal, and dc fault conditions, and of the reported capacitor voltage control scheme are validated experimentally by using a three-phase grid connected HBHMC laboratory prototype. The results demonstrate the effectiveness of the reported HBHMC topology, control techniques, and satisfactory responses of the HBHMC based HVDC system.

M. A. Abdel-Moamen, S. A. Shaaban and F. Jurado, [2] Modular Multilevel Converter (M2C) and Alternate-Arm Converter (A2C) are the prevalent types of voltage-source converter (VSC) topology for HVDC applications. A novel model of the VSC using hybrid Modular M2C and A2C is reported in this work. This new model is applied to high-voltage direct current (HVDC) - transmission system links between France and Spain which has 320 kV, 2000 MW HVDC transmission system by inserting M2C in sending end and A2C in receiving end. The hybrid models are interconnecting two 400 kV high-voltage AC grids.

V. Shahu, T. Bandaru, T. Bhattacharya and D. Chatterjee, [3]Hybrid modular multi-level converter (Hybrid MMC) topology, consisting of both half-bridge (HB) and full-bridge (FB) submodules, is suitable for HVDC application as it combines the advantages of both HB-MMC and FB-MMC. This work focuses on the control aspects of hybrid MMC with the objective of limiting DC fault current. It is also controlled to exchange reactive power with the AC grid during DC fault. Further, a negative sequence current injection method is reported to eliminate the mismatch between the average capacitor voltages of the three legs of MMC appearing during DC faults. The reported methods are tested through simulations in PSCAD/EMTDC platform.

M. Lu, J. Hu, L. Lin and K. Xu, [4]This study presents a comprehensive analysis and a suppression method of sub-modules' (SMs') voltage stress in the hybrid modular multilevel converters when riding through zero DC voltage faults in high-voltage direct-current (HVDC) systems. First, the general DC fault ride through (FRT) strategy considering the redundancy of the arm voltage generation scheme under a reduced dc-link voltage is derived. Then full-bridge sub-modules (FBSMs') voltage stress for the conventional DC-FRT schemes with and without common-mode voltage injection are analysed. Finally, on the basis of the available full-bridge SM capacitor energy control strategy, an improved method implemented by energy interaction between half-bridge sub-modules and FBSMs is presented. The reported DC-FRT scheme can make all SM capacitor voltages balanced at their rated values during the zero DC voltage conditions. Simulated results are provided to demonstrate the validity of the analytical results and the feasibility of the reported DC-FRT scheme.

K. Xu, J. Hu and M. Miao, [5] Modular multilevel converter (MMC)-based high voltage direct current (HVDC) technique has made a great achievement in China, such that three- and five-terminal MMC HVDC systems have been constructed in NanAo and ZhouShan, respectively. Reduced DC voltage operation of HVDC systems under extreme weather conditions is a common practice used in most engineering applications, in particular for the applications using overhead transmission lines. In this work, the control method of the HVDC systems based on hybrid MMC which is composed of half-bridge sub-modules (HBSMs) and full-bridge sub-modules (FBSMs) under reduced DC voltage is illustrated. Because the system has the ability to continue operating with controllable active power and adjustable reactive power under extreme low DC voltage, the operating region of the system has also been analysed with the consideration of the maximum capacity of the connecting transformer at the AC side, the maximum current-through capability of IGBTs in the converter arms, the limit of the modulation ratio of the converter's output voltage and the capacitor voltage balance in SMs. Finally, a method aims to extend the operation region under a certain DC voltage by injecting circular current into the arms is presented and the feasibility of it is verified in PSCAD/EMTDC.

Rui Li, Jing Wu, Liangzhong Yao, Yan Li and B. Williams, [6] A hybrid MMC with reduced three-level (TL) cells is reported. As well as the dc fault blocking capability, the reported hybrid MMC provides the benefits of: lower conduction losses; fewer diode and switching devices, and; fewer shoot-through modes. Guidelines are developed to determine the required number of three-level cells to block a dc-side fault. It is also demonstrated that a further reduction in the number a three-level cells is possible if a rise in cell current and voltage is acceptable. This reduction is investigated. A lower number of three-level cells reduces losses and capital cost further. The hybrid MMC with the reduced number of three-level cells proves to be the most attractive approach compared with other MMCs and hybrid MMCs. The semiconductor count and conduction loss are 92.1% and 90.3% respectively of that of the MMC based entirely on full-bridge cells, without exposing the semiconductors to significant fault currents and over-voltages. The simulation results demonstrate the feasibility of the reported hybrid converter.

R. Li, G. P. Adam, D. Holliday, J. E. Fletcher and B. W. Williams, [7] A new hybrid cascaded modular multilevel converter for the high-voltage dc transmission system is presented. The half-bridge cells are used on the main power stage and the cascade full-bridge (FB) cells are connected to its ac terminals. The main power stage generates the fundamental voltages with quite low switching frequency, resulting in relatively low losses. The cascaded FB cells only attenuate the harmonics generated by the main power stage, without contribution to the power transfer. Thus, the energy-storage requirement of the cascaded FB cells is low and the capacitance of FB cells is reduced significantly. Due to the dc fault reverse blocking capability of the cascaded FB cells, the reported topology can ride-through the pole-to-pole dc fault. In addition, the soft restart is achieved after the fault is eliminated, without exposing the system to significant inrush current. Besides, the average-value model of the reported topology is derived, based on which the control strategy is presented. The results show the feasibility of the reported converter.

J. Qin and M. Saeedifard [8] A parallel hybrid modular multilevel converter (PHMMC) belongs to the class of modular multilevel converters, which have become potential candidates for high-voltage direct-current (HVDC) transmission systems. Due to the circuit topology of a PHMMC, the dc bus voltage contains low-order harmonics and cannot be fully regulated at a constant dc voltage. The dc bus voltage, if not properly controlled, leads to improper power transfer and increases the magnitude of dc current ripple on the dc transmission line. This work proposes a zero-sequence voltage injection (ZSVI)-based model predictive control (MPC) strategy to control the dc current/power flow and simultaneously minimize the dc current ripple. The reported strategy takes advantage of a cost function minimization technique to determine and inject the optimal zero-sequence voltage components into the dc-bus voltage of a PHMMC system. This work derives a discrete-time dynamic model of the dc transmission-line current and, correspondingly, develops a predictive model. The predictive model is used to inject the appropriate amount of zero-sequence voltage components to the dc bus reference voltage waveform. Compared with the existing triplen harmonics injection method, the reported ZSVI-MPC strategy improves the performance of a PHMMC system in terms of minimization of the dc current/voltage ripple. Performance of the reported strategy for a 21-level PHMMC-based HVDC station system is evaluated based on time-domain simulation studies in the PSCAD/EMTDC software environment. The reported results demonstrate superior performance of the PHMMC-HVDC station operating based on the reported ZSVI-MPC strategy, under various operating conditions, as opposed to the existing triplen harmonics injection method.

## IV. PROBLEM IDENTIFICATION

The world energy consumption is expected to increase by more than 54% every ten years. Moreover, population growth and the development of “new economies” require energy sharing that has to keep in step to guarantee electrical grid voltage stability.

On the other hand, the Kyoto protocol to the United Nations framework convention on climate change defined the ways and the constraints of regulating energy production. Those in attendance at this meeting considered renewable energy sources as a good way to achieve the goal.

Since the beginning of the 21st century, many countries have chosen to deregulate the electricity sector. This has created a more flexible mix of energy sources by encouraging higher efficiencies, particularly with the introduction of private investments in the energy market.

In the scenario of electrical energy transmission growth, HVDC systems seem to best meet the purposes given. As affirmed in thanks to their inherent power flow control capability and asynchronous feature, HVDC systems associated with flexible AC transmission systems (FACTS) are spreading all over the world..

## V. CONCLUSION

The next step after the design and simulation of the system is to design a small-scale prototype of the MMC, in order to validate the conclusions reached during the theoretical analysis and perform improvements. The specifications for the prototype are going to be based on the described dimensioning process. A different designing and control approach for the total system is going to be tested based on flat power absorption from the grid. In parallel, an analytical method is going to be searched for the modules ‘voltage balancing/dc-link voltage controller. A dedicated controller for the elimination of the second harmonic component can be designed as well. Furthermore, the techno-economical evaluation of the system and its comparison with other solutions is of great interest. To this direction, the optimal number of modules per arm should be decided. From the technical point of view the semiconductors and the capacitors ratings and the grid current quality define this number.

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