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Capacitor Voltage Balancing in Modular Multilevel Converter

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ABSTRACT

Capacitor voltage balancing is a critical issue for neutral-point-clamped-based converters, including the two/three-level dual-active-bridge dc–dc converters. The unbalanced capacitor voltage increases the voltage stress on power devices and negatively affect the reliability of the converters. The electrical energy is obviously the dominant from among others due to its flexibility of conversion to other forms, case of transmission to the consumption site, low environment effect and its sustainable character. It is obvious that the demand of electrical energy increases tremendously, not only because of the population increase, but also the faster increasing automation in every aspect of life. Current world needs reliable supply of the electrical energy with high quality, meeting the national and international relevant standards. High efficiency, low cost and infrequent maintenance are needed as well as environmental friendliness are being expected from the electrical energy system of today. This paper focuses on different PWM control method for capacitor voltage balancing MMC. The performance of voltage balancing is obtained better than existing methods. The proposed topologies have been simulated in MATLAB/Simulink environment and performances were compared with existing methods.

1. INTRODUCTION

In the 20th century, electricity has become the dominant form of energy due to its ease of conversion to other forms. Today, the modern civilization based its operation on an increasing energy demand, substituting human activities with complex and sophisticated machines mainly run by electric power. Indeed, the world energy consumption is expected to increase by more than 54% every ten years [1]. Electricity will be more dominant than ever while supplying this energy demand since the countries try to bypass especially fossil fuels in the supply chain of energy. In order to meet the increasing demand, electric power generation, transmission, distribution and conversion become more and more important.

The recent attention in environmental protection and preservation has lead countries to shift to sustainable and renewable energy sources. Electric power generation from solar and wind energy is wide spread today. These resources will diffuse and occupy an increasingly important role in energy production in coming years. Therefore, the need of high quality electric power conversion systems to be used in this area is greater than ever. From the beginning of the 21st century, many countries have chosen to deregulate their electricity market. The situation resulted in a mix of energy sources while pursuing higher efficiency, particularly with the introduction of private investments in the energy market.

In the light of above mentioned events, in order to accomplish all requirements both from users and legal regulations, and to reduce the environmental impact, power conversion and control is needed to be reliable, safe, efficient, and available.

Voltage Source Converter (VSC) technology has been becoming common in many of modern demanding electric power systems, such as high-voltage direct current (HVDC) transmission.

Synthesis of output voltage waveform in conventional two- or three-level VSCs is done by reflecting half of the dc-link voltage to the output, which results in high harmonic content and requirement for output harmonic filters which increase both the cost and footprint of the system. On the other hand, that of the MMC topology is based on the sum of small voltage steps reducing harmonic content, and removing the need of harmonic filter at the output.

A. Typical Application Areas of MMC

HVDC transmission is an important and efficient alternative to three-phase ac transmission of electric power over long distances. Advantages for choosing HVDC transmission instead of three-phase ac transmission can be numerous and should be considered in individual situation apart. However, the mostly acknowledged advantages could be summarized as follows: lower transmission losses, the capacity to transfer more power over the same right of way, the ability to interconnect systems that are not synchronized or using different frequencies, short-circuit currents limitation, long distance water crossing capability. One of the most important advantages of HVDC transmission on ac transmission is the ability of controlling active power transmission accurately, while ac lines power flow cannot be controlled in the same direct way. Moreover, in [3] it is shown that the cost of HVDC transmission is less than ac transmission above a distance of 800km overhead line or 50km underground or submarine cables. This is due to the fact that the higher cost of HVDC converters is overcome by the cost of reduced number of transmission line conductors. Figure 1.3 shows the cost.

Systems (especially in offshore wind power transmission), medium-voltage motor drives, STATCOM applications, electric traction/propulsion systems or grid connected energy storage systems. Today, the majority of the applications of these electric power systems are driven by conventional two- or three-level VSC's. However, these conventional VSC's are not able to respond properly to emerging requirements such as high power, high efficiency, reliability of the system, and environmental compatibility. The solution to these problems has been evolved through the use of combinable, standardized, distributed, and simpler converter structures with lower voltage steps. Indeed, standardized and distributed systems have become the recommended solution to achieve modern projects requirements in all engineering areas. These configurations provide a more reliable operation, facilitates fault diagnosis, maintenance, and reconfigurations of control system. Especially in fail safe situations, distributed configuration allows control system to isolate the problem, drive the process in safe state easily, and in many cases allows continuing almost normal operation in faulty conditions. Multilevel converters have been progressed as significant competitors to the conventional VSCs in order to overcome the abovementioned limitations. At present, modular multilevel converter (MMC, MMLC, M2LC, M2C) (Figure 1.1) is at the heart of research and development studies in power electronics area, both for academic and industrial scope. Its unique chopper cell based topological structure was firstly proposed by Lesnicar and Marquardt in 2003 [2]. The initial target was very high-voltage applications, especially network interties in power generation and transmission. Since then, the topology had a great attraction due to its promising features. Compared to conventional VSC technology, MMC offers advantages such as higher voltage and power levels, modular and redundant construction, longer maintenance intervals, improved reliability, and higher efficiency.

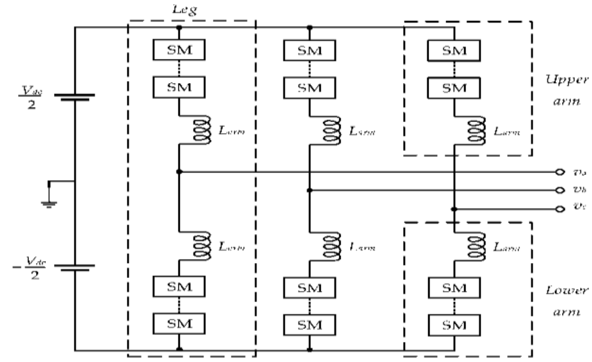

Figure 1: Modular Multilevel Converter

Power systems are driven by conventional two- or three-level VSC's. However, these conventional VSC's are not able to respond properly to emerging requirements such as high power, high efficiency, reliability of the system, and environmental compatibility. The solution to these problems has been evolved through the use of combinable, standardized, distributed, and simpler converter structures with lower voltage steps. Indeed, standardized and distributed systems have become the recommended solution to achieve modern projects requirements in all engineering areas. These configurations provide a more reliable operation, facilitates fault diagnosis, maintenance, and reconfigurations of control system. Especially in fail safe situations, distributed configuration allows control system to isolate the problem, drive the process in safe state easily, and in many cases allows continuing almost normal operation in faulty conditions. Multilevel converters have been progressed as significant competitors to the conventional VSCs in order to overcome the abovementioned limitations. At present, modular multilevel converter (MMC, MMLC, M2LC, M2C) (Figure 1.1) is at the heart of research and development studies in power electronics area, both for academic and industrial scope. Its unique chopper cell based topological structure was firstly proposed by Lesnicar and Marquardt in 2003 [2]. The initial target was very high-voltage applications, especially network interties in power generation and transmission. Since then, the topology had a great attraction due to its promising features. Compared to conventional VSC technology, MMC offers advantages such as higher voltage and power levels, modular and redundant construction, and longer maintenance intervals, of controlling active power transmission accurately, while ac lines power flow cannot be controlled in the same direct way. Moreover, in [3] it is shown that the cost of HVDC transmission is less than ac transmission above a distance of 800km overhead line or 50km underground or submarine cables. This is due to the fact that the higher cost of HVDC converters is overcome by the cost of reduced number of transmission line conductors. Figure 2 shows the cost estimations for ac and HVDC transmission by distance via overhead transmission line.

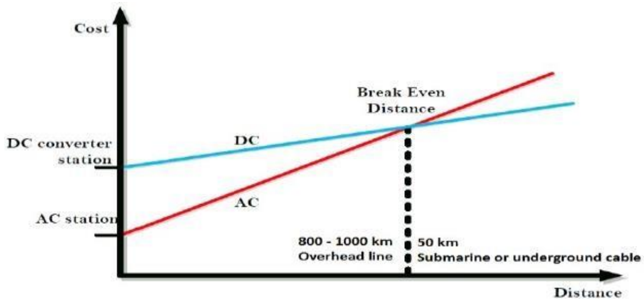

Figure 2: Cost Estimation of AC and HVDC Transmission by distance

Figure 3: HelWin2 offshore HVDC platform of Siemens

Figure 4: Sub-module (up) and MMC (down) structure of MaxSine

Figure 5: MMC based Motor Drive for a converter fed synchronous machine by ABB and Oberhasli Hydroelectric Power Company, Switzerland

B. Reasons for choosing HVDC Transmission System

In an AC system, voltage conversion is simple. An AC transformer allows high power levels and high insulation levels within one unit and has low losses. It is a relatively simple device, which requires little maintenance. Further, a three-phase synchronous generator is superior to a DC generator in every respect. For these reasons, AC technology was introduced at a very early stage in the development of electrical power systems. It was soon accepted as the only feasible technology for generation, transmission and distribution of electrical energy. However, high-voltage AC transmission links have disadvantages, which may compel a change to DC technology.

i. Inductive and capacitive elements of overhead lines and cables put limits to the transmission capacity and the transmission distance of AC transmission links. For AC cable the range is about 40 to 100 km.

ii. Direct connection between two AC systems with different frequencies is not possible. So researchers are now doing research on DC transmission instead of AC transmission.

2. MATERIALS AND METHODS

In the field of high voltage level applications, modular multi-level converter (MMC) has the definite advantages of low power loss and modularity and there have been many studies on its reliability. Some researches focus on the degradation of physical characteristics in the lifetime prediction of key devices, but the degradation of physical characteristics has not been directly used in the research of MMC system level reliability. The traditional exponential distribution failure rate is constant while the Monte Carlo method assumes the random distribution of multiple devices. Neither of these two methods can describe the reliability of a single device with physical characteristics degradation. MMC reliability analysis and design method based on MMC mission profile and insulated-gate bipolar transistor (IGBT) lifetime degradation. According to the IGBT current and power loss in MMC, the annual mission profile and junction temperature result are analyzed by rain-flow counting algorithm. In terms of device degradation, the thermal network updating method is used to calculate the life of IGBT in different time, and the reliability analysis method based on exponential distribution is improved. To optimize the redundancy design of the system, the multi-objective function optimization is processed.

Table 1

Several STATCOM projects based on MMC concept

Project	Installed year	Manufacturer	System voltage (ac)(kV)	Power (MVAr)	Location
Kikiwa	2009	Siemens	220	2x(±50)	New Zealand
The Thanet offshore wind farm	2009	Siemens	11	N/A	UK
Mocuba	2010	Siemens	33	N/A	Mozambique
Cerro Navia	2011	ABB	220	+65/ -140	Chile
The Greater Gabbard offshore wind farm	2011	Siemens	13.9	N/A	UK

STATCOM applications are one of the fields for MMC to penetrate in. In order to improve dynamic stability and power quality of power systems which have been deregulated and liberalized especially from the beginning of the 21st century, STATCOM applications are widely used. The MMC topology provides improved dynamic stability of transmission systems, increased power quality, flexibility to adapt to different power ratings, compact design with low footprint as well as redundancy and minimized engineering costs to STATCOM systems. Different manufacturers have MMC based STATCOM systems, some of which are SVC Plus (full-bridge based, Siemens) and SVC Light (full-bridge based, ABB). In Table 1, several STATCOM projects based on MMC topology

3. RESULTS AND DISCUSSION

To verify the effectiveness of the modulation technique, all the capacitor voltage are assumed to be constant. A three phase five level MMC circuit with conventional MMC model with four SMs in each arm is built in MATLAB simulation. According to the waveforms, it is cleared that the capacitors voltages are so much closer to each other. At the beginning of the simulation process, the frequency of reference signal is measured. The frequencies of carrier signals are measured for determining the time period of those carrier signals. Then compared each carrier signal with the reference signal at a certain time period. If the condition satisfied the next carrier signal will be compared with the reference signal otherwise the reference signal will be compared with current carrier signal.

To verify the propose capacitor voltage balancing method and the system performance, a three phase five level conventional MMC circuit is built.

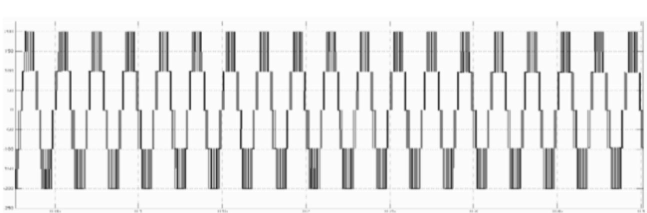

Figure 6: Voltage vs Time curve showing output phase voltage waveform of the 5 level MMC

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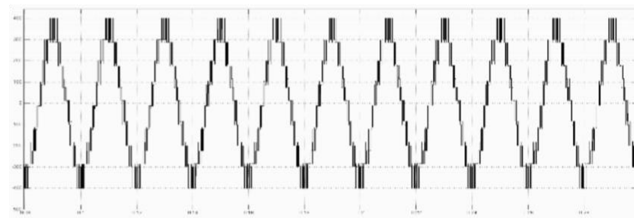

Figure 7: Voltage vs Time curve showing output line voltage waveform of the 5 level MMC

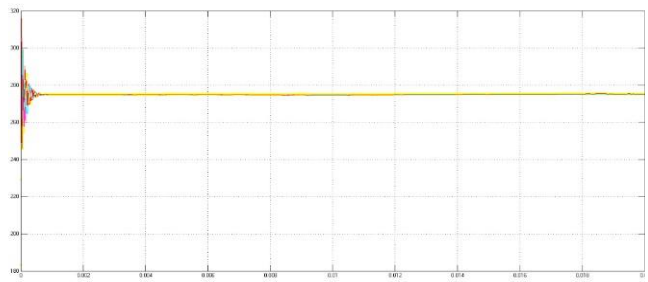

Figure 8: Voltage vs Time curve showing output line voltage graph of the 5 level MMC

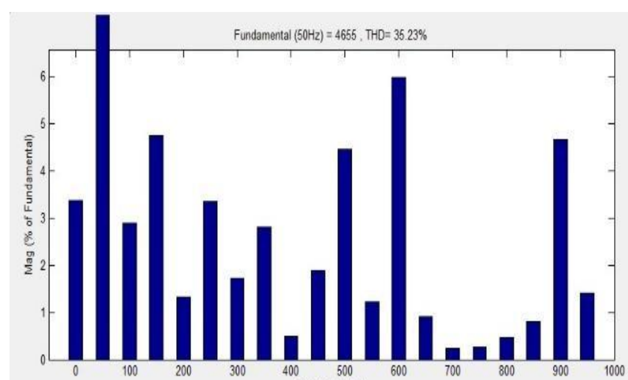

Figure 9: THD in proposed method

The graph of Total Harmonic Distortion (THD) versus frequency typically shows how the THD levels change across different frequencies. In an ideal scenario, THD is expected to be minimal at the fundamental frequency and increase at higher harmonic frequencies. The graph may exhibit a characteristic shape, often resembling a curve or a series of peaks at harmonic frequencies. The goal is to keep THD as low as possible, especially at the fundamental frequency, to ensure efficient and clean operation of the system. Researchers and engineers analyse this graph to assess the performance of devices or systems in terms of harmonic distortion across the frequency spectrum.

Table 2

Summary of the improvement of voltage across each capacitor in each Sub-module which ensure that the amount of circulating current between capacitors is reduced

Sub-Module (SM)	Voltage across each capacitor in volt	
	PD method	Proposed method
SM1	2764	2749
SM2	2735	2746
SM3	2729	2746
SM4	2761	2748

3. CONCLUSION

Energy is the most valuable and vital asset of countries. The energy demand of mankind is increasing day by day. As the machines are replacing manpower since the industrial revolution, modern civilizations have based their survival on energy, anymore. The electrical energy is obviously the dominant form among others due to its flexibility of conversion to other forms, ease of transmission to the consumption site, low environmental effect and its sustainable character. It is obvious that the demand of electrical energy will increase tremendously, not only because of the population increase, but also the faster increasing automation in every aspect of life. Moreover, apart from supplying this increasing demand, renovation of conventional electrical energy sources to sustainable and environmental friendly ones, brings extra workload to electrical power engineering industry. Thus, the electrical energy systems are required to respond properly to this continuously increasing demand [12]. Moreover, they need to be reliable and supply the electrical energy with high quality, meeting the national and international relevant standards. High efficiency, low cost and infrequent maintenance need as well as environmental friendliness are being expected from the electrical energy systems of today.

The conventional two/three-level voltage source converters are not able to respond all these requirements accurately. They have limitations in terms of power capacity, energy quality, semiconductor ratings, reliability, robustness, efficiency, cost, size and footprint and so on. Modular multilevel converter is proposed to overcome these high end requirements. Their modular submodule structure provides many favorable features such as adaptability to broad power and voltage ranges, advanced redundancy, independence from the fast developing state-of-the-art of semiconductor devices, resilience, and ability to continue to operation in case of a fault. Moreover, their stepped output voltage waveform provides low harmonic content compared to conventional VSCs, which eliminates the usage of big, lossy, and costly output harmonic filters. They do not need a centralized energy storage element or separate dc sources. The switching frequency of the semiconductors may even be decreased to fundamental frequency, enabling low switching loss and easing thermal management of semiconductors [12]. Also, the input current distortion and output common-mode voltage of MMC are less than conventional VSCs. In conclusion an improved voltage balancing algorithm is proposed for conventional MMC is proposed. The propose method is effectively balancing the sub-module capacitor voltages. The implementation of proposed methodology, mainly involves with programming MATLAB function. The performances under different circuit parameters or operating conditions of the adapted method are found to be satisfactory. This method improved the balancing of the capacitors voltage better than conventional PD method in each submodule. Though the THD is less than conventional PD method but there are nearly 35% THD in the system which is unwanted. In the future research the THD will be minimized.

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