A Review on Controllers developed for Modular Multilevel Converters

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Abstract-The Modular Multilevel Converter (MMC) has achieved extensive` research interest since it was first presented. MMC has a converter topology with full modularity and easy expandability to meet any voltage/power level requirement. MMC consists of identical but individually controllable sub modules. This paper reviews the state of the art developed to obtain least possible value of total harmonic distortion (THD) and circulating current using different Pulse Width Modulation (PWM) techniques, circulating current control methods and capacitor voltage balancing methods.

Keywords – MMC, THD, PWM, Circulating current.

I. INTRODUCTION

Now a days renewable energy power supplied into the utility grid has attained much attention because of increase in fossil fuel prices, environmental pollution and increase in energy demand. With growing demand for renewable energy sources in the world today, researchers are looking for new ways these sources can be integrated into our electrical network. For large scale photo voltaic installations and wind power generation it is desirable to be able to transfer the maximum amount of power from the solar cell and Wind Turbine (WT) generation to the grid, while maintaining balanced currents with low harmonic content. To transfer the power from the PV and Wind module, the power electronics converters are used for improving the efficiency. Conventional inverter topologies such as voltage source inverter (VSI) and the current source inverter (CSI) are used to convert these dc electrical powers and fed to the utility grid. These topologies require additional DC/DC converters resulting in a two stage power conversion with interfacing transformer to inject power into the grid. These topologies not only increase the circuit complexity but also the cost and space requirements for complete installation. Recently MMC has become very promising and attractive converter used especially in high-power and high-voltage applications. The MMC became the center of interest for many researches leading to the development of configurations and control methods for the same.

Classical multilevel topologies are Neutral Point Clamped (NPC) type, Flying Capacitor (FC) type and Cascaded H Bridge converters (CHB). These can be used in medium power applications such as traction drives and different transmission systems. NPC topology is most widely used for medium voltage ac motor drives and PWM active rectifiers. NPC suffers from the problem of voltage imbalance of dc link capacitors which increases the complexity with an increasing in number of levels. The FC type also consists of number of commutation cells. The number of voltage levels in the line to line voltage depends on the number of commutation cells. CHB needs isolated DC source, usually provided by three phase rectifiers fed by a transformer. It increases the volume and cost of the converter, hence arises the significance of MMC. MMC has been proposed ten years ago by Prof. R Marquardt from University of Munich, Germany. It can be used in high voltage applications [1, 2003] like High Voltage DC (HVDC) transmission.

A key challenge for the application of the MMC to a PV system is the possibility of varied irradiances across panels due to uneven shading [18, 2015]. Many MMC topologies incorporate features which make them ideal for a large scale PV systems and WT systems. These include good output current harmonic performance and direct connection to high voltage networks through their modular and scalable design [12, 2015]. In addition, the MMC will satisfy most of the control objectives like maximum power point tracking (MPPT), synchronization with grid voltage, and lower harmonic content in the output current. MMC are mainly used in high-power medium voltage applications [14, 2003]. The main reasons are higher voltage operation with classic semiconductors and improved power quality with reduced current and voltage THD as well as reduced common mode voltages, and smaller dv/ dt [16, 2013].

A key issue in the fundamental switching scheme is to determine the switching angles (times) so as to produce the fundamental voltage and not generate specific higher order harmonics [16, 2009]. A harmonic elimination technique is presented that allows one to control a multilevel converter in such a way that it is an efficient low THD converter that can be used to interface distributed dc energy sources to a main ac grid or as an interface to a traction drive powered by fuel cells, wind system, PV, batteries or ultra-capacitors [20, 2013]. Many meta-heuristic algorithms like Genetic Algorithm (GA) [36, 2010], Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Bacterial Foraging Algorithm and Artificial Bee Colony (ABC) algorithm have been contingent for THD elimination in PWM converter and reduce the circulating current. GA stirred by the laws of natural selection and genetics has been lengthily studied in the literature for harmonic elimination problem in PWM along with MMC [42,2012]. GA bargains simple structure, easy computation, converges to near optimum solution and earn promising regions of search space rapidly. The method has intrinsic problems of convergence to local optima, premature convergence problem and slower convergence. Instead in comparison with GA, PSO is clear to contrivance as there are limited parameters to be accustomed [20, 2014]. The PSO performance being contingent powerfully on its parameters; it might simply mislay the diversity and may be partial by premature convergence exclusively once the best solution is local [9, 2015].

In literature, there has been lot of research progressed for analyzing the PV/WT system with MMC. Some of the related works were reviewed here. Increased regulations, reduced energy deviations, stable operations, flexibility etc are reviewed in this article.

II. HVDC-MMC SCHEMES

HVDC employed by Sergio Busquets-Monge et.al [34, 2008] offers minimized error with reduced energy deviations, but there may be possibilities for loss in converter. HVDC was implemented by Binayak Bhandari et.al [7, 2014] increased regulation and it also reduces the energydeviations.

Majid *et al.* [22, 2018] has introduced a six-order dynamic representation of the MMC for the HVDC applications. For the primary examination of the function of MMC, a curve based on capability depending on reactive and active power of the MMC was accomplished through a measurement of the six order dynamic formulation. Finally, Matlab/Simulink setting was deployed to systematically confirm the capability of the introduced control method for control of the MMC in HVDC application beneath both load and MMC's constraint variations.

2.1 MMC for PV/Wind turbines

K.Illves et.al [18, 2015] introduced a three phase hybrid cascaded modular multilevel topology developed from a modified H-bridge module. The comparative analysis with classical CHB and flying capacitor shows superior features of less switch count and less capacitor requirement. It reduces the switch count by 50%, gate drive requirement by 43.75% and energy source requirement by 58.33% compared with a three phase 9-level cascaded H-bridge Inverter. The MPPT (Maximum Power Point Tracking) algorithm method have been discussed and evaluated for the proposed topology interfaced with Photo Voltaic Renewable Energy Systems (PV RES).

A modular cascaded H-bridge multilevel inverter for grid-connected PV applications has been presented by Bailu Xiao and Lijun Hang [6, 2015]. The multilevel inverter topology will help in the utilization of connected Photo Voltaic modules if the voltages of the separate dc links can be controlled independently. Thus, a distributed MPPT control scheme for both single and three phase PV systems can be used to increase the overall efficiency of PV systems. For the three-phase grid-connected PV system, PV mismatches can cause unbalanced supplied power that result in unbalanced injected grid current. A modulation compensation scheme, which will not increase the control system complexity or cause additional power loss can be added to balance the grid current.

PedramSotoodeh and Ruth Douglas Miller [29, 2013] proposed an inverter to transfer active power to the grid as well as keeping the power factor of the local grid constant at a target power factor inspite of the incoming active power from the renewable energy source, like from a wind turbine. The aim of the designed inverter with Flexible AC Transmission System (FACTS) capability is to provide utilities with distributive control of VAR (Volt Ampere Reactive) compensation and power factor (PF) on feeder lines. This inverter can control the active and reactive power nevertheless of the input active power required by the DC link.

Generally, there are two modes of operation for this inverter:

a. When active power is obtained from the wind turbine and it powers the DC link, which is called inverter mode

b. When no active power is gained from the wind turbine, which is called D-STATCOM (Distribution Static Compensator) mode.

In other words, the proposed inverter can maintain the power factor of the grid at a certain target value whether the DC link capacitors are charged by the current coming from the rectifier or the DC link has open-circuited and DC link capacitors can be charged by the grid. The power flow between a STATCOM and a line can be expressed by

$P = (E_s E_l Sin\delta) / X$ and $Q = (mE_s E_l Cos\delta - E_l^2) / X$

where E_s, E_l , m and X are the voltage of the STATCOM, voltage of the line, modulation index and inductance between the inverter and grid respectively.

2.2 MMC with Circulating Current control Schemes

VahidRasouliDisfani *et al*. [38, 2015] has introduced the fast model predictive control algorithms for fast-switching modular multilevel converters. Model predictive control (MPC) was one of the switching methods for MMC to obtain the following three challenging objectives, which are following the reference of the current waveform used by upper-level control, mitigating on circulating current and regulating capacitor voltages of sub modules. In this work, a binary integer programming based MPC method was proposed to optimize the above multi-objective problem with minimum computing effort. The main contribution of the paper was to significantly reduce the computationexpenses.

Patrick T. Lewis *et al*. [28, 2016] proposed circulating current control with the Fault Section Identification Protection Algorithm for MMC Based High Voltage DC with a Hybrid Transmission Corridor. The algorithm introduced the capability of transmission restart protection without the use of a communications channel between converter stations so that fast restart can be achieved. Standard relay protection coordination was locally utilized per each converter station. The algorithm used is a fault section identification protection algorithm which utilizes protective relay coordination to protect the system from false circuit breaker reclose as well as enabling fast system restart for nonpermanentfaults.

RamyaGuruambeth *et al*. [31, 2016] have presented the circulating current control and modeling of MMC with grid-connected photovoltaic system. Here, the Fuzzy tuned PI controlled grid-connected MMC designed and implemented under partial shading condition. In the proposed controller, the gain values of PI were determined by FLC based on the operating point. Moreover, the fuzzy tuned PI controller has fast transient response and short setting time.

Lazhar Ben-Brahim *et al*. [21, 2016] proposed a weighted model predictive control that achieve stable and balanced voltage and current control with reduced circulating current in various operating conditions. Here the control method is based on a normalized cost function to select the converter switching patterns which control the load current while minimizing voltage-fluctuation and circulating current. The weighting factors were chosen based on minimizing the load current THD and circulating current.

Edris *et al.* [22, 2018] established a control design scheme of MMC for HVDC applications to function throughout normal and AC fault conditions. Initially, a steady state analysis of the converter was carried out to recognize the deployment of the present components contained by the control scheme. Depending on the initial stationary analysis, an entire converter control structure was suggested that facilitates entire control of the MMC's internal energy throughout normal and AC fault conditions. A thorough design process was involved for the current and energy regulators, for making a certain dynamic response beneath any grid condition. Hypothetical developments were authenticated through simulation outcomes by means of a comprehensive representation in normal function and throughout AC voltage sag.

Fernando *et al.* [12, 2015] has established two novel schemes for current control where a band was described regarding the reference current of the three phases. In the initial approach, only the voltage levels nearby to the grid voltage level were selected; and was known as "constant excitation" and it is most suitable when the amount of modules for each arm was extremely less. The subsequent scheme exploits an excitation proportional to the current error. It is the most suitable one when the amount of modules for each arm was enormous. The hypothetical establishment of the approaches and the simulation outcomes within an exterior active and reactive power control loop were also offered. The current control approaches were deployed to HVDC transmission from offshore wind farm to the onshore grid.

Ardavan *et al.* [5, 2017] suggested a method to attain balanced and stable MMC control while minimizing the ac components of the circulating current. The suggested method was dependent on weighted model predictive control that uses genetic algorithm (GA) to produce the optimum lower and upper arm insertion manifestations. The scheme subsequently generates the equivalent switching patterns by the exploitation of sub module sorting approach. The weighting factors were chosen depending on simulation outcomes. Moreover, the simulations were performed on a single-phase MMC with ten sub modules with probable expansion to advanced levels and stages. Finally, hypothetical examination and simulation outcomes were offered and described that substantiates the efficiency of the suggested scheme.

Lee and Heng [7, 2014] established a novel scheme based on a tuning-less Model Predictive Control (MPC) approach with unbalanced fault-ride-through ability for a three- phase modular multilevel converter. Accordingly, three individual control phases were modelled to provide for the several control intentions in MMC devoid of the requirement for any weighting factor tuning. A theoretically uncomplicated power regulation scheme was introduced into the suggested MPC. Finally, the obtainable simulation outcomes had substantiated the efficiency and probability of the established control technique.

Ahmed *et al.* [3,2017] has proposed a new fusioned MMC that facilitates the functioning with a minimized amount of full bridge sub modules with the similar boosting ability, as a result it facilitates transformer less function. However, the tradeoff was the loss of the dc fault blocking potential distinguished to the 2:1 formation. Accordingly, comprehensive demonstration of the established STATCOM formation together with its controllers was offered. Simulation case investigation was offered to reveal the efficiency of the suggested scheme. The simulation outcomes also demonstrate capable and acceptable performance.

Gebreel and Xu [2, 2016] suggested a scheme which has influences on output voltage and current THD response with a raise in the arm inductance for the MMC performance depending on a closed loop PID controller representation. Accordingly, the association sandwiched between maximum output voltage and arm inductance was described. The hardware model and software model were offered to authenticate the arm inductor value consequence on MMC experimentally. Finally, the investigational outcomes were also described and the superiority of the introduced scheme was verified.

Genetic Algorithm (GA) was introduced in [8, 2005] for circulating current control which offer minimized cost function and constant frequency. However, there was increase in internal loss. In addition, voltage balancing algorithm was deployed in [4, 2016] that offer greater flexibility with reduced computation time, but it includes challenging real time implementation. PWM algorithm was suggested in [15, 2005] that includes boosting capacity along with limited fault occurrence. Anyhow, there was no dc fault blocking ability. Finally, tuning-less algorithm was employed in [18,2015] that minimize the loss of converter and it offers large motor control, however, raise in switching frequency increases the loss. There, these limitations have to be considered for improving the controllers for MMC applications effectively in the current research work.

2.3 MMC with PWM techniques

The modulation techniques for MMC can be classified according to their switching frequencies as shown in Fig.1.

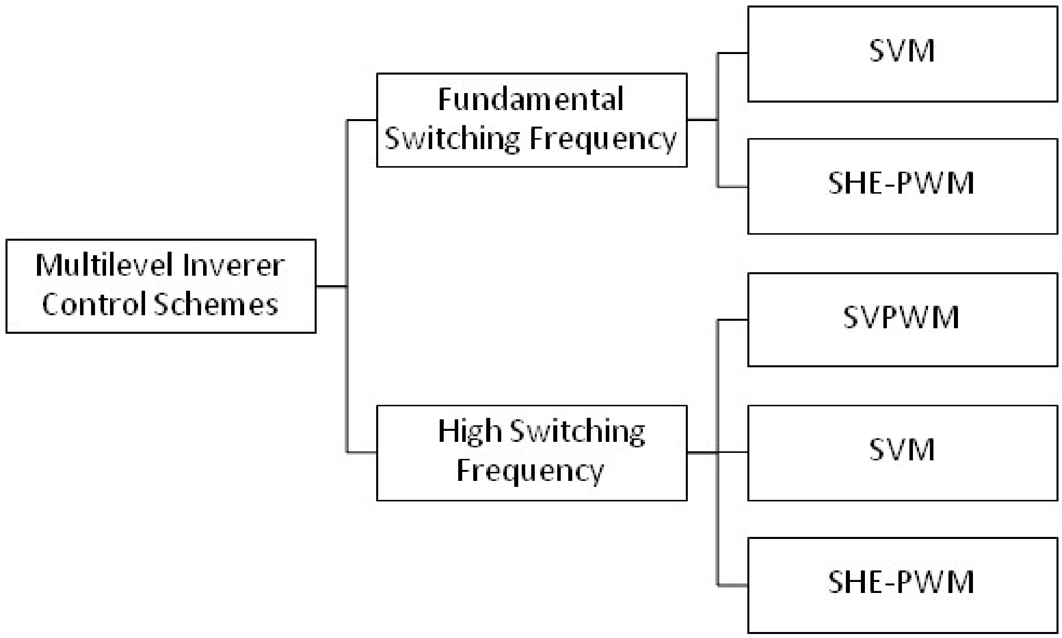

Fig.1 Classification of MMC control schemes.

Fundamental switching frequency methods use one or two commutations of the power semiconductors during one cycle of the output voltages which generates a staircase waveform. Hence, the switching losses are kept low but the output voltage has a high value of low order harmonic current in the motor drive applications. Representative techniques of this family are the multilevel selective harmonic elimination and the space vector control. In the former technique, the switching instants are calculated to eliminate the most significant low order harmonics whereas the high frequency harmonics must be removed by using additional filters. The objective in another technique is to give the load a voltage vector that minimizes the space error or distance to the reference vector. This method is simple and agreeable for high number of levels however when the number of levels decreases, the error increases and the current ripple increases.

By using high switching frequency, the low order voltage harmonics can be reduced at expense of higher switching losses. The number of sub modules required to be on or off in each of the converter's arms are driven by the modulation scheme. Pulse-width modulation (PWM) techniques are usually used in power electronic converters to achieve desired frequency and voltage variability. There are number of techniques that can be used in the production of PWM control signals, which can allow reduction of harmonic distortion in the output waveforms and increased modulation indexes, depending on the application.

Multilevel modulation strategy is one key to the realization of MMC in utility applications [33, 2015]. From the point of view of switching frequency, PWM strategies of the MMC can be classified into two categories, high-frequency modulation technique, such as carrier modulation or space vector PWM and the fundamental frequency modulation technique such as staircase modulation [30, 2011].

Venkat*et al.* [19, 2017] introduced a scheme to exploit a novel counting sort dependent method in combination with Carrier Phase Disposition Pulse Width Modulation Technique (CPD PWM). The enlarged harmonic content in the current waveforms and output voltage may be accredited to the random dynamics of capacitors. For dealing with this, also implements a cascaded voltage and current H infinity repetitive control system beneath fault and normal settings. This whole design has been deployed for back to back linked HVDC systems for justifying the Total Harmonic Distortion (THD) in current and voltage correspondingly. Further, stability investigation for the introduced controllers has been carried out to establish its robust function and at last the entire results have been surveyed.

Md.Rabiul Islam et.al [24, 2014] presents that modular Power Converters require explicit control of capacitor voltages to avoid runaway voltages due to asymmetrical charging and discharging of capacitors. Loss of neutral point voltage balance causes unwanted harmonics in output voltage waveform and capacitors can fail if this unbalance leads to voltage stresses above their rated values. All space vector modulation and non linear current control strategies incorporate voltage imbalances in overall current regulations strategy.

Sebastien Mariethoz [32, 2014] provides a way to generate large voltages that are outside the energy balance domain to maximize the achievable voltage. It also provides an effective way of controlling the system during fast transients. This allows fast control of the load, while maximizing the inverter voltage use, which results in a high energy efficiency. An optimal feedback is proposed to correct phase imbalances using the control of the common mode of the low-voltagecells.

Apparao Dekka*et al*. [4, 2016] has investigated the Modulation Scheme and Voltage Balancing Algorithm for MMC. They proposed a generalized low-cost, less-computational decoupled sampled average pulse width modulation scheme for MMC. The voltage balancing approach uses single relative comparison logic for both positive and negative current directions. In the approach, the reference output voltage was generated by averaging the two nearest voltage levels from the top and bottom arms in each sampling interval. In addition, a simplified voltage balancing approach was proposed for MMC.

Carrier Phase Disposition Pulse Width Modulation Technique was deployed in [39, 2017] that provide increased robustness and reduced delay, but problems could arise if grid voltage is taken as reference. Passivity control theory was suggested in [10, 2013] that provides stable operation along with accurate functions. Anyhow, there is an increase in cost owing to circulating currents.

2.4 MMC in Electric motor drives

Heavy trucks and many military vehicles that have large electric drives need high-power converters (>250KW). Development of electric drives for the large vehicles will result in increased fuel efficiency, lower emissions, and better vehicle performance (acceleration and braking). As well, hybrid electric vehicle (HEV) is an emerging technology in the modern world because of the fact that it mitigates environmental pollutions and at the same time increases fuel efficiency of the vehicles. Moreover charging stations including wired and wireless systems which require high efficiency, low harmonic and low loss converters. Due to decreasing cost of semiconductor switches, multilevel inverters are appropriate for these kinds of applications [27, 2013].

MMC can also be used to feed the induction motor drive in electric ships [26, 2013]. This avoids the problem of ac voltage fluctuations and thereby stability in voltage profile [25, 2013] .This work also deals with control of induction motor in ships using multi variable state control.

III.CONCLUSION

Some important control techniques of MMC have reviewed in this paper. HVDC- MMC systems employing different control systems have been reviewed. MMC systems for PV with MPPT algorithms for both single phase and three phase systems is found to increase the overall efficiency of the systems. MMC for FACTS also discussed for controlling the active and reactive power. The circulating control is a key issue in the operation of MMC. Different control techniques like Fuzzy, PI, MPC can be used for reducing this. Different optimization techniques can also be incorporated in the controller for getting the accurate results.PWM techniques with suitable current controller is found to give the best results in the literature.

The most important application of the MMC is in HVDC transmission which can interconnect different frequency grids and asynchronous grids. MMC is also a current trend of using in HVDC distribution in ships.. In the future, it is expected that MMC will be not only used in HVDC installations but also used in commercial medium voltage applications. Also it will increase the efficiency of HVDC systems. MMC with suitable current controller can be a relevant topic for the future research.

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