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Modular Multilevel Converter based HVDC Transmission system

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***Abstract*- Pakistan energy demand is increasing day by day and a new era of electricity transmission (HVDC) for efficient power transmission for long distances has started. This paper shows the potential of Modular Multilevel Converters for HVDC application. Modular multilevel converters are the most recent advancement in the multi-cell converter family. The most famous sub module configuration for MMC are the Half bridge and full bridge sub modules this study is carried out by using half bridge sub modules for MMC. MATLAB/Simulink model of MMC is presented. By using LSC-PWM and PSC-PWM (with and without interleave angle) result analysis of current, voltage and voltage harmonics were done and concluding remarks were given on the basis of results.**

***Index Terms*— High Voltage Direct Current (HVDC), Modular Multilevel Converter (MMC), Half Bridge (HB), Cascaded H Bridge (CHB), and Pulse Width Modulation (PWM).**

I. INTRODUCTION

Pakistan's energy sector is in crisis due to many reasons like generation problems, transmission losses, distribution problems and due to Pakistan's increasing energy demand which is increasing at the rate of about 3% per annum. Energy generation companies more than 80% uses oil and gas which are limited resources [1]. Electricity pushes up economy of a country and is one of the main keys to improve the economy of a country. In recent times, insufficient policies of energy generation have drawn many countries to power sector crisis. The key source of electricity generation is Coal all around the world it contributes about 40.0% to the energy sector of the world and so is Pakistan moving towards the coal generation as new power plants that generates electricity by coal have been commissioned, which causes harm to the environment and contributes to greenhouse emissions. The best solution for emissions free energy is the use of renewable energy resources whose most important component is converter stations for power conversions and transfer.

Conventional two-level converters can only generate square waves of two polarities either $+V_{dc}$ and $-V_{dc}$ (V_{dc} being the DC bus voltage) which is a very distorted waveform and cannot be used for high power applications without larger size filters which consequently increases the cost of the system, for this problem multilevel converters were introduced as its solution. Neutral point clamped converter (NPC) was the first modification to two level converters that can generate three output voltage levels $+V_{dc}$, 0 and $-V_{dc}$. The zero level was achieved by connecting clamping diodes to each arm of the phase leg, which eventually reduced the voltage stress on the semiconductor devices that reduces the cost of converter, it provided more netter waveforms than two level converters but the main problem associated with NPC is the voltage blocking capability of the clamping diodes as we go beyond three levels [2]. The flying capacitor converter (FCC) is similar to NPC but only the clamping diodes are replaced by flying capacitors and desired output is achieved by different switching states for different current directions, the problems associated with FCC are the capacitor pre-charging and voltage ripple due to capacitor voltage unbalance to reduces this either the size of capacitor is needed to be increased which increases the cost or either the switching frequency is needed to be kept higher which reduces the converter efficiency due to which FCC is generally limited to 4 levels [2, 3]. Cascaded H bridge converter consists of single-phase H Bridge sub modules connected in series. Each submodule consists of 4 IGBT's and an isolated DC source fed by the secondary of the input transformer. This topology is favorable against NPC and FPC as there is no need of pre-charging and capacitor voltage balancing and use of fewer components, the only problem associated with CHB is the use of isolated DC sources which makes it difficult to use in HVDC applications [2]. However, method for CHB implementation in HVDC is presented in [3]. Modular multilevel converter are the most recent advancement in the multi-cell converter family which preserves all the features of Cascaded H Bridge converters but do not require isolated DC sources, due to this features are available in a very wide range of applications [4].

In this paper, mathematical model of MMC is presented based on the model Pulse width modulation of MMC is presented. Section II introduces the system structure and operation principles of the MMC. In Section III basic mathematical model of MMC is presented. Section IV presents PSC-PWM and LSC-PWM techniques. Section V presents the analysis of results obtained by the model developed in MATLAB/Simulink. Section VI concludes this paper.

II. SYSTEM STRUCTURE AND OPERATING PRINCIPLE

Figure 1 shows the circuit configuration of a modular multilevel converter. It consists of a common DC bus or DC link fed by a rectifier station or PV panels; the DC bus consists of a fictional neutral point that is not available in real. The converter consists of six converter arms, three upper and three lower arms, the arm that is connected to the positive side of the DC bus is upper arm and the arm that is connected to the negative side of the DC bus is called lower arm. Each arm consists of series connected N sub modules and an arm inductance to limit the short circuit current and to resist the circulating current due to sub module capacitor voltage unbalance [4].Each sub module consists of two IGBT's and one DC storage capacitor. One upper and one lower arm make a leg which is the phase unit the output is connected between the upper and lower arm [5].

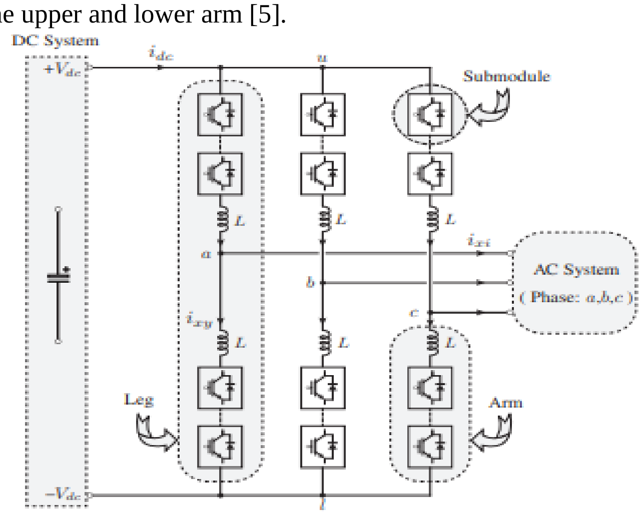


Figure 1: Circuit configuration of MMC

There are two complementary switching states related to the sub module operation [6]. The ON- state the DC capacitor is connected to circuit and it charges or discharges depending on the direction of current positive or negative, the OFF-state the DC capacitor is not connected to the output terminals and no output voltage appears, the charge on the capacitor is unaffected [7]. The simple operating principle of MMC is by different switching combination and by inserting different sub modules from upper and lower arms desired output voltage levels are obtained.

III. MATHEMATICAL MODEL OF MMC

Figure 2 shows the generalized equivalent per phase model of a MMC. The output voltage v_{xi} is connected between the upper and the lower arms. The upper and the lower arms are modeled as controlled AC voltage sources (as their output can be changed by changing the switching pattern). The DC-bus is modeled as ideal DC batteries.

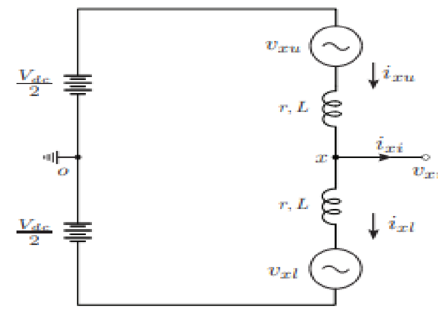


Figure 2: Per phase equivalent circuit of MMC

The upper and the lower arm signals can be obtained by applying Kirchhoff's voltage law (KVL) [8, 9],

$$v_{xu} = \frac{V_{dc}}{2} - v_{xi} - L\frac{di_{xu}}{dt} - ri_{xu} \quad (1)$$

$$v_{xl} = \frac{V_{dc}}{2} - v_{xi} - L\frac{di_{xl}}{dt} - ri_{xl} \quad (2)$$

Where $x \in \{a, b, c\}$ denoting the phases v_{xu}, v_{xl}, i_{xu} and i_{xl} are the upper arm voltage, lower arm voltage, upper arm current and lower arm currents respectively.

The phase modulation signal that is going to be sinusoidal given to the modulation stage is,

$$v_{xi} = m_a \times \frac{V_{dc}}{2} sin(w_o t + \theta_x) \quad (3)$$

Where m_a is the modulation index ranging between 0 to 1 deciding the amplitude of the output voltage, w_o is the angular frequency and $\Theta_x \in \{0^o, 120^o, 240^o\}$ which is the phase difference between three phases.

The output phase voltage v_{xi} is given by,

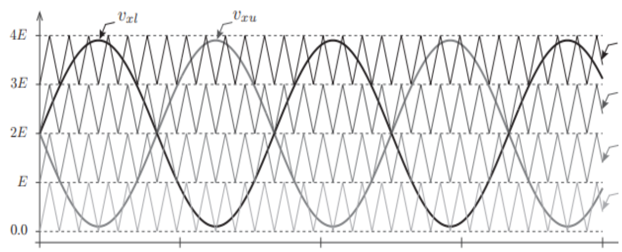
$$v_{xi} = \frac{v_{al} - v_{au}}{2} \quad (4)$$

IV. PULSE WIDTH MODULATION

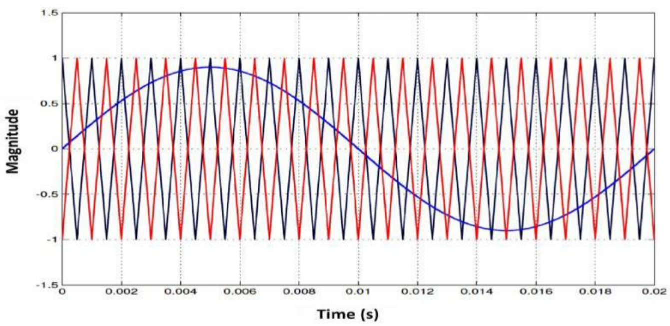
This section deals with switching techniques of modular multilevel converter. The pulse width modulation techniques is widely applied to power electronic converter because of their efficient performance, PWM is simply the switching of converter switching for different duty cycles to vary the output voltages. It consists of one reference signal and carrier signals. The technique in which the carrier signals are disposed vertically on the reference signal is called Level shifted carrier Pulse width modulation (LSC-PWM) shown in figure 3(a) , the output voltage levels that LSC-PWM generates for MMC are N+1 levels, where N is the number of sub modules. The PWM technique in which the carrier signals are disposed horizontally is called Phase shifted carrier PWM (PSC-PWM) shown in figure 3(b), the output voltage levels by using PSC-

PWM with interleave angle are going to be 2N+1 levels and without interleave angle are going to be N+1 levels, where N is the number of sub modules and interleave angle (∅_ci) is given by:

$$\emptyset_{ci} = \frac{360^o}{2N} \quad (5)$$



(a)



(b)

Figure 3: (a) LSC-PWM (b) PSC-PWM

V. SIMULATION & RESULTS

In this section the performance analysis of MMC model developed in MATLAB/Simulink by using LSC-PWM and PSC-PWM discussed in Section IV is presented. Table 1 shows the parameters of the studied Modular Multilevel Converter. In this model four number of sub modules are used for simplicity purpose in order to have better understanding of the output voltage levels generated by modular multilevel converter.

A. LSC-PWM of MMC

LSC-PWM is the vertical disposition of Carrier signal against the reference signal. As the number of sub modules that are used are four so there are going to be four reference signals generated which will level shifted 1/2 from each other. For the case of LSC-PWM ideal DC batteries are used within the sub modules instead of capacitors so the waveforms will be free of voltage balancing problems. At the output for phase voltage 5 levels and for Line voltage 9 Levels are going to be generated.

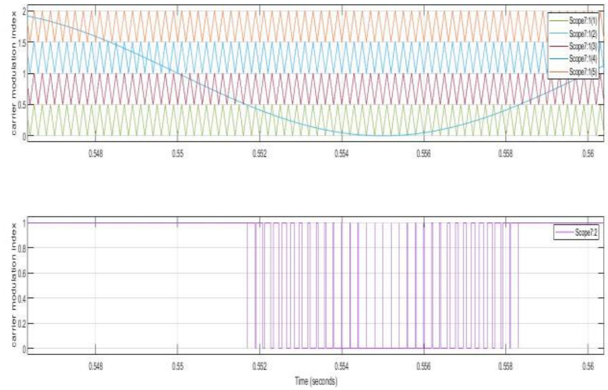
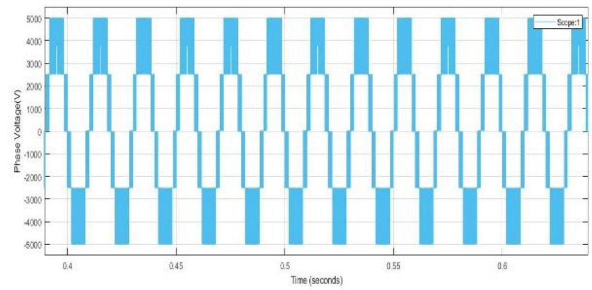
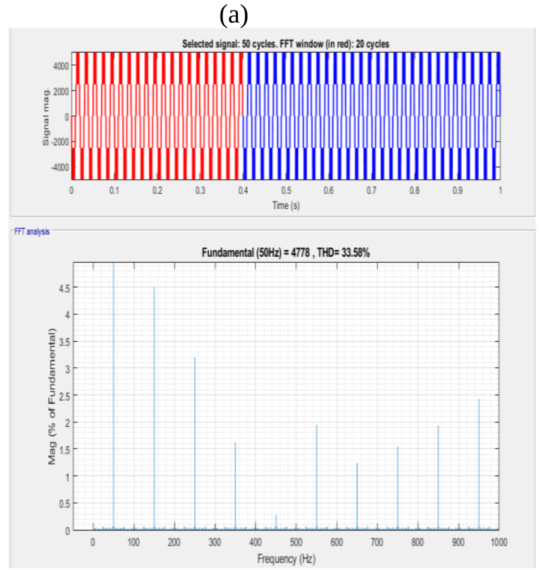


Figure 4: LSC-PWM and gating signal for one IGBT



(a)



(b)

Figure 5: (a) LSC-PWM phase output voltage (b) Total Harmonic distortion of phase voltage

QUANTITY	VALUE
number of sub modules	4
line to line voltage	6KV
apparent power	2MVA
Frequency	50Hz
power factor	0.85
dc bus voltage	10KV
arm inductance	5mH
sub module capacitance	2200µf

Table 1: Model Parameters of MMC

B. PSC-PWM of MMC

PSC-PWM is the horizontal disposition of carrier signals on the reference signals. Four number of carrier signals will be required for PSC-PWM for upper arm and four carrier signals will be required for lower arm. Phase shifted carrier PWM was studied by using the system parameters shown in table 1.

1) *With interleave angle*: the interleave for PSC-PWM carrier signals is given by equation 5, it is the angle between the two upper and the lower arm carrier signals, for four sub modules the interleave angle is going to be 45º, the angle between each of the carrier signals is going to be 90º that is {0º, 90º, 180º, 270º} for upper arm and for lower arm it is going to be {45º, 135º, 225º, 315º}. When interleave angle is provided and the number of sub module in an arm are four then the phase voltage is going to be of 9 levels and the line voltage is going to be of 17 levels.

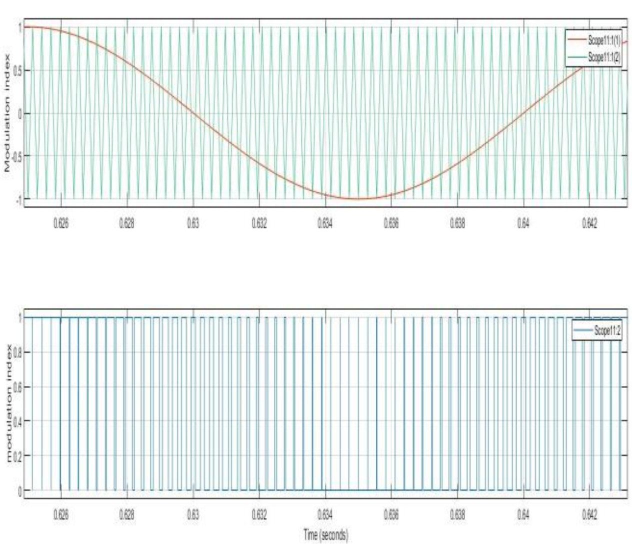
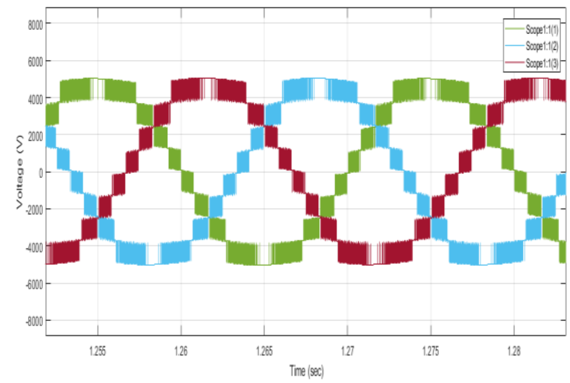
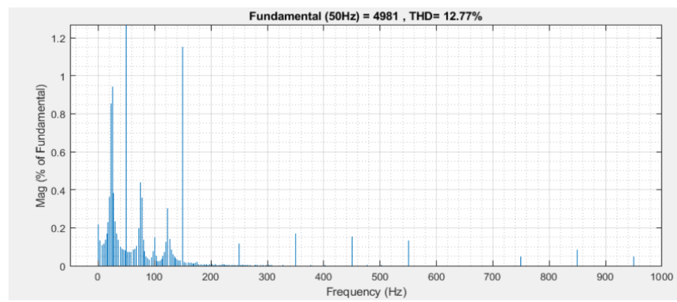


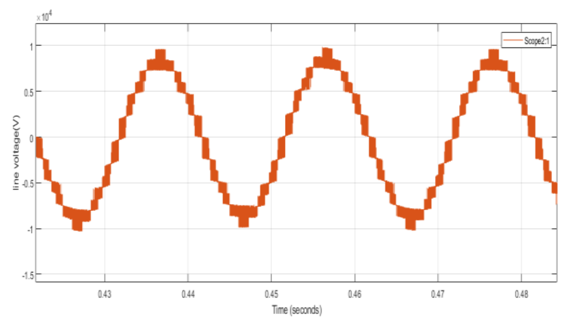
Figure 6: PSC-PWM and switching signal for IGBT



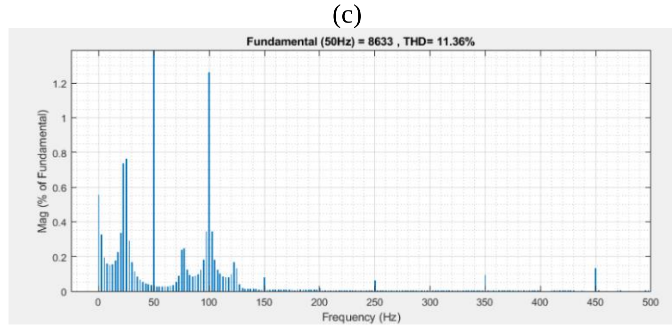
(a)



(b)



(c)



(d)

Figure 7: (a) phase voltage (b) THD analysis of Phase voltage (c) line voltage (d) THD analysis of line voltage

2) *Without interleave angle*: when no interleave angle is provided to carrier signals in the modulation stage then the upper and lower arm signals are going to be similarly displaced from each other that is if the upper arm carrier signals are {0º, 90º, 180º, 270º } then same displacement will

be provided for the lower arm signals. Without interleave angle the output phase voltage levels are going to be 5 and line voltage will have 9 levels.

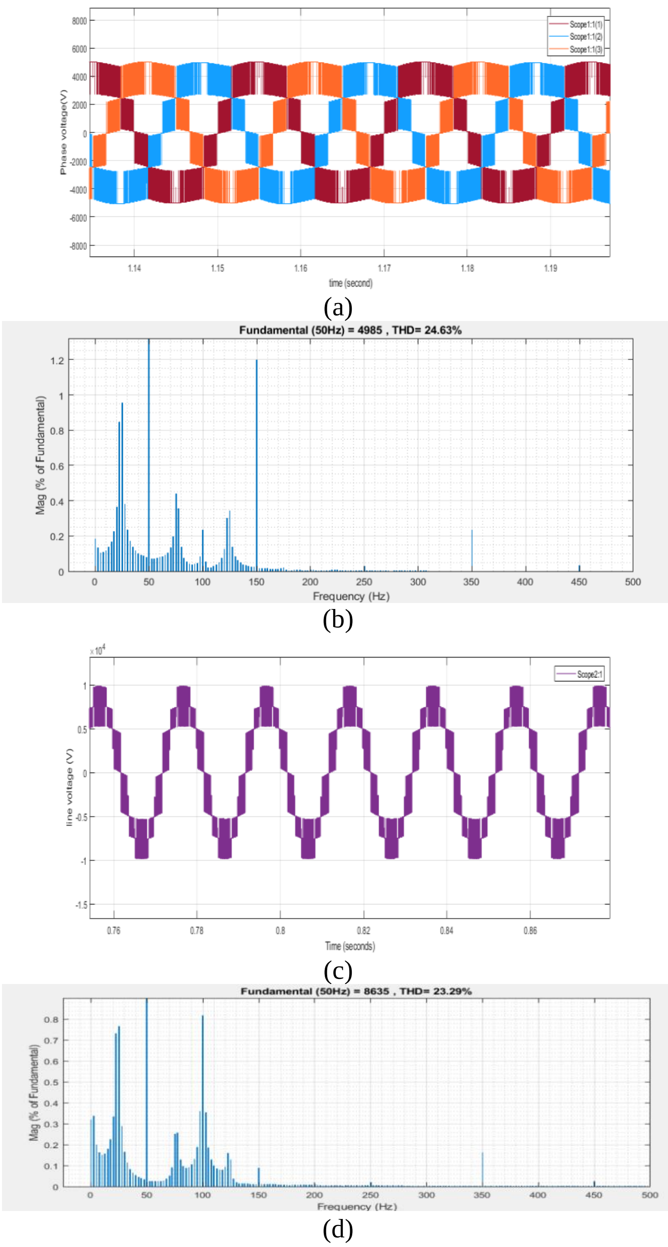


Figure 8: (a) phase voltage (b) THD analysis of phase voltage (c) line voltage (d) THD analysis of Line voltage.

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VI. CONCLUSION

Modular multilevel converters are the most recent advancement in the family of multi-cell converters. They are most popular in research work now a day due to their many advantages over other multilevel converters like no need of isolated DC sources, lowest harmonic components, fault tolerant operation and many others. As the world energy demand is growing the need of more and more energy generation is increasing, but generating electricity through conventional power plants like coal, diesel, gas is causing harm to the environment, so environment friendly resources of electricity generation like wind, solar are needed. To transmit such power at such a large distance as these power plant are situated at very far distance is very uneconomical by using High voltage AC transmission and High Voltage direct current transmission is recommended. The most important part of HVDC is converter station. This paper shows the potential of Modular Multilevel converter for HVDC transmission system using low rated Modular multilevel converter by means of simulation. It was seen that modular multilevel converter is capable of producing high voltage outputs with very low THD harmonic distortion and increasing the number of sub module in each arm can further reduce the total harmonic distortion by a significant amount which shows its potential for HVDC transmission economically as well as technically. PSC-PWM and LSC-PWM performances were analyzed by means of simulation in MATLAB/Simulink environment.

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