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DEVELOPMENT OF AN ENHANCED MULTILEVEL MODULAR POWERED DC-AC INVERTER

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ABSTRACT- *Power DC-AC converter is a power electronics device that converters DC power to AC power at desired voltage and frequency. DC-AC converter system may derive their power sources from solar panels, fuel cells, wind power, geothermal source, supper capacitors. Numerous industrial applications have begun to require higher power apparatus in recent years. Some medium voltage motor derives and utility applications require medium voltage and megawatt power level. For a medium voltage grid, it is troublesome to connect only one power semiconductor switch directly. As a result, a multilevel power converter structure was introduced as an alternative in high power and medium voltage situations. The research modeled, simulated and controlled a five level MMI. The inverter topology was achieved using a 4kV dc source which converts the dc voltage to a 5 level phase voltage at the output and a 9 level line to line voltage at the output. The model presented in this paper was modulated using Phase-Shifted pulse width modulation scheme. This control scheme helped to maintain all the capacitors as fixed voltage sources. The MMI model was carried out using the half bridge sub module: with 8 sub modules, SM per phase: four SMs for the upper arm and 4 for the lower arm respectively; with each of the arms consisting of an inductor which serves as a current limiter. The modeling, simulation and control was done using MATLAB/Simulink blocks.*

Keywords: DC-AC converter, geothermal, semiconductor switch, pulse width modulation, Phase-Shift.

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1.0 INTRODUCTION

A multilevel inverter is a power electronic device which is capable of providing desired alternating voltage level at the output using multiple lower level DC voltages as an input [15]. In recent years, electric energy consumption is increasing rapidly due to the increasing of the energy demand in the world. As result of this numerous fossil fuels sources and other resources which have great contribution in global warming due to greenhouse gases emission are largely consumed. Due to these negatives impacts caused by these resources a rapid progress in finding an alternatives and renewable energy has attained a significant interest in the area of researches to eliminate the shortage of fossil fuels and reduce the global warming concern. In the last three-decade renewable energy (RE) has become challenging field and many researchers have make RE the main focus in order to create new sustainable, natural abundance and environmental friendly nature energy resources [1, 2].

The utilization of multilevel inverter has become a good candidate and a frequently adopted solution for high-power and power quality demanding applications, the term multi-level implies that an n-level inverter is capable of producing an n-voltage level rather than producing two levels as in the convention two level inverter. Beside that the multilevel inverter can draw an input current with low distortion, operate at higher switching frequency and lower switching frequency with lower switching loss and achieving higher efficiency and resulting lower total harmonic distortion in the in the output waveform without using any filter circuit [14].

In real world most of renewable energy resources that has been used is a D C energy in nature such as solar energy, wind, tidal and biomass, however the electrical transmission systems is in AC and not all of the loads (appliances/machines) are using the direct current (DC) power supply as their sources. Most of them need an A C power as their main source. This is where the inverter is needed to convert DC energy to AC energy.

The Inverter is an electrical device which converts direct current (DC) to alternate current (AC). In the early decade inverter was limited to two level inverter which implement a few semiconductors switch, however the with rapid growth in the industry and introducing the higher power application equipment which reaches the megawatt level the conventional two level inverter is not capable of handling high power application .Due to this reasons the need for introducing high level inverter(multilevel inverter) become an essential to overcome the shortage of conventional two level inverter and efficiently high power loads .besides these reasons multilevel inverter is aimed to replace the conventional two level inverter to gain good power quality, low switching losses, and high voltage capability [1] –[10].

Until the 1970s, power electronics for conversion between alternating current (ac) and direct current (dc) was dominated by current source Inverters (CSCs) operating by natural commutation. The main application was rectification, to provide direct voltage for dc motors and industrial processes. Also, high-voltage direct current (HVDC) power transmission originally made use of CSCs. The available current valves, first thyratrons and mercury arc valves and later thyristors, lacked turn-off capability, and were therefore only suited for naturally commutated Inverters. The advent of power semiconductors with turnoff capability, allowing for forced current commutation, paved the way for VSCs which can operate independently from the ac grid [6].

These Inverters offer increased controllability and improved harmonic performance, which radically expanded the field of application. At the same time several new challenges in terms of electric power conversion emerged. Concerns about the negative environmental impact of

traditional energy sources, such as the burning of fossil fuels, have led to a desire to use renewable energy sources (RES), such as wind power and solar power. None of these uses the kind of large synchronous generators operating at constant speed traditionally employed for electricity generation. Therefore, there is a need for a power electronic interface, which in most cases is best implemented by VSC [5]. Similar concerns have also led to demands for energy savings. Within electrical drive systems very significant savings can be achieved by a transition to variable-speed operation [4] [8] .

In the past, pumps and fans, for instance, were usually operated at fixed speed with the fluid flow being controlled by throttling, which caused efficiency to be very poor at low flow rates. If the speed of the electric machine can be controlled overall power losses can be significantly reduced. Additionally, variable speed operation allows for improved control and precision in many industrial processes, contributing to increased automation and the improved quality of the product. The VSC fits these demands very well since it allows for convenient torque and speed control of synchronous machines and induction machines. The speed of dc motors could be controlled by CSCs, but such motors are less attractive because of the high maintenance cost of their brushes and commutators [5].

Also in transmission grid applications such as HVDC and FACTS (flexible alternating current transmission systems), the VSC has made inroads at the expense of thyristor-based naturally commutated: Inverters. Several of the features of VSCs are attractive and sometimes also necessary in this field. The ability to impose a voltage on the ac side and thus control active and reactive power independently from each other is required in several applications. To these belong, for instance, HVDC connection of offshore wind farms as discussed earlier in this book [1] [4] [6] [9].

From the beginning, the prevailing VSC topology was the two-level Inverter and it is still the preferred solution for low-voltage applications. For systems operating at voltages beyond a couple of kilovolts, however, it is less useful since there are no available power semiconductors able to block voltages above this level. An option is to directly connect semiconductor elements in a series to create valves capable of withstanding higher voltages. Such concepts have been developed, but they tend to be complex since several problems need to be solved in order to ensure the operation and fault tolerance of such a valve. Also, this technology is not widely available, making it costly. Instead, a transition to multilevel Inverter topologies offers better prospects for providing cost effective power conversion at higher voltages. These topologies do not require direct series connection for increasing the operating voltage. Furthermore, the harmonic properties are much improved, so that the requirements on voltage and current distortion can be met without excessive switching losses [2].

The first multilevel topology to be used on a large scale was the three-level neutral point clamped (NPC) Inverter. It is still in frequent use for high-power motor drives. However, it cannot easily be extended to additional levels, which limits the field of application to the medium voltage range, at least if the series connection of semiconductors is not used to boost the voltage capability.

Multilevel Inverters have presented an important development in recent years to reach higher power with increasing voltage levels [7]. Large numbers of multilevel inverters topology have been investigated but few of them are practical for industrial applications [8]. Diode clamped and cascaded H-bridge (CHB) are.the most preferred choices [9], [10]. For medium

voltage (2.3, 3.3 and 4.16kV) applications three-level neutral-point clamped is the suitable topology, but having the constrained of mass clamping and the

voltage imbalance of dc-link capacitors in extending its use to higher voltage levels [11], [12]. For applications with voltage higher than 6kV, cascaded H-bridge multilevel inverters are commonly used [11], [13]. Isolated sources are required in this topology. To generate individual voltage sources, conventional method is to employ a multi-winding transformer with the same number of isolated secondary windings, which is huge and expensive.

Owing to shortage of fossil fuels and increasing environmental pollution on a global basis, renewable clean energy has been vigorously developed and utilized. More and more large-scale clean energy bases have been constructed. As a consequence, problems with grid connection for clean energy have been aggravated. In connecting grids for clean energy by traditional AC systems, tremendous and serious impacts are imposed upon power grids and their safe stable operations. Thus, more complex strategies should be developed for coordinated control and protection of the systems [14].

Flexible DC transmission technologies are not only effective for flexible conversion of alternating current into direct current and point-to-point transmission of electric power within a long distance, but can also have AC networks of same or different frequencies interconnected. In addition to guaranteeing advantages of AC systems in power generation, transmission, conversion, distribution and application, power systems including DC power transmission have also dealt with some inherent defects of AC power transmission, so that modern DC power transmission technologies have received

widespread attention and achieved rapid development [16]. The increasing penetration of renewable energies, as ‘well as more demanding requirements in terms of efficiency and reliability in the electrical network leads to a big challenge, as a significant part of the installed capacity will be connected to the distribution levels in the near future. [17]

It is in this scenario where power electronics makes its appearance. Innovative operational equipment based on power electronics and capable to be connected to the medium voltage grids, able to provide several functions to the power operator, such as controlling power flow, reduction in transmission losses and power quality improvement among others will be needed, example of this being HVDC and FACTS technologies [18]

Among the different multilevel topologies, the Modular Multilevel Inverter (MMI) has currently become a subject of intense research. While it shares the appealing properties of other multilevel configurations, it offers some interesting and useful features. As a result of this, the MMI has been an active research topic in recent years [19].

Multilevel Inverters are now a day considered as one of the industrial solutions for high dynamic performance and power quality demanding applications. Multilevel Inverters are the power conversion systems composed of an array of power semiconductor devices and the capacitive voltage sources that can be connected and controlled properly for generating a multistep voltage waveform with variable and controllable frequency, phase and amplitude. That is the sine wave can be approximated to a stepped waveform having larger number of steps. The number of levels of an inverter is defined as the number of steps or constant voltage values that can be generated by the Inverter between the output terminal and an arbitrary reference node called the neutral. Comparing with the two level inverters of the same power rating, multilevel inverters have the advantages of low switching frequency and

hence reduction in the switching losses, reduced EMI issues and also reduction in the harmonic components of the line to line voltages etc [20]-[21].

Among the three different topologies mentioned above the diode clamped or neutral point clamped (NPC) has been commonly used. However, it is difficult to control the real power flow for balancing the neutral point potential. The advantages of multilevel Inverters are the staircase waveform quality, lower or reduced common mode voltages, can operate at both fundamental and high switching frequency PWM, reduced switching stresses on devices etc. [22] - (23].

Recently, the modular multilevel Inverter (MMI) topology has become an alternative to the conventional multilevel inverters in medium and high voltage applications. The MMI consists of series connected half bridges with dc capacitors called as the sub modules. Each phase leg consists of one upper arm and one lower arm connected between the dc terminals. The advantages of modular multilevel Inverter over the conventional multilevel inverters are:

a) Modular construction
b) MMI is extendable to-any number of levels and capacitor voltage balance is attainable etc

2.0 REVIEW OF RELEVANT LITERATURE:

The Modular Multilevel Inverter as one of the topologies of MLI is still undergoing research. However, over the years since it was introduced, many researchers have tried in one way or the other to analyze it's working principles and some have done different modelling and simulations on it with different software. Thus, some of the relevant literatures related to this subject matter were reviewed and presented below. The reviews on this subject matters as made available in this chapter is based majorly on two perspectives; (1) the literatures about the MLI (MMT) topologies and its working principles, and (2) the already existing literatures about MLI (MMI) control strategies.

The first proposed multilevel inverter was to use three level inverter. Subsequently several multilevel inverter has been introduced including a n-level of inverter [14].

According to [13], until the year 2000 no pure cascaded converter topologies for ac/dc conversion were available. High-voltage VSCs (e.g. for HVDC applications), were implemented using direct series-connection of the semiconductor devices in order to withstand the voltage. Converters for reactive power compensation using full-bridge submodules were in use, but these lacked a dc terminal and were therefore not suited for ac/dc conversion.

There existed cascaded converters for ac/dc conversion, but these required individual isolated feeding of the submodules by transformers, and were not truly modular [24].

In 2002, a major breakthrough was made by the introduction of the MMC with half-bridge submodules by Prof. Marquardt [25]. It puts submodule strings to use in an ingenious way so that ac/dc conversion is made possible while maintaining the important benefits of cascaded converters in terms of voltage scalability and harmonic performance. These features have in a relatively short time made it one of the most used cascaded converter topologies.

Murthy and Pandian presented an analysis of multilevel inverter voltage balancing. In their work, a redundancy balancing technique for the five-level diode-clamped inverter is presented, which balances the four dc-link capacitor voltages at high modulation index and high power factor. The technique is based on dividing the vector space of the five-level

inverter into six two-level vector spaces. Dwell times were calculated as for conventional two-level space vector modulation, and the switching sequence was determined depending on the four capacitor voltages, using a redundant state method. The developed technique maintained link capacitor balance for high modulation indices, including over modulation, irrespective of the power factor. The developed algorithm was validated by simulation and practical implementation. The results obtained from the MATLAB/SIMULINK was tabulated to compare the total Harmonic Distortion (THD) for different modulation techniques.

Though the model gave lesser THD compared with the two or three level inverter of same topology, it was still not convenient to work with [26].

E. Solas et al, in [27] presented first the mathematical model of the Modular Multilevel Converter with nm submodules based on differential equations. Secondly, by using this model the simulation block diagram in Simulink was presented. After that, the special output AC voltage control of the converter was analyzed, considering the 'capacitors' voltage control loop that usually is included in this topology. Finally, simulation results showed that the developed model can be useful to simulate the MMI/MMC topology with a large number of submodules, while on the other hand, the developed AC voltage control was valid to regulate the total voltage of the converter capacitors as well as to exchange sinusoidal currents at any operation mode. However, the modulation that also performs the capacitors' voltage balancing was-not deeply studied in this paper.

In [28], the MMC has been modeled from the point of view of the ac side, considering each submodule (SM) as a constant voltage source, disregarding the submodule capacitor dynamics in the ac-side terminal current controller, and taking into account only the fundamental component of the MMC voltages and currents. The approach was considered to be enough for designing the compensator responsible for controlling the power exchanged between the MMC and the ac grid. However, the submodule capacitor voltage variation and the harmonic components in the arm current were not considered.

In [29], the MMC was modeled in open-loop state and with the submodule capacitive dynamics taken into account, which yields non-linear and time varying differential equations. The MMC non-linear time-varying model was developed further in [30] and [31]. The proposed model in [30] and [31] considered the ac-side terminal current compensator and the circulating current suppression compensator, following the control strategy described in [32]. Even though the model presented in [31] was adequate, for the control strategies employed, a steady-state model was nonetheless needed for predicting the steady-state magnitude of the MMC quantities, and, in turn, permitting the sizing of the components of the MMC.

Following the research done by Saeedifard and Iravani in [29], Q. Tu and Z. Xu in [33], developed a parametric model for the steady-state magnitude of the circulating current of an MMI. The model presented a relative high error, in Comparison to the simulation results, and, when applied to HVDC systems, the error became even higher.

In [34], a similar but more detailed steady-state MMI model was developed. The model presented here correctly predicts the amplitude of the circulating Current and, also, predicts the condition for arm current resonance that can destabilize the converter. However, the model was still incomplete, in the sense that did not predict the amplitudes of all harmonic components of the currents and voltages of the MMC.

Q. Song, et al in [35], described a different steady-state MMI model using a different mechanism and providing simpler equations. The predictions or results from this model were

shown to be also accurate. However, just like [34], the model presented here in [35] was still incomplete, in the sense that they do not predict the amplitudes of all harmonic components of the currents and voltages of the MMC.

The dynamic model for MMC control described in [36], [37], [38], and another steady-state model is presented in [39], had no advantages added in comparison to the previously reviewed models presented in [33]-[35], from the point of view of the author.

In [40] a new dynamic model was developed in *dq*-frame, facilitating the designing of the MMC compensators. However, the *dq*-frame model is not suitable for deriving equations for the amplitude of the harmonic components of the voltages and currents of the MMC.

Lavanya and Muruganandham, in [41] said that, Multi-level inverters offer Several advantages such as a better output voltage with reduced total harmonic distortion (THD), reduction of voltage ratings of the power semiconductor switching devices and also the reduced electro-magnetic interference problems etc. Multilevel inverters synthesize the AC output voltages from various DC voltages. Space Vector Modulation (SVM) is one of the most popular PWM techniques used in multilevel inverters. SVM provides a best space vector performance, sequences of different space vectors suitable for voltage source inverter is identified.

A 9 level cascaded H-bridge inverter model for space vector PWM is established and simulated using MATLAB/SIMULINK software and its performance is compared with sinusoidal PWM. The simulation study reveals that space vector PWM utilizes de bus voltage more effectively and generates less THD when compared with sine PWM.

Amir Sajjad, in [42] worked on different topologies of multilevel inverters consisting cascaded symmetric, diode clamped, flying-capacitor, and hybrid asymmetric are investigated. [42] showed that hybrid asymmetric inverter has more reliable topology than others, due to less number of power semiconductor Switches and higher voltage levels. Also different multilevel modulation techniques were studied form voltage waveforms and harmonic spectra aspects. This study proves that Phase Disposition Pulse Width Modulation shows less harmonic distortion than other techniques. According to the study, the hybrid asymmetric multilevel inverter, due to its benefits both in load and line sides is Presented as a new topology for industrial applications, especially in medium voltage drives.

J. Dixon, et al, in [43] presented a 27 level multilevel inverter, obtained by using only 3 H-bridge inverter units with different: dc voltage sources. According to [43], by increasing the level of the inverter we can get several advantages: get a good voltage wave form, very low THD, reduced volume and cost. The need of several sources on the DC side of the converter makes multilevel technology attractive for many high power applications.

R. Bensraj, et al, in [44] presented that ternary DC source multilevel inverter is triggered by the Unipolar PWM strategy having sinusoidal and trapezoidal reference with inverted sine carriers. These Pulse Width Modulating (PWM) techniques: include Phase Disposition (PD), Alternate Phase Opposition Disposition (APOD), and Carrier Overlapping (CO). Performance factors like Total Harmonic Distortion (THD), VRMS (fundamental), crest factor and form factor are evaluated for various modulation indices. It is observed that UISCPDPWM (Unipolar Inverted Sine Carrier Phase Disposition PWM) Strategy with trapezoidal reference provides output with relatively low distortion and UISCOPWM strategy with trapezoidal reference provides relatively higher fundamental RMS output voltage.

In [45], Maruthu and Devarajan presented an optimal solution for eliminating pre species order of harmonics from a stepped waveform of a multilevel inverter topology with equal dc sources. The main challenge of solving the associated honlinear equation which are transcendental in nature and therefore have multiple solutions is the convergence of the relevant algorithms and therefore an initial point selected considerably close to the exact solution is required. An ancient genetic algorithm that reduces significant the computational burden resulting in fast convergence. An objective function describing a measure of electiveness of eliminating selected order of harmonics while controlling the fundamental component is derived. The performance of cascaded multilevel inverter is compared based on computation of switching angle using Genetic Algorithm as well as conventional Newton Raphson approach. A significant improvement in harmonic profile is achieved in the GA based approach.

Jannu Ramu, et al, in [46] compared between single seven levels H-bridge Inverter, which uses equal DC sources and symmetrical MLI and different DC sources an asymmetrical MLI, is used as load to observe the performance output voltages. The ISPWM gave the FFT Analysis THD values 21.84 voltage of 332.7 that the number of bridges and DC sources switching losses are reduced. When compared to symmetrical MLI. Simulations have been carried out in MATLAB SIMULINK to study the performance of the proposed prototype. A predictive current control technique has been carried out to verify the viability of new configuration.

In [47], Feel-soon Kang and Yeun-Ho Joung, presented a Cascaded Multilevel Inverter Using Bidirectional H-bridge Modules. This method presents a multilevel inverter configuration which is designed by insertion of a bidirectional switch between capacitive voltage sources and a conventional] H - bridge module. The modified inverter can produce a better sinusoidal waveform by increasing the number of output voltage levels. They proposed a cascaded Hbridge multilevel inverter using bidirectional switches to increase the number of output voltage levels with minimum devices. The circuit configuration is simple and easy to control. The operational principle and key waveforms were illustrated and analyzed. Also, they have selected two kinds of switching patterns among 24 patterns, which can produce a 9-level output voltage.

The proposed multilevel inverters can be utilized in solar power generation, which has merits as an independent voltage source.

G. Murali Krishna et al, in [48] 2012 presented a cascaded H-bridge Multilevel inverters from five levels to seventeen levels have been simulated using Matlab/Simulink. The symmetrical Cascaded H-bridge multilevel inverter consists of the number of switches which increases with increase in the number of levels. And also control circuit, complexity, maintenance increases. They maintained that, for the asymmetrical cascaded H-bridge multilevel inverters to get the 7 level to 17 level output voltage, the THD decreases to increase the number of levels, some lower or higher harmonic contents remain dominant in each level. But this, [48] posited that it will be more dangerous for induction drives. Hence recommended that the future work may be focus on implementing Closed loop control with suitable harmonic elimination technique to achieve better performance of the converter. The fuel cell and photo voltaic cells are used for multilevel inverter input voltage of dc sources. The future scope is to determine the PWM techniques of asymmetrical multilevel inverters then to reduce the harmonic content in the output voltage of the asymmetrical multilevel inverters.

In [49], it proposes that under balanced conditions, negative sequence component of circulating current in each arm rotates at double the line frequency. So, A (delta) control method was stated which states that by transforming the a-c-b sequence with a double line frequency into d-q sequence at rotational reference frame. But this method was not able to eliminate the circulating current totally at underbalanced conditions.

In [50], Peftitsis D., et al, proposed a control method with analyses of instantaneous power of each leg, and also an algorithm to reduce the circulating currents and d-c link voltages ripples; but has a disadvantage of inclusion of double line frequency ripple.

Dong Cao, et al, in [51], it has proposed a-b-c reference frame to control the Circulating currents but has the disadvantage of generating a delay and it cannot improve the transient response occurring in the inner balancing currents. In [52] it proposed a model predictive control which took ac-side current, circulating currents and sub-module voltage balancing, by detecting the switch status to minimize the cost function.

Multilevel inverters suffer from dc-link capacitor voltage imbalance problems at high modulation indices. Many techniques have been proposed to solve this problem one of these techniques is the redundant state method. This method has power factor and modulation index limitations when used on a five-level inverter. However, SVM technique offers capacitor voltage balance at high power factor and high modulation index by using a state redundancy method. To address the above mentioned issue multilevel inverters is emerged as an important alternative in high power and medium voltage control. There are three multilevel inverter topologies among them diode clamped inverter is extensively used by many researchers. The main advantage of multilevel inverter is to increase the power rating, lower harmonics and synthesized sinusoidal output waveform. The multilevel inverters take care of higher power application equipment' which reaches the megawatt in the industry.

But the cost and control of these MLI as the output voltage levels increases becomes so complex, thus the new topology of MLI called Modular Multilevel Inverter - MMI also called Modular Multilevel Converter MMC.

Thus, this model, MMI seeks to address the above mentioned issue. The Modular Multilevel Inverter emerged as an important alternative in high power and medium voltage control. The MMI topology is to use only one voltage Source, to produce as many output voltage levels are required. In this research, the control of the Model and the voltage balancing of the capacitors is also discussed.

3.0 METHODOLOGY AND ANALYSIS

Modular Multilevel Inverter, MMI as one of the topologies of Multilevel inverters has different methodologies that can be used to realize it. In this chapter the concept and working principles of modular multilevel inverter will be discussed; subsequently a MATLAB/Simulink Model of a five level MMI will be presented, the modulation scheme discussed and the voltage balancing method adopted explained.

3.1 BLOCK DIAGRAM OF MODULAR MULTILEVEL INVERTER:

This research work is made up of five (5) major categories. Figure 3.1 below is a block diagram of the five major stages of the MMI topology carried out I in this work.

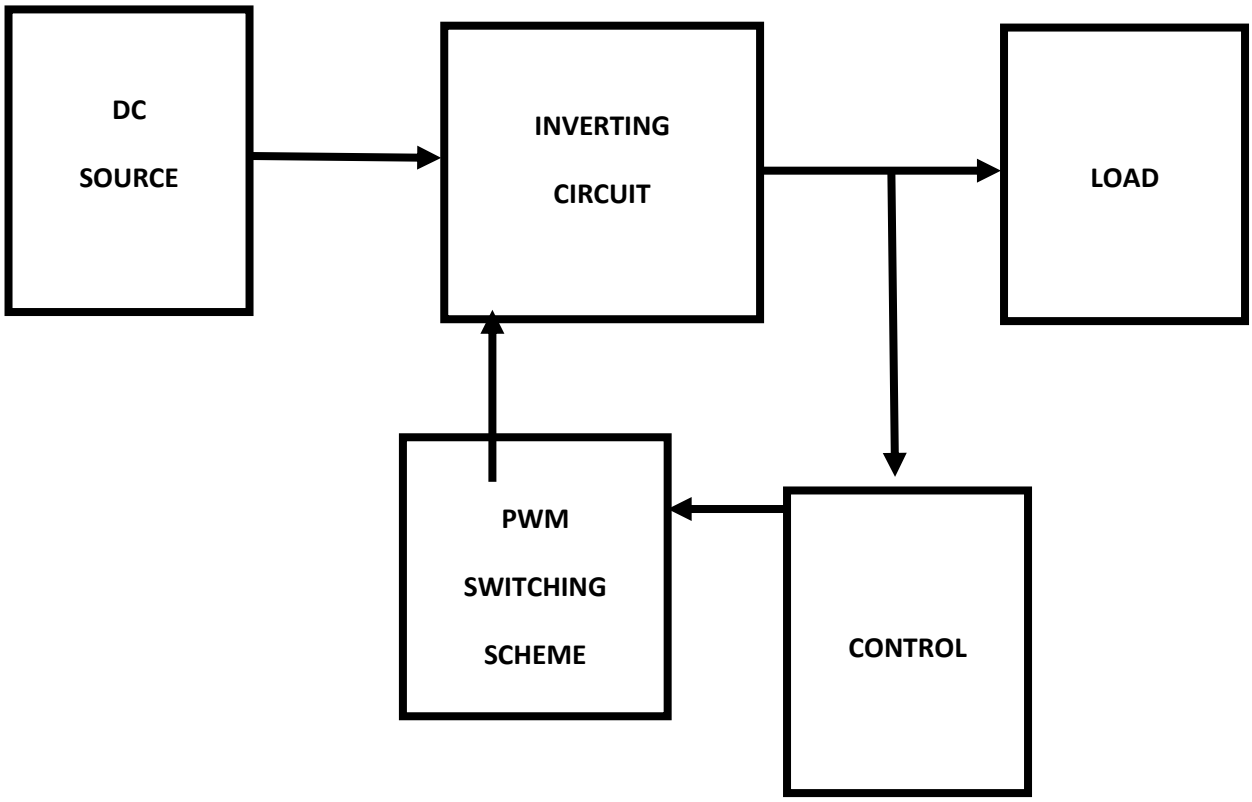


Figure 3.1: Block diagram of MMI topology.

The block diagram as presented above is a general representation of the modular multilevel inverter also called modular multilevel converter. The DC Source block is the supply using battery/cells whose voltage is converted to alternating current, AC voltage. The inverting circuit is made up of switches and diodes which forms a sub module, SM and these SMs are arranged in such a way that a three phase AC voltage is realized. The switching is controlled by the PWM switching scheme block and to balance and stability at the output, the inverter parameters are sensed and used to control the switching pattern of the switches which made up the inverting circuit.

3.2 CONCEPT OF MODULAR MULTILEVEL INVERTER:

The Modular Multilevel Inverter (MMI) is benefits according to its modular topology the only suitable self-commutated converter for high voltage applications as HVDC transmission systems. There are much more advantages within this topology that make the MMI attractive for medium voltage applications or even energy storage applications. All of this lets the MMI emerge as an important issue of contemporary scientific investigations.

The concept of this topology is presented below; taking into account the constituent components that makes up the sub modules and arm structure. This converter is composed by identical power cells connected in series, each one built up with standard components, enabling the connection to high voltage poles.

Although the MMI and derived topologies offer several advantages, simultaneously they also introduce a more complex -design of the power circuit and control goals, which is one of the objectives of this research work.

3.2.1 IGBT SWITCHES/DIODES

The IGBT (insulated gate bipolar transistor) is a three-terminal electronic component, and these terminals are termed as emitter, collector and gate. Insulated Gate Bipolar Transistors (IGBTs) combine the best of conventional bipolar transistors and FETs. Like FETs, they only require a voltage across the base in order to conduct. However, like conventional bipolar, they are efficient conductors of current through their collector/emitters.

The IGBT has the output switching and conduction characteristics of a bipolar transistor but is voltage-controlled like a MOSFET. In general, this means it has the advantages of high-current handling capability of a bipolar with the ease of control of a MOSFET. Figure 3.2 is a basic structure of IGBT/Diode.

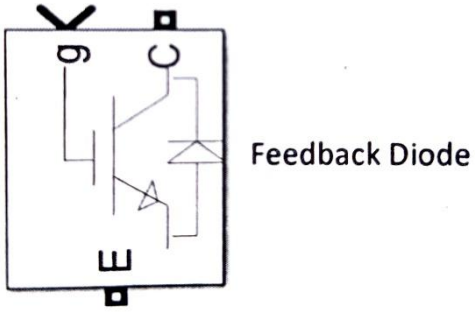


Figure 3.2: Basic structure of IGBT/Diode

An IGBT is simply switched “ON” and “OFF” by triggering and disabling its Gate terminal. A constant positive (+ve) voltage input signal across the ‘g’ and the ‘E* will retain the device in its “ON” state, while deduction of the input signal will cause it to tum “OFF” like BJT or MOSFET.

The main advantages of IGBT compared with various kinds of transistors are jow ON resistance, high voltage -capacity, fast switching speed, ease of drive - and joined with zero gate drive current creates a good option for sensible speed, and various high voltage applications like PWM, SMPS, variable speed control, AC to DC converter powered by solar and frequency converter applications which operates with a hundred’s of KHz.

3.2.2 MODULAR MULTILEVEL INVERTERS SUB MODULES:

A sub module or cell is a basic building block of the MMC. It is a two terminal device consisting of combination of IGBTs, diodes and capacitors used to generate the required voltage level. MMC sub modules come with different configurations. The variation in sub module configuration also determines the behavior of the module and its modulation technique. The dominating type of sub module for HVDC applications is the half-bridge sub module. The reason is that this type of sub module has the lowest losses and the lowest cost. In the midst of several other types of sub modules, the most obvious alternative sub module candidate is the full-bridge sub module, which had been in use in Cascaded-cell converters for medium-voltage drives and static synchronous compensators (STATCOMs) already before the invention of the MMC. The different sub modules are presented below:

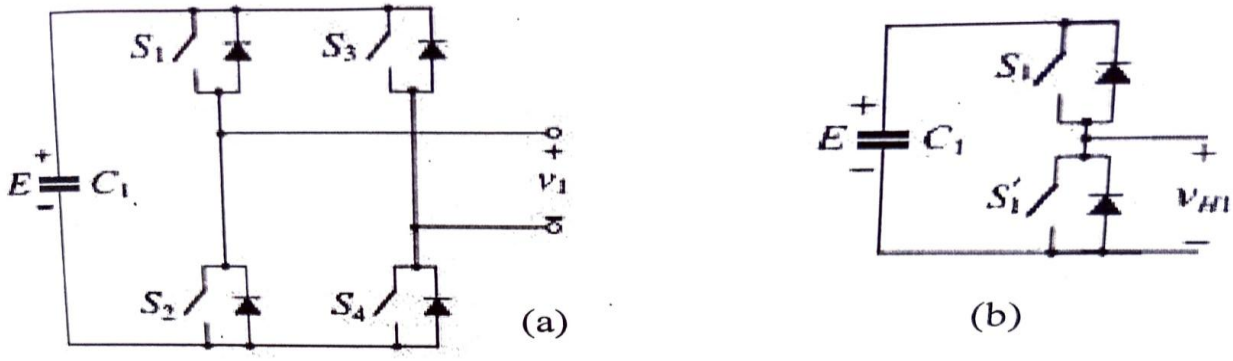


Figure 3.3: Modular Multilevel Inverter Sub modules (SM)
(a) Full bridge SM (b) Half bridge SM

Among all the sub modules, the sub modules presented in figure 3.3 above, the half-bridge and full-bridge sub modules however have the advantage that they can provide a counter voltage in case of dc-side short-circuits, and thereby prevent short-circuit currents flowing from the ac side to the fault on the dc side.

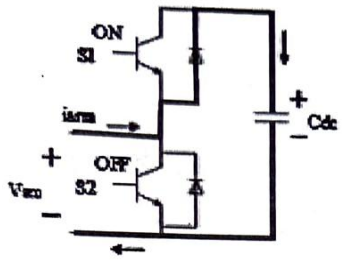
In this research work the half bridge sub module is used.

3.2.3. OPERATING STATES OF THE HALF BRIDGE SUBMODULE:

Generally, the half bridge SM used in this research work operates with four different states. These states of operation are dependent on the current flowing through the sub module. Figure 3.3.1 shows the sub module states and current paths.

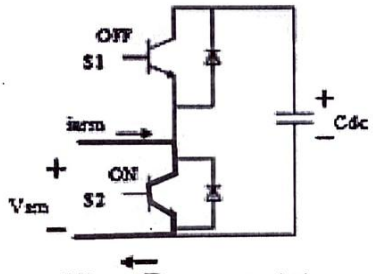
For $i_{arm}>0$:

i. S1 ON and S2 OFF gives **charging state** where Vout = Vsm = Cdc



(i) Charging state

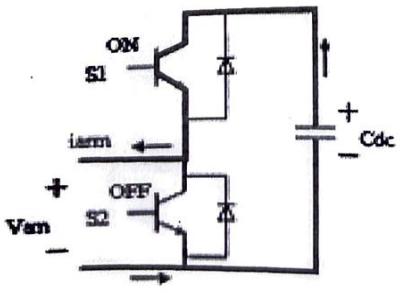
ii S1 OFF and S2 ON gives **by-pass state** where Vout = 0



(ii) By-pass state

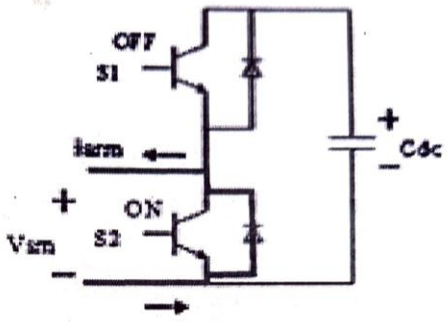
For $i_{arm}<0$:

iii S1 ON and S2 OFF gives **discharging state** where Vout = Vsm = Cdc



(iii) Discharging state

iv S1 OFF and S2 ON gives **by-pass state** where Vout = 0



(iv) By-pass state

Figure 3.3.1: Sub module states and currents paths

33 WORKING PRINCIPLES OF MODULAR MULTILEVEL CONVERTER

Generally, sub modules of modular multilevel converters are mostly designed with half bridge structures. For a single-terminal converter, there are six bridge-arms altogether, which make up three phases. In each bridge-arm, N, SM sub modules are connected in series (N is determined according to voltage class and capacitance), and two bridge-arms are connected in series to compose upper and lower ones in each phase. The topology structure of a MMI is shown below.

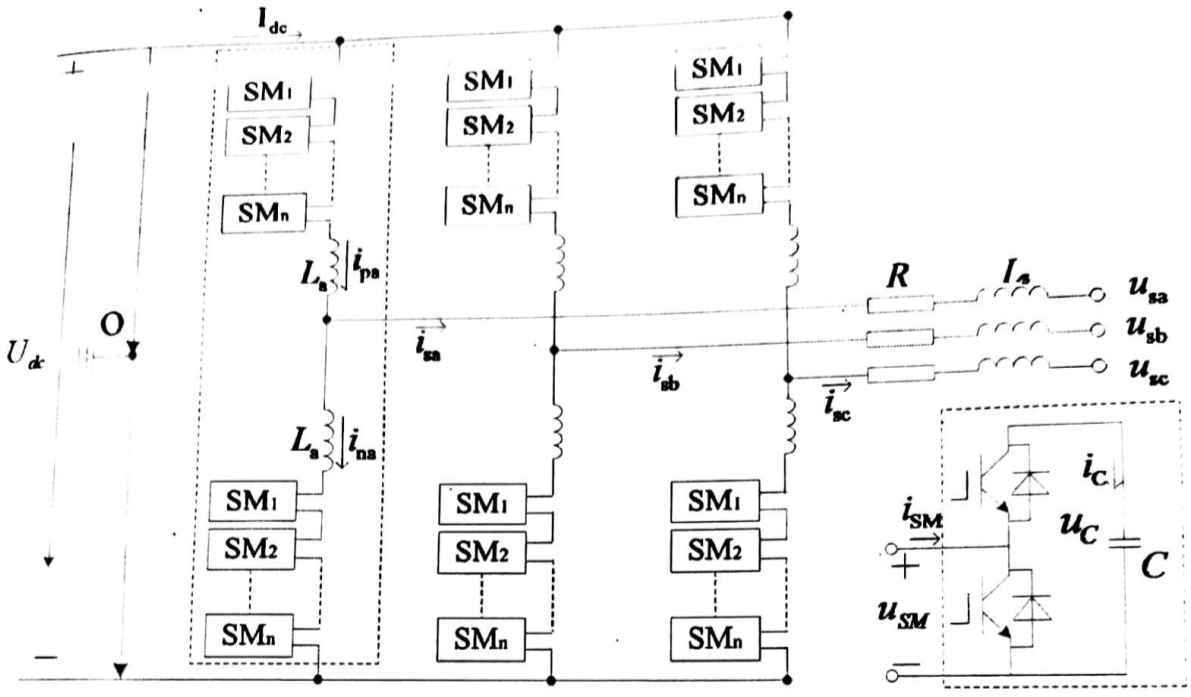


Figure 3.4. The main circuit topology of MMC [16]

From Figure 3.4, U_{dc}, and I_{dc}, represent DC voltage and current of MMI; the current is denoted by i_{pa} and i_{na} on upper and lower arms of Phase A; L_a, is used to represent current-limiting reactance on arms of Phase A; L_a, is effective for suppressing inter-phase circulating current, weakening impulse current in case of short-circuit faults, and reducing changes to current and circumventing damages of switching devices. These values of current and voltage

may be signified by i_{sa}, I_{sb}, $s_{sc}U_{sa}U_{sb}$ respectively for 3-phase AC output power; the structure of a single sub module is indicated by SM, which in this case is a half bridge SM, where C is capacitance and SM is output voltage; voltage and current of Capacitance may be represented by u_c and i_c respectively.

From the arrangement of the SM for both upper and lower arms, the voltage phase voltages: $U_{sa}U_{sb}$ and u_{sc} seen at the output is the sum of the arm voltages for that phase. And each arm voltage is made up of the sum of the connected capacitors within the arm. For this research work, four SMs are used each of which is made up of a capacitor. It thus gives a voltage class (level) at the output of

$$N+1 = \text{Vot levels}$$

Where N is the number of SMs = 4. That is, for each phase we have 4+1=5 voltage steps at the output. The capacitor voltage for each of the arm is given by:

$$U_c = \frac{U_{dc}}{N}$$

For this research, U_c, is 4000

$$U_c = \frac{4000}{2} = 1000V$$

This implies that, for every SM to be connected, it sends out 1000V from the SM capacitor voltage which makes up the arm.

3.4 MATLAB/SIMULINK MODELS: -

The MATLAB/Simulink blocks presented below are the models for the three phase inverting circuit, Pulse Width Modulation (PWM) switching scheme and the control circuitry.

Figure 3.5 gives a general model of the Modular Multilevel inverter and it comprises of the inverting, modulation and control blocks of the three phases. Figures 3.5a and 3.5b are the configuration for the inverting circuit made up of four sub modules per arm and the internal configuration of each sub module respectively.

Figures: 3.7a, 3.7b and 3.7c are the models for voltages averaging, arm current control and the voltage balancing control respectively.

Figure 3.7d is the general control blocks used for the capacitor voltage balancing. The figure is made up of the model presented in figures: 3.7a, 3.7b and 3.7c.

There are different modulation techniques all of which are aimed at realizing a scheme that will give desired stepped voltage output. These techniques are the different ways the switches of the inverting circuit are controlled. Figure 3.8 is a summary of the various modulation techniques employable for obtaining an appropriate switching pattern. In this research paper, the carrier based phase shifted PWM (Pulse-Width Modulation) scheme is used. For the Phase Shifted PWM, an MMC with N sub modules requires N triangular carriers all of which are of the same peak-peak amplitude. The carrier signals are phase shifted from each other by

$$\theta = \frac{2\pi}{N} \text{ or} \theta = \frac{360}{N}$$

$$\text{Which in this case is } \theta = \frac{360}{4} = 90 \; degrees.$$

That is to say, the four carrier signals used are phase shifted 90° from each other and compared with a modulating carrier with a modulation index of 0.8. The frequency of the sinusoidal modulating carrier is 50Hz and that of the four Carrier signals is 6000Hz. The MATLAB/Simulink model of this scheme is Shown in figure 3.6. The result obtained for this modulation scheme is presented in the next chapter, chapter four of this research work.

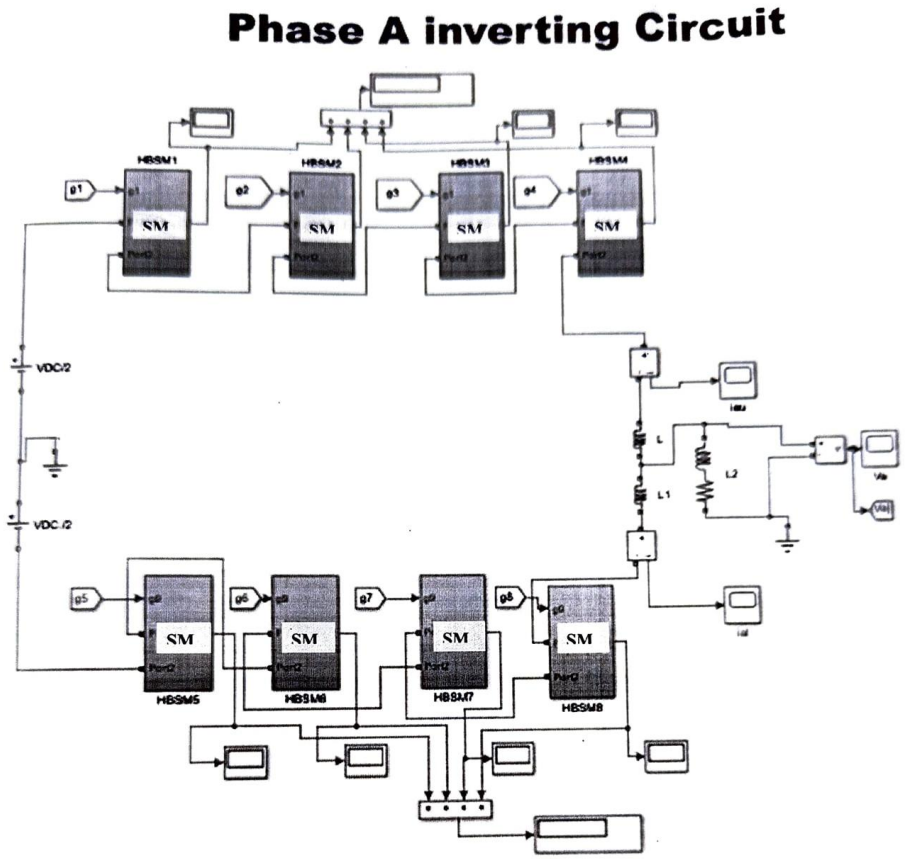


Figure 3.5a: MATLAB/Simulink model of the inverting circuit of single phase MMI

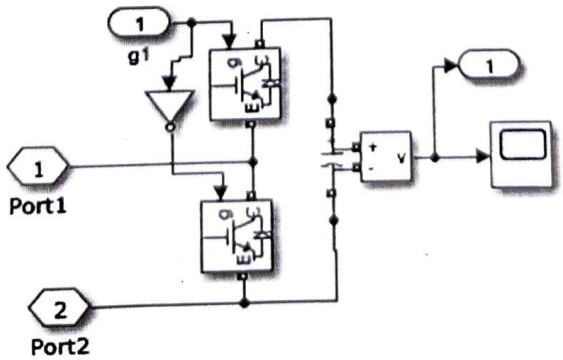


Figure 3.5b: MATLAB/Simulink model of Sub module configuration

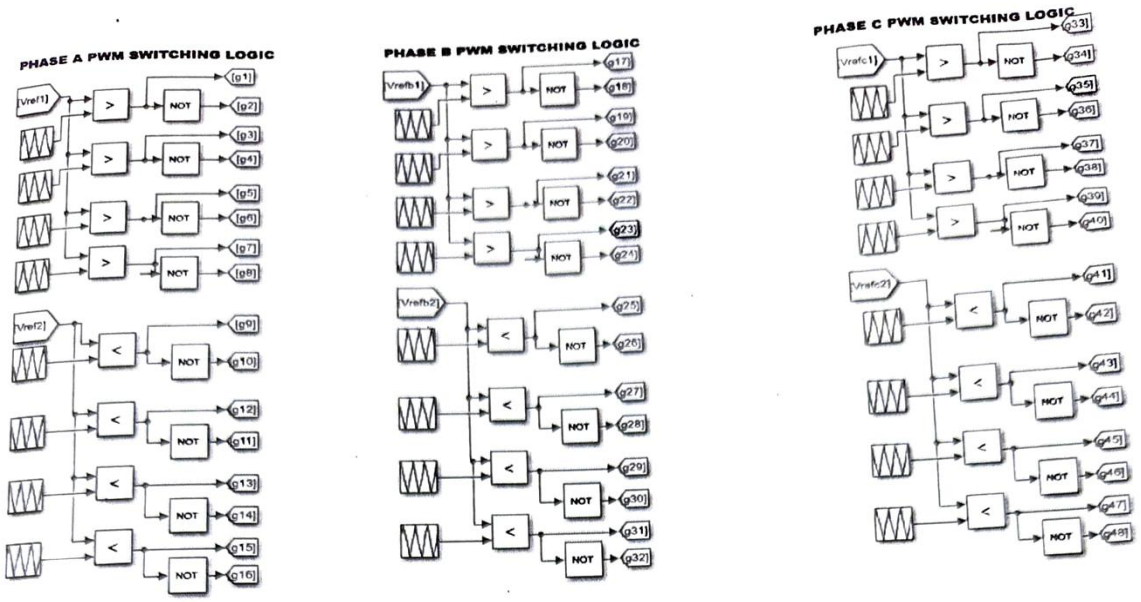


Figure 3.6: MATLAB/Simulink model of Phase-Shifted Pulse width modulation scheme for the three phases: A, B and C.

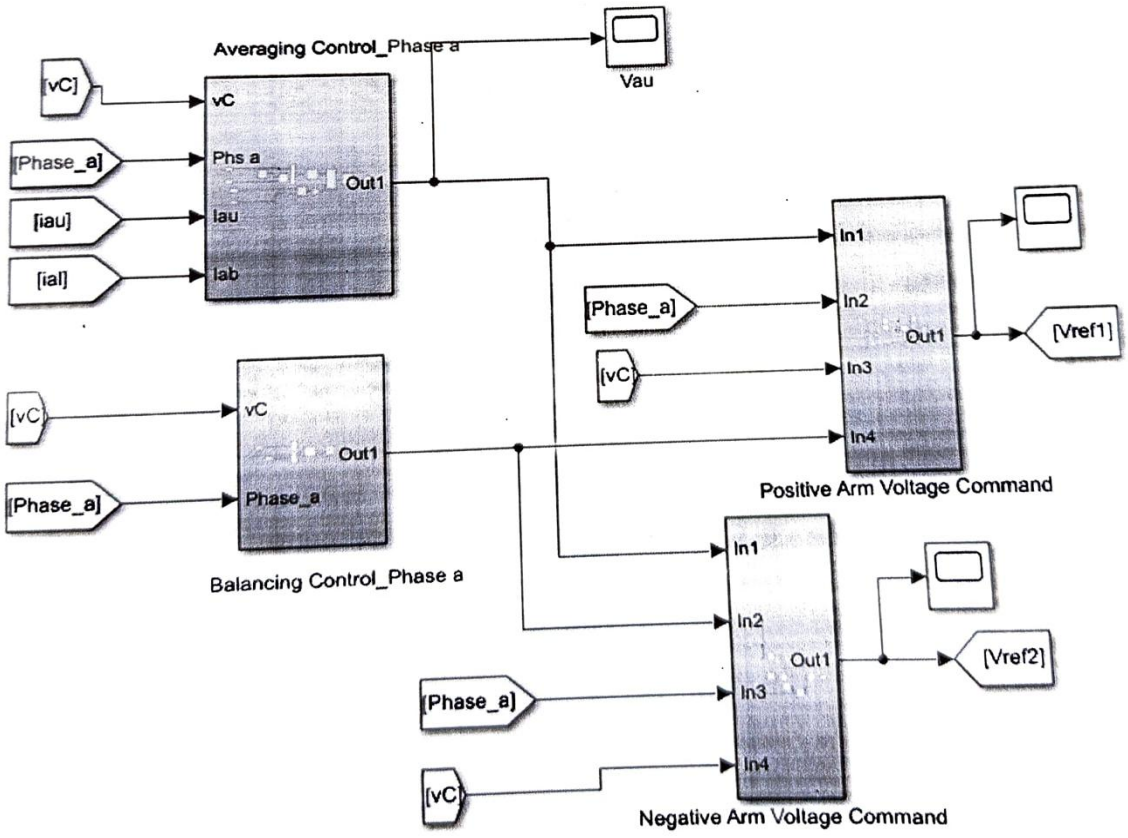


Figure 3.7: MATLAB/Simulink model of the capacitor voltage balancing

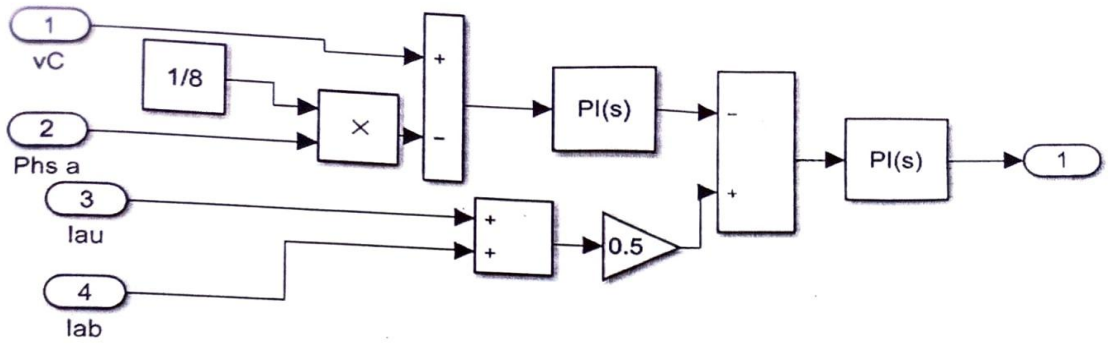


Figure 3.7a: MATLAB/Simulink model of averaging control

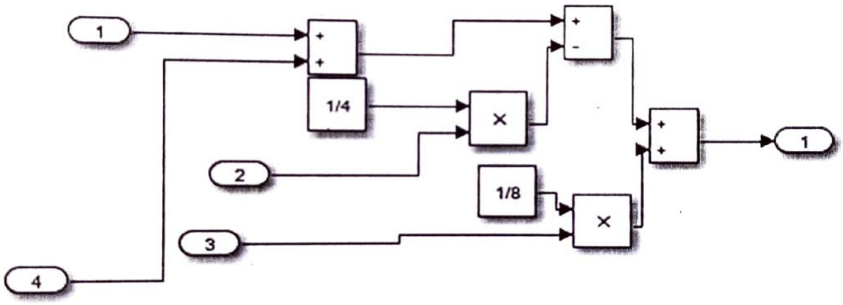


Figure 3.7b: MATLAB/Simulink model of arm current control: the same for both upper and lower arm currents.

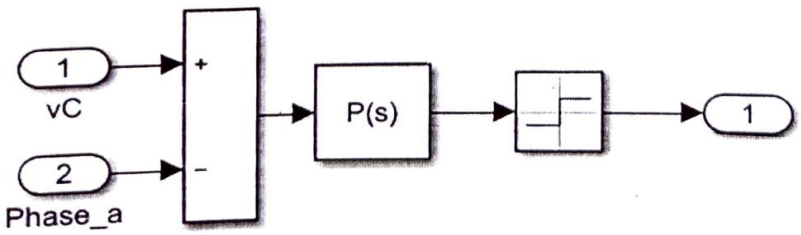


Figure 3.7c: MATLAB/Simulink model of voltage balancing.

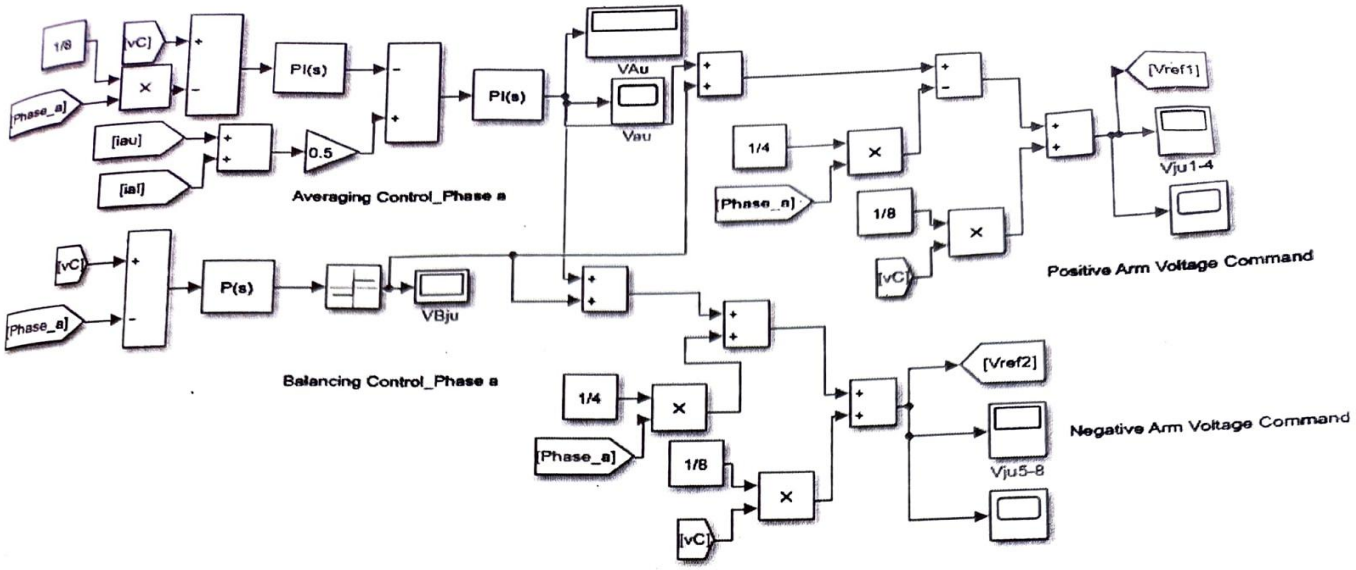


Figure 3.7d: MATLAB/Simulink model of the capacitor voltages.

3.5 MODULATION SCHEME:

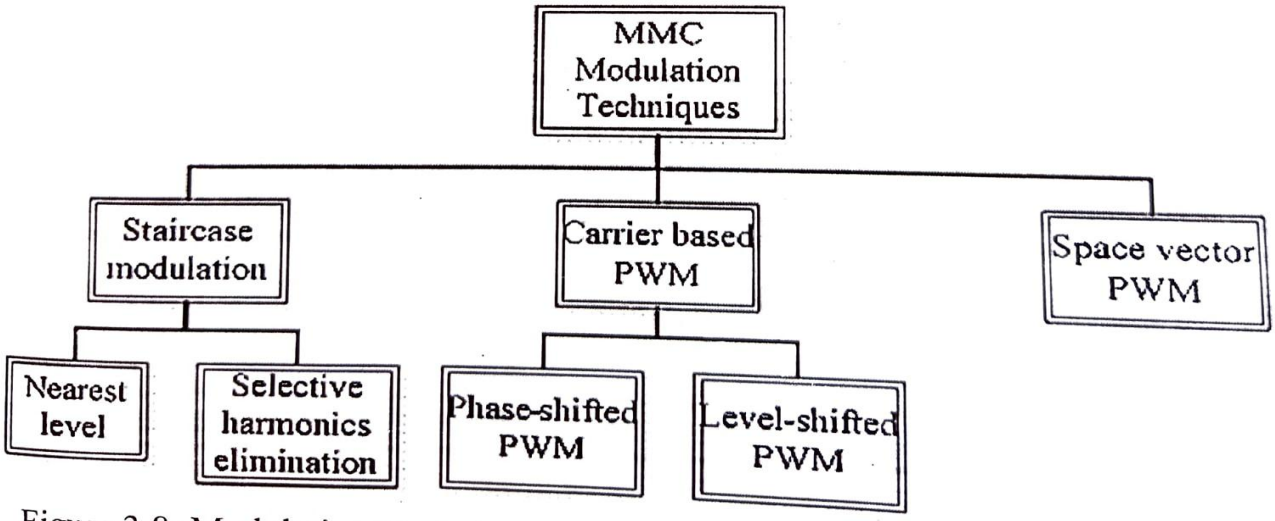


Figure 3.8: Modulation Technique for Modular Multilevel Converters [53]

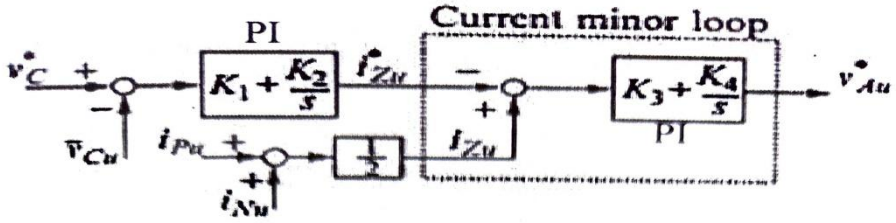
3.6 CAPACITOR VOLTAGE BALANCING TECHNIQUE:

Since each sub module is made up of a capacitor which unlike a fixed dc voltage source charges and discharges while the MMI is in use, thus the need
for balancing the capacitor voltages to ensure optimum performance. Different techniques of capacitor voltage balancing have been proposed by different researchers, some of which are

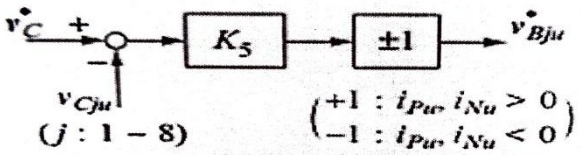
i. **Direct modulation** which is achieved in two ways (a) Capacitor Sorting and Selection (b) Sort and select with reduced switching counts. Phase-Shifted PWM
ii. Phase – Shifted PWM
iii. Modulation strategy
iv. Nearest level modulation
v. Numerical simulation etc.
vi. Floating capacitor voltage balancing scheme, which is made up of
1) averaging control; and
2) balancing control.

For this research, the phase-shifted PWM was used which gave a desired stepped voltage levels at the output as will be seen in the next chapter. But this technique wasn't efficient enough as there was variation in all the different sub module capacitor voltages.

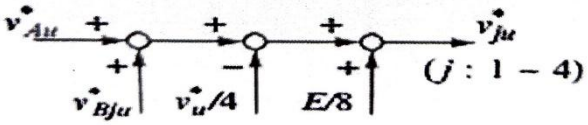
Thus, the averaging control; and balancing control was adopted. a balancing technique was developed from the conventional MMC mathematical model which gave an even distribution of the dc supply voltage, U_{dc}, across all the sub module capacitors.
Here, the arms (upper and lower) voltage and currents sensed for the three phases, controlled and used as the modulating the carrier signals. But tuning the PI is a bit challenging for this kind of complex systems and may not give a desired output if simulated for a long time interval. The MATLAB/Simulink model of this balancing scheme is shown in figure 3.7 and the mathematical models used to achieve the capacitor voltage balancing are represented as follows.



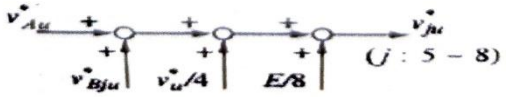
(a)



(b)



(c)



(d)

Figure 3.9: Overall control diagrams of DC-capacitor voltage control:
(a) averaging control, (b) balancing control and voltage command of each arm,
(c) upper arm, (d) lower arm [54, 55]

3.7. PRINCIPLE OF CAPACITOR VOLTAGE BALANCING AND CONTROL

The loops presented in figure 3.9 are used for the balancing and control.

For the averaging control:

From loop (a) $V^*c = \frac{E}{N}$ where: E = 4kV and N=4(number of sub modules for one arm). The average of all the sub modules voltages in one phase is then taken, donated by $\bar{V}cu$ then tuned with a PI control $K_1 + \frac{K_{42}}{s}$ it is then seen as i^*_{zu} which is then subtracted from $\frac{1}{2}(i_{pu} + i_{nu})$ and multiplied by $(K_3 + \frac{K_4}{s})$ to obtain V^*_{Au}.

From loop (b): the loop is realized by the equation below

$$(V^*c - \sum_{j=1}^{8} V_{cju}) * K_5 = V^*_{Bju}$$

Where $V^*_{Bju} = +1: i_{pu}, i_{nu} > 0$

$V^*_{Bju} = -1: i_{pu}, i_{nu} < 0$

NOTE: $\bar{V}cu = \frac{1}{8}\sum_{j=1}^{8} V_{cju}$

$V_{cju} = Capcitor\ Voltage\ for\ each\ SM$

For the voltage command of each arm:

V^*_{Bju} and V^*_{Au}. Are used to obtain loop (c) and (d) in figure 3.9.

The resultant equations are:

$$(V^*_{Au} + V^*_{Bju}) - \frac{V^*_u}{4} + \frac{E}{4} = V^*_{ju(j:1\sim4)}$$

$$\left(V_{Au}^{*} + V_{Bju}^{*}\right) + \frac{V_{u}^{*}}{4} + \frac{E}{4} = V_{ju(j:5\sim8)}^{*}$$

$V_{ju(j:5\sim8)}^{*}$ *is then compare with the triangular carrier signals switching the lower* arm and

$V_{ju(j:1\sim4)}^{*}$ *is then compared with the triangular carrier signals switching the upper arm*

Note: same principle is applied to balance the and control the three phases but V_u^* is what changes.

For phase A: $V_u^* = 0.5Esin2\pi ft$

For phase B : $V_u^* = 0.5Esin(2\pi ft - \frac{2}{3}\pi$

For phase C : $V_u^* = 0.5Esin(2\pi ft - \frac{4}{3}\pi$

4.0 RESULTS AND DISCUSSIONS

The Modular Multilevel Inverter presented in the previous chapter gave some results after the modeling, control, and simulation has been done. Thus, this chapter is focused on presenting the results from the previous chapter and discussing these results. The results discussed here are presented chronologically in like manner as the analysis was done in the previous chapter.

4.1. PHASE SHIFTED PULSE WIDTH MODULATION:

The four carrier voltages shifted by an angle difference of 90° and modulated by a modulating sinusoidal wave form are presented in figures 4.1a and 4.1b.

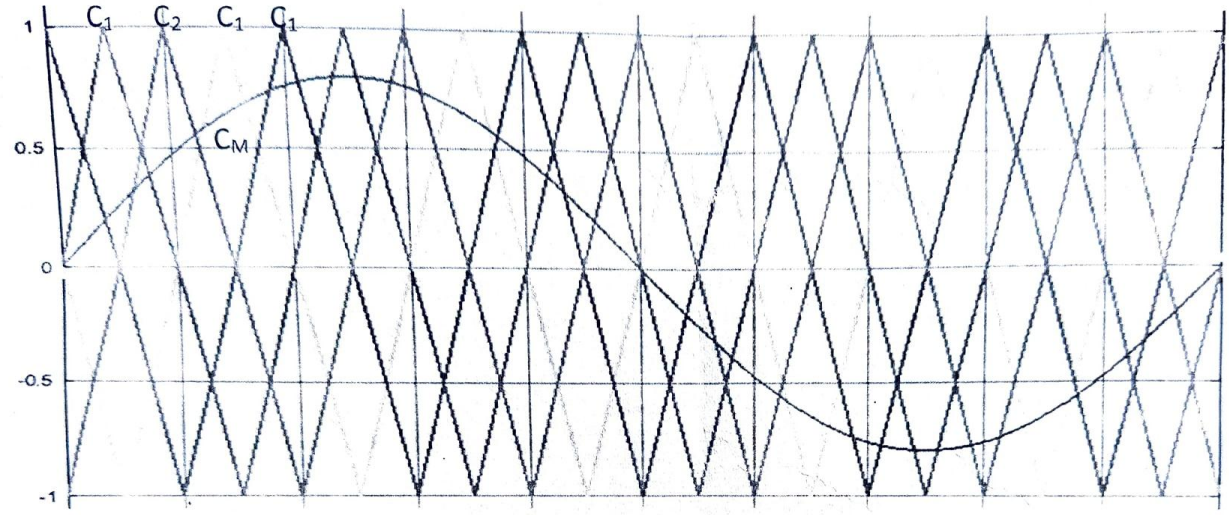


Figure 4.1a: Phase-Shifted PWM for the upper arm of one phase of MMI:
Where, C_1, C2, C3 and C_4 are the carrier signals and C_m, is the modulating carrier.

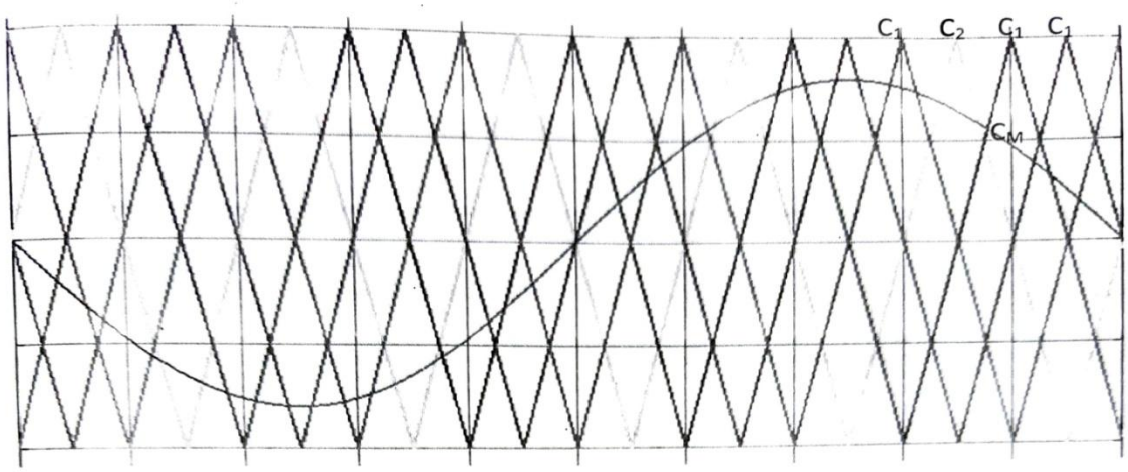


Figure 4.1: Phase-Shifted PWM for the lower arm of one phase of MMI:

After the modulation above, the modulated signals presented in figure 4.2 were obtained and used to control the switching pattern of the inverting circuit. The modulated signals controlling the major switches and the complementary switches are mirror image of each other

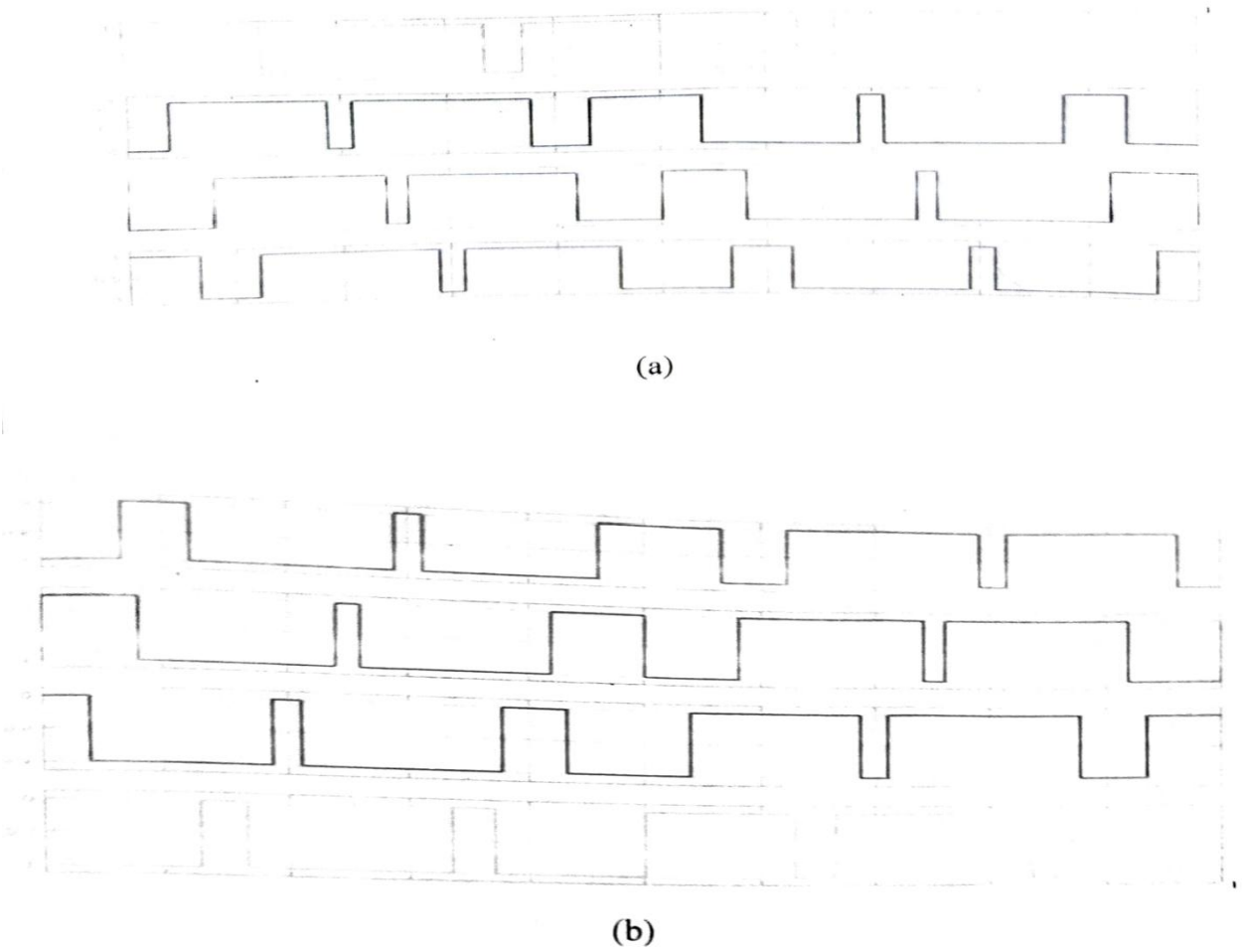


Figure 4.2; PWM modulated signals: (a) Modulated signals for upper arm of one phase (rational logic output) (b) Modulated signals for lower arm of one phase (rational logic output)

4.2 MMC SWITCHING TIME TABLE:

The modulated carrier signals are used to control the switching of the model shown in figure 3.5 for the three phase system. The switching is do following table 4.1 presented below

TABLE 4.1: SWITCHING TIME TABLE OF FIVE OUTPUT VOLTAGE LEVELS (MAIN SWITCHES)

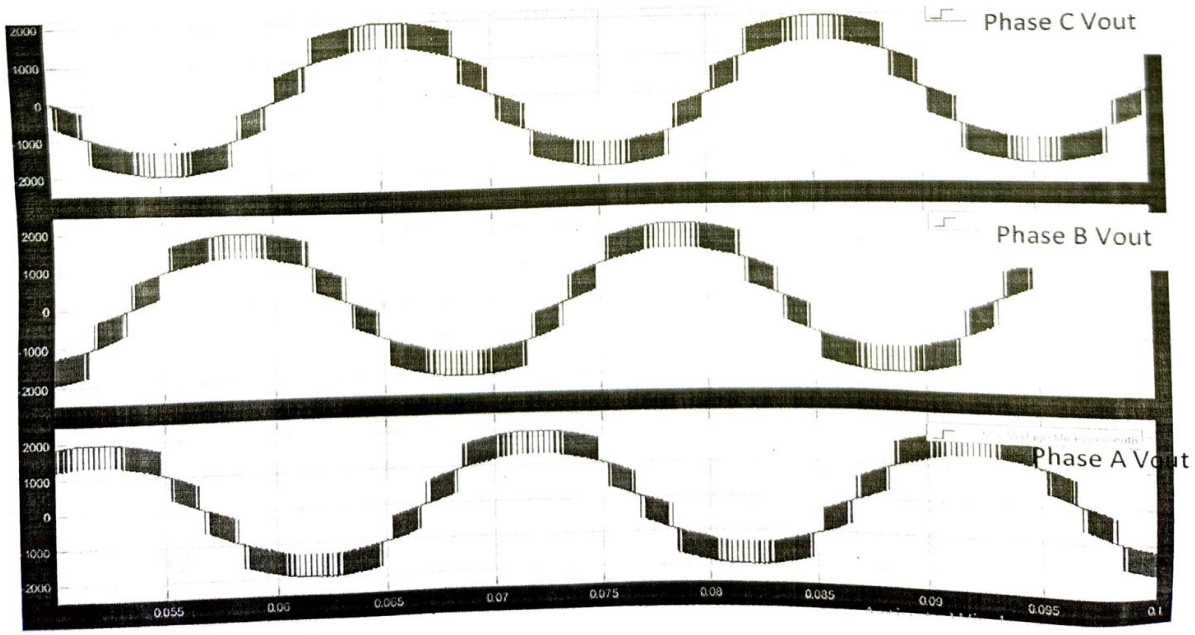
UPPER ARM				LOWER ARM				OUTPUT
S1	S2	S3	S4	S1	S2	S3	S4	
1	1	1	1	0	0	0	0	$\frac{V}{2}$
1	1	1	0	0	0	0	1	$\frac{V}{4}$
1	1	0	0	0	0	1	1	0
1	0	0	0	0	1	1	1	$-\frac{V}{4}$
0	0	0	0	1	1	1	1	$-\frac{V}{2}$

TABLE 4.2: SWITCHING TIME TABLE OF FIVE OUTPUT VOLTAGE LEVELS (COMPLEMENTARY SWITCHES)

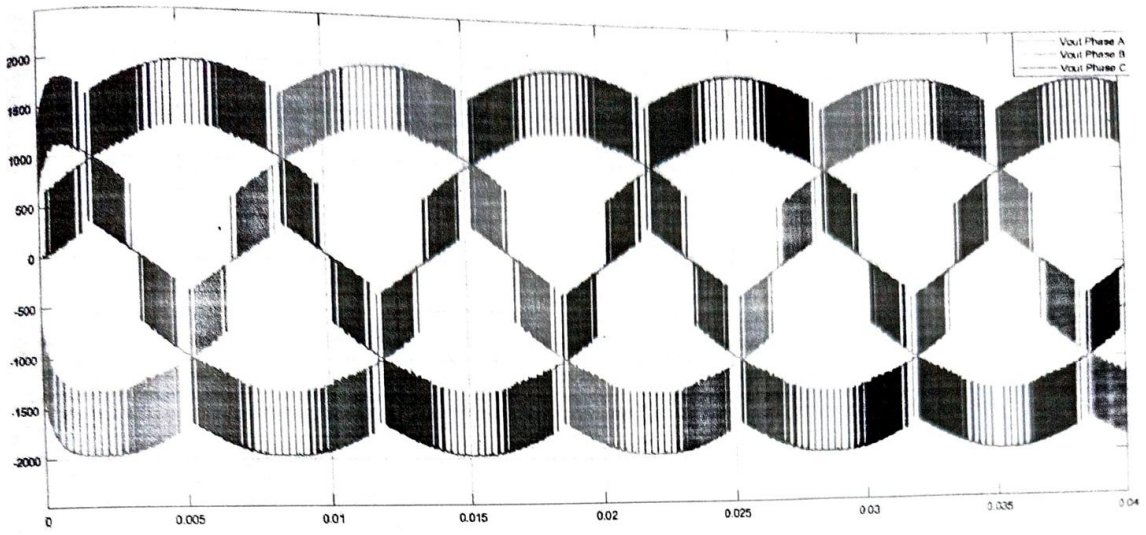
UPPER ARM				LOWER ARM				OUTPUT
S1	S2	S3	S4	S1	S2	S3	S4	
0	0	0	0	1	1	1	1	$\frac{V}{2}$
0	0	0	1	1	1	1	0	$\frac{V}{4}$
0	0	1	1	1	1	0	0	0
0	1	1	1	1	0	0	0	$-\frac{V}{4}$
1	1	1	1	0	0	0	0	$-\frac{V}{2}$

4.3 OUTPUT VOLTAGE WAVE FORMS:

The results of the phase voltages obtained from the scopes of the model in figure 3.5 are presented below.



(a)



(b)

Figure 4.3 (a) and (b) are the output voltages of the three phases.

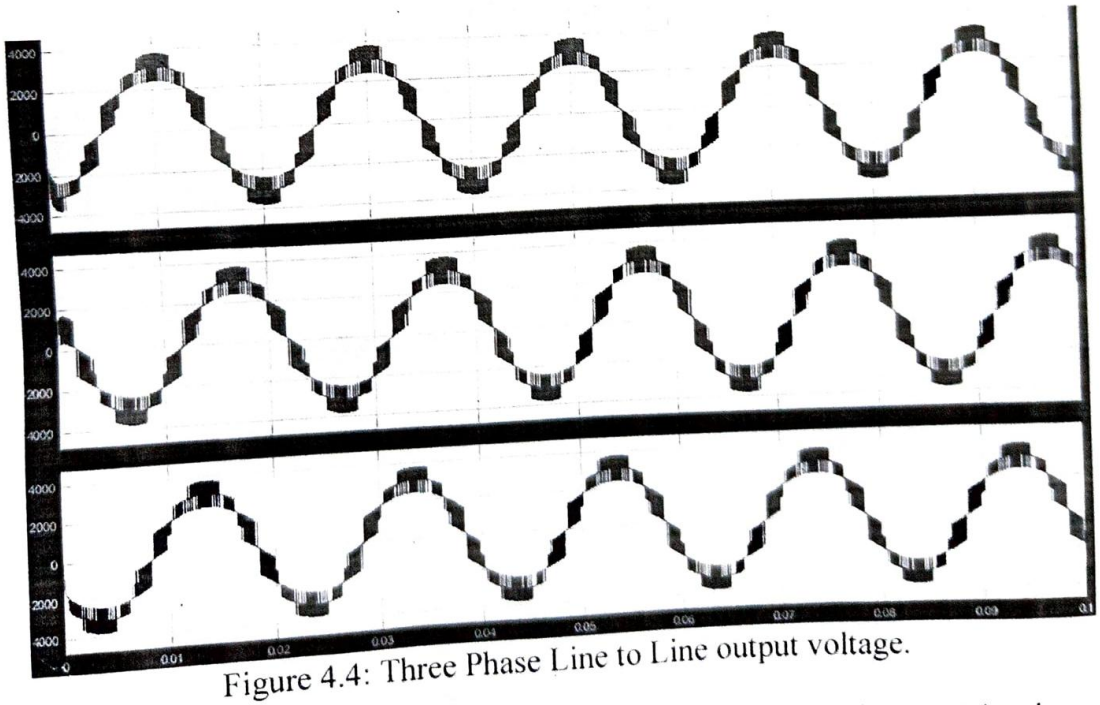


Figure 4.4: Three Phase Line to Line output voltage.

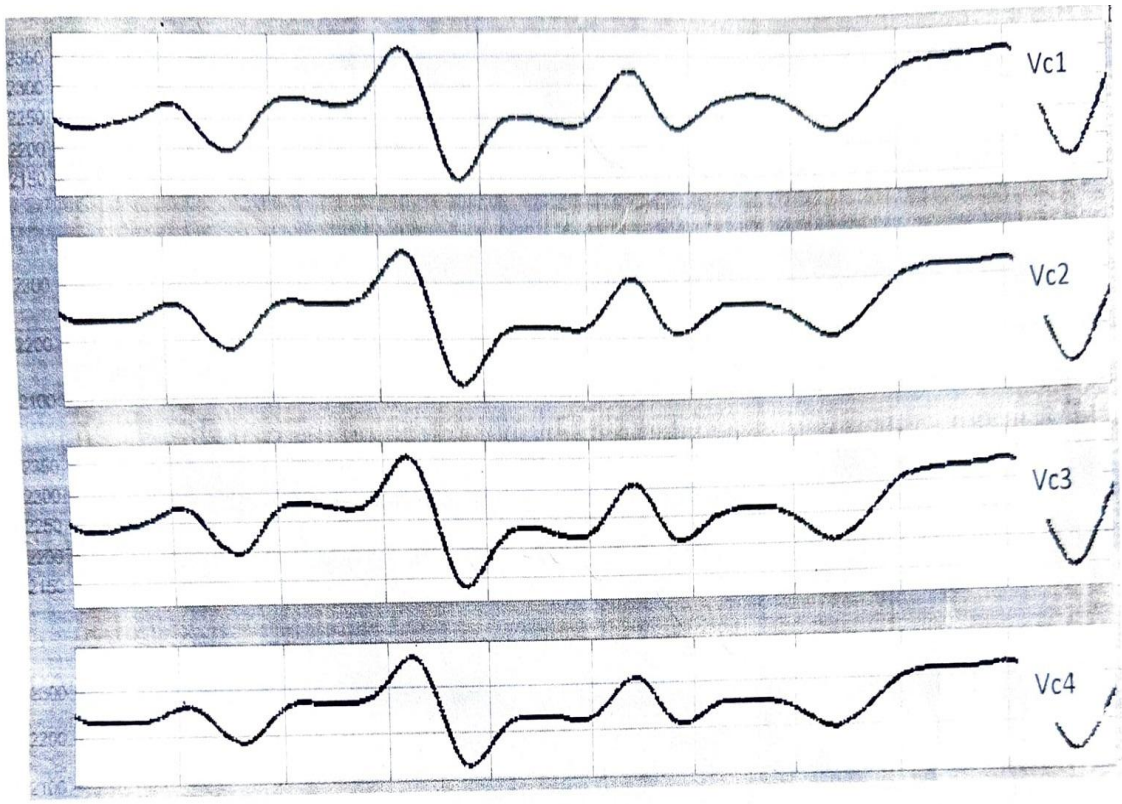
Figures 4.3 (a) and (b) are phase to neutral voltages and it produces a 5 level stepped output voltage.

From figure 4.4, there are 9 Stepped voltage levels at the output for the three phases: Phases A, B and C.

4.4 BALANCED CAPACITOR VOLTAGES:

The results presented in figures 4.3 and 4.4 were obtained only after balancing the capacitor voltages. The capacitor voltage balancing scheme adopted in figure 3.7 was used to achieved

the voltage balancing of the sub module cells. The parameters used for the control loops presented in figure 3.9 are presented in the tables 3.1 and 3.2. |



(b)

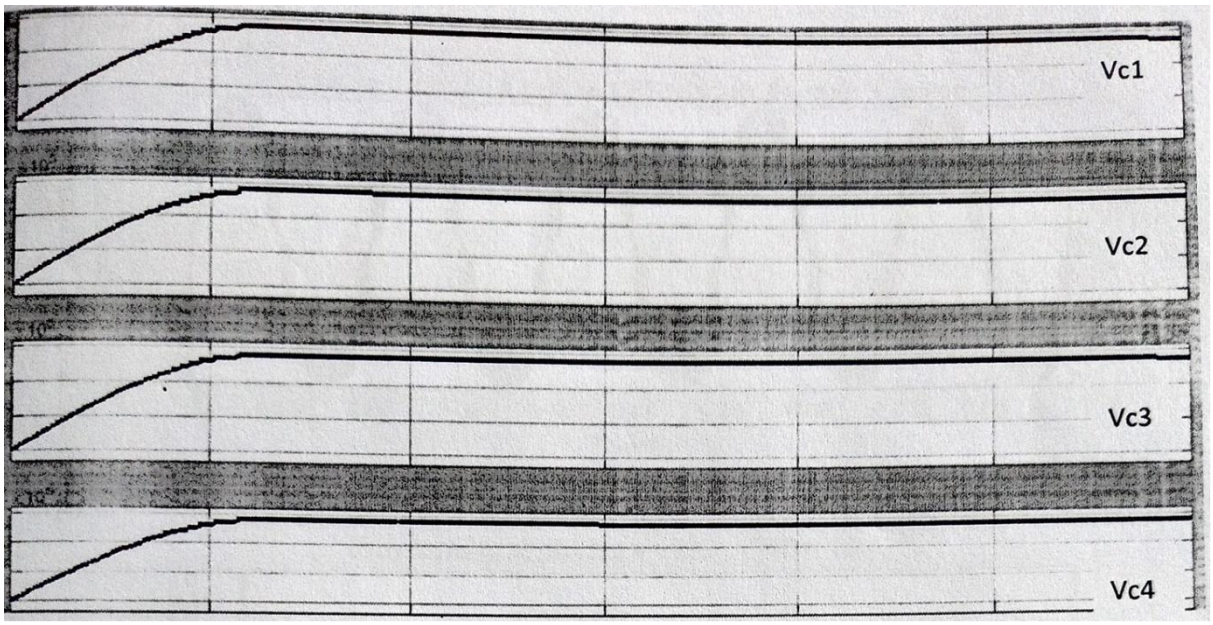


Figure 4.5: Capacitor voltages:
(a) Unbalanced capacitor voltage wave form of one arm of a single phase
(b) Balanced capacitor voltages of one arm of a single phase.

4.59 FAST FOURIER TRANSFORM - FFT:

The fft analysis carried out on the model for a fundamental frequency of 50Hz and a maximum switching frequency of 6kHz, the fft window showed 18.42% harmonics. Figure 4.6 is the matlab fft analysis result.

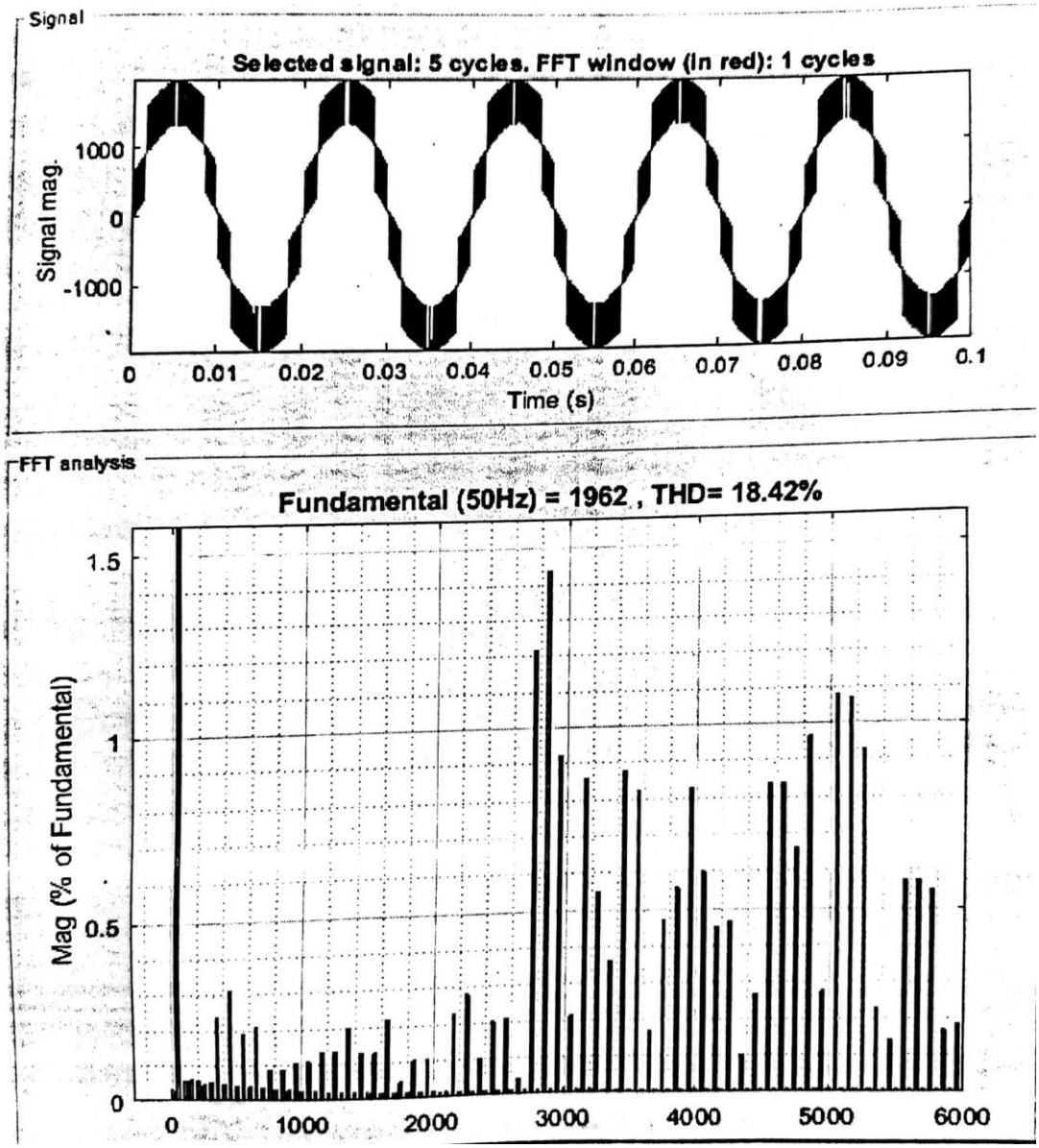


Figure 4.6: FFT –Analysis result

5.0 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION:

The MMI model presented above is a three phase ac output voltage system. Each of the phases are identical to the other, only that each phase is shifted 120° from the other. The model is made of a dc source of 4kv which serves as the supply to the entire system. Each of the phases is made up of 8 sub modules (Half bridge), 4 SM for the upper arm of the phase and 4 SM for the lower arm. Each of the sub modules comprises of two Insulated Gate Bipolar Transistor (IGBT), a capacitor and a feedback diode. The sub modules are all connected in series to each other for each of the arm and an inductor which helps to limit the current flowing through the arm.

The sub module switches are controlled by a phase shifted pulse width modulation scheme which determines the switching pattern of each sub module and thus the behavior of the model. Upon appropriate modulation, the resultant phase voltage at the output is a stepped 5 level ac voltage (that is N+1) and line to line voltage at the output is a steeped 9 level ac voltage (ie 2N+1) where N is the number of sub modules

per arm (N=4).

However, to obtain the results as analyzed in the previous chapter, there is need to size or balance the sub module capacitor voltages. This paper came up with a control strategy of averaging and voltage balancing control. This control strategy helps to track the rafed sub module capacitor voltage to make each of the sub module voltage approximately equal to the rated voltage.

The Modular Multilevel Inverter topology analyzed in this research paper is a complete steady-state model that can be used to predict the harmonic amplitude of each component in the MMC currents and voltages, and an accurate and completely analytical. The harmonic analysis carried out on the model through the Fast Fourier transform analysis shows a harmonic percentage of 18.46%.

The MMI model is switched at a very high frequency, implying that it can only be applicable or used on systems that operates with a very high frequency.

5.2 RECOMMENDATION

The introduction of the modular multilevel de-ac converters, has opened up a new avenue on research and development of medium/high voltage dc-ac converters. To take the full advantage of these converters for various applications, advanced modulation strategies that enable high-voltage conversion ratio, high efficiency and reduced component stresses are recommended. With a significant amount of MMC-derived converter topologies and applications, it is recommended that development of novel modulation and control strategies will be a major driving factor to. shape the future of MMC applications.

FUNDER

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