FLEXIBLE DISTRIBUTION NETWORKS USING DIRECT MMC WITH SIX BRANCHES

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Abstract—*This paper presents a complete analysis of a direct ac-to-ac modular multilevel converter (direct MMC) applied in medium-voltage distribution networks through the soft-open-point concept. The direct MMC is capable of bidirectional power flow between two feeders at any power factor, even when the feeders have different nominal voltages and operate with a phase-shift angle or unbalanced voltages. The converter has six branches, each one composed of full H-bridges cells connected in series to generate a multilevel voltage waveform, to share the blocking voltage of the power switches and to have fault-tolerant operation. This paper presents a suitable control scheme and provides a discussion about the capabilities and limitations of the converter, the capacitor voltage balance control, the efficiency, and the power-loss mitigation at various operation points. Simulation results and power-loss calculations are presented for a three-phase 11-kV 16-MVAdirectMMC with 10 H-bridge cells per branch. The direct MMC is simulated in a distribution network to demonstrate the features of the converter and control under various operation conditions, including grid faults.*

Keywords— AC-AC Power Converters; Direct Power Conversion; Grid-Connected Converters; Matrix Modular Multilevel Converters; Power-Flow Controller; Soft Open Point (SOPs)

1. INTRODUCTION

Because of their distinctive advantages, mainly due to their excellent harmonic performance at higher voltages, independent control of active and reactive power in transmission lines, voltage control in wind farms, high modularity in their construction, simple scalability, usage of low cost filters, robust control schemes, and wider applications in HVDC, MMC based Voltage Source Converters (VSCs) have become the cost effective and high power quality alternative for industry. This article presents the brief review on MMC. More than 120 articles are reviewed and classified in to six major categories. Among those, some of them are further categorized into several categories as shown in Fig.1.1.

(i) The first one is on different topologies proposed in this area since from its original schematics and their comparative study on technical considerations.

(ii) While the second one is on pulse width modulation (PWM) strategies applied to MMC. It is subcategorized in to seven areas depends up on their practical applicability and dominant contribution such as phase disposition(PD) PWM, phase opposition disposition(POD) PWM, alternate phase opposition disposition(APOD) PWM, carrier phase shifted(CPS) PWM, selective harmonic elimination(SHE) modulation, nearest level control(NLC) modulation and pulse dropping switching(PDS) scheme.

(iii) The third category deals with associated voltage balancing issues and their schemes to resolve.

(iv) Fourth category deals with circulating current control (CCC) schemes.

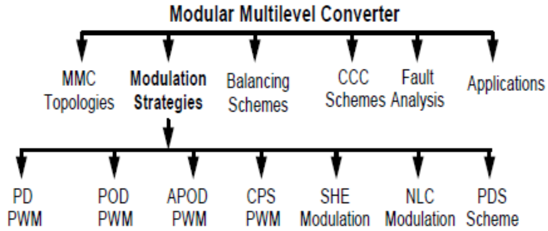


Fig.1.1 Categorization of Modular Multi Level Converters

(v) The fifth category deals with fault management system and last is on its applications.

2. POWER SYSTEM STABILITY

In this chapter, different topologies of MMC are reviewed. Fig.2.1 shows the basic schematic of three phase MMC. A three phase MMC consists of three legs which consists of two arms: upper arm and lower arm. Each arm consists of N number of series connected sub modules(SM) and an arm inductance. The sub modules are the building blocks of MMC. Each sub module can be realized by different circuits as shown in fig.2.2.

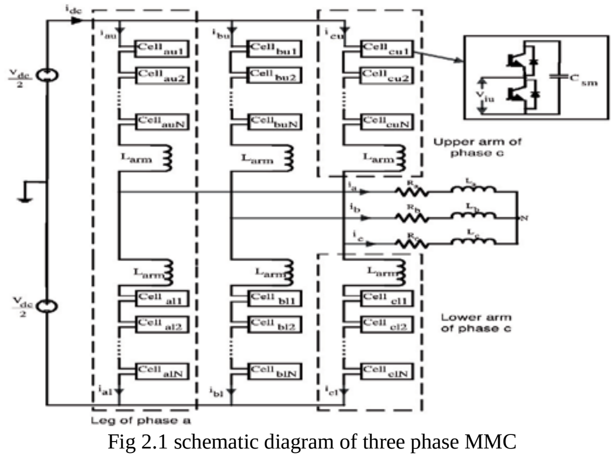


Fig 2.1 schematic diagram of three phase MMC

2.1 Half Bridge Sub Module

As shown in Fig. 2.2 (a), this configuration has simple structure and low losses compared to all other topologies. The output voltage is either equal to capacitor voltage or zero. This configuration can provide only uni-polar output voltage.

2.2 Full Bridge Sub Module

As shown in Fig. 2.2 (b) by connecting two half bridge circuits in parallel, a full bridge circuit is formed. It can provide bipolar output voltage. However, as the number of switching devices is doubled as compared to half bridge, the power loss as well as the cost is also doubled.

2.3 Clamped Double Sub Module

As shown in Fig. 2.2(c) it consists of two half bridge SM's, two additional diodes and an IGBT. It can also provide bipolar output voltage. During normal operation, the IGBT (switch 5) is always ON and the circuit appears like two half bridge SM's connected in series. The losses for this circuit are more than that of half bridge and less than that of full bridge circuit.

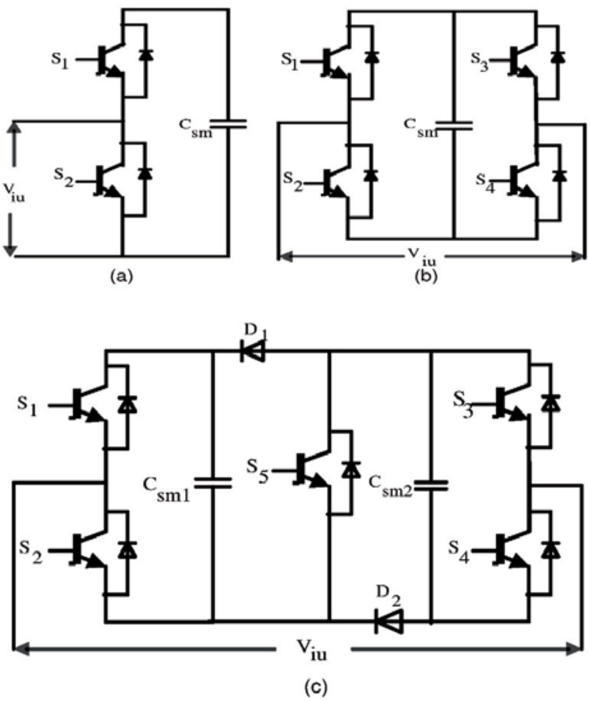
2.4 Three Level Flying Capacitor Sub Module

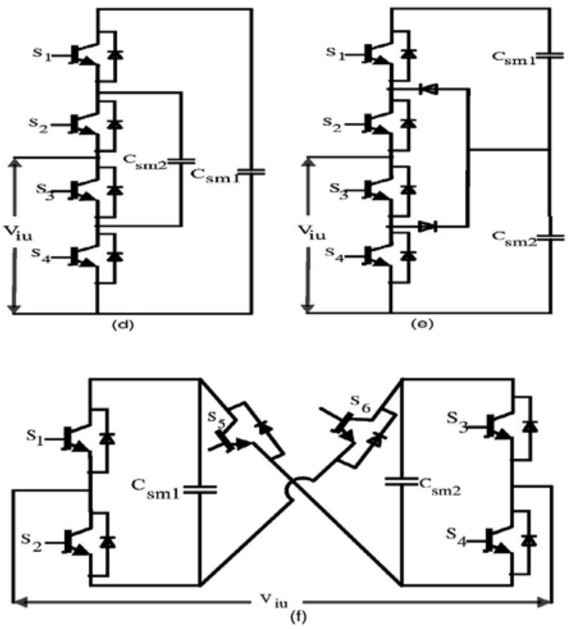
The three level flying capacitor SM is shown in Fig. 2.2(d). It provides only unipolar output voltage. The intermediate capacitor voltages must be balanced. Losses are similar to that of half bridge circuit. This topology is not an attractive one due to its control complexity.

2.5 Three Level Neutral Point Clamped Sub Module

The three level neutral clamped circuit is shown in Fig. 2.2(e). It can provide only unipolar output voltage. Losses are intermediate between half bridge circuit and full bridge circuit.

2.6 Five level cross connected sub module





As shown in fig.2.2(f) it is formed by connecting two half bridge SMs back to back by two IGBTs. It can provide bipolar output voltage. By cross connecting configuration, more number of voltage levels is possible. The losses are intermediate between half bridge and full bridge circuits. Fig2.2 various sub modules (a) half bridge (b) full bridge (c) clamped double (d) three level flying capacitor (e) three level neutral point clamped (f) five level cross connected.

3. PHASE-LOCKED LOOP (PLL) DYNAMICS

Two synchronized three-stage frameworks (abc and ABC) associated through power converters that control the power stream between the two frameworks. These frameworks speak to feeders of the dispersion arrange, so they have a similar recurrence and ordinarily a similar ostensible voltage and stage. Nonetheless, in dissemination arrange it is regular that feeders show unbalance voltages and in some particular cases a stage move on the off chance that they are associated with various transformer designs (feeders from various substations).

A. Topology

The converter appeared in Fig. 3.1(a) is a B2B-MMC with half H-spans and the converter in Fig. 3.1(b) is a direct MMC with full H-spans and just six arms. The two converters are fit for disengaging current faults in any feeder and have accuse tolerant operation on account of the isolation. The direct MMC has no dc-interface and has a comparative number of semiconductors yet a substantial part of the amount of capacitors and inductors than the B2B-MMC. Nonetheless, a more comprehensive investigation of the two topologies must be made to analyze the control adaptability, voltage blocking and current expected of every semiconductor, capacitor and inductor sizes, and power misfortunes. It is compulsory to ensure an AC voltage on each arm constantly to acquire a steady operation of the direct MMC working at synchronous operation (50 Hz).

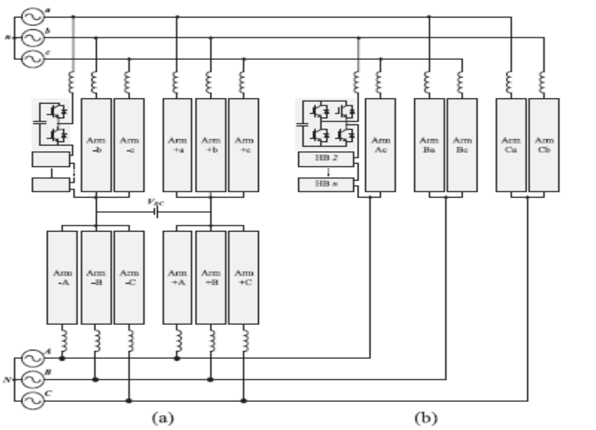


Fig. 3.1. Modular multilevel converters as soft-open-point. (a) Back-to-Back MMC. (b) Direct MMC (Hex-converter).

For instance, Fig. 3.1(b) shows converter arms connecting phase A of the bottom feeder to phases b and c of top feeder. The ac-to-ac topology of the direct MMC converter infers that the streams between the two feeders are not free, as appeared in Fig. 3.2. This involve a coupled responsive power between the two feeders, which implies the converter infuse or expend the very same measure of receptive power in the two feeders. Additionally, the coupled streams convey restrictions if the feeders have uneven voltages, in light of the fact that the converter can give unbalance remuneration just to one feeder at any given moment, ignoring the unbalance pay for the other one.

B. Basic Operation

The direct MMC operation is based on a current controller per each arm to obtain the line reference current, and Fig. 2. The arm currents iAb and iAc operate in concert to generate i*A with the restriction to be at 90◦ from the respective voltages vAb and vAc. Therefore, only their magnitudes change according to the reference line current i*A.

Where, I*A = iAb + iAc

The thought is to work each arm as a responsive current generator to accomplish vitality adjusts of the capacitors. At that point, any reference line current can be gotten from the vector whole of the two responsive streams. In any case, a little dynamic current must be acquainted with modify the vitality adjust blunder of the capacitors. Along these lines, a PI controller is acquainted on each arm with infuse dynamic current if the capacitors are cheated or to expend dynamic current if the capacitors are undercharged.

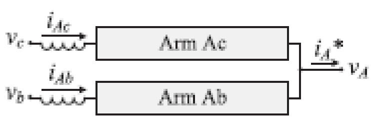


Fig. 3.2. the currents and voltages of arm Ab and Ac under different operation case scenarios.

This PI controller deals with the aggregate vitality of the capacitors on an arm, so it is important to add a moment adjust control to deal with the vitality of every capacitor of an arm, which is done on the regulation through a corresponding controller.

C. Power Rating of the Converter

The voltage of each arm is equivalent to the voltage between the lines of the two feeders as appeared in Fig. 3.2. Consequently, the arm voltage relies upon the ostensible voltage of every feeder, the stage move amongst them and the interconnection picked among the lines. The voltage of each arm can be ascertained utilizing trigonometry and it will be distinctive for each arm if the feeders have a stage move as delineated in Fig. Anyway, the most dire outcome imaginable is the point at which the stage move is Δθ =60◦ in light of the fact that one arm squares double the line-to-ground voltage of the feeder while the other arm just pieces half (e.g., 18 kV pinnacle and 9 kV top for feeders of 11 kV). Thusly, this most extreme blocking voltage is like the B2B-MMC yet just in half of the arms. Then again, the direct MMC needs to square less voltage than the B2B-MMC if the feeders have diverse voltages on the grounds that the B2B dc-interface voltage must be evaluated for the feeder with higher voltage. The current of the IGBTs is equivalent to the arm current and can be computed. This current depends on the nominal voltage of each feeder and can be different for each arm according to the phase shift between feeders and the power factor of operation, ranging from 0.0 pu to 1.15 pu of the feeder line current.

D. CONTROL OF THE DIRECT MMC

Fig. 3.3 illustrates the control block diagram for the leg A of the converter (arm Ab and Ac). The first step is to calculate the positive sequence angles and voltages of both systems through an enhanced phase-locked loop (EPPL) system. The angle of the system abc (θv) is used as reference for the entire control, and the angle of system ABC (θV) is required to calculate the phase shiftΔθ between the two systems.

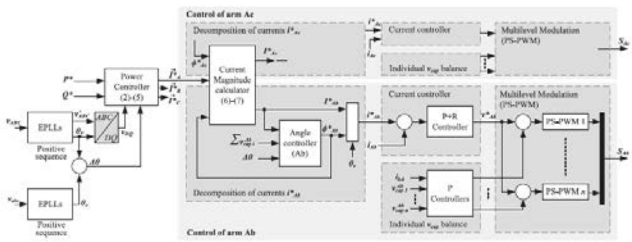


Fig. 3.3. Control Block diagram of leg A of the direct MMC.

Fig. 4.4 shows the angle controller of arm Ab. The bottom block is a feed-forward control which calculates the theoretical reference angle φAb using (8) and (9) to ensure the current _I*Ab operates at 90◦ respect to the arm voltage _VAb, so the phase-shift angle between the two systems Δθ and their nominal voltages Vabc and VABC are taken into account.

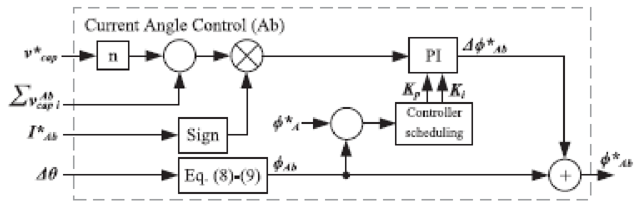


Fig. 3.4. Controller block of the current angle φ*Ab

The PI controller utilizes online pick up planning to enhance the execution and control soundness at various purposes of operation. The additions change as per the rate commitment of the arm to the reference current of the line. The commitment of the two arms in a single leg is correlative and it is a component of the present point φ.

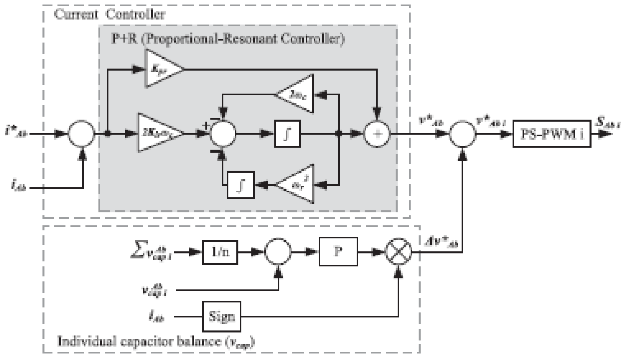


Fig. 3.5. Proportional-Resonant current controller, individual capacitor voltage balance controller and multilevel modulation for cell i.

4. SIMULATION RESULTS

A simulation model of the direct MMC with the proposed control has been realised in Matlab/Simulink using the Sim-Power System toolbox to validate the control performance and to calculate the power losses at various operation points and conditions.

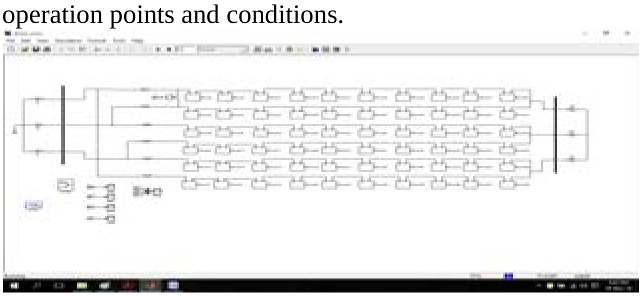


Fig:4.1- Simulation diagram of the direct MMC under ideal conditions.

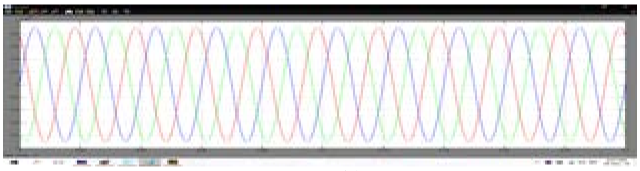


Fig:4.2(a)

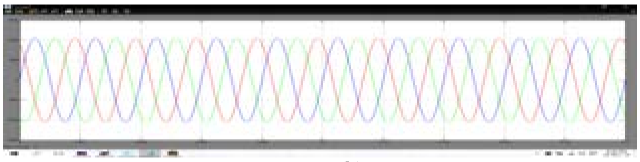


Fig:4.2(b)

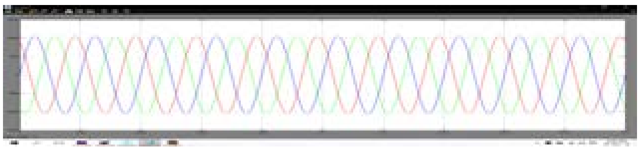


Fig:4.2(c)

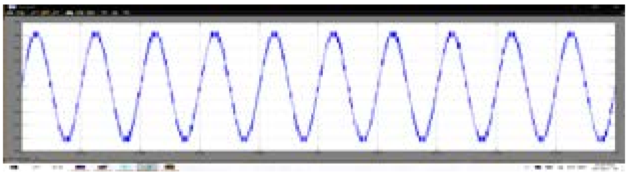


Fig:4.2(d)

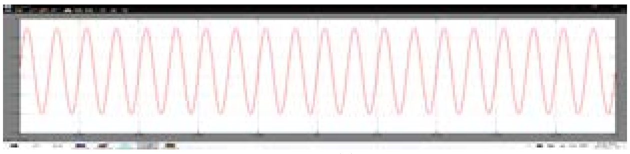


Fig:4.2(e)

Fig:4.2- Simulation of the direct MMC under ideal conditions. (a) voltages of feeder abc, (b) currents of feeder abc, (c) currents of feeder ABC, (d) voltage of arm Ac, (e) capacitor voltages of arm Ac.

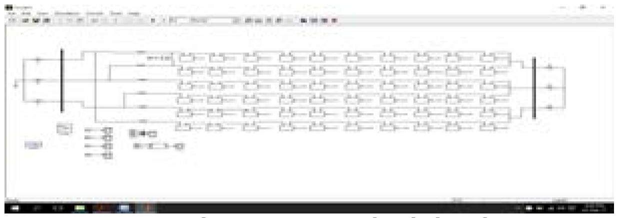


Fig:4.3- Simulation in arm Ac under ideal conditions

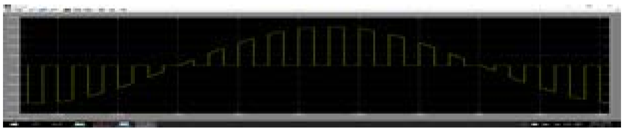


Fig:4.4(a)

Fig:4.4(b)

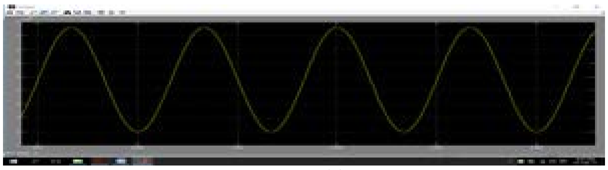


Fig:4.4(c)

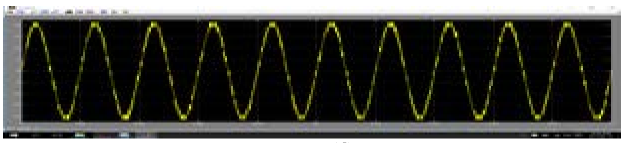


Fig:4.4(d)

Fig:4.4(e)

Fig:4.4- Simulation in arm Ac under ideal conditions. (a) voltage of first cell in arm Ac, (b) current of capacitor in first cell of arm Ac, (c) conduction losses of arm Ac, (d) voltage of arm Ac, (e) capacitor voltages of arm Ac.

The control guideline of the converter lessens the conduction misfortunes on the grounds that the current and the voltage of each arm are dependably at 90◦, as appeared in Fig. 5.2 and 5.4. Under this conditions, the majority of the IGBTs lead when the authority current is low and just a single IGBT per cell conducts when the gatherer current contact me greatest esteem, so the greater part of the current is conveyed by the diodes. Fig. 5.4 delineates the conduction control misfortunes in a single arm, which achieves the greatest esteem when the cells are at zero voltage.

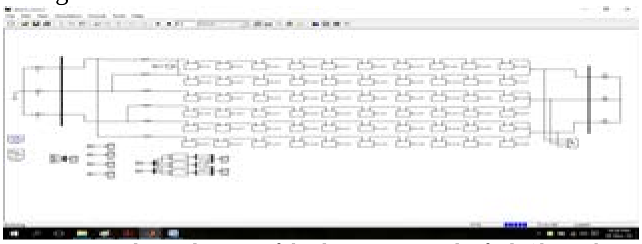


Fig: 4.5- Simulation diagram of the direct MMC under fault (three-phase short circuit).

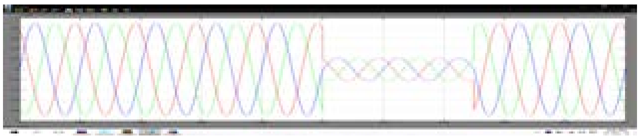


Fig:4.6(a)

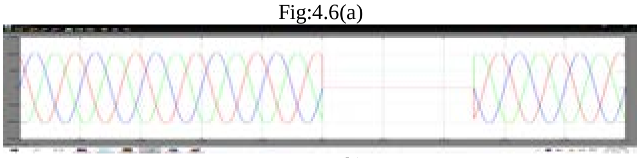


Fig:4.6(b)

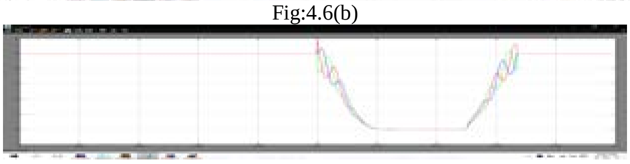


Fig:4.6(c)

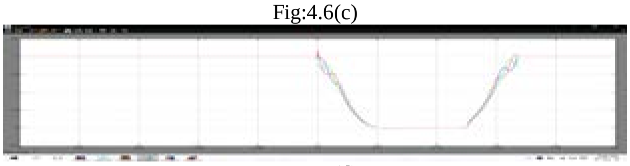


Fig:4.6(d)

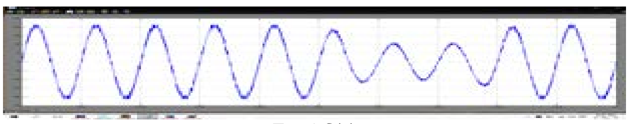


Fig:4.6(e)

Fig:4.6- Simulation of the direct MMC under fault (three-phase short circuit). (a) voltages of feeder ABC, (b) currents of feeder ABC, (c) active power of feeder ABC, (d) reactive power of feeder ABC, (e) voltage of arm Ac.

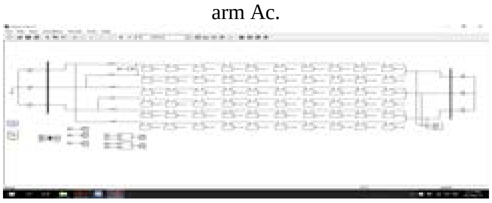


Fig:4.7- Simulation diagram results under dynamic operation.

Fig:4.8(a)

Fig:4.8(b)

Fig:4.8(c)

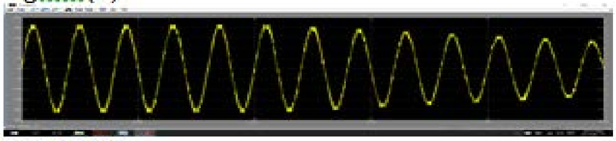


Fig:4.8(d)

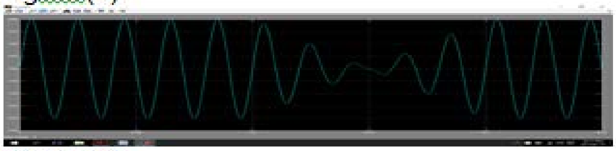


Fig:4.8(e)

Fig:4.8- Simulation results under dynamic operation. (a) active and reactive power of feeder abc, (b) active and reactive power of feeder ABC, (c) currents of feeder ABC, (d) voltage of arm Ac, (e) capacitor voltages of arm Ac.

The direct MMC was reenacted with a dynamic power operation, which comprises of an inversion of control over a time of 0.1 seconds while keeping a main PF = 0.87. Fig. 5.8 demonstrates the reenactments accepting adjusted voltages and no stage move. The dynamic and responsive power are controlled with high exactness consistently. Note that the responsive power is coupled between the two feeders because of the air conditioner to-air conditioning topology and control attributes, which imply that the two sides of the converter produce or expend the very same measure of receptive power.

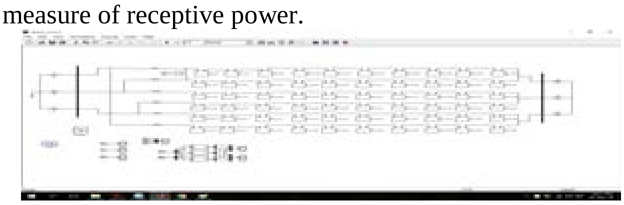


Fig:4.9- Simulation diagram results under worst conditions.

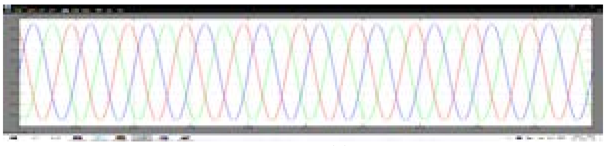


Fig:4.10(a)

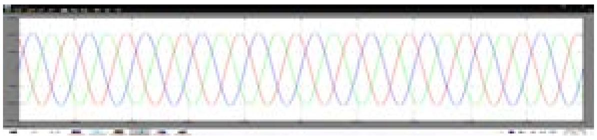


Fig:4.10(b)

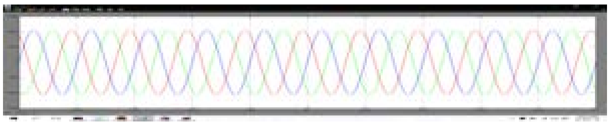


Fig:4.10(c)

Fig:4.10(d)

Fig:4.10(e)

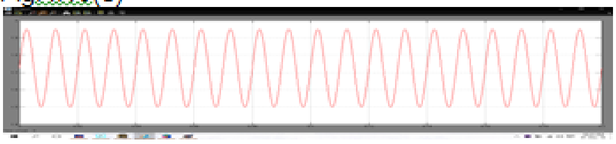


Fig:4.10(f)

Fig:4.10- Simulation results under worst conditions. (a) voltages of feeders abc, (b) currents of feeder abc, (c) currents of feeder ABC, (d) active power of feeder ABC, (e) reactive power of feeder ABC, (f) capacitor voltages of arm Ac.

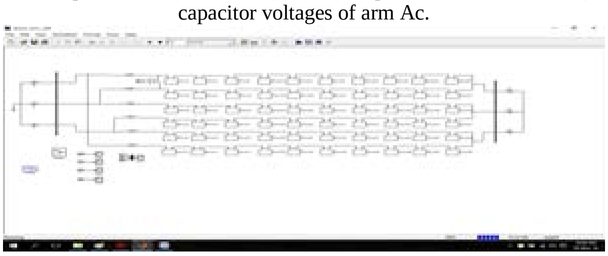


Fig:4.11- Simulation results with systems with different nominal voltages

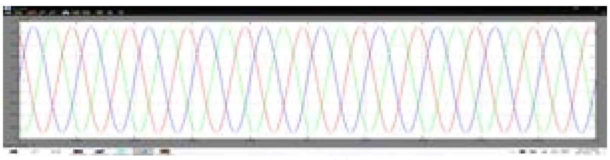


Fig:4.12(a)

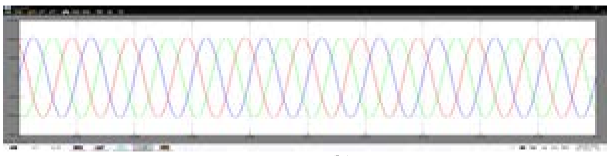


Fig:4.12(b)

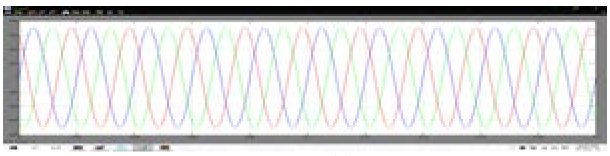


Fig:4.12(c)

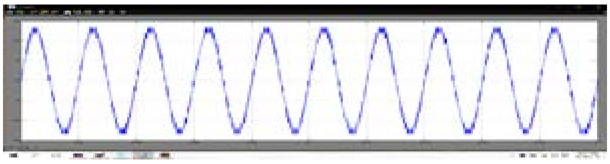


Fig:4.12(d)

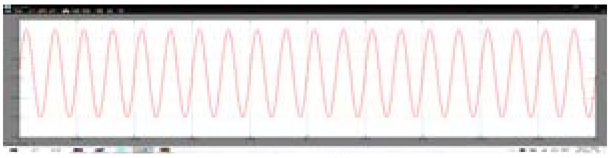


Fig:4.12(e)

Fig:4.12- Simulation results with systems with different nominal voltages. (a) voltages of feeder abc, (b) currents of feeder abc, (c) currents of feeder ABC, (d) voltage arm of Ac, (e) capacitor voltages of arm Ac.

5. CONCLUSION

The direct MMC is an ac-to-ac convertor that mixes a number of the characteristics of the MMC and therefore the matrix converters. The direct MMC uses full H-bridges connected asynchronous, which implies it generates a lot of levels than the half-bridge MMC. Like alternative MMCs, it's extremely standard and ascendable to any power or voltage. It uses identical variety of semiconductors because the consecutive MMC, however it needs the half variety of capacitors and coupling inductors as a result of solely six arms square measure necessary. The smaller variety of modules, module capacitors and section inductors might provide the direct MMC a volume advantage over the B2B-MMC that is vital in retrofitting to substations. However, the direct MMC has no dc-link and therefore the currents within the 2 feeders aren't freelance.

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