Comparative Study of Multicarrier PWM Techniques for Different Levels of Modular Multilevel Inverter

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***Abstract*— This paper mainly presents the simulation results of three phase five-level and nine-level modular multilevel inverter based on double-star chopper-cell (DSCC) having half bridge connection on each sub-module. There are mainly four Multicarrier PWM techniques. They are Phase disposition PWM (PDPWM), Phase opposition disposition PWM (PODPWM), Alternate phase opposition disposition PWM (APODPWM) and Phase shift PWM (PSPWM). All these four techniques are simulated and a cumulative comparison has done for the obtained load voltage and load current waveforms. The simulation has been carried for various modulation indices using MATLAB/Simulink.**

***Keywords*— Modular Multilevel Converter (MMC), Multicarrier PWM, FFT Analysis, Total Harmonic Distortion (THD).**

I. Introduction

Now-a-days, High Voltage Direct Current (HVDC) transmission systems are getting more preferred over High Voltage Alternate (HVAC) Transmission systems as HVDC transmission system is widely used in underground sea cables, bulk power transmission, lower transmission losses because of no reactive power loss, power transmission between asynchronous AC systems, less conductor requirement for the same power transfer, requires lesser insulation for the conductor as the DC voltage is only 71% of the AC (rms) voltage, easy, fast and accurate power flow control, effective short circuit limitation and the HVDC systems maintain more stability than the HVAC systems. It has comparatively low corona losses. Hence, multilevel inverters are developing its topologies to get better voltage stability and low harmonic distortion. Rainer Marquardt invented the Modular Multilevel Converter (MMC) as a development from the Cascaded H-Bridge Converter (CHBC) in 2003. Now, it is currently a subject of intense research because of its wide range of applications in HVDC transmission, Electric Traction (ET) systems, Flexible Alternating Current Transmission Systems (FACTS) and high power motor drives due to its high modularity, high reliability and better fault management [1].

II. STRUCTURE AND CHARCACTERISTICS OF MMC

Based on the literature available till data, MMC has been divided into five types. They are Single Star Bridge Cells (SSBC), Single Delta Bridge Cells (SDBC), Double Star Chopper Cells (DSCC), Double Star Bridge Cells (DSBC) and Double Star Hexagonal Cells (DSHC)[2][3]. The double star configured MMC topologies possess the common DC-link terminals, which enables dc to ac and ac to dc power conversion. However, the remaining topologies have no common DC-link terminals. So that, they have no capability of achieving power conversion although they can control active power flow in both the directions between the three-phase ac terminals and the floating dc capacitors. Hence, the star/delta-configured MMC topologies are not applicable to industrial motor drives, but they are suitable for STATCOMs and energy storage systems. Therefore, comparatively Double star configurations are superior with the other and DSCC is superior in all existence topologies [8], as it consists of less no. of switches and thereby reduces the switching losses and increases the converter efficiency [4].

The general circuit of single phase and three phase equivalent circuit of five-level MMC with DSCC configuration are shown in the fig. 1(a) and 1(c) [7]. The converter circuit has one leg per phase and each leg has two arms namely, upper and lower arms, with each arm having N sub-modules(SM) with a coupling arm inductor to get ‘n’ voltage levels (n = 2N+1). The sub-module consists of two IGBTs which connected in parallel with the diodes connected in series and a capacitor is connected across them. The structure for half-bridge SM is shown in the fig. 1(b). Due to the presence of the coupling inductors, it acts a passive filter [9] [10], so the output wave smoothens by adjusting the value for coupling inductor per arm. It also limits the circulating currents.

The output voltage of each SM is equal to zero if the main switch (S_m) is On and the auxiliary switch (S_c) is Off or is equal to the SM’s capacitor voltage (V_c) if Sm is Off and S_c is On. Each SM has two distinct states in normal operation. The first state is when the capacitor is On (S_c is On and S_m is Off). Depending on the capacitor charge, current either flows into the capacitor through the freewheel diode of S_c or flows out of the capacitor through S_c. The second state is when the capacitor is in the off mode (S_c is Off and S_m is On). Depending on the polarity at the SM terminals, current either flows through S_m or it’s freewheel diode. By properly switching between these two states, proper voltage can be maintained for each SM. Therefore, the total DC side is the sum of all capacitors voltages in one leg. In this topology, the high number of levels reduces the average switching frequency without compromising of power quality. This topology has found practical applications with up to 200 SMs per phase and up to 400 MW.

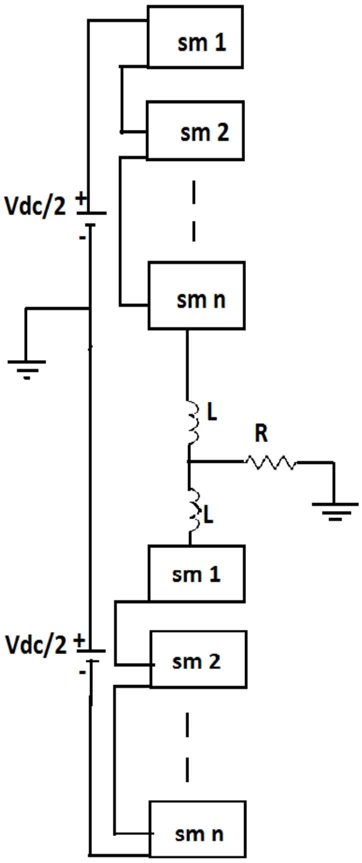

Fig. 1(a): general circuit of single-phase MMC

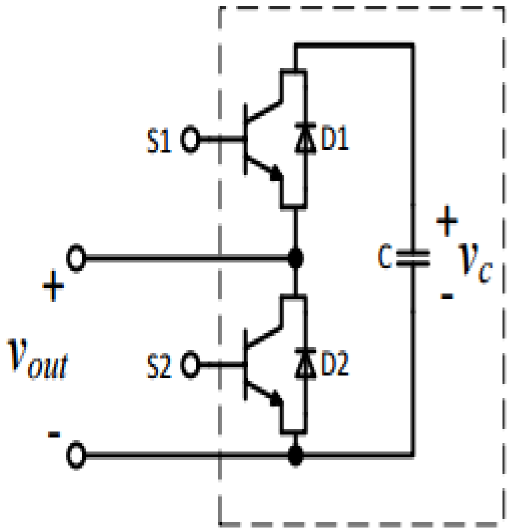

Fig. 1(b): half-bridge sub-module of MMC

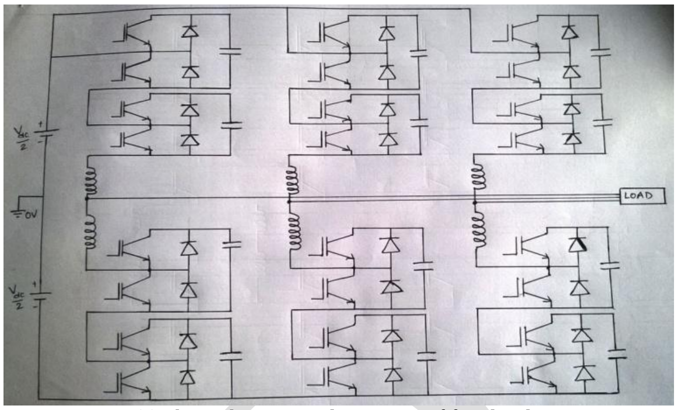

Fig. 1(c): three-phase equivalent circuit of five-level MMC

III. MULTI-CARRIER PWM TECHNIQUES FOR MODULAR MULTILEVEL CONVERTER

Multi-Carrier PWM strategies is widely used because it can be easily implemented to low voltage modules. MCPWM be classified as level shifted PWM and Phase shifted PWM (PS-PWM) techniques. The level shifted PWM (LS-PWM) are Phase Disposition (PD), Phase Opposition Disposition (POD) and Alternative Phase Opposition Disposition (APOD) [11] [12].

The gate pulses are generated by utilizing the simplicity of multi carrier sine PWM. In this technique sine wave is taken as reference wave of amplitude Ar and frequency fr and it is continuously compared with triangular carrier wave of amplitude Ac and frequency fc. If sine wave is greater than triangular wave, the IGBTs is turned on otherwise off. For N level N-1 carrier wave with same frequency fc and same amplitude Ac are disposed such that the bands they occupy are contiguous. The reference waveform has peak-to-peak amplitude Ar, the frequency fr and it is zero centred in the middle of the carrier set. The reference is continuously compared with each of the carrier signals. If the reference is greater than a carrier signal, then the device corresponding to that carrier is switched on otherwise off [5] [6].

The amplitude modulation index (m_a) for the level shifted PWM technique is defined as the ratio of the amplitude of the reference sine wave (A_r) to the amplitude of the carrier wave (A_c).

$$m_a = A_r/A_c$$

Similarly the frequency modulation index (m_f) is defined as the ratio of frequency of the carrier wave (f_c) to the frequency of the reference sine wave (f_r).

$$m_a = f_c/ f_r$$

A. Phase Disposition PWM (PD PWM)

In phase disposition method all the carriers have the same frequency and amplitude. Moreover all the N-1 carriers are in phase with each other. It is based on a comparison of a sinusoidal reference waveform with vertically shifted carrier waveform as shown in Fig. 2(a). This method uses N – 1 carrier signals to generate N level inverter output voltage. All the carrier signals have the same amplitude, same frequency and are in phase. In this method, four triangular carrier waves have compared with the one sinusoidal reference wave. The PD PWM is widely used for MMC as it offers lower THD [13].

Issue 5, Vol. 4 (June.-July. 2015)
ISSN 2249-6149

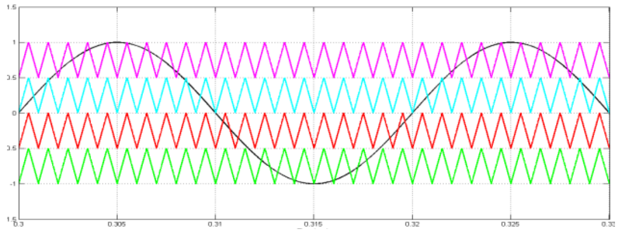

Fig. 2(a): PD PWM technique (mi-1.0)

B. Phase Opposition Disposition PWM (POD PWM)

In phase opposition disposition method all the upper carriers and the lower carriers have the same frequency and amplitude but the upper and lower carriers are in 180 degrees phase shifted. It is based on a comparison of a sinusoidal reference waveform with vertically shifted carrier waveform as shown in Fig. 2(b).

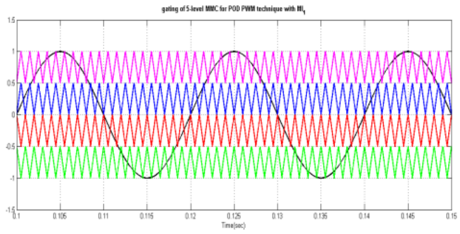

Fig. 2(b): POD PWM technique (mi-1.0)

C. Alternate Phase Opposition Disposition PWM (APOD PWM)

In phase opposition disposition method all the carriers have the same frequency and amplitude and all the carriers are in 90 degrees phase shifted with each other. It is based on a comparison of a sinusoidal reference waveform with vertically shifted carrier waveform as shown in Fig. 2(c).

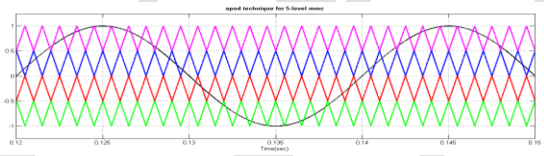

Fig. 2(c): APOD PWM technique (mi-1.0)

D. Phase Shift PWM (PS PWM)

It uses four carrier signals of the same amplitude and frequency which are shifted by 90 degrees to one another as shown in fig. 2(d).

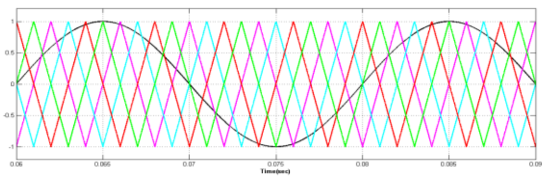

Fig. 2(d): PS PWM technique (mi-1.0)

IV. SIMULATION RESULTS

A three phase five-level and nine-level MMC-DSCC is simulated using MATLAB/Simulink and its performance is studied for RL load.

TABLE I
SIMULATION PARAMETERS

Parameters	**Values**	
	5-level	**9-level**
DC voltage	200	200
No. of sub-modules in each arm	2	4
Sub-module capacitor C	2.2mF	4.4mF
Sub-module capacitor voltage	50 V	25 V
Arm inductor L	3.6mH	5mH
Arm equivalent resistance	1.0Ω	1.0Ω
Amplitude modulation index	0.9	0.9
Frequency modulation index	20	20
Carrier frequency	1000 Hz	1000 Hz
Power frequency	50 Hz	50 Hz
Load	Ω, H	Ω, H

The output phase voltage and currents of three-phase five-level and nine-level MMC employing PD PWM is shown in fig. 3(a), 3(b), 3(c) & 3(d). Fig. 4(a), 4(b), 4(c) & 4(d) show the FFT analysis of the output phase voltage and output phase current for RL load of five and nine- level MMCs. The Total Harmonic Distortion (THD) for phase voltage is given in comparison TABLE II.

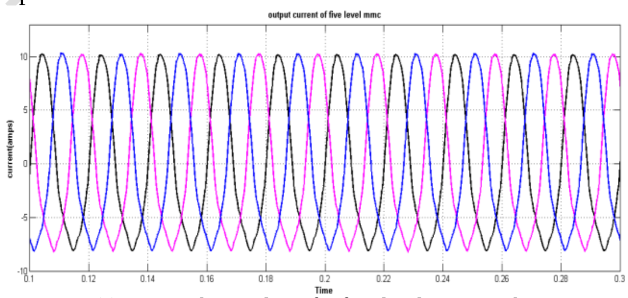

Fig. 3(a): output phase voltage for five-level MMC with PD PWM technique (mi-1.0)

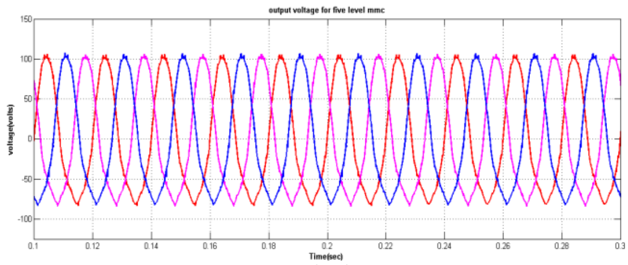

Fig. 3(b): output phase current for five-level MMC with PD PWM technique (mi-1.0)

Issue 5, Vol. 4 (June.-July. 2015)
ISSN 2249-6149

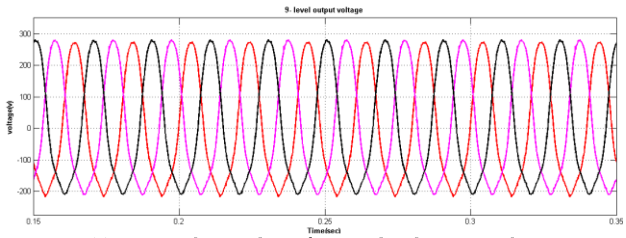

Fig. 3(c): output phase voltage for nine-level MMC with PD PWM technique (mi-1.0)

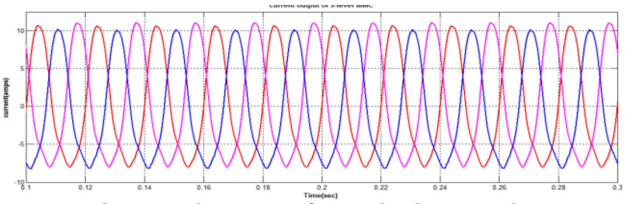

Fig. 3(d): output phase current for nine-level MMC with PD PWM technique (mi-1.0)

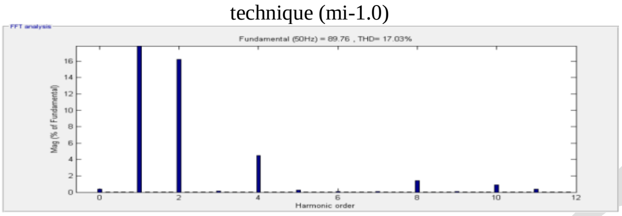

Fig. 4(a)

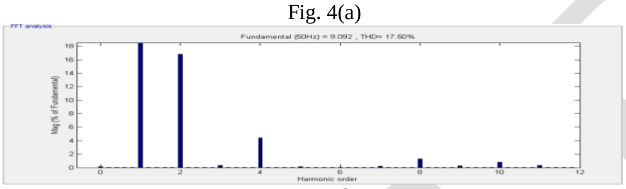

Fig. 4(b)

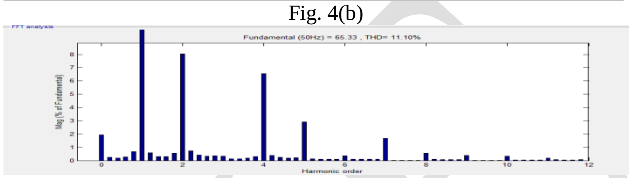

Fig. 4(c)

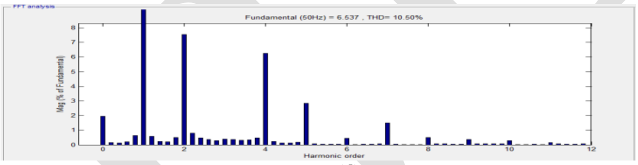

Fig. 4(d)

Comparison of 5- level MMC for various PWM techniques with different modulation indices from 0.6 to 1.0 is done. From the values, PDPWM technique with MI-1.0 is the best technique for simulating 5- level MMC.

TABLE II
COMPARISON IN 5-LEVEL MMC

PWM TECH	PD PWM		PODPWM		APODPWM		PSPWM	
MI	V	I	V	I	V	I	V	I
0.6	23.57	22.12	24.62	23.41	24.27	22.42	24.89	23.17
0.7	19.67	18.53	20.91	19.87	20.40	19.75	20.68	19.81
0.8	18.85	17.83	19.85	17.73	19.01	17.80	19.48	17.98
0.9	18.19	17.5	19.02	17.00	18.70	17.27	18.96	17.66
1.0	17.02	17.50	17.62	17.51	17.95	17.81	17.08	17.52

Similarly, comparison for the 9-level MMC for the above PWM strategies with different modulation indices is given below.

TABLE III
COMPARISON IN 9-LEVEL MMC

PWM TECH	PD PWM		PODPWM		APODPWM		PSPWM	
MI	V	I	V	I	V	I	V	I
0.6	19.74	18.76	23.16	22.19	20.19	19.23	21.34	20.56
0.7	17.00	16.71	20.62	20.68	17.07	16.72	17.74	17.22
0.8	14.51	13.91	18.01	17.94	16.35	15.21	17.55	17.07
0.9	12.83	11.8	15.89	14.07	13.92	13.08	14.89	14.42
1.0	11.08	11.50	13.70	13.50	11.97	11.23	12.46	12.31

A consolidate comparison has done and is given below shown in fig. 5.

CONSOLIDATE COMPARISON BETWEEN 5- & 9-LEVEL MMC

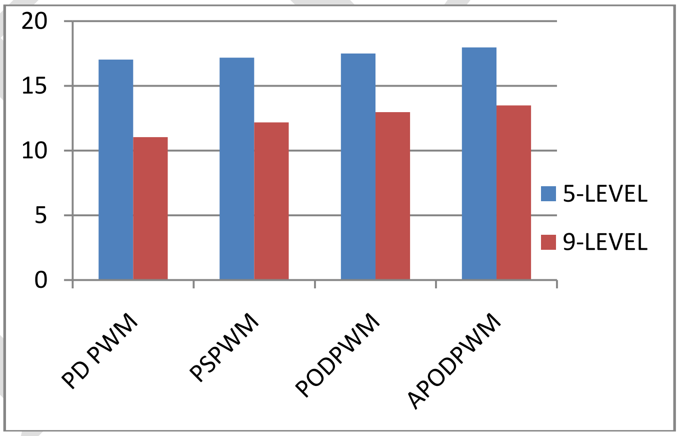

Fig. 5: cumulative comparison between 5- &9- level MMC

V. CONCLUSION

From the results shown in the previous section, the three-phase five-level & nine-level modular multilevel inverter based on the double star chopper cells configuration employing PDPWM, PODPWM, APODPWM and PSPWM multicarrier PWM strategies with RL load is simulated using MATLAB/Simulink software. The detailed comparison is done for the MMC-DSCC employing multicarrier PWM strategies based on the load phase voltage, load phase current and Total Harmonic Distortion. The PD PWM strategy gives the THD of phase voltage 17.02% and THD of phase current 17.50% for the modulation index of 1.0 for the five-level MMC. Similarly, it gives 11.08%, 11.50% THD for phase voltages and phase currents for the modulation index of 1.0 for the nine-level MMC respectively. Thus the PD PWM strategy is the best method providing the better RMS load voltage with low THD compared to other PWM strategies. It is clearly seen that while increasing the no. of sub-modules in each arm of the MMC, the no. of voltage levels increases and thus further reduces the THD in the phase voltages and currents.

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