U.P.B. Sci. Bull., Series C, Vol. 85, Iss. 2, 2023 ISSN 2286-3540

# ANALYSIS OF MODULATION STRATEGIES FOR SWITCHED BOOST MULTILEVEL INVERTER WITH EMBEDDED SOURCE

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*A Cascaded multilevel inverter (c-MLI) in essence, is considered more compact and compatible with, interfacing renewable resources with the grid. The c-MLI can scale the source (voltage) into a stepped output with reduced harmonics, with the help of cascaded power conversion cells. Yet, while considering interfacing a PV array that provides a low output voltage to a utility grid, a simple c-MLI may not be sufficient. Pertaining to this, a high gain, modified switched boost inverter topology is cascaded into a multi-level structure using reduced switching components is considered in this work. To obtain an effective output from the MLI, a suitable modulation method for controlling the reduced switch embedded type multilevel inverter needs to be selected. The different multicarrier and multi-reference modulation techniques are analyzed for the MLI topology, and the results are presented. The fundamental amplitude and harmonic distortion of the output, for each modulation technique over the MLI, is studied with the help of simulation software, Matlab. From the comparison, it is found that the Phase disposition type multicarrier modulation method is the most suitable for the MLIs obtained from cascading any type of impedance type inverter.*

**Keywords**: Embedded source, switched boost inverter, multi-carrier modulation, shoot-through duty cycle, multilevel, THD

## 1. Introduction

Having become the central component of many energy-management schemes, the study of solar energy, and its utilization in grid applications has increased in importance. Currently, the integration of PV or any renewable source with the utility grid has gardened major attention in energy-management systems [1]. However, even under ideal conditions, the energy produced with the help of a photovoltaic (PV) module is inadequate to power direct appliances [2]. Thus, it is essential to connect the PV array with the grid or the load through a PCU (power conditioning unit). Still, they pose some major restrictions, including *1)* a very low range of output, *2)* Fluctuations from the solar input further affecting the output, and *3)* harmonic content is still high to be fed to the grid. Especially for a PCU pertaining to grid-connected PV systems, keen attention is given to the

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converter-inverter arrangement whose design and operation should produce high-efficiency output even at different power configurations.

Owing to its recent growth in medium and large-scale industries, Multilevel inverters (MLI) have received increasing attention in applications involving renewable interfaces [3]. This is mainly due to their step-wise output with reduced harmonics (THD). Multilevel inverters are generally divided into three configurations: diode-clamped (DC-MLI), flying capacitor (FC-MLI), and cascaded multilevel inverters (C-MLI). While each type is considered for many industrial-based applications, the cascaded MLI, consisting of a series of power conversion cells, is more compatible with interfacing renewable energy [4],[5]. As each PV panel can act as a separate DC source for each h-bridge module, that can ensure a minimum continuous output even if one of the PV is damaged.

On the other hand, while implementing any PV-based application, attention needs to be given to the effect of partial shading (PS). Shading over one part of PV induces a current limitation on other unshaded modules. This leads to PV current difference over the array, resulting in hotspots within the PV modules. Many PV array configurations have been studied to protect the unshaded PV modules from this current difference. Primarily through these studies, it is established that the parallel-connected PV panels are less susceptible to PS than the series-connected panels [6],[7]. Hence, to best protect the PV array from PS, more parallel strings made up of less series connected panels are considered in this work. This produces high $I_{PV}$ (output PV current) and low $V_{PV}$ (output PV voltage) that requires a converter that can provide high gain conversion, to boost the voltage according to the application requirement, in this case to the grid voltage level. Thus, a high gain converter is cascaded to form a multilevel inverter, that can boost the low output voltage from the PV array with shorter strings [8] as shown in Fig. 1.

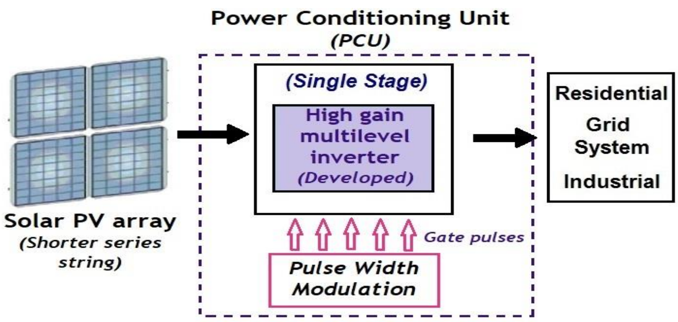



Fig. 1 Multilevel as conditioning unit in grid-connected PV system

With any inverter used, a nominal modulation technique is essential to bring out the maximum output with reduced harmonics. Hence, in this paper, a suitable modulation method for the developed multilevel inverter cascaded using a modular h-bridge network is carried out. To select the suitable modulation technique for the switching control, different PWM techniques are applied to the MLI topology, and their results are analyzed in the following sections.

## 2. Developed Multilevel Inverter

The study of inverters with impedance network (ZSI), gave the much-needed breakthrough in the PV application, resulting in a single-stage buck-boost conversion that reduces the overall cost of the application system. ZSI makes way for an additional state apart from the normal switching states (zero and active), known as the shoot-through (ST) switching state. While in traditional voltage source inverters, these states are forbidden pertaining to the risk of short circuits that damage the component due to the flow of high current. While ZSI effectively utilizes the ST states to boost the energy stored in the inductor and thereby increasing the output voltage. This output is usually in correspondence with the boost factor ($B_f$), which is a factor of the shoot-through duty cycle ($D_S$).

Even with these advantages, the output range of ZSI is still not sufficient to power many real-time applications. Hence, more impedance-based inverters are being studied through the years, to compensate for these shortcomings [9],[10]. Among them, is the embedded switched Z-source inverter (ES-ZSI) [11], which combines the benefits of both the source embedding concept (the source is provided within the boosting impedance network) and switched boost inverter (SBI) from [12]. A brief comparison of switched-inductor-based ES-ZSI with other similar Z-source type inverters whose $B_f$ depends on $D_S$ was carried out [13]. It was stated that, by drawing continuous input current and providing higher gain conversion using low passive components, the ESL-ZSI topology (also known as ESL-SBI) is favorably considered for high-gain applications.

As discussed earlier, this high-gain inverter is cascaded using a modular h-bridge made up of only six switches, to obtain a high-gain five level cascaded type multilevel inverter (ESL-SB MLI) as shown in Fig. 2. The working, switching cycles, and modeling of the developed ESL-SB MLI has been studied in [14]. The $B_f$ for the developed MLI is derived from the output equation (1) given below, where the modulation index is considered as 1.

$$V_o = \frac{(1+D_S)}{(1-3D_S)} V_i \tag{1}$$

It is important to select a proper control pulse for the shoot-through switches along with the auxiliary and h-bridge switches, that best brings out a maximum output under low harmonics. Hence, different modulation techniques are compared and the results are studied in the following section.

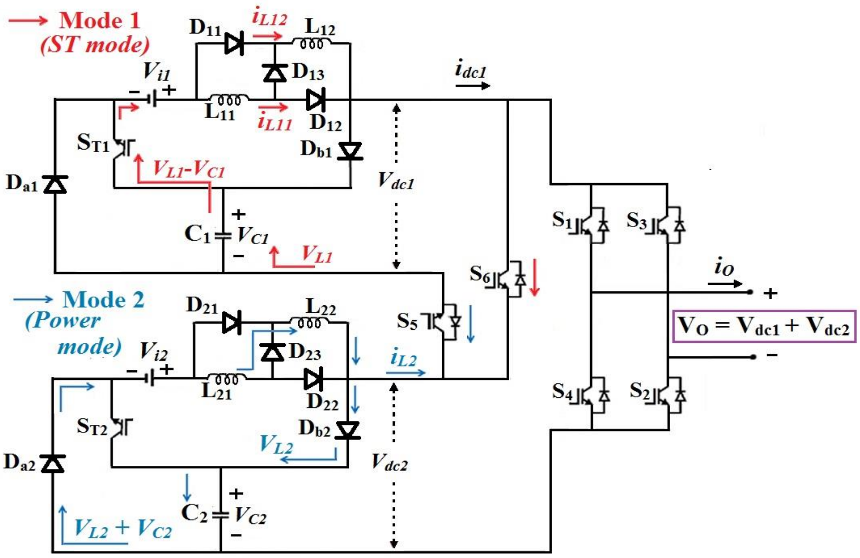



Fig.2 Developed switched boost multilevel inverter

### 3. Modulation Techniques

One of the essential functions of any multilevel inverter is to get the required output level at a possible high efficiency, by triggering the switches at the proper instances. The pulse width modulation (PWM) technique is widely used in many converters for its easy implementation in low-voltage modules [15]. For an MLI, that requires control pulses for a series of h-bridge switches to produce the stepped waveform, multicarrier PWM (MC-PWM) is favored. This method uses several carrier signals (mostly triangular), and a single modulating or reference signal which is mostly sinusoidal in form. The carrier signals have the same frequency and peak-to-peak amplitude, with zero references in the middle of its set. Considering an amplitude-based modulation, based on the required $m_a$ (amplitude modulation index), the amplitudes for both sinusoidal reference ($A_r$), and carrier signals ($A_c$) are chosen. The different modulation techniques used in the literature are given below:

#### 3.1 Phase-shift MC-PWM

Generally, the MC-PWM are classified based on phase shifted and level shifted PWMs. In the Phase-shift MC-PWM, to get *m*-level output from the inverter, (*m*-1) carriers of the same amplitude and frequency are required for the bipolar modulation technique. Hence for the developed five-level MLI, there are four carrier signals [16], as shown in Fig. 3. But these carriers are shifted 90° to one another.

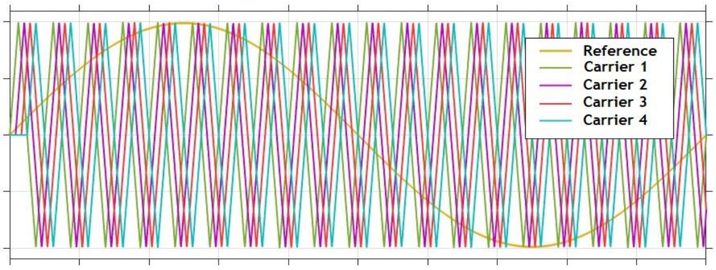



Fig. 3 Phase shifted MC-PWM

The $m_a$ for the phase-shifted MC-PWM is given by the ratio between the amplitude of reference and carrier signal, formulated as (2),

$$m_a = \frac{A_r}{A_c/2} \tag{2}$$

The reference signal is compared with the carrier signals to generate a gate pulse. Though not commonly used in MC-PWM techniques, this method provides a better THD range.

### 3.2 Level-shift MC-PWM

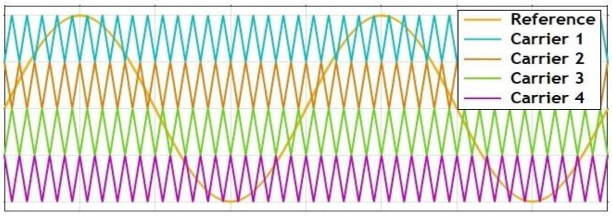
In this method, the levels (peak-to-peak) of the carrier signals are shifted [17]. The $m_a$ for the level-shifted MC-PWM is given by (3)

$$m_a = \frac{2A_r}{(m-1)\times A_C} \tag{3}$$

The level-shifted MC-PWM is further categorized into three types, which are the most implemented modulation techniques (as shown in Fig. 4(a), (b), and (c)). They are *1)* Phase-Disposition (PD) MC-PWM also has four carrier signals arranged in the same phase, with the same switching frequency ($f_s$). *2)* Phase Opposition and Disposition (POD) MC-PWM, where the carrier signals above the zero line are displaced by 180° with the signals below the line.


(a) Phase Disposition


(b) Phase Opposition Disposition




(c) A-Phase Opposition Disposition

Fig. 4 Level-shifted MC-PWMs

Lastly, *3)* A-Phase Opposition and Disposition (APOD), the carrier signals in this method are alternatively opposite in phase, i.e., each signal has a phase difference of 180° from one another.

### 3.3 Inverted Sine (IS) MC-PWM

Apart from the basic methods, to raise the fundamental output from the inverter, the triangular carrier is replaced with an inverted sine carrier (of high frequency) [18]. This considerably helps in maximizing the output values. Hence in this method, four inverted sine carrier signals are compared with a sinusoidal reference wave (Fig. 5). This method is found to have a better spectral quality than the previous methods, increasing its popularity in various applications.

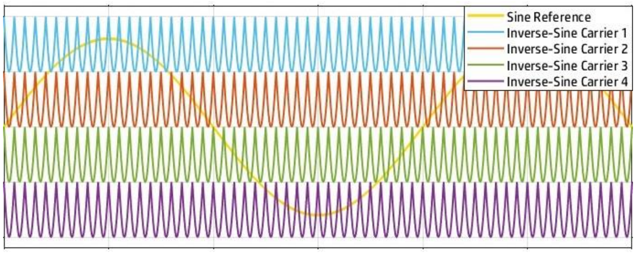



Fig. 5 Inverted sine MC-PWM

### 3.4 Trapezoidal Inverted Sine (TIS) MC-PWM

For many inverters that are expected to produce a high fundamental voltage, trapezoidal PWM is one of the commonly used modulation methods. Though, in general, it increases the lower-order harmonics, it can be restricted by choosing a suitable slope/ramp angle (α) with the relationship given in (4) obtained from [19].

$$A_n = \frac{4}{n^2 \pi} \times \frac{\sin(n\alpha)}{\alpha} \tag{4}$$

In this work, a bipolar trapezoidal reference signal is chosen to interact with the four inverted sine carrier signals (Fig. 6).

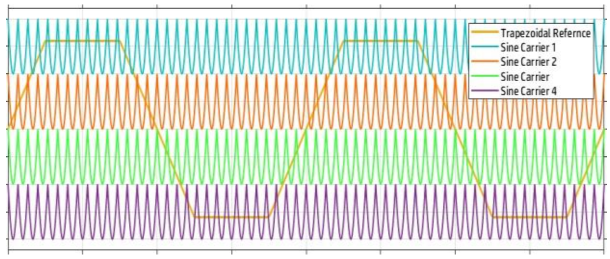



Fig. 6 Trapezoidal inverted sine MC-PWM

Compared to IS MC-PWM, the TIS MC-PWM technique is observed to give results with better spectral quality and enhanced fundamental voltage.

### 3.5 MR (Multireference) PWM

Apart from multicarrier type PWM, a multireference type PWM was also taken into consideration [20], [21]. It uses multiple reference signals with a single carrier signal (Fig. 7). In this technique, for an *m*-level output, (*m*-1)/2 reference signals are used. Reference signals with identical frequency, amplitude, and phase but level-shifted by an offset value are used. This value corresponds to the magnitude of the carrier signal.

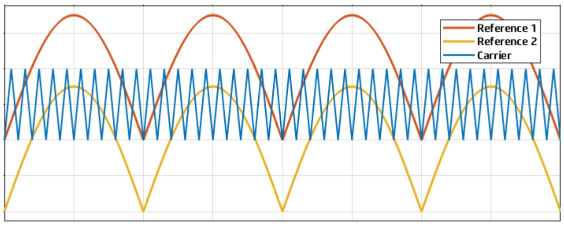



Fig. 7 Multireference PWM

With the basic knowledge of the different modulation methods, whose driving parameters are the $D_S$, the simulation study of the methods for the developed high gain multilevel inverter is carried out in this section.

## 4. Simulation Study

To verify the effects of the discussed modulation strategies on the MLI output, simulations of the MLI under each modulation are carried out, and their performances are compared with each other. The simulation is designed for a power rating of almost 2kW. The source is given from a set of the 4×15 PV array that produces $V_{in1}/V_{in2}$ (Input voltage) = ~60V, $I_{in}$ = ~29A. The pulses for the switches are generated for a switching frequency ($f_s$) = 25 kHz, with modulation index (M) = 0.8-0.9 and $D_S$ = 0.2. Hence, a $B_f$ (Boost factor) is expected to be around 3. The boosting network is made of inductors ($L_1$, $L_2$) of 2.5 mH and capacitor (C) of 50 μF. The pulse control circuit for all the switching components of the developed MLI is shown in Fig. 8, with four carrier signals and one modulating signal.

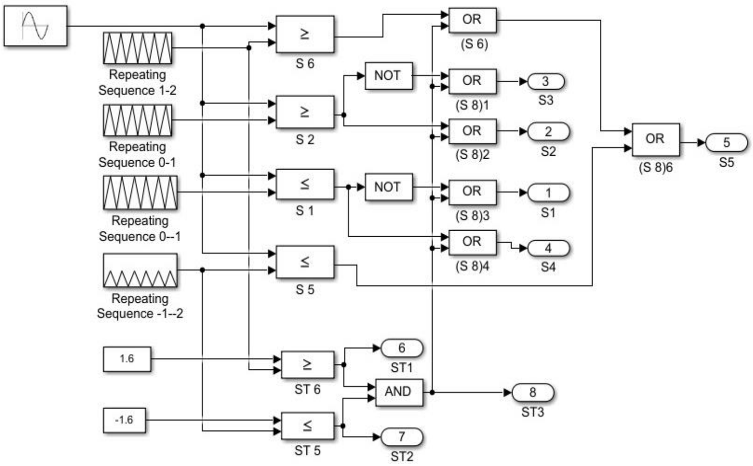



Fig. 8 Pulse generation for developed high gain MLI

For any inverter developed to feed an application or a grid, the measure of harmonics is imperative. In this work, the THD is calculated from the fft analysis through the simulation. But by definition, the THD can be calculated from (5),

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_{rms,n}^{2}}}{V_{rms,\, fund}} \tag{5}$$

The different voltage waveforms with their respective THD analysis for each modulation technique are presented through Fig. 9 to Fig. 14. The values for MR PWM are directly considered from the literature.

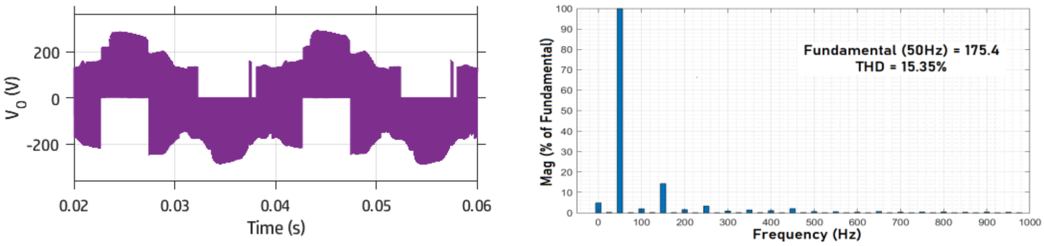



Fig. 9 Output voltage and the THD analysis of phase-shifted type modulation

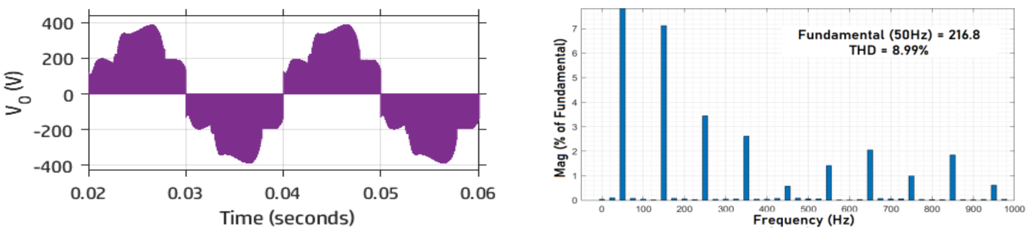



Fig. 10 Output voltage and the THD analysis of Phase disposition type

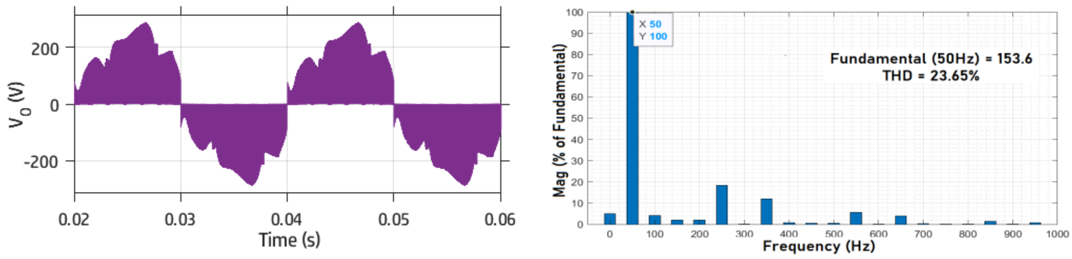



Fig. 11 Output voltage and the THD analysis of phase opposition disposition type

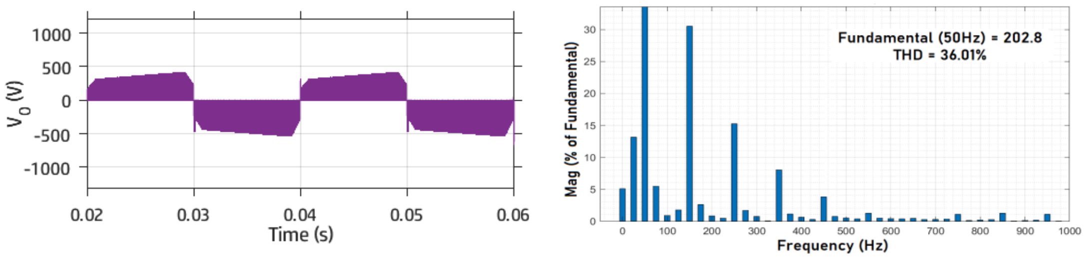



Fig. 12 Output voltage and the THD analysis of A-phase opposition disposition type

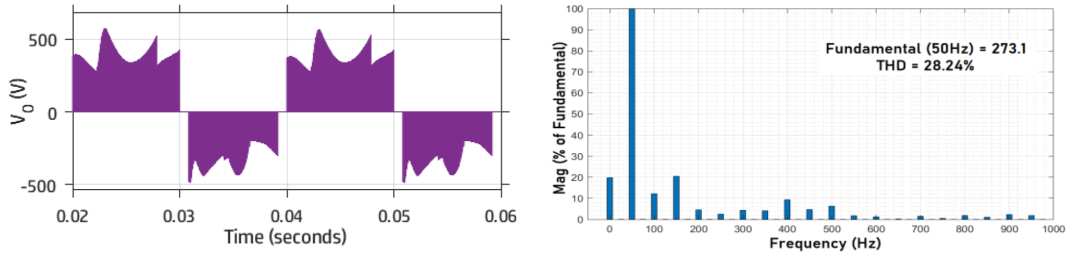



Fig. 13 Output voltage and the THD analysis of inverted sine type

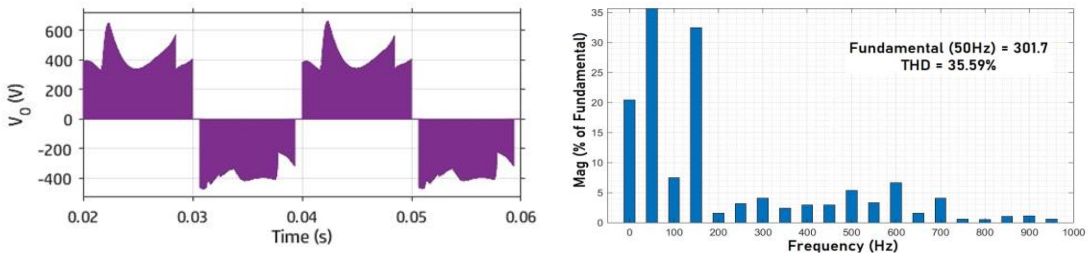



Fig. 14 Output voltage and the THD analysis of trapezoidal inverted sine type

Apart from the harmonics of the MLI, the RMS of the output is also considered important, as it serves as a factor to obtain the effective voltage of the AC signal. The RMS value is calculated from the peak value as given in (6).

$$V_{RMS} = \frac{V_{peak}}{\sqrt{2}} \tag{6}$$

From the simulation study, the comparison graph for both the fundamental ($V_{rms}$) and THD for different $D_S$ are presented below, in Fig. 15 and Fig.16 respectively. These graphs will aid in the selection of a suitable and convenient modulation technique for the MLI, based on the requirement.

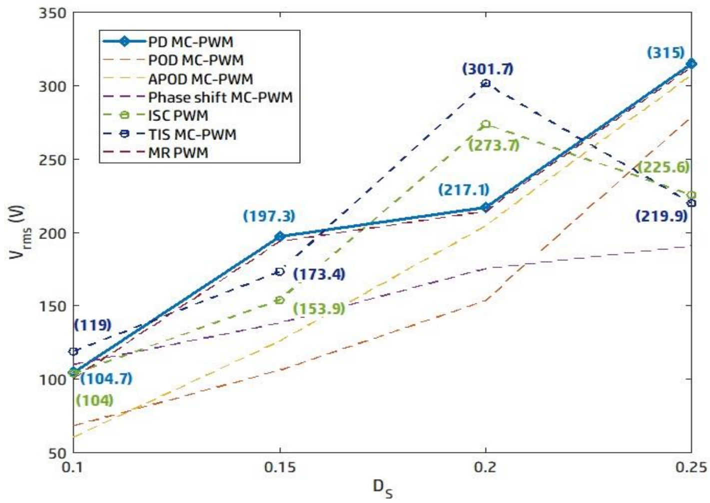



Fig. 15 $V_{RMS}$ of output vs $D_S$

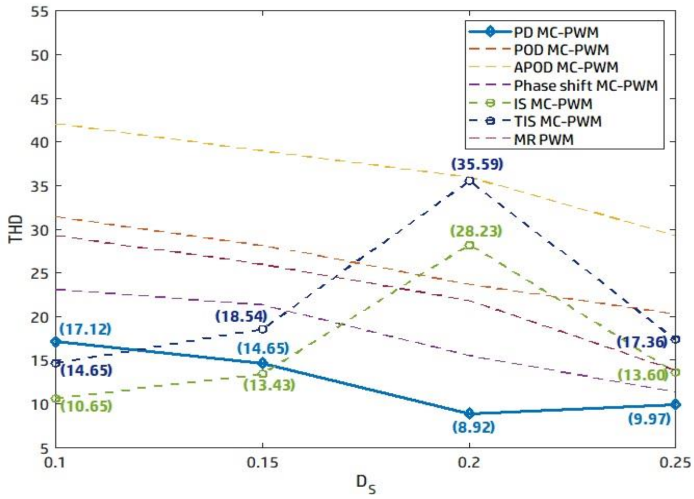



Fig. 16 THD of output vs $D_S$

From the above figures, both Phase Disposition and Phase-shifted MC-PWM methods exhibit low THD compared to other multicarrier modulation techniques. Yet while considering high gain inverters, the RMS value of output voltage is important. In which case, we can observe that the Phase-shifted MC-PWM exhibits very low RMS even at the given standard modulation index. From the THD graph, compared with IS and TIS type MC-PWM, though they give an output with a higher RMS value, it can be observed that PD MC-PWM yields output at a nominal THD value. So, Phase Disposition MC-PWM is selected as a trade-off between high RMS and low THD, that is more suited for the proposed MLI to get better performance at $D_S$= 0.2 (nominal $D_S$ value).

## 5. Conclusion

Focusing majorly on reducing the current difference through the PV module due to partial shading, an array with shorted series strings is considered. Hence, a high-gain converter is required to boost the low voltage to the required level and to connect it to the grid. Aiding to this, a five-level inverter topology was obtained by cascading into two symmetrical high-gain impedance type inverters, where the Bf of the inverter is a function of the DS. The developed MLI is implemented with reduced switches in an effort to cut down the overall loss. The various multicarrier and multireference modulation techniques are compared, to identify the method that best provides a high RMS output value at low THD.

From the simulation study, it can be observed that the inverter sine type modulations (IS and TIS MC-PWM) produce a high fundamental output value. But to connect the inverter to a grid, a voltage of low THD is of extreme importance, to avoid disrupting the utility grid. Hence, it is detected that the phase disposition (PD) MC-PWM method is the more suitable modulation method for the proposed C-MLI, irrespective of the impedance inverter cascaded. Easy to implement, the PD type MC-PWM is considered to have the best trade-off between the fundamental and the THD. To aid the findings of this work, a hardware implementation will be carried out in future work. To extend further, the developed MLI for higher levels (7, 11, etc.) will be studied, with suitable modulation techniques to extract efficient output with low harmonics and reduced leakage current.

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