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MULTICARRIER TRAPEZOIDAL PWM STRATEGIES FOR A SINGLE PHASE FIVE LEVEL CASCADED INVERTER

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Abstract

This paper presents a novel approach for controlling the harmonics of output voltage of chosen Cascaded Multilevel Inverter (CMLI) employing trapezoidal PWM switching strategies. Carrier Disposition (CD) methods and Phase Shift (PS) method employed are evaluated using spectrum of the output voltage and other performance measures such as crest factor, form factor etc and the use of inverter state redundancies to perform additional application specific control tasks such as power flow control from each DC source. This paper focuses on Multicarrier Trapezoidal PWM (MCTPWM) techniques with Phase Disposition (PD), Phase Opposition Disposition (POD), Alternative Phase Opposition Disposition (APOD) and PS of carrier for the chosen CMLI. Simulations are performed using MATLAB/SIMULINK. Harmonic analysis and evaluation of performance measures for various modulation indices have been carried out. It is observed that PD method provides output with the lowest distortion. Of the four strategies developed, POD is found to perform relatively better since it provides relatively higher fundamental RMS output voltage and relatively lower stress on the devices for moderate modulation index.

Keywords: CMLI, Total harmonic distortion, PWM, PD, POD, APOD, PS.

1. Introduction

Power conditioning systems are often designed to supply an AC load from DC source. An inverter should provide constant and ripple free AC voltage to ensure the safety of the equipments .The design of such systems must achieve an output voltage behavior as close as possible to the ideal AC voltage in the sense of fast transient response to load variation and low THD. With the expansion of power electronics towards the medium voltage and high power applications in the past few

Nomenclatures

A_c	Carrier peak-to-peak amplitude, V
A_m	Reference waveform amplitude, V
f_c	Carrier frequency, Hz
f_m	Reference waveform frequency, Hz
M	Number of modules
m	Total number of positive, negative and zero levels
m_a	Amplitude modulation index
m_f	Frequency ratio

Abbreviations

APOD	Alternative phase opposition disposition
CD	Carrier disposition
CF	Crest factor
CFD	Control freedom degree
CMLI	Cascaded multi-level inverter
DF	Distortion factor
FF	Form factor
HWM	Hybrid PWM
MCTPWM	Multicarrier trapezoidal PWM
MLI	Multilevel inverter
MSMI	Modular structured multilevel inverter
PD	Phase disposition
POD	Phase opposition disposition
PS	Phase shift
PWM	Pulse width modulation

years, multilevel power conversion is an emerging area. Multilevel voltage source inverter offers several advantages which makes it preferable over the conventional (two level) inverter. These include the possible utilization of higher DC link voltage, improved harmonic performance, reduced power device stress etc. Several multilevel topologies, namely the diode clamped multilevel inverter, the flying capacitors Multilevel Inverter (MLI) and cascaded multilevel inverter, have evolved and are applied in adjustable speed drives, electric utilities and renewable energy systems. Among the multilevel inverter topologies, cascaded multilevel inverter has more advantages than the other two. Cascaded MLIs use more than one DC voltage source to generate an AC output voltage that resembles a sine wave.

A new pulse width modulation (PWM) scheme that used multiple trapezoidal modulating signals with a single triangular carrier is discussed in [1]. A switching scheme was proposed for the cascaded MLI with a single carrier and multiple modulating signals in [2]. Some novel multilevel PWM strategies to take advantage of the multiple levels by utilizing all of the levels in the inverter even at low modulation indices were proposed in [3]. Different multicarrier PWM methods for a single phase five level cascaded inverter were investigated and analyzed in [4] .The PWM techniques employed in inverters may be unipolar or bipolar type [5].

Unipolar switching provides better quality output than bipolar switching. Ramprasad Panda and Tripathi [6] presented a symmetrical hybrid sine PWM switching technique for full bridge inverter. Hybrid PWM (HPWM) switching not only reduces overall switching loss but also reduces circuit complexity. Lai and

Ngo [7] experimentally proved that the overall switching losses are approximately the same in HPWM and unipolar PWM. Random switching method for HPWM full bridge inverter is proposed in [8] where it was experimentally proved that when each switch gets high and low gating signals alternatively instead of conventional hybrid PWM signals, switching loss of all the switches are equalized and good output performance is obtained. Multilevel PWM methods based on control degrees of freedom combination and their theoretical analysis are discussed in [9]. Three kinds of novel PWM methods for multilevel inverter are analyzed in [10] and these methods utilized vertical offsets among carriers as the control freedom degree. A new variation of selective harmonic elimination pulse width modulation technique suitable for a high power five level voltage source converter is used in constant frequency utility applications [11].

This paper presents a novel approach for controlling the harmonics of output voltage of chosen CMLI employing trapezoidal PWM switching strategies. Simulations are performed using MATLAB/SIMULINK. Harmonic analysis and evaluation of performance measures for various modulation indices have been carried out.

2. Multilevel Inverter

Multilevel inverters are being considered for an increasing number of applications due to their high power capability associated with lower output harmonics and lower commutation losses. Multilevel inverters have become an effective and practical solution for increasing power and reducing harmonics of AC load. Figure 1 shows a configuration of the single phase five level cascaded type Modular Structured Multilevel Inverter (MSMI). The MSMI is unique when compared to other types of multilevel inverters in the sense that it consists of several modules that require separate DC sources. Compared to other types of multilevel inverters, the MSMI requires less number of components with no extra clamping diodes or voltage balancing capacitors that only further complicate the overall inverter operation. As can be seen from Fig. 1, each module of the MSMI has the same structure whereby it is represented by a single phase full-bridge inverter. This simple modular structure not only allows practically unlimited number of levels for the MSMI by stacking up the modules but also facilitates its packaging.

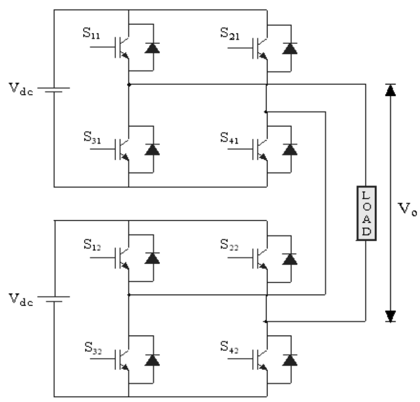

Fig. 1. Five Level MSMI.

The operation of the MSMI can be easily understood. The load voltage is equal to the summation of the output voltage of the respective modules that are connected in series. The number of modules, *M*, which is equal to the number of DC sources required depends on the total number of positive, negative and zero levels, *m*, of the MSMI. It is usually assumed that *m* is odd as this would give an integer valued *M*.

In this work, load voltage consists of five levels which include $+2V_{DC}$, $+V_{DC}$, 0, $-V_{DC}$ and $-2V_{DC}$ and the number of modules needed are 2. Equation (1) gives the relationship between *M* and *m*

$$M = (m-1)/2 \quad (1)$$

The gate signals for chosen five level cascaded inverter are simulated using MATLAB-SIMULINK. The gate signal generator model developed is tested for various values of modulation index m_a and for various PWM strategies.

Figure 2 shows a sample SIMULINK model developed for PD method. The simulation results presented in this work in the form of the outputs of the chosen multilevel inverter are compared and evaluated.

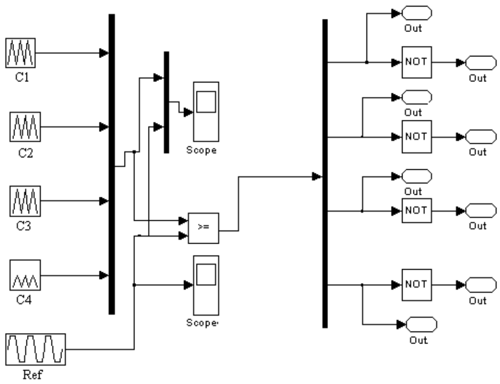

Fig. 2. Sample PWM Generation Logic Using SIMULINK Model Developed for PD Method.

3. Modulation Strategies for MLIs

A number of modulation strategies are used in multilevel power conversion applications. They can generally be classified into three categories:

- Multistep, staircase or fundamental frequency switching modulation strategies.
- Space vector PWM strategies.
- Carrier based PWM strategies.

Carrier based strategies are divided into two groups: single carrier and multicarrier strategies. Different multilevel topologies lend themselves to different multicarrier based PWM schemes. Multicarrier PWM methods can be categorised into two groups: Carrier disposition methods where the reference waveform is sampled through a number of carrier waveforms displaced by contiguous increments of the waveform amplitude and phase shift PWM methods where multiple carriers are shifted accordingly. Carrier based PWM methods have more than one carrier that can be triangular waves or saw tooth waves and so on.

As far as the particular carrier signals are concerned, there are multiple Control Freedom Degree (CFD) including frequency, amplitude, phase of each carrier and offsets between carriers. The modulating/ reference wave of multilevel carrier based PWM strategies can be sinusoidal or trapezoidal. As far as the particular reference wave is concerned, there is also multiple CFD including frequency, amplitude, phase angle of the reference wave and as in three phase circuits, the injected zero sequence signal to the reference wave. This paper focuses on multicarrier based trapezoidal PWM strategies which have been used in CMLI.

4. Carrier Disposition Methods

The following sections briefly describe the carrier disposition PWM methods. This paper presents four types of bipolar PWM strategies. The reference is trapezoidal.

For an m-level inverter using bipolar multicarrier technique, (m-1) carriers with the same frequency f_c and same peak-to-peak amplitude A_c are used. The reference waveform has amplitude A_m and frequency $f_{m.}$ and it is centred about the zero level. The reference wave is continuously compared with each of the carrier signals. If the reference wave is more than a carrier signal, then the active devices corresponding to that carrier are switched on. Otherwise, the devices switch off. The frequency ratio $m_f$is defined in the bipolar PWM strategy as follows in Eq. (2):

$$m_f = f_c / f_m \quad (2)$$

The amplitude modulation index m_a is defined for CD methods by Eq. (3)

$$m_a = 2A_m/(m-1)A_c \quad (3)$$

4.1. Phase disposition method

In phase disposition all the carriers are in phase. The PD method yields only odd harmonics for odd m_f and yields odd and even harmonics for even m_f. Figure 3 shows the multicarrier arrangement for PD method for m_a= 0.8 and m_f = 22.

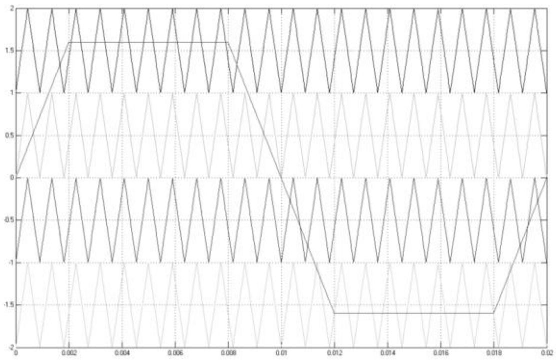

Fig. 3. Multicarrier Arrangement for PD Method.

4.2. Phase opposition disposition method

With the POD method the carrier waveforms above the zero reference value are in phase. The carrier waveforms below are also in phase but are 180 degrees phase shifted from those above zero. The POD method yields quarter wave symmetry for even m_f and odd symmetry for odd m_f. Figure 4 shows the multicarrier arrangement for POD method for m_a= 0.8 and m_f =22.

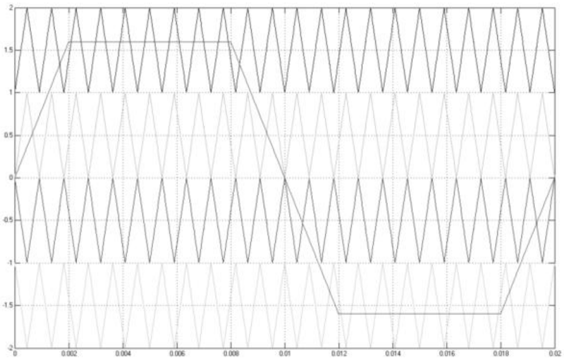

Fig. 4. Multicarrier Arrangement for POD Method.

4.3. Alternate phase opposition disposition method

This method requires each of the four carrier waves for a five level inverter to be phase displaced from each other by 180 degrees alternately. The APOD method yields quarter wave symmetry for even m_f and odd symmetry for odd m_f. Figure 5 shows the multicarrier arrangement for APOD method for m_a=0.8 and m_f =22.

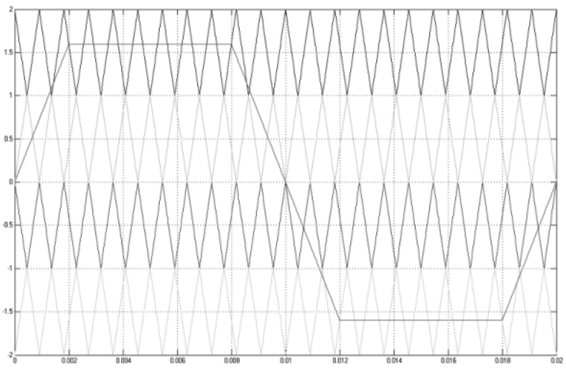

Fig. 5. Multicarrier Arrangement for APOD Method.

5. Phase Shift Method

The phase shift multicarrier PWM technique uses four carrier signals of the same amplitude and frequency which are shifted by 90 degrees to one another to generate the five level inverter output voltages. The gate signals for the cascaded inverter can be derived directly from the PWM signals (comparison of the carrier with the trapezoidal reference). There is a certain degree of freedom in the allocation of the carriers to the inverter switches. In the case of sinusoidal reference (i) for odd m_f the waveforms have odd symmetry resulting in even and odd harmonics and (ii) for even m_f, PS wave have quarter wave symmetry resulting in odd harmonics only. But in the case of trapezoidal reference, the waveforms have odd symmetry resulting in only odd harmonics. Figure 6 shows the multicarrier arrangement for PS method for m_a= 0.8 and m_f = 22.

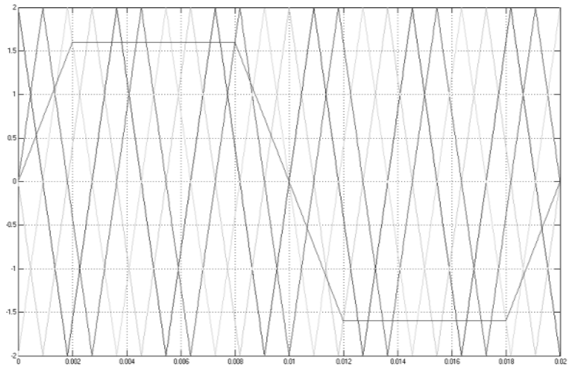

Fig. 6. Multicarrier Arrangement for PS Method.

The amplitude modulation index is defined for this strategy as follows in Eq. (4):

$$m_a = A_m/(A_c/2) \quad (4)$$

In this paper, m_f =21 and m_a is varied from 0.6 to 1.m_f is chosen as 22 as a trade off in view of the following reasons:

(i) to reduce switching losses (which may be high at large m_f).

(ii) to reduce the size of the filter needed for closed loop control, the filter size being moderate at moderate frequencies.

6. Simulation Results

The cascaded five level inverter is modelled in SIMULINK using Power System block set. Switching signals for MSMI are developed using bipolar PWM techniques discussed previously. Simulations are performed for different values of m_a ranging from 0.6 – 1. The corresponding %THD values are measured using the FFT block and they are shown in Table 1. Table 2 displays the V_{rms} of fundamental of inverter output (a measure of DC bus utilisation) for same modulation indices. Tables 3- 5 display the corresponding Crest Factor (CF), Distortion Factor (DF) and Form Factor (FF) respectively.

Table 1. % THD for Different Modulation Indices.

m_a	PD	POD	APOD	PS
1	19.38	19.38	20.07	20.05
0.9	18.60	19.92	20.26	20.09
0.8	19.65	20.92	21.61	21.61
0.7	20.09	21.74	22.94	22.86
0.6	19.48	20.61	23.93	23.92

Table 2. V_{rms} for Different Modulation Indices.

m_a	PD	POD	APOD	PS
1	168.2	167.7	168.01	168.3
0.9	151.4	151.8	151.4	151.5
0.8	134.8	135.7	134.8	134.7
0.7	118	119	117.8	117.8
0.6	101	100.8	101	101

Table 3. Crest Factor for Different Modulation Indices.

m_a	PD	POD	APOD	PS
1	1.167	1.171	1.164	1.165
0.9	1.298	1.292	1.295	1.293
0.8	1.455	1.443	1.450	1.451
0.7	1.661	1.642	1.654	1.655
0.6	1.944	1.943	1.926	1.925

Table 4. Distortion Factor for Different Modulation Indices.

m_a	PD	POD	APOD	PS
1	0.0209	0.0185	0.0202	0.0201
0.9	0.0203	0.0198	0.0199	0.0200
0.8	0.0203	0.0214	0.0200	0.0196
0.7	0.0202	0.0221	0.01975	0.0196
0.6	0.0202	0.0197	0.01959	0.0202

Table 5. Form Factor for Different Modulation Indices.

m_a	PD	POD	APOD	PS
1	271.95	∞	8587.79	8580
0.9	244.44	3095.62	2206.78	7729.36
0.8	∞	13863.97	∞	∞
0.7	261.65	∞	4028.67	2013.96
0.6	168.69	1029.178	1038.52	3461.49

Figures 7–14 show the simulated output voltage of MSMI and corresponding FFT plots with above strategies but for only one sample value of m_a = 0.8.

Figure 7 shows the five level output voltage generated by PD strategy and its FFT plot is shown in Fig. 8. From Fig. 8, it is observed that the PD strategy produces significant 3^{rd}, 7^{th}, 8^{th}, and 20^{th} harmonic energy.

Figure 9 displays the five level output voltage generated by POD strategy and its FFT plot is shown in Fig. 10. The FFT spectrum of POD strategy shows significant 3^{rd}, 7^{th}, 9^{th} and 19^{th} harmonic energy content in the inverter output.

Figure 11 shows the five level output of APOD strategy where significant energy is present in the 3^{rd}, 13^{th}, 15^{th} and17^{th} harmonics. Figure 13 shows the five level output voltage generated by PS strategy and its FFT plot is shown in Fig. 14.

From Fig. 14, PS strategy has significant amount of harmonic energy present in 3^{rd}, 7^{th}, 13^{th}, 15^{th} and 17^{th} harmonics. The following parameter values are used for simulation: V_{DC} =100V and R(load) = 100 ohms.

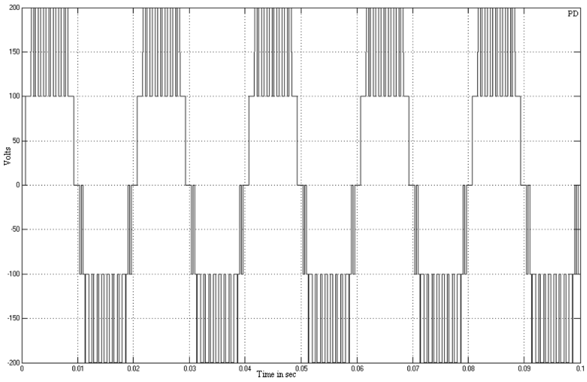

Fig. 7. Output Voltage Generated by PD Method.

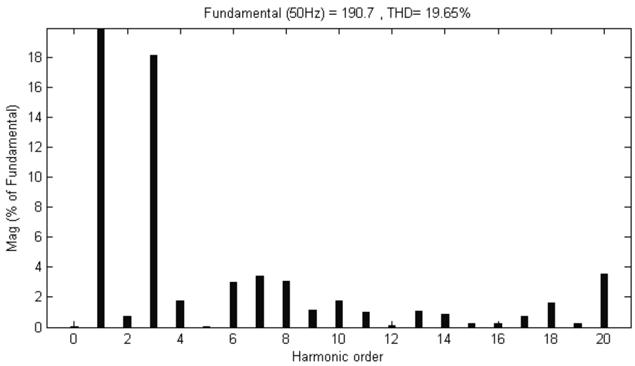

Fig. 8. FFT Plot for Output Voltage of PD Method.

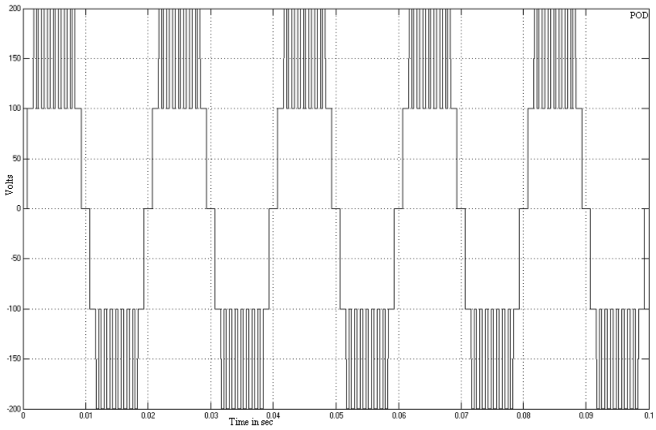

Fig. 9. Output Voltage Generated by POD Method.

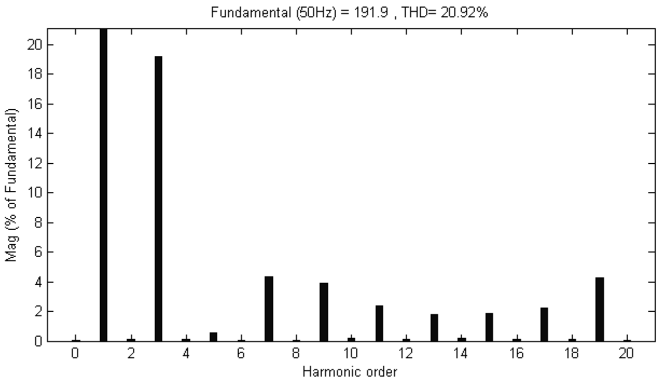

Fig. 10. FFT Plot for Output Voltage of POD Method.

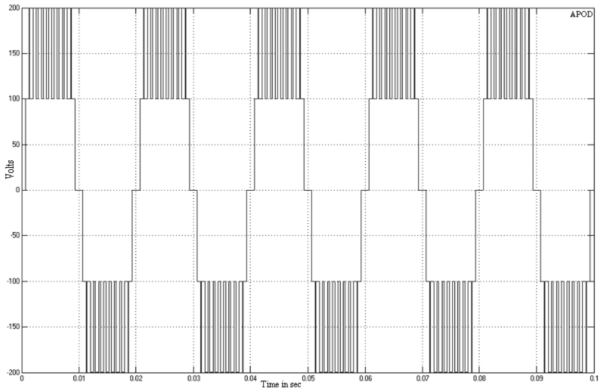

Fig. 11. Output Voltage Generated by APOD Method.

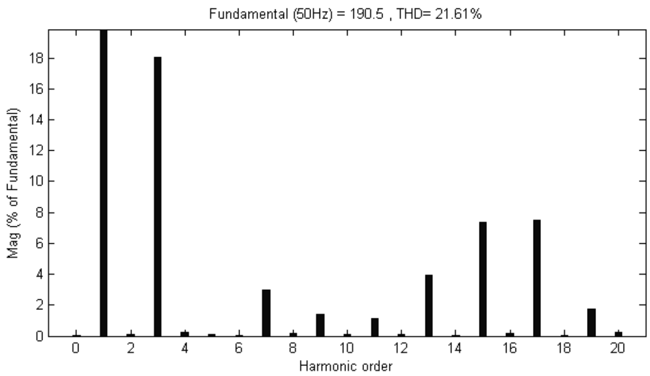

Fig. 12. FFT Plot for Output Voltage of APOD Method.

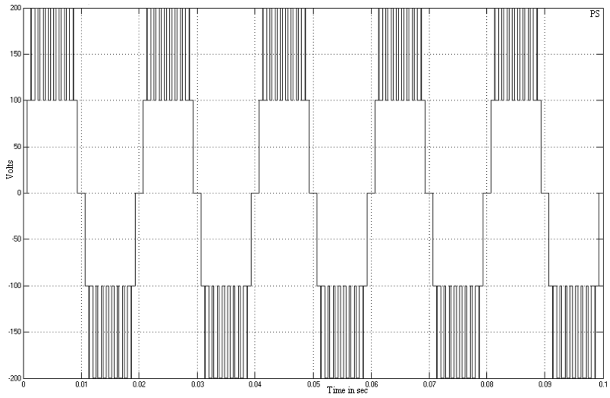

Fig. 13. Output Voltage Generated by PS Method.

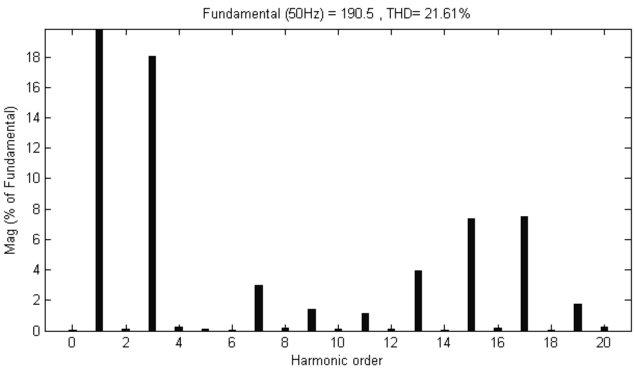

Fig. 14. FFT Plot for Output Voltage of PS Method.

It is observed from Table 1 and Figs. 7-14, PD method provides output with the lowest distortion. Of the four strategies developed, POD is found to perform relatively better since it provides relatively higher fundamental RMS output voltage (Table 2 and Figs. 7-14) and relatively lower stress on the devices (Table 3) for moderate m_a.

7. Conclusion

Various MCTPWM strategies for chosen MSMI have been developed and simulation results are presented. Performance indices like %THD (a measure of closeness in shape between a wave form and its fundamental component), V_{rms} of fundamental, DF (measure of amount of harmonics that remains in the output after it has been subjected to second order attenuation), CF (used to specify peak current rating of the devices) and FF (a measure of the shape of the output voltage) have been evaluated and tabulated. Appropriate PWM strategies may be employed depending on the performance measure required in a particular application.

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