# Waveform Quality Comparison of Scalar PWM Methods for Modular Multilevel Converters

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## Abstract

**Modular Multilevel Converter (M2C) is the preferential topology used for high power applications in the recent years. Its high quality of output waveforms and high efficiency make it a powerful alternative to conventional two level converters. This paper gives an output waveform quality comparison of scalar PWM methods, used for M2C switching. It is found that output voltage characteristics are highly dependent on the PWM method used. Therefore, selection of the switching method is an important design issue in M2C studies. Comparison is based on Matlab generated switching pulse patterns and the results are validated by Simplorer based computer simulations.**

## 1. Introduction

Modular Multilevel Converter (MMLC, M2LC, M2C), as a voltage sourced converter, does dc to ac conversion. The topology emerged a decade ago [1] and has gained a high popularity in research and development studies due to its outstanding properties. M2C operates in a wide range of voltage and power rating, and it is especially evolved through multi MW applications. Output voltage waveforms of the topology are closer to ideal sinusoidal than conventional two-level converter, resulting in lower voltage (in consequence current) harmonic distortions. Its high efficiency, modular structure and ability for rapid and accurate conditioning of electrical energy are the other distinctive properties from several topologies. M2C is used conveniently for high power applications such as HVDC transmission, medium-voltage motor drives, STATCOM applications and solar/wind power conditioning applications. More detailed topological information can be found in [2]. Figure 1 shows a three phase double star configured M2C.

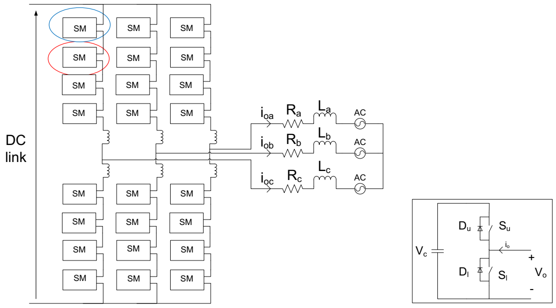

***Fig. 1***. Modular Multilevel Converter (double-star configured) on the left and a chopper cell sub-module on the right

As shown on Fig 1. M2C topology is based on sub-module structure. Switching of these sub-modules is one of the fundamental research areas for M2C studies. Switching methods for M2C can be classified as below [3]:

- I. High Frequency Switching
  - A. Scalar Pulse Width Modulation
    - 1. Level Shift Methods
      - a) Phase disposition (PD)
      - b) Phase opposition disposition (POD)
      - c) Alternative phase opposition disposition (APOD)
    - 2. Phase Shift Method
  - B. Space Vector Pulse Width Modulation
- II. Fundamental Frequency Switching
  - A. Selective Harmonic Elimination
  - B. Space Vector Control

It is aimed with this paper to further the understanding of performance evaluation of M2Cs, when switched with scalar PWM techniques.

## 2. Scalar Pulse Width Modulation Methods for M2C

As listed in part 1, in the literature, there exist two methods for scalar PWM switching which have been used on M2C: *level shift method* and *phase shift method*. Moreover, level shift method branches into three different sub-methods: phase disposition (PD), phase opposition disposition (POD) and alternative phase opposition disposition (APOD) [4]. For all the methods, in order to provide a balanced exploitation of the sub-modules, amplitudes of the carriers should be equal to each other, which is a necessary but not a sufficient condition. Unbalanced usage of sub-modules, certainly, causes heterogeneous aging of the modules causing a decrease on the return on investment. Implementation of level shift methods is based on distributing the carriers contiguously on the whole $V_{dc}$ band in an amplitude shifted manner; whereas that of phase shift method is based on distributing the carriers on the $V_{dc}$ band in a phase shifted manner. Carriers of the PD method are all in phase. For POD method, positive and negative carriers are 180° phase shifted. For APOD method, carriers are alternately 180° phase shifted. For phase shift method, on the other hand, carriers are phase shifted by 360°/N where N is the number of carriers. More detailed information about scalar PWM methods and their implementation to the converter can be found in [5].

This paper gives an assessment of performance in terms of switching pulse patterns, dominant harmonics of output phase and line voltages and WTHD (weighted total harmonic distortion) values for level shift methods and phase shift method. Assessment is based on the fundamental pulse pattern generations which only result from the comparison of triangular carrier and sinusoidal reference signals, without using any control and cell capacitor voltage balancing technique. Therefore, it is intended to have a fundamental data and guiding principles about the scalar PWM methods with their purest form, before going into more complex control mechanisms.

## 3. Waveform Quality Analysis

Waveform quality analysis is conducted in two parts. Firstly an analysis of switching pulse patterns generated by different PWM methods is conducted by Matlab studies; then, a simulation work is done by Simplorer computer simulation program, in order to validate the Matlab study.

### 3.1 Analysis of Switching Pulse Patterns

Output voltage waveform of a converter takes on a shape starting from the switching pulse patterns generated by PWM signals. In order to get a fundamental insight on the voltage characteristics, switching pulse patterns and respective normalized line voltage waveforms (*1 unit of voltage* for each level) were obtained by Matlab. Studies on all the methods were conducted using a double-star chopper cell topology with four sub-modules in each arm as shown on Fig. 1. Performances of the PWM methods were investigated using different amplitude modulation ($m_a$) and frequency modulation ($m_f$, ratio of the carrier frequency to the reference signal frequency) indices. For M2C, calculations of $m_a$ for different scalar PWM methods are shown on Table 1 below. For a 5-level system as in our example, $m_a$ value of the level shift methods is twice of the $m_a$ value of the phase shift method, for the same $A_m$.

**Table 1.** $m_a$ calculation for scalar PWM methods [6]

| | Level shift methods | Phase shift method |
|---|---|---|
| $m_a$ | $\dfrac{A_m}{\frac{n-1}{2} * A_c}$ | $\dfrac{A_m}{A_c}$ |

n : number of output phase to neutral voltage levels
$A_m$: amplitude of modulation signal
$A_c$ : amplitude of carrier signal

In Figs. 2, 5, 8 and 11, switching pulse patterns (semiconductor on/off signals) generated by different modulation techniques (phase shift, PD, POD, and APOD, respectively) in *one period of modulation signal (1/50Hz=20ms)* are shown. Regarding simplicity and readability, two of the generated pulse patterns (corresponding to carriers for red and blue circled sub-modules on Fig. 1) out of four for the whole phase arm, are shown on the figures. One of the pulse patterns (red) is scaled by two in order to distinguish among each other.

Analyzing the pulse patterns generated by the level shift methods reveals that:

- Switching functions resulting from PD, POD and APOD are similar in terms of number of switching.
- Number of switching and switching manner resulting from different carriers in a system are not equal to each other. These methods generate highly heterogeneous switching functions.
- Number of switching for each carrier is dependant both on $m_a$ and $m_f$.
- Total number of switching for all the carriers of a phase is dependent on mf.
- Depending on the sign of the carriers (being negative or positive), switching occurs in one of the half periods (for our case, in the first half cycle). In the other half period, switching function is constant, since the reference and carrier signals do not cross in that half period.
- Depending on $m_a$, starting from the uppermost and lowermost carriers and going through to the zero crossing, some carrier pairs may not generate switching functions, having constant value.

Analyzing the pulse patterns generated by the phase shift method reveals that:

- Number of switching and switching manner resulting from different carriers in a system are highly similar to each other. This method generates much more homogeneous switching functions than that of level shift methods.
- Number of switching for each carrier and also total number of switching for all the carriers of a phase are dependant just on the $m_f$.
- All the carriers generate switching functions.
- Switching occurs in both of the half periods, since the carriers cover full dc band and so the carrier and modulation signal cross in both half periods.
- For the same $m_a$ and $m_f$, phase shift method generates much greater number of switching than level shift methods, which means much greater switching losses.

Differences between the pulse patterns of level shift and phase shift methods induce, naturally, differences between the dominant voltage harmonics. After analyzing pulse patterns with different $m_a$ and $m_f$ levels, it is concluded that POD and APOD of level shift methods produce dominant phase and line voltage harmonics around the carrier frequency ($f_c$). Although it is not as clear as POD and APOD methods' dominant voltage harmonics, PD method produces dominant phase voltage harmonics just on the carrier frequency ($f_c$); and line voltage harmonics around carrier frequency ($f_c$). On the other hand, phase shift method always produces dominant voltage harmonics at four (number of carriers) times of the carrier frequency sidebands ($f_{cs}$). In other words, converter switching frequency of phase shift method is multiplied by the number of carriers, although semiconductors of sub-modules are switched at carrier frequency. This property of converter frequency multiplication makes phase shift method more advantageous over level shift methods in terms of low voltage harmonics; for sure, in return for higher switching losses. Table 2 summarizes dominant voltage harmonics frequencies for all the scalar PWM methods.

**Table 2.** Dominant voltage harmonics locations

| | **PD** | **POD** | **APOD** | **PHASE SHIFT** |
|---|---|---|---|---|
| $\mathbf{V_{ph}}$ | $f_c$ | $\approx f_c$ | $\approx f_c$ | $\approx 4 \times f_{cs}$ |
| $\mathbf{V_{l\text{-}l}}$ | $\approx f_c$ | $\approx f_c$ | $\approx f_c$ | $\approx 4 \times f_{cs}$ |

Output line voltages of a 4-carriered M2C system, operated with above-mentioned PWM methods, are shown on Figs. 3, 6, 9 and 12 for phase shift, PD, POD and APOD methods, respectively. Properties of pulse patterns are reflected to the line voltages. Due to its homogeneous pulse pattern, phase shift method has a well balanced quarter wave symmetrical output line voltage. Level shift methods, on the other hand, do not have symmetry on the output line voltage, particularly POD and APOD methods. Harmonics of these output line voltages are shown on Figs. 4, 7, 10 and 13 with the same sequence above. It is still possible to see the properties of pulse patterns and waveforms. Phase shift method has harmonics just around four times of the carrier frequency. However, level shift methods have spectrums which are much more spread. This noteworthy difference results from the pulse patterns. Since the number of switching and switching manner of different carriers for the phase shift method are highly similar to each other, they all contribute to the same harmonics. However, level shift methods have different numbers of switching for different carriers, and so they contribute to the different frequency harmonics, which results in spreading on the harmonics spectrum. In order to prevent this spreading, number of switching for different carriers should be made as close to each other as possible, like that of phase shift method. Carrier rotation techniques are developed for this aim [7]. Another property for PWM methods is obtained when the voltage harmonics are investigated with different $m_f$ values. It is revealed that PD method has even voltage harmonics when $m_f$ is even, while POD and APOD methods have even harmonics when $m_f$ is odd. However, phase shift method, irrespective from the $m_f$ value, has never even harmonics.

WTHD is one of the powerful tools used for performance comparison of the PWM methods. Classical output line-to-line voltage THD calculation does not mind the orders of harmonics. However, for most AC motor drive and utility interface applications, magnitudes of current harmonics are directly dependent on load impedance, (continued after Fig. 13)

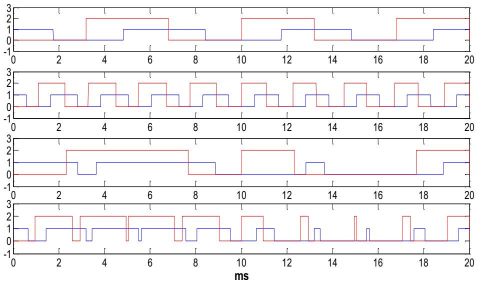

***Fig. 2.*** Switching pulse patterns of phase shift for ($m_a$=0.1, $m_f$=3), ($m_a$=0.1, $m_f$=9), ($m_a$=0.9, $m_f$=3) and ($m_a$=0.9, $m_f$=9) from the top to the bottom, respectively

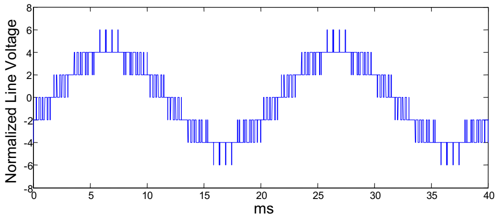

***Fig. 3.*** Line voltage of phase shift for $m_a$=0.6, $m_f$=9

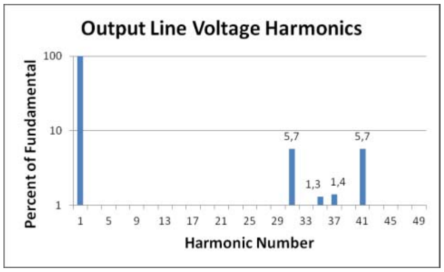

***Fig. 4.*** Line voltage harmonics of phase shift for $m_a$=0.6, $m_f$=9

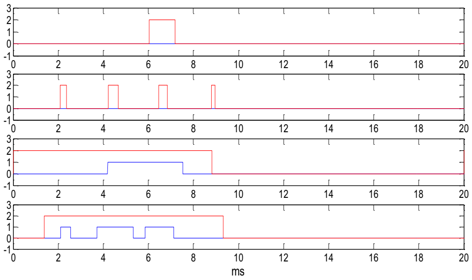

***Fig. 5.*** Switching pulse patterns of PD for ($m_a$=0.1, $m_f$=3), ($m_a$=0.1, $m_f$=9), ($m_a$=0.9, $m_f$=3) and ($m_a$=0.9, $m_f$=9) from the top to the bottom, respectively

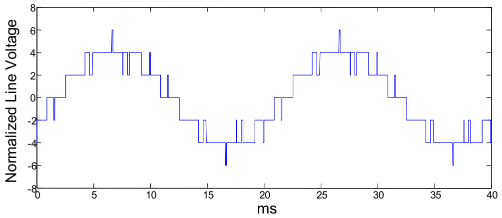

***Fig. 6.*** Line voltage of PD for $m_a$=1.2, $m_f$=9

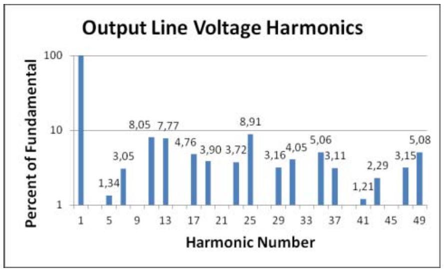

***Fig. 7.*** Line voltage harmonics of PD for $m_a$=1.2, $m_f$=9

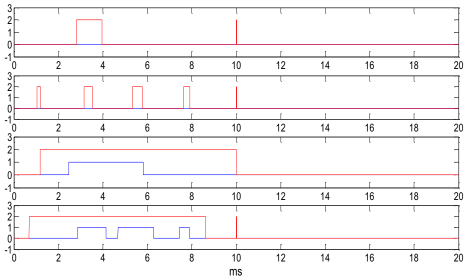

***Fig. 8.*** Switching pulse patterns of POD for ($m_a$=0.1, $m_f$=3), ($m_a$=0.1, $m_f$=9), ($m_a$=0.9, $m_f$=3) and ($m_a$=0.9, $m_f$=9) from the top to the bottom, respectively

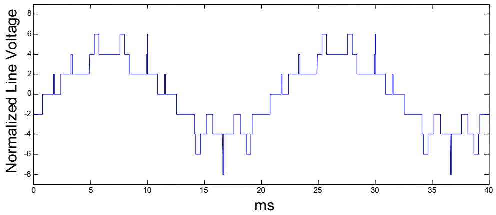

***Fig. 9.*** Line voltage of POD for $m_a$=1.2, $m_f$=9

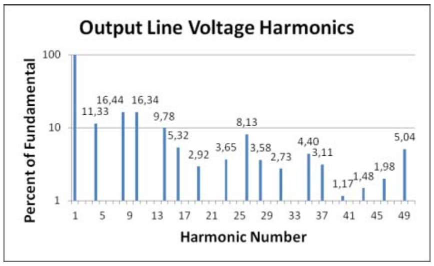

***Fig. 10.*** Line voltage harmonics of POD for $m_a$=1.2, $m_f$=9

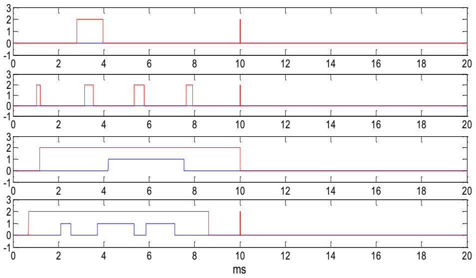

***Fig. 11.*** Switching pulse patterns of APOD for ($m_a$=0.1, $m_f$=3), ($m_a$=0.1, $m_f$=9), ($m_a$=0.9, $m_f$=3) and ($m_a$=0.9, $m_f$=9) from the top to the bottom, respectively

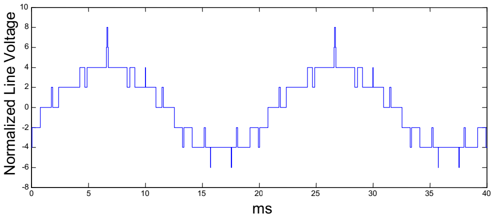

***Fig. 12.*** Line voltage of APOD for $m_a$=1.2, $m_f$=9

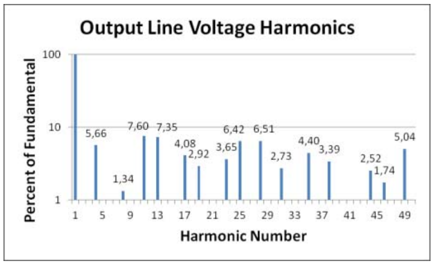

***Fig. 13.*** Line voltage harmonics of APOD for $m_a$=1.2, $m_f$=9

having a low pass character due to load inductance. Different from classical THD calculation, output line-to-line WTHD calculation involves the effect of orders of harmonics, thus giving a more meaningful data for performance comparison. WTHD is defined as:

$$WTHD = 100\,x\,\frac{\sqrt{\sum_{i=2}^{n}\left(\frac{V_{LLi}}{i}\right)^{2}}}{V_{LL1}} \qquad (1)$$

where i is the harmonic order and $V_{LLi}$ is the amplitude of the $i^{th}$ line-to-line harmonic voltage. WTHD values of the four scalar PWM methods are calculated for changing $m_a$ and changing $m_f$ separately. Figure 14 shows WTHD values for fixed $m_f$ ($m_f$=9) and changing $m_a$. Figure 15, on the other hand, shows WTHD values for fixed $m_a$ ($m_a$=0.6 for phase shift method and $m_a$=1.2 for level shift methods) and changing $m_f$. Both of the figures clearly reveal that phase shift method has lower WTHD values throughout the $m_a$ range (from 0.1 to 2) and the $m_f$ range (from 2 to 19). This result is expected as the pulse pattern graphics, dominant voltage harmonics table and output line voltage harmonics spectrum suggest. Level shift methods, compared to each other, have different WTHD characteristics. For fixed $m_f$, PD method has always the best performance throughout the range. In the linear range of $m_a$, POD and APOD methods have the same performance and the difference occurs in the over modulation range. For fixed $m_a$, PD and APOD methods have better results, and the best changes according to $m_f$ value. Level shift methods, especially $m_f$ up to 10, have oscillations on the WTHD values. This mainly results from the fact that they have even harmonics depending on the value of $m_f$. On the other hand, phase shift method has a much steadier WTHD characteristic, since it does not have even harmonics, irrespective from $m_f$ value.

It is important to note here that WTHD comparisons in this paper stand on abovementioned ideal case pulse pattern generations. For this case, total numbers of switching resulting from these pulse patterns are different for level shift and phase shift methods. Irrespective from changing $m_a$ or changing $m_f$ range, while level shift methods produce similar total number of switching; phase shift method produces four times that of level shift methods, which means four times greater switching losses. Another approach for WTHD comparison stands on equal total number of switching in a phase leg, which is out of the content of this paper.

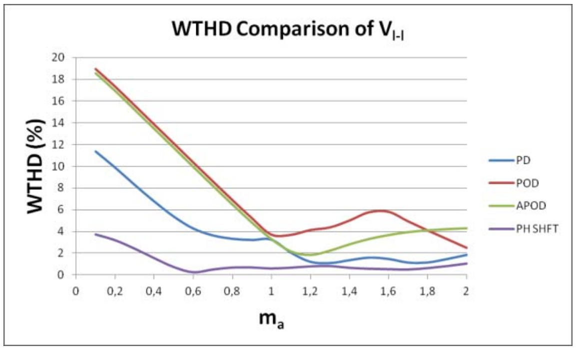

***Fig. 14.*** WTHD values for fixed $m_f$ and changing $m_a$

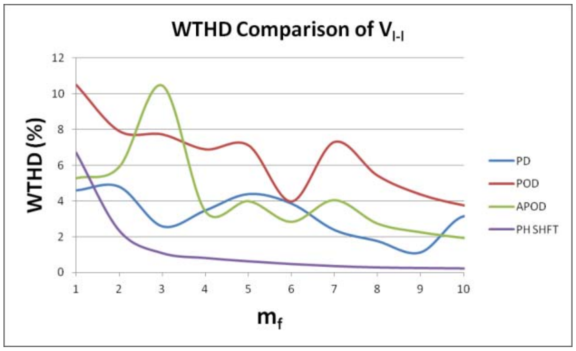

***Fig. 15.*** WTHD values for fixed $m_a$ and changing $m_f$

## 3.2 Simulation Results

Results obtained from Matlab studies are implemented to a simulation circuit on Simplorer simulation program. A medium voltage motor drive circuit is simulated with above-mentioned PWM techniques. A three phase double star chopper cell circuit, as in Fig. 1, with four sub-modules per arm, is used with a 15kV sub-module dc sources and 10Ω+18mH load impedance. Output line voltages (blue) and output currents (red) are illustrated on Fig. 16 through 19. Waveforms on these figures confirm the results of the studies with Matlab. The voltage waveforms are approximately the same. THD values of output line voltages and currents are listed in Table 3. Phase shift method, as expected, has the output current with least distortion.

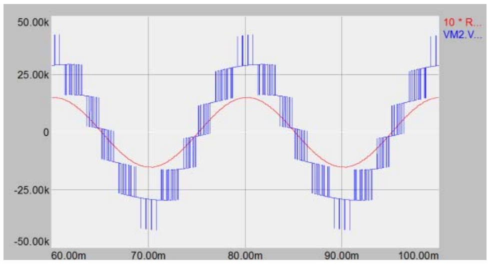

***Fig. 16.*** Line volt. and current of phase shift for $m_a$=0.6, $m_f$=9

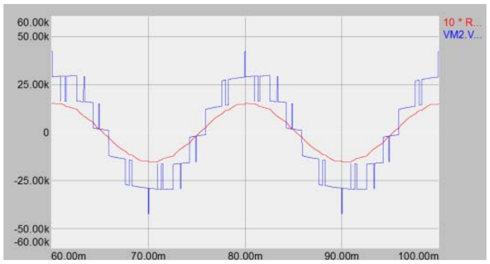

***Fig. 17.*** Line voltage and current of PD for $m_a$=1.2, $m_f$=9

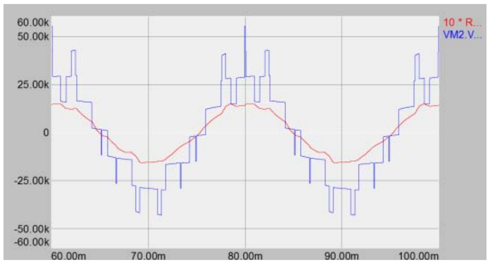

***Fig. 18.*** Line voltage and current of POD for $m_a$=1.2, $m_f$=9

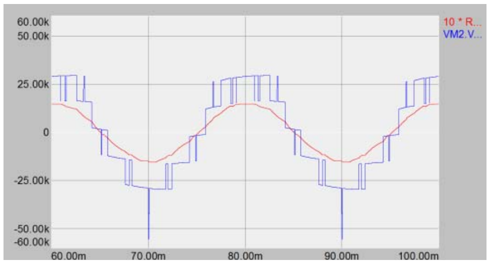

***Fig. 19.*** Line voltage and current of APOD for $m_a$=1.2, $m_f$=9

**Table 3.** THD values of output currents

| | **PD** | **POD** | **APOD** | **PHASE SHIFT** |
|---|---|---|---|---|
| **THD** | 2.26 | 7.31 | 3.25 | 0.63 |

## 4. Conclusion

In this paper, scalar PWM methods for M2C switching are compared for their pulse patterns, dominant output voltage harmonics, output line voltages and their harmonics spectrum and also WTHD values. The study is based on the fundamental pulse pattern generations without using any control and cell capacitor voltage balancing technique.

The results show that, phase shift method can produce homogeneous and symmetrical switching pulse pattern considering the whole sub-modules in a phase leg. Number of switching for different sub modules are very close to each other. These lead balanced switching loss throughout the phase leg, equal semiconductor exploitation and thermal stress on the devices. Level shift methods, on the other hand, produce heterogeneous switching pulse patterns, causing unbalance on the abovementioned criteria. For level shift methods, more spread and greater low order harmonics of output voltage requires larger output filters to be used. Therefore, phase shift method is more promising considering initial converter cost utilization. Phase shift method, also, has lower WTHD characteristics of output voltage waveform than level shift methods' in return for higher total number of switching which means higher switching loss for the same amplitude modulation and frequency modulation indices. Level shift methods, compared to each other, have similar total number of switching and semiconductor usage manner. However, PD method, generally, stands for a better alternative in terms of output voltage harmonics and WTHD value throughout different $m_a$ and $m_f$ values.

## 5. References

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