The Combination of Newton-Raphson Method and Curve-Fitting Method for PWM-based Inverter

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ABSTRACT

This paper presents the combination of two different methods to perform the waveform analysis for PWM-operated inverter. The two techniques are Newton-Raphson method and Curve-Fitting as a PWM concept to operate PWM-based inverter, the proper solutions of switching angles can valuate the initial values by using the Newton-Raphson method with the wide-step calculation of modulation indices. The solutions are then compared using a curve in order to study the behavior. Then, the Curve-Fitting method is used to estimate the missing solutions between any points of wide-step calculation. This combination method can estimate the probable solutions that cannot be solved by Newton-Raphson method in a wide-ranging of the modulation index and reduce the calculation time. PWM-based inverter, which is obtained the switching angles by Newton-Raphson method and the combination of two different methods, is verified by the simulation results showing faster performance with improved Total Harmonic Distortion (THD) than both methods alone when compared the same values of switching angles.

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1. INTRODUCTION

PWM-based Inverter is DC-AC converter using pulse-width modulation (PWM) technique to improve the output waveform with the aim of reducing the total harmonics distortion (THD). In addition, Voltage-Source Inverter (VSI) and Current-Source Inverter (CSI) are two different types of inverters [1], [2]. PWM-based Inverters are commonly used in applications including Adjustable Speed Drive (ASD) [3], Uninterrupted Power Supply (UPS) [4], [5], active power filter [6], Flexible AC transmission systems (FACTS) [7], [8], voltage compensators [9], and renewable energy power generation [10], [11]. In this respect, various PWM techniques are proposed such as carrier-based PWM technique [12-14], carrier-less PWM technique [15], space-vector modulation technique [16-18], and selective harmonic elimination technique [19].

The inverter's development research challenges nowadays are investigating the novel PWM scheme and apply it to the real-time system controller. The Selective Harmonic Elimination PWM technique, SHEPWM, is a common technique that used in various inverter topologies and applications. It needs mathematical method/algorithm to solve non-linear trigonometric system Equations to figure out the values of switching angles. Some numerical methods/algorithm are reported in many research works to solve these Equations. These methods are Newton-Raphson Method [20], Genetic Algorithm [21], Homotopic

Algorithm [22], Particle Swarm Optimization [23], Ant Colony Optimization [24], Resultant Theory Method [25]. These methods are associated with the inherited different advantages and disadvantages such as complex procedure, and extra processing times.

This paper presents the combination of Newton-Raphson method and Curve-Fitting method to perform the waveform analysis for PWM-based inverter and compares the results with the original Newton-Raphson method. PWM-based inverter topology, SHEPWM technique, analytical method for SHEPWM have explained accordingly in this paper and simulation results validate the usage of proposed method for SHEPWM.

2. PWM-BASED INVERTER TOPOLOGY

An H-bridge inverter is a universal inverter topology for various power electronics applications with a few number of circuit elements, also be known as Full-bridge inverter. This structure includes four power switches and a DC source whereas Va is the output terminal which connects to load that illustrates in Figure 1(a). It can generate three levels different voltage outputs such as positive voltage, +Vdc, negative voltage, -Vdc, and zero-voltage, its operated waveforms are illustrated in Figure 1(b).

To obtain the positive output voltage, Sa1 and Sa4 are turned on. On the other hand, while Sa2 and Sa3 are turned on, the negative output voltage is generated. Moreover, there are two patterns to obtain zero voltage at the output terminal those are turned on by Sa1, Sa3 and Sa2, Sa4. With the patterns to obtain zero-voltage is called the overlap signals. Several PWM techniques are proposed for controlling H-bridge inverter to produce output voltage waveform that approximates closely to a sine waveform which can reduce the total harmonics distortion (THD) of the output voltage.

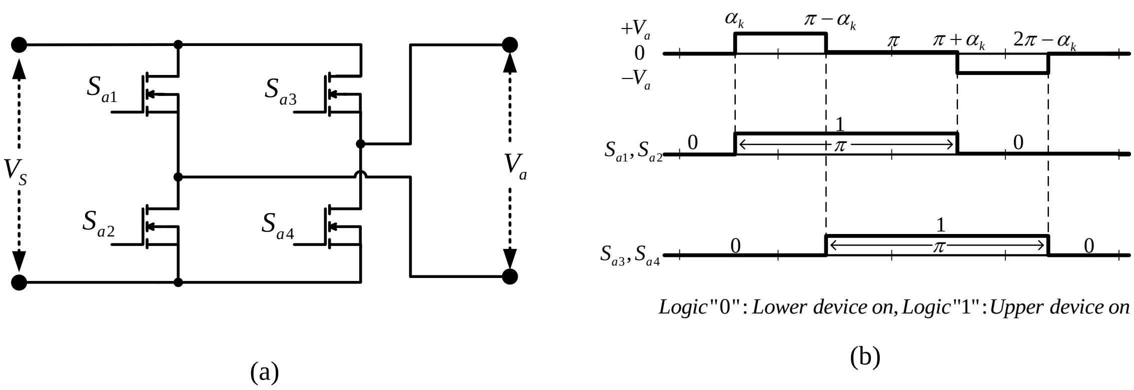


Figure 1. (a) H-bridge inverter circuit and (b) its operated waveforms

3. SELECTIVE HARMONIC ELIMINATION PWM TECHNIQUE

There are several pulse-width modulation (PWM) techniques were proposed in the last decade for controlling VSI inverter topologies to produce the output voltage that approximates closely to a sinewave form with reduced total harmonics distortion (THD) of the output voltage.

SHEPWM, its scheme is given in Figure 2, is the determination of the switching patterns by selecting unwanted harmonics of the expected output waveform to eliminate, normally, the frequency components those nearest fundamental frequencies are selected to eliminate, but remaining the fundamental component, 50Hz or 60Hz, by computation of the proper conducting angles (α_k) on the first quarter of a cycle of the output voltage of the H-bridge inverter between the range of 0 to $\pi/2$; it can be written in the form of the Fourier series expansion of the symmetric waveform given in Equation (1). As a symmetrical alternative stepped waveform, the proper conducting angles on the rest three quarters, 2nd, 3rd, and 4th quarters, are calculated by using the proper conducting angles of the first quarter of a cycle as the reference to complete a cycle of waveform generation is shown in Table 1.

$$V_n = \frac{4}{n\pi}\sum_{k=1}^{m}\left((-1)^{(k-1)} \cdot \cos\left(n\alpha_k\right)\right) \quad (1)$$

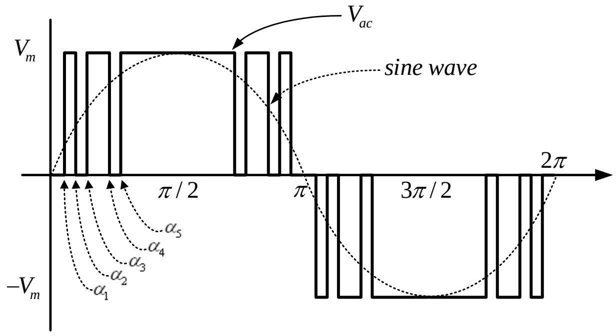


Figure 2. SHEPWM scheme output waveform

where V_n is the harmonic components, n is an odd harmonic order, k is the number of switching angles, and $(m-1)$ is the number of selected unwanted harmonics. The function of the switching angles in trigonometric terms is described in the harmonic components. In addition, the number of switching angles in the computation process depends on the number of selected unwanted harmonics.

Table 1. The Switching Pattern Calculation Guide

The Quarters	Switching Angles
First quarter	$\alpha_1, \alpha_2, \ldots, \alpha_{s-1}, \alpha_s$
Second quarter	$\alpha_{s+1} = \pi - \alpha_s, \alpha_{s+2} = \pi - \alpha_{s-1}, \ldots, \alpha_{2s-1} = \pi - \alpha_2, \alpha_{2s} = \pi - \alpha_1$
Third quarter	$\alpha_{2s+1} = \pi + \alpha_1, \alpha_{2s+2} = \pi + \alpha_2, \ldots, \alpha_{3s-1} = \pi + \alpha_{s-1}, \alpha_{3s} = \pi + \alpha_s$
Fourth quarter	$\alpha_{3s+1} = 2\pi - \alpha_s, \alpha_{3s+2} = 2\pi - \alpha_{s-1}, \ldots, \alpha_{4s-1} = 2\pi - \alpha_2, \alpha_{4s} = 2\pi - \alpha_1$

For example, PWM-based inverter operation requests to generate the output voltage with 4 orders of eliminated unwanted harmonics, 3rd,5th, 7th, and 9th harmonic which are the nearest to the fundamental frequency. This operation needs five appropriate switching angles for computation process ($\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$). Following that, Equation (2) is a term of the fundamental component. The fundamental magnitude of the output voltage is described by the right-hand side of the Equation. Additionally, the Mi in Equation (2) represents modulation index that is the ratio of the magnitude voltage of the fundamental component (V_1) and the DC voltage source of the inverter (V_{dc}), following Equation (7). The numerals 3, 5, 7 and 9 in Equations (3), (4), (5), and (6) respectively are the numbers of unwanted harmonics selected for elimination, zero on the right-hand side of the Equations are described. The THD calculation of the output voltage can use Equation (8).

$$\cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3) - \cos(\alpha_4) + \cos(\alpha_5) = Mi\frac{\pi}{4} \tag{2}$$

$$\cos(3\alpha_1) - \cos(3\alpha_2) + \cos(3\alpha_3) - \cos(3\alpha_4) + \cos(3\alpha_5) = 0 \tag{3}$$

$$\cos(5\alpha_1) - \cos(5\alpha_2) + \cos(5\alpha_3) - \cos(5\alpha_4) + \cos(5\alpha_5) = 0 \tag{4}$$

$$\cos(7\alpha_1) - \cos(7\alpha_2) + \cos(7\alpha_3) - \cos(7\alpha_4) + \cos(7\alpha_5) = 0 \tag{5}$$

$$\cos(9\alpha_1) - \cos(9\alpha_2) + \cos(9\alpha_3) - \cos(9\alpha_4) + \cos(9\alpha_5) = 0 \tag{6}$$

To solve the non-linear system Equations to figure out the values of alphas, several papers presented mathematical methods or algorithms such as Newton-Raphson Method, Genetic Algorithm, Homotopic Algorithm, Particle Swarm Optimization, Ant Colony Optimization, Resultant Theory Method. Those mentioned methods and/or algorithms are advanced and complicated mathematical techniques. Moreover, the real-time calculation is hardly implemented due to the complex procedure and extra-time of the calculation process. Generally, the mentioned mathematical methods or algorithms are applied on the computer to solve the nonlinear system Equations to calculate the values of alphas as a group of needed solutions and stored in a look-up table as a programmed PWM. Thus, the challenges of this research area are for reducing procedure and time of calculation.

$$Mi = \frac{V_1}{Vdc} \tag{7}$$

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty}\left(\frac{1}{n}\sum_{k=1}^{m}(-1)^{(k-1)}\cdot\cos\left(n\alpha_k\right)\right)^2}}{\sum_{k=1}^{m}(-1)^{(k-1)}\cdot\cos\left(\alpha_k\right)} \tag{8}$$

4. ANALYTICAL METHOD FOR SHEPWM

4.1. Newton-Raphson Method

Newton-Raphson method, NR method, is the simplest approach and the most widely used to figure out all root-locating of non-linear Equation and nonlinear system Equations as well. This method requires the initial guess solution or a group of them in the case of system Equations. Then, the initial guess solution is improved to obtain a better second solution and it becomes the initial guess solution for the second round. This procedure is repeated until the error of the current solution is acceptable which is compared to the previous solution. The flowchart for Newton-Raphson method is given Figure 3.

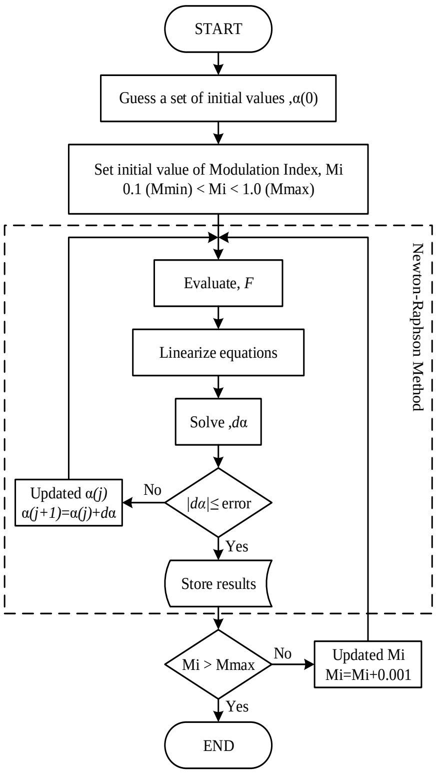


Figure 3. Flowchart of Newton-Raphson Method

In the case of PWM-based Inverter that needs multi-switching angles to operate the output waveform, the Newton-Raphson method procedure starts by guessing the initial solution following Equation (9).

$$\alpha^j = \left[\alpha_1^j \; \alpha_2^j \; \alpha_3^j \; \alpha_4^j \; \alpha_5^j\right]^T \tag{9}$$

Next step, forming two non-linear system matrixes of Equations (2), (3), (4), (5), and (6) as shown in Equations (10), and (11). Also, one corresponding harmonic amplitude matrix shows in Equation (12).

$$F(\alpha) = \begin{bmatrix} \cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3) - \cos(\alpha_4) + \cos(\alpha_5) \\ \cos(3\alpha_1) - \cos(3\alpha_2) + \cos(3\alpha_3) - \cos(3\alpha_4) + \cos(3\alpha_5) \\ \cos(5\alpha_1) - \cos(5\alpha_2) + \cos(5\alpha_3) - \cos(5\alpha_4) + \cos(5\alpha_5) \\ \cos(7\alpha_1) - \cos(7\alpha_2) + \cos(7\alpha_3) - \cos(7\alpha_4) + \cos(7\alpha_5) \\ \cos(9\alpha_1) - \cos(9\alpha_2) + \cos(9\alpha_3) - \cos(9\alpha_4) + \cos(9\alpha_5) \end{bmatrix} \tag{10}$$

$$\left[\frac{\partial F}{\partial \alpha}\right]^j = \begin{bmatrix} -\sin(\alpha_1) & \sin(\alpha_2) & -\sin(\alpha_3) & \sin(\alpha_4) & -\sin(\alpha_5) \\ -\sin(3\alpha_1) & \sin(3\alpha_2) & -\sin(3\alpha_3) & \sin(3\alpha_4) & -\sin(3\alpha_5) \\ -\sin(5\alpha_1) & \sin(5\alpha_2) & -\sin(5\alpha_3) & \sin(5\alpha_4) & -\sin(5\alpha_5) \\ -\sin(7\alpha_1) & \sin(7\alpha_2) & -\sin(7\alpha_3) & \sin(7\alpha_4) & -\sin(7\alpha_5) \\ -\sin(9\alpha_1) & \sin(9\alpha_2) & -\sin(9\alpha_3) & \sin(9\alpha_4) & -\sin(9\alpha_5) \end{bmatrix} \tag{11}$$

$$K = \left[\frac{\pi}{4} \; 0 \; 0 \; 0 \; 0\right]^T \tag{12}$$

After finished guessing the initial values and setting the matrixes, calculate the value of *F* following the Equation (13). Then, using $F(\alpha) = K$ to linearize about α^j (14).

$$F(\alpha^j) = F^j \tag{13}$$

$$F^j = \left[\frac{\partial f}{\partial \alpha}\right]^j d\alpha^j = K \tag{14}$$

Where

$$\left[\frac{\partial f}{\partial \alpha}\right]^j = \begin{bmatrix} \frac{\partial f_1}{\partial \alpha_1} & \frac{\partial f_1}{\partial \alpha_2} & \frac{\partial f_1}{\partial \alpha_3} & \frac{\partial f_1}{\partial \alpha_4} & \frac{\partial f_1}{\partial \alpha_5} \\ \frac{\partial f_2}{\partial \alpha_1} & \frac{\partial f_2}{\partial \alpha_2} & \frac{\partial f_2}{\partial \alpha_3} & \frac{\partial f_2}{\partial \alpha_4} & \frac{\partial f_2}{\partial \alpha_5} \\ \frac{\partial f_3}{\partial \alpha_1} & \frac{\partial f_3}{\partial \alpha_2} & \frac{\partial f_3}{\partial \alpha_3} & \frac{\partial f_3}{\partial \alpha_4} & \frac{\partial f_3}{\partial \alpha_5} \\ \frac{\partial f_4}{\partial \alpha_1} & \frac{\partial f_4}{\partial \alpha_2} & \frac{\partial f_4}{\partial \alpha_3} & \frac{\partial f_4}{\partial \alpha_4} & \frac{\partial f_4}{\partial \alpha_5} \\ \frac{\partial f_5}{\partial \alpha_1} & \frac{\partial f_5}{\partial \alpha_2} & \frac{\partial f_5}{\partial \alpha_3} & \frac{\partial f_5}{\partial \alpha_4} & \frac{\partial f_5}{\partial \alpha_5} \end{bmatrix} \tag{15}$$

and

$$d\alpha^j = \left[d\alpha_1^j \ d\alpha_2^j \ d\alpha_3^j \ d\alpha_4^j \ d\alpha_5^j \right]^T \quad (16)$$

then, solving $d\alpha^j$ in Equation by

$$d\alpha^j = INV\left[\frac{\partial f}{\partial \alpha}\right]^j (K - F^j) \quad (17)$$

where $INV\left[\frac{\partial f}{\partial \alpha}\right]^j$ is the inverse matrix of $\left[\frac{\partial f}{\partial \alpha}\right]^j$

then, updating the initial values by Equation

$$\alpha^{j+1} = \alpha^j + d\alpha^j \quad (18)$$

At this point, repeating the process from Equations (13) to (18), until $d\alpha^j$ is satisfied to the desired degree of accuracy, and the solutions must satisfy the condition as Equation (19) follow:

$$0 < \alpha_1 < \alpha_2 < \alpha_3 < \alpha_4 < \alpha_5 < \frac{\pi}{2} \quad (19)$$

4.2. Curve Fitting Method

Curve fitting method, CF method, is one of the numerical methods by the concept of catching the trend of initial data and constructing a curve across the total range of initial data that has the proper line of fitting to a group of data points. Fitted curves can be used as an assistance method for approximate the trend of data and prediction of the relationships among two or more data. There are many common methods for curve fitting such as Nonlinear, Smoothing, and Least Squares. This paper selected Least Squares (LS) for curve fitting consideration. LS curve fitting method minimizes the square of the error between the initial data and the values approximated by the polynomial Equation. However, the widely different data point among the majority data, LS curve fitting is sensitivity to outliers from a curve plot. So that, the initial group of data should be selected by properly point to be a guide for fitting a curve.

LS curve fitting uses Polynomial function to achieve the curve thoroughly the data points. The degree of the polynomial Equation must be carefully chosen for prediction the possible of the exact solutions. For example, a first-degree polynomial Equation can be used for curve fitting to construct the straight line with slope to connect any two data-points, a second-degree polynomial Equation can be used for curve fitting to construct the simple curve to three data points, a third-degree polynomial can be used for curve fitting gives a smoother curve to four data points, and the fitted curve would be smoother curve when increasing the degree of polynomial Equation. Polynomial function for fitting the data is obtained by Equation (20) or (21).

$$y(x, w) = w_0 + w_1 x + w_2 x^2 + ... + w_M x^M \quad (20)$$

or

$$y(x, w) = \sum_{j=0}^{M} w_M x^M \quad (21)$$

where *M* is the degree of the polynomial.

$$E(w) = \frac{1}{2}\sum_{n=1}^{N}\left\{\left(\sum_{j=0}^{M} w_M x^M\right) - t_n\right\}^2 \quad (22)$$

Error Function Minimization is obtained by Equation (22). It is a sum of squares of the errors between the predictions for each data point and the target value.

4.3. Numerical Techniques NR-CF Combination

The Newton-Rapson method is the most used for figuring out the solution of SHEPWM technique, but it takes more time for the calculation process. Additionally, Curve fitting method can be used for solving this solution but it needs a group of guide solutions for fitting the solution. So that, Curve fitting method needs another method for making a guide of solutions such as Newton-Rapson method. Cooperative solving solutions of the switching angles is combined by making a ten-points guide solutions at 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 of the modulation index that given by using Newton-Rapson method on Figure 5(a) which is used for being a guide to Curve fitting method to solve the solutions between a gap of any points of guide solutions, starting on 0.1 until 1.0 of the modulation index. In addition, each point of the modulation index has five separate switching angles. The flowchart for NR-CF combination is given Figure 4.

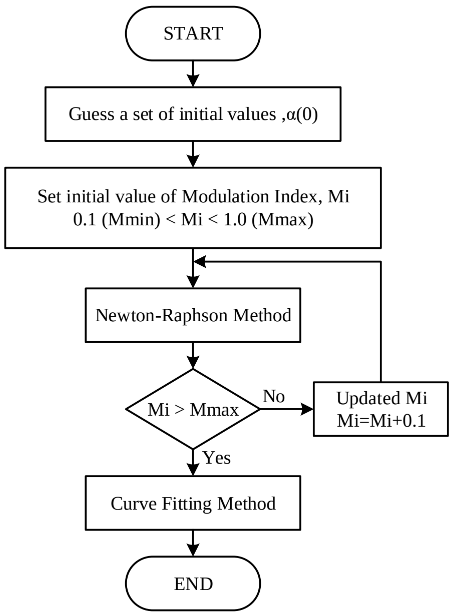


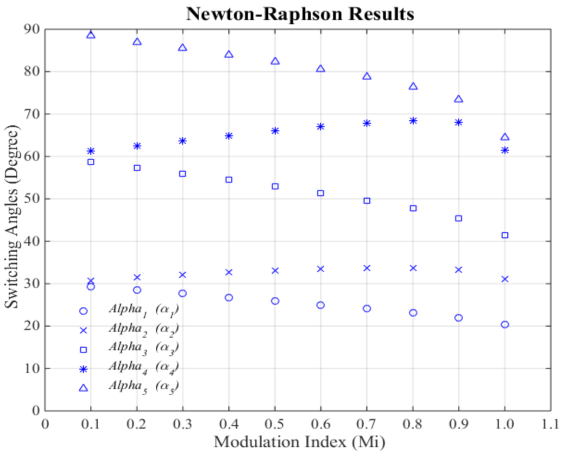
Figure 4. Flowchart of NR-CF combination

The 1st, 2nd, 3rd,5th, and 9th order Curve fitting method are applied by using the group of guide solutions on Figure 5 to predict the solution of switching angle. The straight-line solutions are only given by 1st order Curve fitting while increased the number of order the lines become curves until the 9th order of Curve fitting which gives the curves to tail with the solution guide.

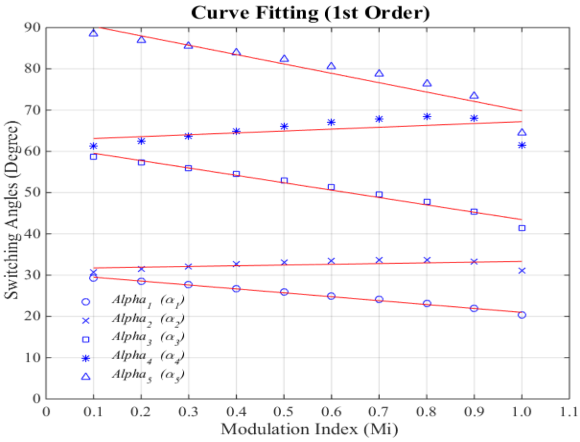
5. SIMULATION RESULTS

PWM-based Inverter simulation using five switching angles from the analytical results of Newton-Rapson and Curve fitting method are shown in Table 2. These switching angles are selected at Mi=0.85 to operate H-bridge inverter for releasing the PWM-based output waveform and showing its harmonic spectrums.

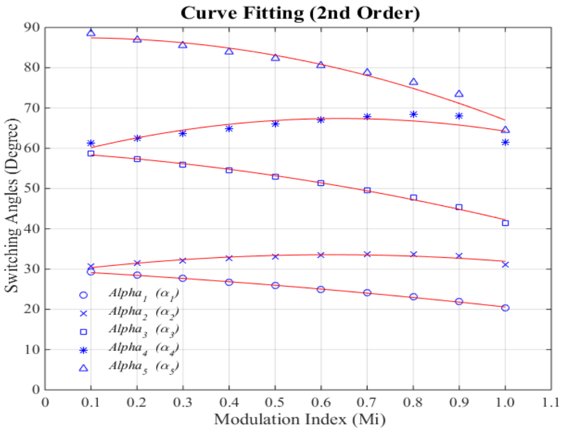
The switching angles of the Newton-Rapson method are applied to this simulation to show the output voltage waveform and its harmonic spectrums in Figure 6. To compare the results, 1st, 3rd, and 9th order Curve fitting method are also shown in Figure 7, Figure 8, and Figure 9 respectively. As it can be seen, the output voltage waveform on the time domain of Figure 6(a), Figure 7(a), Figure 8(a), and Figure 9(a) are not clearly to see the their different, so that, the simulation results on the frequency domain are represented the magnitude of harmonics.



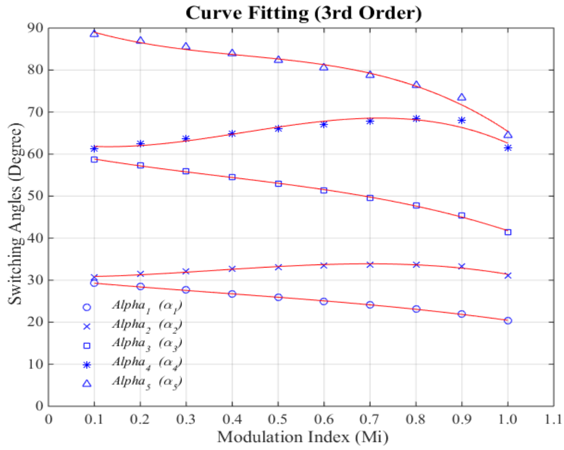
(a)



(b)



(c)



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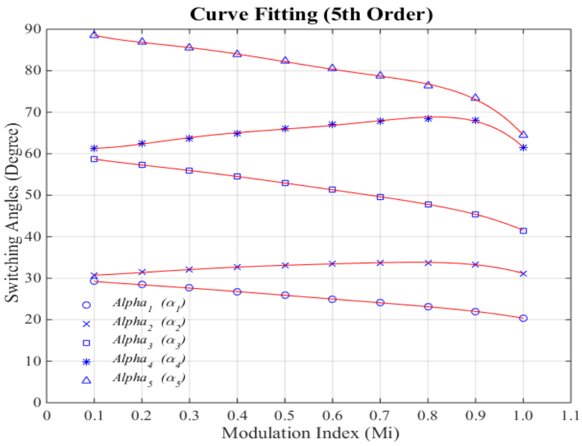
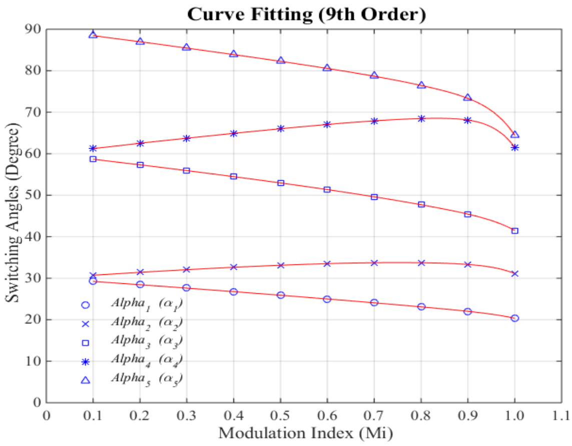
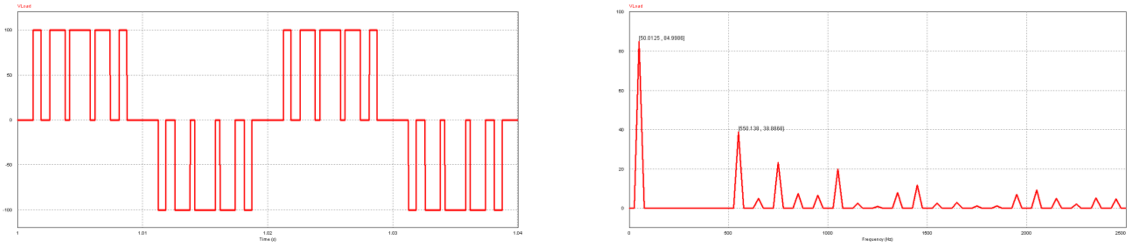


(e)



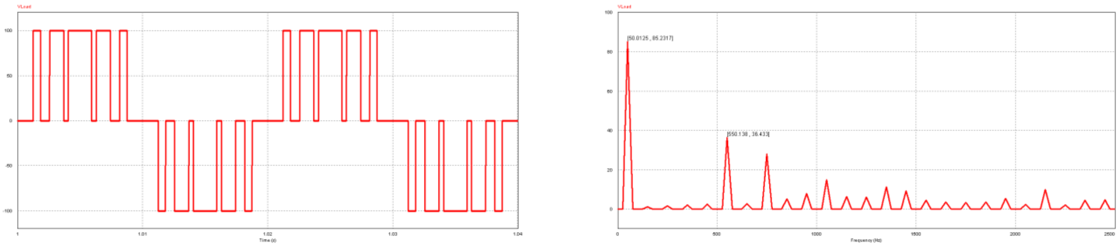
(f)

Figure 5. Switching angle solutions Vs Modulation Index (a) Newton-Raphson method-Based, (b) 1st Order Curve fitting method-Based, (c) 2nd Order Curve fitting method-Based, (d) 3rd Order Curve fitting method-Based, (e) 5th Order Curve fitting method-Based, and (f) 9th Order Curve fitting method-Based



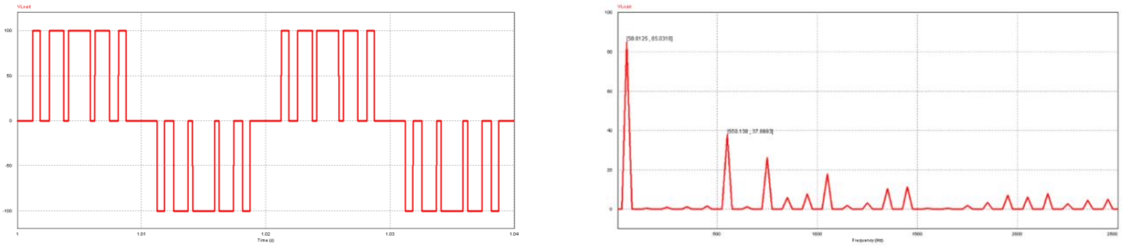
(a) (b)

Figure 6. (a) simulation result of PWM-Based Inverter of output voltage at Mi=0.85 and (b) its spectrums releasing by using Newton-Raphson method



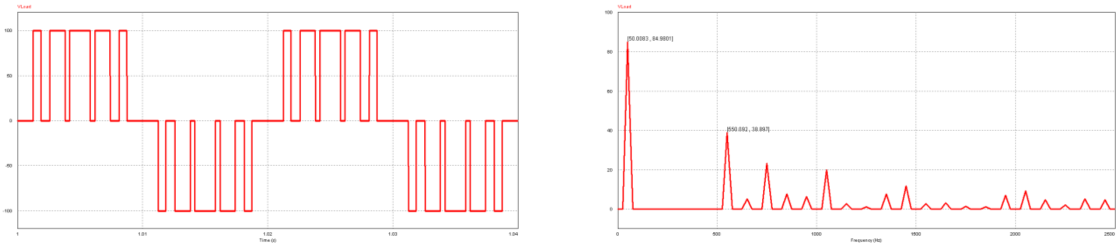
(a) (b)

Figure 7. (a) simulation result of PWM-Based Inverter of output voltage at Mi=0.85 and (b) its spectrums releasing by using 1st order Curve fitting method



(a) (b)

Figure 8. (a) simulation result of PWM-Based Inverter of output voltage at Mi=0.85 and (b) its spectrums releasing by using 3rd order Curve fitting method



(a) (b)

Figure 9.(a) simulation result of PWM-Based Inverter of output voltage at Mi=0.85 and (b) its spectrums releasing by using 9th order Curve fitting method

The 3rd, 5th, 7th, and 9th harmonic spectrums in Figure 6(b) are eliminated that represents the unwanted harmonics elimination of SHEPWM technique by using the Newton-Rapson method. On the other hand, PWM-based Inverter using switching angles based on Curve fitting method cannot eliminate the 3rd, 5th, 7th, and 9th harmonic, except 9th order Curve fitting method which is almost completely mocking the switching angle solution of Newton-Rapson method.

Table 2. The analytical results of Newton-Rapson and Curve fitting method at *Mi* = 0.85

Switching angle	Newton-Rapson method	1st Order Curve fitting method	3rd Order Curve fitting method	9th Order Curve fitting method
α_1	22.5835°	22.4083°	22.4872°	22.5867°
α_2	33.6015°	33.0696°	33.3353°	33.6096°
α_3	46.6433°	46.1416°	46.3877°	46.6515°
α_4	68.4980°	66.5218°	67.4564°	68.5246°
α_5	75.0978°	73.2437°	74.1309°	75.1214°

The total harmonics distortion (THD) of this PWM-Based Inverter simulation based on 9th order Curve fitting method gives the same value with Newton-Rapson method. Nevertheless, the THD values based on 1st order Curve fitting method and 3rd order Curve fitting method is also given by this simulation circuit with the almost the same value of Newton-Rapson method, the THD values are displayed in Table 3. Additionally, this simulation using 100-volt DC for supplying the inverter and Mi = 0.85, the expected magnitude of fundamental component, V_f, would be 85-volt. Table 3 shows that any value of V_f is given around the expected value.

Table 3. Thd and the magnitude of fundamental component at *Mi* = 0.85

Switching angle	Newton-Rapson method	1st Order Curve fitting method	3rd Order Curve fitting method	9th Order Curve fitting method
THD	55.54%	55%	55.39%	55.54%
V_f	84.99 V.	85.22 V.	85.03 V.	84.98 V.

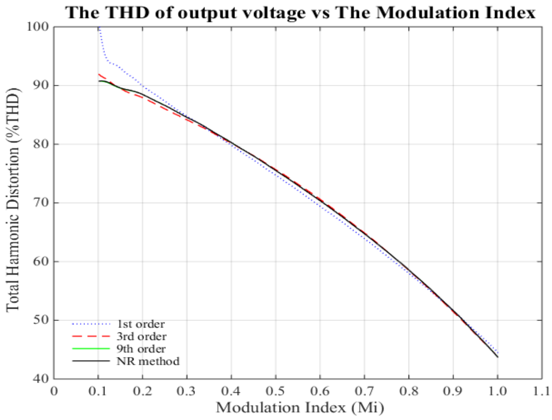


Figure 10. THD Vs. Modulation Index

In addition, The THD values of PWM-Based Inverter simulation based on Newton-Rapson, 1st order Curve fitting, 3rd order Curve fitting, and 9th order Curve fitting method are compared in a wide-range of the modulation index, as shown in Figure 10. Only for the THD values curve of 9th order Curve fitting method tails with the values of the Newton-Rapson method.

6. CONCLUSION

This paper has proposed the combination of Newton-Raphson and Curve-fitting methods for PWM-operated Inverter. The analytical derivation for solving the switching angles of SHEPWM technique is explained and compared with the simulation results of lone Newton-Raphson method and the combination.

The simulation and analytical results verify that the combination of Newton-Raphson method and the 9th order Curve fitting method gives the same solution when compared to lone Newton-Raphson method. Even, the calculation procedure of this combination has more steps compared to lone Newton-Raphson method, but this combination spends 2.5 seconds for solving 900 groups of solutions of switching angles for 0.1 to 1.0 of the modulation index for PWM-based Inverter while lone Newton-Raphson method spends more than 200 seconds.

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