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International Journal of Engineering, Science and Technology
Vol. 7, No. 3, 2015, pp. 109-117

INTERNATIONAL JOURNAL OF ENGINEERING, SCIENCE AND TECHNOLOGY
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A simple output voltage control scheme for single phase wavelet modulated inverters

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Abstract

Wavelet based techniques have been extensively used in various power engineering applications. Recently, wavelet has also been proposed to generate switching signal for single-phase pulse-width-modulated (PWM) dc-ac inverter. The main advantage of the wavelet modulated (WM) scheme is that a single synthesis function, derived using wavelet theory, can be used to generate the switching signal as well as to model the inverter output which is not possible with other modulation techniques. But, unlike other popular PWM schemes e.g. sinusoidal PWM, which offers independent control to both magnitude and frequency of fundamental inverter output voltage, the existing WM scheme can only control the frequency of the fundamental. This paper proposes an improved WM scheme for single-phase H-bridge voltage source inverter. The main emphasis of the research work carried out in this paper is to find a feasible solution to the magnitude control problem for existing WM scheme.

Keywords: PWM inverter; single-phase four pulse voltage source inverter; wavelet inverter; wavelet modulation (WM)

DOI: http://dx.doi.org/10.4314/ijest.v7i3.13S

1. Introduction

Carrier-based PWM techniques, e.g. sinusoidal pulse width modulation, SPWM, are classical and widely used methods to generate inverter switching signal. SPWM is the most popular scheme owing to its simplicity and ease of implementation. The basic idea of SPWM method is to compare a high frequency carrier signal, a triangular waveform, with a sinusoidal modulating waveform of the same frequency as desired inverter output to obtain the inverter switching instants. In the linear modulation region, SPWM provides an ac output voltage that varies linearly as a function of the modulation index and harmonics are shifted towards higher frequency bands. To extend the linear modulation range and to avoid the distortion in the output of three-phase inverter in over-modulation region, several modifications to the basic SPWM scheme (like zero sequence signal injection and 60^0 modulations) were introduced resulting in different nonsinusoidal carrier-based PWM schemes (Holtz, 1992; Holmes et al, 2003; Boost et al, 1988). Several other techniques has been proposed in the literature to improve the performance of dc-ac inverters like Random PWM (RPWM), Selective harmonic elimination (SHE), space vector modulation (SVM) etc. (Ranganathan, 1997, Habetler et al, 1991, Wells et al, 2005, Kato, 1999).

The More recently, a completely different and a promising PWM switching method, based on wavelet modulation (WM) has been reported in Saleh et al, 2009, and Saleh et al, 2011 for single phase inverters. The basic idea of this approach is to view inverter switching instants as groups of nonuniform recurrent samples of a continuous time (CT) signal and to view variable width switching pulses as reconstruction of sinusoidal reference modulating signal from these nonuniform samples. For implementation of this idea, a scale-based linearly combined nondyadic scaling function, capable of creating nonuniform recurrent sampling and a nondyadic synthesis scaling function which is capable of reconstructing the signal from its nonuniform recurrent samples has been developed using basic Haar wavelet functions. The WM scheme has been tested for open loop steady-state performance testing of a single-phase H-bridge voltage-source (VS) inverter using MATLAB simulations. Higher magnitudes of fundamental components and lower harmonics content than those obtained from the conventional PWM and RPWM inverters are reported. However, a major problem with WM scheme in its present form is that it does not provide true control on inverter output voltage. Unlike other popular PWM schemes, e.g. SPWM, which provides independent control to both frequency and magnitude of the fundamental inverter output voltage, WM can only control the frequency of the inverter output voltage by means of controlling the frequency of reference sinusoidal modulating signal. Therefore, WM scheme in its present form cannot control inverter output voltage magnitude at a constant switching frequency.

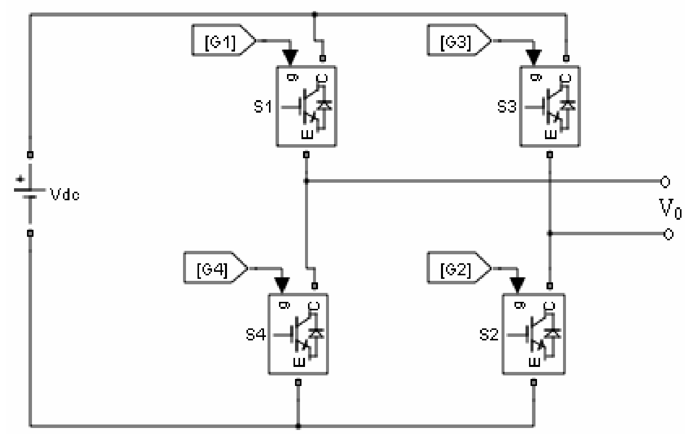


Figure 1. Single phase four pulse H-bridge inverter

Considering the limitations of the basic WM scheme as discussed above, the main emphasis of the research work carried out in this paper is to find a feasible solution to the magnitude control problem and also to present some important investigations related to implementation and harmonics performance issues of existing WM scheme. The proposed wavelet modulation scheme of four pulse single phase inverter presented in the paper is implemented using a MATLAB.

2. Wavelet Modulation

A Wavelet is a widely used technique in many scientific and engineering fields and has also been extensively used in several power engineering related applications (Heydt et al, 1997, Dwivedi, and Singh, 2009 and 2010). A brief and critical review of the basic-WM scheme (Saleh et al, 2009) is provided in this section. As, the start and end of a rectangular PWM switching pulse is defined by the two time instants or time samples and the width of each of these pulses varies over half cycle of the sinusoidal modulating signal. Therefore, these switching instant can be viewed as groups (pairs) of non-uniform time samples generated through non-uniform sampling of the continuous time signal and rectangular pulses viewed as sets of interpolation functions that aim to recover a sinusoidal signal from its samples. Further, the periodic nature of the sinusoidal reference signal makes it a non-uniform recurrent (periodic) sampling-reconstruction case. The complex mathematical derivation should be placed in the appendix of the paper, which is placed at end of the paper.

As demonstrated in (, this analogy provides a way to generate PWM switching pulses using nonuniform recurrent sampling and reconstruction (through interpolation) of continuous time sinusoidal modulating signal. Though, the generation of switching pulses using nonuniform sampling and Lagrange interpolation functions is a complex procedure but, it provides a theoretical foundation (to develop a model of the inverter operation using concepts of the sampling theorem) for a naval way of generating PWM switching actions. Apart from computational complexity, another problem with the interpolation based pulse generation method is that it needs a carrier signal to generate the nonuniform time samples. Therefore, in (Saleh et al, 2009, and Saleh et al, 2011) nondyadic-type wavelet multiresolution analysis (MRA) which is capable of supporting a nonuniform sampling generation and reconstruction process has been suggested to device a new class of carrier-less switching scheme.

Wavelets (Chui, 1997, and Daubechies, 1988) are defined by the wavelet function $\psi(t)$ (also called the mother wavelet) and a scaling function $\varphi(t)$. The Haar wavelet's mother wavelet function $\psi_H(t)$ can be described as

$$\psi_H(t) = \begin{cases} 1 & 0 \le t < 1/2, \\ -1 & 1/2 \le t < 1, \\ 0 & \text{otherwise}; \end{cases} \tag{1}$$

and its scaling function $\varphi_H(t)$ can be described as

$$\phi_H(t) = \begin{cases} 1 & 0 \le t < 1, \\ 0 & \text{otherwise}. \end{cases} \tag{2}$$

In order to represent a signal at different resolution levels, the used scaling function must be dilated (scaled) and translated (shifted).

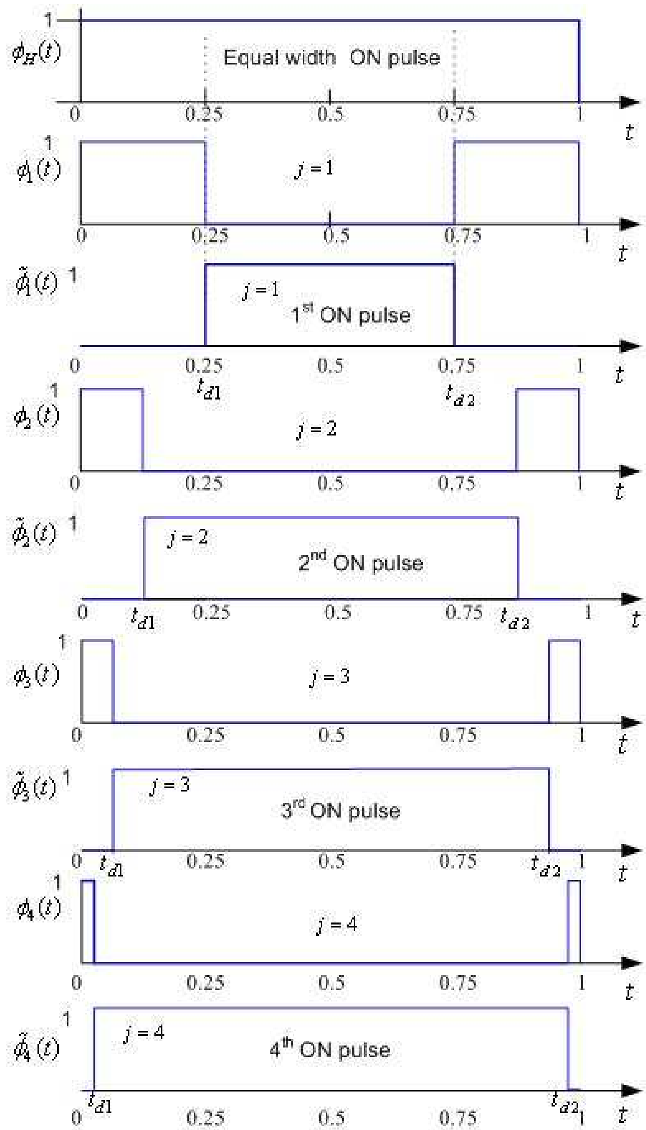


Figure 2. Variable width switching pulse generation using analysis function & synthesis scaling function at normalized time scale

Scaling and translation of the basic Haar wavelet and scaling function results in a family of scaling function presented as

$$(\phi_H)_{j,k}(t) = \phi_H(2^j t - k), \tag{3}$$

where, $j = 1, 2, 3, \ldots n \in Z$, is the scaling factor and $k = 0, \ldots\ldots, 2^j - 1$, is the translation factor. Among the large family of different mother wavelets and associated scaling function, only Haar scaling functions qualify to accurately model rectangular shaped ON/OFF switching pulses. Therefore, to generate variable width switching instants, two Haar scaling functions with same scale parameters but different translation parameters (time shift) are combined to construct a new scaling function given as

$$\phi_j(t) = \phi_H(2^{j+1} t) + \phi_H(2^{j+1}(t - 1 + 2^{-(j+1)})). \tag{4}$$

This scale-based linearly combined scaling function $\phi_j(t)$ creates two samples at each dilation (scale) j. These samples are created at

$$t_{d1} = 2^{-(j+1)},$$
$$t_{d2} = 1 - 2^{-(j+1)}, \tag{5}$$

with respect to an arbitrary origin. The new analysis scaling function thus constructed is subtracted from the original Haar scaling function to obtain the synthesis function expressed as

$$\tilde{\phi}_j(t) = \phi_{H\,j}(t) - \phi_j(t). \tag{6}$$

This nondyadic synthesis function which is the dual of the analysis function is capable of generating variable width inverter switching signal (Saleh et al, 2009).

Let f_m, be the desired frequency of the inverter output voltage and D is the number of desired ON switching pulses per cycle. To explain the working of WM scheme, at first, these N numbers of ON pulses are assumed to be of equal width T_m/D, where a next ON pulse starts immediately after the previous ON pulse. Hence, these pulses can be modelled using the Haar scaling function ϕ_H that has a normalized (by T_m/D) interval of support [0 1]. But, PWM scheme requires variable width ON/OFF switching pulses. Therefore, the main idea in the basic WM pulse generation scheme is to change the width of successive ON switching signal using $\phi_j(t)$ and $\tilde{\phi}_j(t)$ by changing the value of j as shown in the Figure 2.

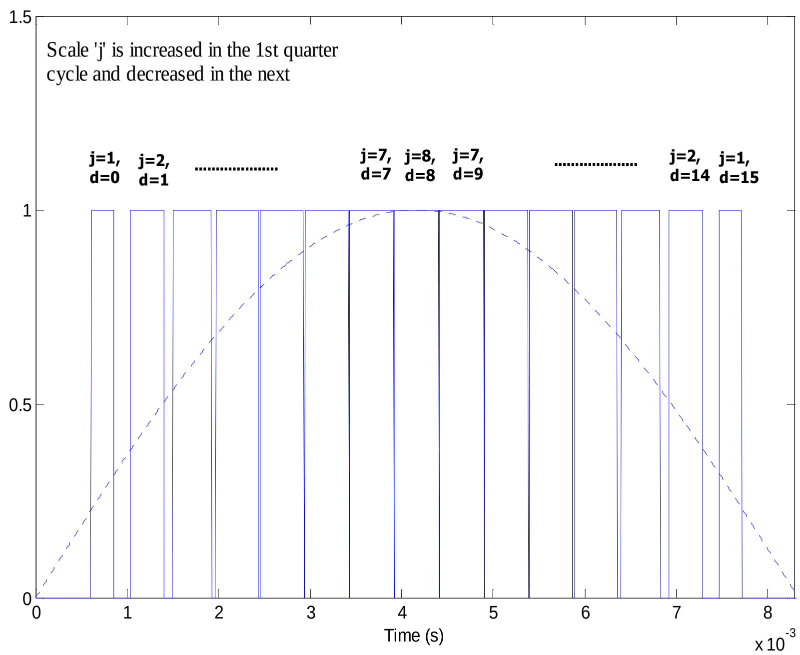


Figure 3. WM based switching pulses with D=30, and fm=60 Hz

The algorithmic implementation of the above approach requires calculations of switching instants of successive ON pulses using (5). Since t_{d1} and t_{d2} are defined with respect to an arbitrary origin therefore, for each successive pulse this arbitrary origin is shifted forward in time by T_j, which is its interval of support. Therefore, switching instants with respect to the zero crossing of reference modulating signal can be calculated as

$$t_{d1} = T_j.[d + 2^{-(j+1)}],$$
$$t_{d2} = T_j.[d + 1 - 2^{-(j+1)}], \quad \text{for } d = 0, 1, 2, ..., D-1, \tag{7}$$

where, t_{d1} and t_{d2} represents start and end of an ON pulse. In the present study T_j has been calculated as $T_j = T_m/D$ to make the analysis simple.

Owing to the quarter-cycle symmetry of sinusoidal reference modulating signal, the width of inverter ON pulses needs to be increased successively in the first-quarter of each half-cycle while decreased successively in the second-quarter of each half-cycle.

Therefore, scale j is required to be increased over the intervals $[0, (T_m/4)]$ and $[T_m/2, 3T_m/4]$ and is required to be decrease over the intervals $[(Tm/4), (T_m/2)]$ and $[3T_m/4, T_m]$. It is to be noted that scale j, which is initialised to 1 at the beginning of each half cycle, is increased by 1 for each successive pulse. Scale j takes its maximum value for the pulse occurring at the peak of sinusoidal reference modulating signal after which it decreases by 1 for each successive pulse to attain the same initial value (i.e. j=1) at the end of the half cycle.

Figure 3, shows the generated switching pulses with $D=30$ and f_m=60 Hz using the above described WM scheme for the positive half cycle. Similar pulses are obtained for the negative half cycle of the modulating wave using basic-WM scheme. This WM scheme has been applied for single-phase inverter, Figure 1, in (Saleh et al, 2009).

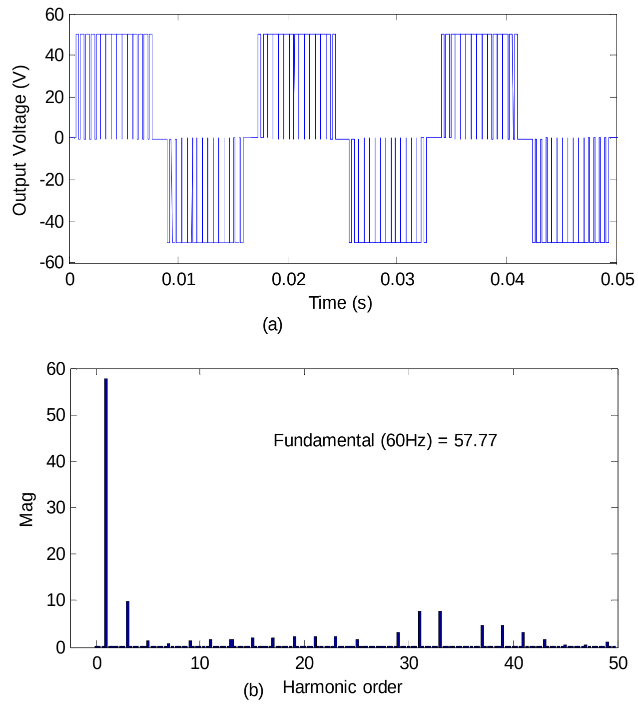


Figure 4. The switched dc-ac inverter output voltage due to basic wavelet modulation switching signals, (a) the output voltage, and (b) its spectrum

Figure 4 shows the ac voltage obtained at the output terminals of single phase inverter activated by basic-WM switching and with a 50V dc at its input and without any load connected at its output. From a simple observation of the WM switching pattern and inverter output waveform, it can be seen that practically, switching pulses (and hence, the output voltage pulses) don't offer much variation in width. Furthermore, the basic-WM scheme provides no provision to vary the width of ON/OFF switching pulses. Hence, for a particular value of D, (or switching frequency) the magnitude of fundamental output voltage remains constant. In comparisons to SPWM where magnitude of fundamental output voltage can be varied by changing the modulation index, WM scheme in its present form cannot control inverter output voltage magnitude. Extensive simulations have been performed to test the performance of basic-WM based single phase inverter at different switching frequencies and with different dead-time. Fast Fourier transform (FFT) analysis of the basic-WM inverter output voltage reveals the presence of strong low order harmonics in the output voltage spectra. Judicial selection of interval of support T_i can generate good quality ac output with harmonics content lower than those obtained using SPWM.

2. Wavelet Modulation

To improve the performance of the basic-WM, a generalized wavelet modulated (GWM) scheme is developed and presented in this section. The proposed scheme is obtained by introducing some important innovation to the basic-WM scheme. The main advantage of the WM scheme is that a single function $\tilde{\phi}_j(t)$ can be used to generate the switching signal as well as to model the inverter output which is not possible with other modulation techniques (Saleh et al, 2009).

To provide a control on the magnitude of inverter output voltage, the basic-WM scheme has been modified by introducing a new parameter μ, without affecting its basic design structure. Moreover, it can be proved that the basic-WM scheme is a special case of the proposed GWM scheme. The proposed new scale-based linearly combined scaling function $\varphi_j(t)$ is defined as

$$\varphi_j(t) = \phi_H(2^{\mu.j+1}t) + \phi_H(2^{\mu.j+1}(t - 1 + 2^{-(\mu.j+1)})), \text{ where} \mu \le 1 \quad (8)$$

It is to be noted that $\varphi_j(t)$ is also constructed using two Haar scaling functions but with a non-integer scale parameter. At each dilation j, $\varphi_j(t)$ also creates two samples with respect to an arbitrary origin at

$$t_{d1} = 2^{-(\mu.j+1)},$$
$$t_{d2} = 1 - 2^{-(\mu.j+1)}, \quad (9)$$

The proposed new synthesis function is obtain using the following expression

$$\tilde{\varphi}_j(t) = \phi_H(t) - \varphi_j(t). \quad (10)$$

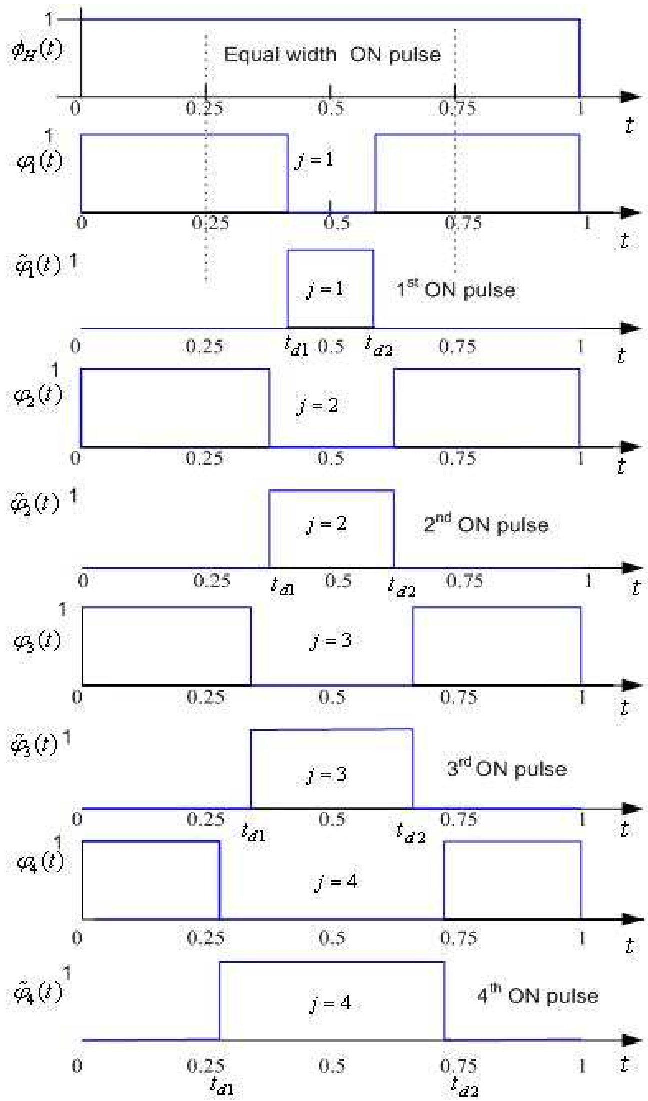
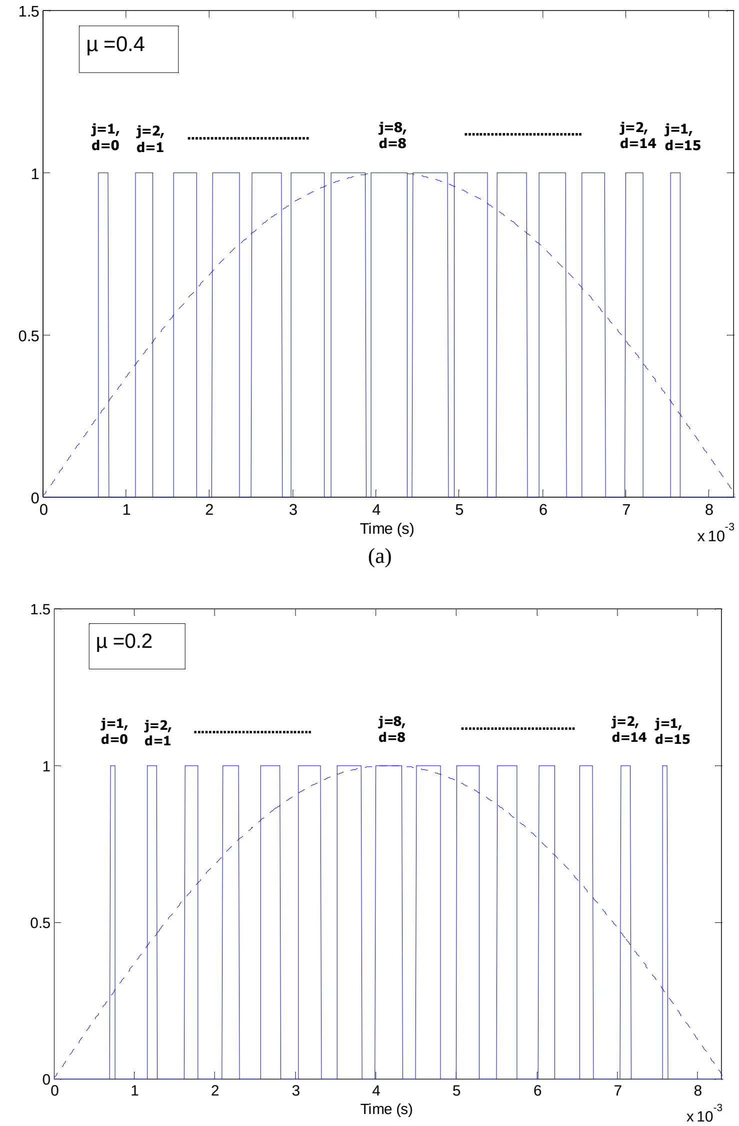


Figure 5. Variable width switching pulse generation using proposed method for μ=0.2 at normalized time scale.

Using the newly designed synthesis function $\tilde{\varphi}_j(t)$, the switching instants with respect to the zero crossing of reference sinusoidal modulating signal are generated at

$$t_{d1} = T_i.[d + 2^{-(\mu.j+1)}],$$
$$t_{d2} = T_i.[d + 1 - 2^{-(\mu.j+1)}], \quad \text{for } d = 0,1,2,....., D-1. \quad (11)$$

Equations (4)-(7) can be obtained by putting μ =1 in (8)-(11) thus proving that the basic-WM is a special case of GWM.



(a)

(b)

Figure 6. GWM based switching pulses with D=30, and f_m=60 Hz for, (a) μ=0.4, (b) μ=0.2.

The proposed GWM scheme is used to generate the gating signals for a single-phase H-bridge inverter. It is to be noted that in each inverter leg, lower switches receive complementary gating signal to that of their corresponding upper switches. Fig. 6., show the generated switching pulses for inverter switch S_1 when *D=30* and f_m=60Hz using the proposed GWM scheme for two different values of μ.

The proposed generalized wavelet modulation scheme of four pulse single-phase inverter presented in this paper is implemented using a MATLAB code and is finally converted to an equivalent SIMULINK block. Simulations have been carried out on single phase voltage source inverter using the developed SIMULINK block to analyse the performance of the proposed scheme. Tests are also carried out in order to investigate the performance of the proposed scheme with different values of μ when supplying an R-L load. For this an R − L load of 10 + j7.36 Ω is connected to the inverter output side. The dc input voltage is set to V_{DC} = 50 V.

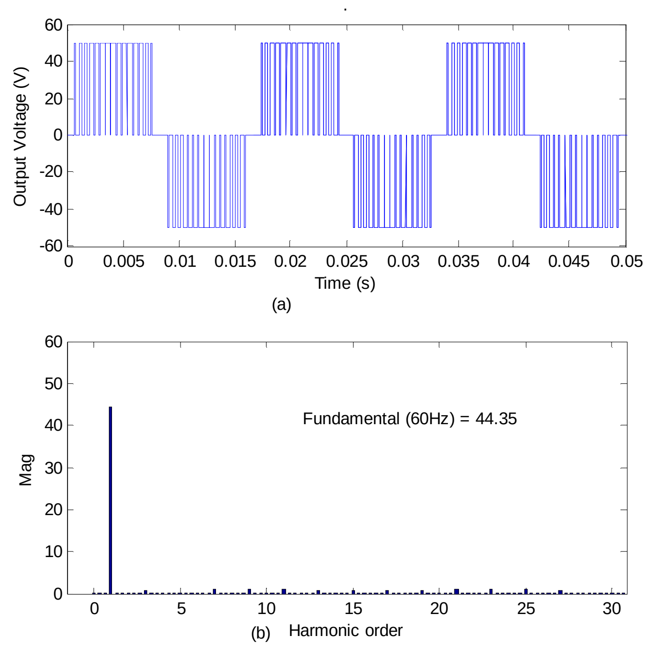


Figure 7. The switched dc-ac inverter output voltage due to generalized wavelet modulation switching signals for D=30 and μ=0.4, (a) the output voltage and (b) its spectrum

Table 1. Fundamental Inverter Output Voltage (peak) for Different Values of μ

μ	1	0.9	0.8	0.7	0.6	0.5	0.45	0.4	0.35	0.3	0.25	0.2	0.15	0.1	.05	.02	.01
V_0 (V)	57.4	56.5	55.4	53.6	51.4	48.5	46.52	44.3	41.6	38.3	34.6	30.7	24.5	17.9	9.7	4.1	2.0

Figure7, show the output voltage waveforms of single phase inverter activated with these switching pulses for μ=0.4. Figure 7(b) shows Fast Fourier transform (FFT) of the GWM inverter output voltage waveform, shown in Figure 7(a). Significant reduction in the harmonics (specially, lower order harmonics) can be observed in the output voltage spectra. From the observation of the GWM switching pattern and inverter output waveform, it can be seen that the width of the switching pulses and hence, the output voltage pulses, can be changed by changing the value of μ. Therefore, the proposed method is capable of producing a variable magnitude fundamental output voltage at inverters output terminal by varying the value of index μ. Table 1, shows the obtained magnitude of the fundamental ac output voltage for some discrete values of parameter μ.

4. Conclusions

Wavelet modulation has been found to be a promising carrier-less PWM scheme as a single synthesis function, derived using wavelet theory is used to generate the switching signal as well as to model the inverter output which is not possible with other modulation techniques. However, the existing WM scheme in the literature for single-phase inverters has an inherent inability of controlling the fundamental output voltage magnitude and shows strong lower order harmonics in its output voltage spectra, limiting its use in practical applications. Improvement to these problems without altering the basic structure of the existing WM scheme are proposed and demonstrated in this paper.

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Received March 2015
Accepted July 2015
Final acceptance in revised form July 2015