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Selective Harmonic Elimination in Seven-Level Multilevel Inverter by using Newton-Raphson Method

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Abstract: *The output voltage of two-level H-bridge inverter has high Total Harmonic Distortion (THD). Multilevel inverter is introduced to reduce the THD at the output voltage. This paper presents a design of cascaded H-bridge (CHB) multilevel inverter. Selective Harmonic Elimination Pulse Width Modulation (SHE-PWM) is applied to reduce the third and fifth harmonics of the inverter output voltage. Transcendental equations describing the fundamental and harmonics are solved by using Newton-Raphson (N-R) method which is written in MATLAB script. The simulation through Simulink has shown that the N-R method has successfully reduced the THD if compared with equal step method.*

Keywords: multilevel inverter, selective harmonic elimination, Newton-Raphson method

1. Introduction

Inverter is an electronic device to convert DC voltage to AC voltage. The simplest and most common design of inverter is H-bridge two-level inverter. Figure 1 (a) and (b) show the structure and the output voltage waveform of two-level inverter. S_1, S_4 and S_2, S_3 are complementary pairs. When the output is V_{DC}, S_1, S_4 are on and S_2, S_3 are off. It is vice versa for output is $-V_{DC}$. The output of two-level H-bridge waveform has high Total Harmonic Distortion (THD). High THD can lead to equipment overheating and shorten the lifetime (Ajenikoko & Ojerinde, 2015). Therefore, multi-level inverter is introduced.

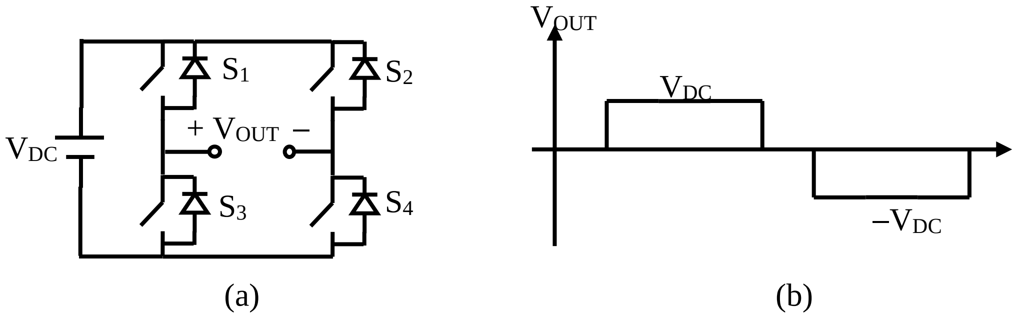


Figure 1: H-bridge two-level inverter and (b) the corresponding output waveform

Multilevel inverter has various advantages if compared with two-level inverter such as lower THD, lower switching loss due to low switching frequency, voltage stress on power semiconductors is small due to small dv/dt, lower peak inverse voltage on main switches and smaller common mode voltage (Farakhor, Ahrabi, & Ardi, 2015; Qashqai, Sheikholeslami, Vahedi, & Al-haddad, 2015). There are three well established topologies of multilevel inverters, which are flying capacitor, neutral point clamped and cascaded H-bridge (W. Abd Halim, S. Ganeson, M. Azri, 2016). The advantage of CHB multilevel inverter is it does not need any diode for clamping or flying capacitors (Suraj Raiyani, Ravindra Gamit, Balvant Solanki, 2017).

The selection of pulse width modulation (PWM) technique to an inverter will significantly affect the performance of the inverter. The common PWM techniques are carrier-based sinusoidal PWM (SPWM), space vector modulation (SVM) and selective harmonic elimination PWM (SHE-PWM) (Dahidah et al., 2014). There are two advantages of SHE-PWM. The first advantage is able to select switching angles so that the fundamental output voltage is maximized to desired voltage and lower order harmonics are minimized. The second advantage that it can operate at a low switching frequency which reduces the switching loss in medium and high power conversion (Kala, 2018). In this paper, CHB seven-level multilevel inverter by using SHE-PWM is introduced. Newton-Raphson (N-R) method is used to find the switching angles so that the third and fifth harmonic contents of output waveform are minimized. The result is then compared with equal step method.

2. Seven-Level Multilevel Inverter

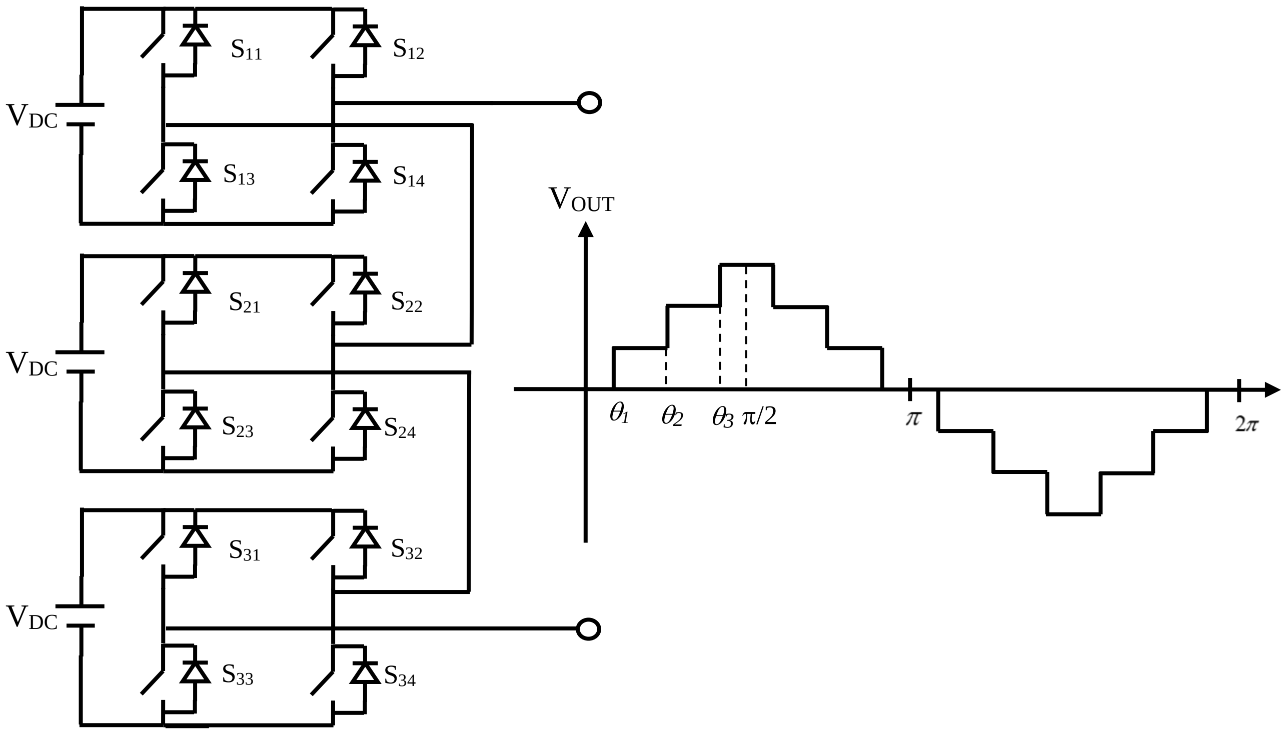
Figure 2 shows a CHB seven-level multilevel inverter (K.Mahendran, 2015; Sanoop & Chellappan, 2016) and its output voltage waveform. This inverter comprises of three H-Bridge cell. All the DC sources are in equal value. The number of output voltage levels, *n* is determined via (K.Mahendran, 2015)

$$n = 2i + 1 \tag{1}$$

where *i* is the number of DC voltage source. Table 1 shows the switching scheme for seven-level CHB multilevel inverter. “1” means the switch is on while “0” means the switch is off.

Table 1: Switching scheme for CHB seven-level inverter

V_{OUT}	S_{11}	S_{12}	S_{13}	S_{14}	S_{21}	S_{22}	S_{23}	S_{24}	S_{31}	S_{32}	S_{33}	S_{34}
$3V_{DC}$	1	0	0	1	1	0	0	1	1	0	0	1
$2\ V_{DC}$	1	0	0	1	1	0	0	1	0	0	1	1
V_{DC}	1	0	0	1	0	0	1	1	0	0	1	1
0	0	0	1	1	0	0	1	1	0	0	1	1
$-V_{DC}$	0	1	1	0	0	0	1	1	0	0	1	1
$-2V_{DC}$	0	1	1	0	0	1	1	0	0	0	1	1
$-3V_{DC}$	0	1	1	0	0	1	1	0	0	1	1	0



(a) (b)

Figure 2: CHB seven-level multilevel inverter schematic and (b) the corresponding output waveform

3. Selective Harmonic Elimination Pulse Width Modulation

Selective Harmonic Elimination Pulse Width Modulation (SHE-PWM) is used to reduce THD by eliminating the lower order harmonics. SHE-PWM was introduced by Patel and Hoft in 1973 (Bendib, Larbes, Guellal, & Khider, 2017). It is widely used low switching power converter, grid connected applications, High-Voltage Direct Current (HVDC) power transmission and high-power motor drives. The idea of this technique is to choose switching angles to set the fundamental to desired amplitude while other harmonic set to zero. To achieve this, Fourier series is used to derive the equations of all harmonics.

According to Fourier series states that a periodic function can be expressed an infinite sum of sine and cosine functions, which

$$v = a_o + \sum_{n=1}^{\infty} a_n \cos(n\theta_o) + b_n \sin(n\theta_o) \quad (2)$$

where n = rank of harmonic, 1, 2, 3, ...

$\theta_o = \omega_o t$

$\omega_o = 2\pi f_o$

f_o = fundamental frequency of the periodic function

a_o = average value, sometimes referred to dc level

$$= \frac{1}{2\pi}\int_0^T v(\theta)dt \tag{3}$$

a_n = Fourier coefficients

$$= \frac{2}{2\pi}\int_0^{2\pi} v(\theta)\cos(n\theta_o)d\theta \tag{4}$$

b_n = Fourier coefficients

$$= \frac{2}{2\pi}\int_0^{2\pi} v(\theta)\sin(n\theta_o)d\theta \tag{5}$$

An odd function has the property of $f(t) = -f(-t)$. For example, a sine function is an odd function. The periodic odd function has zero average value and infinite series of sine functions only. Furthermore, the amplitude of these sine functions can be found by integrating over the quarter fundamental period. The above properties are shown below:

$$a_o = 0 \tag{6}$$

$$a_n = 0 \text{ for all } n \tag{7}$$

$$b_n = \frac{8}{2\pi}\int_0^{\frac{\pi}{2}} v(\theta)\sin(n\theta_o)d\theta \qquad ; n = 1,3,5,7,.... \tag{8}$$

According to equation (8), the fundamental (b_1), third harmonic (b_3) and fifth harmonic (b_5) of Figure 2(b) are shown below:

$$b_1 = \frac{4E}{n\pi}(\cos\theta_1 + \cos\theta_2 + \cos\theta_3) = V_{1m} = \frac{n\pi}{4}m \tag{9}$$

$$b_3 = \cos 3\theta_1 + \cos 3\theta_2 + \cos 3\theta_3 \tag{10}$$

$$b_5 = \cos 5\theta_1 + \cos 5\theta_2 + \cos 5\theta_3 \tag{11}$$

where m is the modulation index. The objective of this paper is to reduce the THD by maximize the fundamental component and minimize the third and fifth harmonics components.

Challenge of applying SHE-PWM is to solve the transcendental equations as shown in equation (9), (10) and (11) which contain of trigonometric terms and multiple variables. Newton-Raphson (N-R) method is proposed to optimize equation (9), (10) and (11).

4. Newton-Raphson method

N-R method is one of the fastest numerical methods to find the root(s) (Ehiwario, 2014). This method starts with and arbitrary initial solutions. The following steps describe the N-R method:

1) Guess an initial value for all variables:

$$\theta^m = \begin{pmatrix} \theta_1^{\,m} \\ \theta_2^{\,m} \\ \vdots \\ \theta_i^{\,m} \end{pmatrix}$$

2) Calculate value of all function with the substitution of θ^m:

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$$F^m = \begin{pmatrix} F_1(\theta_1^m, \theta_2^m, \ldots, \theta_i^m) \\ F_2(\theta_1^m, \theta_2^m, \ldots, \theta_i^m) \\ \vdots \\ F_i(\theta_1^m, \theta_2^m, \ldots, \theta_i^m) \end{pmatrix}$$

3) Calculate the Jacobian matrix:

$$J = \begin{pmatrix} \frac{\partial F_1}{\partial \theta_1} & \cdots & \frac{\partial F_1}{\partial \theta_i} \\ \vdots & \ddots & \vdots \\ \frac{\partial F_i}{\partial \theta_1} & \cdots & \frac{\partial F_i}{\partial \theta_i} \end{pmatrix}$$

4) Calculate the inverse Jacobian matrix, J^{-1}

5) Solve the following linearized equation:

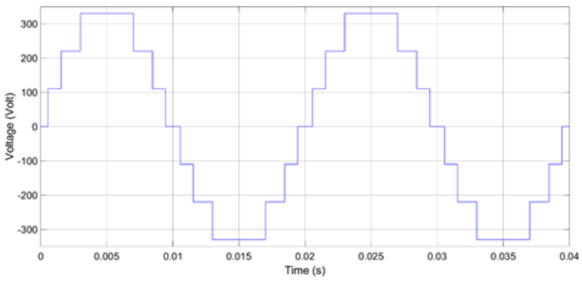
$$\theta^{m+1} = \theta^m - J^{-1} F^m$$

6) Repeat step 2 to step 6 with initial value of θ^{m+1}. This iteration is continuing until a convergence criterion is achieved.

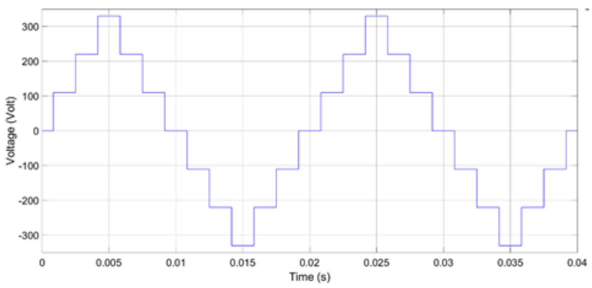
5. Simulation Results and Discussion

The N-R method is written in MATLAB script which is performed at different values of modulation index from 0.1 to 1 by step 0.1. The total switching angles and THD for each modulation index are recorded as shown in Table 2. The performance of the N-R method is compared with equal step method. For equal step method, the switching angles are not computed and the switching period for every step is equal.

From Table 2, the lowest THD happens when the modulation index equal to 0.5. The corresponding switching angles are 10°, 27.7° and 53.9°. Figure 4 shows the harmonic content of inverter output voltage for N-R and equal step methods. From Figure 4, it is shown that the THD due to the N-R method is reduced 7.59% if compared with equal step method. Besides, it is observed that the 3^{rd} and 5^{th} harmonics due to the N-R method are lower than equal step method. Therefore, it can be concluded that SHE-PWM by using the N-R method is able to reduce the specific selected harmonic. The inverter output voltage waveforms for both N-R and equal size methods are shown in Figure 3.



(a)



(b)

Figure 3: Inverter output voltage waveform for (a) N-R method and (b) equal step method

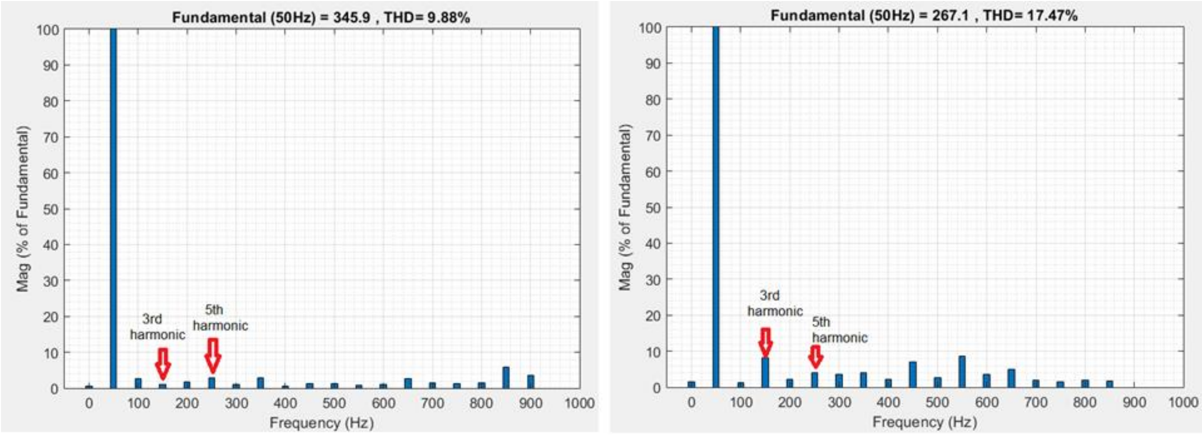


Figure 4: Harmonic content in output voltage waveform of seven-level multilevel inverter by using (a) N-R method and (b) equal step method

Table 2: Switching angles with different modulation indices for N-R method

modulation index	θ1 (degree)	θ2 (degree)	θ3 (degree)	THD (%)
0.1	4.6	11.1	18	27.79
0.2	11	18	37.6	15.68
0.3	3	67.8	85	34.63
0.4	29.4	30.4	36.7	29.44
0.5	10	27.7	53.9	9.88
0.6	21.8	29.3	46.8	17.52
0.7	7.2	11.9	24.2	26.91
0.8	51.8	56.5	71.8	62.61
0.9	3.6	17.6	31.8	21.7
1	1.2	3.9	49.2	25.4

6. Conclusion

In this paper, seven-level CHB multilevel inverter is proposed. The modulation technique applied is SHE-PWM. The switching angles are optimized by using the N-R method. At first, seven-level CHB multilevel inverter, SHE-PWM and N-R method are reviewed. Simulations and comparative analysis between N-R and equal step methods are carried out. The performance of N-R and equal step methods are evaluated based on the value of THD. The simulation result has shown that N-R method exhibits lower THD equal step method.

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