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Selective Harmonic Elimination PWM using Generalized Hopfield Neural Network for Multilevel Inverters

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Abstract - *Multilevel inverter is considered as one of the most recent & popular type of advances in power electronics .It synthesizes desired output voltage waveform from several DC sources used as input for multilevel inverter. These multilevel inverters found there applications in induction motor drives, STATCOM, UPS system, laminators, mills, conveyors & compressor. The core rationale of using inverter is to fabricate a sinusoidal ac voltage with controllable magnitude & frequency .The output waveform of the discretely switched inverters contains harmonics. Various strategies based on switching frequency and harmonics may be employed. In SHEPWM, the presence of lower order harmonics are eliminated or minimized by implementing transitions at controllable points on the time axis. In this paper the SHEPWM is applied to a single phase H-bridge inverter by using GHNN. The simulation and hardware results prove that this method is simple and more applicable in the real time applications.*

Key Words: Static Var compensator , Generalized Hopfield neural network , Modulation index, Selective harmonic elimination pulse width modulation , Fast Fourier Transform (FFT), Ordinary differential equations (ODEs)

1. INTRODUCTION

Multilevel inverters have been widely used in medium-and high-voltage applications. Selective harmonic elimination for the staircase voltage waveform generated by multilevel inverters has been studied extensively in the last decade. Most of the published methods on this topic were based on solving high-order multivariable polynomial equation groups derived from Fourier series expansion. This paper presents a different approach, which is based on equal area criteria and harmonic injection. With the proposed method, regardless of how many voltage levels are involved, only four simple equations are needed. The results of a case study with maximum of five switching angles show that the proposed method can be used to achieve excellent harmonic elimination performance for the modulation index range at least from 0.2 to 0.9. To demonstrate the adaptability of the proposed method for waveforms with a high number of switching angles, experimental results on a multilevel inverter are also shown at the end of this paper.

In medium and high-voltage applications, the implementation of high-frequency pulse width-modulation (PWM)- based two-level inverters is limited due to voltage and current ratings of switching devices, switching losses, and electromagnetic interferences caused by high *dv/dt*. Thus, to overcome these limitations, multilevel inverters have been proposed for applications such as medium-voltage drives, renewable energy interfaces, and flexible ac transmission devices [1]–[11]. A typical multilevel inverter utilizes voltage levels from multiple dc sources. These dc sources can be isolated as in cascade multilevel structures or interconnected as in diode-clamped structures. In most published multilevel inverter circuit topologies, the dc sources in the circuits need to be maintained to supply identical voltage levels. Based on these identical voltage levels and proper control of the switching angles of the switches, a staircase waveform can be synthesized, such as a six-level staircase waveform with five switching angles.

One of the greatest benefits of this staircase waveform is that the switches in the inverters only need to be switched on and off once during one fundamental cycle; thus, the switching loss of the devices is reduced to minimum. However, with reduced switching frequencies, even with additional voltage levels, low frequency harmonics can be found in this type of staircase voltage [12]–[19] .

2. SHE BASIC CONCEPTS

Until now, there are two major approaches to eliminate low frequency harmonics: 1) increasing the switching frequency in sinusoidal–triangular PWM and space vector PWM for two-level inverters or adopting phase shift in multicarrier-based PWM for multilevel inverters [1]–[19] and 2) optimizing switching angles for selected harmonic elimination (SHE) [1]–[19]. The first approach is limited by switching loss and is usually used when the available voltage steps are limited, e.g., two or three steps. SHE-based methods have been proposed for both two-level

This paper is focusing on the SHE-based methods for multilevel inverters. Ideally, in the multilevel inverters, for every voltage level, there could be multiple switching angles. The number of eliminated harmonics is decided by the number of voltage steps and number of switching angles in each voltage step. However, because of the complexity of the problem, most studies proposed so far are for one switching angle per one voltage level. In this case, the Fourier series expansion of the staircase waveform can be expressed.

A cascade multilevel inverter (CMLI) has a modular structure and requires least number of components as compared to other multilevel inverter topologies and as a result, it is receiving increasing attention for use in many different applications such as electric drives, utility interfacing of renewable energy sources, STATCOM etc. For these high power applications, output voltage produced by a multilevel inverter must meet limitations on individual harmonic components as well as on total harmonic distortion as specified in various standards like IEEE-519, IEC 61000-2-2, EN 50160 etc. to minimize the undesirable effects of harmonics in the power system .A suitable switching technique is required in order to meet the above objectives. Among different switching strategies, fundamental frequency switching schemes are generally preferred over the high switching frequency based methods for various applications because of the low switching losses. Among the fundamental switching frequency based modulation strategies, the most commonly used technique is selective harmonic elimination (SHE) method. In this method, the switching angles are computed by solving a set of transcendental equations in such a way that certain numbers of selected lower order harmonics are eliminated from the output voltage. Different techniques have been suggested in the literature for solving these transcendental equations such as Newton-Raphson (N-R) method, resultant theory , theory of symmetric polynomial , genetic algorithm etc. For N-R method, good initial guess of the solutions are required and also all possible solutions cannot be evaluated. The problems with use of resultant theory and theory of symmetric polynomials are that the solutions of the resultant polynomials becomes quite complex for higher order transcendental equations. For implementation of GA algorithm there is no straight forward method for determining the size of the population, crossover and mutation probabilities, learning rate etc. and therefore these are determined heuristically on a case to case basis. The proposed method minimizes the huge data storage and look up tables as compared to other methods. Although SHE technique effectively eliminates certain lower order harmonics, the magnitudes of the higher order harmonics increase simultaneously, thereby increasing the overall total harmonic distortion (THD) in the output voltage. One more problem associated with SHE technique is that the solutions cannot be obtained for complete range of modulation indices.

3. FFT EXPANSION OF STAIRCASE WAVEFORM

The procedure for switching angles calculation is as follows:

The Fourier series expansion of the staircase output voltage waveform as shown in Fig. 1 is given by the following expression:

$$v_{a0} = \sum_{n=1,2,3..}^{\infty} \frac{4V_{dc}\sin(n\omega t)}{n\pi} \times (\cos(n\theta_1) + \cos(n\theta_2) + ... + \cos(n\theta_5)) \quad (1)$$

It can be seen from equation (1) that the output voltage waveform consists of fundamental as well as higher order odd harmonic components (higher order even harmonic components are absent due to odd symmetry of the waveform). Thus, the components of the output voltage can be divided into three parts, namely i) fundamental component, ii) triplen odd harmonic components and iii) non-triplen odd harmonic components as given by following equations (2) -(5):

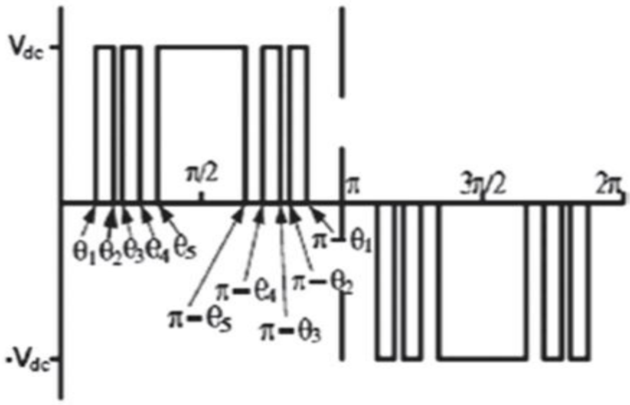

Fig. 1staircase output voltage waveform

$$v_{a0}(wt) = v_{p1}(t) + v_{p2}(t) + v_{p3}(t) \quad (2)$$

i) Fundamental frequency component:

$$v_{p1}(t) = \frac{4V_{dc}\sin(n\omega t)}{\pi} \times (\cos(\theta_1) + \cos(\theta_2) + ... + \cos(\theta_5)) \quad (3)$$

ii) Triplen harmonic voltages:

$$v_{p2}(t) = \sum_{n=3,6,9..}^{\infty} \frac{4V_{dc}\sin(n\omega t)}{n\pi} \times (\cos(n\theta_1) + \cos(n\theta_2) + ... + \cos(n\theta_5)) \quad (4)$$

iii) Odd harmonic (except triplen) voltages:

$$v_{p3}(t) = \sum_{n=5,7,11..}^{\infty} \frac{4V_{dc}\sin(n\omega t)}{n\pi} \times (\cos(n\theta_1) + \cos(n\theta_2) + ... + \cos(n\theta_5)) \quad (5)$$

In three-phase applications, triplen harmonic voltages in each phase need not to be eliminated as they cancel out automatically in line-to-line voltages. Therefore, only non-triplen odd harmonic voltages need to be eliminated while synthesizing desired fundamental frequency output voltage.

As the harmonic content in the output voltage waveform depends on the angles $\theta_1, \theta_2, \ldots \theta_5$ (as shown in Fig. 1), these angles must be chosen properly. Following the principle of SHE, for a given desired fundamental peak voltage V_1, the switching angles should be determined such that $0 \le \theta_1 < \theta_2 < \ldots < \theta_5 \le \frac{\pi}{2}$ and some predominant lower order harmonic components of the phase voltage are zero. Among these five switching angles, generally one switching angle is used for fundamental voltage selection and the remaining four switching angles are used to eliminate certain predominant lower order harmonic components .

In this context, two important terms, namely modulation index (*m*) and harmonic factor (component) need to be defined as these two terms would be used repeatedly in this as well as in subsequent chapters. The modulation index, *m*, is defined as the ratio of the fundamental output voltage magnitude (V_1) to the magnitude of maximum obtainable fundamental voltage (V_{1max}). The maximum fundamental voltage magnitude is obtained when all switching angles are zero i.e. V_{1max}= 20Vdc/π(from equation (1). Therefore, the expression for M is

$$M = \frac{V_1 \times \pi}{4 \times V_{dc}} \tag{6}$$

The percentage harmonic factor (component) of nth harmonic order is defined as

$$HF_n = \frac{v_n}{v_1} \times 100 \qquad n > 1 \tag{7}$$

In equation (7), the magnitude of nth harmonic component (V_n), is given as (from equation (1).

$$v_n = \frac{4V_{dc}}{n\pi} \times (\cos(n\theta_1) + \cos(n\theta_2) + \ldots\ldots\ldots + \cos(n\theta_5)) \quad n > 1 \tag{8}$$

In the above equation, the magnitude of fundamental output voltage is obtained by substituting $n = 1$ with the above background, the SHE technique as developed in this work is described in the next section.

4. APPLICATION OF GHNN

4.1. Formulation of the Transcendental Equations

The Fourier series expansion of the unipolar waveform shown in Fig. 3.1 is given as

$$v(\omega t) = \frac{4 \times V_{dc}}{\pi} \left\{ \sum_{n=1,2,3\ldots}^{\infty} \frac{\sin(n\omega t)}{n} \times (\cos(n\theta_1) - \cos(n\theta_2) + \cos(n\theta_3) - \cos(n\theta_4) + \cos(n\theta_5) \right\}. \tag{9}$$

Given a desired fundamental voltage V_1 and for the elimination of the 5th, 7th, 11th, and 13th harmonics, the problem here is to determine the switching angles θ_1, θ_2, θ_3, θ_4, and θ_5 such that

$$\begin{aligned}
&\cos(\theta_1) - \cos(\theta_2) + \cos(\theta_3) - \cos(\theta_4) + \cos(\theta_5) = M \\
&\cos(5\theta_1) - \cos(5\theta_2) + \cos(5\theta_3) - \cos(5\theta_4) + \cos(5\theta_5) = 0 \\
&\cos(7\theta_1) - \cos(7\theta_2) + \cos(7\theta_3) - \cos(7\theta_4) + \cos(7\theta_5) = 0 \\
&\cos(11\theta_1) - \cos(11\theta_2) + \cos(11\theta_3) - \cos(11\theta_4) + \cos(11\theta_5) = 0 \\
&\cos(13\theta_1) - \cos(13\theta_2) + \cos(13\theta_3) - \cos(13\theta_4) + \cos(13\theta_5) = 0
\end{aligned} \tag{10}$$

where $M = \frac{V_1 \times \pi}{4 \times V_{dc}}$. This is a system of five nonlinear algebraic transcendental equations in the unknowns' θ_1, θ_2, θ_3, θ_4, and θ_5.

4.2 Formulation of the Energy Function

The energy function for the above system of equations is given by

$$\begin{aligned}
E = &-0.5(\cos(\theta_1) - \cos(\theta_2) + \cos(\theta_3) - \cos(\theta_4) + \cos(\theta_5) - M)^2 \\
&+ (\cos(5\theta_1) - \cos(5\theta_2) + \cos(5\theta_3) - \cos(5\theta_4) + \cos(5\theta_5))^2 \\
&+ (\cos(7\theta_1) - \cos(7\theta_2) + \cos(7\theta_3) - \cos(7\theta_4) + \cos(7\theta_5))^2 \\
&+ (\cos(11\theta_1) - \cos(11\theta_2) + \cos(11\theta_3) - \cos(11\theta_4) + \cos(11\theta_5))^2 \\
&+ (\cos(13\theta_1) - \cos(13\theta_2) + \cos(13\theta_3) - \cos(13\theta_4) + \cos(13\theta_5))^2
\end{aligned} \tag{11}$$

The differential equation governing the behavior of the network dynamics is calculated using energy function and is given as follows:

$$\frac{d\theta_1}{dt} = -\frac{\partial E}{\partial \theta_1}$$
$$\frac{d\theta_2}{dt} = -\frac{\partial E}{\partial \theta_2}$$
$$\frac{d\theta_3}{dt} = -\frac{\partial E}{\partial \theta_3}$$
$$\frac{d\theta_4}{dt} = -\frac{\partial E}{\partial \theta_4}$$
$$\frac{d\theta_5}{dt} = -\frac{\partial E}{\partial \theta_5} \quad (12)$$

4.3 Steps for solving ODEs with RK4 method

1. Get the initial values of switching angles
2. Decide step size h normally step size used is h=0.00012 and h =0.0025
3. Initialize t=0,t is number of iterations
4. By using given ODE find out K1,K2,K2,K4 that is RK4 method constants
5. Then find new switching angle by equation

y(n+1) = y(n) +(K1+2*K2+2*K3+K4)*h/6

6. Then continue the steps from (1) to (5) up to three iterations
7. End the process and get the final values

5. MATLAB SIMULATION

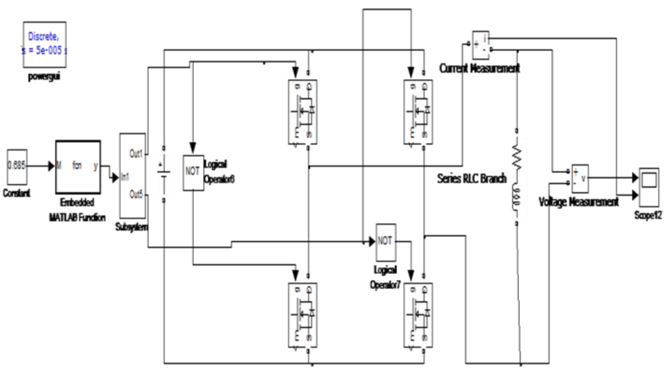

Fig. 2 MATLAB Simulink diagram proposed method

A MATLAB simulation was carried out for the implementation of SHEPWM by use of GHNN method.The observations for MI and Harmonic content were tabled as shown below.

Table 1 Observations of Voltage Harmonics

MI	Harmonics percentage with respect to Fundamental					
	Fundamental	5th	7th	11TH	13th	THD
0.1	100	2.07	8.58	5.93	1.83	264.57
0.3	100	2.27	0.25	0.71	0.12	139.08
0.6	100	0.72	1.38	0.37	3.05	69.31
0.7	100	0.87	1.13	1.50	1.20	58.84
0.9	100	1.59	0.87	0.83	0.77	37.95

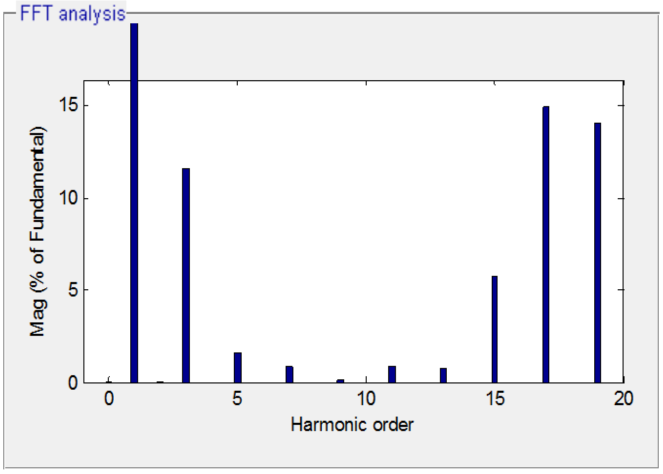

Chart -1 Voltage Harmonic spectrum up to 20th Harmonic for MI=0.9

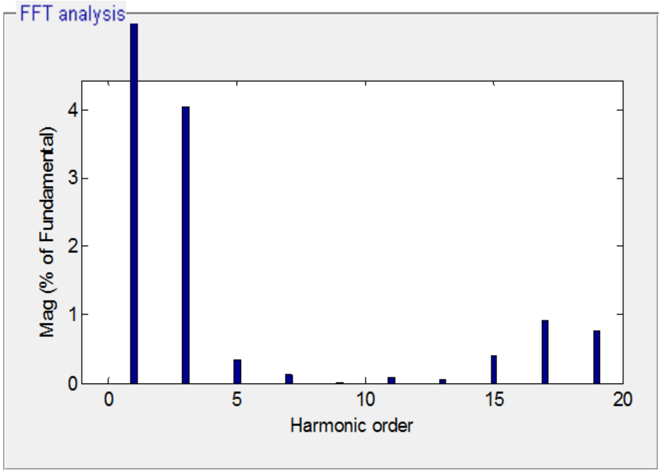

Chart-2 Current Harmonic spectrum up to 20th Harmonic for MI=0.9

6. HARDWARE IMPLEMENTATION

Hardware built using H-bridge inverter and dsPIC microcontroller the results obtained and tabled. Fluke power analyzer was used for studying the hardware performance.

Table 2 Observations of Voltage Harmonics

MI	Harmonics percentage with respect to Fundamental				
	Fundamental	5^{th}	7^{th}	11^{th}	THD
0.1	100	0.1	0.2	0.1	34
0.3	100	0.1	0.2	0.1	23.5
0.4	100	0.1	0.2	0.1	18
0.6	100	0.1	0.2	0.1	11.1
0.7	100	0.1	0.2	0.1	8
0.9	100	0.1	0.2	0.1	2.5

Fig.3 Hardware Setup

7. CONCLUSION

After going through the Simulation and Hardware observations it was observed that the individual harmonics and THD levels have less percentage. As the Modulation Index is increased there is decrease in THD .The proposed method is focused on reduction of lower order harmonics, using simple understanding of ODEs. The proposed method is more applicable to use of industrial application. As the real time implementation of this method only needs the knowledge of ODEs. This method is superior to analytical method such as Newton-Raphson method as with latter there is problem in finding initial solution set and based on trial and error method. The proposed method is useful in Real-time implementation. This methodology can further be studied and analyzed for more improvement in algorithm and more accurate approach. There is a scope for future of extending the applicability of ODEs in engineering applications. The main advantage of this method is only knowledge of ODEs is required. This method can be applied to various applications such as multilevel inverters, ac voltage controllers, and for the source current harmonic elimination in PWM rectifiers.

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