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Dual Phase Analysis Based Linear Regression Trained Neural Network For Selected Harmonic Elimination In A Multilevel Inverter

*** 1V.J.Vijayalakshmi, 2Dr.C.S.Ravichandran, 3Dr.A.Amudha, 1A.Mohamed Ibrahim**

1 Assistant Professor Department of EEE, KPR Institute of Engineering and Technology, Tamilnadu, India
2 Dean, Department of EEE, Sri Ramakrishna Engineering College, Tamilnadu, India
3Professor, Department of EEE, Karpagam University, Tamilnadu, India

ABSTRACT:

The concept of dual phase analysis based harmonic elimination in multilevel inverter is introduced in this paper. To obtain accurate THD value and the harmonic spectrum, inclusion of higher order harmonics is very essential. A novel concept of application of Heuristic Optimization techniques for estimating the optimum switching angles for the voltage and harmonic control of cascaded multilevel inverters is performed. The Selected Harmonic Elimination strategy is used for harmonic control. In this paper, neural network based on Gradient Descent Optimization is the preferred Heuristic algorithm. The Neural Network can be trained offline and online. It is trained off line using the voltage profile of the desired switching angles given by the classic harmonic elimination strategy to any value of the modulation index. Dual Phase Analysis (DPA) is used in analyzing the voltage profile and the harmonic spectrum of the multilevel inverter output. After training the proposed Artificial Neural Network (ANN) system, a large and memory demanding look-up table is replaced with trained neural network to generate the optimum switching angles with lowest Total Harmonic Distortion (THD) for a given modulation index.

Key words: Dual Phase Analysis, Total harmonic distortion, Artificial Neural Network, selective harmonic elimination, inverters.

1. INTRODUCTION:

An inverter is a power electronic device that produces an Alternating Current (AC) from a Direct Current (DC) source. Harmonics are undesired oscillations in a system and they oscillate at integer multiples of the fundamental frequency. The voltage and current waveform in an AC system should be sinusoidal with constant amplitude, constant and single frequency. The magnitude of the harmonics, decrease with increase in the harmonic number. Harmonics must always be limited below threshold levels prescribed by standards [1], both in their THD and individual magnitudes. The amount of distortion in the voltage or current waveform is quantified by means of an index called the THD. The THD in the voltage or current waveform is mathematically defined as the ratio of distortion current to the fundamental current. The formula to compute THD is given in equation 1.

$$\mathrm{THD} = \frac{\mathrm{I_{dist}}}{\mathrm{I_1}} * 100 \qquad (1)$$

Where,

I_{dist} – Distortion Current
I_1- Fundamental Current

The THD of a system greatly affects the active power in the system. Multilevel Converters (MLC) [2] emerged as a solution to produce a closer to sinusoidal output voltage and minimize the need for filtering. In addition, the multilevel converter operates at the fundamental switching frequency, which makes the multilevel converter suitable for high power applications [3]. MLC commonly operate as inverters. Multilevel converters include a string of semiconductor devices, fed by capacitor voltage sources or separate DC sources (SDCS) [4]. There are three main types of multilevel converters: diode-clamped [5], capacitor-clamped [6], and cascaded H-bridges [7]. The simplest diode-clamped converter [8] is commonly known as the Neutral Point Clamped Converter (NPC). The draw backs are different voltage ratings for clamping diodes are required, real power flow is difficult because of the capacitors imbalance, Different current ratings for switches are required due to their conduction duty cycle. The capacitor-clamped multilevel topology allows more flexibility in waveform synthesis and balancing voltage across the clamped capacitors. The disadvantage of capacitor-clamped multilevel topology are Large number of capacitors is bulky and more expensive, Poor switching utilization and efficiency, control methods are complicated. Cascaded H-bridge converters have separate DC sources. The main advantage of such converters is it allows a scalable, modularized circuit layout, No extra clamping diodes or voltage balancing capacitors is necessary. There are four kinds of control methods for multilevel converters. They are the selective harmonic elimination method [9], space vector control method [10], traditional Pulse Width Modulation (PWM control method and space vector PWM method [11]. The traditional PWM, space vector PWM and space vector modulation methods cannot completely eliminate harmonics. Another disadvantage is space vector PWM and space vector modulation methods cannot be applied to multilevel converters with unequal DC voltages [12]. The carrier phase shifting method for traditional PWM method also requires equal DC voltages. Until now, the number of harmonics in the selective harmonic elimination method can eliminate is not more than the number of the switching angles in the transcendental equations. Due to the difficulty of solving the transcendental equations, real-time control of multilevel converters with unequal DC voltages is impossible now [13]. No such method can be used to directly compute the output voltage pulses to eliminate any number of the harmonics without any restriction of the number of unknowns in the harmonic equations and available solutions for the equations.

In a traditional selective harmonic elimination method, the number of harmonics to be eliminated is limited by the unknowns in the harmonic equations and available solutions [14]. If there are no solutions for some modulation index range, the traditional selective harmonic elimination cannot be used. But for the active harmonic elimination method, if the harmonic equations have no solutions for a set of harmonics, they may have solutions for other sets of harmonics. The cost is just additional switching.

2. PROBLEM FORMULATION:

Harmonic elimination technique is a method to get rid of harmonics by judicious selection of the firing angles of the inverter. The harmonics elimination technique eliminates the need for expensive low pass filters in the system. The harmonic elimination begins with the Fourier series of the produced voltage. The fundamental voltage of the produced output is given by equation (2)

$$V_1(t) = \frac{4}{\pi}\left(V_1 \cos(\theta_1) + V_2 \cos(\theta_2) + V_3 \cos(\theta_3)\right)\sin(\omega t) \quad (2)$$

The third, fifth and the seventh harmonic of the system are given by the following set of equations (3-5)

$$V_3(t) = \frac{4}{\pi}\left(V_1 \cos(3\theta_1) + V_2 \cos(3\theta_2) + V_3 \cos(3\theta_3)\right)\sin(3\omega t) \quad (3)$$

$$V_5(t) = \frac{4}{\pi}\left(V_1 \cos(5\theta_1) + V_2 \cos(5\theta_2) + V_3 \cos(5\theta_3)\right)\sin(5\omega t) \quad (4)$$

$$V_7(t) = \frac{4}{\pi}\left(V_1 \cos(7\theta_1) + V_2 \cos(7\theta_2) + V_3 \cos(7\theta_3)\right)\sin(7\omega t) \quad (5)$$

The fifth and seventh harmonic voltages are to be eliminated from the system. The number of harmonics that can be eliminated from the system depends on the number of levels in the output voltage of the MLC. In an m-level converter, m–2 number of harmonics can be eliminated. Therefore, in the four-level converter in this discussion, two harmonics can be eliminated. The equations are written as follows,

$$(cos(\theta_1) + cos(\theta_2) + \ cos(\theta_3))\, sin\, \omega t\, = \frac{V1\pi}{4Vdc} \qquad (6)$$

*V*1 is the desired peak value of the fundamental voltage.

$$\begin{aligned} \cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) = 0 \\ \cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) = 0 \end{aligned} \qquad (7)$$

By solving the above transcendental equations, the fifth and the seventh harmonic voltages can be eliminated from the system. The more the number of levels in the system, the more harmonics eliminated from the system.

The objective of Selective Harmonic Elimination Pulse Width Modulation (SHEPWM) is to eliminate the lower order harmonics while optimizing remaining harmonics that are removed with filter. In this paper, without loss of generality, a 7-level inverter is chosen as a case study to eliminate its low-order harmonics (fifth and seventh). A nine level inverter is also considered for evaluation purposes. Constructed fitness function and its limitations are shown in equation (8) and equation (9),

$$\mathrm{f} = \min\theta_{\mathrm{i}} \left\{ \left(100 * \frac{(V_1 - V_2)}{V_1}\right)^4 + \sum_{s=2}^{S} \frac{1}{\mathrm{hs}} \left(50 \frac{\mathrm{V_{hs}}}{\mathrm{V_1}}\right)^2 \right\} \qquad (8)$$

$$i = 1, 2 \ldots\ldots S$$

Subject to

$$0 \le \theta \le \frac{\pi}{2} \qquad (9)$$

Where

θ_1, θ_2, θ_3 are the switching angles

V_{dc} is the voltage of the DC source

V_1 is the desired fundamental harmonic,

S is the number of switching angles, and

hs is the order of *s*th viable harmonic at the output of a three-phase multilevel inverter,

e.g., $h_2 = 5$ and $h_3 = 7$. In this switching angles are found such that low-order harmonics (fifth and seventh) are eliminated and the magnitude of the fundamental harmonic reaches to its desirable value, i.e., V_1.

If the fundamental harmonic violates its set point by more than 1%, the first term of equation (8) fines it by a power of 4. Because of the use of the power of 4, corresponding penalties for any deviations under 1% get a negligible value. The second term of (8) neglects harmonics under 2% of fundamental. But, when any harmonic exceeds this limit, the objective function is subject to a penalty by power of

2. Finally, each harmonic ratio is weighted by inverse of its harmonic order, i.e., $1/hs$. By this weighting method, reducing the low-order harmonics gets higher importance.

3. PROPOSED METHODOLOGY:

The novel technique of ANN is used in the optimization of THD by Selected Harmonic Elimination. The ANN is backed up by Gradient Descent for first order optimization and is the most effective tool for fixing the parameters of the neural network. The linear regression technique is used for filtering the huge dataset to the best group of possible switching angles that can be used to train the ANN. The training data for the network has been obtained from the classical solutions of harmonic elimination problem. A new method called DPA has been introduced to provide a better understanding of the harmonic spectrum and thus providing a better training data to the neural network. This improves the efficiency of the overall system in the process. The block diagram of the developed system is shown in Fig (1)

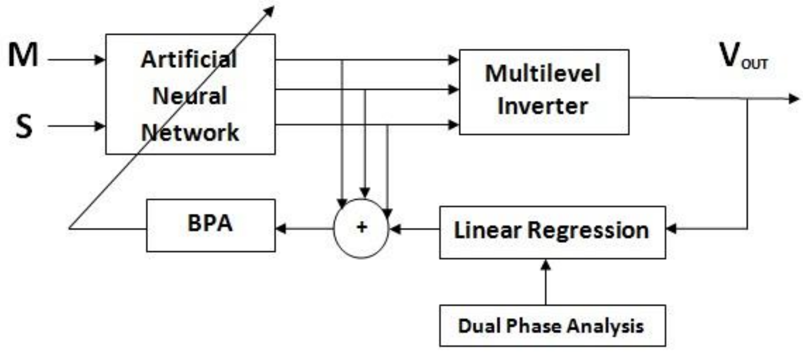

Fig.1. Block diagram of the proposed system

3.1 Dual Phase Analysis

This is an effective tool to analyze the various higher order components of the harmonic spectrum. The extended analysis of [15] is done for frequency spectrum. The analysis of harmonic spectrum by Finite Fourier Transform (FFT) yields a very good result for lower order harmonics. But due to the approximation of decimal in FFT, the results of the analysis for higher order harmonics are not satisfactory. As the formula suggests in equation (10),

$$Y_k = \sum_{j=0}^{n-1} W^{jk} y_j \qquad (10)$$

where,

Y_k- kth harmonic (k=0……n-1)
W- Transform Parameter
y_j- Input Sample

$$W = e^{-2\pi i/n} \qquad (11)$$

is the complex n^{th} root of unity.

3.2 Algorithm

1. Start the process.
2. Get the input from the user (modulation index and inverter level).
3. Perform dual phase analysis for the given level of inverter.
4. Train the linear regression based on dual phase analysis results.
5. From the voltage profile input, predict the switching angle range for the required modulation index.
6. Calculate error between required and predicted output switching angles.
7. Based on the error generated, train the artificial neural network further by back propagation algorithm.
8. Output the final switching angle to the inverter.
9. The voltage profile from the inverter is analyzed.
10. End the process.

4. RESULTS AND DISCUSSION

We consider a seven-level and a nine-level inverter for the illustration of the results, without loss of generality. The seven-level inverter consists of three H-bridge inverters constructed by IGBTs. The inverters are assumed to be supplied from a constant and equal voltage source initially. For verifying the solutions, a 3-phase 2-kW Simulink model of 7-level inverter is built. In Figure 2 of the detailed Harmonic Spectrum of line to line waveform, it can be clearly seen that the triplen harmonics are absent and the net harmonic distortion has also come down considerably. The fifth and the seventh harmonics have reduced considerably too. Thus the algorithm has performed certainly better in these cases

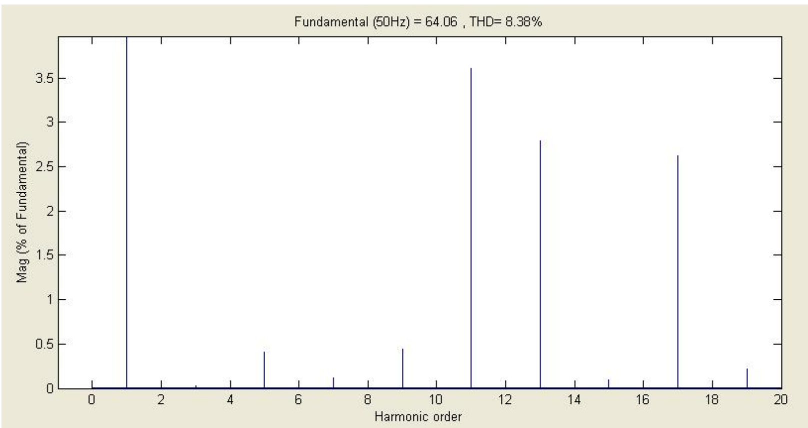

Figure 2: Detailed Harmonic Analysis of Line to Line Voltage

The method of harmonic elimination is compared with the conventional and the various previously available solutions to the same problem to analyze the efficiency of the algorithm. The modulation index of 0.8 is used for the analysis. Compared to the other methods this method gives us a better result. Thus the THD is minimized by this method compared to other methods.

6. CONCLUSION

In this paper, the use of the DPA aided ANN is proposed to solve the selective harmonics elimination problem in PWM inverters. The paper successfully demonstrates the validity of feed forward neural networks trained by back propagation for the estimation of optimum switching angles of staircase waveform generated by multilevel inverters. This technique allows successful voltage control of the fundamental as well as suppression of a selective set of harmonics. An ANN is trained offline/online to produce these switching angles without constrain for any value of the modulation index. For a real-time control, it is enough to implement the obtained network after the training process. Simulation results are compared for a seven-level and nine-level inverter to validate the accuracy of proposed approach to estimate the optimum switching angles which produce the lowest THD among the all possible set of solutions. The estimation principle can be extended to high level inverters.

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