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SHE in Multilevel Inverters by Dual Phase Analysis

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ABSTRACT

The concept of dual phase analysis (DPA) 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. Previous research was mainly concentrated on eliminating the selected lower order harmonics depending on the level of inverter. The analysis of harmonic spectrum by Finite Fourier Transform yields a very accurate result for lower order harmonics. For obtaining accurate Total Harmonic Distortion (THD) value and the harmonic spectrum, inclusion of higher order harmonics is essential. The method for accurate estimation is proposed in this paper. 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 in this paper.

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INTRODUCTION

The harmonics distort the waveform of the fundamental. The magnitude of the harmonics, decrease with increase in the harmonic number. Harmonics must always be limited below threshold levels prescribed by standards (Jose Rodriguez, 2002), 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 performance of a power-electronic device is dependent on the harmonic content in the output waveform. 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.

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

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) (Rodrıguez, J., 2000) 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 (Damoun Ahmadi, 2011). There are three main types of multilevel converters: diode-clamped (Yuan, X., I. Barbi, 2000), capacitor-clamped (Lai, J.S. and F.Z. Peng, 1995), and cascaded H-bridges (Nami, A., 2011). 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. 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 (Dahidah, M.S.A. and V.G. Agelidis, 2008), space vector control method (Amit Kumar Gupta 2006), traditional Pulse Width Modulation (PWM control method and space vector PWM method (Bowes, S.R. and S. Grewal, 1999). The traditional PWM, space vector PWM and space vector modulation methods cannot completely eliminate harmonics. 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

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equations, real-time control of multilevel converters with unequal DC voltages is impossible now (Enjeti, P.N., 1990).

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 (Chiasson, N., 2004; Dahidah, M.S.A., V.G. Agelidis, 2005). 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:

The scope of Dual Phase Analysis is predetermination of Higher Order Harmonics is to determine the exact magnitude difference between the higher order harmonics by DUAL PHASE ANALYSIS. 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)

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

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

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

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

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

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,

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

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

$$\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) = 0$$
$$\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) = 0 \quad (7)$$

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),

$$f = \min_{\substack{\theta_i \\ i=1,2\ldots\ldots S}} \left\{ \left(100 * \frac{(V_1 - V_2)}{V_1}\right)^4 + \sum_{s=2}^{S} \frac{1}{hs}\left(50\frac{V_{hs}}{V_1}\right)^2 \right\} \quad (8)$$

Subject to

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

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)

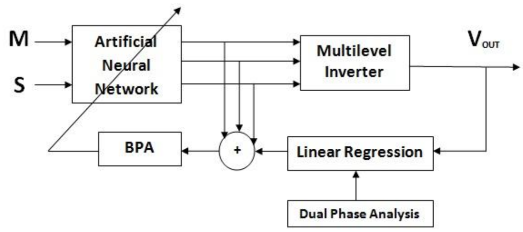

Fig. 1: Block diagram of the proposed system

3.1. *Dual Phase Analysis:*

Micro phase analysis is the analysis of harmonic spectrum on a small scale or within a small spectrum. It is the measurement of lower order harmonics of the base frequency of analysis. In this method, the harmonics up to a predefined level are measured with respect to the base frequency. The entire magnitude spectrum is not taken into consideration. The level of harmonics is decided based on the accuracy required and the total number of stages permissible. In this case the harmonics up to 11^{th} order are measured in the micro stage. The initial base frequency is 50Hz. The micro phase analysis at this frequency leads to the analysis of frequencies up to 550Hz. Since the number of harmonics considered for evolution in this method is 100, which is up to a frequency of 5000Hz, this stage is not sufficient for the complete analysis. Extending the order of harmonics will result in decrease of accuracy of the measurement.

Macro phase analysis is the large scale harmonic spectrum analysis at frequencies greater than that are possible in micro phase analysis. It is the measurement of higher order harmonics. The higher order harmonics are measured at a different scale of magnitude as compared to the base. This measurement of higher order harmonics is obtained by temporary change of base frequency. The base frequency is moved from the fundamental component to the harmonic that closely resembles the fundamental frequency. The criterion for shifting the base frequency is the next harmonic frequency that closely resembles the harmonic spectrum known till then. Eg: If Fundamental: 100%, 1^{st} harmonic: 15%, 2^{nd} harmonic: 0.3%, 3^{rd} harmonic: 11%, 4^{th} harmonic: 0.23% and so on, 3^{rd} harmonic is chosen because the ration of 0.3 (2nd harmonic) to 15 (1^{st} harmonic) is approximately the same as 0.23(4^{th} harmonic) to 11(3^{rd} harmonic). If there is absolutely no resemblance to previous spectrum, the frequency is chosen in order (1, 3, 5, 7 etc...). This moves the analysis to the next stage of execution. In this stage, the micro phase analysis is carried out with the new base frequency. The harmonics up to the 11^{th} order of the new base frequency are measured. These harmonics are values scaled by shifting of base i.e their magnitude is measured with respect to another harmonic. Thus the higher order harmonics are scaled and measured in terms of lower order harmonics. Thus the analyzed higher order harmonics are at a different scale of magnitude when compared to original. Thus, we do a normalization to bring them back to the original scale. This feature normalization is carried out to remove the abnormalities in magnitude that arise out of varying magnitude scales. Now the closest resemblance to the new base frequency is selected and the next stage of micro phase analysis is carried out. This process is repeated until the maximum range of frequency chosen for analysis is reached. This process of shifting the base followed by the micro phase analysis is termed as macro phase analysis.

Now, this process is rolled back to the initial stage and the next closest resemblance is selected. The steps illustrated above are repeated again until all possible frequencies are generated. Thus all the frequencies are subject to this process at least once and have a modified value. The conflict of overlap or repetition of certain frequency values are resolved by taking maximum of the feature normalized values of all the available values and then converting it back to original scale. If a frequency has repeated analysis and more than one modified value, the value arising out of the closest harmonic base is selected as the final value. When the base is the closest, the harmonic is better identified by FFT.

The variations in magnitude scales of harmonics are normalized by two different means,

1. Reverse scaling with corresponding base
2. Feature Normalization and roll-back on common base

These techniques have their own advantages and disadvantages.

1. Reverse scaling with corresponding base:

This process involves scaling back the obtained magnitude of harmonics to the original base (base frequency of analysis) by using the corresponding base of each magnitude as reference. This means that the effect of scaling is removed by means of relative operations with respective base.

If the magnitude is with respect to fifth harmonic, then the magnitude of fifth harmonic with original base is used to convert the magnitude to per unit value and then multiplied with the common original base of the system. For example, if the magnitude of fifth harmonic is 0.12 with respect to base and we select 5^{th} harmonic as the next base, we multiply all the values obtained by the new analysis by a factor of 0.12 to bring them back to the original scale of reference. This is a very simple means of normalization and is preferred.

2. Feature Normalization and roll-back on common base:

This process involves feature normalization of all values at once to form a common bunch of values with a very small standard deviation. This is carried out by,

Feature normalized value = (Old value – mean of all values on the scale)/Standard deviation of all values on the scale:

This process is performed to each scale individually. This feature normalized values yield a bunch of values which are on a common scale. The range of this scale is determined by the difference between the integer closest to the highest value of the bunch and the integer closest to the smallest value of the bunch. The entire bunch is divided by the scale of the value to obtain the per unit value.

3.2. Procedure:

The procedure used in this method is based on the Neural Network which is capable of mimicking the transfer function of the method that it controls for its training.

Initially, DPA described above is performed and the training data is generated based on classical solutions. This training data is used for the optimization of the parameters of the Linear Regression classifier used for supplying the filtered training data to the ANN. Evidently, the training data comprises of the voltage profile of the inverter for various modulation indices. So the training process is carried out for the optimization of harmonics (fifth, seventh and THD) and hence the parameters are dependent on them. These parameters are used for the prediction of training set based on switching angles for the Network. So the comparison for error generation in the regression classifier for refining and fine tuning of the parameters by gradient descent has to be done which allows direct control of the output of the network. Since the optimization objective is a convex function, the initialization of the gradient descent is irrelevant to the final output. This overcomes the need for good initial guess and thus the disadvantage of the previous methods is overcome.

So the voltage profile of the inverter is obtained and compared with the DPA training data which gives the required magnitude of the fundamental waveform. The error between them is minimized and the set of training data over which the required details are accurate are selected. In this range, the minimum value of fifth and seventh harmonic are determined using gradient descent. Multiple random initializations are used by the algorithm to arrive at the local minimum.

Thus the new parameters are used to generate the new training data for the neural networks which are fed to the error detector which determines the error between the neural network output and the linear regression output. This error data is used in tuning the neural network through BPA. The modulation index and inverter level are taken as inputs and the parameters for their weightage is determined from the training data by the BPA.

The output layer has a parabolic transfer function to determine the minimum THD in the available set in a trade-off that does not sacrifice the Selected Harmonic Elimination. This process is carried out by the optimization of the objective function stated in Equation (8) by Gradient Descent. Finally the output layer produces the final switching angle required for the minimum THD.

3.*3. Algorithm:*

1. Start the process.

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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.

RESULTS AND DISCUSSION

We consider a seven-level and a nine-level inverter for the illustration of the results, without loss of generality. The results of the analysis are found to match closely with those found in the algorithm. Figure 2 shows the harmonic spectrum of 7 level inverter from the toolbox.

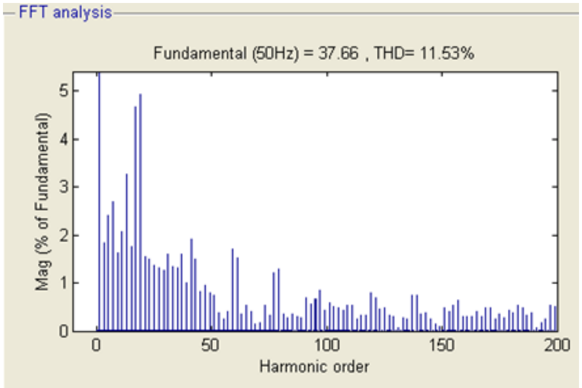

Fig. 2: Harmonic Spectrum for 7 level inverter.

In Figure 3 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.

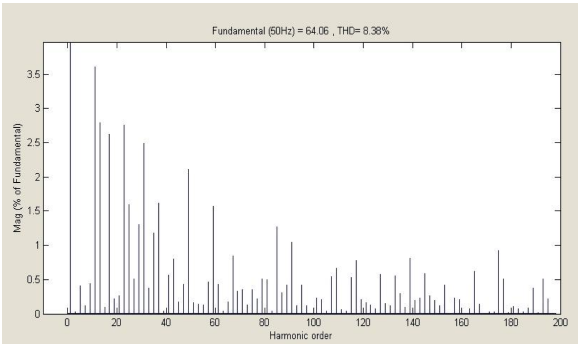

Fig. 3: Harmonic Spectrum of Line to Line Voltage.

Similarly, the table of switching angles and the harmonic spectrum for a nine-level inverter is shown in table.1 to illustrate the generality of the algorithm. A modulation index of M=0.9 is chosen for illustration.

Table 1: Switching Angles for nine-level inverter m=0.9.

M	Θ1	Θ2	Θ3	Θ4
0.9	7.012	20.954	34.876	59.142

In Fig 4 the THD is **9.23%**, which is considerably low for nine level inverter. Thus the algorithm performs reasonably well with a nine-level inverter also. This shows that the algorithm is not over fitting.

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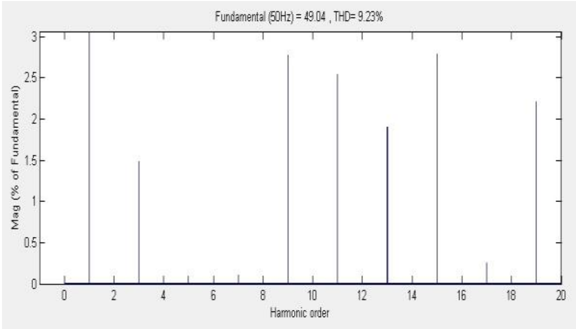

Fig. 4: Harmonic Spectrum of nine-level inverter.

5. *Comparative Analysis:*

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. This illustrates the efficiency of the method without being too specific. The results of the analysis are tabulated in Table.2 below.

Table 2: Comparative Chart.

Method	Fundamental Voltage (V)	THD of Phase Voltage (%)	THD of Line Voltage (%)
Conventional SPWM	34.73	47.97	30.63
Genetic Algorithm[13]	35.92	13.01	-
Bee Algorithm [14]	35.34	12.53	8.92
ANN [15]	36.4	14.57	9.79
Proposed ANN - GD	36.11	11.53	8.38

The comparison of various results goes on to show that the proposed method is very effective in handling the harmonic elimination problem. The only comparable result is from the Bee Algorithm which produces a similar output at the phase voltage but greater harmonics at the line voltage.

Thus the proposed algorithm is capable of handling both single phase and three phase applications effectively. It can handle various levels of inverters as illustrated with seven and nine-level inverters. This makes sure that the proposed method is among the better solutions available for solving the SHEPWM technique.

Conclusion:

In this paper, the use of the DPA aided ANN is proposed to solve the selective harmonics elimination problem in PWM inverters. In this paper predetermination of harmonics in multilevel inverter has been carried out. The simulation result shows the accuracy of determining the harmonics. By performing the Dual Phase Analysis, the harmonics are predetermined accurately. 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. With optimized switching angles Total Harmonic Distortion is reduced, thus increasing the total Power Quality of the system.

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