

Minimization of THD in Cascaded Multilevel Inverter with SHE Technique

Rashmita Rani Panda¹, Manoj Kumar Swain², Rojalin Rout³ and Chakradhara Karan⁴

^{1,3}Assistant Professor, Department of Electrical & Electronics Engineering, Gandhi Institute for Technology, Bhubaneswar, Odisha, India

^{2,4}Assistant Professor, Department of Electrical & Electronics Engineering, Gandhi Engineering College, Bhubaneswar, Odisha, India

Publishing Date: 7th March, 2018

Abstract— This paper presents method of selecting switching angles of a cascaded multilevel inverter so as to produce required fundamental voltage along with improved staircase waveform in terms of harmonics. Cascaded multilevel inverter uses number of DC sources, for k sources number of levels will be $2k+1$ and leads to k number of non-linear equations to be solved. Many approaches can be made regarding the solution but this paper focuses on Specific Harmonic Elimination (SHE) technique for angle optimization. Newton-Raphson method is used and the difficulty with this method is a closed initial guess. Variation of angles with modulation index is observed and THD is calculated for selected modulation indexes and all attempts are made so as to get lowest THD. Results are simulated in MATLAB/Simulink environment.

Index Terms - Cascaded multilevel inverter, SHE, Switching angles, THD.

I. INTRODUCTION

Now a day's multipulse voltage source inverters have been widely accepted as the state-of-the-art reactive power controllers of power systems which includes thyristor controlled reactor and thyristor switched capacitors. Traditionally a conventional multipulse converter(48-pulse) is used with zig-zag arrangement transformers so as to reduce harmonics [1], these transformers 1) are the most expensive equipment in the system; 2) produce about 50% of the total losses of the system; 3) occupy a large area of real estate, about 40% of the total system; 4) cause difficulties in control due to dc magnetizing and surge overvoltage problems resulting from saturation of the transformers; and 5) are unreliable. Dynamic response of these conventional converters is slow and pulse width modulation will cause more switching losses [2].

A cascaded multilevel inverter(CMLI) has been proposed for static VAR compensation which eliminates use of zig-zag transformers, there can be different modulating strategies for output control here switching is done at low frequency i.e fundamental frequency and in order to improve THD specific low harmonics are reduced with the help of specific harmonic elimination(SHE) technique.

This paper is organized as follows: section II includes CMLI structure, section III and IV includes optimization method and simulation result.

II. CMLI - STRUCTURE

Cascaded multilevel inverters are based on the series connection of single-phase full-bridge (H-bridge) inverters. This structure can avoid clamping diodes and voltage balancing capacitors, essential in diode-clamped and capacitor clamped inverters, but requires separate DC

sources.

This characteristic is well suited for various renewable energy sources such as fuel cell, photovoltaic and biomass. The number of output voltage levels is $2k+1$, where k is the number of cells or DC link voltages. Number of components in this type is least compared with diode clamped and flying capacitor multilevel converter. The basic unit or cell is called as H-bridge as shown in figure 1 and voltage level can be synthesized through different combinations of the four switches, S1-S4, each converter level can generate three different voltage outputs, +V1, -V1 and zero. The AC outputs of different full-bridge converters in the same phase are connected in series such that the synthesized voltage waveform is the sum of the individual converter outputs. Figure 2 shows 11-level CMLI structure, advantage of using SHE algorithm is that in each cycle each switching device (MOSFET, BJT, etc) conducts for half cycle hence uniform switching losses will be there for each switching device.

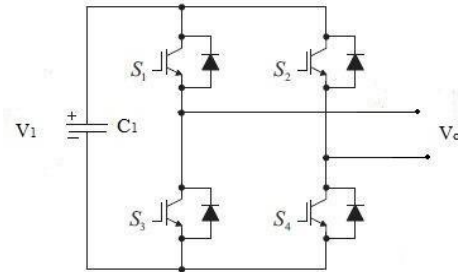


Figure 1. H-Bridge

The stepped output waveform of CMLI with $2k+1$ levels (Fig. 3) is Fourier analyzed and peak of n^{th} harmonic can be written as (1), k is number of DC sources and α is triggering angle.

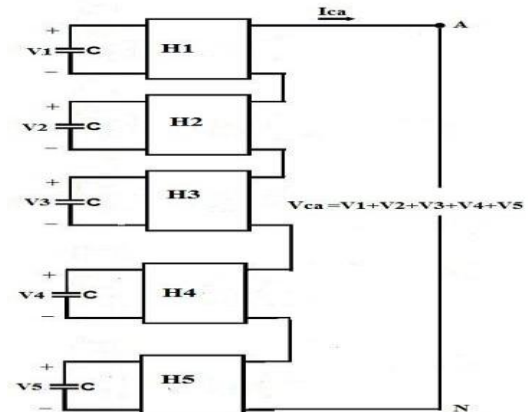


Figure 2. CMLI structure with 5 H-Bridge

III. N-R METHOD FOR OPTIMIZED ANGLES

In this method [3] output voltage of CMLI can be Fourier analyzed and its nth harmonic amplitude can be expressed as:

$$V_n = \frac{4V_{dc}}{n\pi} \sum_{m=1}^k \cos(n\alpha_m) \quad (1)$$

Where, H_n = peak of nth harmonic
 $V_{dc} = V1 = V2 = V3 = V4 = V5$ = capacitor/source voltage of each cell in each phase
 K = number of bridges in each leg/phase
 N = number of levels in each phase = $2K + 1$
 α_m = switching angle of mth cell

According to Equation (1) α_1 through α_5 must satisfy the following condition:

$$0 \leq \alpha_1 \leq \alpha_2 \leq \alpha_3 \leq \alpha_4 \leq \alpha_5 \leq \frac{\pi}{2}$$

Because of their symmetric characteristic, no even-harmonic components exist in staircase waveform and triplens will be absent in line voltage, thus switching angles are so chosen that they eliminate lower order harmonics, only $k-1$ harmonics can be eliminated i.e. for 11 level inverter with $k=5$ only 4 harmonics can be eliminated and here 5th, 7th, 11th, 13th harmonics are to be removed, thus equation (1) when expanded will take form as:

$$\begin{aligned} \cos \alpha_1 + \cos \alpha_2 + \cos \alpha_3 + \cos \alpha_4 + \cos \alpha_5 &= 5M \\ \cos 5 \alpha_1 + \cos 5 \alpha_2 + \cos 5 \alpha_3 + \cos 5 \alpha_4 + \cos 5 \alpha_5 &= 0 \\ \cos 7 \alpha_1 + \cos 7 \alpha_2 + \cos 7 \alpha_3 + \cos 7 \alpha_4 + \cos 7 \alpha_5 &= 0 \\ \cos 11 \alpha_1 + \cos 11 \alpha_2 + \cos 11 \alpha_3 + \cos 11 \alpha_4 + \cos 11 \alpha_5 &= 0 \\ \cos 13 \alpha_1 + \cos 13 \alpha_2 + \cos 13 \alpha_3 + \cos 13 \alpha_4 + \cos 13 \alpha_5 &= 0 \end{aligned} \quad (2)$$

Where M is modulation index and is defined as:

$$M = \frac{\text{Desired fundamental peak for k level converter (single leg)}}{\text{Maximum obtainable output peak for N level converter (single leg)}} = \frac{\pi v_f}{4M v_{dc}} \quad (3)$$

Where, V_f is the desired fundamental single phase peak and V_{dc} is the input voltage to each H-bridge, M can be varied from 0-1.

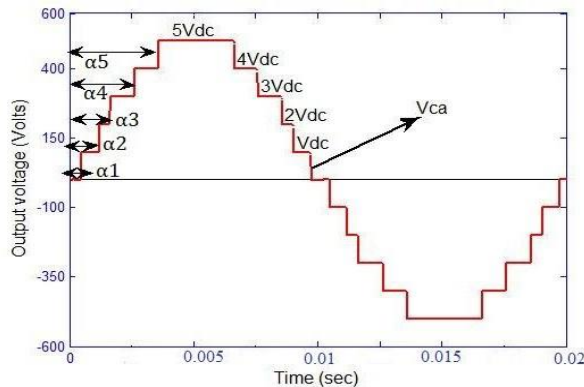


Figure 3. CMLI staircase 11-level output voltage

Above set of non linear equation can be solved with the help of Newton-Raphson method and switching angles can be optimized.

Above set of non linear equation can be written as:

1. Main function $F(\alpha) = D$

$$\begin{aligned} \cos \alpha_1 + \cos \alpha_2 + \cos \alpha_3 + \cos \alpha_4 + \cos \alpha_5 \\ \cos 5 \alpha_1 + \cos 5 \alpha_2 + \cos 5 \alpha_3 + \cos 5 \alpha_4 + \cos 5 \alpha_5 \\ \cos 7 \alpha_1 + \cos 7 \alpha_2 + \cos 7 \alpha_3 + \cos 7 \alpha_4 + \cos 7 \alpha_5 \\ \cos 11 \alpha_1 + \cos 11 \alpha_2 + \cos 11 \alpha_3 + \cos 11 \alpha_4 + \cos 11 \alpha_5 \\ \cos 13 \alpha_1 + \cos 13 \alpha_2 + \cos 13 \alpha_3 + \cos 13 \alpha_4 + \cos 13 \alpha_5 \end{aligned}$$

$$5M$$

$$= \begin{matrix} 0 \\ 0 \\ 0 \\ 0 \end{matrix}$$

2. Initial guess can be made and $F(\alpha)$ can be obtained.
3. $d\alpha = \frac{D-F(\alpha)}{dF(\alpha)}$
4. For each iteration $\alpha_{new} = \alpha_{old} + d\alpha$.

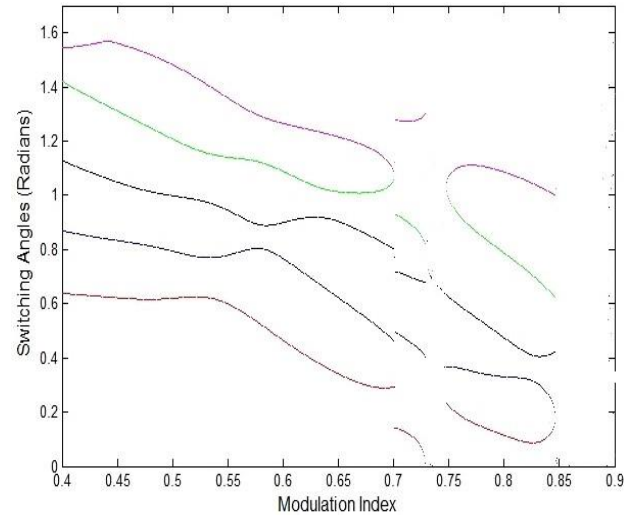


Figure 4. Optimized switching angles

With the above algorithm for different values of M switching angles can be obtained shown in figure 4, this method is widely used but for certain range of M solution doesn't exist therefore, for these ranges, the angles can be calculated such that the aggregate contribution of the 5th, 7th, 11th, and 13th harmonic components is least. The aggregate contribution of the above four harmonic components are calculated by the THD due to the harmonics up to 13th order as:

$$THD_{13} = \frac{\sqrt{v_5^2 + v_7^2 + v_{11}^2 + v_{13}^2}}{v_1} \times 100 \quad (4)$$

Here v_5 , v_7 , v_{11} and v_{13} are magnitudes of the fundamental, 5th, 7th, 11th, and 13th harmonic components, respectively. This objective function is to be minimized (4).

For $k=5$, $N=11$, $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$ are calculated offline for modulation index range [0.4-0.9] as shown in Table I. and the range in which solution doesn't exist can be found out by minimizing objective function given in equation (4) or some other optimized techniques can be used [4,5], thus for whole range of M [0-1] angles are calculated and fed to inverter.

Table I. Optimized switching angles with different modulation index.

Modulation index	switching angles for phase 'a'(radians)					THD%
	α_1	α_2	α_3	α_4	α_5	
0.5	0.6236	0.8179	1.007	1.2117	1.4518	8.88
0.6	0.465	0.7667	0.8994	1.0891	1.2654	7.268
0.7	0.292	0.628	0.9815	1.0881	1.5423	7.763
0.8	0.1146	0.3305	0.4743	0.788	1.0863	5.56
0.9	0.0695	0.16	0.3135	0.498	0.7076	5.78

For the desired output voltage i.e M , inverter output can be controlled with the help of pre calculated offline switching angles. For multilevel inverters, harmonics elimination

follows the same equation sets as (2). Multiple methods, such as fuzzy proportional integral controller [6], control algorithm [7] genetic algorithm [8], [9] etc., have been proposed.

IV. SIMULATION AND INTERPRETATION

For 11-level CMLI with source voltage 100V optimized angles so as to reduce THD are obtained with the help of N-R algorithm for non-linear set of equations, with these angles THD is calculated at selected modulation indexes and a general interpretation can be made that as M increase THD reduces. Figure 5 shows FFT analysis of line voltage at 0.82 modulation index and each H-bridge switch conducts for half cycle, lower order selected harmonics are eliminated and dominating triplens are absent in line voltage. Switching angle variation with M can be seen in figure 6. In most cases, there are probably more appropriate solutions to eliminate the same harmonics of the output voltage of the inverter; it needs a calculation of total harmonic distortion for different solutions. The final solution to be used is the one with the lowest THD similarly optimum angles can be obtained for any number of levels and THD can be calculated. Thus for a inverter by controlling α period for which output exist can be varied and an improved waveform in terms of harmonics can be obtained.

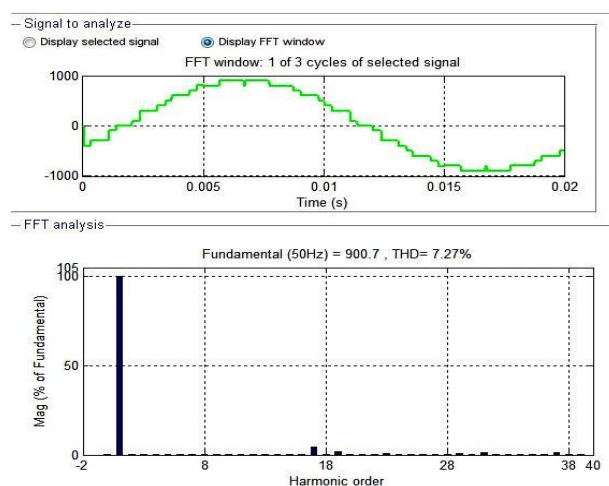


Figure 5. FFT window for CMLI line voltage.

V. CONCLUSION

This paper has enabled us to appreciate the principle of a substitute solution among several approaches for the same problem available to us, each approach has merits and demerits, we note that by calculating optimum switching angles for multilevel inverters harmonics of lower order are eliminated which improves the performance of the inverter, the moment levels are known in advance. The main drawback of the technique of Newton-Raphson method applied to solving systems of nonlinear equations of this technique is the difficulty of choosing initial values of switching angles. This technique can also be used to power the induction machines fed by inverters which are adopted primarily for medium and large motor and can also be used in conjunction with the transmission line for harmonic filtering and VAR compensation. Allows the selection of harmonics to be eliminated, also allows control of the amplitude of the fundamental and allows the reduction of the number of inverters at the interconnection.

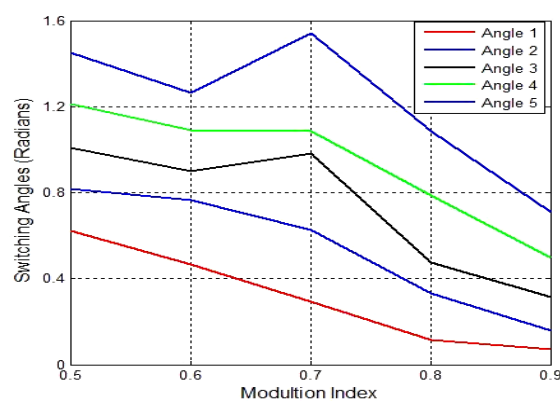


Figure 6. Optimized Switching angles for selected M.

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