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Harmonics Minimization Method for Cascaded Hybrid Multilevel Converter

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ABSTRACT

Recent advancements in the field of power electronics have made possible the worldwide application of converters in dc power source utilization, uninterruptible power supplies, electric motor speed control, switched mode power supplies, flexible alternating current transmission systems devices including static synchronous compensator and their controls. Power semiconductor devices such as converters have been emerged as powerful devices in the power industries. As such, harmonics free output of inverters is assuming extreme importance. Over the past decades, depending upon the topologies and control strategies, numerous optimization techniques have been proposed for desired output waveform. This paper presents a review of optimization techniques used for multilevel inverters. The pros and cons of optimization techniques are discussed. The objective of these optimization techniques is to find out the optimum firing angles of multilevel inverters, which results in minimum harmonics. As a preferred option for proposed work, reduction of total harmonic distortion with the aid of particle swarm optimization technique to multilevel inverters is suggested.

Keywords: Power Converters, Multilevel Inverters (MLI), Cascaded Hybrid Bridge (CHB), Modulation, Switching Frequency, Harmonic Distortions.

1. INTRODUCTION

Ever since the advent of thyristors in mid 1960s, the field of power electronics has become very popular in almost all industrial applications; whether it may be electrical, electronics, chemical, aerospace, textile etc. [1-3]. Power converters have taken a very important place in the industrial world. Initially the scope was limited up to two level converters but nowadays multilevel converters such as three levels, five levels and higher levels converters have been designed depending upon the various topologies. The main concern of system designers and application engineers has been the task of appropriate designing of multilevel converters which produce desired staircase wave with fewer harmonics. This has been mainly due to the reason that on increasing the number of levels, more harmonics are introduced in the output of the inverters. The multilevel inverter having harmonics free output attracted importance in all industrial, commercial, domestic and defense applications [4]. Hence, there has arisen the need for suitable control strategies and optimization techniques to achieve harmonics free output in multilevel inverters [5-7].

Neutral point clamped (NPC), flying capacitor (FC) and cascaded hybrid bridge (CHB) are the three multilevel converter topologies and well documented in the literature [8]. A proper selection of topology using power semiconductor devices forms the most ideal inverter for a variety of industrial applications. More emphasis will be given here to the features related to the CHB, since it is the topology to be used in this paper for harmonic control. In the late 1960s, with the series connected hybrid bridge multilevel stepped waveform concept, CHB topology came into existence [9]. Compared with NPC and FC topologies, cascaded hybrid bridge converters require the minimum number of components for producing the same number of voltage levels because of elimination of clamping diodes and voltage balancing capacitors. But CHB inverter needs separate dc sources for each cell. After selection of multilevel inverter topology; there is need to decide the control or modulation strategies and optimization techniques, which result in minimum total harmonic distortion (THD) as mentioned in standards like IEEE-519, EN 50160, IEC 61000-2-2, IEEE 61000-2-4 etc. [10].

This paper is arranged into six sections. Section I deals with the introduction, gives the brief history of multilevel inverter topologies, control strategies and optimization techniques. Most widely used CHB topology is described in section II. Suitable modulation techniques for designing of multilevel inverters are mentioned in section III. Section IV enlists the optimization techniques for finding the optimum firing angles. Comparison of all the existing optimization techniques has done in this section. Challenges and future scope are mentioned in section V. Finally, conclusion has drawn in section VI.

2. CASCADED HYBRID MULTILEVEL TOPOLOGY

Cascaded hybrid multilevel is an important topology of multilevel inverters because of various advantages [11]. This topology includes the series of H-bridge inverter units with separate dc sources for each unit. A n level topology requires 2(n-1) switches and (n-1)/2 isolated power supplies per phase. Fig.1 shows one leg of 7 level CHB inverter. Three different voltage levels are produced by each H- bridge, say bridge H1 will produce: +Vdc, 0 and –Vdc voltages by different switching patterns of four switches i.e. S1, S2, S3 and S4. In the same manner, other bridges also produce the voltages. Each H-bridge produces the ac output. The synthesized output voltage waveform is sum of all individual H-bridges voltages.

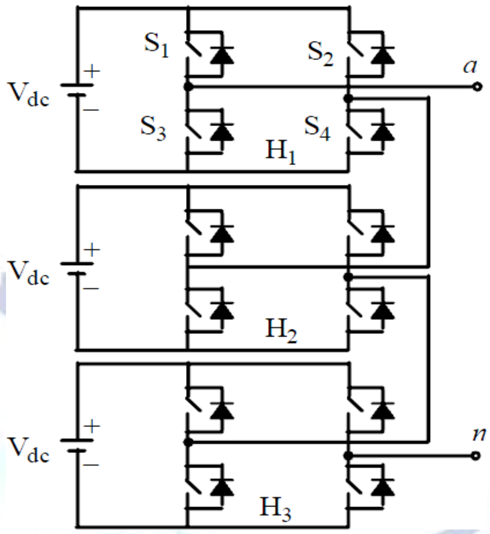

Fig-1: Configuration of Seven Level Cascaded Inverter

The sinusoidal output voltage produced by cascaded multilevel inverter depends upon the firing angles of switching devices used in H-bridge. Switching devices of each H-bridge are fired at different angles. For e.g. in 7 level CHB inverter, three bridges i.e. H1, H2 and H3 are fired at three different angles $\alpha 1$, $\alpha 2$ and $\alpha 3$ respectively. Firing angles value are selected in such a way so that the inverter produces the harmonics free sinusoidal waveform.

Fig.2 shows the output waveform for 7 level MLI. As the output voltage generated by cascaded MLI depends on these firing angles, the output voltage needs to vary from zero to maximum (corresponding variation in modulation index is from 0 to 1). Generally, these firing angles are calculated with the aid of optimization techniques and are stored in a look up table and accordingly switching devices are fired.

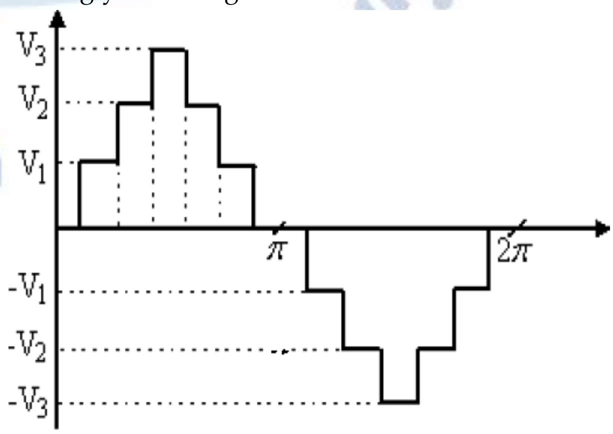

Fig-2: Typical Output Voltage Produced by Seven Level Cascaded Inverter

3. MULTILEVEL INVERTER CONTROL STRATEGIES

Another important feature of MLI is the various control strategies applied to it [12]. The objective of these modulation techniques is to get a switched stepped waveform with fewer harmonics and losses. Fig.3 shows the classification of modulation techniques based on the switching frequency. Numerous pulse width modulation (PWM) and space vector control (SVC) strategies, which result in less complexity and better output waveform have been reported in the literature [13]. High power applications require fundamental or low switching frequency modulation techniques to keep the losses below the acceptable values. Another option is selective harmonic control (SHC) technique. SHC strategy includes selective harmonic elimination (SHE) and selective harmonic mitigation (SHM). SHE technique is also known as fundamental switching frequency method as per the harmonic elimination theory proposed by Patel et al [14, 15],. In this control strategy, firing angles are selected such that the THD is minimum in the output voltage waveform.

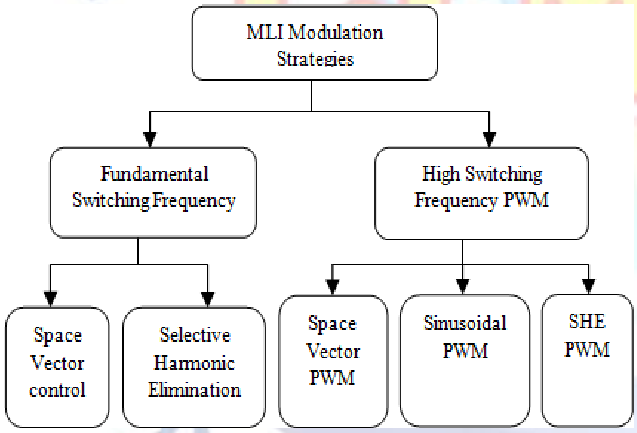

Fig-3:Classification ofModulationTechniques

4. OPTIMIZATION TECHNIQUES

In MLIs, output voltage is represented using fourier seriesas:

$$V_{an}(wt) = \sum_{m=1,3,5,\ldots} \frac{4V_{dc}}{m\Pi}(\cos(m\alpha_1) + \cos(m\alpha_2) + \ldots\ldots\ldots\ldots + \cos(m\alpha_n))\sin(m\,wt)$$

Where Vdc = dc voltage and $0 \circledcirc \circledcirc 1 \circledcirc \circledcirc 2 \circledcirc \circledcirc 3 \circledcirc \circledcirc / 2$

The harmonic factor (percentage) of the nth harmonic is calculated as:

$$HF_n = \frac{V_n}{V_1} X100; n > 1$$

Here Vn represents the n[th] harmonic voltage and $V1$ is fundamental output voltage

Equation (i) can be divided into three parts as:

$Van(wt) \circledcirc Vl1(t) \circledcirc Vl2(t) \circledcirc Vl3(t)$

Where $Vl1(t)$ is the fundamental frequency voltage, represented as:

$$V_{l1}(t) = \frac{4V_{dc}}{\Pi}(\cos\alpha_1 + \cos\alpha_2 + \cos\alpha_3)\sin wt$$

For 7 level cascaded MLI]

$Vl2(t)$ is the triplen harmonic voltages as:

$$V_{l2}(t) = \sum_{m=3,9,15,\ldots} \frac{4V_{dc}}{m\Pi}(\cos(m\alpha_1) + \cos(m\alpha_2) + \cos(m\alpha_3))\sin(mwt)$$

$V_{l3}(t)$ is the odd harmonic (except triplen) voltages as:

$$V_{l3}(t) = \sum_{m=5,7,11,\ldots} \frac{4V_{dc}}{m\Pi}(\cos(m\alpha_1) + \cos(m\alpha_2) + \cos(m\alpha_3))\sin(m\,wt)$$

In three phase applications, triplen harmonic voltages in each phase cancel out automatically, hence no need to cancel these voltages. Another important parameter is modulation index (m_I), which represents the relationship between the fundamental voltage (V_1) and the maximum obtainable voltage (V_{1max}). It is defined as the ratio of the fundamental output voltage to the maximum obtainable fundamental voltage. Switching angles $\circledcirc 1$, $\circledcirc 2$ and $\circledcirc 3$ (in case of 7 level cascaded MLI) can be found using optimization techniques

Equation (i) is known as non linear transcendental equations. For solving these transcendental equations, different optimization techniques have been suggested in the literature. In [16], a method was suggested so as to produce the required output voltage and simultaneously to suppress the higher order harmonics. The transcendental equations involving the harmonic content are converted into polynomial equations. These equations are further solved by the method of resultants. But in this technique, the degree of polynomials become quite large when there are numerous dc sources, which further results in high computational burden of resultant polynomials. Also, due to the computational complexity associated with these techniques, theory of resultant and symmetrical polynomials has been applied up to 11 level multilevel converter only. Limitation of resultant theory appears when applied to MLIs with unequal dc sources, where transcendental equations are no longer symmetrical and requires the solution of a set of higher degree equations.

In [17,18] switching angles are calculated using Newton Raphson (N-R) numerical technique, where certain number of harmonic components have eliminated. But N-R methods have some drawbacks like divergence problems, need to define initial value and also provides no optimum solution.

Genetic algorithm (GA) technique is used in [19] for eliminating some higher order harmonics while maintaining the required fundamental voltage. GA is a computational approach by which optimization problems can be solved using genetic methods and the theory of evolution. But for implementation of this method, proper selection of certain parameters such as initial population size, crossover operation, mutation operation etc. are required, thereby implementation of this algorithm becomes tedious for higherMLIS.

In [20, 21], a new approach has discussed for real time calculation of firing angles using artificial neural networks (ANN). The approach is accomplished by first transforming the nonlinear transcendental harmonic elimination equations for all possible switching schemes into a one input (modulation index) and multi output (switching angles) three layers ANN. Then, the complete set of solutions of the equations is found using the back propagation of the errors between the desired harmonic elimination and the non linear equation systems output using the switching angle given by the ANN. Simulations in the [21] indicates that the switching angles issued by look up table and through trained neural network are almost equal. Therefore, a conclusion has drawn that a look up table can be replaced by a trained neural network, hence reducing the computational effort and storing capacity. Further a trained neural network produces switching angles by interpolation/extrapolation even for those values of modulation index, where switching angles are not calculated

In [22], generalized pattern search (GPS), simulated annealing (SA) and genetic algorithm (GA) are used for calculating the firing angles to eliminate harmonics in 13 level inverter. The proposed algorithms can be applied to higher MLIs. The simulation results showed that GPS and SA methods are more efficient than GA.

Real time calculation of switching angles for minimum THD has done using step modulation [23]. However, the limitation of stepped modulation technique lies in its narrow modulation index. Bee optimization technique is used in [24] for harmonic elimination in cascaded MLI. In this paper, 7 level cascaded MLI is used. The algorithm is based on food foraging behaviour of a swarm of a honeybees. Simulation results showed that bee algorithm (BA) has higher precision and probability of convergence than GA.

Harmony search algorithm (HSA) and particle swarm optimization (PSO) are other optimization techniques for finding out the firing angles of cascaded MLIs [25]. HSA searches those certain values which optimize the fitness function and also simultaneously satisfy the problem's constraints. HSA imposes fewer mathematical requirements and does not require initial value settings for decision variable. For optimization of non linear transcendental equations, PSO methodology is a very powerful approach. In [26], a novel PSO technique to determine the optimum firing angles of MLIs is presented. This optimization technique is applied to non linear transcendental equations characterizing the harmonic content to minimize the low order harmonics. Figure (iv) shows the flowchart of PSO technique. Simulation results showed that PSO can simply find the optimum switching angles and has faster convergence with better quality solutions than GA approach. PSO completely outperforms both GA and HSA. [27] presents PSO based optimal switching technique for harmonic elimination in cascaded MLIs.

A species based PSO (SPSO) method, which includes the suitable adjustment of niche radius for calculation of the optimum firing angles of MLIs, has been proposed in [28]. Simulation and hardware results are mentioned for cascaded hybrid 11 level inverter. Results indicate that all the lower as well as higher order harmonics are effectively minimized in the output sinusoidal voltage waveform of MLI. Also the switching frequency of multilevel inverter and the THD have decreased dramatically.

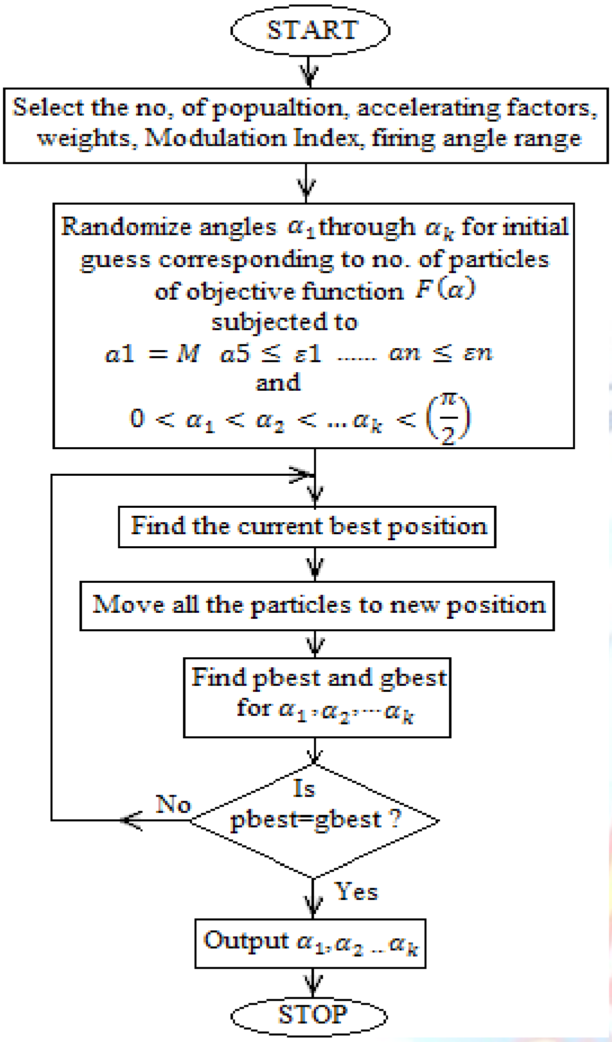

Fig-4: Flowchart of Particle Swarm Optimization Algorithm

CHALLENGES AND FUTURE SCOPE

Numerous harmonics optimization techniques for cascaded MLIs have been reported in the literature but still there are some challenges which need to be overcome. Some of these challenges are discussed in the succeeding paragraphs.

In cascaded MLIs, with increase in levels output voltage waveform tends to become more sinusoidal but also leads to more harmonics. Optimization techniques eliminate or minimized the lower order harmonics; still there exist some higher order harmonics. For minimizing these higher order harmonics use of active filters are necessary, which ultimately leads to overall increase in cost of MLI [29]. However, some optimization techniques minimize the higher order harmonics too; but those techniques have computational burden and are time consuming. In this context, selection of suitable optimization technique is an important consideration while designing the cascaded MLIs. For a particular value of modulation index, multiple set of solutions of non linear transcendental equations exists. The main challenge is to select that solution, which results in minimum THD of output voltage waveform of cascaded MLI.

In optimization techniques, no solution exists for a particular value of modulation index. However, in the literature optimization techniques have been reported which provide a solution set for complete range of modulation index [30]. Even after lots of advancement in harmonic optimization techniques, there is further scope to reduce the THD of output voltage waveform by selection of suitable optimization technique while maintaining the permissible switching frequencies.

5. CONCLUSION

The different optimization techniques such as Newton Raphson method, resultant theory and symmetric polynomial, genetic algorithm, harmony search algorithm, particle swarm optimization etc. have been proposed to minimize the total harmonic distortion in cascaded multilevel inverters. Maintaining the desired level of fundamental output voltage, all the lower order harmonics are minimized or controlled within the permissible limits. Thereby, results in minimum total harmonic distortion and the corresponding firing angles are determined. The proposed methods are able to find the optimum firing angles in a simple manner. These techniques ensure the accuracy and quality of firing angles of cascaded multilevel inverters such that output voltage waveform results in minimum total harmonic distortion.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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