A Modified Selective Harmonic Elimination switching strategy for Hybrid Flying Capacitor Multicell Converter

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Abstract

Selective Harmonic Elimination Pulse Width Modulation (SHEPWM) switching strategy is commonly applied for the elimination of low order harmonics in the multilevel converter with stepped waveform. In this paper, this switching algorithm is utilized to a Hybrid Flying Capacitor Multicell converter to produce the required fundamental voltage and in the same time cancel out specified higher order harmonics in this converter. Hybrid Flying Capacitor Multicell is a new multilevel converter that reduces elements for same level of output voltage compared with the classic multilevel converters. For a range of the modulation index (m), angels obtain from resultant theory are trained to neural network, since the neural network is trained, give the best angles for the entire modulation index. In resultant theory for a range of the modulation index (m>1.15)in the seven-level converter, the switching angles can be chosen to produce the desired fundamental output while making the fifth and seventh harmonics identically zero. But the main drawback is that for a range of the modulation index (m<1.15) there are not any solutions in resultant theory, to overcome this problem a DC‒DC buck converter has been used to have adjustable dc source in input of converter to coordination between modulatio nindex and output voltage. The simulation results has been carried out using SIMULINK/MATLAB present the effectiveness of the SHEPWM strategy for the proposed converter.

1. Introduction

Multilevel converters have been continuously developed in the last year due to necessity of increase the power level on industry. The main reason for this, is the capability of these topologies to handle voltage in the range of kV and Megawatts with medium voltage semiconductors[1].

The desired output of a multilevel converter is synthesized by several sources of dc voltages. With an increasing number of dc voltage-sources, the inverter voltage output waveform approaches a nearly sinusoidal waveform while using a fundamental frequency switching scheme. This results in low switching losses, and because of several dc sources, the switches experience lower voltage stresses [2].

Some of the fundamental multilevel topologies include the diode-clamped, flying capacitor, and cascaded H -bridge structures. Recently, with the increase in the rating of the available switches, there has been much interest in new topologies aiming to reduce the amount of semiconductor devices [3,4].

With respect to the switching frequency of multilevel converters, the switching strategies can be classified into two categories. Methods that work with high switching frequencies, including classic carrier based Sinusoidal Pulse Width Modulation (SPWM) and the Space Vector Modulation (SVM), strategy and methods that work with low switching frequencies, generally equal to the fundamental component frequency and generate a staircase waveform. Representatives of this family are Space Vector Control (SVC), Minimization of the Total Harmonic Distortion (MTHD), and Selective Harmonic Elimination PWM (SHEPWM) [5]. In the second group, because of low switching frequency, switching losses reaches to its minimum level; efficiency is maximized, so implement is easy [6].

Generally, in SHEPWM technique, switching angles are calculated off-line through some famous algorithm such as: Newton-Raphson (N-R), Sequential Quadratic Programming (SQP), Resultant Theory, Homotopy algorithm, Genetic algorithm (GA), PSO and Harmony Search Algorithm (HSA). However, Resultant theory can find all solutions of the SHEPWM equation, analytically [5].

In this paper SHEPWM strategy has been used for the switching of the Hybrid Flying Capacitor Multicell converter. Angels obtained from resultant theory are trained to neural network for various modulation index. Output of Multi Layer Perceptron (MLP) neural network [7] are the switching angels of Hybrid Flying Capacitor Multicell. For a specific range of the modulation index that there are no solutions in resultant theory, a DC−DC buck converter [8] has been used to have adjustable dc source in the input of Hybrid Flying Capacitor Multicell to coordination between modulation index and output voltage.

2. Multilevel converters

2.1.Multilevel converter topologies

Multilevel converters are categorized into two general topologies: Neutral Point Clamped (NPC) converter and Multicell converter. The Neutral Point Clamped (NPC) converter, presented in the early 80's [3,9], is now a standard topology in industry on its 3-level version. However, for a high number of levels, this topology presents some problems, mainly with the clamping diodes and the balance of the dc-link capacitors. An alternative for the NPC converter are the Multicell topologies. Different cells and ways to interconnect them generate many topologies which the most important ones are the Cascaded Multicell (CM) and the Flying Capacitor Multicell (FCM) with its sub-topology Stacked Multi-cell (SM) converters [3, 10].

2.2. Flying capacitor multicell (FCM)

The Flying Capacitor topology was introduced by Meynard in 1992,this topology is based in the connection of two level cells, as shown in Fig. 1, for this reason the maximum number of levels at the output of this converter is:

$$l=n+1 \qquad (1)$$

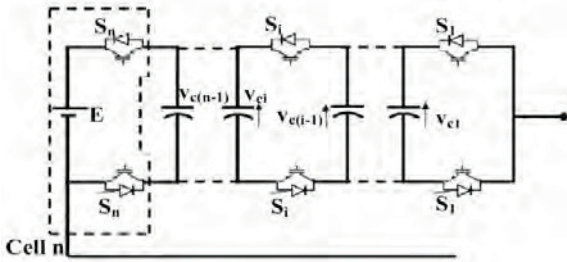Where n is the number of cells connected.

Fig.1. (n+1)-level flying capacitor multicell inverter

For a proper operation, the DC link voltage on each cell must accomplish with:

$$V_{ci=}(i/n)E \qquad (2)$$

Fortunately, this condition is reached by the converter itself if the modulation strategy applies the redundancy states in alternate way [1].
Main advantage of flying capacitor over cascaded converter are that flying capacitor does not require a complex input transformer and the number of separate DC voltage sources are reduced.

2.3. Hybrid flying capacitor multicell converter

The three-level H-bridge converter topology used in the CM converter presents some advantages over two level topologies. Beyond the obvious advantage on the number of output levels, this structure allows to double the peak to peak voltage from v_{dc} to $2v_{dc}$, by applying to the load the voltages: $+v_{dc}$, 0 and $-v_{dc}$. This topology would be even more powerful if the dc-link voltage could be adjusted according the load requirements , turning in to a variable dc-link voltage V_m, as shown in Fig. 2.
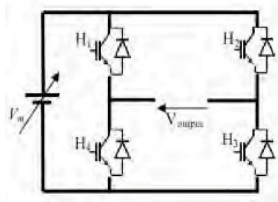

Fig.2. H-bridge converter

The proposed way to achieve this adjust is by the use of a FCM topology on the dc-link of three-level H-bridge converter, as shown in Fig. 3, in this way, with a proper modulation of

switches S_1 to S_n (being n the number of FCM sub-cells used), the values for V_m can be:

$$v_m = \begin{cases} E \\ \cdots \\ iE/n \qquad , 1 \le i < n \\ \cdots \\ 0 \end{cases} \qquad (3)$$

With a proper modulation, the number of levels that this new topology can reach is:

$$L=2n+1 \qquad (4)$$

Where n is the number of FCM sub-cells connected.
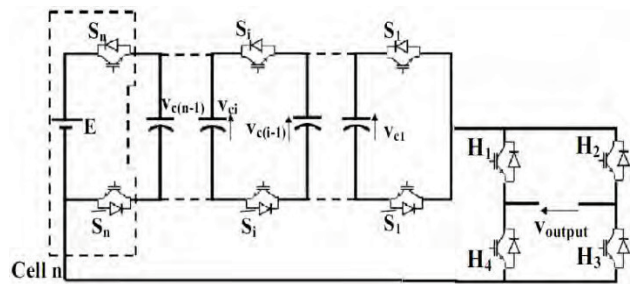

Fig.3. (2n+1)-level Hybrid Flying Capacitor Multicell inverter

3.Switching algorithm

3.1. Resultant Theory

The Fourier series expansion of the (stepped) output voltage waveform of the multilevel converter as shown in Fig.4 is

$$V(\omega t) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4E}{3n\pi}(\cos n\theta_1 + \cos n\theta_2 + \cdots + \qquad (5)$$
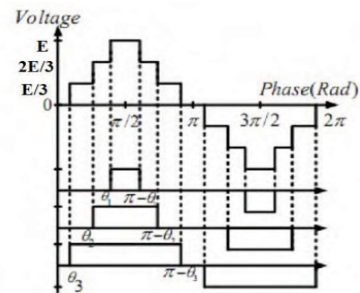$$\cos n\theta_s)\sin n\omega t$$

Fig.4. output waveform of a 7-level multilevel converter

Where (s) is the number of dc voltages. Ideally, given a desired fundamental voltage V_1 , one wants to determine the switching angles $\theta_1,\ldots,\ \theta_s$ so that (5) becomes $V(\omega t) = V_1\sin(\omega t)$. In

practice, one is left with trying to do this approximately. Two predominate methods in choosing the switching angles are 1) eliminate the lower frequency dominant harmonics or 2) minimize the total harmonic distortion. The more popular and straightforward of the two techniques is the first, that is, eliminate the lower dominant harmonics and filter the output to remove the higher residual frequencies. Here, the choice is also to eliminate the lower frequency harmonics [5, 6].

The goal here is to choose the switching angles to make the first harmonic equal to the desired fundamental voltage and specific higher harmonics of equal to zero. The triplen harmonics in each phase need not be canceled as they automatically cancel in the line-to-line voltages. Specifically, in case of s=3 dc voltages, the desire is to cancel the fifth-, and seventh- order harmonics as they dominate the total harmonic distortion [5]. The mathematical statement of these conditions is then

$$\frac{4E}{3\pi}(\cos\theta_1 + \cos\theta_2 + \cos\theta_3) = V_1$$
$$\cos5\theta_1 + \cos5\theta_2 + \cos5\theta_3 = 0 \qquad (6)$$
$$\cos7\theta_1 + \cos7\theta_2 + \cos7\theta_3 = 0$$

This is a system of three transcendental equations in the three unknown's θ_1, θ_2, θ_3. One approach to solving this set of nonlinear transcendental (6) is to use an iterative method such as the Newton-Raphson method, and the other approach to solving this set of nonlinear transcendental (6) is to use resultant theory [5]. The correct solution to the conditions (6) would mean that the output voltage of the 7-level converter would not contain the fifth-, seventh- order harmonic components [5].

In this paper, resultant theory has been used to obtain θ_1, θ_2, θ_3 for ranges of the modulation index $m \triangleq V_1$ (4E/3π) that a solution exist. The results are summarized in Fig.5 which shows the switching angles θ_1, θ_2, θ_3 versus m for those values of m in which equation (6) has a solution. The parameter m was incremented in steps of 0.01. Note that for m in the range from approximately 1.49 to 1.85, there are two different sets of solutions that solve (6). On the other hand, for $m \triangleq [0, 0.8]$, $m \triangleq$ [0.83, 1.15], and $m \triangleq [2.52, 2.77]$, there are no solutions to (6). In the range for which there are two sets of solutions, the solution which gives the smallest distortion due to the 11th and 13th harmonics is a good choice [5].
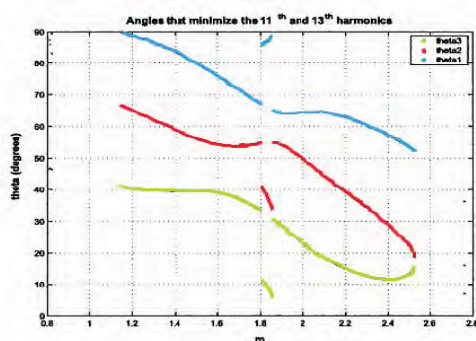

Fig.5. switching angels θ_1, θ_2 and θ_3 in degrees versus *m*

3.2.Neural network structure

Fig.6 shows the structure of neural network [7], it has 10 neurons in the first hidden layer and 3 neurons in the last layer, both with tangent hyperbolic transfer function.
Training process is performed by M-files of MATLAB software. The output result of resultant theory method is trained to neural network and results shows that the neural network tracked them.
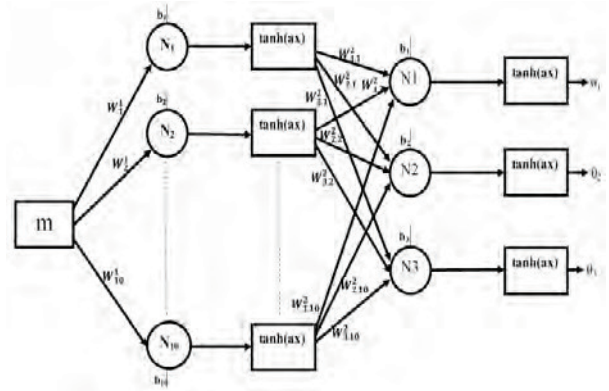

Fig.6. structure of neural network

3.3. Aplication of selective harmonic elimination strategy for new converter

In this paper, SHEPWM strategy has been used for Hybrid Flying Capacitor Multicell converter. Switching angels of converter obtained from resultant theory are trained to neural network for various modulation indexes as offline. For a range of the modulation index that resultant theory has a result, the neural network generate the desired switching angels, but for a specific range of the modulation index that there are no solution in resultant theory, a DC-DC converter [8] is proposed to regulat the input voltage of Hybrid Flying Capacitor Multicell to coordination between modulation index and output voltage.
The desired fundamental voltage of output is $V_1 = m$ (4E /3π). For small value of V_1, m must be selected small in which there is not any solution, as a result DC-DC converter decreases E instead of m inorder to obtaining small V_1. For new modulation index resultant theory has a solution, sothis method for a wide range of modulation indexes is effective, Fig.7. shows the proposed topology for 7-level Hybrid Flying Capacitor Multicell.
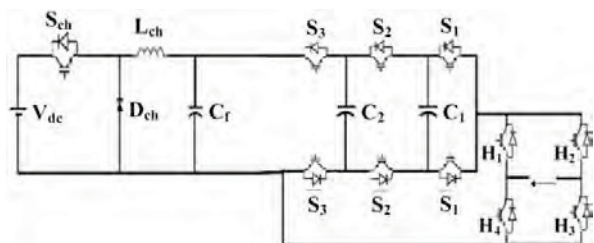

Fig.7. proposed 7-level Hybrid Flying Capacitor

4. Simulation results

Computer simulation is provided to verify the well-performance of the Hybrid Flying Capacitor Multicell converter by proposed switching algorithm. The converter is simulated using Simulink/MATLAB software. The main parameters used in the simulations are given in Appendix. Fig.8. indicates output voltage of the 7-level Hybrid Flying Capacitor Converter controlled by SHEPWM and operated with a wide range of modulation index. It is considered that Hybrid Flying Capacitor Multicell converter can generate multilevel voltage by proposed switching algorithm for a wide range of modulation index.
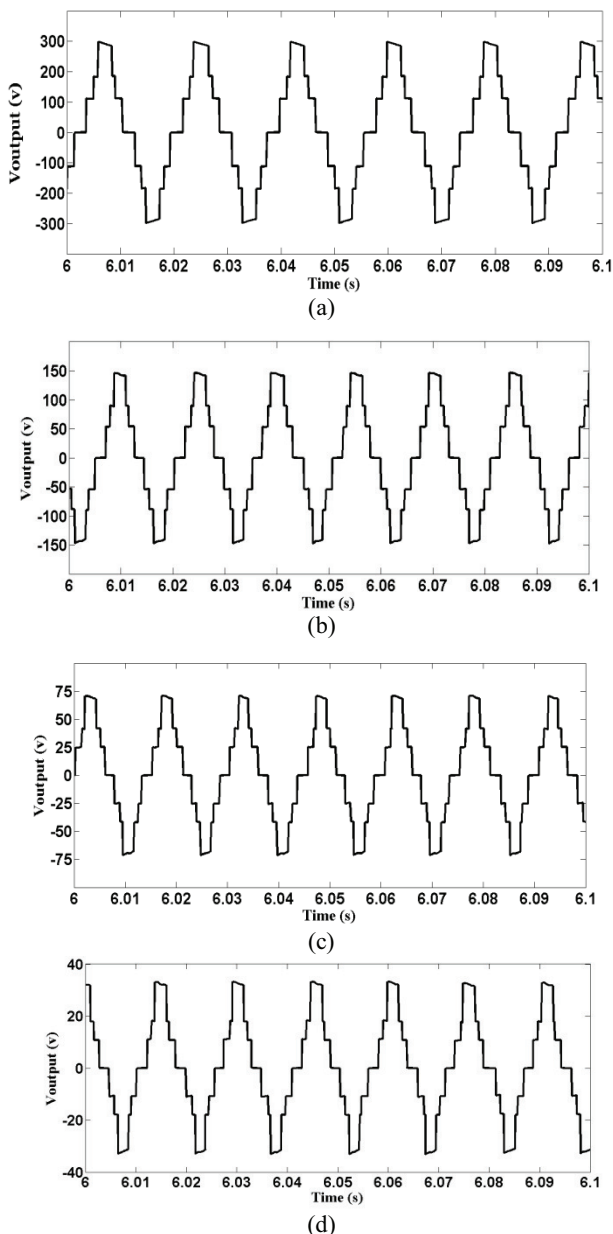

Fig.8. output voltage of a 7-level Hybrid flying capacitor for different m:
a) m=2; b)m=1; c)m=0.5; d)m=0.25

Fig.9. (a), (b), (c), (d) show FFT analysis of output voltage for different modulation index. It is obvious thatfifth and seventh harmonics are omitted for various modulation indexes. The triplen harmonics in each phase need not to be canceled due to these harmonics are mitigated in the line-to-line voltages.
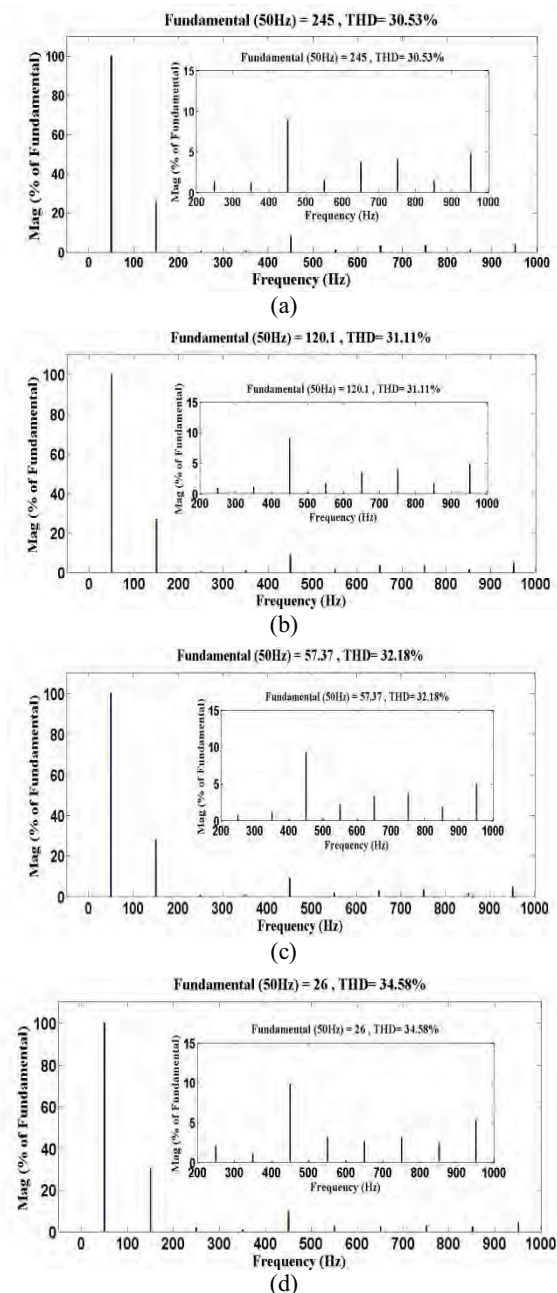

Fig.9. FFT Analysis of output voltage for different *m:*
a)m=2; b)m=1; c)m=0.5; d)m=0.25

Fig.10. indicates input voltage of Hybrid Flying Capacitor (output voltage of chopper) for various modulation indexes. According to these figures it is considered that for low modulation index that resultant theory has not solution, chopper reduce the input voltage of Hybrid Flying Capacitor to coordination between modulation index and output voltage.
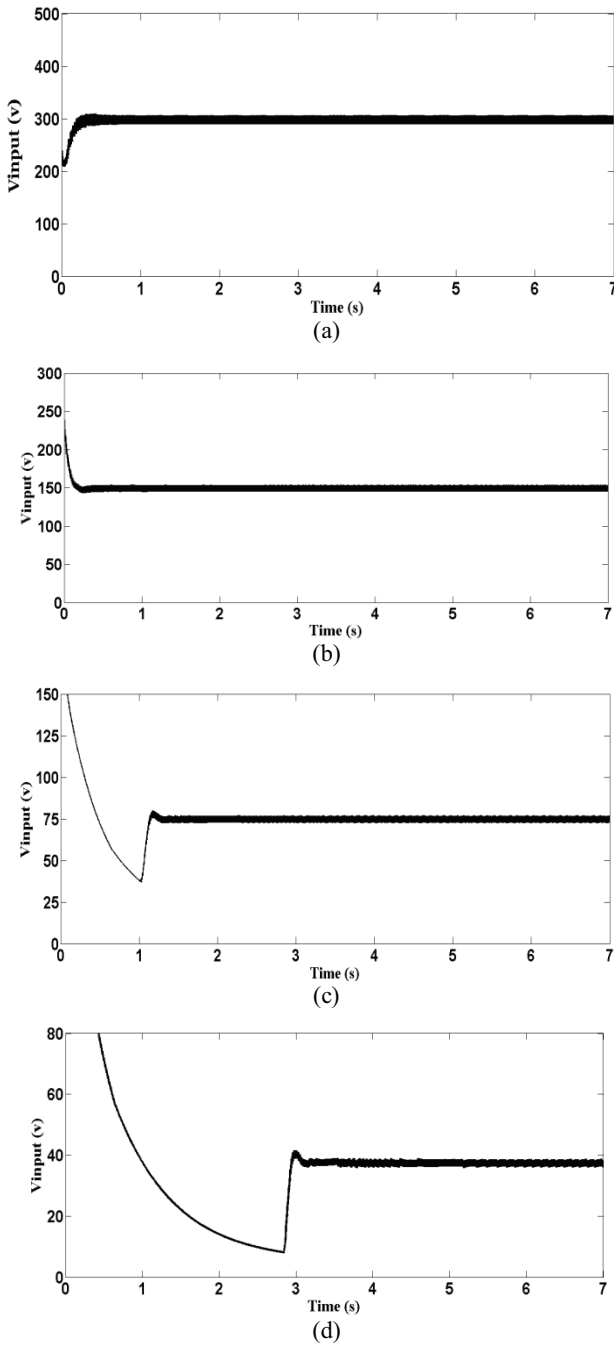
Fig.10. input voltage of Hybrid Flying Capacitor for different m
a)m=2; b)m=1; c)m=0.5; d)m=0.25

5. Conclusions

In this paper, SHEPWM strategy has been used for a Hybrid Flying Capacitor Multicell converter. Switching angels calculated by resultant theory and angels obtain from resultant theory trained to neural network as off-line, neural network give the best switching angels for converter versus different modulation indexes as on-line. Also for a specific range of modulation index that resultant theory has not solution, a DC-DC converter is used to overcome this problem. The simulation results carried out by SIMULINK/MATLAB show well performance of Hybrid Flying Capacitor Multicell converter using this method.

APPENDIX

The test converter parameters are given in Table.1

Table 1. value of test converter parameters

parameters	V_{dc}	L_{ch}	C_f	C_1	C_2	R_{load}
Value (unit)	300 (v)	10 (mH)	800 (µF)	1 (mF)	1 (mF)	20 (Ω)

6. References

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