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Research paper

A fifteen level modified active neutral point clamped multilevel converter for isolated power supply systems

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Abstract

The application of multilevel level power converters in various fields of electrical industry gained momentum during the last decade. Hybrid multilevel converters (HMC) are emerging as an alternative to the conventional two stage inverter topology in high and medium power industrial sectors. Consistency in operation, quality of output power and litheness in enhancement are the vital factors contributed to the development of hybrid multilevel converters. The major challenge met by HMC's are to attain a trade-off between the number of dc sources, switching devices and voltage levels. This paper presents the development of a modified active neutral point clamped fifteen level multi-level converter for isolated power supply electric systems. A Variable Frequency Overlapped Carrier (VFOC) modulation scheme is implemented for capacitor voltage balancing and switching loss reduction. Proposed system has been simulated under Matlab Simulink environment and a low power laboratory prototype is developed for endorsing the reliability and efficiency of the proposed converter.

Keywords: *Active Neutral Point Clamped Converter; Flying Capacitor; Isolated Power Supply Systems; Variable Frequency Carrier Overlapped –PWM.*

1. Introduction

Multilevel inverters are evolving as a potential candidate in replacing conventional power converters employed in electric drives. They have been extensively used in high and medium power application for the last three decades due to its low power losses, increased efficiency, improved reliability, better dynamics and extended power range. Neutral point clamped (NPC), Flying capacitor type (FC) and Cascaded H- Bridge are the most broadly used in industry due to its renowned reliability in operation [1]. Modular multilevel converters (MMC) are another group of multilevel converters developed and utilized in high power industrial sector. The application of MMC's are limited to high voltage and high-power areas due to its requirements for sub modules (SM). Complex control strategy employed also make the topology less accepted in low power converter systems [2], [3]. Active neutral point clamped (ANPC) multilevel inverters are another segment of medium power multilevel power converter. Several ANPC topologies has been investigated in industry and academia due to its wide area of possibilities. The classical topology of a 5L-ANPC is shown in Fig. 1.

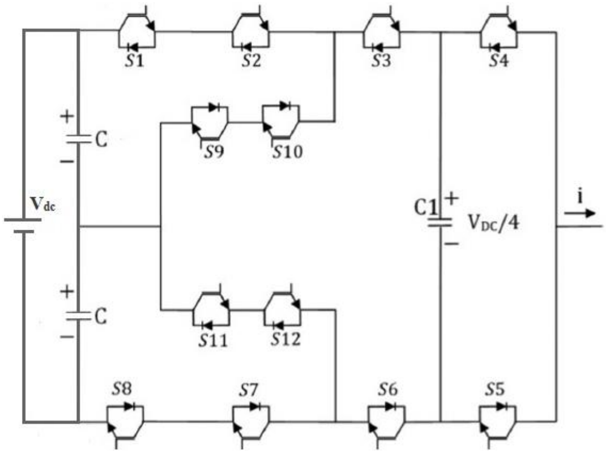

Fig. 1: Classical Topology of A Five Level ANPC Topology.

They encase the advantages of Neutral Point Clamped (NPC) and Flying capacitors (FC) converters. Five level ANPC is the most popular ANPC employed in industry, several modified topologies are also under research [4].

In [4] H. Wang et.al presented a five level seven switch hybrid topology. The authors investigates the performance of three types of 5L-ANPC's, they compare the proposed ANPC topology with the conventional two stage converter topology. The authors claimed to have reduced the switching stress and relatively mitigated the level of Total Harmonic Distortion (THD) also. ANPC and FC aided multilevel converters encompasses a capacitor voltage balancing problem in most of its topologies. Harmonic elimination is also a matter of concern while employed for critical applications. Ample investigations are done on this area to alleviate

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the voltage imbalance effect of the floating capacitors. Accurate voltage balancing of FC's is vital for the correct switching of FC aided converters. The capacitor voltage balancing technology is mainly divided into two, natural voltage balancing and active voltage balancing method. Natural voltage balancing technique is attained through open loop control of converters through a PWM modulator. Active voltage balancing method is achieved by means of sensing the voltage and current of the FC's. The values are compared with the reference value and the error signal is processed to generate switching signals. A five level seven switch topology is shown in Fig. 2.

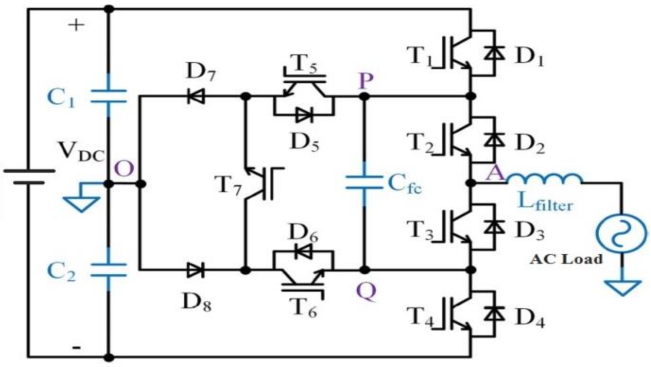

Fig. 2: An NPC Five Level Seven Switch Topology.

In [4] an active voltage balancing technique for stacked multi cell converter is proposed. The control strategy detects voltage difference by the direction of load current and generates PWM switching signals to avoid voltage imbalance in capacitors. A digital sliding mode observer for active control of sub modules in MMC is presented in [5]. In [6] a cost function optimization method is proposed to regulate the voltage in Flying/Floating Capacitor (FC). The most prominent method of capacitor voltage balancing witnessed is by employing redundant switching states and regulating level transitions optimally [7], [8]. A nine-level inverter topology with reduced number of components is presented in [9], [10]. The proposed topology is a combination of a three level T type neutral point inverter with FC. The authors claimed to have reduced the complexity of the proposed converter by means of simple equation based PWM, thereby avoiding the need of voltage-current sensors.

In [11] emphasis has been made on multilevel voltage generation by switched DC sources. During the recent period of research, efforts are made to separate the polarity and level generation parts of the converter, in order to reduce the number of dc sources and power semiconductor devices [12], [13]. Extensive investigations are made on modulation strategies employed in neutral point clamped multilevel converters. Carrier based modulation techniques, Space vector modulation techniques, selective harmonic elimination [14], [15] are the popular modulation techniques implemented in Neutral point clamped converter. In [16] it is validated through detailed mathematical modelling of FC multilevel converters that capacitor voltage balancing (self-balancing) is inherently possible by the application of phase shifted carrier-based pulse width modulation (PSC-PWM) technique.

2. Proposed system

The paper focuses on the development of a modified active neutral point clamped converter (MANPC) for isolated power supply electric drive systems. MANPC topology is formed by the congregation of an ANPC module with a T- Bridge structure. Battery powered or independent DC sources are related to the category of Isolated power supply systems. Phase shifted VFOC pulse width modulation strategy is employed for the generation of voltage levels. This research aims at developing an MANPC topology with inherent capacitor voltage balancing and capability to maintain voltage steps even at lower modulation index. Phase shifted VFOC modulation technique possess the capability of intrinsic harmonic reduction and self-balancing of flying capacitor voltages. The voltage balancing of FC's are achieved by balancing neutral point potential through switching cycle adjustment.

The modified active neutral point clamped converter topology comprises of nine switching devices S1-S9, eight diodes, two floating capacitors of equal rating and three dc sources. The proposed fifteen level MANPC topology is shown in Fig. 3.

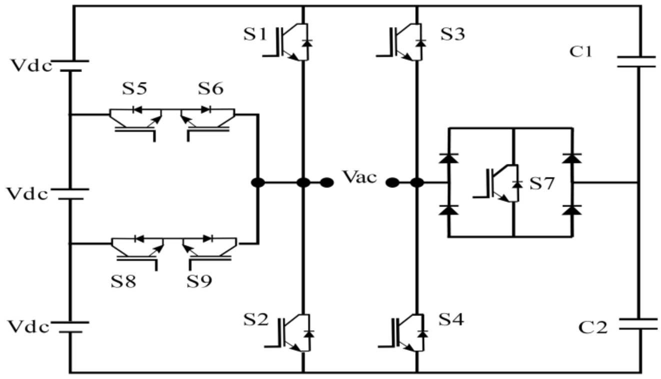

Fig. 3: The Proposed MANPC Converter Topology.

It can be viewed as three parts, first part is the neutral point clamped (NPC) side which consists of switches from S5,S6,S8,S9 and the second part is the T Bridge with a bidirectional switch interconnection S7. Switching devices S1-S4 forms the load feeder (LF) part. Higher power rated switches will be selected for the LF side due to its operation time. Switching signals are generated with the proposed VFOC modulation strategy as discussed in Section III. The switching sequences corresponding to the positive and negative output voltages of are shown in Table I.

3. VFOC modulation strategy

VFOC modulation strategy is a hybrid modulation technique retaining the benefits of level shifted modulation technique, overlapped carrier modulation technique [17] and variable frequency carrier modulation technique [18].

Phase shifted or level shifted modulation strategy possess quarter wave symmetry when the modulation frequency m_f is even. Even modulation frequency results only odd harmonics and even harmonics are eliminated (Modulation frequency is chosen to be 40 in this proposed system). This hybrid modulation technique compares the carrier signals with a sinusoidal reference waveform to generate PWM switching signals for switches S1-9.

The modulation amplitude m_a (modulation index) of the PWM signals is given by:

$$m_a = \frac{\text{Amplitude of the Reference Signal(Sine Wave)}}{(n-1).\text{Amplitude of the Carrier}} \tag{1}$$

Where n is the number of phase voltage levels. Modulation frequency is given by:

$$m_f = \frac{\text{frequency of the Carrier}}{\text{frequency of the modulating wave}} \tag{2}$$

Overlapped Carrier techniques can control the dead time between the switching states, they can also maintain voltage levels even at low modulation indices. Variable frequency operation of the carriers are incorporated to equalize the switching cycles between switches S1-9. The switching states corresponding to the generation of 15 levels (line voltage) and 7 levels (Vao-phase voltage) in phase is shown in Table I.

Table 1: Switching States of MANPC

Switching States

Voltage Levels	S1	S2	S3	S4	S5	S6	S7	S8	S9
V	1			1					
5V/6	1			1			1		
2V/3				1		1			
V/2	1						1		
V/3				1					1
V/5				1			1		1
V/6						1	1		
0V		1		1					
(-)V/6							1	1	
(-)V/5			1		1		1		
(-)V/3			1		1				
(-)V/2		1					1		
(-)2V/3			1					1	
(-)5V/6		1	1				1		
V		1	1						

From the Table.1 it can be observed that the switching states are derived in such a way that the utilization of ANPC section and T-Bridge section is well balanced. Topological peculiarity also aids for the inherent balancing of capacitor (C1,C2) voltages . Equal utilization of ANPC and T-Bridge helps in keeping the voltage imbalance minimum throughout the operation of the converter [19], [20]. The T-Bridge switch S7 is the active switch involved in voltage balancing, a special bidirectional power flow arrangement is provided for the switch S7 with the help of a diode bridge topology. Analytical determination of natural voltage balancing dynamics are depicted in [21] [22].
The triangular carrier waveform for the first cell can be defined as:

$$\Omega_{P1}(t) = \begin{cases} E_c\left(\frac{2}{T_c}t - 2q\right), qTc \le t \le qTc + \frac{T_c}{2} \\ -E_c\left(\frac{2}{T_c}t - 2q - 2\right), qTc + \frac{T_c}{2} \le t \le (q+1)T_c \end{cases} \quad (3)$$

Where $f_c = \frac{1}{T_c}$ and E_C are the triangular carrier waveform frequency(f_{sw}) and amplitude respectively[17]. ANPC switches are under operation throughout the working period whereas LF switches works mostly on the reference frequency. The voltage stress on the switching devices at the ANPC side are restricted to a maximum of Vdc/3.
Redundant switching states are integrated into switching sequence for prominent voltage levels. Integrating or replacing a normal switching state with only one redundant state in a switching sequence can create an imbalance in the FC voltages, hence the redundant states are utilized in consecutive pairs to avoid the capacitor voltage imbalance, i.e., to achieve a voltage level of V/3, switches S4, S9 are switched and the redundancy of the level can be achieved through switches S1, S5, S7.
If the positive side polarity is achieved through redundancy, to avoid the voltage imbalance negative polarity of -V/3 is also shifted to redundant state. The schematic diagram of the proposed modulation strategy is shown in Fig. 4.

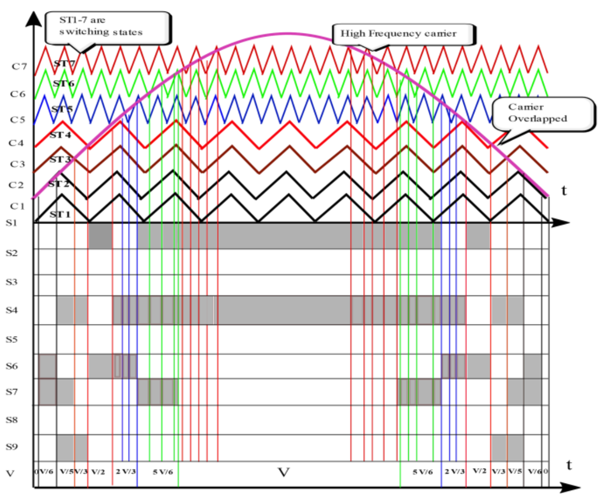

Fig. 4: Novel VFOC Modulation Strategy Employed in MANPC.

Switches S5 and S6, S8 and S9 are complementary to each other, hence their switching signals will be opposite in states. Output voltage corresponding to any instantaneous switching states can be derived from equation (2), consider the switching function of switches (1 for ON state and 0 for OFF state) S4, S9, S8 as Sf4, Sf9 i.e., for an output voltage of V/3 the voltage equation will be:

$$V_{out} = \frac{V}{3}[(S_{f4} - S_{f9})] \quad (4)$$

4. Results and discussion

4.1. Simultion results

A single-phase fifteen level MANPC is simulated in Matlab Simulink environment with VFOC based PWM method. The simulation results show the harmonic performance of the proposed system under different modulation indices. Simulation parameters are shown in Table II.

Table 2: Simulation Parameter of the Proposed System

Particulars	Specification
Input DC Voltage (Vdc)	300V
Switching Frequency	2000Hz
Output frequency	50Hz
Floating Capacitors(C1-C2)	4700μF
RL,Load	12 Ω, 3mH

The harmonic spectra of the output waveforms prove the effectiveness of the modulation technique with reduction in higher order harmonics. Fig 5 to Fig 8 shows the output phase voltage of the proposed MLI for different modulation indices.
Fig.8 to Fig.12 shows the detailed analysis done on the 15 level MANPC converter with inductive loads. The output results confirm the usability of the proposed MLI for electric drive applications where the THD minimization is of prime concern.

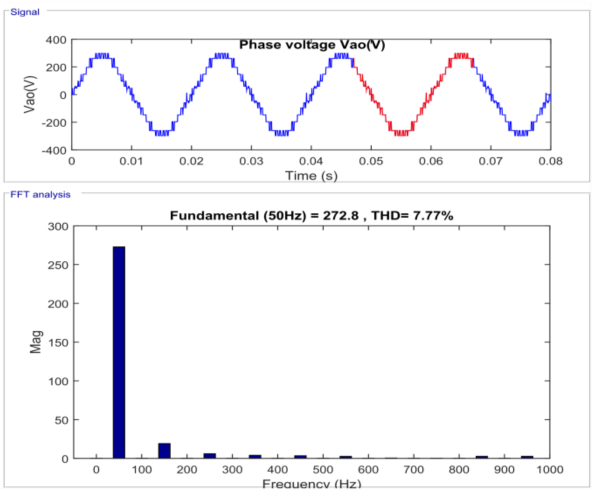

Fig. 5: Output Phase Voltage and Harmonic Spectra for M_A=1 with THD Value 4.99%.

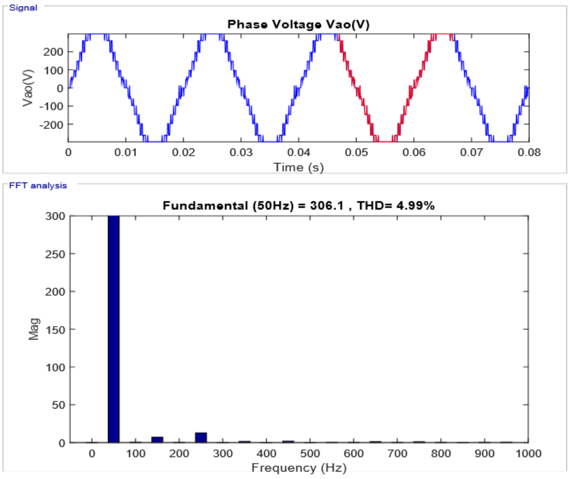

Fig. 6: Output Phase Voltage and Harmonic Spectra for $M_A = 0.8$ with THD Value 7.77%.

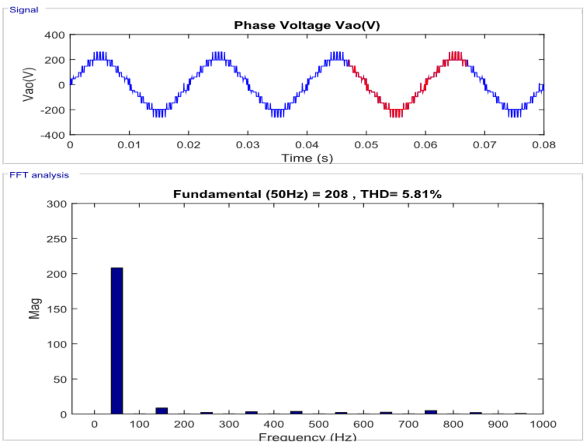

Fig. 7: Output Phase Voltage and Harmonic Spectra for $M_A = 0.6$ with THD Value 6.81%.

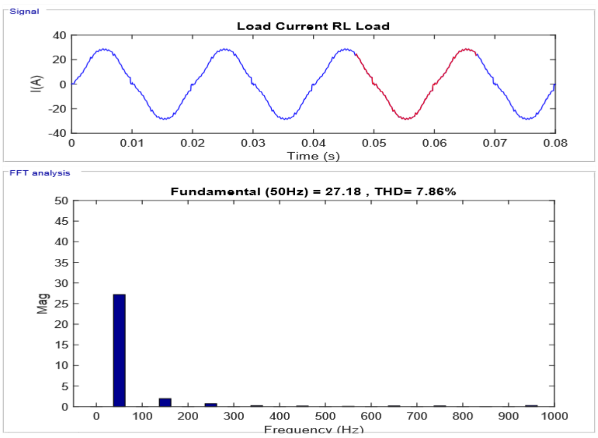

Fig. 8: Output Phase Voltage and Harmonic Spectra for $M_A = 0.4$ with THD Value 5.81%.

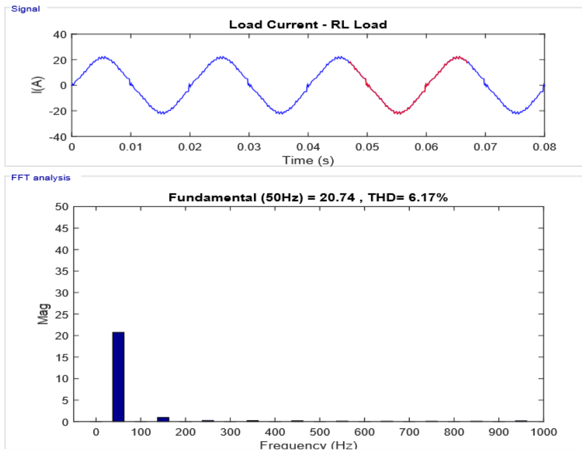

Fig. 9: RL Load Output Current and Harmonic Spectra for $M_A = 1$ with THD Value 7.86%.

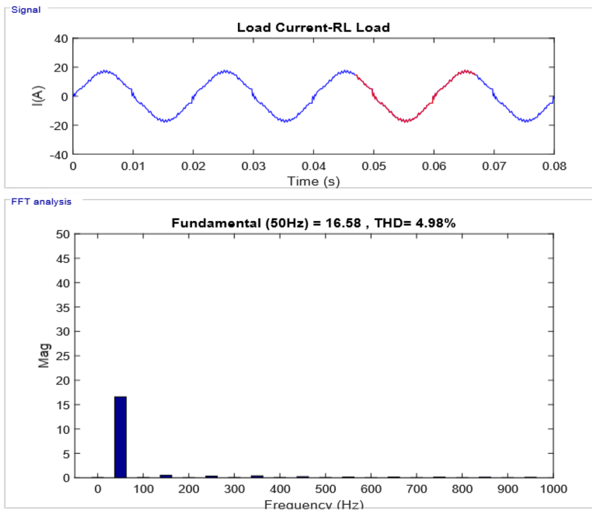

Fig. 10: RL Load -Output Current and Harmonic Spectra for $M_A = 0.8$ with THD Value 6.17%.

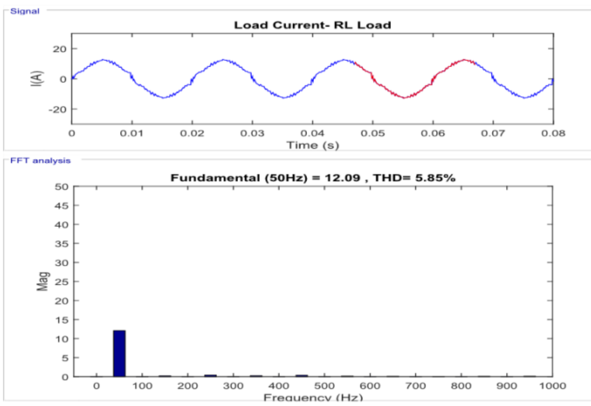

Fig. 11: RL Load Output Current and Harmonic Spectra for $M_A = 0.6$ with THD Value 4.98%.

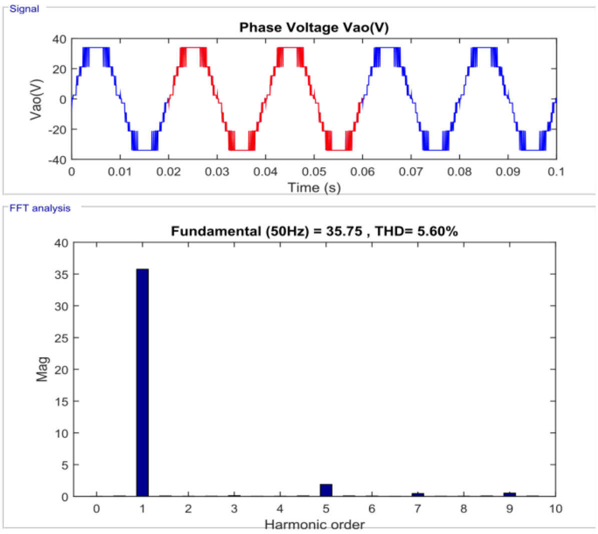

Fig. 12: RL Load Output Current and Harmonic Spectra for $M_A = 0.4$ with THD Value 5.85%.

Linear variation between output phase voltage and modulation index can be seen from Fig. 13.

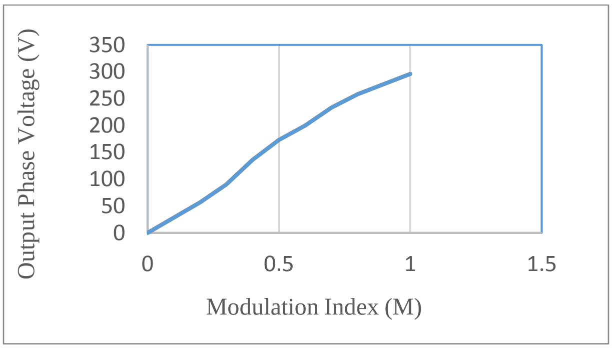

Fig. 13: Fundamental Output Voltage vs. Modulation Index.

4.2. Capacitor voltage balancing

VFOC modulation strategy balances the capacitor voltages as shown in Fig.14. Duration of switching signals are arranged in such a way that the duty cycle for a particular voltage state and corresponding capacitor falls within the period of charging cycle. Hence the charging and discharging period of floating capacitors will not affect the output voltage of the system.

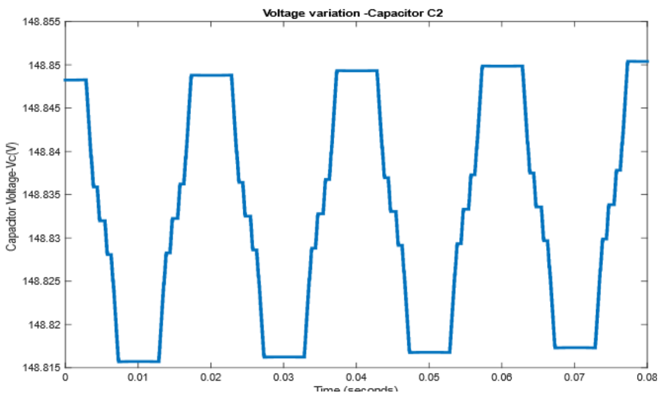

Fig. 14: Charging and Discharging Cycles of Capacitor C2.

The simulation result depicts the performance of the proposed converter under varying load conditions. The voltage levels are maintained even at a very low modulation index.Fig.13. Linear variation of output voltage with respect to modulation index can be clearly seen from the result analysis.

Matlab Simulation for a 36V prototype (Fig.15) is done to confirm the correlation between hardware prototype and simulated results.

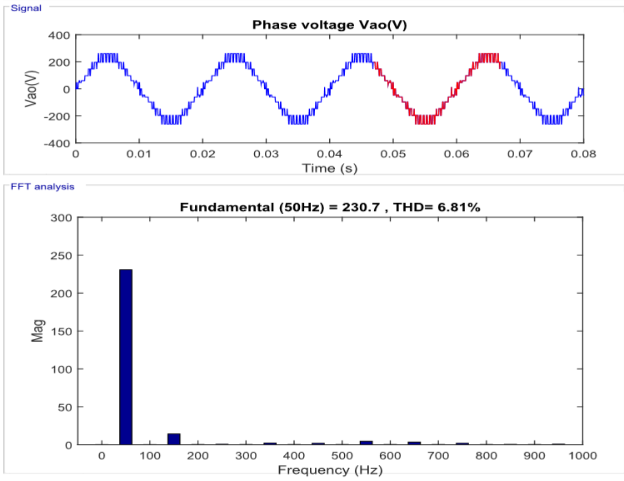

Fig. 15: Output Phase Voltage and Harmonic Spectra for $M_A = 1$ with THD Value 5.60%.

A hardware prototype has been developed for experimental verification. The system parameters employed for developing a low power hardware prototype is show in Table III.

Table 3: Specification and Components List for the Proposed 15 Level MLI

Particulars	Specification
Semiconductor Switch, IGBT	FGA25N120
Electrolytic Capacitor	4700µF
Diode	IN540
DC Source-Battery	36V(12V X 3)
Microcontroller	DSPIC30F4011, Adruino Mega

Hardware prototype of the proposed system is shown in Fig.16

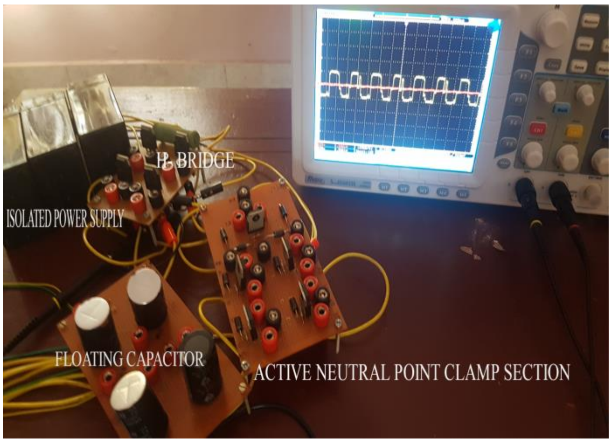

Fig. 16: Hardware Prototype of the Proposed MANPC Converter.

The hardware prototype has been tested under varying load conditions and different modulation indices to confirm the adaptability of the system in rugged industrial conditions. Output phase voltage of the proposed system at a modulation index of 0.2 is shown in Fig.17. The output waveform confirms that, even at a low modulation index of 0.2 the voltage levels are maintained without relative degradation in harmonic spectrum.

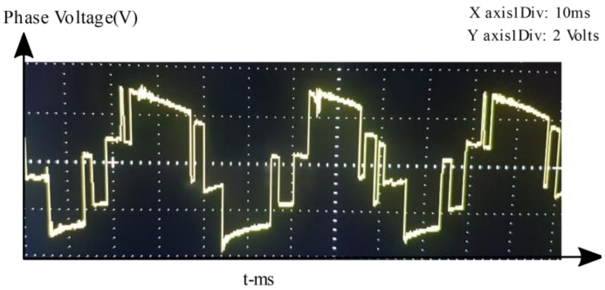

Fig. 17: Output Phase Voltage of 36 V System with Modulation Index $M_A = 0.2$.

5. Conclusion

A novel topology and switching strategy is proposed for a modified active neutral point fifteen level multilevel converter. Inherent voltage balancing of floating capacitors are achieved through a VFOC based switching strategy. The THD levels present in the output voltages and currents are also reduced to a minimum level through the proposed switching strategy. Loss of voltage levels under a low modulation index is avoided with this hybrid modulation technique. The performance of the proposed prototype is justified through MATLAB/ Simulink simulation. The system finds its application in the area of isolated power supply electric systems and low power electric drives due to its modularity and reliability in operation. The reliability of the system is validated by the redundancy in switching states. Integration of a charging circuit for the batteries in isolated power supply drives with a minimum modification in the topology can enhance the effectiveness of the converter.

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