ADVANCED REFERENCES AND CARRIERS BASED PWM IN A SYMMETRICAL MULTILEVEL INVERTER

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ABSTRACT

This paper propose a Multilevel inverter with reduced switch count. The proposed inverter is a symmetrical type of inverter with bipolar PWM strategies. Phase Disposition (PD) strategy for Sinusoidal, Trapezoidal and Triangular reference with Triangular, Saw-tooth and Inverted Saw-tooth carrier strategy are simulated with the proposed topology. The performance has been analyzed with MATLAB/SIMULINK. By comparing the various references with various carrier strategies, it is observed that Trapezoidal signal provides less THD and higher fundamental RMS output voltage.

KEYWORDS

THD, PD, SRTC, SRSC, SRISC, TRTC, TRSC, TRISC, TRTC, TRSC, TRISC, PWM

1. INTRODUCTION

The power electronics device which converts DC input voltage to AC output voltage at required voltage and frequency level is known as inverter. The AC output voltage could be of fixed or variable magnitude at fixed or variable frequency. Inverters can be broadly classified into two level inverter and Multi Level Inverter (MLI). MLIs as compared to two level inverters have advantages like minimum harmonic distortion, reduced Electro Magnetic Interference/Radio Frequency Interference (EMI/RFI) and operation at several voltage levels. MLIs are being utilized for multi-purpose applications such as active power filters, static VAR compensators etc. The output of MLI is voltage with stepped waveform. Inverters are mainly classified according to the nature of input source as voltage source and current source inverters. The inverters can also be classified according to the nature of output voltage waveform as square wave, quasi-square wave and PWM inverters.

Some of the important industrial applications of MLIs are:

- Variable speed AC motor drives
- Uninterruptible power supplies
- Induction heating
- Automated process controllers
- Hospital instruments
- High voltage DC transmission lines
- Aircraft power supplies
- Battery vehicle drives
- Electric utility applications
- Static VAR generation

- Heavy duty trucks
- Military combat vehicles
- Medium voltage variable speed drives
- Voltage regulation, VAR compensation and harmonic filtering in power system
- Parking meter, navigation buoy and telemetry system with PV cell

An inverter topology for high voltage and high power applications that seems to be gaining interest is the MLI. Wu and Chou [1] proposed a solar power generation system with a seven-level inverter new topology for sub-multilevel inverter. Lakshmi et al [2] describes two topologies with 9 switches and 7 switches with level shifting technique and uses 1 KHz SPWM pulses with a modulation index of 0.8. Nedumgatt et al [3] explains a new topology of a cascaded multilevel inverter with PWM techniques. Gupta and Jain [4] suggested a novel multilevel inverter based on switched DC sources. Espinosa et al [5] discussed a new modulation method for a 13-level asymmetric inverter toward minimum THD. Leon et al [6] introduced a generalized modulation technique for cascaded H-bridge converter based on o multidimensional control region. Shukla et al [7] deals two improved natural balancing strategies for FCMI under PD scheme, which use the same (n - 1) carrier signals as used in the standard PD scheme. Zheng et al [8] proposed a hybrid cascaded multilevel converter for battery energy management applied in electric vehicles. Tsunoda et al [9] suggested a level and phase shifted PWM for seven level switched capacitor inverter using series or parallel conversion. Shanthi et al [10] analyzed a carrier overlapping PWM methods for single phase cascaded multilevel inverter. Buticchi et al [11] proposed a nine-level grid-connected converter topology for single-phase transformerless PV systems. Baier et al [12] discussed the methods for improving power quality in cascade multilevel converters based on single-phase non regenerative power cells. Islam et al [13] suggested a high-frequency link multilevel cascaded medium-voltage converter for direct grid integration of renewable energy systems.Chattopadhyay et al [14] also proposed a new multilevel inverter topology with self-balancing level doubling network.

2. THE PROPOSED MULTILEVEL INVERTER

Multilevel inverters have some disadvantages. One of the most obvious disadvantages is the numerous of power semiconductor switches required. The requirement of multiple gate driver circuit results in large expense. Consequently in practical applications a reduction in the number of switches used is crucial. The proposed topologies particularly with higher number of output levels require fewer carrier signals, gate drives and fewer components compared to existing inverters. A multilevel inverter adopting appropriate PWM techniques and having lower THD would require more compact passive filter. In this paper, new inverter topologies with reduced switch count are proposed.

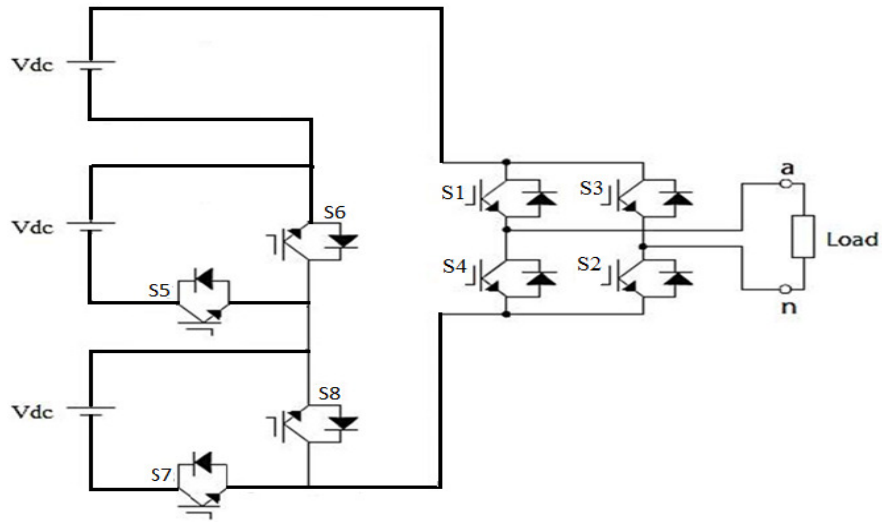

Figure 1. Schematic diagram of proposed symmetrical inverter

Proper switching control of the auxiliary switch can generate half level of dc supply voltage. This paper proposes various techniques to eliminate lower order harmonics. In the H-bridge, switches in the same leg should not conduct simultaneously, appropriate gate pulses should be given in order prevent short circuit condition. Table I shows the switching states and possible output voltage of the converter.

Table 1. Switching state of proposed topology

S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	States
✓	✓	×	×	✓	×	✓	×	**$3V_{dc}$**
✓	✓	×	×	✓	×	×	✓	**$2V_{dc}$**
✓	✓	×	×	×	✓	×	✓	**V_{dc}**
×	×	×	×	×	×	×	×	**0**
×	×	✓	✓	×	✓	×	✓	**$-V_{dc}$**
×	×	✓	✓	✓	×	×	✓	**$-2V_{dc}$**
×	×	✓	✓	✓	×	✓	×	**$-3V_{dc}$**

2.1. Modulating Strategies

Several CFDs exist in multi-carrier PWM strategies for MLIs. These strategies have more than one carrier option that can be triangular, saw tooth, a new function etc. The following sections briefly describe the CFDs on carrier as well as reference. This paper presents two types of reference (sinusoidal and triangular references) and three types of carrier (triangular, saw tooth and inverted saw tooth carrier) for bipolar PDPWM, PODPWM, APODPWM, VFPWM and COPWM strategies.

The most popular PWM techniques for inverter are Phase Shifted Carrier PWM (PSCPWM) and Level Shifted Carrier PWM (LSCPWM).

1. Phase Shifted Carrier PWM (PSCPWM):

In general, the number of carriers required is varied depending upon the level of the inverter. In phase shifted carrier method the adjacent carriers are going to have a phase of 90^o or 180^o.

2. Level Shifted Carrier PWM (LSCPWM):

The various techniques for level shifting carrier is given as: Phase Disposition PWM (PDPWM), Phase Opposition Disposition PWM (PODPWM), Alternate Phase Opposition Disposition PWM (APODPWM), Carrier Overlapping PWM (COPWM) and Variable Frequency PWM (VFPWM)

2.2. Types of Reference Signals

1. Sinusoidal Reference:
2. Trapezoidal Reference:

2.3. Types of Carrier Signals

1. Triangular Carrier:
2. Saw-tooth Carrier:
3. Invert Saw-tooth Carrier:

2.4. Simulation Results

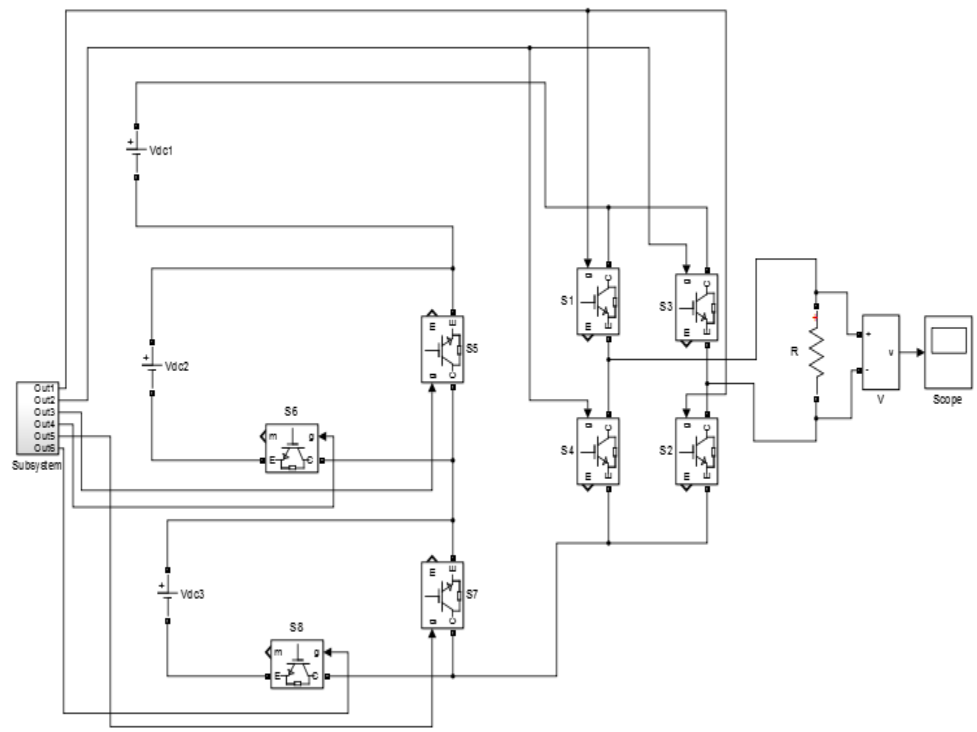

Figure 2. MATLAB/Simulink model of the 7-level proposed topology

Simulation studies are performed by using MATLAB-SIMULINK to verify the proposed PDPWM strategy for chosen proposed symmetrical inverter for various reference like sinusoidal, trapezoidal, stepped and triangular signals and also for various carriers like triangular, saw tooth, invert saw tooth, sinusoidal and invert sinusoidal signals and corresponding %THD values are measured using FFT block and they are shown in Table 2. Table 3 shows the V_{RMS} of fundamental of inverter output for the same reference and carrier signals. Figure 3-29 shows the seven level output voltage of chosen proposed inverter and the corresponding FFT plots with various reference and carrier signal for Phase Disposition technique. It is also possible that this various reference and carrier signals are analysed with PD, APOD, POD, CO and VF. The figure below shows the simulated model with eight IGBT switch. In a practical scenario each of the switches requires a separate gate driver circuit. DC power source of 100 volts are used with a load of 10 ohms.

2.5. Sinusoidal Reference with various Carriers PWM strategy

1. Sinusoidal Reference with Triangular Carrier PWM Strategy:

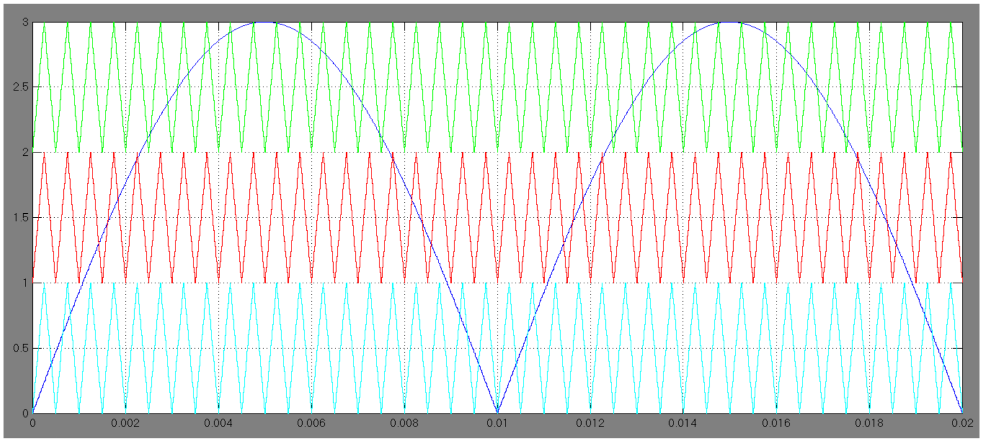

Figure 3. Sinusoidal References with Triangular Carrier (SRTC) waveform

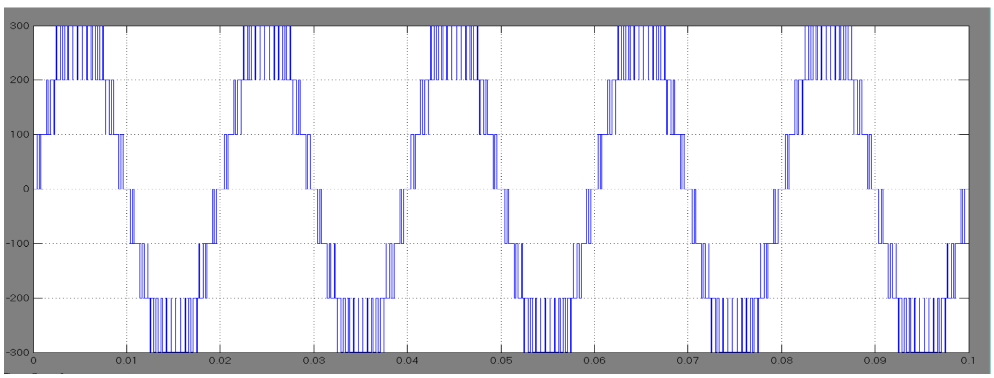

Figure 4. Simulated output voltage waveform for SRTC PWM strategy

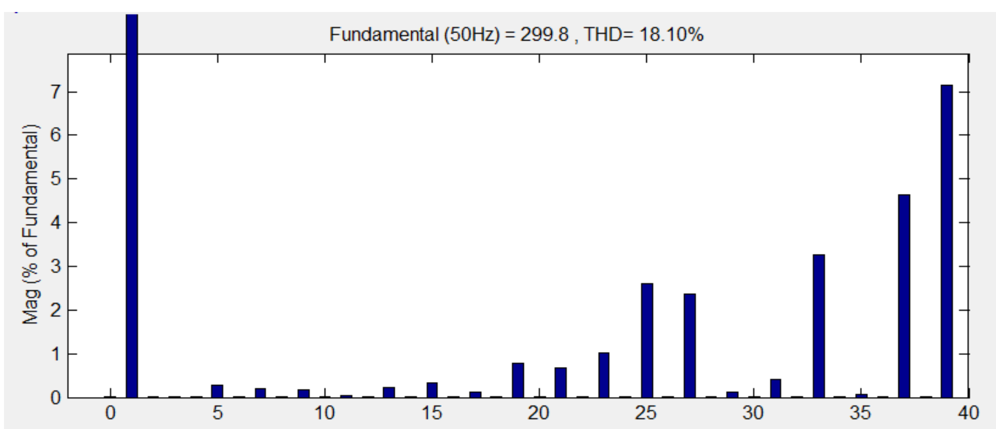

Figure 5. FFT plot analysis for SRTC PWM strategy

2. Sinusoidal Reference with Saw-tooth Carrier PWM Strategy:

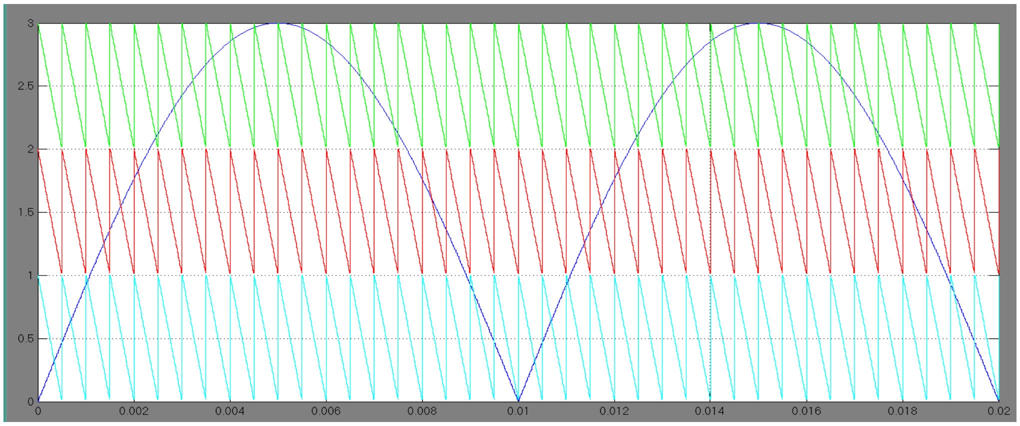

Figure 6. Sinusoidal References with Saw-tooth Carrier (SRSC) waveform

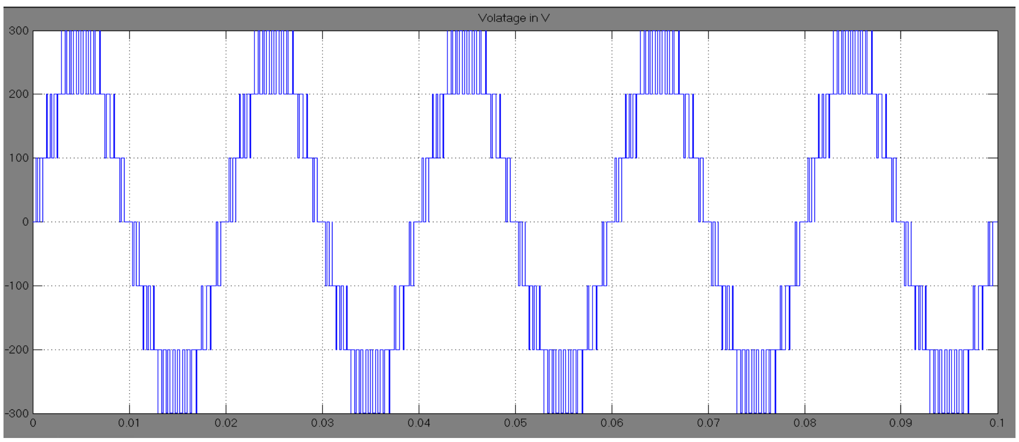

Figure 7. Simulated output voltage waveform for SRSC PWM strategy

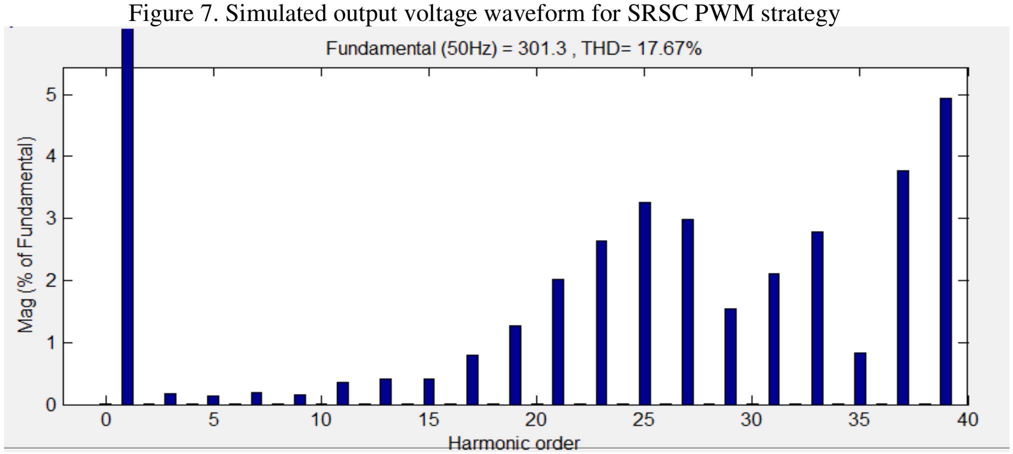

Figure 8. FFT plot analysis for SRSC PWM strategy

3. Sinusoidal Reference with Inverse Saw-tooth Carrier PWM Strategy:

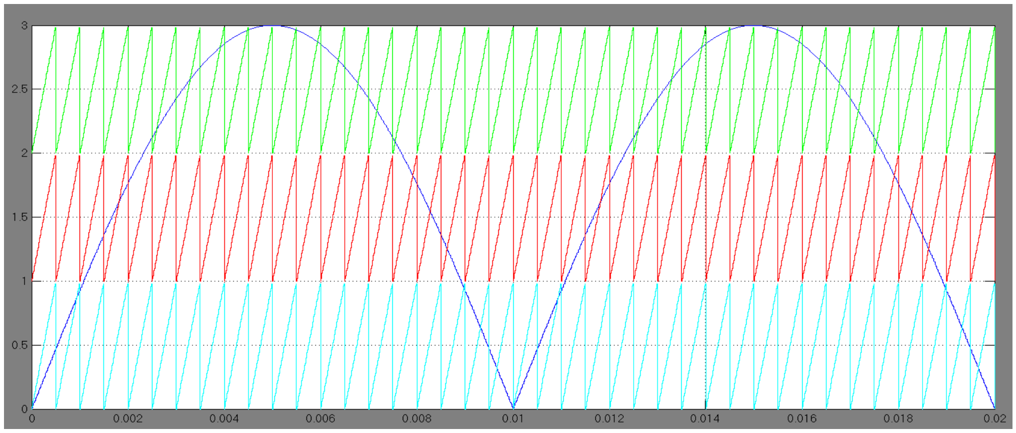

Figure 9. Sinusoidal References with Inverse Saw-tooth Carrier (SRISC) waveform

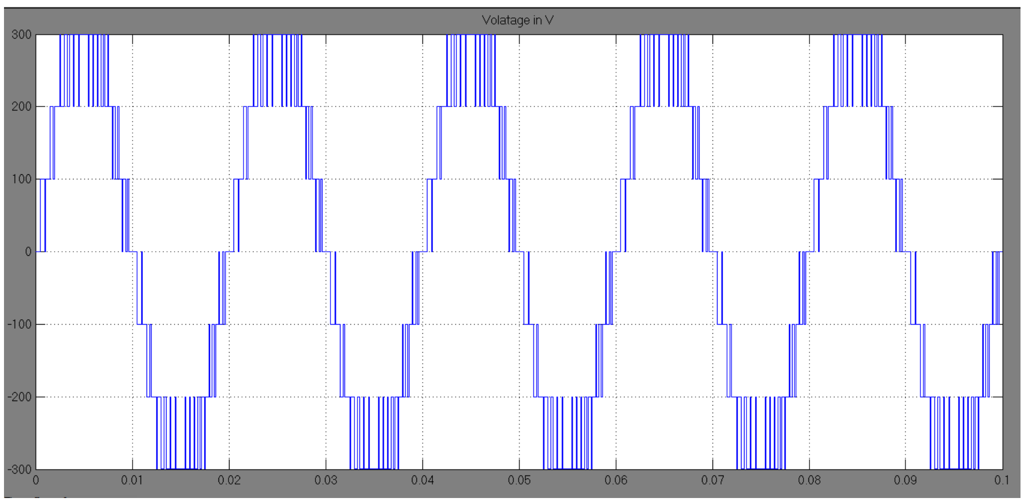

Figure 10. Simulated output voltage waveform for SRISC PWM strategy

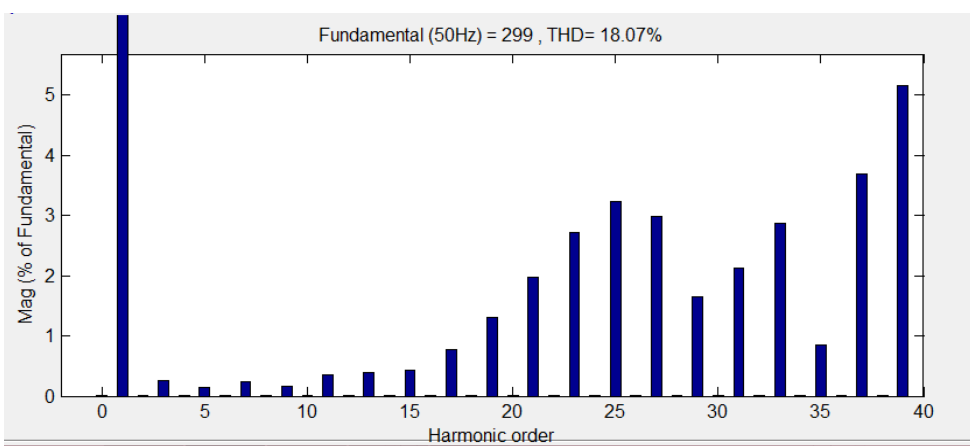

Figure 11. FFT plot analysis for SRISC PWM strategy

2.6. Trapezoidal Reference with various Carrier PWM strategy:

1. Trapezoidal Reference with Triangular Carrier PWM Strategy:

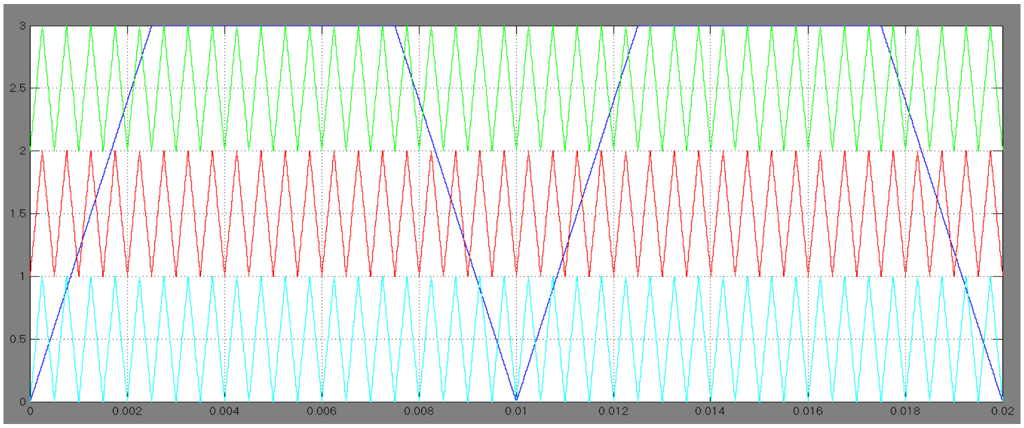

Figure 12. Trapezoidal References with Triangular Carrier (TRTC) waveform

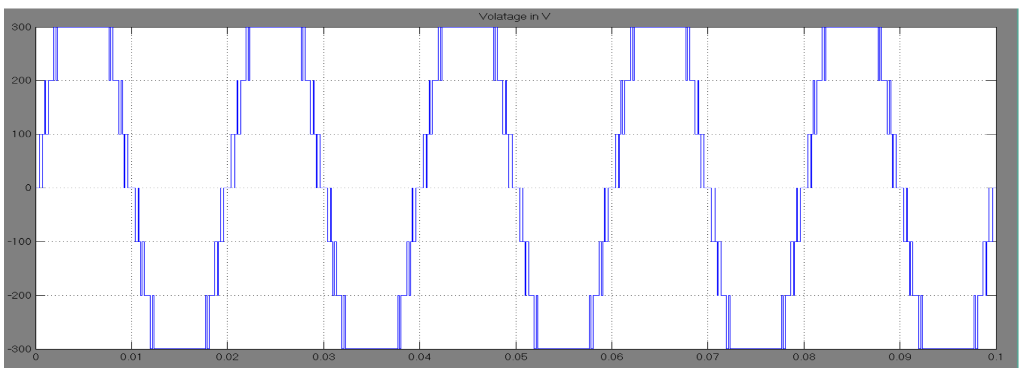

Figure 13. Simulated output voltage waveform for TRTC PWM strategy

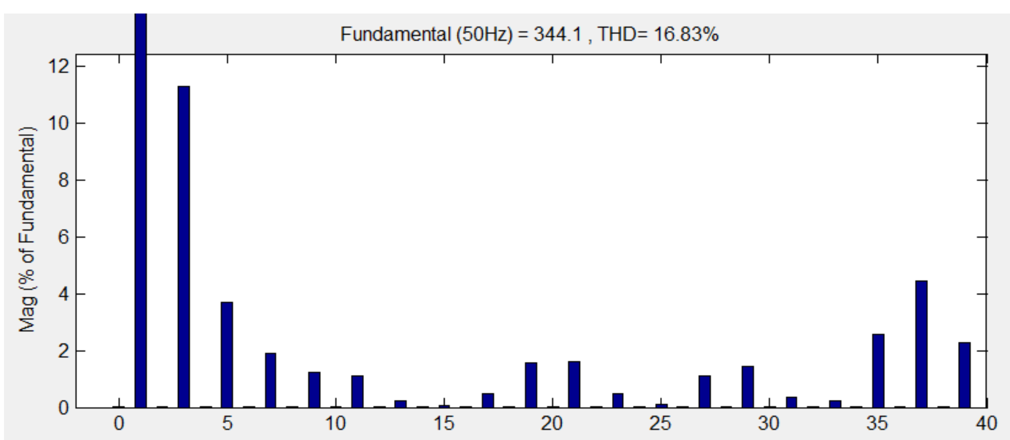

Figure 14. FFT plot analysis for TRTC PWM strategy

2. Trapezoidal Reference with Saw-tooth Carrier PWM Strategy:

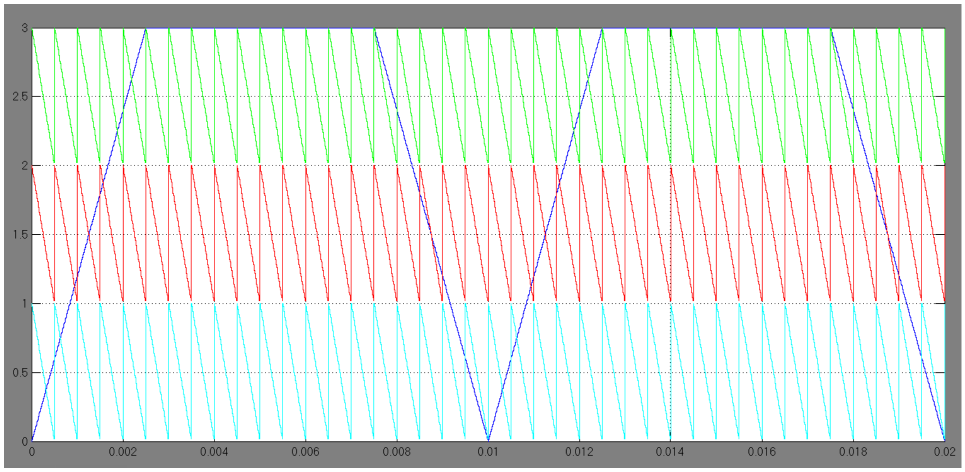

Figure 15. Trapezoidal References with Saw-tooth Carrier (TRSC) waveform

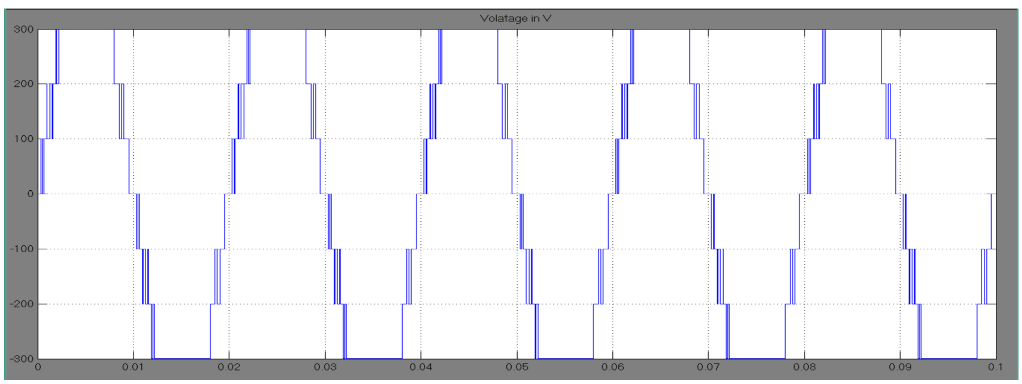

Figure 16. Simulated output voltage waveform for TRSC PWM strategy

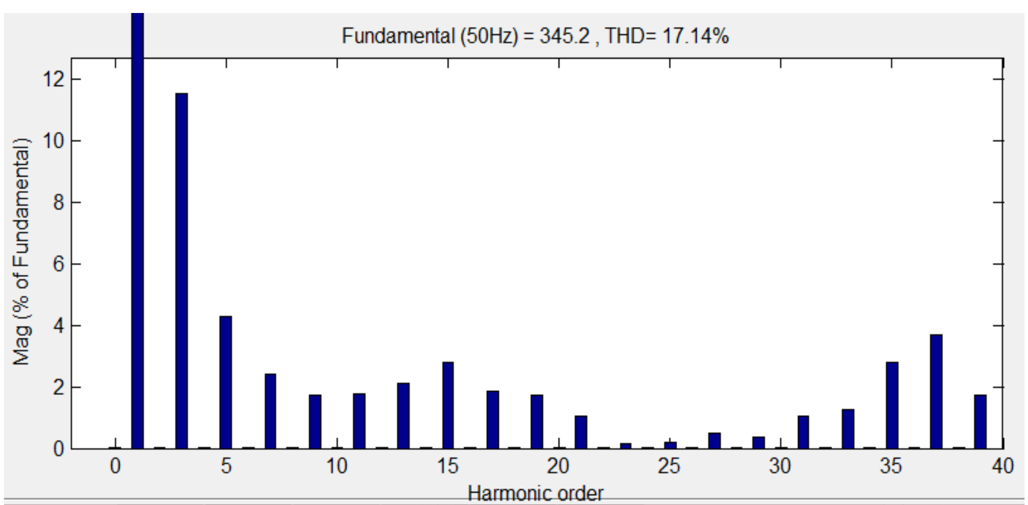

Figure 17. FFT plot analysis for TRSC PWM strategy

3. Trapezoidal Reference with Invert Saw-tooth Carrier PWM Strategy:

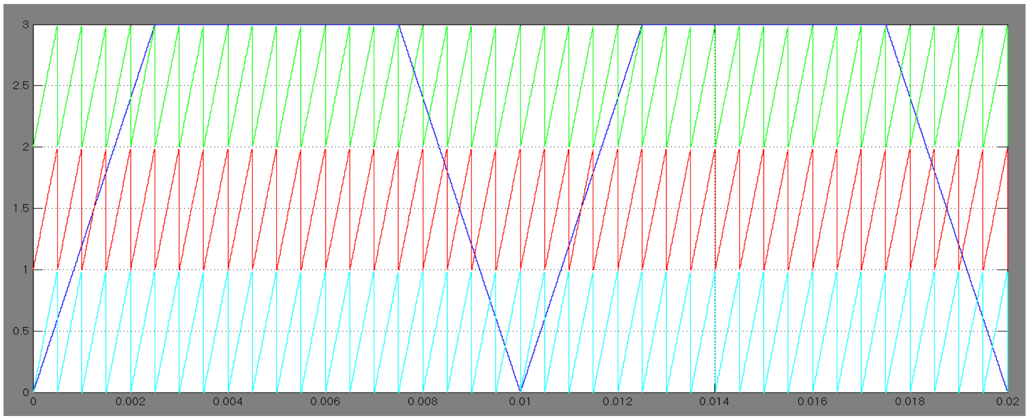

Figure 18. Trapezoidal References with Inverse Saw-tooth Carrier (TRISC) waveform

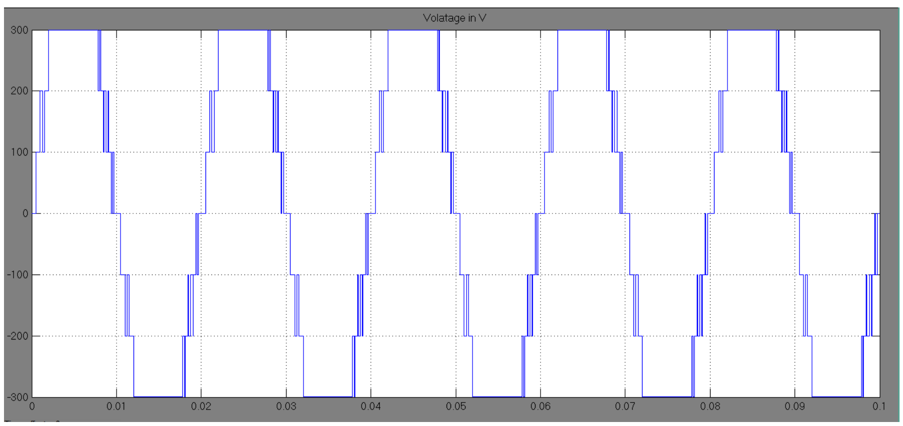

Figure 19. Simulated output voltage waveform for TRISC PWM strategy

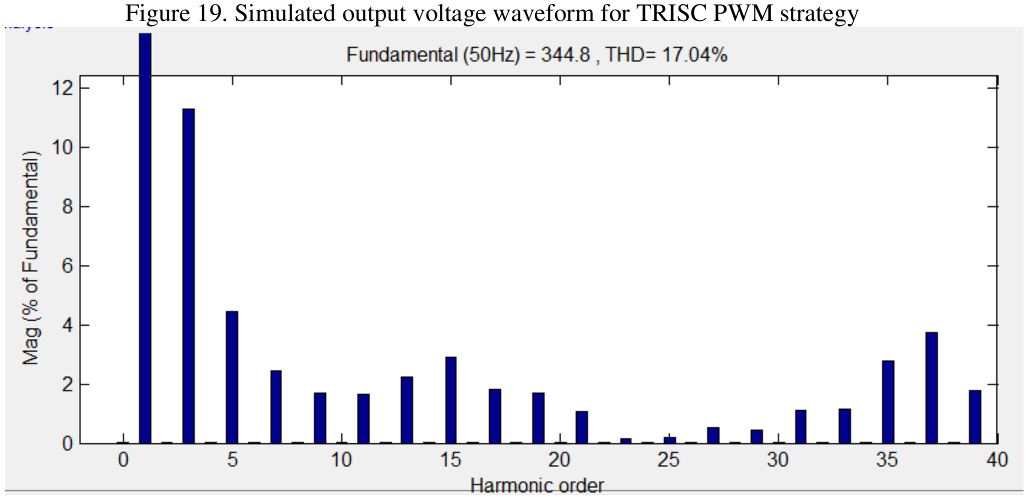

Figure 20. FFT plot analysis for TRISC PWM strategy

2.7. Triangular Reference with various Carrier PWM:

1. Triangular Reference with Triangular carrier PWM Strategy:

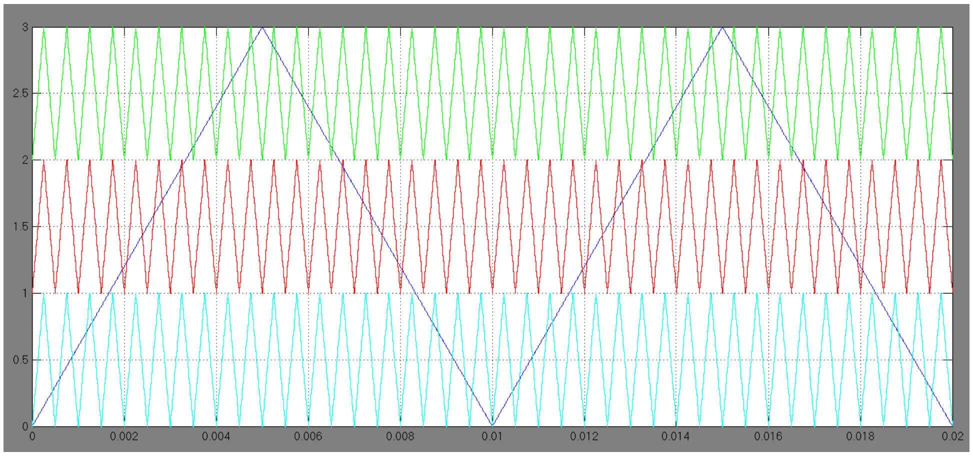

Figure 21. Triangular References Triangular Carrier (TrRTC) waveform

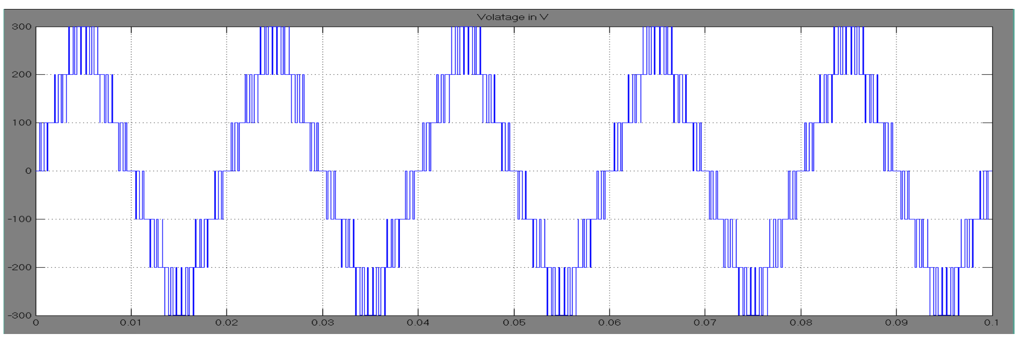

Figure 22. Simulated output voltage waveform for TrRTC PWM strategy

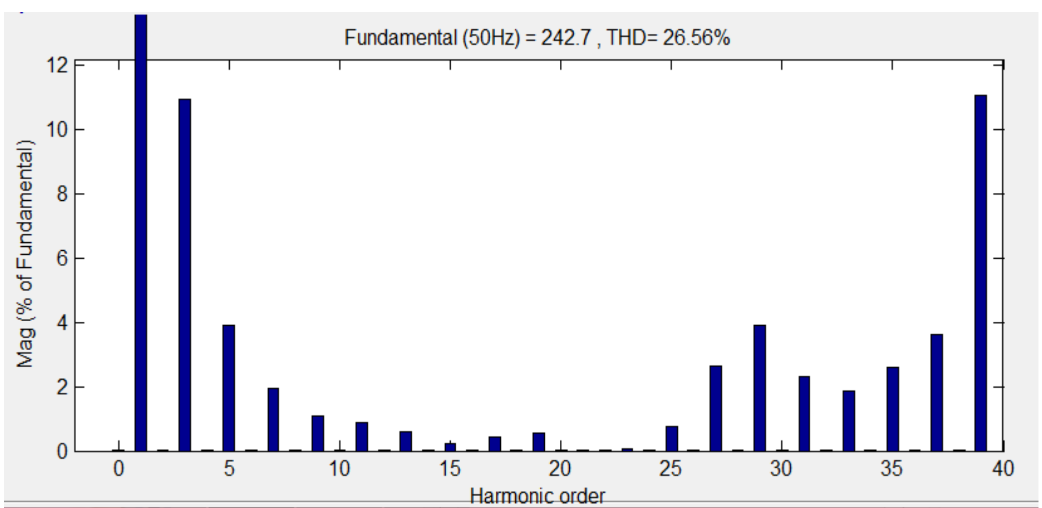

Figure 23. FFT plot analysis for TrRTC PWM strategy

2. Triangular Reference with Saw-tooth carrier PWM Strategy:

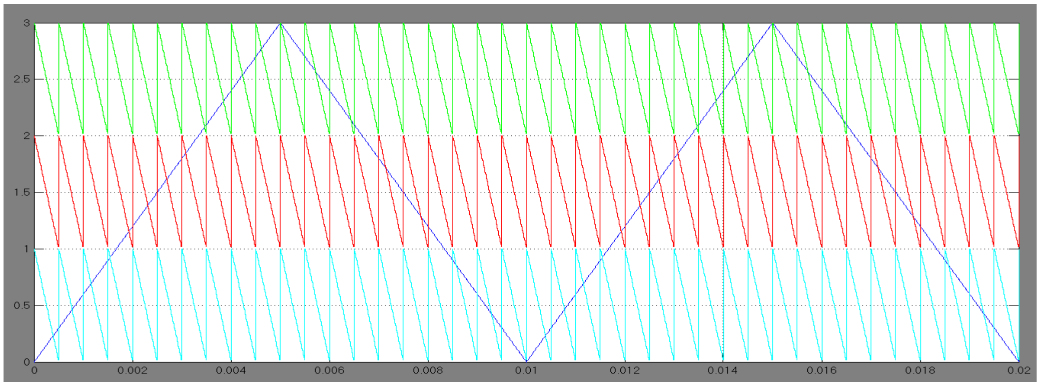

Figure 24. Triangular References with Saw-tooth Carrier (TrRSC) waveform

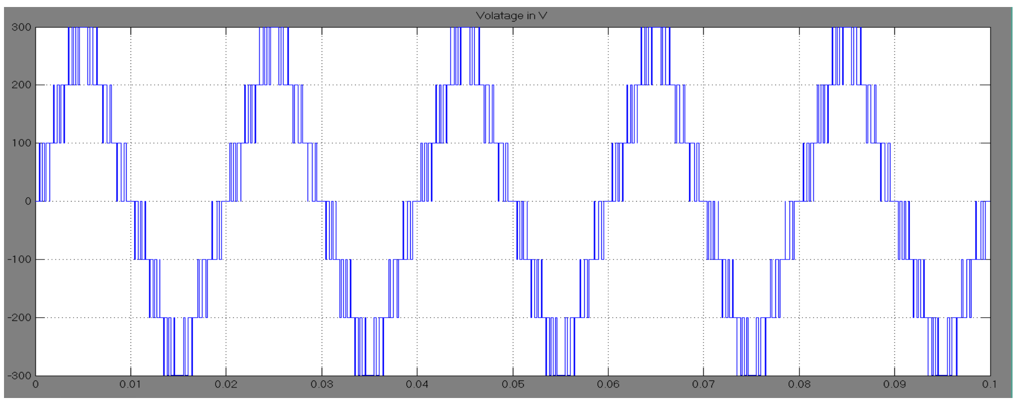

Figure 25. Simulated output voltage waveform for TrRSC PWM strategy

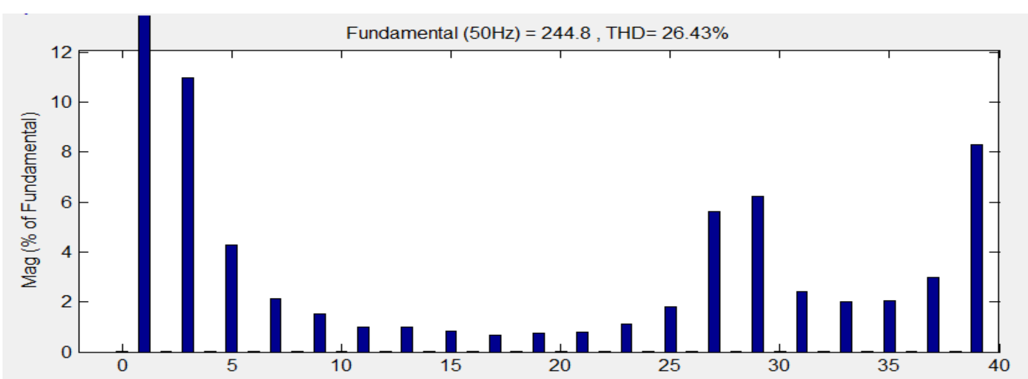

Figure 26. FFT plot analysis for TrRSC PWM strategy

3. Triangular Reference with Invert Saw-tooth carrier PWM Strategy:

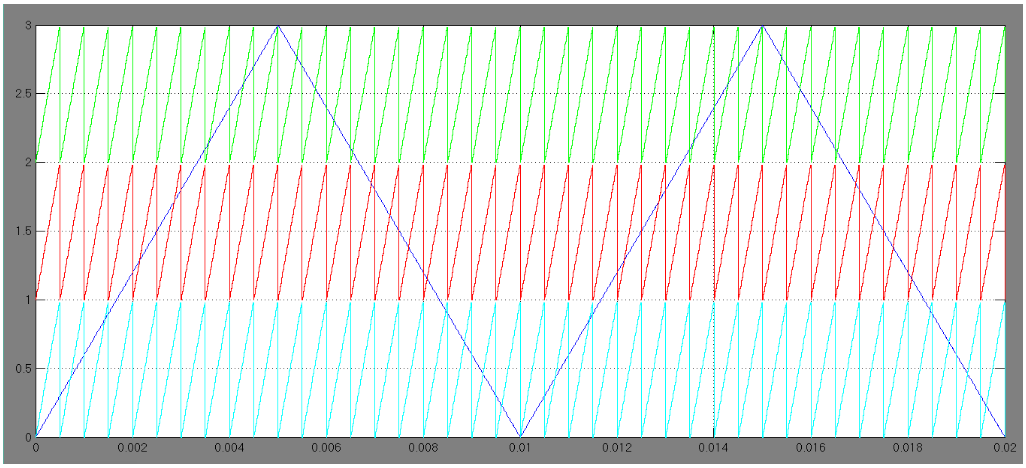

Figure 27. Triangular References with Inverse Saw-tooth Carrier (TrRISC) waveform

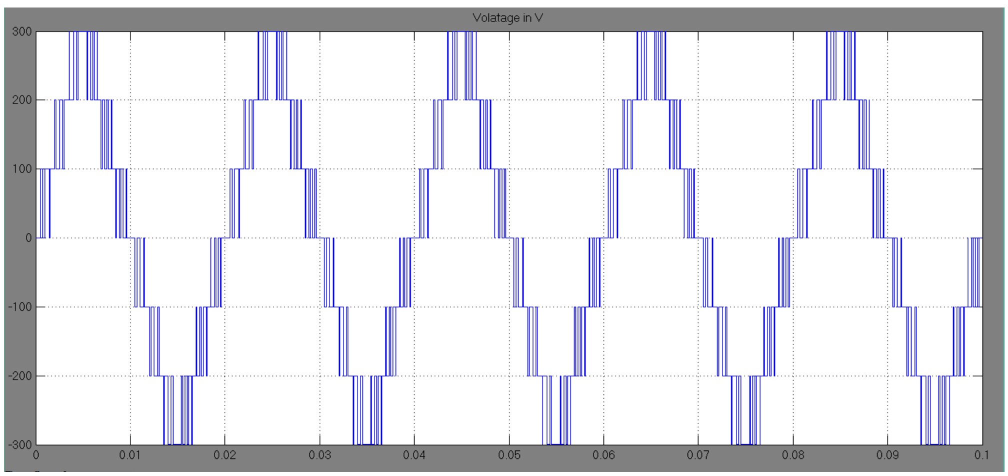

Figure 28. Simulated output voltage waveform for TrRISC PWM strategy

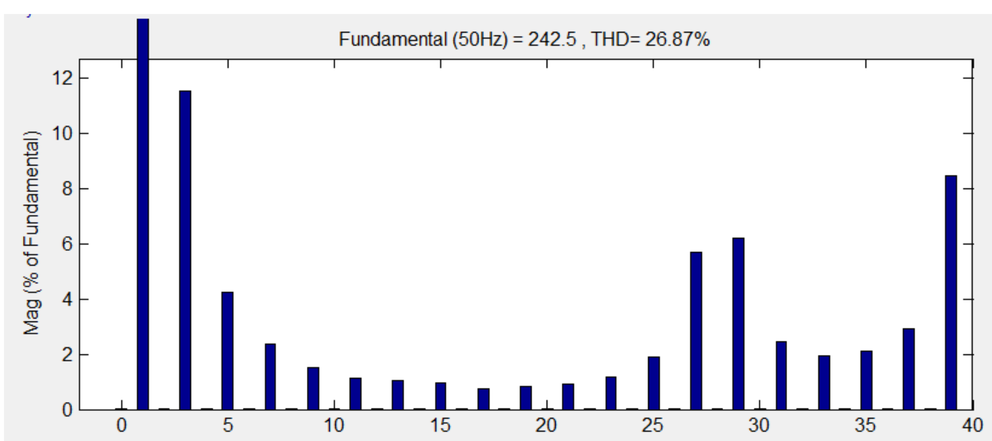

Figure 29. FFT plot analysis for TrRISC PWM strategy

Table 2. Comparison of THD for various References and Carriers of Proposed Topology

Reference	Triangular Carrier	Saw Tooth Carrier	Invert Saw Tooth Carrier
Sinusoidal	18.10%	17.67%	18.07%
Trapezoidal	16.83%	17.14%	17.04%
Triangular	26.56%	26.43%	26.87%

Table 3. Comparison of V_{RMS} for various References and Carriers of Proposed Topology

Reference	Triangular Carrier	Saw Tooth Carrier	Invert Saw Tooth Carrier
Sinusoidal	212	213.1	211.4
Trapezoidal	243.3	244.1	243.8
Triangular	171.6	173.1	171.5

3. CONCLUSIONS

In this paper the proposed inverter with fewer switches, controlling the overall circuit becomes less complex, the size and installation area reduces. Based on the simulation results, UPDPWM techniques for proposed 7-level inverter have been presented for various references and various carrier signals. Performance factors like %THD, V_{RMS} have been evaluated, presented and analyzed. It is found that the Trapezoidal reference with Triangular carrier (TRTC) strategy provides lower %THD as in table 2. Trapezoidal reference with Saw-tooth carrier (TRSC) strategy is found to perform better since it provides relatively higher fundamental RMS output voltage as in table 3. Various performance factors like (i) THD and harmonic spectra indicating purity of the output voltage, (ii) V_{RMS} indicating the amount of DC bus utilization, (iii) CF specify the peak current ratings of devices and components, (iv) FF measure the shape of the output voltage and (v) DF indicates the amount of harmonics that remains in the output voltage after it has been subjected to second order attenuation related to power quality issues have been evaluated, presented and analyzed. The proposed PWM methods with less THD and higher RMS voltage can be implemented in industrial applications such as AC Power conditioners, static VAR compensators, drive systems, etc and in power generation industries.

REFERENCES

[1] Jinn-Chang Wu, Chia-Wei Chou, "A Solar Power Generation System With a Seven-Level Inverter," IEEE Trans. Power Electron., vol. 29, no. 7, pp. 3454-3462, Jul. 2014.

[2] T. V. V. S. Lakshmi, Noby George, S. Umashankar and D. P. Kothari, (2013) "Cascaded seven level inverter with reduced number of switches using level shifting PWM technique", proc. IEEE Conference Rec. 978-1-4673-6030-2, pp 676-680.

[3] Jacob James Nedumgatt, Vijayakumar, Kirubakaran and Umashankar, (2012) "A multilevel inverter with reduced number of switches", proc. IEEE Conference Rec. 978-1-4673-1515-9, pp 1-4.

[4] Krishna Kumar Gupta, Shailendra Jain, "A Novel Multilevel Inverter Based on Switched DC Sources," IEEE Trans. Ind. Electron., vol. 61, no. 7, pp. 3269-3278, Jul. 2014.

[5] Eduardo E. Espinosa, Jose R. Espinoza, Pedro E. Melín, Roberto O. Ramírez, Felipe Villarroel, Javier A. Muñoz, and Luis Morán, "A New Modulation Method for a 13-Level Asymmetric Inverter Toward Minimum THD," IEEE Trans. Ind. Appl., vol. 50, no. 3, pp. 1924-1933, May/Jun. 2014.

[6] Jose Ignacio leon, Samir Kouro, Sergio Vazquez, Ramon Portillo, Leopoldo Garcia Franquelo, Juanmanuel Carrasco and Jose Rodriguez, (2011) "Multidimensional modulation technique for cascaded multilevel converters", IEEE Transaction on Industrial Electronics, Vol. 58, No. 2, pp 412-420.

[7] Anshuma Shukla, Arindam Ghosh and Avinash Joshi, (2011) "Natural balancing of flying capacitor voltage in multi cell inverter under PD carrier-based PWM", IEEE Transaction on Power Electronics, Vol. 26, No.6, pp 1682-1693.

[8] Zedong Zheng, Kui Wang, Lie Xu and Yongdong Li, "A Hybrid Cascaded Multilevel Converter for Battery Energy Management Applied in Electric Vehicles," IEEE Trans. Power Electron., vol. 29, no. 7, pp. 3537-3546, Jul. 2014.

[9] Asuka Tsunoda, Youhei Hinago and Hirotaka Koizumi, "Level- and Phase-Shifted PWM for Seven-Level Switched-Capacitor Inverter Using Series/Parallel Conversion," IEEE Trans. Ind. Electron., vol. 61, no. 8, pp. 4011-4021, Aug. 2014.

[10] B. Shanthi and S. P. Natarajan,(2008) "Carrier overlapping PWM methods for single phase cascaded multilevel inverter", International Journal of Science and Techniques of Automatic Control and Computer Engineering, IJ-STA, special issue, CEM, pp 590-601.

[11] Giampaolo Buticchi, Davide Barater, Emilio Lorenzani, Carlo Concari and Giovanni Franceschini "A Nine-Level Grid-Connected Converter Topology for Single-Phase Transformerless PV Systems," IEEE Trans. Ind. Electron., vol. 61, no. 8, pp. 3951-3960, Aug. 2014.

[12] Carlos R. Baier, José R. Espinoza, Marco Rivera, Javier A. Muñoz, BinWu, Pedro E. Melín and Venkata Yaramasu, "Improving Power Quality in Cascade Multilevel Converters Based on Single-Phase Nonregenerative Power Cells," IEEE Trans. Ind. Electron., vol. 61, no. 9, pp. 4498-4509, Sep. 2014.

[13] Md. Rabiul Islam, Youguang Guo and Jianguo Zhu, "A High-Frequency Link Multilevel Cascaded Medium-Voltage Converter for Direct Grid Integration of Renewable Energy Systems," IEEE Trans. Power Electron., vol. 29, no. 8, pp. 4167- 4182, Aug. 2014.

[14] Sumit K. Chattopadhyay, Chandan Chakraborty, "A New Multilevel Inverter Topology With Self-Balancing Level Doubling Network," IEEE Trans. Ind. Electron., vol. 61, no. 9, pp. 4622-4631, Sep. 2014.

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He is a life member of Instrument Society of India and Indian Society for Technical Education.