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# Power quality assessment of novel multilevel and multistring inverters for electric vehicle applications

**Sri Krishna Kumar Sampathkumar, Dhal Pradyumna Kumar**
Department of Electrical and Electronics Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India

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**ABSTRACT**

The requirement and demand of electric vehicles is extravagantly increasing in the current era for avoiding pollutions and as well to overcome the consumptions of liquid fuels. Under this scenario, for the production and applicability of electric vehicles, inverters play a major role to render appropriate battery power supply for the perfect operation of the electric vehicle. This research study devises a novel modified multilevel inverter and a new multistring inverter designed by reducing the number of switches and enabling the effective operation of the electric vehicle. Both the developed multilevel and multistring inverter is analyzed with respect to their switching states, their output voltage and the evaluated harmonic distortion. For comparison, a sinusoidal alternating current voltage is considered as reference and all the newly modeled configurations are compared with that of the existing inverter models to prove their superiority. The switched states of the designed inverters as applicable for electric vehicles are examined to attain a logical analysis with respect to the duty cycle of the individual switches. The power quality assessment of the designed inverter models are guaranteed based on the minimized total harmonic distortion and on comparison with the other inverter models from the earlier state-of-the-art techniques.

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***Corresponding Author:***

Sri Krishna Kumar Sampathkumar
Department of Electrical and Electronics Engineering
Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology
No. 42, Avadi-Vel Tech Road, Vel Nagar, Chennai, Tamil Nadu 600062, India
Email: kkumarveltech@gmail.com

## 1. INTRODUCTION

The importance and need of electric vehicles has grown to its excellence due to the wide spread use and applicability of the same and also the utilization of alternating current power has been increasing in the recent days. The main source of alternating current utilised by every sector is delivered from the power grid. Increased consumption of power and depletion of conventional fossil fuels has lead the power sector to direct its attention towards a cleaner energy source such as solar, wind, and other renewable energy sources. The variations in the energy expenditure categorises the utility into domestic and industrial sectors. In respect of the industrial sectors, the primary sector is the manufacturing of electric vehicles wherein it requires battery operated power source and supported by a perfect and reliable inverter model.

In consideration of the existing various forms of power generation and transmission devices, there is a higher need for a power handling circuitry as well. These power handling devices shall be an electromagnetic device or an electronic device. Electronic power handling devices varies pertaining to the input power, output power and frequency. Designing and implementing various power modulating circuitry has been easier in electric vehicle and power sector with the advancements in the field of power electronics.

With the steep growth of electric vehicles, the mostly used term is the inverter and is one of the most key components present beneath the EV and the motor and the battery of any electric vehicle (EV) is incompatible without the presence of an inverter. It's a power electronic device employed in the conversion of power from a direct current (DC) source to an alternating current (AC) source such that this power shall be used to drive any device. Figure 1 shows the configuration of an inverter in an EV. The importance and need of inverters in electric vehicles include: i) batteries always produce DC power and an inverter is always required to invert the DC power to an AC power for driving the electric motor to drive the vehicle, ii) inverter needs to switch the electrical charge thousands of time per second and hence inverters are designed with silicon power transistors (mostly in current scenario, insulated gate bipolar transistors (IGBTs) are widely used, as they operate at 20 kHz frequency and switches current upto 20000 times/second), and iii) MOSFETs employed in inverters possess the switching charge capability upto 80 kHz. Considering the importance and need of inverters as above, they should be designed to be: i) smaller and of light weight, ii) highly efficient, iii) get the most out of the battery power, iv) higher switching speed is capable in inverters to drive the miniature high speed motors and as well its power density gets improved with the increase in switching speed, and v) inverter should possess better power to weight ratio.

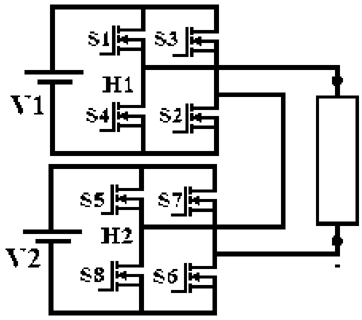



Figure 1. Circuit configuration of proposed modified multilevel inverter

– Literature review

This section of the research study presents a detailed review on the design and development of various inverter models including variants of multilevel and multistring inverters. Wu and Chen 2016 proposed an enhanced-battery-balancing strategy for seven-level inverter. There are three separate battery strings as the input voltage, the cascaded multilevel inverter and the digital controller [1]. Jha and Singh 2016 implemented a Zeta converter fed power factor correction (PFC) for high power light emitting diode (LED) driver [2]. Sangwongwanich *et al*. [3] presented a cost-effective solution to realize delta power control (DPC) for grid-connected photovoltaic (PV) systems, where the multistring PV inverter configuration was adopted.

Stonier and Lehman [4] developed an intelligent-based fault-tolerant system for a solar PV inverter. The cascaded multilevel inverter is connected across the combination of solar PV panel and battery for DC-AC conversion. A control scheme of a three-phase multi-level multi-string inverter for grid integration of PV power systems was presented by Agoro *et al*. [5]. String inverter has advantages in terms of higher efficiency with independent strings, reduced overall system cost in comparison to micro inverter and optimizers. Khan *et al*. designed a hybrid string inverter with energy storage for grid independent power systems [6]. Common-mode resonance of single inverter and multi-parallel inverters are analyzed by Yu *et al*. [7].

Maity and Roy [8] proposed a novel structure of cascaded multilevel inverter (MLI). Each module of the MLI possesses the capability of generating bipolar voltage level at its output terminals with the help of H-bridge. A holistic power electronic circuits design was proposed by Wang *et al*. [9] to achieve 4× power density at 98% peak efficiency for a compact 250 kW three-phase three-level (3-L) T-type traction inverter. George and Badawy 2018 presented a novel energy management system (EMS) for hybrid energy storage devices in EVs. A modular multi-converter was configured to manage the energy between the different storage cells for an EV application [10].

Rajasegharan *et al*. [11] proposed the modelling and controller design for quasi-Z source cascaded multilevel inverter (QZS-CMI) based three-phase grid-tie PV power system. A pulse width modulated cascaded multilevel inverter for high power traction applications was modeled and analyzed by Yamini *et al*. [12]. Two types of filter capacitors of varying capacity were connected to the battery packs of a cascaded H-bridge single-star multilevel vehicle traction inverter, and their influence on the battery losses has been analyzed by Kersten *et al*. [13]. Sheir and Youssef [14] introduced new modified power imbalance mitigation without adding any extra voltage or current sensors. A solution of the power imbalance between the phases was presented if separate DC sources are connected to each phase of the three-phase neutral point clamped multilevel inverter [14]-[17]. Based on the review made on the existence of various inverter models for vehicle sector as above, the following subsection presents the challenges to be met in designing and developing the inverter models.

– Need for the proposed approach

Always there is a higher requirement for the design and development of power inverters so as to be applicable for switching and power conversion in electric vehicle applications. In spite of their applicability for power conversion, the challenges encountered in the design of inverter models are listed as shown in: i) selection of suitable power semiconductor device is always a greater challenge. Silicon powered MOSFETs possess an operating voltage of only up to 250 V. IGBTs operate from 400 V to 1600 V but have only switching frequency less than 30 kHZ. It is required to select wide band gap devices, ii) appropriate functioning and coordination of the inverter power semiconductor devices with the diodes and DC bus capacitor which suppresses the voltage ripples, iii) requirement of temporary storage system to store the battery power, iv) during the acceleration of the vehicle, inverter is likely to become extremely hot and hence proper coolant support has to be provided with the inverter module, v) sizing of the inverter model is also a challenging task, vi) coming across higher voltage changes (dv/dt), resulting in common mode voltage across the windings of the motor, and vii) occurrence of imbalance current flow, resulting in unachievable power ratings.

– Proposed research solution and motivation for the study

Under this scenario of existing challenges, the motivation for this research study in developing novel multilevel inverter and multistring inverter for EV applications is as shown in: i) to achieve perfect flow of current thereby maintaining the required power rate, ii) with the designed inverter model, to increase the level of switching frequency, iii) to minimize the number of switches employed, iv) to design the inverter models so as to reduce the voltage ripples and thereby enhance the power rating, v) switches are to be designed with low heating capacity, vi) wide band gap devices shall be employed for better inverter operations and to drive the traction motor effectively, and vii) employed inverter devices should minimize the voltage changes (dv/dt). Considering all the above, this research study is intended to model efficient and effective inverter models with increased switching frequency and low total harmonic distortion.

## 2. PROPOSED APPROACH–DESIGN OF MODIFIED MULTI-LEVEL INVERTER

The existing classic multilevel inverter has its own merits and demerits; the main demerit is it's utilization of multiple bridges and multiple DC sources to obtain the required output levels. The multilevel inverter can be modified to utilize minimal number of bridges and hence minimized number of DC sources shall be employed to produce the required levels. A single H-bridge is capable of producing a three-level output. The output voltage generated by the cascaded multilevel inverter is actually the sum of the voltages generated by each cell.

When two inverters are connected in cascade, the inverter modelled under this condition possesses the capability to produce an output up to nine levels. In other words when 2 bridges are connected in cascade, it is possible to attain 3 level or 5 level or 7 level or 9 level output levels, depending on the switching scheme. The 5-level output of the proposed multilevel inverter remains to be the same as that of original multilevel inverter model. Figure 1 shows the circuit configuration of the proposed modified multilevel inverter. The seven-level output for the proposed modified multilevel inverter differs in whole from the seven-level conventional multilevel inverter. Here, the multilevel inverter explores all the possible outcomes from the cascaded combination of two inverter bridges, with their supply voltages being different.

For a symmetrical change between the output levels, the DC sources are maintained at a ratio of 1:2, i.e., $V_1$=V and $V_2$=V. Switches $S_1$ and $S_2$ conducts to produce an output of $V_1$, i.e., 'V'. The current follows the path; $V_1^{(+)}$ ►$S_1$►Load►$S_2$►$V_1^{(-)}$. Switches $S_5$ and $S_6$ conducts to give an output of $V_2$, which is '2V'. To achieve this, current flows through; $V_2^{(+)}$ ►$S_5$►Load►$S_6$►$V_2^{(-)}$. $S_1$ & $S_2$ and $S_5$ & $S_6$ conducts together to provide $V_1$+$V_2$, which is equal to '3V'. $V_1^{(+)}$ ►$S_1$►Load►$S_6$►$V_2$ ►$S_5$► $S_2$►$V_1^{(-)}$. Similarly, $S_3$ & $S_4$ for '-V', $S_7$ & $S_8$ for '-2V' and $S_3$, $S_4$, $S_7$ & $S_8$ for '-3V'. The peak output voltages are $V_1$, $V_2$ and $V_1$+$V_2$ when $H_1$ alone operates, $H_2$ alone operates and $H_1$, $H_2$ operates together in that order. Figures 2(a) to (c) illustrates the conduction modes of the proposed modified multilevel inverter model for V, 2V & 3V respectively. Figures 3 and 4 present the simulation diagram and corresponding output of the proposed multilevel inverter for the 7-level output respectively.

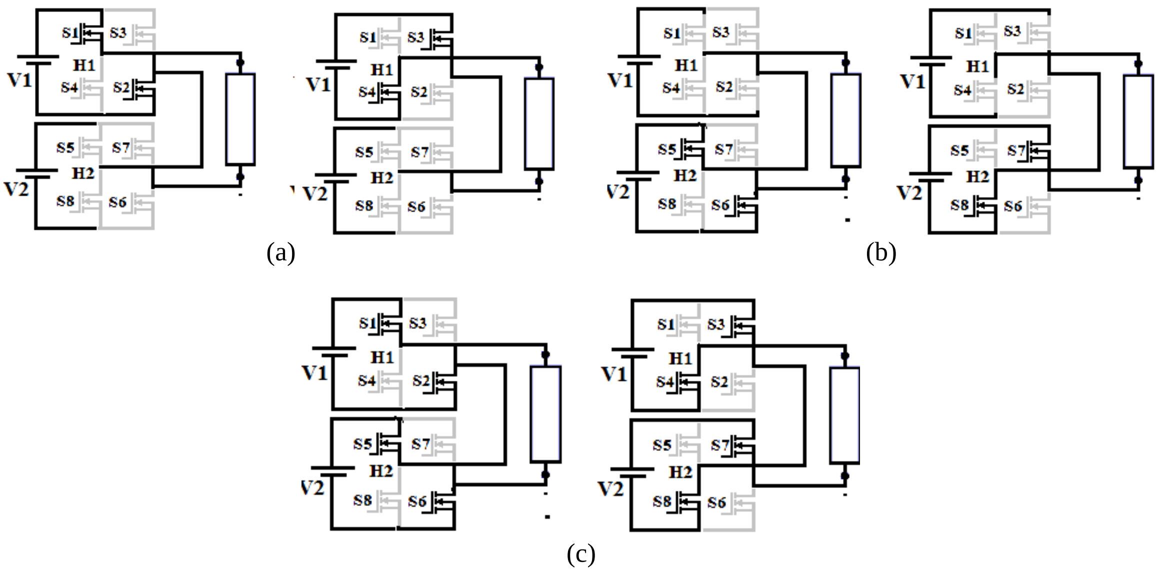



Figure 2. Conduction modes of 7-level output of new modified multilevel inverter (a) V & -V, (b) 2 V & -2 V, and (c) 3 V & -3 V

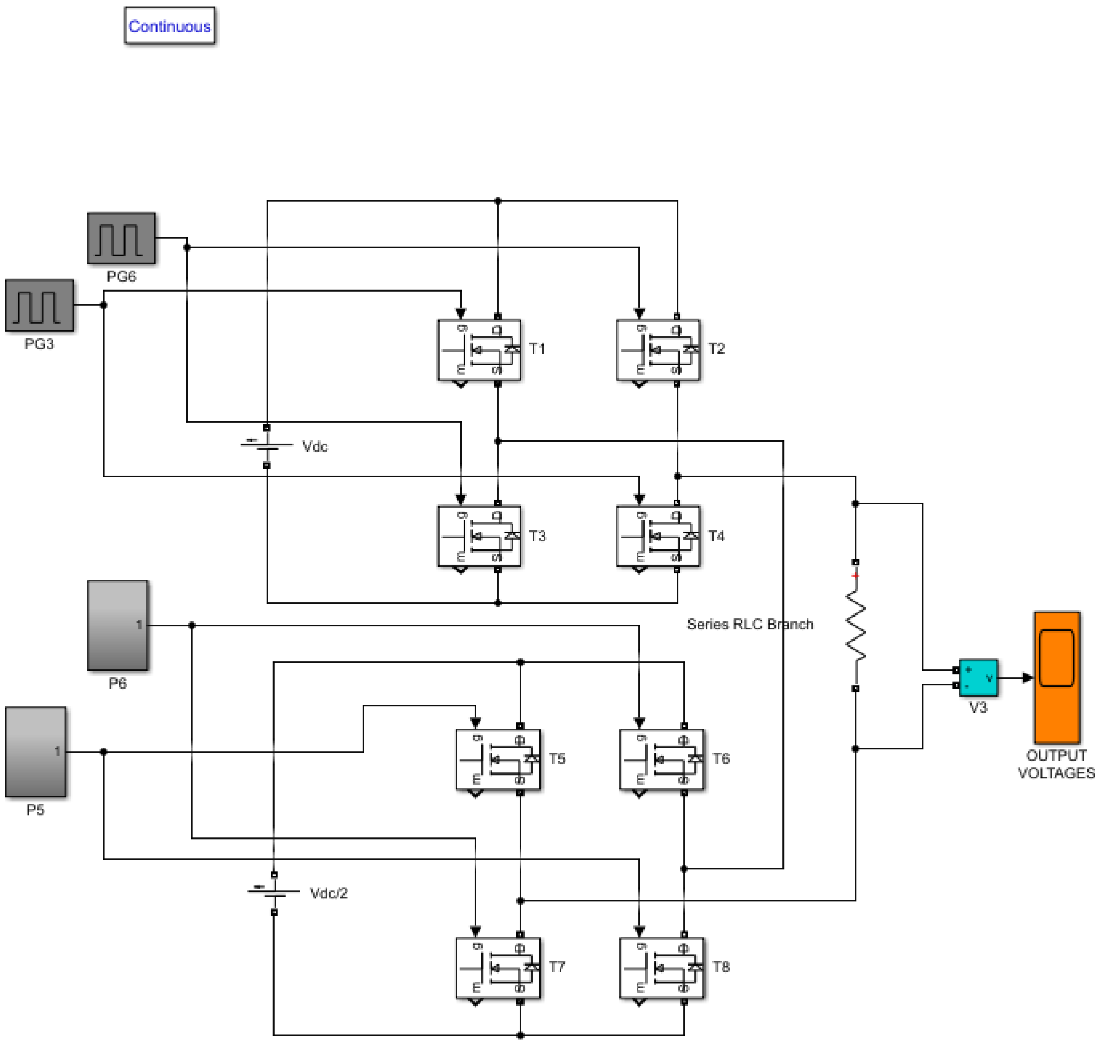



Figure 3. Simulation diagram of proposed modified multilevel inverter

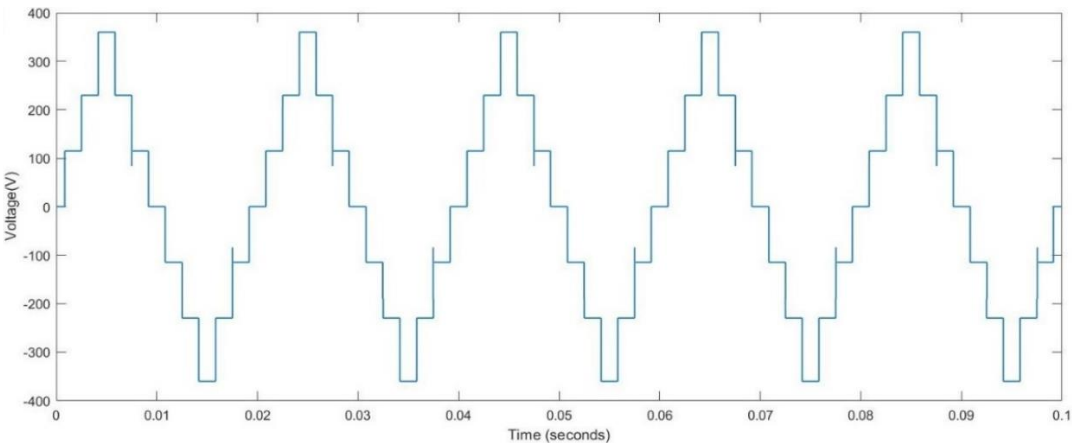



Figure 4. Output response plot of proposed modified multilevel inverter

## 3. PROPOSED MULTISTRING INVERTER MODEL

Multi string inverter is an inverter model which uses three switches per leg with two legs per phase and two DC sources. The newly modelled multi string inverter has six switches per phase. With six switches, there is a likelihood of sixty-four switching states. For the multi string inverter to produce an output, three switches should conduct. Hence out of sixty-four combinations, only twenty switching states comprise a permutation of three conducting switches. Here all the three switches should not conduct within the same leg. Considering the possibilities, only six switching states are viable to obtain an output. The multi string inverter, in general, has half conduction and full conduction modes.

The proposed multi string inverter with two sources can produce three levels, five level, and seven level output. To achieve three levels and five level output, the DC sources should be equal. When the DC inputs are maintained in the ratio 3:2, the output obtained can be of seven levels. Figure 5 presents the newly designed multistring inverter as applicable for electric vehicles.

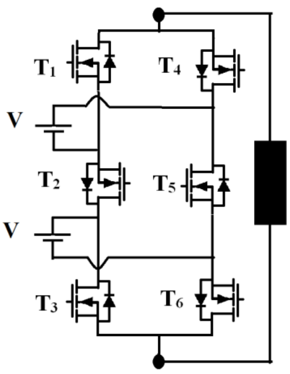



Figure 5. Proposed design of multistring inverter model

In the proposed multistring inverter to obtain a five-level output, the input DC sources are retained to be the same value. If the input DC source is considered to be ‘V’, then the output voltages would be 0, ±V, ±2 V. To obtain an output voltage of ‘V’ or ‘–V’, one of the half conduction modes is utilized. To achieve an output voltage of ‘2 V’ or ‘-2 V’, the full conduction modes are employed. For the output voltage to be V, any of the positive half conduction modes is used, either T2, T3, and T4 is kept on or T1, T2, and T6 are kept on. Similarly for the output voltage to be ‘-V’, any of the negative half conduction modes is used, T1, T5, and T6 are kept conducting or T3, T4, and T5 are kept conducting. To obtain an output of ‘2 V’, T2, T4, and T6 are turned on, which falls under the full conduction mode. The other full conduction mode is utilised for negative output, which is T1, T3, and T5, to derive an output of ‘-2 V’. Figures 6(a)-(c) presents the conduction modes of the new multistring inverter for V, -V, 2 V, and -2V in respect of 5-level output.

With the new multistring inverter for obtaining a seven-level output, the input DC voltages are to be maintained unequal. To keep the difference between the output levels equal, the input DC voltages must be maintained in the ratio 3:2. For the output voltage to be V, one of the positive half conduction modes is used, which is T2, T3, and T4 is kept on; and the output voltage is ‘2 V’ when the other half conduction mode, i.e., T1, T2, and T6 are kept on. Correspondingly for the output voltage to be ‘-V’, one among the negative half conduction modes, T1, T5, and T6 are kept conducting, is used. To derive an output voltage of ‘-2 V’, the remaining half conduction mode comes into picture, i.e., T3, T4, and T5 are kept conducting. To acquire an output of ‘3V’, T2, T4, and T6 are turned on, which falls in the full conduction mode. The other full conduction mode is utilised for negative output, which is T1, T3, and T5, to derive an output of ‘-3 V’. Figures 7 (a)-(c) presents the conduction modes of the new multistring inverter for V, 2 V, and 3 V in respect of 7-level output. Figures 8(a)–(b) presents the output response plots attained for 5-level and 7-level cases.

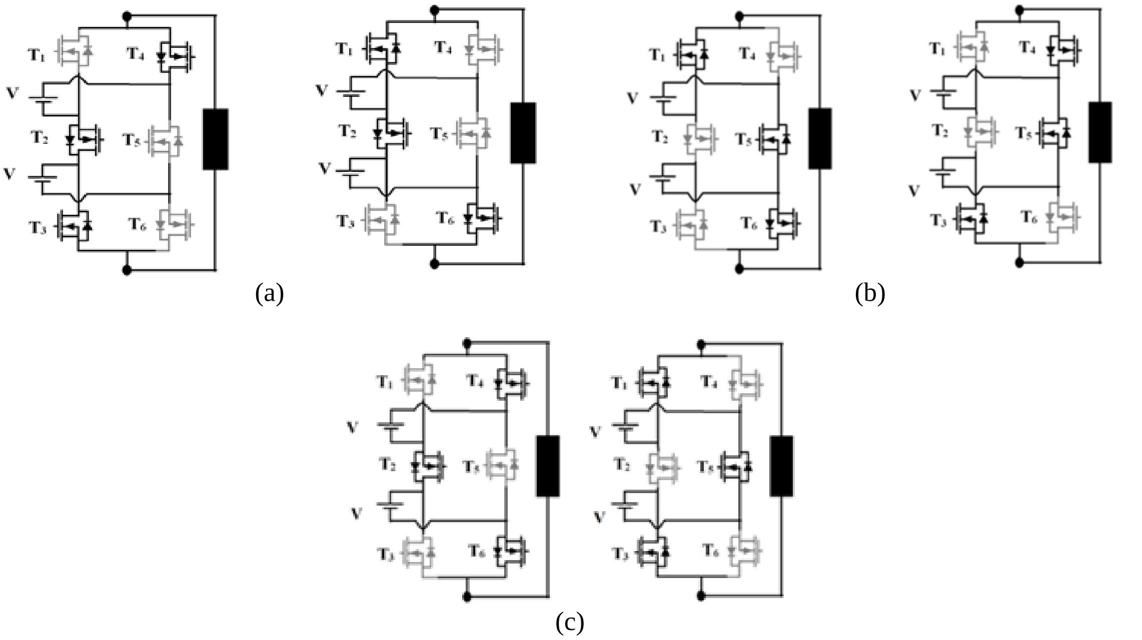



Figure 6. Conduction modes of proposed multistring inverter for 5-level output (a) V output, (b) –V output, and (c) 2 V & -2 V output

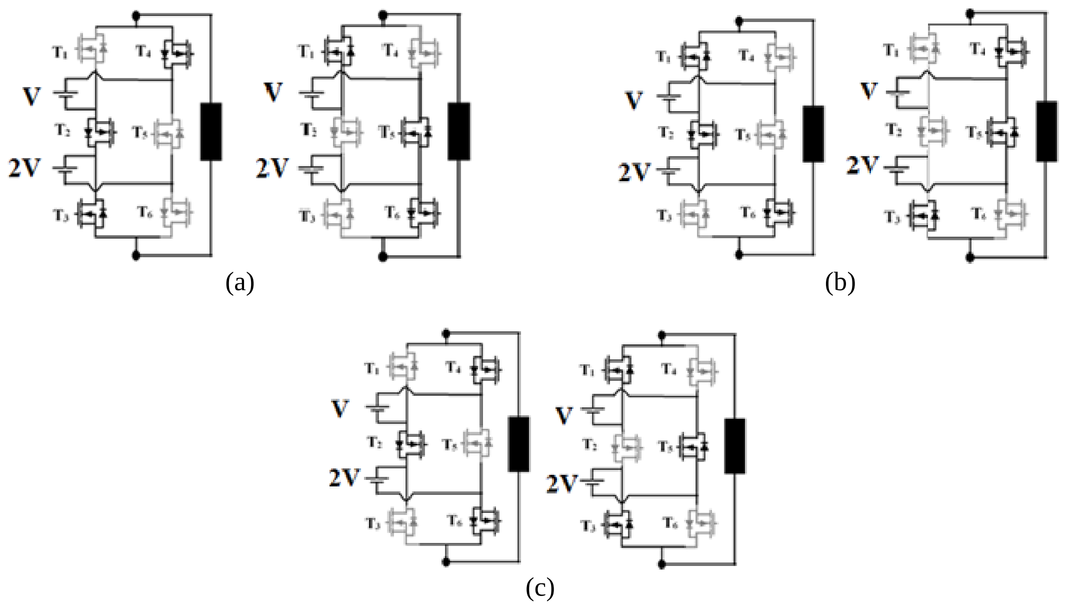
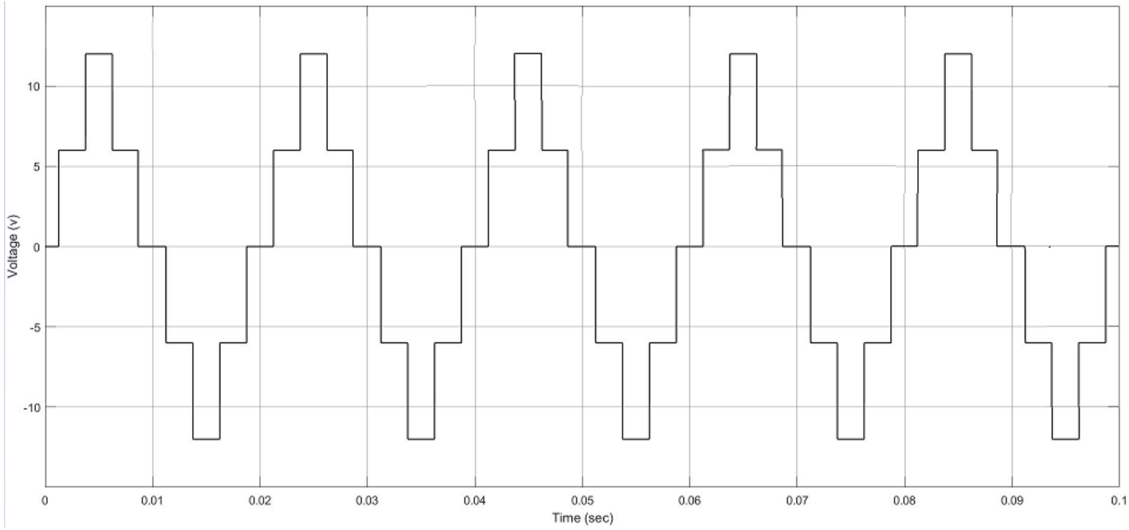
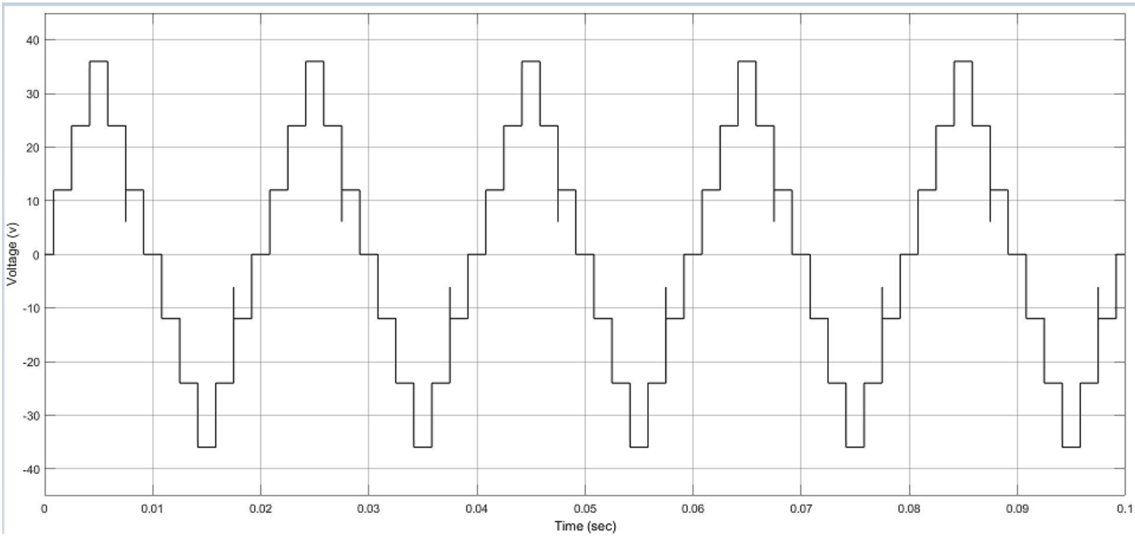



Figure 7. Conduction modes of proposed multistring inverter for 7-level output (a) V output, (b) 2 V output, and (c) 3 V output



(a)

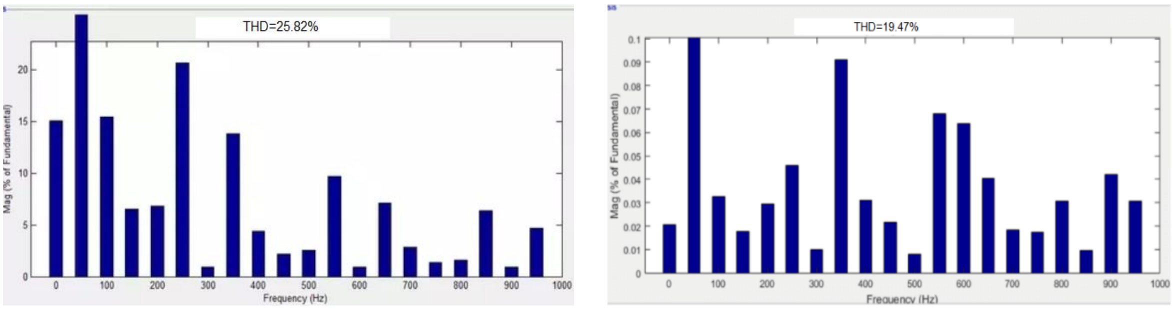


(b)

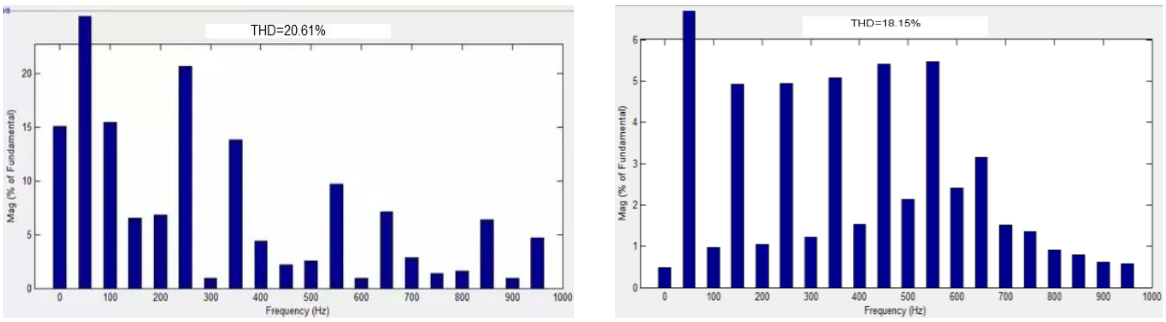
Figure 8. Output response plot for proposed multistring inverter (a) 5-level output and (b) 7-level output

## 4. RESULTS AND DISCUSSION

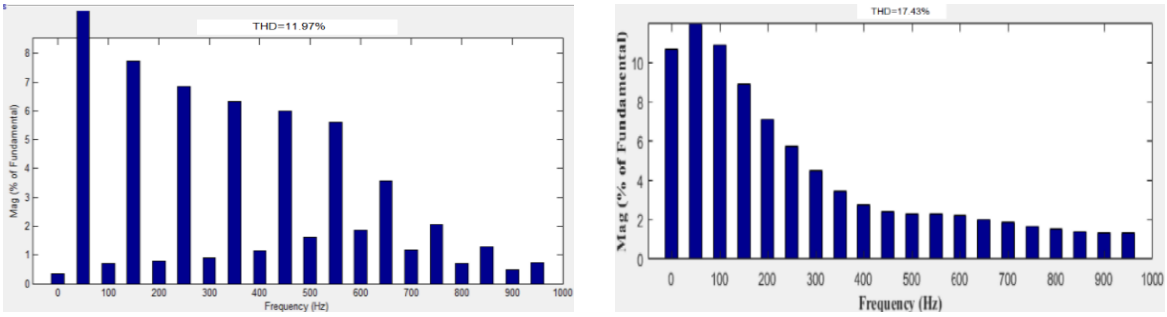
In this research study, all the proposed two configurations–modified multilevel inverter and new multistring inverter along with the classic multilevel inverter are analysed for five level and seven level outputs. Figures 9 (a)–(c) presents the plots of the fast fourier transform (FFT) analysis carried out for evaluating total harmonic distortion (THD) values of the respective inverter models classic multi-level inverter, proposed modified multi-level inverter, and proposed multistring inverter. The classic multilevel inverter sets a benchmark for the THD values for five level and seven level inverter output, which are 25.82% and 19.47%. The modified multilevel inverter or the modular inverter proves to be producing lower level of harmonics than the classic multilevel inverter with varied output levels. But the multistring inverter produces much lower THD value for five level output 11.97%, which is less than half of the THD of classic multilevel inverter. In case of a seven-level output, the THD values of classic inverter is higher the multistring inverters and the modified multilevel inverter. Modifications in the driver circuit and proper implementation of a filter circuit can bring about changes in the THD values. Table 1 provides the total harmonic distortion value evaluated using the proposed inverter models. It infers that the power quality is better with the proposed new multistring inverter possessing minimized THD value of 11.97% and 17.43% for 5-level and 7-level outputs respectively. Table 2 lists the comparison of the THD values with that of the existing inverter models and the minimal THD value attained confirms the superiority of the proposed multistring inverter model.




(a)




(b)




(c)

Figure 9. FFT analysis of inverter models (a) classic multi-level inverter, (b) proposed modified multi-level inverter, and (c) proposed multistring inverter

Table 1. Computed THD (%) values for better power quality

| Inverter configuration | 5-level output | 7-level output |
|---|---|---|
| Classic multilevel inverter | 25.82 | 19.47 |
| Proposed modified multilevel inverter | 20.61 | 18.15 |
| Proposed multistring inverter | 11.97 | 17.43 |

Table 2. Comparison of THD values with existing inverter models

| Inverter Configuration | 5-level | 7-level |
|---|---|---|
| Wide bandgap (WBG) inverter [18] | 35.09 | 32.17 |
| Distribute auxiliary inverter [19] | 34.50 | 31.66 |
| Multilevel DC/AC traction inverter [20] | 34.28 | 30.73 |
| Traction inverter with silicon carbide (SiC) module [21] | 31.03 | 29.96 |
| Inverter system [22] | 30.62 | 28.77 |
| Modified class E inverter [23] | 29.80 | 28.45 |
| Traction inverter [9] | 27.63 | 25.89 |
| 250 kW silicon carbide MOSFET based three-level traction inverter [24] | 28.91 | 27.48 |
| Space vector modulation based transistor clamped H-bridge inverter [25] | 26.47 | 22.65 |
| Classic multilevel inverter model | 25.82 | 19.47 |
| Proposed modified multilevel inverter model | 20.61 | 18.15 |
| Proposed multistring Inverter model | 11.97 | 17.43 |

## 5. CONCLUSION

This research paper has modelled two new configurations of inverters; proposed modified multilevel inverter and new multistring inverter as applicable for the electric vehicle applications. The proposed modified multilevel inverter has been designed with reduced switches and the novel multistring inverter model formulates effective permutation of the conducting switches. In this manner, both the inverter models overcome the limitations of the classic multilevel inverter and other models considered for comparison from previous literature works. The new modified multilevel inverter model and multistring inverter model has minimized the total harmonic distortion thereby rendering better power quality to convert to AC power for the electric vehicles to drive the traction motors. The designed new modified multilevel inverter model and multistring model are tested for both five level and seven level output and has proved their superiority with minimized harmonic distortion value and thereby rendering quality power for the electric vehicles. The limitation of this paper is that with the growing demands for electric vehicles, there is always a variation and need of inverters to be designed to meet the vehicle requirement. Further enhancement is required to further reduce the total harmonic distortion and to make the inverter model more stable. The future scope of this research paper involves in designing more versatile inverter models with less switching time, minimized THD value, highly reliable, and is able to withstand for higher speed driven electric vehicle models.

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## BIOGRAPHIES OF AUTHORS

**Sri Krishna Kumar Sampathkumar** has completed his graduation in Electrical and Electronics Engineering from RVSCET, Dindigul under Anna University during 2008, and post-graduation in Power Electronics and Drives from Government College of Engineering, Salem under Anna University during 2011. He has teaching experience of nearly 10 years in engineering colleges. His current area of research includes power electronic converters, power electronic applications to power system, and circuit analysis for power electronic circuits. Mr. S. Sri Krishna Kumar holds life membership in professional society IAENG, ICST, EAI (eu), and ISTE. He can be contacted at email: kkumarveltech@gmail.com.

**Dhal Pradyumna Kumar** was born on 1969 and received his M.E. degree (Power Systems) from Madurai Kamaraj University (2002), Madurai, India. He received his Ph.D in Power System from Sathyabama University, Chennai, India (2014). He published technical papers in International and National Journals and Conferences. He is currently working as a Professor of Electrical and Electronics Engineering Department at Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India. His areas of interest are power system optimization, power quality, and power system application to power electronics. He acquired membership in ISTE and IEEE in India. He can be contacted at email: pradyumna.dhal@rediffmail.com.