Reduction of total harmonic distortion of three-phase inverter using alternate switching strategy

Nur Arifah Ramli[1], Auzani Jidin[2], Zulhani Rasin[3], Tole Sutikno[4]
[1,2,3]Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Malacca, Malaysia
[1,2,3]Research Laboratory of Power Electronics and Drives, Universiti Teknikal Malaysia Melaka, Malacca, Malaysia
[4]Department of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[4]Embedded System and Power Electronics Research Group, Yogyakarta, Indonesia

Article Info

Article history:

Received Apr 17, 2021
Revised Jul 7, 2021
Accepted Jul 20, 2021

Keywords:

Alternate switching
IGBT
Inverter
Switching frequency
Total harmonic distortion

ABSTRACT

Alternating current (AC) electrical drives mainly require smaller current (or torque) ripples and lower total harmonic distortion (THD) of voltage for excellent drive performances. Normally, in practice, to achieve these requirements, the inverter needs to be operated at high switching frequency. By operating at high switching frequency, the size of filter can be reduced. However, the inverter which oftenly employs insulated gate bipolar transistor (IGBT) for high power applications cannot be operated at high switching frequency. This is because, the IGBT switching frequency cannot be operated above 50 kHz due to its thermal restrictions. This paper proposes an alternate switching strategy to enable the use of IGBT for operating the inverter at high switching frequency to improve THD performances. In this strategy, each IGBT in a group of switches in the modified inverter circuit will operate the switching frequency at one-fourth of the inverter switching frequency. The alternate switching is implemented using simple analog and digital integrated circuits.

Corresponding Author:

Auzani Jidin
Faculty of Electrical Engineering
University Technical Malaysia Malacca
Jalan Hang Tuah Jaya, 76100 Durian Tunggal, Malacca, Malaysia
Email: auzani@utem.edu.my

1. INTRODUCTION

A three-phase inverter is the main part in alternating current (AC) electrical drives, which is used to produce desired magnitude and frequency of AC voltages from an unregulated or a regulated direct current (DC) voltage. The DC voltage is obtained from a rectifier or a series of batteries. Along with power electronic controller and electrical machine, AC motor drives is well known through all sectors in the industry. In terms of system efficiency, controllability and overall performance, it can guarantee for excellent performances. Figure 1 illustrates the use of three-phase inverter in AC motor drives, in which the inverter can be performed as voltage source inverter (VSI) and current source inverter (CSI). Several AC drives perform the inverter as VSI, for examples in direct torque control (DTC), space vector modulation (SVM). The application of VSI can be applied in both single-phase and three-phase applications [1]. Usually, VSI takes place of the full converter in most applications [2]. They are widely used in power generation applications, three-phase UPS systems and islanded operation of three-phase system, where the balanced three-phase voltage output is required when the loads are unbalanced [3]. On the other hands, there are many AC motor drives perform the inverter as CSI, such as field-oriented control (FOC) and induction motor.

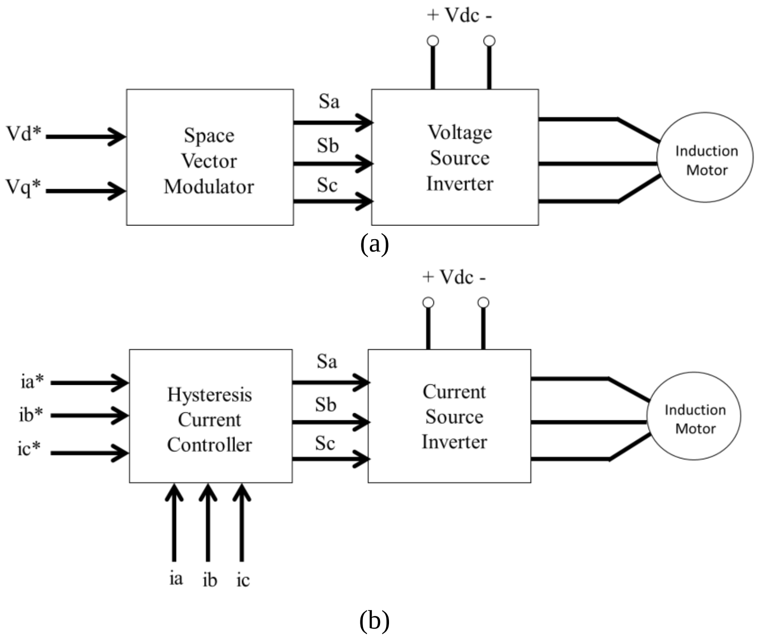


Figure 1. The use of inverter in AC motor drives, where inverter performed as (a) voltage source inverter (VSI), (b) current source inverter (CSI)

CSI is very rarely implemented alternative to the VSI but quite well known for its function [4]. Nevertheless, the significant practical application of CSI regarding of self-commuted variant is not found yet [5]. Some applications have applied CSI with independent dc link to balance the dc-link currents with proper control of the rectifiers [6]. The output of inverter is generated by the AC voltage that can be a variable or constant depending on the requirements of the applications [7]. The AC output is controlled independently by VSI that behave as a voltage source that is required by many industrial applications. On the other hand, CSI produce high quality current waveforms that are widely used by medium-voltage industrial applications. In order to produce a smooth current waveform, VSI needs to generate AC output voltage waveform that is composed with the discrete values so that the load can be inductive at the harmonic frequencies. VSI will generate large current spikes in a capacitive load that is prevented by inductive filter between the AC side of VSI and the load. In the conjunction of the VSI, CSI produced large voltage spikes in the inductive load. If this happened, capacitive filter will be used between CSI at the AC side and the load [8]. To control the inverter, some aspects need to be taken into account such as the efficiency of the inverter. This include the switching losses and harmonic reduction that principally depended on the modulation strategies [9]. The inverter control techniques are based on the fundamental frequency and high switching frequency.

The regular pulse width modulation (PWM) modulation methods can be divided into two class which are open loop and closed. Open loop is applied for VSI while closed loop is usually used for the CSI. This proposed research is mainly focused on open loop which is VSI. Open loop consists of PWM techniques such as sinusoidal pulse width modulation (SPWM) [10], space vector pulse width modulation (SVPWM) [11] and third harmonic pulse width modulation (THPWM) [12]. The modulation methods developed to control the multilevel inverters that are based on multi-carrier orders with PWM. SPWM is the most common control schemes that control the multilevel inverters. In conventional SPWM, a sinusoidal reference waveform is compared with a triangular carrier waveform to generate switching sequences for power semiconductor in inverter modules. The fundamental frequency SPWM control method was proposed to minimize the switching losses. The multi-carrier SPWM control methods are also implemented to increase the performance of multilevel inverters and are classified according to vertical or horizontal arrangements of carrier signal [13]. Its switching scheme is easy to implement in both analogue and digital circuit. In the simplest form, it involves the high switching frequency triangular carrier voltage with a sinusoidal modulating signal that represents the desired fundamental component of the voltage waveform [14]. The peak magnitude of the modulating signal should remain limited to the peak magnitude of the carrier signal. The proposed method is developed by considering the side band harmonics and modulation bandwidth in Simulink during simulation. The experimental verification of the modeled system is analyzed by controlling the IGBT modules with developed SPWM algorithm generated by high switching strategy.

SVM or SVPWM was originally developed as vector approach to PWM for three phase inverters. It is a more sophisticated technique for generating sine wave that provides a higher voltage to the motor with lower total harmonic distortion. The main aim of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics. SVPWM method is an advanced computation intensive PWM method [15]. Despite the advancement, the analysis of the SVPWM contained a complex implement in the software compared to SPWM [16]. Even though the SVPWM has more advantage of less harmonic content, the differences between the two modulations are small. Thus, with intangible differences, SPWM is chosen as the circuit is much simpler than SVPWM when executed in the software.

The sinusoidal PWM is the simplest modulation scheme to understand but it is unable to fully utilize the available DC bus supply voltage. Due to this problem, the THPWM technique was developed to improve the inverter performance. The sinusoidal PWM technique causes decrease maximum achievable output voltage. In this case, an increase of maximum achievable output voltage is studied. Hence, by simply adding a third harmonic signal to each of the reference signals, it is possible to obtain a significant amplitude increase at the output voltage without loss of quality [17]. It is remarkable that the reference signal resulting from the addition of the third (V3) and first harmonic (V1) is smaller in amplitude than the first harmonic. At the output, the obtained amplitude of the first harmonic is equal to the amplitude of the first harmonic reference. Note also that the third harmonic is not seen at the output voltage. However, the phase of the third harmonic injected must be strictly synchronous with the phase of the reference voltage. The synchronization will cause the difficulty of the injected third harmonic generation [18]. Thus, SPWM technique is more lenient compared to the THPWM to obtain the THD voltage of the motor.

The growth in AC motor drives is drastically as over the past years due to the following factors:
- Rapid technology development of microprocessor in calculating/executing complex algorithms [19],
- Rapid technology development of solid state switching devices which able to operate the switching at higher power and switching frequencies [20],
- High demand for industrial applications, e.g. electric vehicle application fraction drives, automation industry [21].

Based on the factors above, in addition, there are several researchers used the fully optimization of the inverters has invented the topologies that undergone constant change which the first was CSI followed by VSI based on application [22]. AC motor drives give benefits in term of process control, system stress and energy savings [23]. It enables the users to control the speed of motor at a constant speed. The process output needs to match the different synchronizing part as to lock the flow become smooth between sub processes in the process control. AC drives do have its own disadvantages. It tends to have complexity in the circuit and costly compared to other motor. The horsepower rating expensive is expensive as it has a modern technology build inside the drives [24]. For an example, if the AC motor tends to rotate faster than the command AC drive, the motor itself will acts as regenerates that it can pump energy into drive again. The drive will short circuit if the energy that are regenerated cannot absorb this energy which can lead audible noise.

In this research method, the main concern is to minimize the Total Harmonic Distortion (THD) of output voltage as well as output current, and filter size. Based on the research report in [25], THD can be minimize by operating the inverter at high switching frequency without degrading IGBT switching performance . In such way, the undesired harmonic components can be located at higher frequencies and hence small filter size can be effectively eliminate the harmonic components. In this paper, IGBT is chosen due to its advantage which can operate at higher power capability [26]. However, IGBT cannot be operated at very high switching frequency, i.e. above 50 kHz due to its thermal restriction as reported in [27]. This paper provides a simple solution to enable the use of IGBT to operate at very high switching frequency without degrading its switching performances.

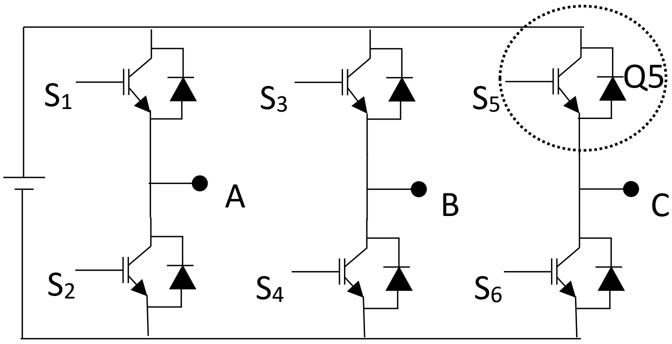
The objective of this paper is to study, implement and improve the performances of AC drives using alternate switching and high switching frequency strategy. The main objectives of this research are:
- To reduce THD of output voltage and current and filter size by operating the inverter at high switching frequency without degrading IGBT switching performances.
- To design an ‘Alternate Switching Strategy’ using analog and digital ICs, which allows IGBT based inverter to operate at high switching frequency.
- To verify the improvements of the inverter (i.e. reduction of THDs) through simulation and hardware results.

2. PROPOSED ALTERNATE SWITCHING STRATEGY

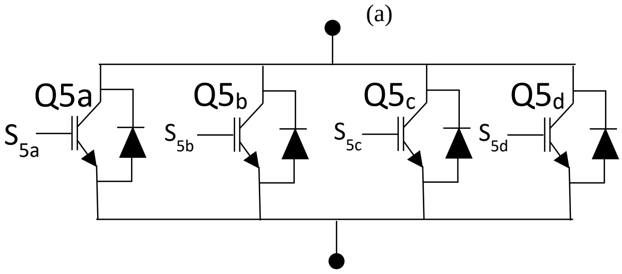
In order to improve AC drive performances, specifically in reducing output phase voltage THD, it is necessary to operate the inverter at very high switching frequency. As discussed above, the use of IGBT in the inverter circuit is strongly recommended due its high-power operation capability. However, the IGBT cannot be operated at very high switching frequency, i.e. above 50 kHz. To enable the three-phase inverter using IGBTs to operate at very high switching frequency, an alternate switching strategy is proposed. Generally, in this strategy, the conventional inverter circuit needs to be modified and the switching frequency as well as switching states for switching each IGBT is splitted such that the IGBT switching frequency is one-fourth of the inverter switching frequency.

2.1. Modification of three-phase inverter circuit

The modification of the inverter circuit with additional IGBTs can be illustrated in Figure 2. For example, the top IGBT in Leg 3 (or c-phase) of the conventional three-phase inverter, i.e. Q5 is represented as a group of four IGBTs in the modified inverter which are connected in parallel, i.e. Q5a, Q5b, Q5c and Q5d. This means every single IGBT in the original inverter circuit is now being replaced with a group of four IGBTs. Therefore, the modified inverter circuit consists of 24 IGBTs.



(a)



(b)

Figure 2. Modification of inverter circuit (a) the conventional three-phase inverter, (b) a group of four IGBTs connected in parallel

In this way, the inverter switching frequency can be divided into four, so that every IGBT in a group has a one-fourth of inverter switching frequency. For examples, if the inverter switching frequency is chosen as 200 kHz, therefore every IGBT in each group has a switching frequency of 50 kHz. It should be noted that the inverter still operates at switching frequency of 200 kHz as each IGBT in a group is switched alternately, i.e. one-by-one and one IGBT is switched at one time. Therefore, the switching operation of IGBT is prevented to operate beyond its limitation and at the same time the reduction of high frequencies components of output voltage as well as output current can be obtained with smaller size of filters.

2.2. Generation of switching states for alternate switching

This section explains the proposed alternate switching strategy that allows the inverter to operate at very high switching frequency for improving AC drive performances. For simplification, the explanation of the proposed strategy will only consider for switching alternately for four IGBTs in a group, e.g. as illustrated in Figure 2. Figure 3 shows the block diagram and timing diagram of the proposed alternate switching strategy for switching IGBTs $Q5_a$, $Q5_b$, $Q5_c$ and $Q5_d$ in the modified inverter with their respective switching states S_{5a}, S_{5b}, S_{5c}, and S_{5d}. The block diagram of the proposed strategy has two main parts, i.e. two-bit counter and demultiplexer. The proposed alternate switching strategy employs a 1-to-4 demultiplexer and a two-bit counter, where the input PWM signal $S_{x=}S_5$ is obtained from PWM generator and the output signals, i.e. S_{5a}, S_{5b}, S_{5c}, and S_{5d} are used to control the switching operation of IGBTs. The operation of the proposed alternate switching strategy to produce alternate switching states can be illustrated by timing diagram in Figure 3(b).

Figure 4 shows a simulation model of two-bit counter using Gray Code and 1-to-4 demultiplexer for producing alternate switching states, e.g. S_{5a}, S_{5b}, S_{5c}, and S_{5d}. The simulation model requires two inputs which are a S5 (PWM) signal and enabling signal (i.e. designated as *ENB*), to produce two-bit output, i.e. A_1 (MSB) and A_0 (LSB). These two-bit outputs are used to index the selection table given in Table 1, for splitting a PWM signal into four switching states in demultiplexer operation. Note that the enabling signal is set to logic 1 to activate the counting operation.

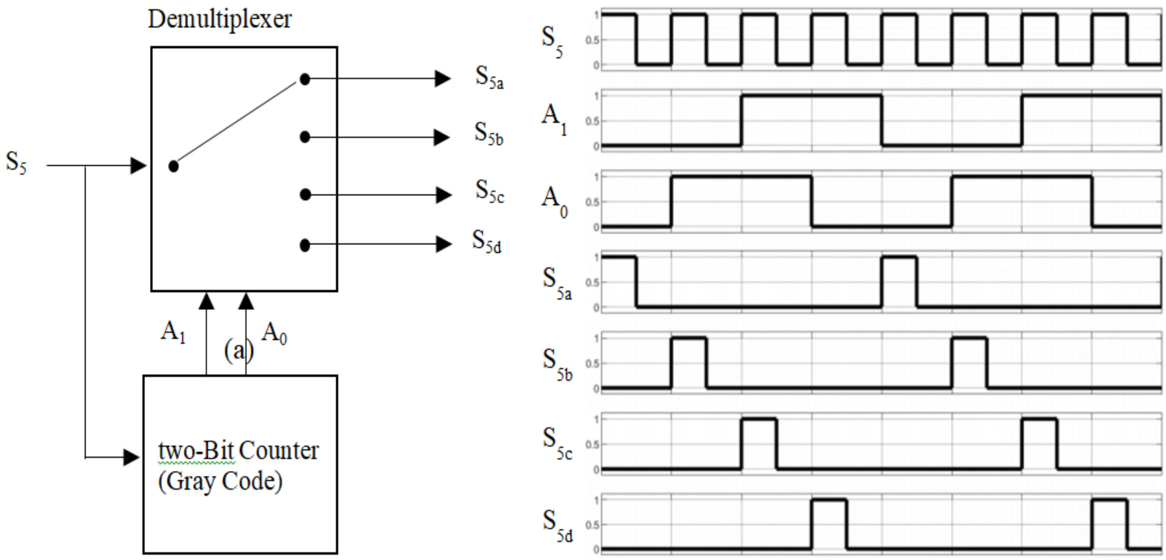
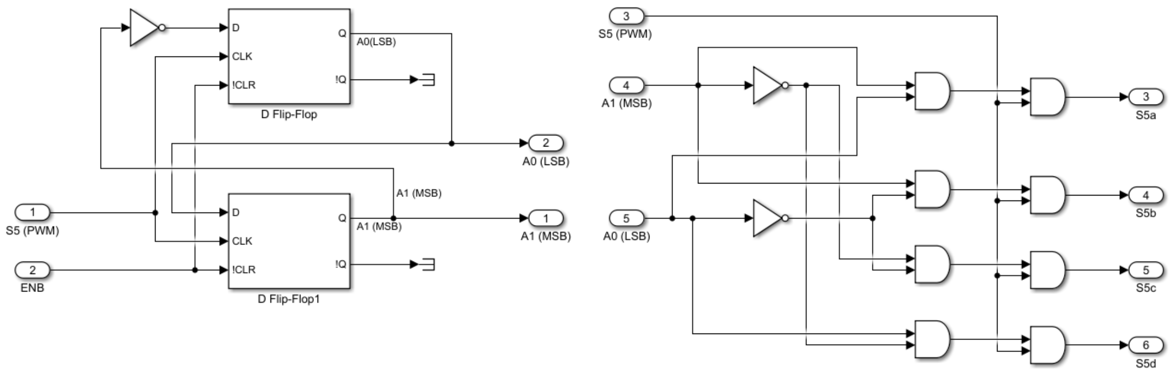


Figure 3. The proposed alternate switching strategy for switching four IGBTs in a group: (a) block diagram (b) timing diagram waveform



(a) (b)

Figure 4. Simulation model of the proposed alternate switching strategy for controlling a group of four switches: (a) two-bit counter (b) 1-to-4 demultiplexer

Table 1. Splitting of PWM signals to produce switching state for each channel output

Address data (from two-bit counter)		Output of demultiplexer			
A_1 (MSB)	A_0 (LSB)	S_{5a}	S_{5b}	S_{5c}	S_{5d}
0	0	S_5	0	0	0
0	1	0	S_5	0	0
1	0	0	0	S_5	0
1	1	0	0	0	S_5

The two-bit counter employs two *D Flip-flop* and a *NOT* logic gate, and 1-to-4 demultiplexer employs a set of logic gates which is constructed based on Boolean expression given in (1).

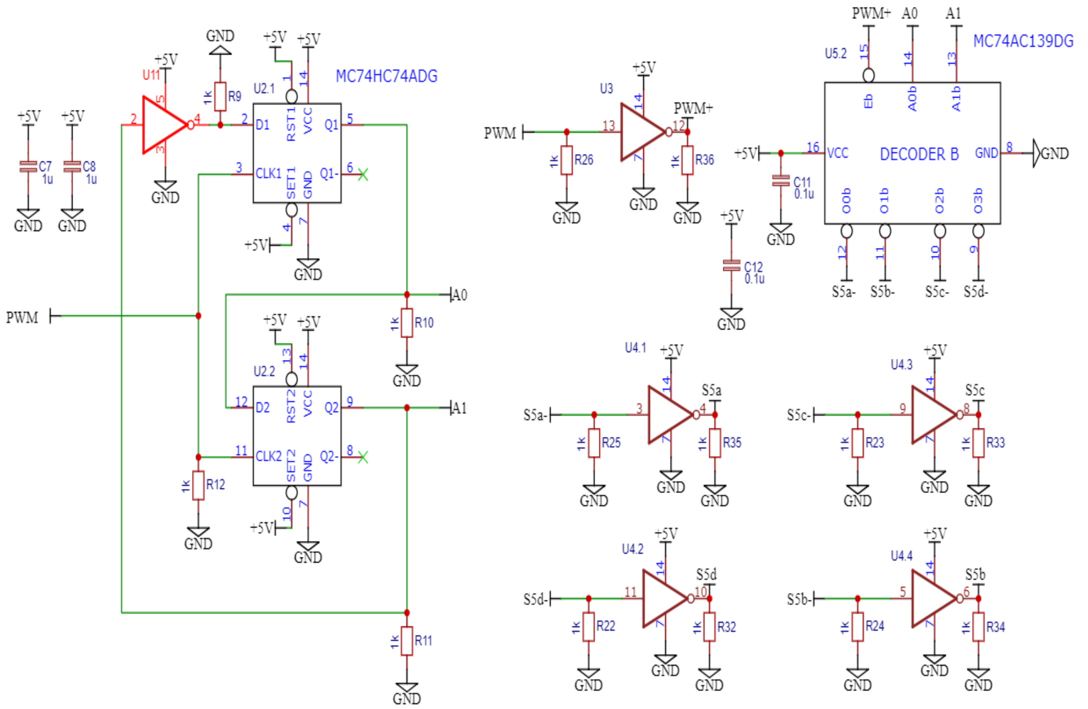
$$
\begin{aligned}
S_{5a} &= \overline{A_1} \cdot \overline{A_0} \cdot S_5 \\
S_{5b} &= \overline{A_1} \cdot A_0 \cdot S_5 \\
S_{5c} &= A_1 \cdot A_0 \cdot S_5 \\
S_{5d} &= A_1 \cdot \overline{A_0} \cdot S_5
\end{aligned}
\quad (1)
$$

Where the Boolean expression for each switching state is functioned of PWM signal and two-bit address, which can be obtained from the demultiplexer operation given in Table 1.

3. EXPERIMENTAL SETUP

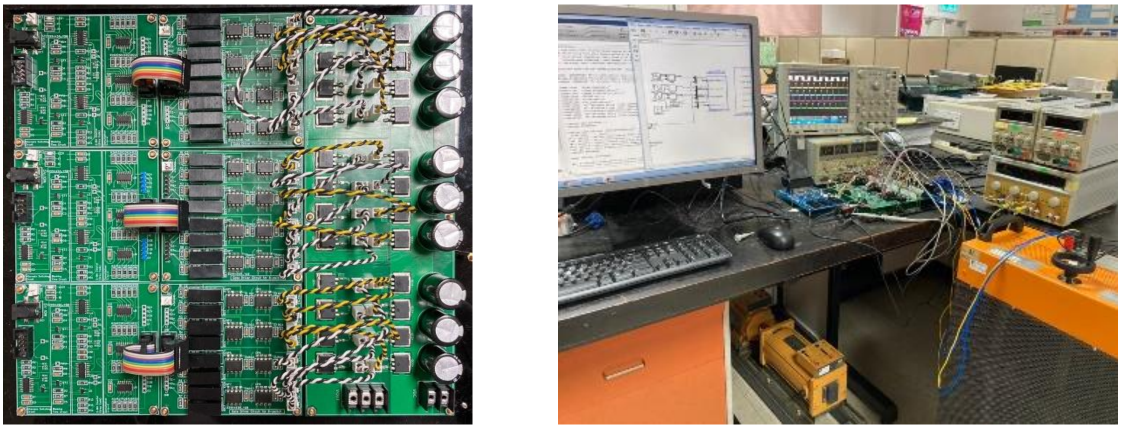
This section discusses the experimental setup of the proposed alternate switching strategy for minimizing THD of output voltage. Figure 5 shows an electronic circuit of the proposed alternate switching strategy for controlling four switches in a group, i.e. S_{5a}, S_{5b}, S_{5c}, and S_{5d}. The two-bit counter with *Gray* code is implemented using integrated circuit (IC) model: MC74HC74ADG, and 1-to-4 demultiplexer is implemented using IC model: MC74AC139DG. The input of the circuit is a *PWM* signal, e.g. S_5 and this signal is splitted into four switching states, i.e. S_{5a}, S_{5b}, S_{5c}, and S_{5d}, where each switching state performs at one-fourth of the *PWM* signal frequency.

Figure 6 shows two photos of the experimental setup of the proposed alternate switching strategy. Specifically, the modified three-phase inverter circuit consist of 6x4 IGBTs, gate driver and the proposed alternate switching circuits is shown in Figure 6(a), while the complete experiment setup is shown in Figure 6(b). A three-phase resistor bank is used as a loading unit and the *PWM* signals are generated from dSPACE1104 controller board.



(a) (b)

Figure 5. Electronic circuit of the proposed alternate switching strategy: (a) two-bit counter (b) 1-to-4 demultiplexer



(a) (b)

Figure 6. Experimental setup of the proposed alternate switching strategy: (a) alternate switching circuit, gate driver circuit and the modified inverter, (b) complete experiment setup

4. RESULTS AND DISCUSSION

Some experiments are carried out to validate the THD reduction in the proposed method. The experiments are carried out by applying Sinusoidal pulse width modulation (SPWM) technique for three different inverter switching frequencies, i.e. $f_{sw=}5$ kHz, $f_{sw=}10$ kHz and $f_{sw=}50$ kHz. Each experiment applies a dc voltage of 50 V and a simple low pass filter with cut-off frequency, f_c=10 kHz. Figures 7 and 8 show experiment results of output phase voltages and their frequency spectrums, before and after filtering actions, for three different switching frequencies. From these figures, some observations can be made which can be stated are:

- The wave shape of output phase voltage is closely to sinusoidal wave shape after filtering action applied, particularly at the highest inverter switching frequency, i.e. $f_{sw=}50$ kHz,
- Harmonic components are located at higher frequencies when the inverter switching frequency increases, before and after filtering action applied,
- Output phase voltage seems to contain insignificant harmonic components after filtering action is applied for each inverter switching frequency, and
- The fundamental component of output phase voltage after filter is applied is less than that produced before the filter is applied due to low pass filter gain.

Thus, it obviously shows that the quality of output phase voltage waveform improved if the inverter operates at higher switching frequency, and it is significantly improved after filter applied.

Table 2 shows the THD of output phase voltages corresponding to the results obtained in frequency spectrum shown in Figure 8. From the table, the THD of the output phase voltage decreases when the inverter switching frequency increases. Obviously, the THD of output phase voltage is significantly minimized to 10.15% after the filter is applied and when the inverter operates at the highest inverter switching frequency. This is because the filter with low cut-off frequency can effectively eliminate and minimize harmonics at higher frequencies. Therefore, this clearly shows that the improvement of output phase voltage waveform is due to low THD as given in Table 2. Moreover, this also highlights that less filter size is required to minimize THD for improving output phase voltage waveform if the inverter operates at the highest switching frequency.

Table 2. Total harmonic distortion (THD) of output phase voltages for three different switching frequencies; before and after filter circuit is applied.

Switching frequency, f_{sw} (kHz)	Total Harmonic Distortion (%) Before filter	After filter
5	68.55	40.11
10	68.54	27.20
50	67.75	10.15

Before filtering action After filtering action

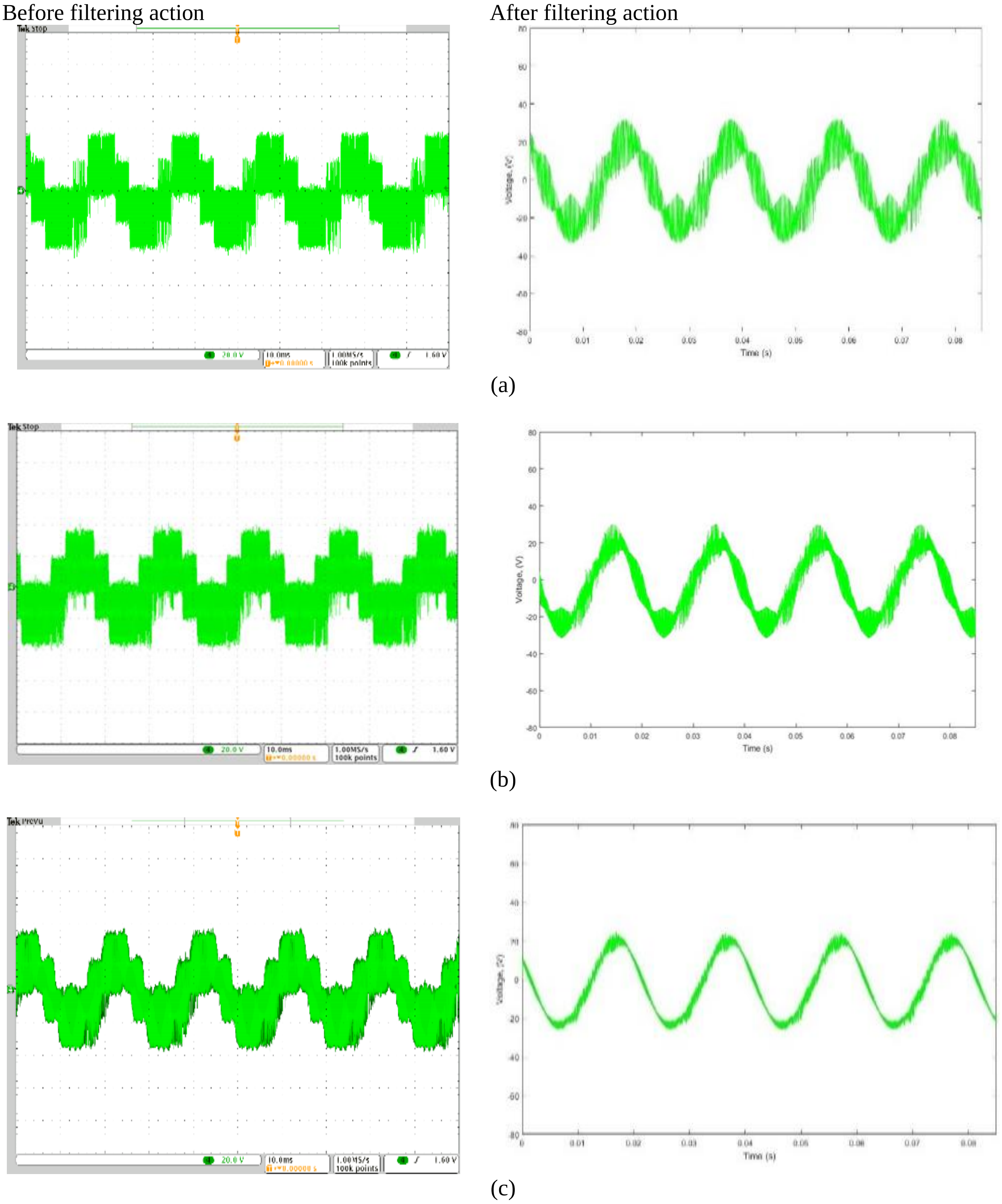


Figure 7. Experiment Results of output phase voltage before and after filtering action for different switching frequencies: (a) 1 kHz, (b) 10 kHz and (c) 50 kHz

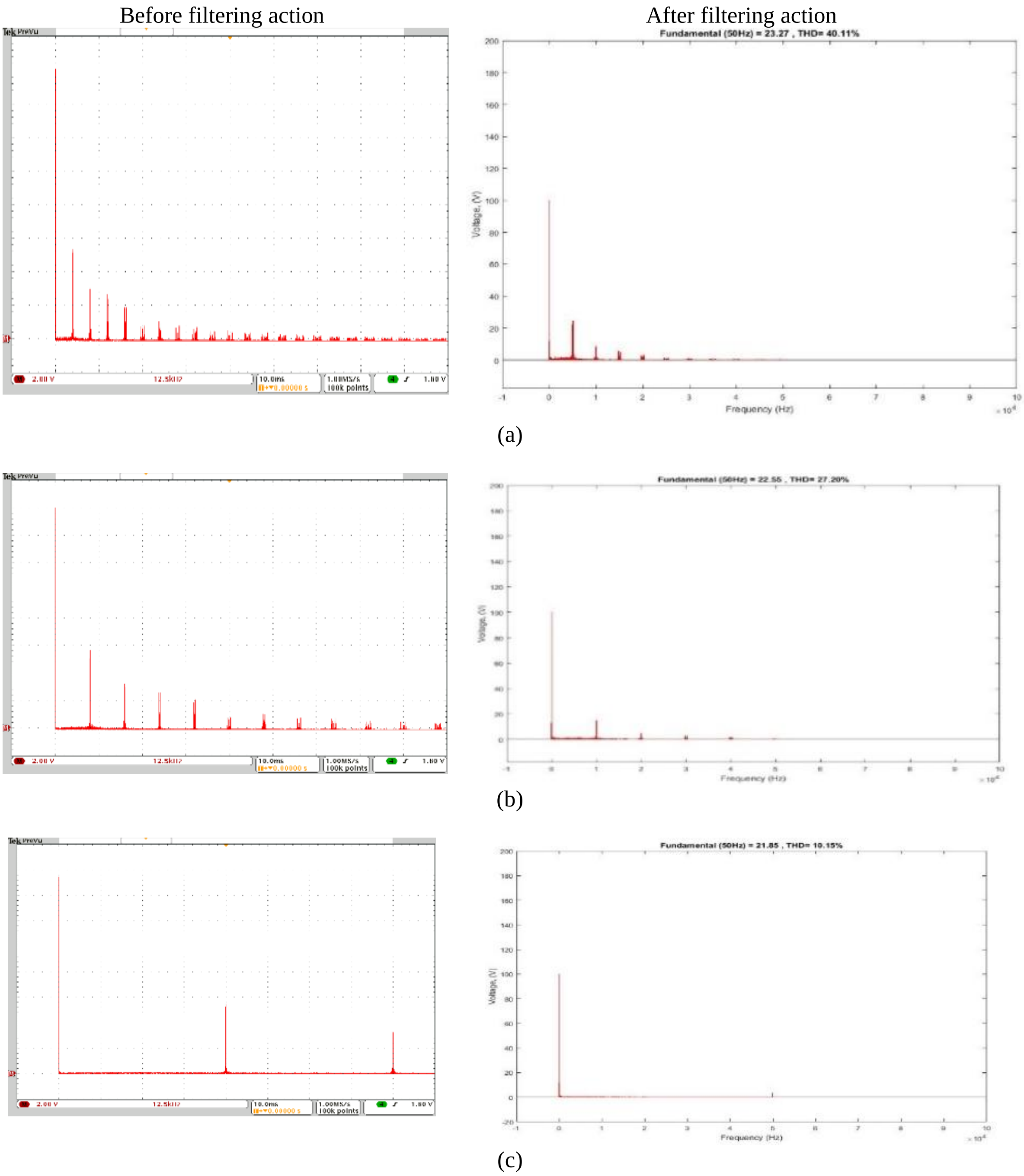


Figure 8. Experiment Results of output phase voltage frequency spectrum before and after filtering action for different switching frequencies: (a) 5 kHz, (b) 10 kHz and (c) 50 kHz, (x-axis scale: 12.5 kHz/div.)

5. CONCLUSION

This paper has proposed an improvement of THD of output phase voltage by operating the inverter at high switching frequency. In practice, IGBT power switch is not recommended to be applied at high switching frequency operation due to its limitations, i.e. it cannot operate above 50 kHz and thermal restriction. This paper has suggested to apply the proposed alternate switching strategy so that IGBTs can be employed for high inverter switching frequency. In this strategy, the inverter operates at high switching frequency, e.g. 200 kHz, however, each IGBT in a group of four switches in the modified inverter circuit is switched alternately, and as a result each IGBT operates at one-fourth of the inverter switching frequency, e.g. 50 kHz which is still below its maximum frequency. Some experiment results have verified the effectiveness of the proposed alternate switching operation to improve output phase voltage wave shape as well as THD performance. The main benefit of the proposed method is to facilitate the use of IGBT in high power applications, such that it can be used for operating the inverter at high switching frequency for improving THD performances.

ACKNOWLEDGEMENTS

The authors would like to thank Ministry of Education Malaysia, Universiti Teknikal Malaysia Melaka (UTeM) for providing the research grants RACER/2019/FKE-CERIA/F00398 to complete the paper.

REFERENCES

[1] S. Kharjule, "Voltage source inverter," *International Conference on Energy Systems and Applications*, 2015, pp. 537-542, doi: 10.1109/ICESA.2015.7503407.
[2] Z. Huang, T. Yang, P. Giangrande, S. Chowdhury, M. Galea, P. Wheeler, "An Active Modulation Scheme to Boost Voltage Utilization of the Dual Converter With a Floating Bridge," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5623-5633, July 2019, doi: 10.1109/TIE.2018.2873539.
[3] M. Zhang, D. J. Atkinson, B. Ji, M. Armstrong, M. Ma, "A Near-State Three-Dimensional Space Vector Modulation for a Three-Phase Four-Leg Voltage Source Inverter," *IEEE Transactions on Power Electronics*, vol. 29, no. 11, pp. 5715-5726, 2014, doi: 10.1109/TPEL.2013.2297205.
[4] G. Migliazza *et al*., "DC Current Control for a Single-Stage Current Source Inverter in Motor Drive Application," *IEEE Transactions on Power Electronics*, vol. 36, no. 3, pp. 3367-3376, March 2021, doi: 10.1109/TPEL.2020.3013301.
[5] B. Sahan, S. V. Araújo, C. Nöding P. Zacharias, "Comparative Evaluation of Three-Phase Current Source Inverters for Grid Interfacing of Distributed and Renewable Energy Systems," *IEEE Transactions on Power Electronics*, vol. 26, no. 8, pp. 2304-2318, Aug. 2011, doi: 10.1109/TPEL.2010.2096827.
[6] L. Ding, Y. W. Li, "Simultaneous DC Current Balance and Common-Mode Voltage Control With Multilevel Current Source Inverters," *IEEE Transactions on Power Electronics*, vol. 33, no. 11, pp. 9188-9197, Nov. 2018, doi: 10.1109/TPEL.2018.2790950.
[7] I. Colak, E. Kabalci, "Developing a novel sinusoidal pulse width modulation (SPWM) technique to eliminate side band harmonics," *International Journal of Electrical Power & Energy Systems*, vol. 44, no. 1, pp. 861-871, 2013, doi: 10.1016/j.ijepes.2012.08.024.
[8] Yaow-Ming Chen, Chih-Hung Hsieh, Yuan-Ming Cheng, "Modified SPWM control schemes for three-phase inverters," *4th IEEE International Conference on Power Electronics and Drive Systems. IEEE PEDS 2001 - Indonesia. Proceedings (Cat. No.01TH8594)*, 2001, pp. 651-656 vol.2, doi: 10.1109/PEDS.2001.975396.
[9] E. Babaei, S. H. Hosseini, G. B. Gharehpetian, "Reduction of THD and low order harmonics with symmetrical output current for single-phase ac/ac matrix converters," *International Journal of Electrical Power & Energy Systems*, vol. 32, no. 3, pp. 225-235, 2010, doi: 10.1016/j.ijepes.2009.07.004.
[10] Z. ghuoPan, F. Z. Peng, "A Novel SPWM Method with Voltage Balancing Capability for Multilevel Rectifier/Inverter Systems," *APEC 07 - Twenty-Second Annual IEEE Applied Power Electronics Conference and Exposition*, 2007, pp. 1109-1115, doi: 10.1109/APEX.2007.357654.
[11] D. V. Bramhanaidu, A. Sreenivasulu, "Implementation of Space Vector Pulse Width Modulation Technique on Three Phase Two Level Inverter," *IOSR Journal of Electrical and Electronics Engineering*, vol. 12, no. 3, pp. 14-24, 2017, doi: 10.9790/1676-1203021424.
[12] M. Esa, M. Abdul, M. Nawaz, "THD analysis of SPWM & THPWM controlled three phase voltage source inverter," *International Research Journal of Engineering and Technology*, vol. 4, no. 10, pp. 391-398, 2017, [Online]. Available: https://irjet.net/volume4-issue10.
[13] J. Rodriguez, S. Kouro, J. Rebolledo, J. Pontt, "A Reduced Switching Frequency Modulation Algorithm for High Power Multilevel Inverters," *IEEE 36th Power Electronics Specialists Conference*, 2005, pp. 867-872, doi: 10.1109/PESC.2005.1581729
[14] P. S. Shete, "Performance of Sinusoidal Pulse Width Modulation based Three Phase Inverter," *International Conference on Emerging Frontiers in Technology for Rural Area,* 2012, pp. 22-26.
[15] G. Annapurna, G. Tulasiramdas, "Simulation and comparison of SPWM and SVPWM control for two level UPQC," *Journal of Theoretical and Applied Information Technology*, vol. 78, no. 1, pp. 24-33, 2015.
[16] H. K. Kim, S. I. Ao, M. A. Amouzegar, "Transactions on engineering technologies: Special issue of the world congress on engineering and computer science," *Springer Science & Business Media*, 2013. 2014.
[17] K. B. Nagasai, T. R. Jyothsna, "Harmonic Analysis and Application of PWM Techniques for Three Phase Inverter," *International Research Journal of Engineering and Technology*, pp. 1228-1233, 2016.
[18] B. Tan, Z. Gu, K. Shen, X. Ding, "Third Harmonic Injection SPWM Method Based on Alternating Carrier Polarity to Suppress the Common Mode Voltage," *IEEE Access*, vol. 7, pp. 9805-9816, 2019, doi: 10.1109/ACCESS.2018.2890014.
[19] V. Dygalo, E. Salykin, V. Kotov, "Methods of Development and Adaptation of Engineering Microprocessor Engine Control Unit in Real Time to Ensure the Possibility of Research Work in Various Modes," *International Conference on Industrial Engineering, Applications and Manufacturing ICIEAM*, 2019, pp. 1-6, doi: 10.1109/ICIEAM.2019.8743053.

[20] A. Edpuganti, A. K. Rathore, "A Survey of Low Switching Frequency Modulation Techniques for Medium-Voltage Multilevel Converters," *IEEE Transactions on Industry Applications*, vol. 51, no. 5, pp. 4212-4228, Sept.-Oct. 2015, doi: 10.1109/TIA.2015.2437351.

[21] M. B. Arias, S. Bae, "Electric vehicle charging demand forecasting model based on big data technologies," *Applied Energy*, vol. 183, pp. 327-339, 2016, doi: 10.1016/j.apenergy.2016.08.080.

[22] W. T. Villet, M. H. A. Prins, C. W. Vorster, M. J. Kamper, "Saliency performance investigation of synchronous machines for position sensorless controlled EV drives," *IEEE International Symposium on Sensorless Control for Electrical Drives and Predictive Control of Electrical Drives and Power Electronics (SLED/PRECEDE)*, 2013, pp. 1-8, doi: 10.1109/SLED-PRECEDE.2013.6684520.

[23] Y. Zhang, B. Xia, H. Yang, J. Rodriguez, "Overview of model predictive control for induction motor drives," *Chinese Journal of Electrical Engineering*, vol. 2, no. 1, pp. 62-76, June 2016, doi: 10.23919/CJEE.2016.7933116.

[24] P. Karlovsky, J. Lettl, "Induction motor drive direct torque control and predictive torque control comparison based on switching pattern analysis," *Energies*, vol. 11, no. 7, 2018, doi: 10.3390/en11071793.

[25] A. Ruderman, "About Voltage Total Harmonic Distortion for Single- and Three-Phase Multilevel Inverters," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 3, pp. 1548-1551, March 2015, doi: 10.1109/TIE.2014.2341557.

[26] H. Converters, "High-Power Semiconductor Devices 2.1," 2006.

[27] X. Fu, P. Dai, Q. Yuan, X. Wu, "Overview of low switching frequency control of high power three-level converters," *Electrical Power Systems and Computers*, vol. 99 LNEE, pp. 877-883, 2011, doi: 10.1007/978-3-642-21747-0_113.

BIOGRAPHIES OF AUTHORS

Nur Arifah Ramli was born in Rembau, Negeri Sembilan. She received the B.Eng (Hons) degree in electrical engineering from the University of Technical Malaysia Malacca. She is currently working toward the M.Sc degree with the Power Electronics, University of Technical Malaysia Malacca. Her research interests include the field in multilevel inverters and power electronics.

Auzani Jidin received B.Eng, M.Eng and PhD degrees in Electrical Engineering from University of Technology Malaysia, Johor. He is currently a senior lecturer at Faculty of Electrical Engineering, University of Technical Malaysia Malacca. His research interests include power electronics and drive, power quality and control systems.

Zulhani Rasin received B.Eng degree in Electrical Engineering at University of Electro-Communication, Tokyo. He then received M.Eng degree in Electrical (Electronics and Communications) at University of Technology Malaysia, Johor. Along with that, he received PhD degree in Electrical Engineering at University of New South Wales, Australia. He is currently a senior lecturer at University of Technical Malaysia Malacca that specialized in electronics, communication and wireless sensor network.

Tole Sutikno is a Lecturer in Electrical Engineering Department at the Ahmad Dahlan (UAD) University, Yogyakarta, Indonesia. He received his B.Eng., M.Eng. and Ph.D. degrees in Electrical Engineering from Diponegoro University, Universitas Gadjah Mada and Universiti Teknologi Malaysia, in 1999, 2004 and 2016, respectively. He has been an Associate Professor in UAD, Yogyakarta, Indonesia since 2008. He is currently an Editor-in-Chief of the TELKOMNIKA and the Head of the Embedded Systems and Power Electronics Research Group. His research interests include the field of digital design, industrial applications, industrial electronics, industrial informatics, power electronics, motor drives, renewable energy, FPGA applications, embedded system, artificial intelligence, intelligent control and digital library.