Comparative investigations on different types of inductors in single-phase inverter

M. Z. Aihsan¹², A. M. Yusof¹², Hasliza A Rahim³⁴, B. Ismail¹, W. A. Mustafa¹⁵, M. Saifizi¹, M. I. Fahmi¹²

¹ Faculty of Electrical Engineering Technology, University Malaysia Perlis (UniMAP), Malaysia.
² Electric Vehicle Energy Storage System (eVess) Research Group, Center of Excellence Renewable Energy (CERE), Universiti Malaysia Perlis, Kampus Tetap Pauh Putra, 02600 Arau, Perlis, Malaysia.
³ Faculty of Electronic Engineering Technology, University Malaysia Perlis (UniMAP), Malaysia.
⁴ Advanced Communication Engineering, Centre of Excellence (ACE), Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia.
⁵ Advanced Computing (AdvComp), Centre of Excellence (CoE), Universiti Malaysia Perlis (UniMAP), Campus Pauh Putra, 02600 Arau, Perlis, Malaysia.

zaid@unimap.edu.my

Abstract – This article organized in two sections where it compares the performance of single-phase inverters using various types of inductors with differences modulation technique of pulse width modulation (PWM). Not all inductors perform the same function, even the inductance value is the same. The study will investigate the capability of each inductor on its performance to convert the unfiltered AC voltage into filtered sinusoidal AC voltage. The drum core and toroidal core inductors were used in this investigation. For both inductors, the performance will be analyzed based on Bipolar and Unipolar switching schemes in a single unit H-bridge circuit. The validation of results are through experimental assessment only and it will be evaluating the shape of sinusoidal AC voltage and the content of total harmonics distortion in the AC voltage for both inductors.

1. Introduction

Nowadays, inverters with LC filters are used in a variety of applications, including electrical vehicle systems, stand-alone renewable energy applications, and uninterruptible power supplies (UPS) [1]-[2]. The LC filters are usually connected to the single H-bridge inverter and its primary function is to attenuate output voltage ripple and to limit the high-frequency ripple current generated by inverter switches [3]-[4]. The attenuation of the switching frequency voltage at the output node is proportional to the filter cut-off frequency. To design the LC filter, selecting the cut-off frequency of the filter and determining the L and C values is a critical part, as they affect the ripple current of the inverter switches, the output impedance of the inverter, its efficiency [5]-[7], transient response [8], and the inverter cost [9]. For the components of L and C, there are many models available in the market and not all models are suitable for low pass LC filter study. In this case, the selected type of inductor to be used in this investigation are the drum core and toroidal core type.
A drum core inductor consists of a core in the form of a bobble [10]. It has two flat discs at every end of the cylinder. The inductor is also known as the bobbin core inductor. The spindle is wounded by the coil. The bobbin core does not provide a closed magnetic path instead the flux goes through the disc into the air gap & then enters the core through the second disc at the other end [11]. It has a big air gap to store more energy in its magnetic field. As a result, the inductor saturation current increases. This means that the inductor can withstand high peak currents without saturation but at the cost of electromagnetic interference (EMI) radiation. This drum core is reported suitable for noise cancellation and filtering in many components datasheet from the well-known companies.

A toroidal core inductor has a circular ring core, as the name implies. The substance used to make the core is ferromagnetic [12]. The magnetic field is confined within the core, and there is very little magnetic flux leakage, which is an advantage of this circular core. The magnetic field in the core is higher due to less leakage flux. This raises the toroidal core inductor's inductance, which is higher than rod or bar-shaped core inductors of the same material. The other important aspect of the toroidal core is that it emits less electromagnetic interference (EMI) than other inductors [13]. As a result, they are preferable when constructing tiny devices with components that are close together. This kind of inductor is reported to be used in power supplies, control circuits, and communication. Only some of the manufacturers still using the toroidal core in inverter manufacturing. Proposed Inverter System

Based on the literature search, most of the researcher focusing on the improvement of switching scheme of the inverter either by using Bipolar or Unipolar Sinusoidal Pulse Width Modulation (SPWM), Selective Harmonic Elimination Pulse Width Modulation (SHEPWM), Phase Disposition PWM, and Space vector PWM especially for three-phase system [14]-[18]. Besides the improvement in the switching patterns, many research also works on LC Filter design for a good sinusoidal waveform [19]-[22]. However, there are least research reported on the types of inductors towards the performance of the inverter waveform shape and its quality. A good sinusoidal waveform will be noise and ripple free and very low in Total Harmonic Distortion (THD) reading [23]. This paper proposed a basic inverter configuration with modification at the inductor section as it will be more easier for the researcher to select the type of inductor as in Figure 1. A detail on LC filter design will not be discussed in this paper. The proposed configuration allows the inverter to operate multiple inductor condition by changing the connection using the wire probe. The system is built in a complete prototype as in Figure 2 and it has a selection button for selecting the Bipolar scheme or Unipolar scheme for easier monitoring process.

2. Circuit Description and Operation

The arrangement of capacitors in the parallel connection as shown in Figure 1 is to lower down the Equivalent Series Resistance (ESR) potential resulting the switching stress in the inverter will be reduced [24]-[25]. The open connection at the inductor section is connected to the red connector as depicted in Figure 2. From here, the types of inductors can be easily selected by controlling the wire connection from Ax to Bx1 or Bx2 before making the assessment. In this case, the drum core inductor will be connected to the Bx1 and the toroidal core inductor to Bx2. The Bipolar and Unipolar switching mentioned will drive the proposed circuit as in Figure 1.
3. Methodology

The parameter used in the study shown in Table 1. For both the Bipolar and Unipolar switching scheme, the inverter is operating at a 5kHz switching frequency speed. The digital oscilloscope of Tektronix TPS2014 is used to measure the output results and it has the capability to measure the total harmonic distortion in a FFT display mode which later will be presented in the results section.

![Figure 1. Proposed Inverter configuration](image)

**Figure 1.** Proposed Inverter configuration

**Figure 2.** Experimental assessment

The prototype is shown in Figure 2 using the basic microcontroller PIC16F877A controller to produce the SPWM pulses to be injected into the full-bridge inverter. The pulsation from the microcontroller has a peak of 5Vdc voltage and it needs to be converted into 15Vdc voltage by using the MOSFETs gate driver.

| Parameters          | Value        |
|---------------------|--------------|
| Fundamental         | 50 Hz        |
| Switching speed     | 5000 kHz     |
| Resistor            | 25 ohm       |
| Inductor 1 (Drum)   | 210 uH       |
| Inductor 2 (Toroid) | 210 uH       |
| Capacitor           | 1 uF (5 units)|
4. Results and Discussion

This section will be divided into two sections where the results will be demonstrated under two conditions between the Bipolar switching scheme and the Unipolar switching scheme and also the comparison between the two types of inductors.

4.1. Bipolar SPWM switching scheme

The Bipolar inverter switching scheme is generated from the intersection single unit of amplitude modulation sinusoidal reference with the triangular carrier wave. The pulsation will be converted into a digital timing sequence through a microcontroller algorithm and projected to the MOSFET 1 – MOSFET 4 as in Figure 3.

Figure 3. Bipolar SPWM switching pulses

Figure 4 shows the converted DC voltage from the battery into unfiltered AC voltage. The unfiltered waveform has to be monitored properly its rise and fall angles before injecting into the LC filter as it might face a leading or lagging effect if the fundamental concept is wrong. It can be seen clearly that the output voltage CH2 mimics the shape of the sinusoidal wave reference of the modulating signal.

In this section, the unfiltered voltage will be injected into the LC filter and for this case, drum core results of the Bipolar inverter shown in Figure 5 and the toroidal drum core as in Figure 6.
Based on the results shown above, the waveform of the drum core inductor in Figure 6 has a better wave in terms of sinusoidal wave shape even it has many noises compared to the toroidal core waveform results. The toroidal core inductor has almost zero noise, but the waveform is not in sinusoidal waveform and more likely trapezoidal waveform. These two behaviors will have different in THD reading as the nature of the waveform itself is far different from the original sine wave shape.

For the harmonic content in the waveform, Figure 7 and Figure 8 shows the results respectively for the drum core and toroidal core. The results of drum core inductors have a high value approximately of 13.25% harmonic compared to the toroidal core. It is due to harmonic is a measure or captured whenever the wave is in high oscillations condition just like in Figure 5. Even so, the voltage waveform of toroidal is not in the sinusoidal waveform, it is still quite low THD score around 8.35%.

4.2. Unipolar SPWM switching scheme

A different scheme for Unipolar inverter as the digital pulsation is generated from the intersection of two modulating sinusoidal waveforms with the triangular carrier waveform. The pulsation of Unipolar inverter slightly different with Bipolar inverter as in Figure 9 as it will result in the output voltage alternate in between positive and negative side as in Figure 10.
Figure 10 shows the unfiltered output voltage for the Unipolar inverter. The voltage has two-level and separate on the positive and negative sides. This condition is expected to facilitate the filtering process as the burden of filtering the high switching frequency like the bipolar inverter is excluded.

Figure 11 and Figure 12 show the filtered output voltage for the Unipolar inverter under drum core and toroidal core inductor in the LC filter. In Figure 11, the filtered output voltage is in good sinusoidal AC voltage and the shape is almost in zero noise condition. While for Figure 12, the filtered output voltage has a voltage spike at every switching sequence, and the natural shape of the waveform is like a square wave shape and not a sinusoidal waveform.
FFT display in Figure 13 and Figure 14 shows the THD performance of the Unipolar inverter under the drum core and toroidal core respectively. It shows the huge difference in harmonic value between the two inductors. The noise cancelation drum core inductor has proved its capability as in Figure 11. While for the toroidal core inductor, it seems like the waveform has a charging effect at every switching sequence. The value of THD in the drum core inductor has the least value among all SPWM schemes and types of the inductor.

5. Conclusion

Based on the results shown above for every case, it can be concluded that the most acceptable waveform for the inverter is the waveform that is filtered by the drum core inductor as for both Bipolar and Unipolar scheme, the waveform is in sinusoidal waveshape. It is just a matter of noise for the Bipolar scheme. While for toroidal core inductor, both Bipolar and Unipolar scheme does not filter well and the shape of the waveform is not in a sinusoidal waveform.

Acknowledgement

The authors would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2018/TK04/UNIMAP/03/7 from the Ministry of Education Malaysia.

References

[1] M. S. Kumar and S. T. Revankar, “Development scheme and key technology of an electric vehicle: An overview,” Renew. Sustain. Energy Rev., vol. 70, no. August 2015, pp. 1266–1285, 2017, doi: 10.1016/j.rser.2016.12.027.

[2] H. A. Rahim. et al. “Evaluation of a Broadband Textile Monopole Antenna Performance for Subject Specific On-body Applications,” Appl. Phys. A 123 1-6 (2017).

[3] F. H. Gandoman et al., “Status and future perspectives of reliability assessment for electric vehicles,” Reliab. Eng. Syst. Saf., vol. 183, no. November 2018, pp. 1–16, 2019, doi: 10.1016/j.ress.2018.11.013.

[4] L. Y. Seng, F. H. Wee, H. A. Rahim. et al. “EMI shielding based on MWCNTs/polyester composites,” Appl. Phys. A 124, 140 (2018). https://doi.org/10.1007/s00339-018-1564-y

[5] D. Atkar, P. S. Udakhe, S. Chiriki and V. B. Borghate, "Control of seven level cascaded H-Bridge inverter by hybrid SPWM technique," 2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), 2016, pp. 1-6, doi: 10.1109/PEDES.2016.7914435.
[6] K. K. Naik and N. Venugopal, "1kW Home Inverter Using Cascaded Current Fed Push Pull Converter and SPWM Inverter," 2018 9th International Conference on Computing, Communication and Networking Technologies (ICCCNT), 2018, pp. 1-5, doi: 10.1109/ICCCNT.2018.8494158.

[7] Z. Liu, G. Fei and Z. Chen, "Simulation Study of Double Closed-loop SPWM Inverter Based on Fuzzy Neural Network," 2018 IEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), 2018, pp. 241-245, doi: 10.1109/IAEAC.2018.8577665.

[8] I. López, E. Ibarra, A. Matallana, J. Andreu, and I. Kortabarria, “Next generation electric drives for HEV/EV propulsion systems: Technology, trends and challenges,” Renew. Sustain. Energy Rev., vol. 114, no. August, p. 109336, 2019, doi: 10.1016/j.rser.2019.109336.

[9] S. Hannan, S. Aslam and M. Ghayur, "Design and real-time implementation of SPWM based inverter," 2018 International Conference on Engineering and Emerging Technologies (ICEET), 2018, pp. 4-6, doi: 10.1109/ICEET1.2018.8338637.

[10] N. N. Daud, M. N. Osman, M.R. Kamarudin, A.R. Kram, M.M. Azizan, “A Compact Antenna Design for Fifth Generation Wireless Communication System,” MATEC Web Conf. 140 01009 (2017). DOI: 10.1051/matecconf/201714001009.

[11] M. Aktas, K. Awaili, M. Ehsani, and A. Arisoy, “Direct torque control versus indirect field-oriented control of induction motors for electric vehicle applications,” Eng. Sci. Technol. an Int. J., no. xxxx, 2020, doi: 10.1016/j.jestch.2020.04.002.

[12] Muhammad Hafiz Ab Aziz, Muhammad Mokhzaini Azizan, Zaliman Sauli, and Mohd Wafiuddin Yahya, "A review on harmonic mitigation method for non-linear load in electrical power system", AIP Conference Proceedings 2339, 020022 (2021) https://doi.org/10.1063/5.0044251

[13] N. S. Azizan, M. M. Azizan, M. I. Fahmi, M. Z. Ahsan, M. Jusoh, N. F. M. Nasir, and M. Z. Zakaria, "Medium sized industrial motor solutions to mitigate the issue of high inrush starting current", AIP Conference Proceedings 2339, 020014 (2021) https://doi.org/10.1063/5.0044280

[14] Y. Xia, J. Roy and R. Ayyanar, "Optimal Variable Switching Frequency Scheme to Reduce Loss of Single-Phase Grid-Connected Inverter With Unipolar and Bipolar PWM," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 1, pp. 1013-1026, Feb. 2021, doi: 10.1109/JESTPE.2019.2956034.

[15] M. Z. Mohd Radzi, M. M. Azizan, and B. Ismail, “Observatory case study on total harmonic distortion in current at laboratory and office building,” J. Phys. Conf. Ser., vol. 1432, no. 1, 2020, doi: 10.1088/1742-6596/1432/1/012008.

[16] M.A. Memon, S. Mekhlief, M. Mubin, M. D. Siddique and M. Dardeer, "Comparative Analysis of Optimal and Fixed Input DC Sources with Selective Harmonic Elimination Pulse Width Modulation," 2019 IEEE Conference on Power Electronics and Renewable Energy (CPERE), 2019, pp. 94-98, doi: 10.1109/CPERE45374.2019.8980153.

[17] R. Sakr, "Phase Disposition PWM (PD-PWM) Technique to Minimize WTHD from a Three-Phase NPC Multilevel Voltage Source Inverter," 2020 IEEE 1st International Conference for Convergence in Engineering (ICCE), 2020, pp. 220-224, doi: 10.1109/ICCE50343.2020.9290697.

[18] J. Jacob et al., "Space vector pulse width modulation for a seven level inverter applied to an induction motor drive," 2017 International Conference on Innovations in Electrical, Electronics, Instrumentation and Media Technology (ICIEIMT), 2017, pp. 117-122, doi: 10.1109/ICIEEMT.2017.8116818.

[19] A. B. Afarulrazi, M. Zarafi, W. M. Utomo and A. Zar, "FPGA implementation of Unipolar SPWM for single phase inverter," 2010 International Conference on Computer Applications and Industrial Electronics, 2010, pp. 671-676, doi: 10.1109/ICCAIE.2010.5735019.

[20] M. Jiang, W. Wang, H. Fu and K. Wu-Chang, "A novel single-phase soft-switching unipolar PWM inverter," 8th International Conference on Power Electronics - ECCE Asia, 2011, pp. 2874-2879, doi: 10.1109/ICPE.2011.5944785.
[21] F. Wu, X. Li and J. Duan, "Improved Elimination Scheme of Current Zero-Crossing Distortion in Unipolar Hysteresis Current Controlled Grid-Connected Inverter," in IEEE Transactions on Industrial Informatics, vol. 11, no. 5, pp. 1111-1118, Oct. 2015, doi: 10.1109/TII.2015.2470540.

[22] K. Sabi and D. Costinett, "Design and Implementation of a Bipolar-Unipolar Switched Boundary Current Mode (BCM) Control GaN-Based Single-Phase Inverter," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), 2019, pp. 6473-6480, doi: 10.1109/ECCE.2019.8913020.

[23] J. M. Miller, C. W. Ayers, L. E. Seiber and D. B. Smith, "Calorimeter evaluation of inverter grade metalized film capacitor ESR," 2012 IEEE Energy Conversion Congress and Exposition (ECCE), 2012, pp. 2157-2163, doi: 10.1109/ECCE.2012.6342448.

[24] S. Prabhakar, N. Deshmukh and S. Anand, "Stability Improvement of Series Stacked Buffer Circuit in Single Phase Solar Inverter," 2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), 2020, pp. 1-6, doi: 10.1109/PEDES49360.2020.9379650.

[25] N. Agarwal, M. W. Ahmad and S. Anand, "Quasi-Online Technique for Health Monitoring of Capacitor in Single-Phase Solar Inverter," in IEEE Transactions on Power Electronics, vol. 33, no. 6, pp. 5283-5291, June 2018, doi: 10.1109/TPEL.2017.2736162.