Journal of Electrical Technology UMY (JET-UMY), Vol. 7, No. 1, June 2023
ISSN 2550-1186 e-ISSN 2580-6823

Electrical Design of a Portable Pure Sine Wave Inverter Using Ferrite Core Transformer and Double Stage Technique

Kunnu Purwanto*, Aditya Agus Wijayanto, Yudhi Ardiyanto, Karisma Trinanda Putra

Department of Electrical Engineering, Faculty of Engineering, Universitas Muhammadiyah Yogyakarta, Bantul 55183, Indonesia

*Corresponding Author email: kunnu_p@umy.ac.id

Abstract – *The size of the iron core transformer in an inverter is large and heavy because it has more conductor turns and works at low frequencies. In contrast, ferrite core transformers are designed to work at high frequencies, so the number of turns of the conductor is less, and the transformer size is relatively small and light. Device portability is a significant challenge in designing high-power inverters. This research uses a ferrite core transformer to design a portable pure sine wave inverter. A two-stage technique is proposed in designing the inverter so that the dc-link voltage and capacitor size can be flexibly selected, and the device size can be compacted. The design consists of two stages. First, a circuit to generate a 400-Volt DC voltage is designed using IC SG3525, a MOSFET power amplifier, and a ferrite core step-up transformer. Second, a pure sine wave generator circuit is constructed using an EGS002 module, MOSFETs, and a filter circuit. Experiments are performed by measuring the output voltage, monitoring power and frequency, and observing the waveform with an oscilloscope. The results reveal that the designed inverter can generate a 220-volt pure sine wave output, a maximum power of 500 Watts, a frequency of 50 Hz, and an efficiency between 91.4% to 98.1%.*

Keywords*: ferrite core transformers; device portability; pure sine wave inverter; two-stage technique.*

I. Introduction

Currently, the use of electrical energy from renewable energy sources such as fuel cells, solar cells, piezoelectric, and other renewable energy sources has begun to be developed in Indonesia. However, the energy produced from these renewable energy sources is still mostly in the form of direct current (DC). Another type such as wind power is more efficient and less capital intensive if it is implemented in DC voltage distribution [1 – 3]. However, the electrical load that must be supplied is mostly in the form of alternating current (AC) voltage. The need for electronic conversion tools that can convert DC energy into AC energy [4, 5] is rapidly increasing.

An inverter is an electronic conversion tool that converts DC voltage source into an AC voltage source with the desired magnitude and frequency. This tool is needed to support the generation of electrical energy, especially in areas that are not covered by electricity, such as in the territory of Indonesian archipelago. In these remote areas, the need for compact supporting tools such as inverters is a must [6, 7]. A cheap and compact inverter can be used in areas that have limited AC power supply. With the availability of this inverter, people can use batteries or solar cells to supply ordinary household appliances e.g., TVs, electric fans, computers, refrigerators, and washing machines. Portable inverters are also useful for the development of light electric vehicles e.g., electric bicycles, segways, or electric scooters.

An inverter can generate special types of voltage waveforms including a square wave [8], a modified sine wave [9], and a pure sine wave inverter [10 – 11]. For specific purposes, a pure sine wave inverter is used to drive AC motor systems [11]. Other types of inverters are not optimal in handling AC motor loads [12 – 13]. A pure sine wave inverter is also needed to connect a private power generation system

Manuscript received February 2023, revised April 2023

to an ordinary power grid [14 – 16]. The inverter generally consists of several parts, namely an oscillator circuit, a switching circuit, and a transformer as shown in Figure 1. The battery power source in the form of DC voltage is connected to the transformer's secondary center tap. Then, the two ends of the other pins are connected through the switching circuit to the ground. The alternation of the "on" and "off" conditions on the switching circuit changes from DC voltage to AC voltage [17]. The switching circuit is controlled by an oscillator circuit that has a function as a frequency generator that is determined as needed, e.g., 50 Hz. To increase the voltage to reach the typical power grid voltage, a step-up transformer and MOSFET drivers are used, converting 12 V_{AC} to 220 V_{AC}. MOSFET-based driver circuit also functions as a power amplifier to drive high power component e.g., electric motor or heater element using low voltage signal such as pulse width modulation (PWM) from microcontroller. This circuit will determine the final specification of the maximum power of the prototype to be designed.

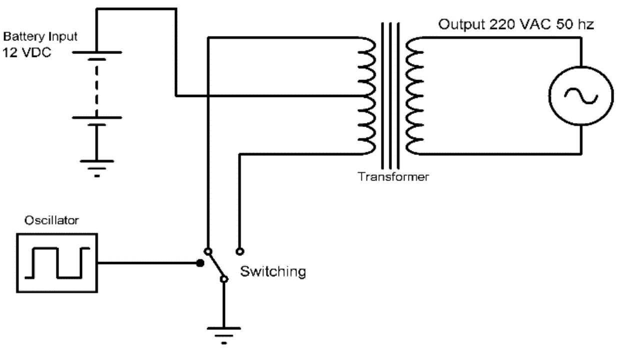


Fig. 1. The fundamental concept of DC to AC power conversion.

In general, the inverters use iron core step-up transformers. One of the disadvantages of iron core transformers is that they are large and heavy [18, 19]. They work at a low frequency and take quite a lot of wire turns to develop induction force [20]. In terms of portability, iron core transformers are less efficient [21]. This is different from the ferrite core transformer, where this transformer is designed to work at high frequencies [22, 23]. The number of turns of wire required is less so that the size of the transformer is relatively small, lightweight, and more efficient in terms of circuit design. Device portability is a major challenge in designing high-power inverters even though the ferrite core transformer is used in the design [24 – 25]. A portable inverter extends its functionality due to its smaller and lighter weight than traditional inverters but with similar efficiency.

In this research, a double-stage pure sine wave inverter was designed using a ferrite core transformer. The design consists of two stages, namely a circuit to generate a voltage of 500 Volts DC and a pure sine wave generator circuit. The circuit for increasing the voltage to 500 Volts DC is designed using IC SG3525, MOSFETs, and a step-up ferrite core transformer. A sine pulse width modulation (SPWM) technique is used to develop an adjustable sine wave generator circuit. The pure sine wave generator circuit is designed using the EGS002 module, MOSFETs, and filter circuit.

The rest of this paper is outlined as follows. The basic design of a pure sine wave inverter is described in Section II. Section III provides an electrical design of a portable pure sine wave inverter. Section IV reveals experimental results. Section V concludes this study.

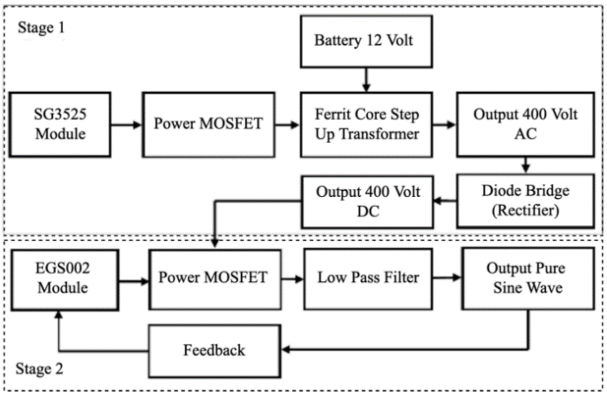


Fig. 2. The proposed block diagram of portable pure sine wave inverter using ferrite core transformer and double stage technique. The diagram consists of two stages, stage 1 uses SG3525 module and stage 2 uses EGS002 module.

II. Design of Pure Sine Wave Inverter

Pulse Width Modulation (PWM) is a technique used in generating constant amplitude pulses by modulating the width of the signal which is represented by a duty cycle within a certain period. The duty cycle value is a parameter that represents the average output voltage. The PWM technique is used in applications related to analog-digital control. The duty cycle of the waveform can be adjusted to obtain a varying output voltage, which is the average value of the waveform [26]. PWM signals generally have a fixed amplitude and base frequency, however, their pulse width can vary from 0% to 100%.

PWM inverters used in single-phase power supplies can be implemented with bipolar switching and unipolar switching [27 – 29]. Bipolar switching is a switching state that produces a positive and negative voltage pulse state. On the other hand, in unipolar switching, it is the switching state that produces a positive, negative, and zero voltage.

II.1. IC SG3525

IC SG3525 is used to generate a PWM signal, adjust the frequency, and set the duty cycle. The value of the oscillation frequency on the SG35 IC control circuit is regulated by two pins, namely pins 5 and 6 as shown in Figure 2. Equation (1) is used to find the working frequency according to the IC SG3525 datasheet [30]. The output of the IC SG3525 is square waves that are opposite to each other between the two output legs. These waves can be used as inverter triggers. The inverter to be designed is capable of operating in the frequency range of 20 kHz – 60 kHz.

$$f_{osc} = \frac{1}{CT(0.7RT+3RD)} \quad (1)$$

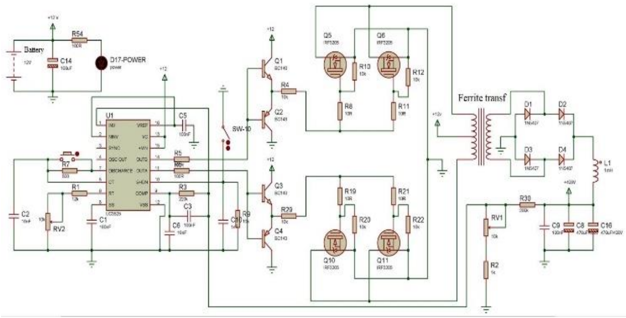
where, f_{osc} is frequency (in Hertz), CT = timing capacitor at pin 5 (in Farads), RT is timing resistor at pin 6 (in Ohms), and RD is deadtime resistor connected between pin 5 and pin 7 (in Ohms).

II.2. EGS002 Module

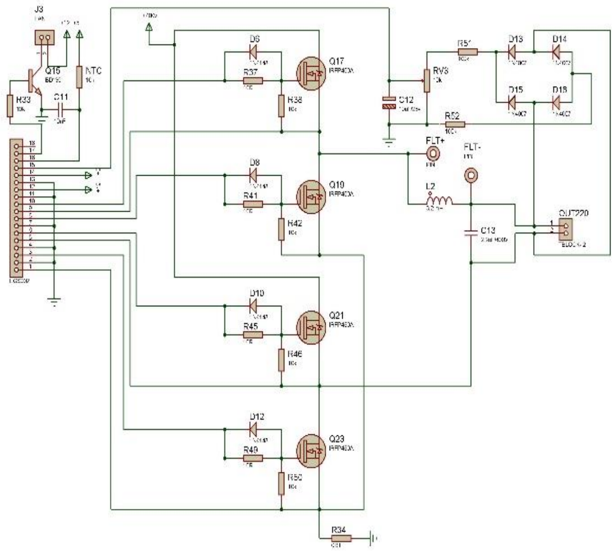
The EGS002 module as shown in Figure 2 is an electronic component in the form of a PCB board that is integrated with a set of chips and other supporting components such as resistors and capacitors so that it becomes a single unit that works with a specific purpose. The EGS002 board module functions as a controller on a stage 2 inverter circuit. Basically, this module has two ICs, namely IC 2110S as a control chip and IC EG8010 as a pure sine wave generator [31]. This module has features to detect and secure the voltage value, current value, and temperature value when working. In addition, this module can also be connected to an LCD to display values such as voltage, current, temperature, frequency, and other peripherals.

II.3. MOSFET

Metal oxide semiconductor field effect transistor (MOSFET) is a type of transistor with a controlled voltage that functions to control the flow of current. One type of this transistor is the power MOSFET which is specifically used to handle high power circuits. This device has advantages such as high switching speed and good efficiency at low voltage levels [32].



(a)



(b)

Fig. 3. Electrical design of a portable pure sine wave inverter using ferrite core transformer and double stage technique. (a) Schematic of the inverter stage1. (b) Schematic of the inverter stage 2.

In choosing MOSFETs, there are several parameters that become a major concern [33, 34], namely: (1) $R_{DS(on)}$ is the resistance between drain and source when the MOSFET is in the ON position. (2) $V_{GS(on)}$ is the reference voltage used by the MOSFET to trigger the Gate which makes the MOSFET channel carry the maximum current. (3) $I_{D(max)}$ is the maximum current that can pass through the drain to the source. (4) Power dissipation (PD) is the maximum power that can be dissipated by the MOSFET. In the inverter circuit, MOSFETs are used as the on-off driver of the oscillator to convert the DC input voltage into AC voltage according to the desired frequency and amplify the output power.

III. Electrical Design of the Proposed Portable Pure Sine Wave Inverter

The proposed inverter circuit consists of two circuit blocks, namely the stage 1 circuit and the stage 2 circuit as shown in Figure 3. The stage 1 circuit block consists of a 12 Volt battery, EGS002 module, MOSFET, ferrite core step-up transformer and rectifier diode. Meanwhile, stage 2 consists of the EGS002 module, MOSFET, low pass filter and feedback.

The SG3525 module functions as a square wave frequency generator. The MOSFET power amplifier functions as an inverter power amplifier. The ferrite transformer functions as a voltage booster from 12 Volts to 400 Volts. The bridge rectifier diode functions to rectify the 400 V_{AC} voltage to 400 Volt DC. The EGS002 functions as a control chip to generate a pure sine PWM signal. The pure sine voltage generated from the 400 V_{DC} voltage as the output of the stage 1 circuit, is passed through the stage 2 MOSFET circuit with the EGS002 controller. The final output of the circuit is passed through a low-pass filter circuit so as to produce a pure sine voltage. Feedback is used to control the inverter output voltage stable at 220 V_{AC}.

III.1 The First Stage of Inverter Circuit

The stage 1 circuit as shown in Figure 3 (a) is a circuit that functions to produce a high voltage inverter, converting from DC 12V to DC 400V. The 400 V_{DC} voltage is used as the input voltage for the stage 2 circuit which is then processed into a pure sine wave voltage.

III.2 The Second Stage of Inverter Circuit

The stage 2 circuit in Figure 3 (b) functions as a PWM signal generator which generates a pure sine wave. This circuit consists of three four blocks, namely the EGS002 module as a PWM generator, a high voltage MOSFET as a power amplifier, a filter, and a feedback circuit. The EGS002 module as a PWM signal generator module produces 4 outputs 1H1, 1LO, 2HO, 2LO. These output pins are connected to the IRFP460 high-voltage MOSFET circuit. Furthermore, the output voltage of the MOSFET, which is arranged in a full bridge configuration, is still in the form of a square wave PWM. Finally, this signal is filtered by a 3.3 *u*H inductor and a 2.2*u*F/400-volt capacitor to produce a pure sine wave. The feedback circuit which is arranged using a rectifier diode and a capacitor is used as a controller so that the output voltage remains stable at a voltage of 220 V_{AC}.

IV. Experimental Results and Discussion

Tests are carried out to determine the performance of the system that has been designed. The tests are performed for each stage. At the end, the efficiency of the conversion power from the output to the input will be revealed.

IV.1. Stage 1: Testing of Matching Transformer

In Figure 4, impedance-matching transformer is tested. ferrite transformer is tested by connecting a 12-volt input, SG3525 circuit, and the output is a 10 Watt LED lamp. The test is carried out by adjusting the frequency value generated by IC SG3525 gradually by changing the RD value as written in Equation (1), until the lights are dimmed or extinguished. A dim or extinguished light indicates that the transformer is matched because the current from the primary winding is maximally transferred to the secondary winding [35, 36]. From the test results, it can be revealed that the EE42 transformer is matched at a frequency of 50-60 kHz. This shows that at this frequency, maximum energy is channeled to the secondary side of the transformer and the power losses are very minimal. The test results in Figure 4 (a) show that the output voltage of the stage 1 circuit i.e., passing through a ferrite transformer, produces an output voltage of 406 volts. This test shows that the output of the transformer is in accordance with what is desired, namely 400 Volts with an error value of 1.5%.

IV.2. Stage 1: Testing of the Output of EGS002 Module

The stage 2 output voltage is measured to evaluate the performance of the proposed inverter design. Before the EGS002 module is used in the inverter circuit, it is necessary to test the function of each output pin of the EGS002 module used. Testing the EGS002 module requires a supply voltage of 12V and 5V for this module to work normally. The input circuit according to the initial design is ±400 Volts. Furthermore, this voltage is controlled by the SPWM technique by the EGS002 module so as to generate a pure sine signal at the output pin.

To find out that the EGS002 module can work normally, it can be seen from the output waveform on the EGS002 output pin with an oscilloscope. The module output voltage test uses a test scheme according to the dataset [31]. The test uses 2 channel oscilloscopes connected to the IFB, VS1, VS2, VFB, and TFB pins to ground. Testing the output waveform with an oscilloscope on channel 1 of pins 1LO (Test 1) and 1HO (Test 2) produces a square wave output waveform as shown in Figure 4 (b). Then, testing the output waveform with an oscilloscope on channel 2 from pins 2LO (Test 3) and 2HO (test 4) produces a unipolar modulation waveform. Testing the output on pins 2LO and 2HO, an RC filter is added so that the output voltage is a filtered voltage as shown in Figure 4 (c). The test results show the same results as those shown in the EGS002 module datasheet so it can be concluded that the module can work normally.

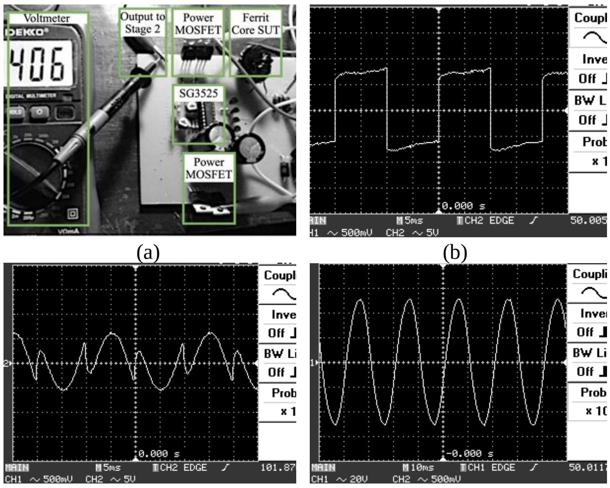


Fig. 4. (a) Experiment on the output of stage 1 circuit. (b) Experiment on 1LO pin dan 1HO pin on stage 2 circuit. (c) Experiment on 2LO pin dan 2HO pin on stage 2 circuit. (d) Output voltage without load attached to the inverter.

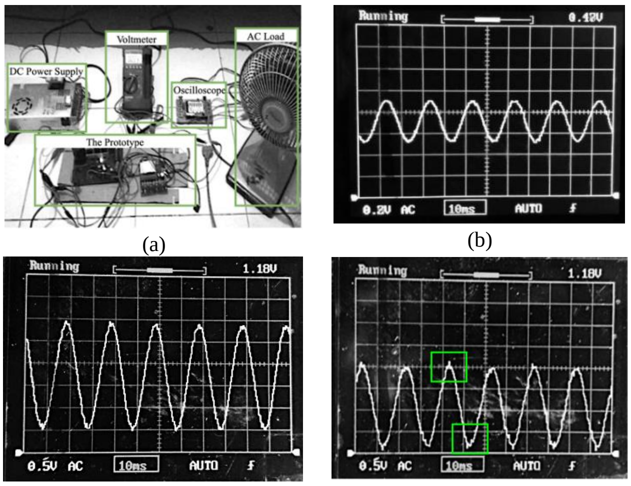


Fig. 5. (a) Experiment of the final prototype. (b) Output voltage without load attached to the inverter. (c) Output voltage with a 27-watt electric fan load. (d) Output voltage with a 100-watt electric drill load. Small ripples appear on the green box due to harmonic frequency of inductive loads.

IV.3 Stage 2: Testing of Filter Circuit

One very important part of a pure sine inverter is the filter. The filter used is a low pass type consisting of an inductor and a capacitor. The filter is installed at the output of the inverter. As an output filter, this inverter uses a 2.2 *u*F 450V ceramic capacitor and a 3.3 mH inductor according to the EGS002 datasheet which is connected in parallel with the output. The designed filter produces a cutoff frequency of 50 Hz. The test results show that the filter output is a pure sine voltage with a frequency of 50 Hz as shown in Figure 4 (d).

IV.4 Testing of the Inverter without Load

The test aims to determine the magnitude of the output voltage and the waveform of the inverter. Tests were carried out on step 1 and step 2 outputs using a multimeter and an oscilloscope. The test without load connected to the inverter can be seen in Figure 5 (a). As the input power supply, a 12-volt 7 AH battery is used. It can be seen that the DC source voltage from the battery of 12.56 V_{DC} is increased to 362 volts by the stage 1 circuit. Then, this voltage is used as input to the stage 2 circuit. After passing through the filter circuit, an output voltage of 222 V_{AC} is produced. The output waveform of the inverter circuit has been in the form of a pure sine wave as shown in Figure 5 (b). From the results of testing the output voltage and waveform of the no-load inverter, it can be concluded that the inverter is working as planned.

IV.5 Testing with Resistive and Inductive Loads

After testing the functionality of the inverter without a load attached, then the next experiment is performed by connecting the prototype with the load. The test was carried out using 4 different types of loads: a 10-watt incandescent lamp, a 25-watt fluorescent lamp as resistive loads, a 27-watt electric fan, a 100-watt electric drill and a 500-watt soldering tool as inductive loads. The loading test is simulated using the input voltage from a 12 Volts adapter, with measurement devices i.e., a multimeter, an ammeter, and an oscilloscope. The results of the testing can be seen in Table 1. From the results, it can be revealed that the inverter has a good control and system performance according to the designed specification.

The shape of output waveform can be visualized in Figures 5 (c) and 5 (d). Figure 5 (c) shows that the output waveform for a load of 10 watts to 25 watts as a resistive load of inverter wave quality is still good, while in Figure 5 (d) the load in the form of an electric drill of 100 watts inverter wave quality is still in the form of sine wave but with small ripples appear and the voltage drop. Changes in waveform and voltage drop can be caused because the drill is an inductive load that has a large harmonic value so that it can distort the sine output wave [37 – 40].

TABLE I
ELECTRICAL CHARACTERISTICS OF THE PROPOSED PURE SINE WAVE INVERTER

No.	Load	Battery Voltage (V_{DC})	Input Current (Ampere)	Input Power (Watt)	Output Voltage (V_{AC})	Efficiency (%)
1	LED lamp (10 Watt)	12.56	0.86	10.8	221	92.6
2	Fluorescent lamp (25 Watt)	12.56	2.03	25.49	219	98.1
3	Electric fan (27 Watt)	12.56	1.97	24,74	221	97.8
4	Electric drill (100 Watt)	12.04	9.07	109.2	209	92.4
5	Soldering (500 Watt)	12.02	45.5	546.91	212	91.4

V. Conclusion

A power inverter suitable for constant frequency applications with high portability is designed in this article. The inverter is designed in a two-phase circuit. The three main advantages of the proposed inverter are (1) reduced number of components, (2) single DC source, and (3) small size transformer. In accordance with the proposed double stage inverter, SPWM methods are presented, and a 500-watt laboratory prototype has been developed. The experimental results show that a pure sine inverter single phase with 2 stages using a ferrite core transformer with the SPWM method works optimally at an input voltage between 12 V_{DC} – 15 V_{DC}. The inverter works optimally if the output voltage of the stage 1 circuit produces an output of 360 – 400 V_{DC}. The EE42 ferrite transformer works well in the 50 kHz – 60 kHz frequency. The inverter is capable of producing an output of 209 – 222 V_{AC} with a pure sine voltage and works optimally at inductive loads up to 500 Watts at a frequency of 50 Hz. The experimental results validate the system's performance by prioritizing device portability with efficiency in the range of 91.4% to 98.1%.

Acknowledgment

This work was supported by Universitas Muhammadiyah Yogyakarta, Research and Innovation Institute of UMY under the grant numbers 01/RIS-LRI/I/2021 and 01/RIS-LRI/I/2022.

References

[1] P. Hu, R. Yin, B. Wei, Y. Luo and F. Blaabjerg, "Modular Isolated LLC DC/DC Conversion System for Offshore Wind Farm Collection and Integration," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 6, pp. 6713-6725, Dec. 2021.

[2] A. A. Aboushady, K. H. Ahmed and B. W. Williams, "Compact multi-modular design of high-power DC/DC resonant converters for offshore wind energy HVDC transmission," IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, 2013, pp. 5236-5241.

[3] M. Pape and M. Kazerani, "A Generic Power Converter Sizing Framework for Series-Connected DC Offshore Wind Farms," in IEEE Transactions on Power Electronics, vol. 37, no. 2, pp. 2307-2320, Feb. 2022.

[4] Precedence Research, "Solar Inverter Market Size to Worth Around US$ 16.88 Bn by 2030," Available online: https://www.globenewswire.com/en/news-release/2022/04/25/2428595/0/en/Solar-Inverter-Market-Size-to-Worth-Around-US-16-88-Bn-by-2030.html (accessed on 15 August 2022).

[5] Market Analysis Report, "PV Inverter Market Size, Share & Trends Analysis Report by Product (Central, String, Micro), By End-use (Residential, Commercial & Industrial, Utilities), Report ID: GVR-3-68038-022-4, Grand View Research, 2021.

[6] A. Adiyabat and K. Kurokawa, "Performance analysis of portable photovoltaic power generation systems based on measured data in Mongolia," Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, 2002., 2002, pp. 1664-1667.

[7] S. Liyanage, Y. Wang, Y. Dong and B. Ren, "A Sustainable, Portable, and Efficient Electricity Delivery (SPEED) System," 2019 IEEE Green Technologies Conference (GreenTech), 2019, pp. 1-4.

[8] P. Wang, J. Li, J. Wang, A. Cavallini and J. Zhang, "A high voltage repetitive square wave voltage generator used for endurance evaluation of inverter-fed motors," 2017

International Symposium on Electrical Insulating Materials (ISEIM), 2017, pp. 411-414.

[9] S. Sheng, P. Li and B. Lehman, "Parallel operation of digital controlled modified sine wave inverters," 2013 IEEE Energy Conversion Congress and Exposition, 2013, pp. 3440-3447.

[10] P. Wang, J. Wang, H. Xu, K. Zhou, Y. Lei and Q. Zhou, "Comparative study of PD characteristics for inverter-fed motor insulation under sinusoidal and repetitive square wave voltage conditions," 2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE), 2016, pp. 1-4.

[11] A. Jamal, A. N. N. Chamim, K. T. Putra, N. N. Masfiyah, Y. Jusman, " Analysis of Losses of propulsion systems on Electric Diesel Rail Trains," Journal of Electrical Technology UMY, vol. 2, no. 3, pp. 89-101, 2018.

[12] P. Wang, N. Yang, C. Zheng and Y. Li, "Effect of repetitive impulsive and square wave voltage frequency on partial discharge features," 2018 12th International Conference on the Properties and Applications of Dielectric Materials (ICPADM), 2018, pp. 152-155.

[13] P. Wang, H. Xu, J. Wang, A. Cavallini and G. C. Montanari, "Temperature effects on PD statistics and endurance of inverter-fed motor insulation under repetitive square wave voltages," 2016 IEEE Electrical Insulation Conference (EIC), 2016, pp. 202-205.

[14] J. Lin et al., "Frequency Coupling Suppression Control Strategy for Single-Phase Grid-Tied Inverters in Weak Grid," in IEEE Transactions on Industrial Electronics, vol. 69, no. 9, pp. 8926-8938, Sept. 2022.

[15] J. Ji, W. Wu, Y. He, Z. Lin, F. Blaabjerg and H. S. -H. Chung, "A Simple Differential Mode EMI Suppressor for the $LLCL$-Filter-Based Single-Phase Grid-Tied Transformerless Inverter," in IEEE Transactions on Industrial Electronics, vol. 62, no. 7, pp. 4141-4147, July 2015.

[16] Y. Xiong and Y. Ye, "Physical Interpretations of Grid Voltage Full Feedforward for Grid-Tied Inverter," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 66, no. 2, pp. 267-271, Feb. 2019.

[17] Fiji Electric Global, "How does an inverter work?" Available online: www.fujielectric.com/products/column/inverter/inverter_02.html (accessed on 15 August 2022).

[18] P. Rasilo, A. Salem, A. Abdallh, F. De Belie, L. Dupré and J. A. Melkebeek, "Effect of Multilevel Inverter Supply on Core Losses in Magnetic Materials and Electrical Machines," in IEEE Transactions on Energy Conversion, vol. 30, no. 2, pp. 736-744, June 2015.

[19] A. Krings, J. Soulard and O. Wallmark, "PWM Influence on the Iron Losses and Characteristics of a Slotless Permanent-Magnet Motor with SiFe and NiFe Stator Cores," in IEEE Transactions on Industry Applications, vol. 51, no. 2, pp. 1475-1484, March-April 2015.

[20] S. Xue et al., "Iron Loss Model for Electrical Machine Fed by Low Switching Frequency Inverter," in IEEE Transactions on Magnetics, vol. 53, no. 11, pp. 1-4, Nov. 2017, Art no. 2801004.

[21] M. A. Taha, M. H. Bechir, O. N. Adam, A. O. Bechir, B. M. Issa, Y. D. Dari, D. Pietroy, and J. J. Rousseau, "Integrated Transformer with Buried Windings in Ferrite Core," Journal of Electrical and Electronic Engineering, vol. 10, no. 1. Science Publishing Group, p. 10, 2022.

[22] P. Dworakowski, A. Wilk, M. Michna, B. Lefebvre, F. Sixdenier, and M. Mermet-Guyennet, "Effective Permeability of Multi Air Gap Ferrite Core 3-Phase Medium Frequency Transformer in Isolated DC-DC Converters," Energies, vol. 13, no. 6. MDPI AG, p. 1352, 14-Mar-2020.

[23] S. Somkun, T. Sato, V. Chunkag, A. Pannawan, P. Nunocha, and T. Suriwong, "Performance Comparison of Ferrite and Nanocrystalline Cores for Medium-Frequency Transformer of Dual Active Bridge DC-DC Converter," Energies, vol. 14, no. 9. MDPI AG, p. 2407, 23-Apr-2021.

[24] M. Trabelsi, H. Vahedi and H. Abu-Rub, "Review on Single-DC-Source Multilevel Inverters: Topologies, Challenges, Industrial Applications, and Recommendations," in IEEE Open Journal of the Industrial Electronics Society, vol. 2, pp. 112-127, 2021.

[25] A. Poorfakhraei, M. Narimani and A. Emadi, "A Review of Multilevel Inverter Topologies in Electric Vehicles: Current Status and Future Trends," in IEEE Open Journal of Power Electronics, vol. 2, pp. 155-170, 2021.

[26] Y. Zhang, W. Xie, Z. Li and Y. Zhang, "Model Predictive Direct Power Control of a PWM Rectifier with Duty Cycle Optimization," in IEEE Transactions on Power Electronics, vol. 28, no. 11, pp. 5343-5351, Nov. 2013.

[27] 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.

[28] L. Sun, F. Zhuo, F. Wang and T. Zhu, "A Nonisolated Bidirectional Soft-Switching Power-Unit-Based DC–DC Converter with Unipolar and Bipolar Structure for DC Networks Interconnection," in IEEE Transactions on Industry Applications, vol. 54, no. 3, pp. 2677-2689, May-June 2018.

[29] Y. Mi, H. Wan, C. Bian, W. Peng and L. Gui, "An MMC-based modular unipolar/bipolar high-voltage nanosecond pulse generator with adjustable rise/fall time," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 26, no. 2, pp. 515-522, April 2019.

[30] SG3525A Datasheet, "Pulse Width Modulator Control Circuit," ON Semiconductor, Available online: https://www.onsemi.com/pdf/datasheet/sg3525a-d.pdf (accessed on 17 August 2022).

[31] EGS002 Datasheet, "EGS002 Sinusoid Inverter Driver Board User Manual," EG Micro Corp., Available online: http://www.mkpochtoi.ru/EGS002_manual_en.pdf (accessed on 17 August 2022).

[32] A. Kar et al., "Simulation-Based Power-Loss Optimization of General-Purpose High-Voltage SiC MOSFET Circuit Under High-Frequency Operation," in IEEE Access, vol. 9, pp. 23786-23794, 2021.

[33] H. Tsukamoto, M. Shintani and T. Sato, "Statistical Extraction of Normally and Lognormally Distributed Model Parameters for Power MOSFETs," in IEEE Transactions on Semiconductor Manufacturing, vol. 33, no. 2, pp. 150-158, May 2020.

[34] Jin He, Xing Zhang, Yangyuan Wang and Ru Huang, "New method for extraction of MOSFET parameters," in IEEE Electron Device Letters, vol. 22, no. 12, pp. 597-599, Dec. 2001.

[35] S. -M. Song, I. -D. Kim, B. -H. Lee and J. -M. Lee, "Design of Transformer with Impedance Matching Circuit for High

Power Transmitter of Active Sonar," 2019 10th International Conference on Power Electronics and ECCE Asia (ICPE 2019 - ECCE Asia), 2019, pp. 2126-2131.

[36] K. Orikawa, S. Ogasawara, M. Takemoto and J. -I. Itoh, "A Frequency Multiplying Circuit Containing a High-frequency Output Inverter and an Impedance Matching Transformer," IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, 2019, pp. 6603-6608.

[37] K. D. Hoang, Z. Q. Zhu and M. P. Foster, "Influence and Compensation of Inverter Voltage Drop in Direct Torque-Controlled Four-Switch Three-Phase PM Brushless AC Drives," in IEEE Transactions on Power Electronics, vol. 26, no. 8, pp. 2343-2357, Aug. 2011.

[38] B. Diong, H. Sepahvand and K. A. Corzine, "Harmonic Distortion Optimization of Cascaded H-Bridge Inverters Considering Device Voltage Drops and Noninteger DC Voltage Ratios," in IEEE Transactions on Industrial Electronics, vol. 60, no. 8, pp. 3106-3114, Aug. 2013.

[39] H. Zhang, J. Yao, B. Kou and J. Wei, "High-Precision Control for ZVS Inverter to Reduce Nonlinear Distortion of Semiconductor Voltage Drop," in IEEE Transactions on Power Electronics, vol. 35, no. 4, pp. 3337-3342, April 2020.

[40] W. Wu, J. Ji and F. Blaabjerg, "Aalborg Inverter - A New Type of "Buck in Buck, Boost in Boost" Grid-Tied Inverter," in IEEE Transactions on Power Electronics, vol. 30, no. 9, pp. 4784-4793, Sept. 2015.

Authors' information

Kunnu Purwanto obtained his B.Eng. in Electrical Engineering from the Universitas Muhamadiyah Yogyakarta, Indonesia. His Master study was done at the Electrical Engineering, Gadjah Mada University,Indonesia. He currently is a lecture in Department of Electrical Engineering, Universitas Muhammadiyah Yogyakarta, Indonesia.

Aditya Agus Wijayanto was active in student organizations in Electrical Engineering from Universitas Muhamadiyah Yogyakarta, Indonesia. He obtained his B.Eng. in 2017

Yudhi Ardiyanto obtained his B.Eng. in Electrical Engineering from the Universitas Muhamadiyah Yogyakarta, Indonesia. His Master study was done at the Electrical Engineering, Gadjah Mada University, Indonesia. He currently is a lecture in Department of Electrical Engineering, Universitas Muhammadiyah Yogyakarta, Indonesia

Karisma Trinanda Putra graduated with Master degree from Sepuluh Nopember Institute of Technology in 2015. He received his Doctoral degree from Asia University, Taiwan, in degree in January 2022. He is currently an Assistant Professor and Director at Department of Electrical Engineering, Faculty of Engineering, Universitas Muhammadiyah Yogyakarta, Indonesia