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Low power three phase inverter pure sinusoides output voltage design

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Abstrak: Konversi daya dari tegangan arus searah (dc) ke tegangan arus bolak-balik (ac) disebut inverter umumnya menghasilkan bentuk gelombang tegangan atau arus yang belum mendekati sinusoidal atau dengan kata lain gelombang tersebut masih memiliki bentuk gelombang riak atau distorsi dengan tinggi Total Nilai Harmonic Distortion (THD). Salah satu faktor yang mempengaruhi bentuk gelombang inverter yang dihasilkan adalah sistem pemicu saklar inverter. Metode pembangkitan pulsa PWM (Pulse Width Modulation) adalah cara yang diusulkan untuk mengatasi masalah ini. Untuk menghasilkan sistem tegangan tiga fasa dibutuhkan 3 rangkaian konverter daya yang identik namun memiliki sistem pengapian yang berbeda yaitu 1200 fasa untuk setiap rangkaian inverter. Hasil simulasi menunjukkan bahwa inverter dengan tegangan input 24 V menghasilkan tiga gelombang tegangan 230/340 V dengan nilai kandungan Total Harmonic Distortion (THD) sebesar 3,565%.
Kata kunci: Inverter; Modulasi Lebar Pulsa; Sinusoida Murni; Total Harmonic Distortion (THD)

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Abstract: *Power conversion from direct current (dc) to alternating current (ac) voltage is called an inverter, generally producing a voltage or current waveform that is not yet close to sinusoidal or in other words, the wave still has a ripple or distortion waveform with a high Total Harmonic Distortion Value (THD). One of the factors that affect the resulting inverter waveform is the inverter switch trigger system. The PWM (Pulse Width Modulation) pulse generation method is a proposed way to solve this problem. To produce a three-phase voltage system, 3 identical power converter circuits are needed but have different ignition systems, namely 1200 phases for each inverter circuit. The simulation results show that the inverter with an input voltage of 24 V produces three waves of 230/340 V voltage with a value of Total Harmonic Distortion (THD) of 3.565%.*
Keywords*: Inverters; Pulse Width Modulation; Pure Sinusoids; Total Harmonic Distortion (THD)*

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INTRODUCTION

The electrical energy has a very vital role in every side of life. This energy is used to serve the power needs of various kinds of electrical equipment, both household, office, industrial and transportation electrical appliances. The electrical equipment requires voltage and current with a certain format as a power source in its performance. Lots of equipment that requires a direct current (dc) power supply or alternating current (ac) with a fixed voltage and frequency or an ac power source with variable voltage and frequency. Through power electronics the power format can be changed according to the needs of the load. One of the products of power electronics is an inverter. Inverter is a power electronic circuit that is used to convert or change the direct voltage into alternating voltage with a fixed frequency or adjustable frequency. However, the inverter output voltage has ripple and harmonic content so that it is not in the form of a sinusoid and if not handled properly it will be dangerous for loads that require a sinusoidal voltage format. Several attempts to reduce the presence of these harmonics by building active and passive filters.(Rahardjo et al., 2021) (Birbir et al., 2019),(Hutabarat et al., 2020),(Mustagisin et al., 2021) . I.A. Rahardjo, suppresses the harmonics on the inverter with a filter Using passive capacitive and inductive filters on the load side with the result is that the harmonic content can be reduced below 5% according to the IEEE 1531 – 2003 standard. Tiago Davi Curi Busarello in his article builds an inverter connected to a single phase LCL filter network capable of eliminating high frequency harmonics (Curi Busarello et al., 2020). Several researchers have developed a tiered array inverter, better known as a multilevel inverter (5,7,11,17 levels) with the aim of making the output voltage sine wave as more perfect (Curi Busarello et al., 2020), (Wang et al., 2020),(Lone & Bakhsh, 2020) , (Matalata & Yusiana, 2020), (Reza Muhammad Rizki et al., 2020),(Panigrahi & Thakur, 2019), (Aboadla et al., 2019) harmonics and higher power factor compared to classical diodes and thyristor rectifiers (Zhou et al., 2018). Tao XU, in his paper said that the Global Synchronous Discontinuity Pulse Width Modulation (GSDPWM) three-phase inverter method effectively weakens the frequency harmonic current at the Point of Common Coupling (PCC) (Xu et al., 2016) (Hora, 2019) (Ratnawati et al., 2020) . This SPWM method has the advantage of being able to reduce the harmonic content of the voltage. output is compared with single pulse width modulation and multi pulse modulation) (Hassaine & Bengourina, 2020). The development of PWM and SPWM signal generation methods is still ongoing, both analog and digital. Hendi Matalata compared the switching techniques used between Pulse Width Modulation (PWM) and Sinus Pulse Width Modulation (SPWM) for a five-level multistage inverter. From his research, it produces an output voltage with a low harmonic level [9]. A K Podder1, in his paper compares the inverter ignition method using the PI PWM approach and the MPCC approach. As a result, the MPCC approach succeeded in reducing power loss by 70.16% (100.16 W) compared to using the PI-PWM method (Podder et al., 2020).

Digital controllers are widely used to generate PWM signals due to their reliability in solving complex algorithms in a short time. (Kang et al., 2020), (Gani et al., 2019) , (Diouri et al., 2018), SPWM can be generated in two ways, namely SPWM with Bipolar Voltage Switching SPWM with Unipolar Voltage Switching which produces an ignition pulse pattern with a certain amplitude and pulse width. These amplitude values are used as the PWM duty cycle. By adjusting the PWM pulse width or duty cycle, the harmonics on the output side can be minimized or even eliminated(Xia et al., 2018),(Journal et al., 2016) (Sutopo et al., 2020). This research focuses on inverter design that converts 24 Volt dc voltage into pure sinusoidal three-phase voltage output using PWM (Pulse Width Modulation) technique with PI control for switching on the inverter switch through modeling simulation using Matlab Simulink tools. Another method was developed by Xiaoqiang GUO, which is an analysis using the Abc-frame complex-coefficient filter coefficient approach which aims to achieve a sinusoidal balance in the distribution voltage. The result is that the harmonic current can be reduced by this method approach .

Inverter switch ignition technique plays an important role to produce a voltage that is close to pure sinusoid. One method of generating a trigger pulse is using the Sinusoidal Pulse Width Modulation (SPWM) method. Sinusoidal Pulse Width Modulation (SPWM) is a technique for manipulating pulse width by comparing two different signals, namely a reference signal (sinusoidal signal) and a carrier signal (saw tooth signal). Pulse width modulation (PWM) based rectifier. is one of the most popular types of rectifier. The PWM rectifier has a lower input current harmonics and higher power factor compared to classical diodes and thyristor rectifiers(Zhou et al., 2018) (Purnomo & Triyono, 2018) . Tao XU, in his paper said that the Global Synchronous Discontinuity Pulse Width Modulation (GSDPWM) three-phase inverter method effectively weakens the frequency harmonic current at the Point of Common Coupling (PCC)(Xu et al., 2016). This SPWM method has the advantage of being able to reduce the harmonic content of the voltage. output is compared with single pulse width modulation and multi pulse modulation)(Hassaine & Bengourina, 2020) .

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METHOD

This research was related by designing a three-phase inverter which is composed of three single-phase inverters connected in parallel. The circuit design is then simulated by modeling using the Simulink Matlab tools. The inverter topology that is designed is a full bridge single phase inverter (Full Bridge), which uses 4 transistor devices. Fig. 1 describes the working order of the system design. The first stage is to determine the dc voltage that will be converted into an ac voltage of 24 V. The second stage is to design a single-phase inverter circuit using a transistor device. The 3-phase inverter switch circuit is obtained by building 3 identical single-phase inverter strands arranged in parallel. The third stage is to increase the inverter output voltage for each phase with a transformer. The load side is the end of the circuit and at this point the observation of the inverter output voltage waveform is whether it is sinusoidal or not. The system design is then simulated using the simulink matlab tools.

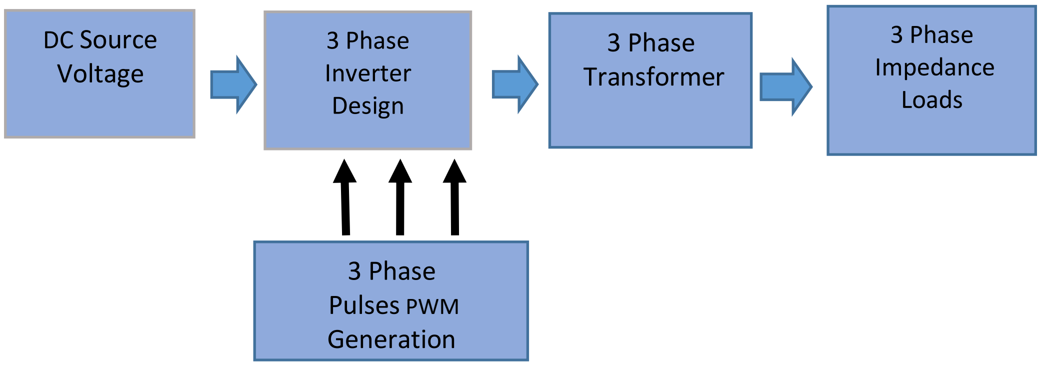

Figure 1. Work Flow Research Metodology

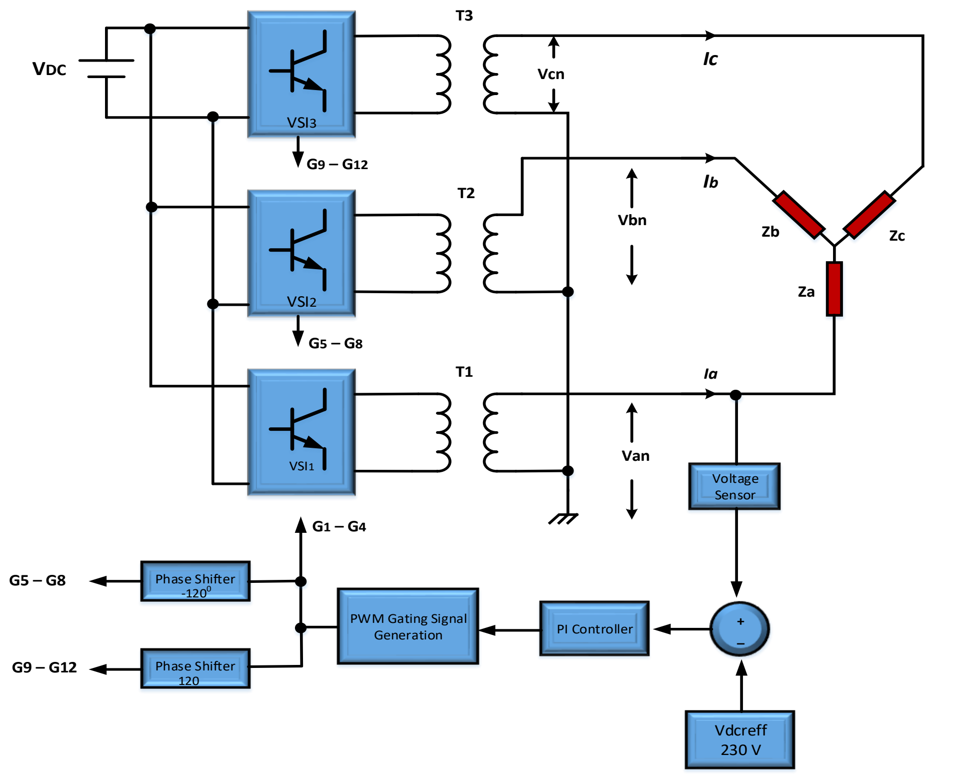

Figure 2. Three Phase Inverter Design at Resistive Loads with PWM Control

Figure 2 is a 24 V dc source that will be converted into an alternating voltage of 230 V using three identical single-phase inverters (VS1, VS2, VS3) each connected to transformers T1, T2, and T3 (1 kVA) as a voltage boost each inverter. The load of each phase $\mathbf{Z_a}$, $\mathbf{Z_b}$, and $\mathbf{Z_c}$ is balanced connection to the star in the form of the impedance of the recipient and the inductive recipient which are alternately installed during the test. Then the model is run and observations are made by looking at several waveform parameters, including 24 V dc source voltage, switch pulses, output voltage at each load, and measuring the total harmonic index (THD) of the three-phase inverter circuit design. The results of the observations were then analyzed and compared with the literature used.

Single phase inverter

The single-phase inverter unit is built with a semiconductor device switch (Transistor, MOSFET, SCR). The full-bridge is shown in Fig. 3, composed of 4 transistor switches. This inverter is capable of producing a power output (output power) that is twice as large when compared to a half-bridge inverter topology at the same Vdc input voltage. Fig. 3 is an inverter circuit with a full-bridge topology using 2 upper side switches, namely S1A and S2B, and the lower switch, namely S2A and S2B. Some of the working rules of the switch that must be fulfilled are as follows, the arm pairs S1A and S1B, S2A and S2B work complementary, meaning that if S1A is on then S1B is off as well as if S2A is ON then S2B is OFF to avoid short circuits. While S1A and S2B, S1B and S2A work simultaneously or simultaneously. To provide a neutral point in the inverter circuit two series capacitors are installed and the midpoint between the two capacitors acts as the neutral point (N).
Table 1 describes the patterns and conditions for each switch pair where there are 4 switch states in a specified condition (1,2,3,4) and one unspecified state (condition 5), the maximum fullness-bridge inverter output voltage is Vi/2 and a minimum –Vi/2 following the active elements.

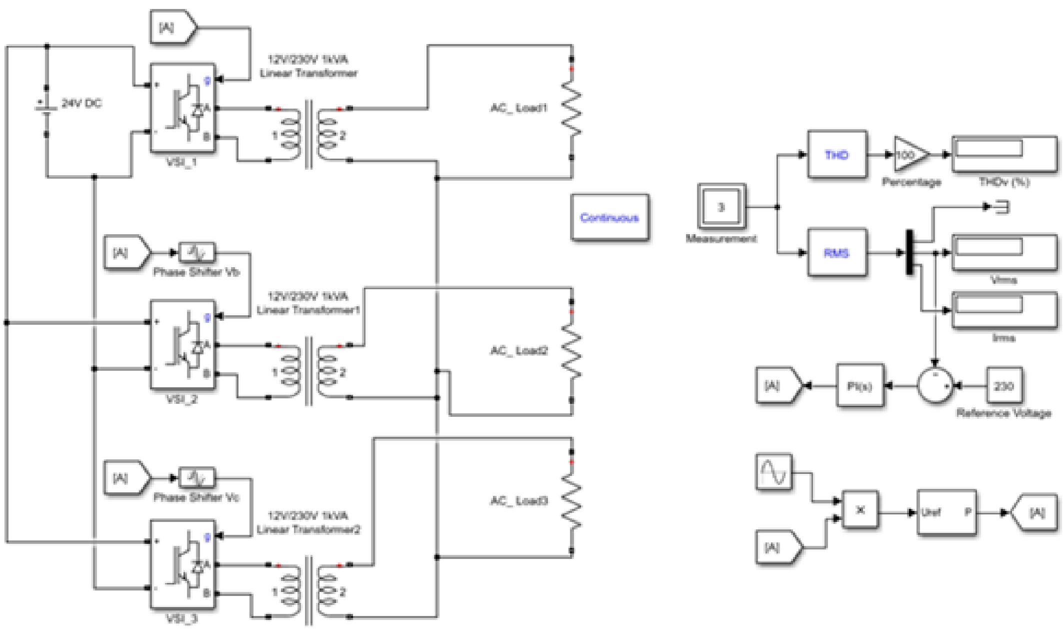

Figure 3. Three phase inverter modeling at 24 V DC input voltage

Voltage Sensor

The voltage sensor is used to measure the value of the rms (root means square) voltage output of the inverter on the secondary transformer winding side. The principle is simple, namely by installing a resistance of 10 kΩ in parallel with the load so that the voltage drop on the 10 Ω resistance is used as the rms voltage value which will be compared with the 230 V reference voltage. The difference between the root means square voltage and the reference voltage is in the form of a voltage error which will be input for the PI control for further processing.

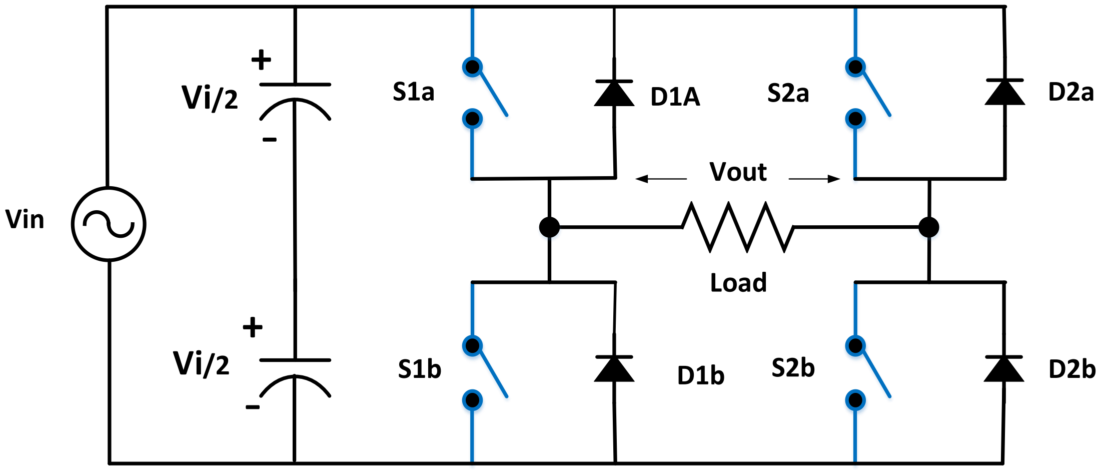

Figure 4 . Full bridge single phase voltage source inverter (VSI)

PI Controller

Proportional-Integral (PI) control is a simple controller and has a stable response so that it is quite effective in various control system implementations. Easy control operations, which is enough to set the proportional constant (Kp) and the integral constant (Ki) accordingly. PI control in system design aims to maintain the shape of the inverter output voltage in accordance with the reference signal. The proportional constant Kp only acts as an amplifier, has a low dynamic effect on the controller performance. Although it has weaknesses and limitations, however, the use of this controller is quite often used because it can improve transient responses, especially the rise time and settling time. The constant I can increase and also eliminate the steady-state response, but if the Ki setting is not correct it can result in a high transient response so that system instability can be reduced. The PI controller output is then multiplied by a sinusoid generator with a frequency of 50 Hz where the multiplication of this wave is used as a modulation signal in the PWM signal generator circuit.

Fig.5 describes the flow of the trigger signal generation used to turn on the inverter switches for each phase. Broadly speaking, the performance of the ignition signal generation begins with measuring the output voltage on the side of the transformer. Then this voltage is compared with a reference voltage of 230 V AC. If the sensor voltage is the same as the reference voltage, this result is then processed by the PI control to achieve a steady state value. The output of the PI control is then multiplied by the 1 V amplitude sinusoidal signal with a frequency of 50 Hz into a signal (Vsin) and then compared with the triangular carrier signal (Vc) at a frequency of 1 kHz using a comparator strand.

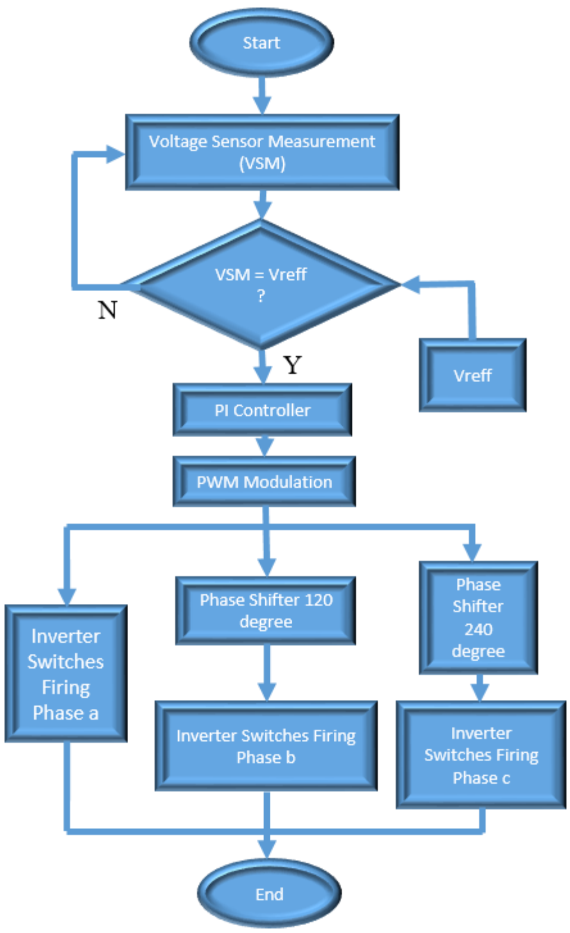

Figure 5. Flowchart SPWM Generation

Table 1. Switch conditions on single phase full wave inverter

Switch States	Condition	VaN	VbN	Vo	Active Components
S1A and S2B ON , S1B and S2A OFF	1	Vi/2	-Vi/2	Vi	S1A and S2B if Io>0 D1A and D2B if Io<0
S1B and S2A ON , S1A andS2B OFF	2	-Vi/2	Vi/2	-Vi	D1A and D2B if Io>0 S1B and S2A if Io<0
S1A and S2A ON , S1B and S2B OFF	3	Vi/2	Vi/2	0	S1A and D2A if Io>0 D1A and S2A if Io<0
S1B and S2B ON , S1A and S2A OFF	4	-Vi/2	-Vi/2	0	D1B and S2B if Io>0 S1B and D2B if Io<0
S1B,S2B,S1A and S2A all are OFF	5	-Vi/2 Vi/2	Vi/2 –	-Vi Vi	D1B and D2A if Io>0 D1A and D2B if Io<0

Vi/2

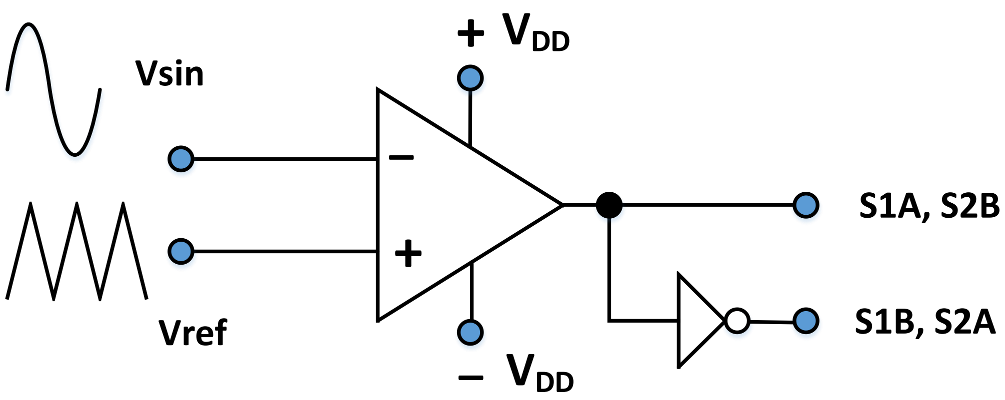

Figure 6. The Concept of Generating PWM Pulses

Fig. 6 is a concept of pulse generation using a comparator that compares the Vsin signal with the Vtri carrier wave to generate PWM pulses and their complementary pulses through the inverting unit (NOT Gate).

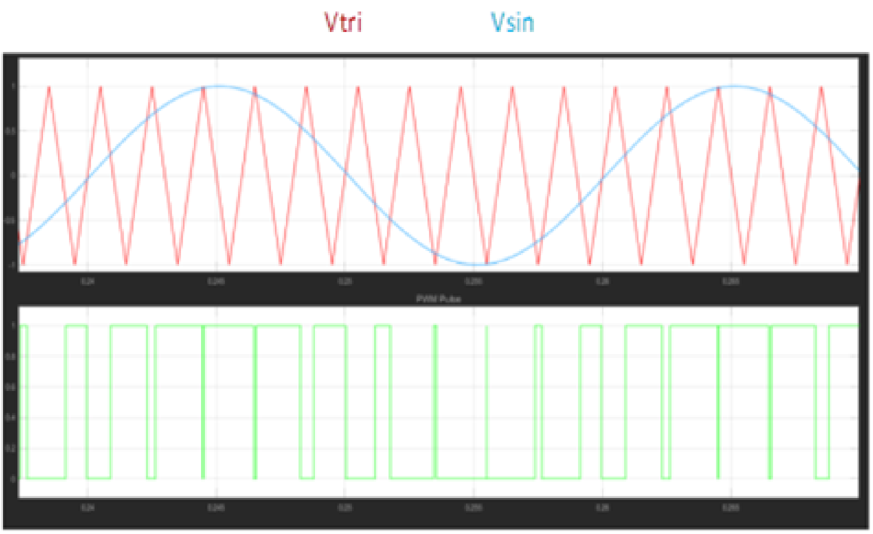

Figure 7. Illustration of SPWM Pulse generation

Fig.7 illustrates the principle of generating a PWM signal. When $V_{sin} > V_{tri}$, the PWM pulse = 1 V and when $V_{tri} > V_{sin}$ the PWM pulse = 0 V.

Phase Shifter

In the second inverter circuit (VSI_2) and the third, inverter (VSI_3), the inverter switch requires a different ignition pulse of -120^0 and 120^0 phases with the first inverter switch. This requires a phase shift circuit using a Wien Bridge circuit. Fig. 8. The phase shift Wien Bridge circuit where the ignition pulse of the first inverter (VGVSI_1) is the input of the second inverter phase shift circuit (VGVSI_2) and the third inverter (VGVSI_3). The displacement pulse amplitude is set at 1 Volt with the shift angle θ where

$$\theta = 2\,\mathrm{arctg}\; f\,\pi\,R_i\,C_i \quad (1)$$

thus the resistance value R_i can be determined by the equation:

$$R_i = \frac{\mathrm{tg}\left(\frac{\theta}{2}\right)}{2\pi\, f\, C_i} \quad (2)$$

When $\theta = -120^0$ value C_i = 1 uF and R_i = 5.51 kohm.

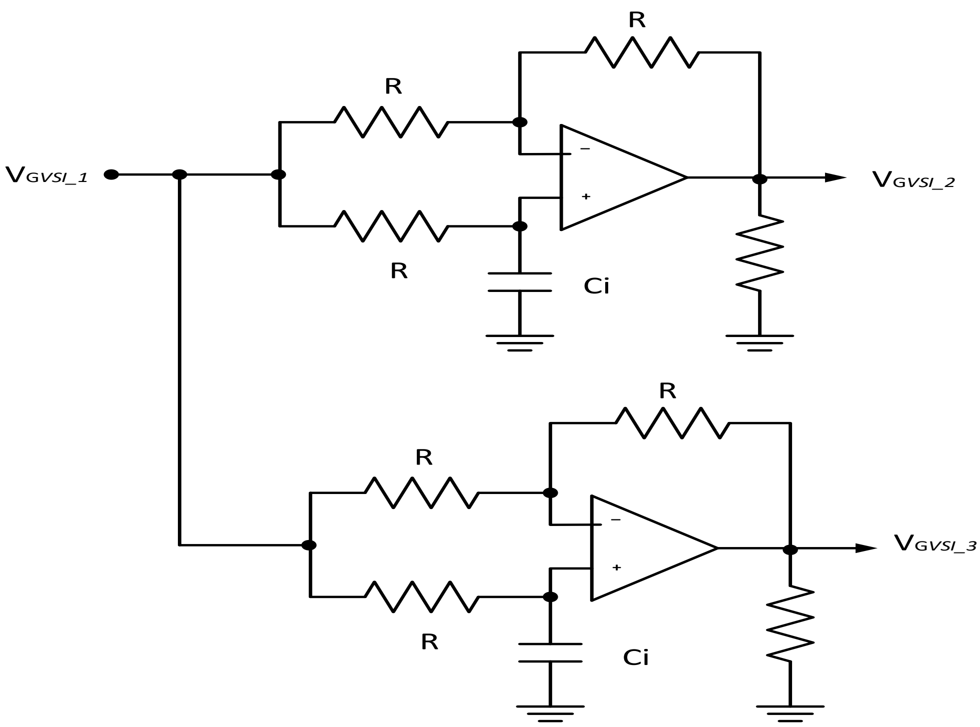

Figure 8. Wien Bridge Phase Shifter Circuit

RESULTS AND DISCUS

The next step is to simulate the completed model to see several parameters including Vrms voltage waveform, the reference voltage (Vreff), error value, PI Controller output signal, modulation signal, carrier signal, a row of gate ignition pulses, voltage PWM inverter output, transformer gain output voltage, three-phase voltage format, and Total Harmonic Distortion (THD) value. Following are the simulation results and a discussion of each parameter obtained.

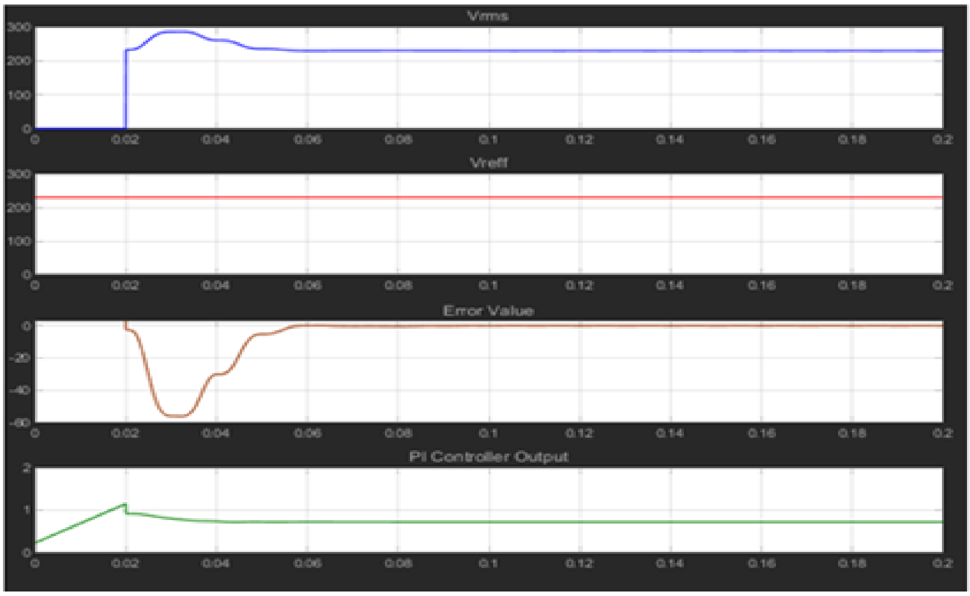

Figure 9. Comparison of Vrms, Vreff, Error Values and PI Control Signal Output

Fig. 9 explains that the voltage sensor produces a V_{rms} voltage measurement of 230.1 V which is constant at t = 0.06 s. The rms voltage is obtained from the dc voltage raised by the 12/230 kV 1 kVA transformer through the oscillation performance of the inverter. This rms voltage value is then compared with the reference voltage, V_{reff} of 230 V. The result of the comparison between the rms voltage and the reference voltage is the difference in voltage called the voltage error value of 0.1 V. This amount then becomes the PI control input to be kept constant.

The PI signal is then multiplied by a 1 Volt sinusoidal generator with a frequency of 50 Hz as the V_m modulation signal. To obtain the gate ignition signal, V_m is modulated on the V_c carrier signal with a frequency of 1 kHz using a comparator circuit.

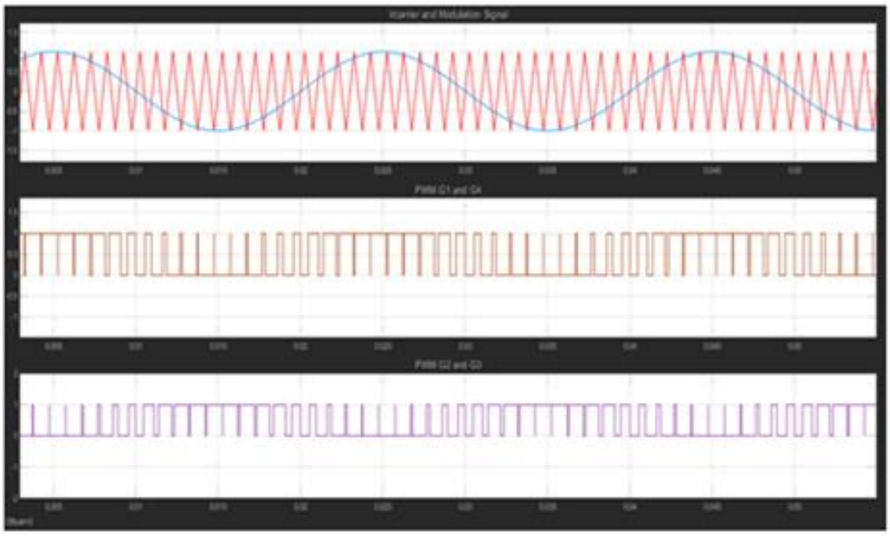

Figure 10. Carrier Signal, Modulator and PWM Pulse Series

Fig. 10, the 1 Vpp 50 Hz sinusoidal modulated signal is modulated on a carrier signal in the form of a triangular wave with an amplitude of 1 Volt with a frequency of 1 kHz. The result is a series of PWM pulses which changes the pulse width with time. This pulse is used as the ignition signal for switch switches G1, G2, G3, and G4 on the first inverter (VSI-1). Each gate pulse has an amplitude of 1 volt with the pulse width changing with time. Signal G1 has the same pattern and phase as G4, as well as the flight pulses of G2 and G3 but between the two pairs work complementary as far as 180^0.

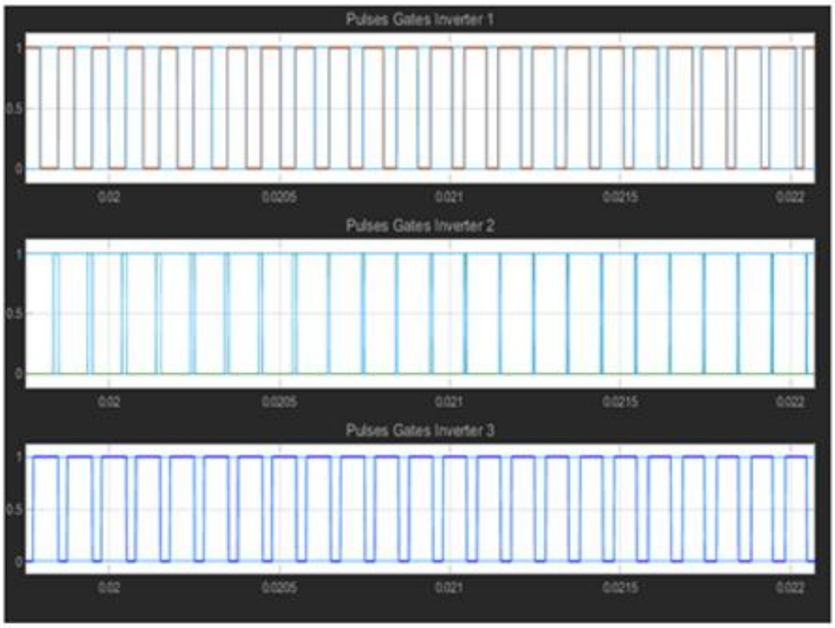

Figure 11. Pulse array VSI-1, VSI-2 and VSI-3

Figure. 11 is the firing pulses of the first VSI-1 inverter, the second inverter (VSI-2), and the third inverter (VSI-3) have the same shape but shift as far as 120^0 with respect to the ignition pulse of the VSI-1 switch and 240^0 to the VSI-ignition pulse. 3. This phase difference is obtained from the phase delay circuit on the VSI-2 and VSI-3. In the VSI-2 inverter pulse generator unit it works by shifting the phase of the VSI-1 ignition pulse series as far as 120^0, and the VSI-3 phase-shifting circuit shifts phase width of 240^0. The pulse width varies with time, this will affect the value of the output voltage of the inverter so that the amplitude of the inverter output voltage will also change as well. Thus the inverter output voltage pattern will approach the sinusoidal shape.

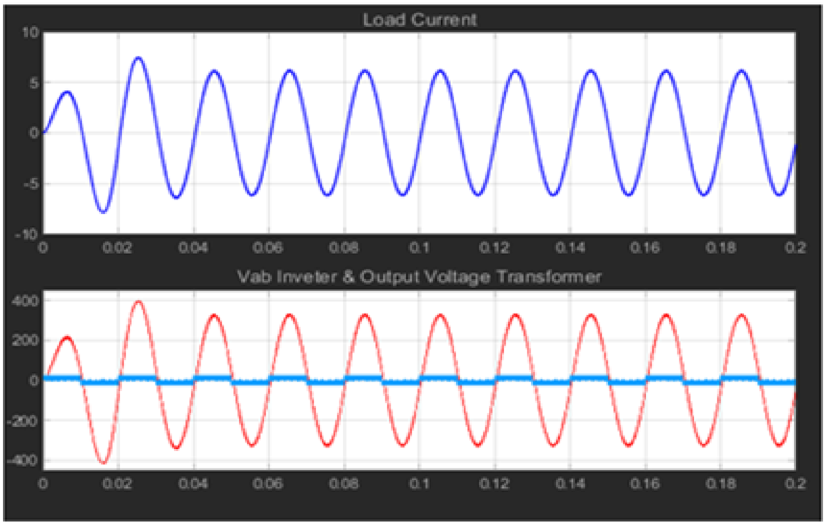

Figure 12. Load Current Wave, Inverter Voltage and Reinforcement

Fig 12. When the resistive load is 1 kW or power factor one, it shows that the load current is in the form of a sinusoid with a peak amplitude of 6.15 A. The voltage of the per phase inverter is around 48 Volts (24 V_{pp}) and then amplified using a transformer (12V / 230 V 1 kW). The inverter amplification voltage is close to a sinusoid with an amplitude of 460 V (230 V_{pp}) and has a Total Harmonic Distortion index of 3.565%. According to the IEEE 519 rules, this THD value indicates that the inverter voltage is suitable for use in power systems.

Table 2. Inverter Measurement Parameters on Power Factor One

Load Resistive	Vrms (V)	Irms (A)	THD (%)
P =1000 W	230.1	4.349	3.565
P = 850 W	230.1	3.967	4.006
P = 500 W	230.1	2.174	5.973
P = 200W	230.1	0.8698	10.09
P = 100 W	230.1	0.4349	11.73

Table 2. Describes the observation data results of the performance inverter simulation, when a load with a power factor of one absorbs power from 100 W to 1 kW. It can be seen that the rms voltage is constant wherever the power is absorbed, the rms current changes with changes in the power

absorbed. The THD value decreases as the power decreases. These results present an unfiltered system. To get a smaller THD value, it is necessary to install a filter on the output side of the inverter so that the resulting waveform becomes more sinusoidal.

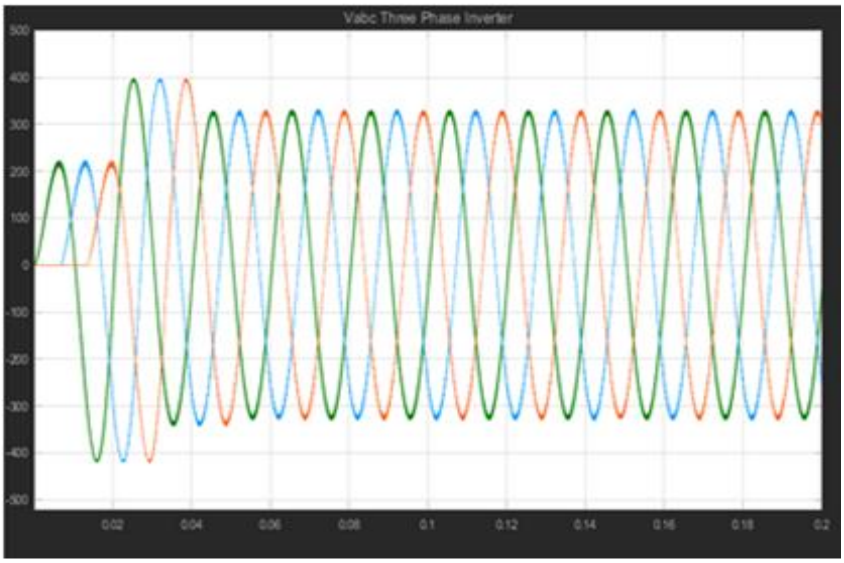

Figure 13. The inverter output voltage wave on the transformer side

Fig. 13 shows the output waveform of the inverter after going through the amplification by transformer on the secondary winding side. It appears that this voltage is a three-phase voltage system with an amplitude of 320 V with a frequency of 50 Hz with a phase difference between the channels of 120^0.

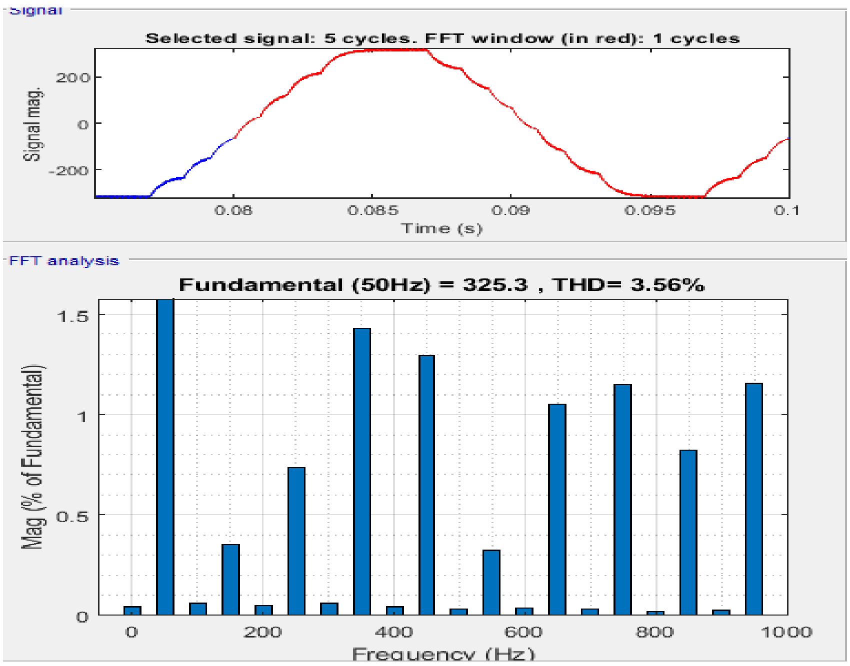

Figure 14. Indext THD Value at 1000 W Load

Fig. 14, when the load is 1000 W the system has a THD index of 3.565%. This shows that at high loads the system is able to reduce the presence of harmonics below 5%. The harmonic disturbance signal that appears occurs at the frequencies of 150 Hz, 250 Hz, 350 Hz, 450 Hz, 550 Hz, 650 Hz, 750 H, 850 Hz, and 950 Hz or on odd order harmonics 3,5,7,9,11, 13 ,15 and so on with a maximum amplitude of 1.5% of the basic signal amplitude. So, to reduce the value of the THD Index even smaller, a filter or filter that is tuned at the above frequency is needed.

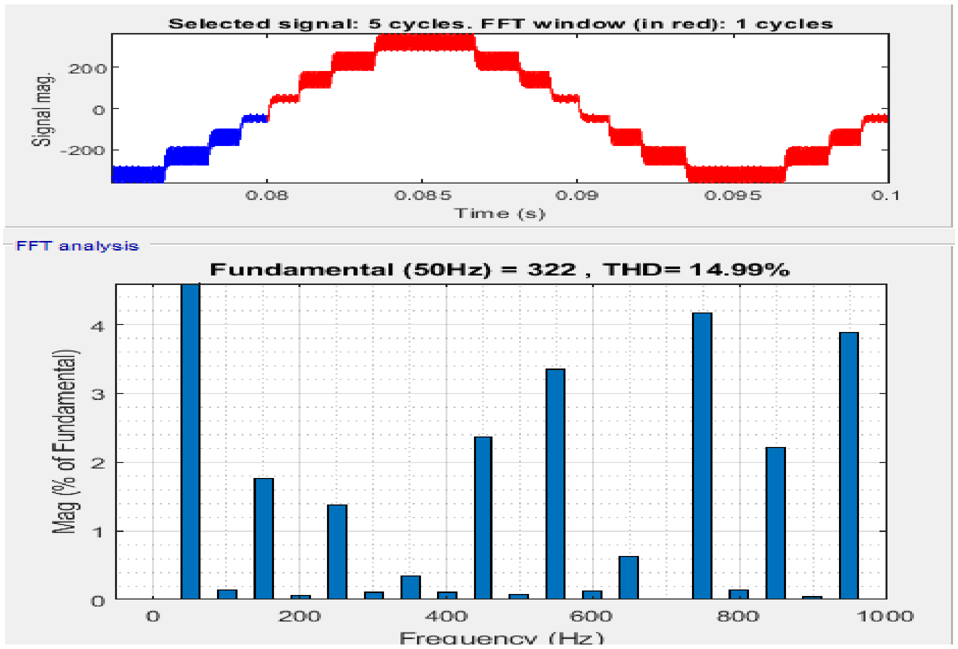

Figure 15. THD Index value at low power 100 W

Fig. 15, when the load is 100 W the system has a THD index of 14.99%. This shows that at low load the system is not able to reduce the presence of harmonics below 5%. How many disturbing harmonics are at the frequencies of 150 Hz, 250 Hz, 350 Hz, 450 Hz, 550 Hz, 750 Hz, 850 Hz, and 950 Hz or on odd order harmonics 3,5,7,9,11, 13 and so on. So it is necessary to develop further research so that the THD index value does not exceed 5% by adding a filter or filter in the form of a capacitor or inductor or a combination of both.

CONCLUSION

Low power three phase inverter design using PI control has been completed. The inverter converts a 24 V DC voltage into an alternating voltage of 320 V. A three-phase voltage system can be arranged using three single-phase inverters with a full bridge rectifier using a transistor device in parallel. The performance of the inverter pair switch pairs is turned on with a row of PWM (Pulse Width Modulation) pulses. Each switch pair has a ignition pulse pattern with a phase difference of 180^0. The second and third inverter ignition pulses have a phase difference of 120^0, this phase difference is obtained by shifting the ignition pulses of the first inverter by 120^0 on each pulse of the next inverter on. The simulation results show that the three-phase voltage is almost close to the sinusoidal form with a THD content of 3.565% when the inverter delivers 1 kW of power to the load. So that this voltage is suitable for use in a power system.

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