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Design and Implementation of Proportional-Integral Controller for Single Phase Stand-Alone Inverter with an LC-Filter

Tamarah Kareem [a,1], Salam Waley Shneen [b,2,*], Mohammed Al-Abbasi [a,3]

[a] Electro-Mechanical Engineering Department, University of Technology-Iraq, Iraq
[b] Energy and Renewable Energies Technology Center, University of Technology-Iraq, Baghdad, Iraq
[1] Tamarah.A.Kareem@uotechnology.edu.iq; [2] salam.w.shneen@uotechnology.edu.iq;
[3] Mohammed.S.Dawood@uotechnology.edu.iq
* Corresponding Author

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ABSTRACT

Obtaining a sine wave from a DC source using an inverter and a filter is a challenge that requires a suitable design to meet load requirements as operating conditions change. This work aims to develop a suitable design for an LC-type pass-through filter and a suitable design for a conventional controller. A simulation model for the implementation and operation of a single-phase standalone inverter is being developed and designed using Matlab. In this work, the researchers demonstrate the behavior of a simulated system using a single-phase inverter model connected to a 400 V DC power supply. An LC-type filter is also connected to the inverter and the load. Tests are conducted to determine the system's behavior under various conditions. The researchers are interested in changing operating conditions, and the problem of load variations, on the one hand, and transients and the system's return to a steady state, on the other. The researchers propose one method for overcoming system fluctuations using a conventional controller (PI controller). Tests can cover identifying system behavior, and from there, using the controller, an appropriate reference voltage can be set to supply the load. The proposed model consists of a power supply, four IGBT transistor switches to build a single-phase bridge inverter, a filter with an inductor (4.06e-3H) and a capacitor (6.23e-6F), as well as a reference voltage of 200V and 300V, and a load of 55Ω and 100Ω. A suitable conventional microcontroller (PIC) is also designed. The feasibility of providing a sine wave with the proposed reference voltage has been verified, proving the feasibility of the model and its potential for future use. Matlab was used to conduct simulation tests of the proposed model, and high performance, accuracy, and quality were obtained at a level suitable for real-time applications.

1. Introduction

The importance of using an inverter becomes apparent when there is an available DC power source, such as solar or batteries, and a DC source with a specific voltage that does not meet the demand of the AC loads [1]-[3]. Inverters of this type dampen harmonics and can rely on reference voltage control techniques, such as using a conventional proportional-integral controller. The controller regulates the desired controller output when the lowest possible input is reached, representing the difference between the actual value and the reference value (error signals). This requires the addition of a voltage inverter to supply the load with the appropriate electrical quantity [4]-[6]. To obtain a sine wave to power the load from the inverter output, a filter designed to match the required output is required. The inverter varies according to the number of electronic switches [7]-[9]. For example, there may be four to suit a single-phase inverter, while a three-phase inverter requires six electronic switches, making the inverter type what is called a single-phase bridge inverter or a three-phase bridge inverter [10]-[12]. These switches may also be transistors or thyristors, which requires regulating the operation of these switches and adding technology such as pulse width modulation [13]-[15]. In addition to the above, and by examining the different operating conditions, it is important to emphasize the importance of control systems based on a process of determining a reference value and comparing it with the actual waveform [16]-[18]. The comparator output is then fed into the microcontroller, which works to accurately and quickly reduce the error value to achieve a stable system. Inverters are used in many industrial, agricultural, and other systems and applications. They are connected to the grid, loads, power sources, and storage units such as batteries [19]-[21].

Loads are classified according to the type of power supply and according to the number of phases. These include DC loads and AC loads. There are also single-phase and three-phase AC loads [22]-[24]. The sources used to cover the loads are often from the national grid, which requires connecting power transformers to provide the appropriate electrical quantities to meet the load requirements. Other energy sources include sustainable and environmentally friendly energy systems, such as solar energy, which provide direct voltage [25]-[27]. When using a DC source to cover an AC load, a voltage inverter is required to convert the DC current to alternating current. The inverter plays an important role in providing a sine wave alternating voltage that operates efficiently to meet the load requirements [28]-[30]. Pulse width modulation (PWM) technology is used to regulate the inverter's operation, and to improve performance, control units are added to ensure the appropriate reference value is obtained for the load supply [31]-[33].

A simulation model is being developed and designed to conduct a number of proposed tests to cover the research contributions. Changing the reference value ensures the validity and quality of the control unit to provide an output consistent with the reference voltage. The change in current can also be identified with changes in the load value and the output voltage remaining constant at the reference value. An inverter acts as a conversion device and is defined as a converter from a constant DC voltage to a variable AC voltage. There are single-phase and three-phase inverters, and electronic switches can be used to distinguish between them based on the number of electronic switches. A single-phase inverter is usually built using four electronic switches, for example, using a thyristor or transistor, while a three-phase inverter can be built using six electronic switches. Electronic switches vary the inverter's output from the inverter's input by varying the switches' opening and closing times. The inverter's operation can be regulated to produce the desired output by adding pulse width modulation (PWM) techniques and various control units. A filter can also be added to eliminate harmonics associated with the inverter's output waveform. Control systems are of three types: traditional, such as the PID controller, in addition to other types. There is also an expert type, such as neural networks and fuzzy logic. There is also a third type, which is the optimal controller using genetic algorithms and others. A single-phase inverter can be simulated to understand the inverter's behavior. A simulation model is built and an engineering program is employed to operate the system under different conditions to verify the possibility of handling system fluctuations, improving its performance and increasing its efficiency, thus ensuring high reliability. This research proposes the simulation and use of a single-phase inverter and operating it for conducting tests, including the first open-loop system condition to study the case and understand the system behavior. Another test is proposed, including operating the inverter under the closed-loop system condition using a conventional PI controller to identify the difference between the two test conditions by determining the reference and desired values at the inverter output. To eliminate the harmonics associated with the inverter output signal, an LC filter is proposed to be added to the system in an attempt to obtain a pure sine wave.

2. Methodology

Single Phase Inverter, Fig. 1 show the simple system that has the single phase inverter with dc voltage source and ac load. Fig. 2 show the full wave single phase inverter that has four IGBT swatches. Fig. 3 show the LC filter that connected between the load and the inverter. Fig. 4 show the system include the source, inverter, LC filter and load [34]-[37].

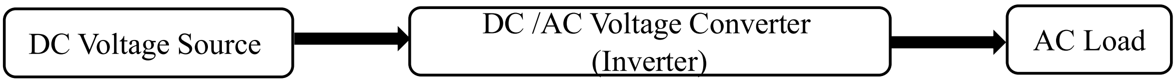

Fig. 1. Block diagram for single phase inverter with dc voltage source and AC load

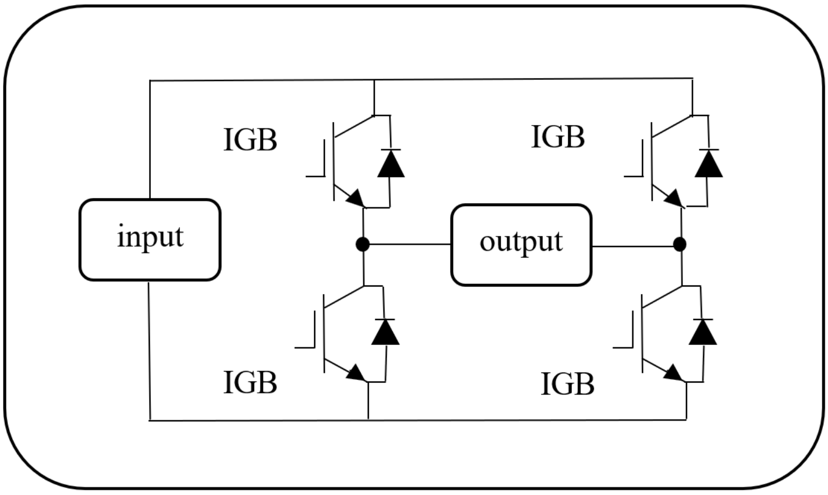

Fig. 2. Block diagram of full wave single phase inverter that has four IGBT swatches

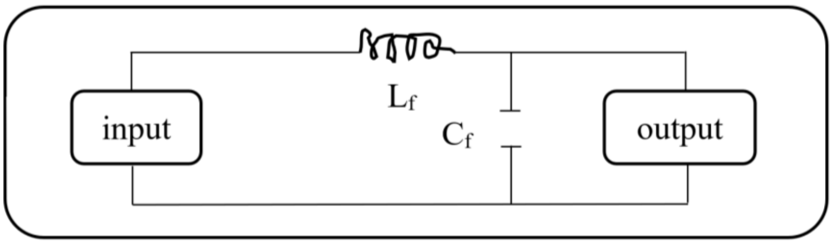

Fig. 3. Block diagram of LC filter

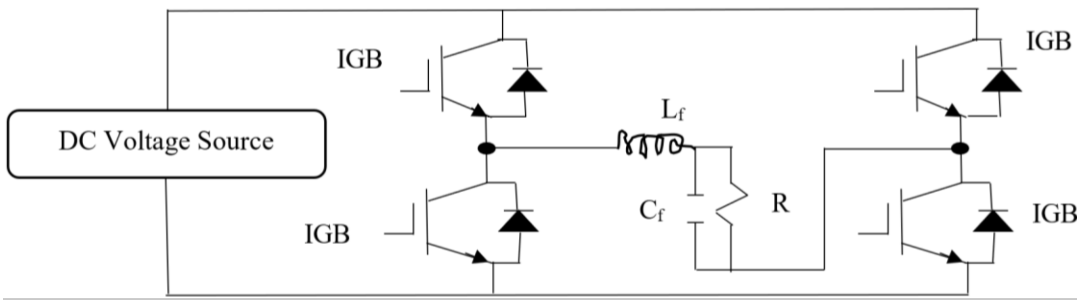

Fig. 4. Block diagram of the system includes the source, inverter, LC filter and AC load

There are electrical circuits made up of passive components called filters. These circuits are divided into types based on their components. When the filter is built with a single coil and a capacitor, it is called an LC, while when it is built with two coils and a capacitor, it is called an LCL [38]-[40]. Filters are commonly used in many applications. One of these uses is adding a filter to a circuit between the load and the inverter output, which removes harmonics from the inverter output. The filter is designed based on the electrical quantity in the input and output that matches the inverter output and the load input [41]-[45]. The filter can be designed using mathematical equations and depending on the filter type. Previous studies have presented a number of challenges that could be addressed in future studies, potentially contributing to research with achievable objectives. These include developing a unique controller design and improving the filter to distinguish it from previous studies. They also provide important research motivations for developing approaches for modern studies that incorporate the use of a conventional controller plus an LC filter, which are considered alternatives to represent one of the advanced control techniques [46]-[49].

Traditional controllers come in a variety of forms, including proportional, integral-proportional, differential-proportional, and integral-differential. Designing and implementing a controller of this type, such as a proportional-integral controller, requires regulating and modifying the controller's specific gain parameters—both the proportional and integral—to achieve the desired output and appropriate response with high speed and accuracy [50]-[54]. Modeling for PI Controller Fig. 5.

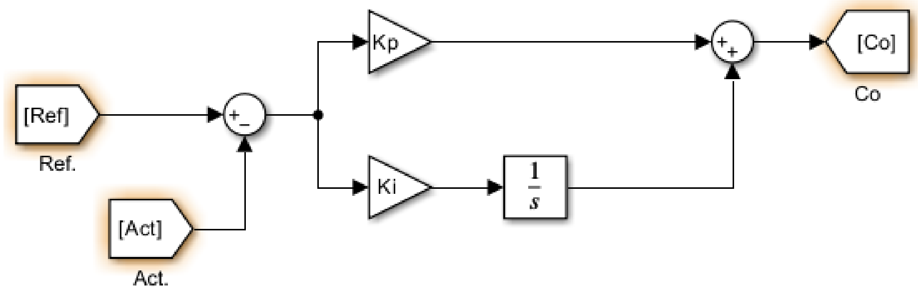

Fig. 5. Modeling for PI controller

$$Co\_PIC\,(t) = Kp\,.\,e(t) + Ki\,.\int e(t)\,dt \tag{1}$$

To obtain an effective filter that gives the desired output through the design process using the mathematical representation of the LC filter connected to a single-phase inverter to eliminate harmonics in the inverter output. To design the filter, we first rely on the power output equation, which can be calculated from the current times the voltage and the RMS value.

$$Pout\_LC\ Filter = Vrms * Irms \tag{2}$$

Where, $Vin = 400\ volt$, $Rload = 55ohm\ \&\ 100\ ohm$, $Vout\_rms = Vin * \sqrt{2}\,sinwt$, $Io = Vo/R_{load}$, $Po = Vo/Io$

Design of Single Phase Inverter, designing and operating a single-phase inverter is one of the most significant challenges. This requires first determining the specifications of the inverter to be designed, taking into account the type of electronic switches used, which can be clarified through the design and operation processes. Fig. 2 represents a model of the proposed inverter, which includes the following specifications. Input voltage (Vin) for inverter is equal 400 volts. Output voltage for inverter is equal 230 volts. Also, output frequency (fo) is equal 50 Hz, Power (Po) is equal 2KW, Switch frequency (fs) is equal 10KHz. Total harmonic distortion (THDv) = <5% and the ripple current (Irip) is equal 20 %. The design steps begin with designing the coil, one end of which is connected to the inverter and the other end to the load. The first end of the coil is the inductor's input voltage, while the other end represents the inverter's output voltage. The second end of the coil is the inductor's output voltage, which is the same as the load voltage. When it is proposed to use pulse width modulation technology to regulate the operation of the electronic switches of the type EGPT used to build the inverter, and assuming that the voltage and current signals of the inverter can be represented as shown in Fig. 6, the time periods and the change in these electrical quantities resulting from the operation of the system can be identified.

LC filter design include, first inductor design and capacitor design. First inductor design, for any inductor, the amount of voltage applied across the two ends of the inductor is calculated using the mathematical relationship in equation (3).

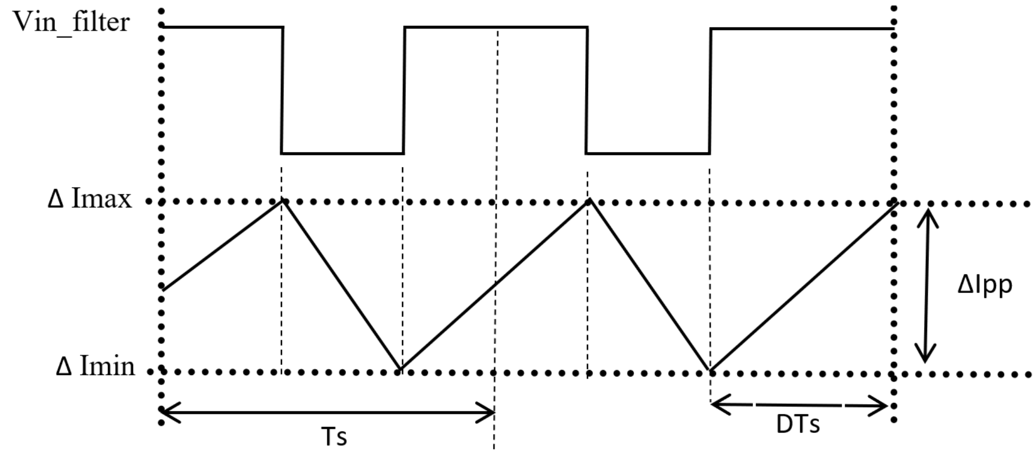

Fig. 6. Model representing the input voltage and output current signals of an inductor

$$V = \text{Li}\frac{di}{dt} \tag{3}$$

The relationship between the input and output of an inductor can be written using the data in the figure, which represents electrical quantities and their change with time, as in equation (4). For any sine wave, the duty cycle $D(\omega t)$at any time can be calculated from the mathematical relationship in the equation (6) where modulation index is (ma).

$$\text{Vin} - \text{Vout} = \text{Li} * \frac{\Delta\,\text{Ipp}}{\text{D Ts}} \tag{4}$$

$$\Delta\,\text{Ipp} = \frac{\text{D Ts}}{\text{Li}} * (\text{Vin} - \text{Vout}) \tag{5}$$

$$D(\omega t) = \text{ma} * \sin(\omega t) \tag{6}$$

$$\text{Vout} = \text{Vin} * D \tag{7}$$

$$\Delta\,\text{Ipp} = \frac{(\text{ma} * \sin(\omega t)\,) * \ \text{Ts}}{\text{Li}} * (\text{Vin} - (\text{Vin} * \text{ma} * \sin(\omega t)\,)) \tag{8}$$

$$\Delta\,\text{Ipp} = \frac{(\text{ma} * \sin(\omega t)\,) * \ \text{Ts}}{\text{Li}} * (\text{Vin} * (1 - \text{ma} * \sin(\omega t)\,)) \tag{9}$$

When, $\frac{d(\Delta\,\text{Ipp})}{dt} = 0$

Then, $\sin(\omega t) = \frac{1}{2*\text{ma}}$

Now

$$\Delta\,\text{Ipp\_max} = \frac{\text{Vin} * \text{Ts}}{4 * \text{Li}} \tag{10}$$

$$\text{Li} = \frac{\text{Vin}}{4 * \text{Fsw} * \Delta\,\text{Ipp\_max}} \tag{11}$$

$\text{Li} = \frac{\text{Vin}}{4*\text{Fsw}*\Delta\,\text{Ipp\_max}} = \frac{400}{4*10000*8.69*1.414*0.2} = 4.06\text{mH}$

Second capacitor design, to design a capacitor within an LC filter, the mathematical representation of the cut-off frequency can be adopted as in equation (12).

$$\mathrm{Fc} = \frac{1}{2 * \pi * \sqrt{\mathrm{LC}}} \tag{12}$$

To obtain a good filter, one can take advantage of the relationship between the filter's cut-off frequency (Fc) and the operating frequency of the inverter's electronic switches (Fsw), which can be represented mathematically by the equation (13).

$$\mathrm{Fc} <= \frac{\mathrm{Fsw}}{10} \tag{13}$$

$$\frac{\mathrm{Fsw}}{10} = \frac{1}{2 * \pi * \sqrt{\mathrm{LC}}}$$

$$C = \left(\frac{10}{2 * \pi * \mathrm{Fsw}}\right)^2 * \frac{1}{L} \tag{14}$$

$$C = \left(\frac{10}{2 * \pi * 10\mathrm{KHz}}\right)^2 * \frac{1}{L4.06\mathrm{mH}} = 6.23 microF$$

3. Matlab Simulink

The proposed system model can be described as consisting of four parts, the first of which represents the power supply, which is a 400V DC source that can be obtained from a renewable energy source such as solar, batteries, DC microgrid, etc. The first part, which is a constant voltage DC source, is added during the 0.3 second simulation period of the system operation, to other parts such as the second, which is a single-phase full-wave inverter consisting of four IGPT transistor electronic switches. The third part, which is the inverter, can be connected to the load via an LC pass-through filter, which is the fourth part.

Fig. 7 represents a simulation model of the system and includes a DC power source in addition to a single-phase bridge inverter, a filter, a load, in addition to voltage and current sensors and control systems.

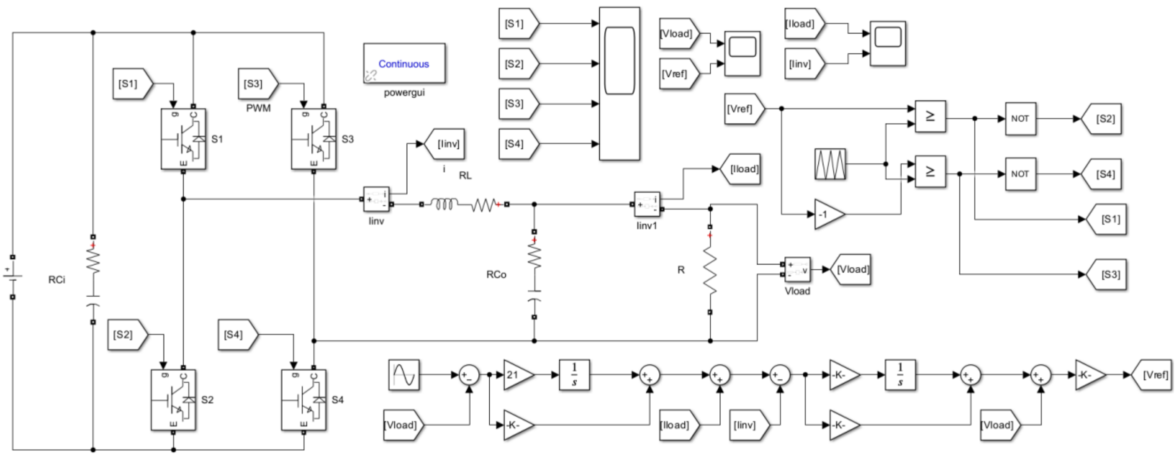

Fig. 7. Modeling of single phase stand-alone inverter

Description of the proposed system model, the proposed system model for testing consists of seven blocks. The first includes the power supply, as shown in Fig. 8, which is connected to the second block on the input side, representing a single-phase voltage inverter, as shown in Fig. 9. The second block consists of four IGBT transistor electronic switches connected using a bridge method. The output is connected to the third block, which is an LC-type pass-through filter and the system load, as shown in Fig. 10. The fourth block represents the control unit for both current and voltage, with a

Vol. 5, No. 2, 2025, pp. 1498-1518

reference value selected according to the appropriate value to cover the load, as shown in Fig. 11. The fifth block represents the pulse generator model for triggering electronic switches using pulse width modulation technology, as shown in Fig. 12. The simulation results for the sixth and seventh blocks include the trigger pulses, current waveform, and voltage waveform, as shown in Fig. 13, Fig. 14 and Fig. 15.

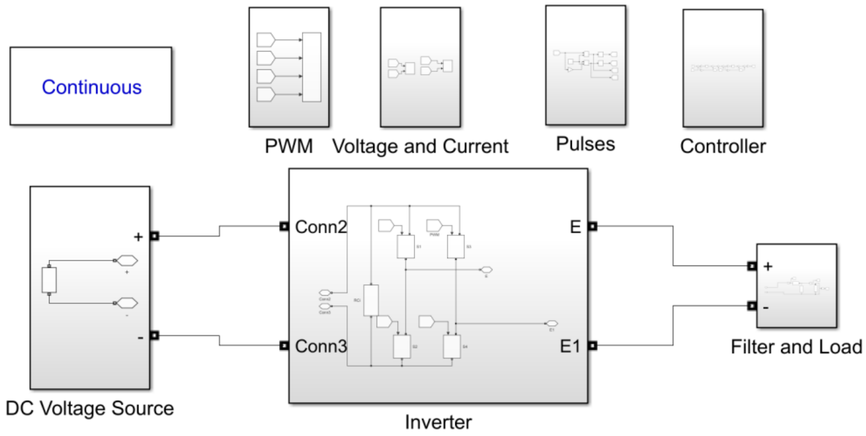

Fig. 8. Modeling for testing consists with seven blocks of single phase stand-alone inverter

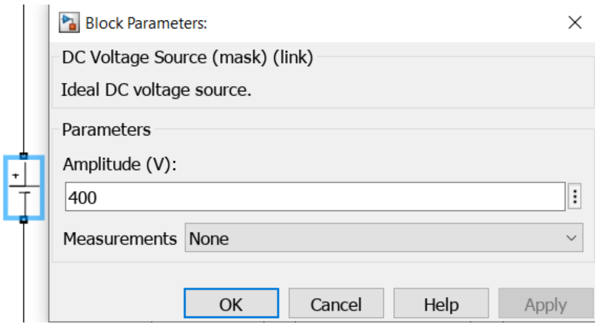

Fig. 9. Modeling of DC voltage power supply

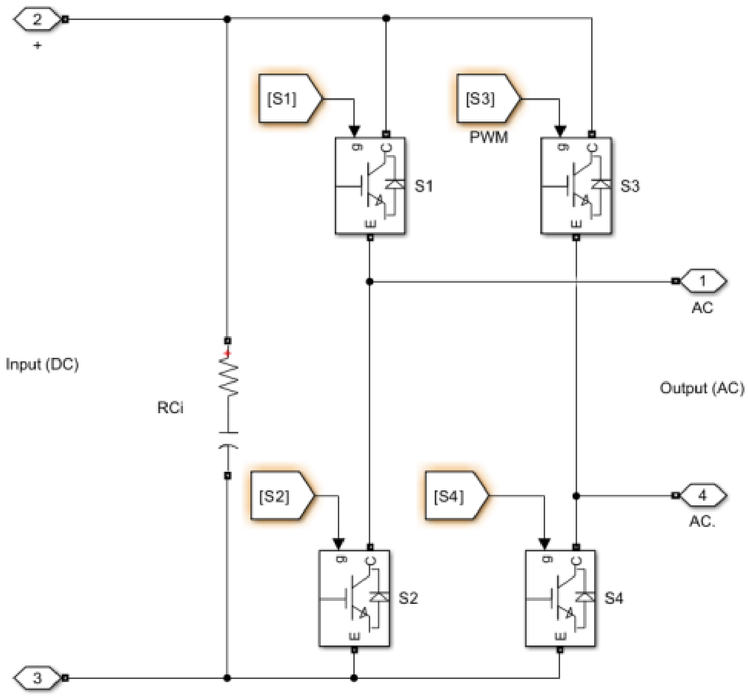

Fig. 10. Modeling of single-phase voltage inverter

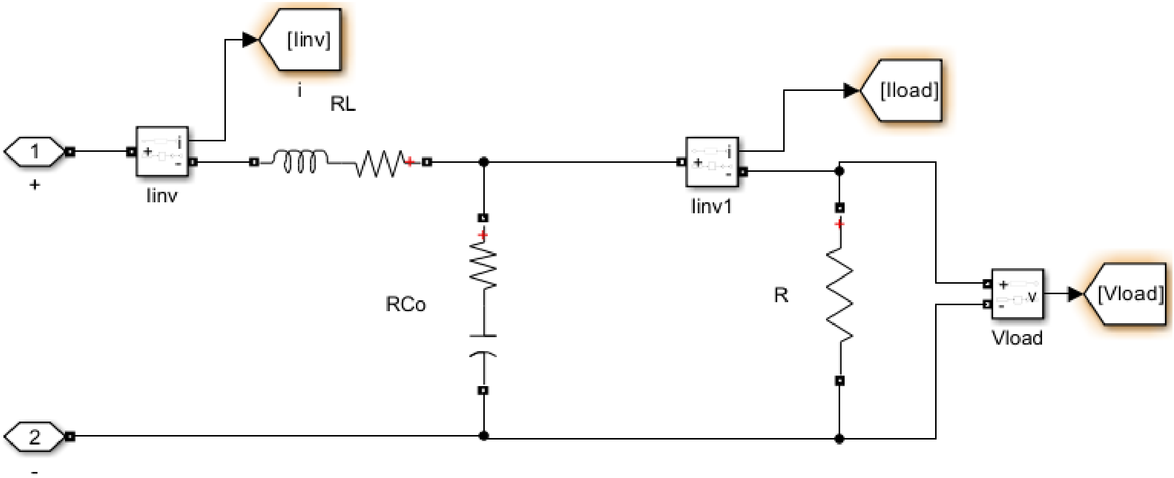

Fig. 11. Modeling of LC_filter and R load

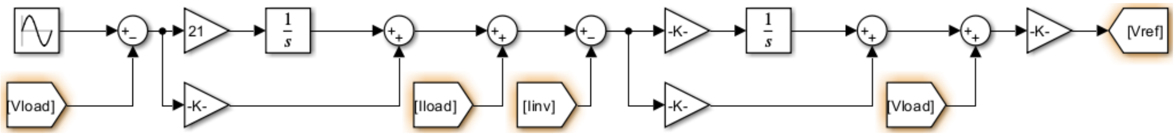

Fig. 12. Modeling of controller

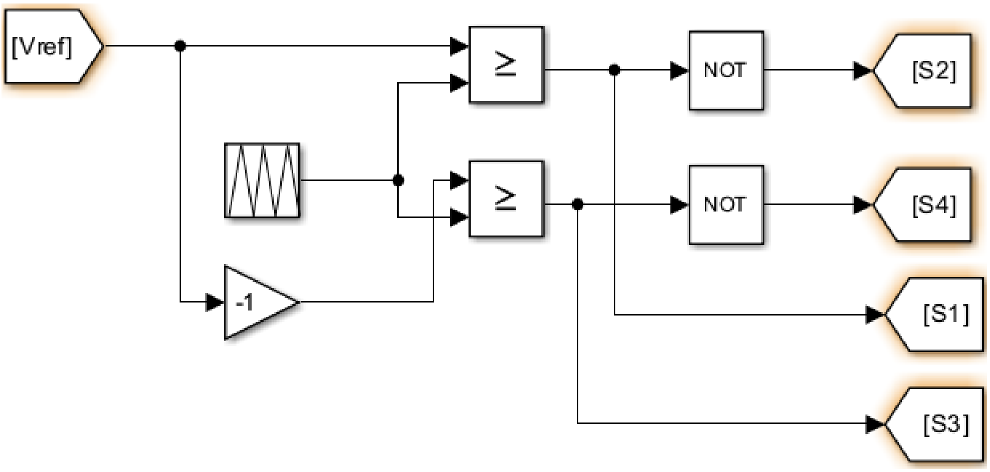

Fig. 13. Modeling of pulses generator

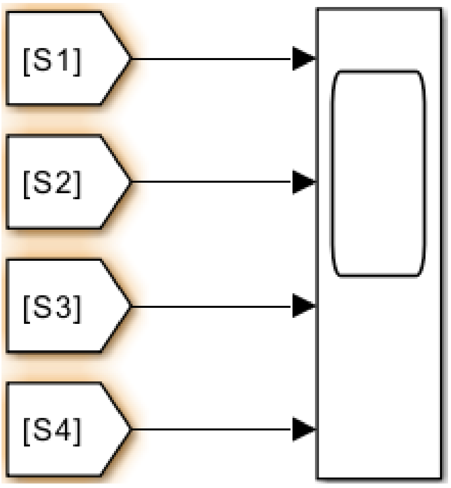

Fig. 14. Modeling of sensor for pulses

Vol. 5, No. 2, 2025, pp. 1498-1518

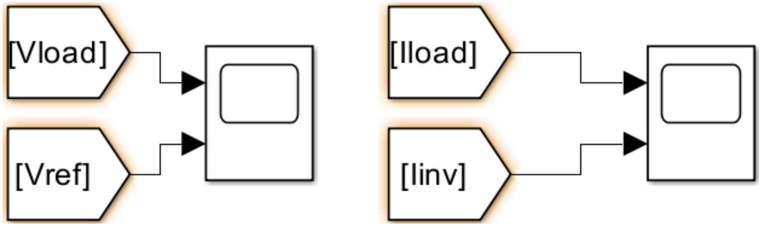

Fig. 15. Modeling of sensor for voltage and current

4. Modeling and Results of Single Phase Stand-Alone Inverter

Using the system model in Fig. 8, the test can be performed with a resistive load of 55 ohms as in Fig. 16 and a reference wave of 300 volts AC as in Fig. 17, in addition to a carrier wave to regulate the trigger pulses, the details of which are shown in Fig. 18.

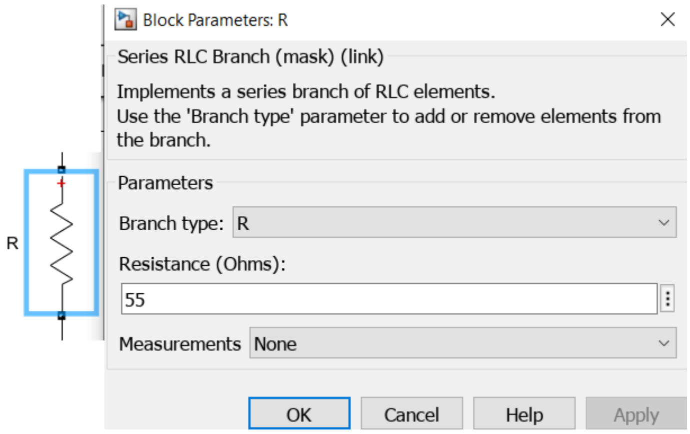

Fig. 16. Modeling of R load at 55 Ohm

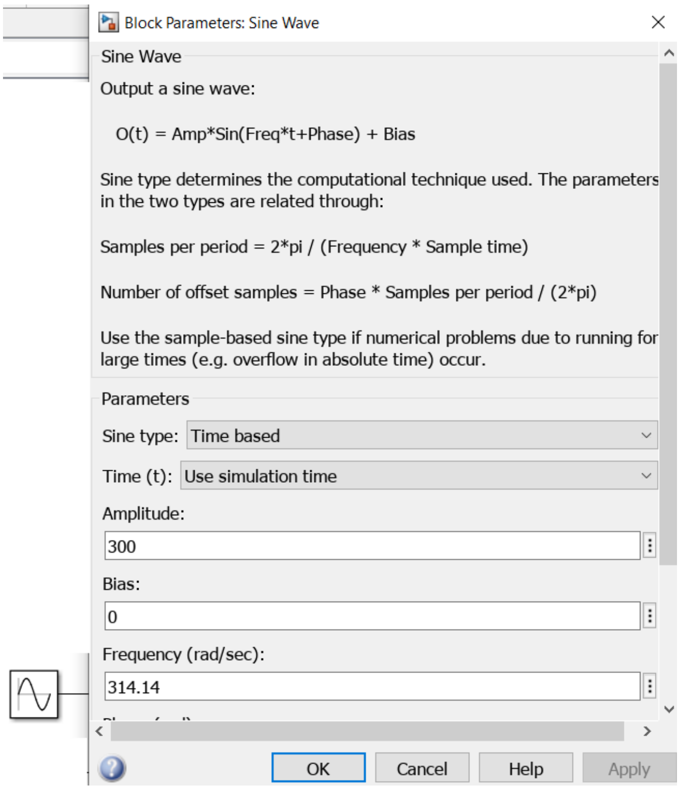

Fig. 17. Modeling of Vref at 300 volt

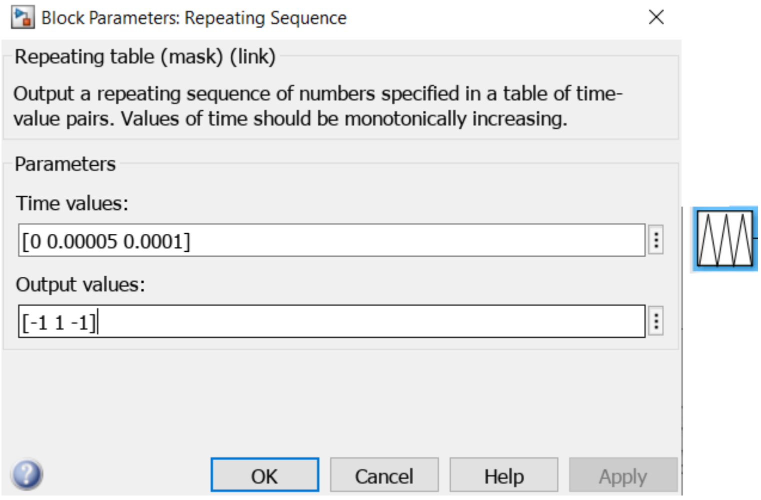

Fig. 18. Modeling of carrier wave to regulate the trigger pulses

Using the model in Fig. 13, we can identify the system's response in the process of generating the four trigger waves to regulate the operation of the electronic switches, the results of which can be seen as in Fig. 19.

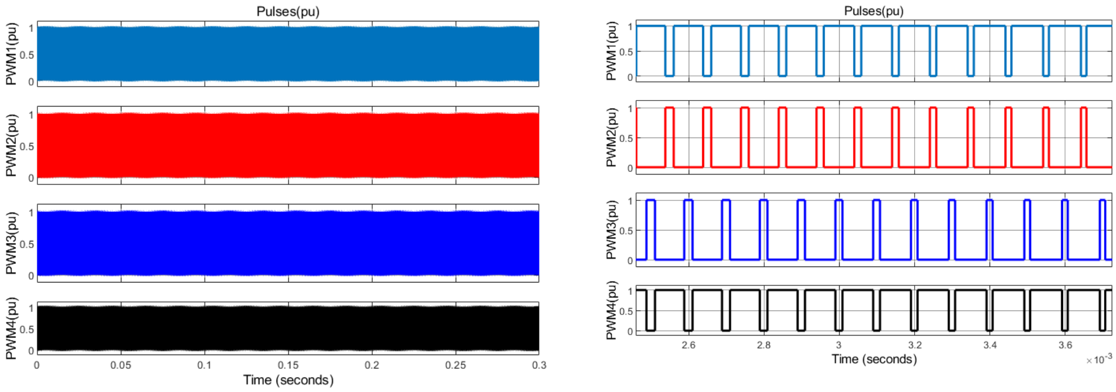

Fig. 19. Response of pulses for electronic switches

Using the model in Fig. 15, the system response can be identified in the process of drawing the voltage and current signals for the load and inverter and the reference voltage value, the results of which can be seen as in Fig. 20, Fig. 21:

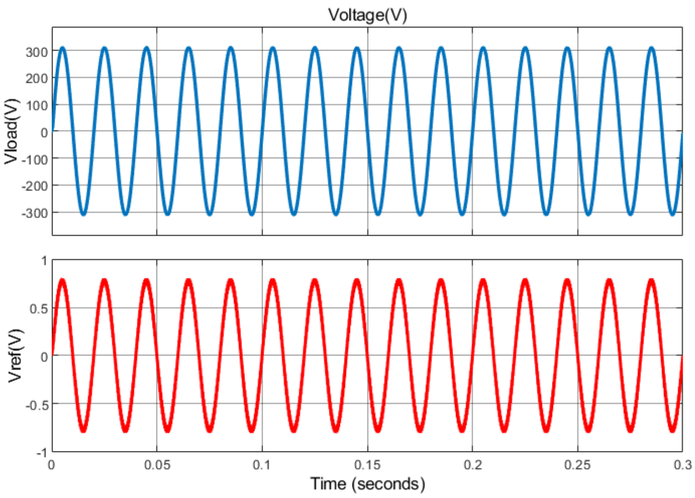

Fig. 20. Response of the reference voltage and the load voltage with Vref at 300 volt

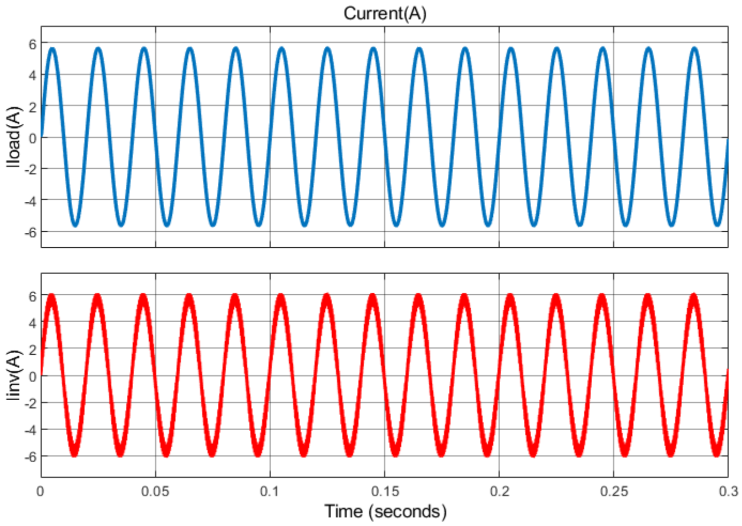

Fig. 21. Response of the inverter current and the load current at 55 ohm

Another test case involves changing the load value from 55 to 100 ohms, as shown in Fig. 22. Using the model in Fig. 15, the system's response can be identified by plotting the current signals for the load and inverter, the results of which can be viewed in Fig. 23:

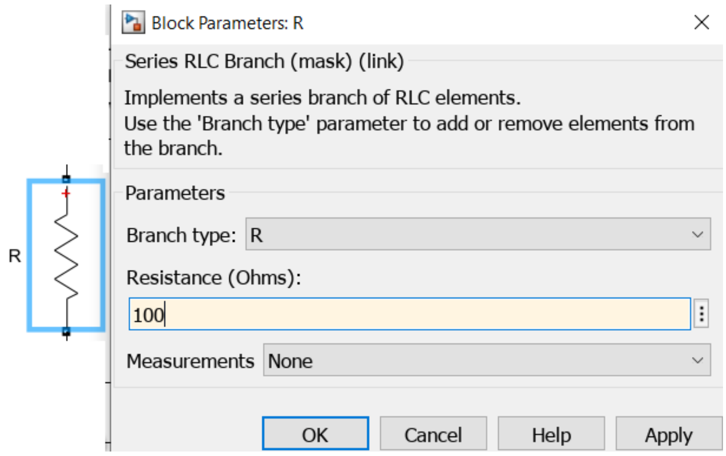

Fig. 22. Modeling of R load at 100 Ohm

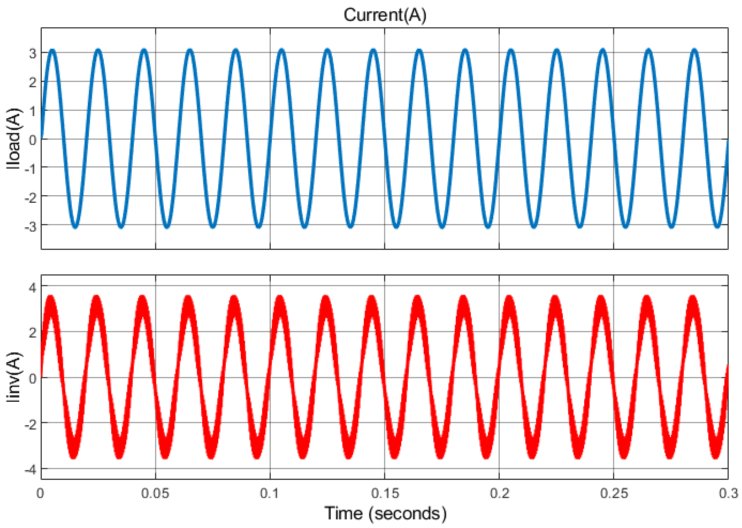

Fig. 23. Response of the inverter current and the load current at 100 Ohm

Another test case involves changing the reference voltage value from 300 to 200 ohms, as shown in Fig. 24. Using the model shown in Fig. 15, the system response can be determined by plotting the voltage and current signals of the load, the inverter, and the reference voltage value. The results can be viewed as shown in Fig. 25 and Fig. 26:

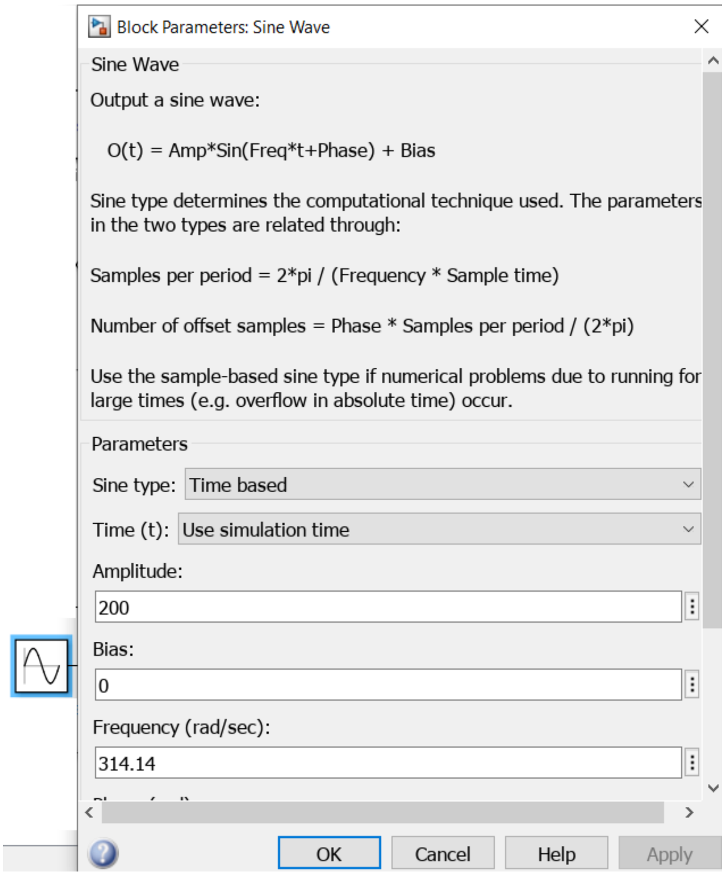

Fig. 24. Modeling of Vref at 200 volt

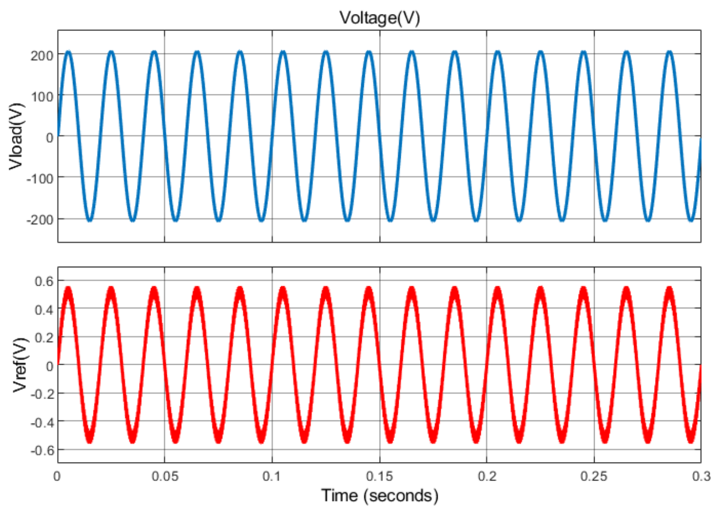

Fig. 25. Response of the reference voltage and the load voltage with Vref at 200 volt

After verifying the system's behavior, a comparison can be made between open-loop (no feedback) and closed-loop (PI controller) models using a specified reference value for the inverter output to supply the specified amount of power to the load. The Fig. 27, Fig. 28, Fig. 29, Fig. 30 show the simulation model, the inverter output, and the electrical quantities, including voltage and current.

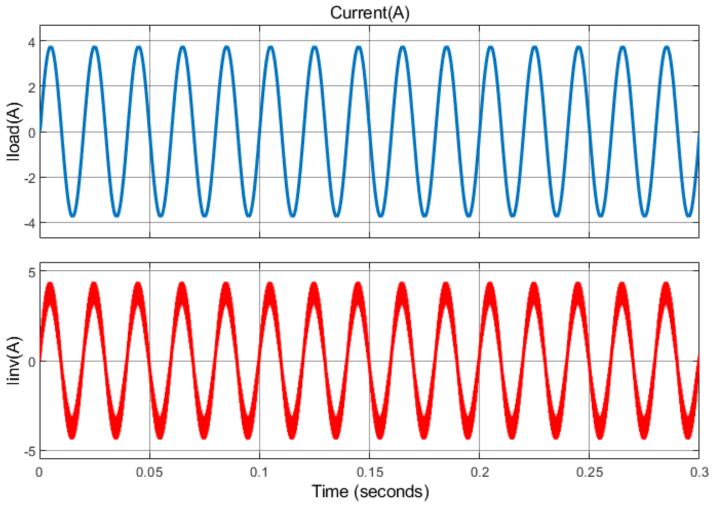

Fig. 26. Response of the inverter current and the load current

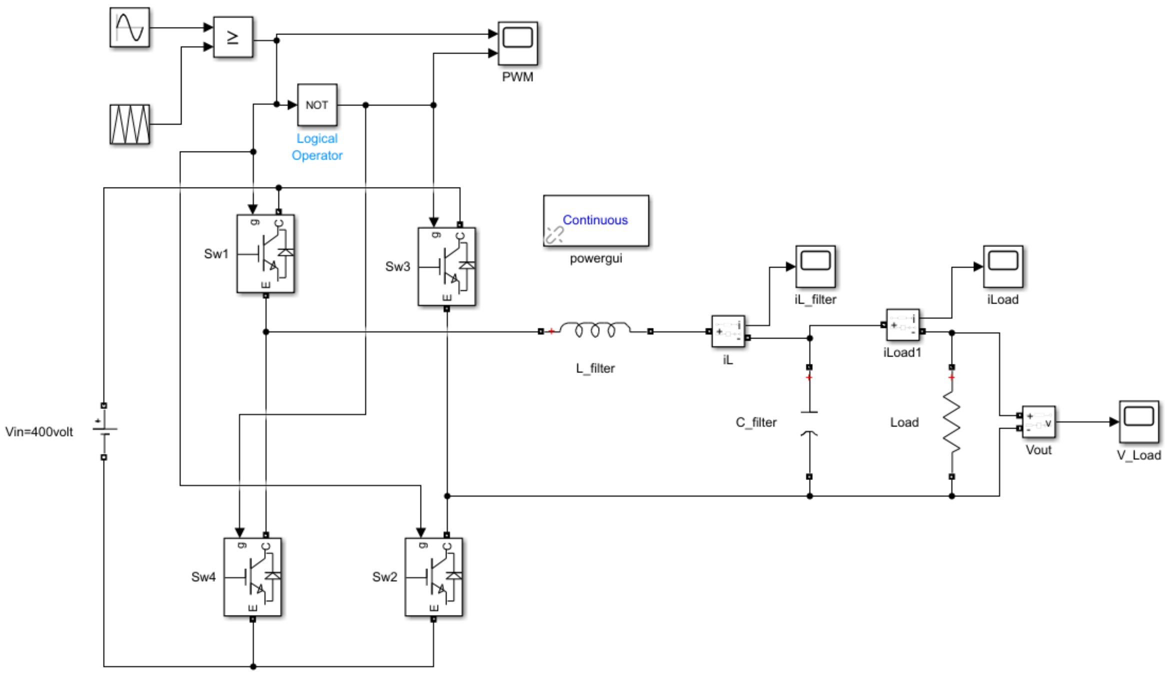

Fig. 27. Simulation model of open loop for single phase inverter

In Fig. 28, this figure shows the output voltage around 180v and output current around 1.8A when ma = 0.45. In Fig. 29, this figure shows the output voltage around 370v and output current around 3.7A when ma = 0.9. Fig. 30 show Response of the THD for open loop system, Fig. 31 show response of the THD and FFT window for voltage load at open loop system, Fig. 32 show response of the THD and FFT window for current load at open loop system, Fig. 33 show simulation model of close loop for single phase inverter, Fig. 34 show response of the current and the load current when Vref = 300 Volt, Fig. 35 show response of the THD for close loop system, Fig. 36 show response of the THD and FFT window for voltage load at close loop system, Fig. 37 show response of the THD and FFT window for Current load at close loop system.

After conducting the simulation, the potential for performance improvement was verified and the required reference value for powering the load was achieved. The results showed the difference between the open-loop and closed-loop test cases, using total harmonic distribution. The values for the open and closed-loop systems were as follows, THD equal 2.76% with 180 volts at open loop system while the value of THD = 1.45% with 300 volts that is the reference value of the voltage load.

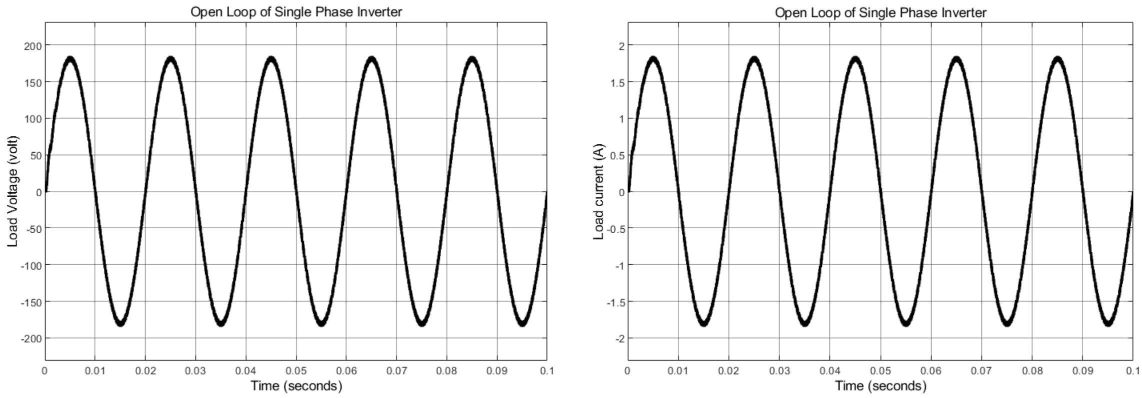

Fig. 28. Response of the current and the load current when ma = 0.45

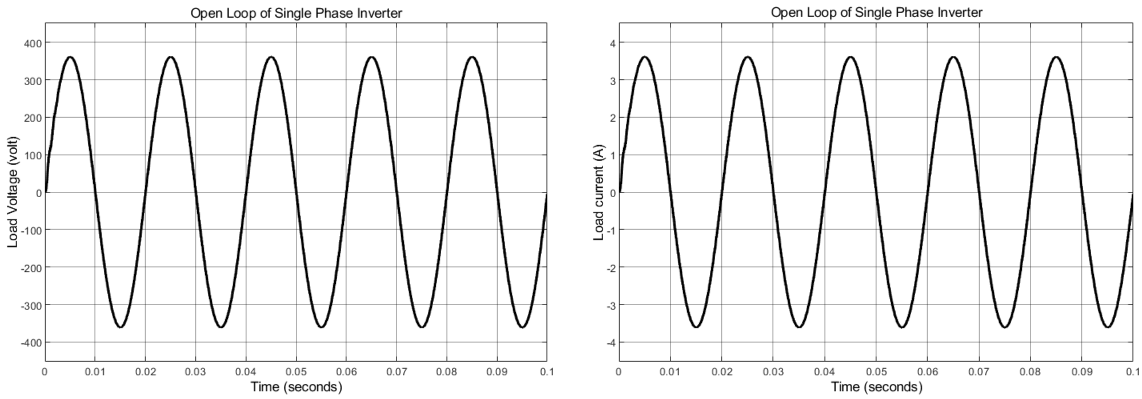

Fig. 29. Response of the current and the load current when ma = 0.9

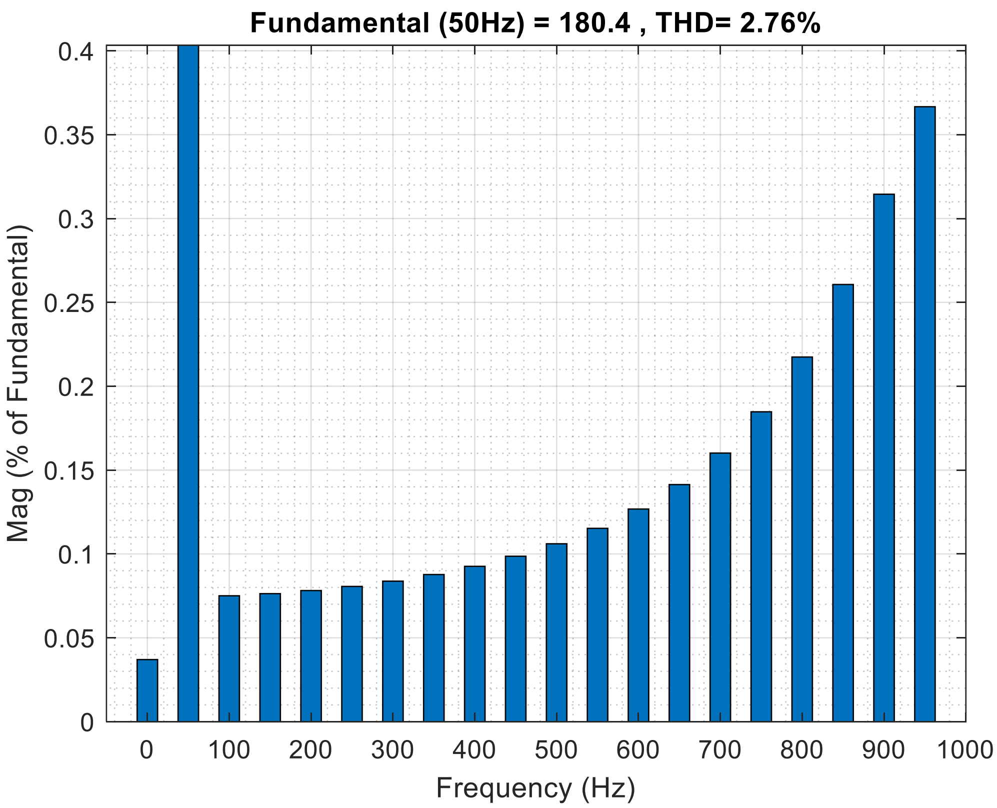

Fig. 30. Response of the THD for open loop system

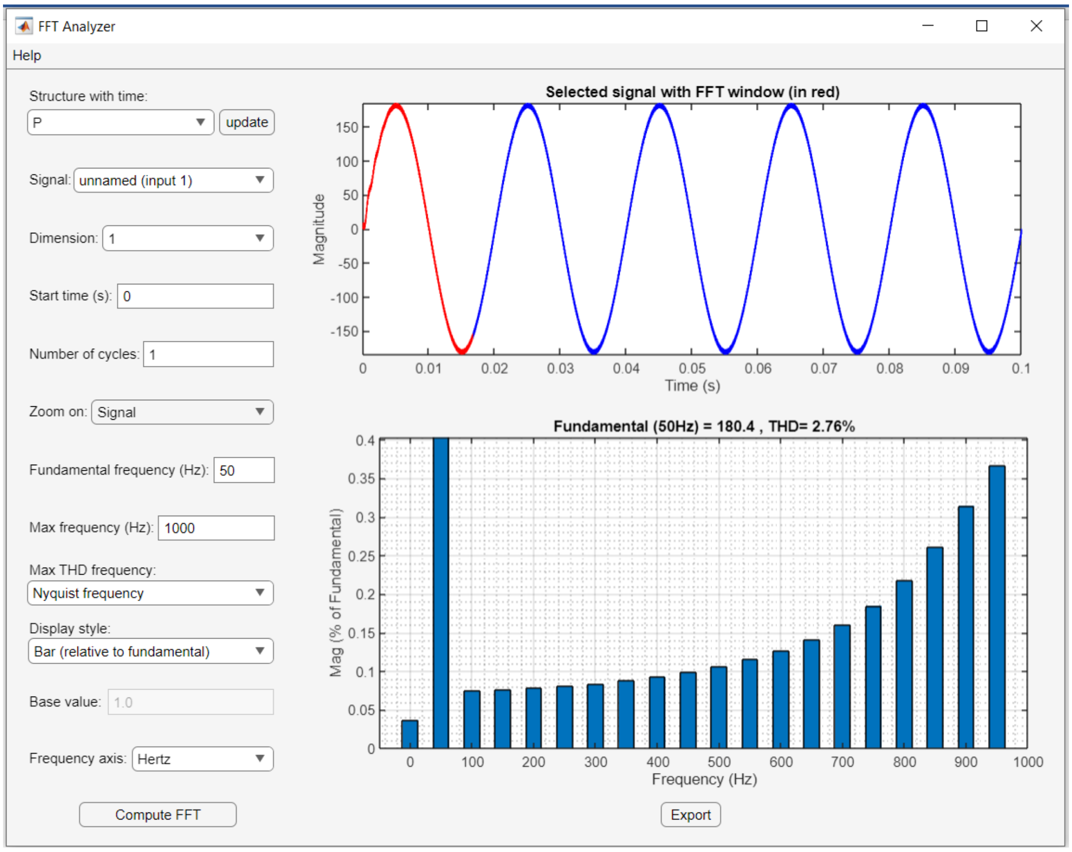

Fig. 31. Response of the THD and FFT window for voltage load at open loop system

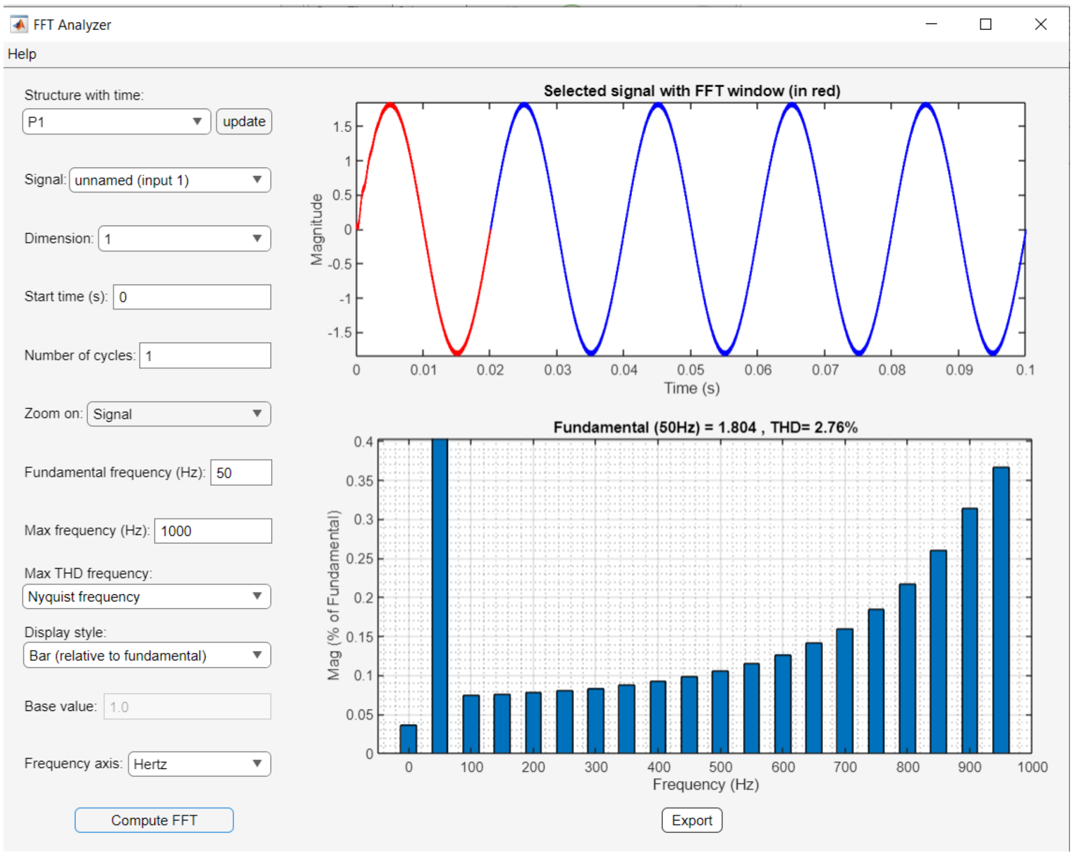

Fig. 32. Response of the THD and FFT window for current load at open loop system

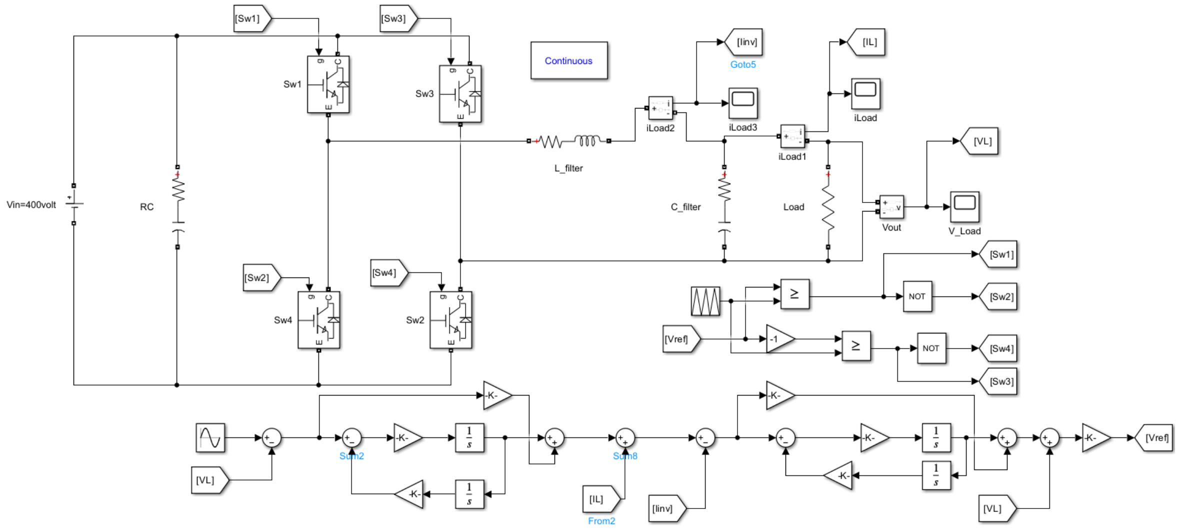

Fig. 33. Simulation model of close loop for single phase inverter

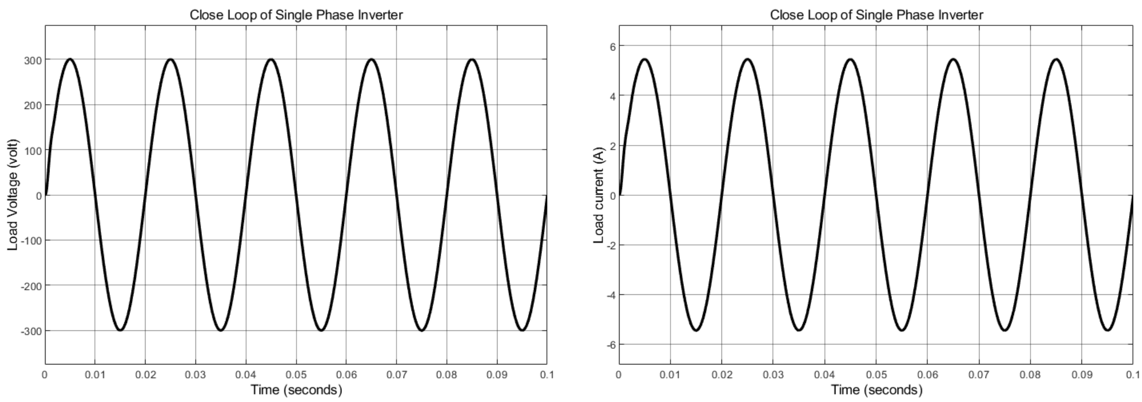

Fig. 34. Response of the current and the load current when Vref = 300 volt

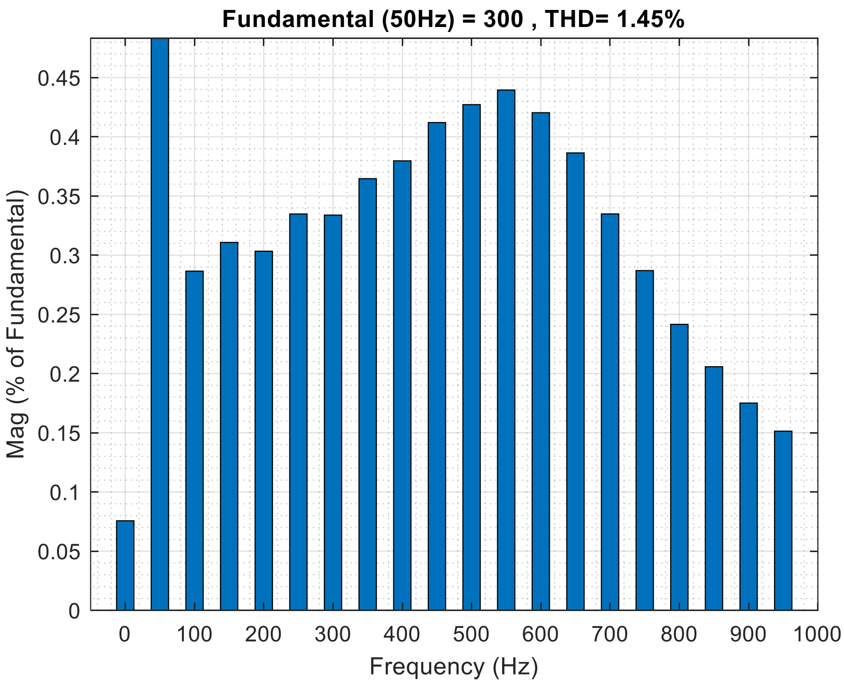

Fig. 35. Response of the THD for close loop system

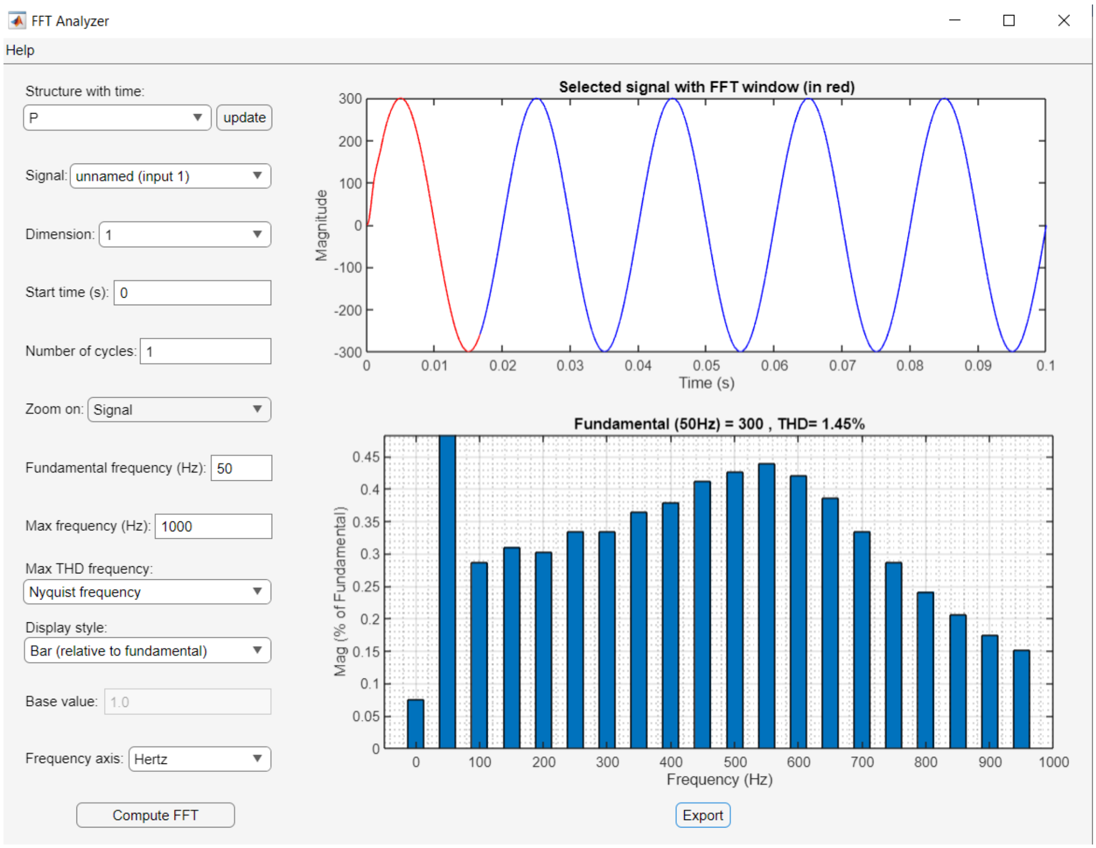

Fig. 36. Response of the THD and FFT window for voltage load at close loop system

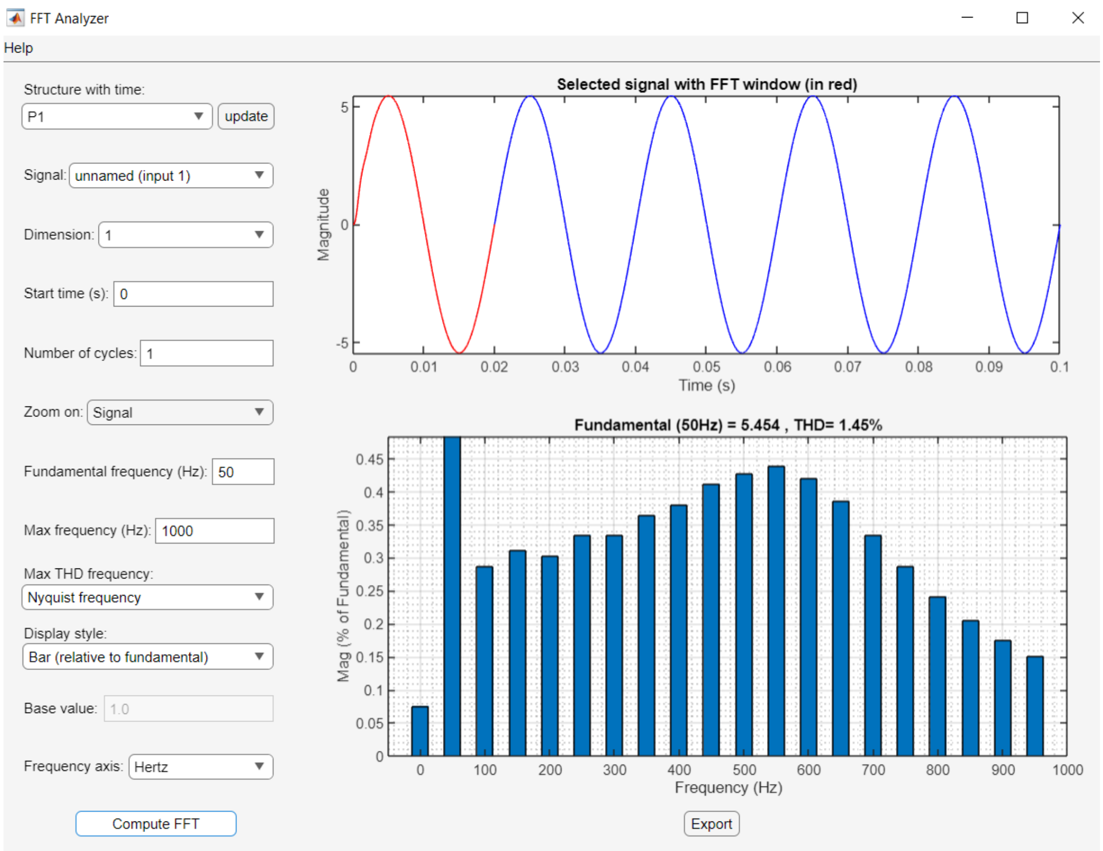

Fig. 37. Response of the THD and FFT window for current load at close loop system

5. Conclusion

By conducting open-loop and closed-loop tests on a single-phase inverter, it was found that performance could be improved by adding a filter and a control unit to reduce harmonics and obtain a pure sine wave. The test results demonstrated the effectiveness of the model and succeeded in providing a high-performance inverter. A highly efficient inverter output control unit was also designed. The results also demonstrated the quality of the output waveforms for voltage and current despite changes in operating conditions through changes in the reference value and load. The results proved that tracking the reference value using a conventional controller succeeded in providing the required voltage to cover the load. Based on the simulation results, it can be recommended to use the proposed simulation model in future applications.

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