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Design of PFC converter with stand-alone inverter for microgrid applications

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Abstract

The proposed topology is used to connect a single-phase and a three-phase renewable energy resources to the grid. The single-phase source is coupled to a single-phase PFC boost converter, which enhances the input PF utilizing two feedback loops: outer voltage loop control and inner current loop control. The basic hightlight is to study the PFC converter in microgrid application where renewables are integrated with the systems. The basic aim is to observe the overall performance of the converters with various disturbances such as load variations, etc. Here, the single-phase and three-phase stand-alone inverter is used to get the the output of the PFC boost converters. A symmetrical sinusoidal output voltage waveform should be produced and maintained by the inverter. The three-phase source is also coupled to a PFC buck converter, which enhances the input PF utilizing two feedback loops: outer voltage loop control and inner current loop control. The single-phase stand-alone inverter receives the output of the PFC buck converter. The transformer receives the outputs of both the inverters as it is a multi-winding high-frequency transformer and offers isolation between the grid and the source. The pulses for the switches in the single-phase inverter coupled stand-alone system were generated using a sinusoidal pulse width modulation approach. Both the PI controllers are implemented to maintain the regulations. The simulation results are achieved by varying the load, maintaining a constant voltage, and observing whether the current varies as the load changes. It also provides the efficacy of the study.

Introduction

With the rising demand for energy over the past several years, power shortages have been identified as a critical concern. It has been more than a century since the creation of an electric grid, which distributes electricity from producing units to customers. The use of these nonrenewable resources (such as coal, oil, etc.) has the advantage of enabling power plants to produce more energy in response to customers' needs. However, the combustion of nonrenewable sources to create energy results in the production of gases that trap heat, such as carbon dioxide. The world is experiencing energy crises due to the rapidly dwindling of fossil fuels and an over-reliance on nonrenewable sources. With the increased demand for electricity in recent years, power shortages have become a critical issue. Renewable energy resources are gaining traction as a result of

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their unique characteristics, which enable them to meet the ever-increasing demand. In comparison with traditional energy sources, they are inexpensive, long-lasting, and have lower operating costs. However, electric power is utilized, and the sources from which the electric energy is acquired are many. Microgrids that include more than one type of electric power source are growing. Designing and controlling such hybrid systems optimally are of supreme importance. Interconnecting the microgrid to the distribution network requires proper control and management of the microgrid power flow. Such a requirement plays a pivotal role that deciding how advantageous it is to interconnect a microgrid to the network.

These days, having a low PF is a significant issue which has acquired increasing significance in the area of power electronics. It is possible to create single-phase PFC circuit architecture and applying linearized voltage control. In this instance, the diode bridge rectifier is assumed to be the nonlinear load, and a converter is coupled to the back end of it for performing PFC operation. The boost converter, on the other hand, is very easy to use and has the potential to dramatically enhance the PF of the circuit. The boost PFC rectifier is the one that has garnered the most interest among these potential solutions. When designing a single-phase PFC boost converter, it uses a dual-loop control design that incorporates the inner inductor current and outside voltage loops [1].

In most cases, loads which are nonlinear are the primary cause of harmonics. The control strategy to correct for the harmonic current that is produced by the diode rectifier in order to obtain a PF that is closer to unity and to manage the voltage on the DC bus. In order to follow the line current command, the hysteresis current controller must be used. If there is no diode rectifier present, also known as a nonlinear load, the PFC boost converter will pull entirely sinusoidal current from the source. The PFC single-stage converters are unique in that the power conversion and PFC processes are performed concurrently by a single converter that also controls the output. The result is an increase in the THD at the input source [2]. The PFC converter's voltage control loop and current control loop are independent, low-frequency output voltage ripple has no effect on the current control loop, unlike with ACM control. As a result, a high PF and a rapid dynamic response are both achievable [3].

The technique for designing an LC filter used in the inverter output filter is outlined below. The value of the capacitor, together with the time constant of the system, is used to characterize the transfer function of the load current in relation to the output voltage of the filter. The system controller is also taken into consideration [4, 5]. This inverter will include the capabilities of both a stand-alone power supply and a power supply that are linked to the grid [6]. Its output voltage has low THD when used as a stand-alone power supply, and when it is coupled to the grid, it has a high PF, so that it may give an AC output with high-performance power quality. The pure sine waves inverters that are highly efficient and cost effective are seeing a high level of demand on the local market as a direct result of the increasing rise of PV power production. By utilizing a guarantee that the inverter's output waveform is optimized by using an appropriate harmonic removal approach, error in the output signal can be kept to a minimum for both inductive and capacitive loads. This is accomplished through the use of an inverter [7]. Harmonic distortion may be kept to a minimum with the use of appropriate PWM control schemes. The PWM approaches regulate inverter output voltage [8–11]. The usage of power electrical gadgets is commonplace in a variety of settings, including business and consumer settings. These home appliances are responsible for a significant number of issues with the electricity system's quality. Some of the most prevalent issues relating to power quality are voltage sags, spikes, poor PF, electrical noise, harmonic distortion, and so on. Recent years have seen a rise in the amount of focus placed on low PF within this industry. The design of PFC boost converter with stand-alone inverter for microgrid applications is also reported in [12–14].

This work proposes a PFC boost and PFC buck converters which are cascaded with the H-bridge inverter, and the outputs of the H-bridge inverters are connected to the high-frequency multi-winding transformer. The output of the PFC boost is given to the H-bridge inverter. The PFC boost and the PFC buck converters improve the input PF of the source and maintain a regulated DC output voltage. The controllers for the PFC boost and the PFC buck are designed by mentioning the inner current loop control and the outer voltage loop control. In order to ensure system dependability, the output voltage of stand-alone systems is adjusted. In order to fulfil this need, the controller has been developed specifically for use with stand-alone systems. The inverter output is maintained sinusoidal, the unipolar PWM switching scheme is used for the generation of switching pulses for the inverter. The inverter control loop is discussed. The advantages of using a high-frequency multi-winding transformer are discussed.

Block diagram of the topology

The block diagram shows the outline of the topology and the converters which are involved in the topology. Here, two different supplies are shown in the block diagram; one is a single-phase supply, and the other is a three-phase supply. The PFC boost receives the supply that is linked to a stand-alone inverter, and PFC buck receives the supply that is connected to a stand-alone inverter. The single-phase supply is delivered to PFC boost, and the three-phase supply is given to PFC buck. The inverters are linked to a high-frequency multi-winding transformer, which, in turn, is linked to a PFC boost converter. The load is linked to the stand-alone inverter, which, in turn, is coupled to the PFC boost converter.

Design of PFC boost converter

A PFC uses a single-phase diode bridge rectifier, which includes a boost converter. The bridge rectifiers and DC–DC converters with filtering, as well as energy storage devices, are the theoretical solutions, and capabilities may be combined to form a variety of converter configurations. Designing a boost circuit is quite straightforward. It employs a range of specialized control approaches to provide low-distorted input currents and a PF that is close to one. The output is additionally controlled by the PFC boost converter, which is likewise used to regulate the input (Fig. 1).

Due to the fact that the current is constantly passing through three semiconductor elements, which are two diodes in series with diode D or switch S_1, depending on the state of S_1 whether it is on or off, the converter shown in Fig. 2 has significant conduction losses due to the constant passage of the current through these elements. As a consequence, the efficiency of the converter diminishes, which is especially noticeable at low input voltage. In

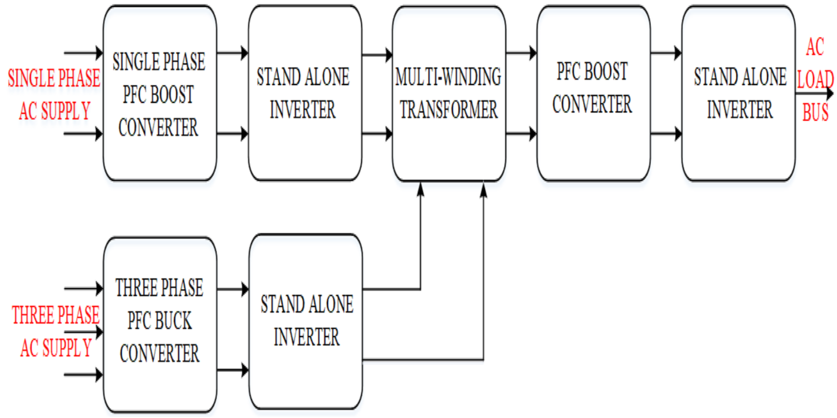

Fig. 1 The block diagram of the topology

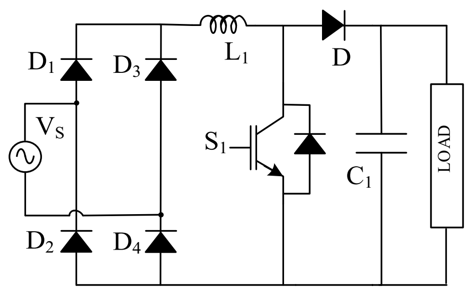

Fig. 2 PFC boost converter

a hard-switching boost converter, the output diode operating at high voltage suffers significant reverse recovery losses as the switching frequency of the converter is increased.

Analysis of boost converter

The analysis of the converter when the switch is on

$$V_{\mathrm{in}} = L\frac{\mathrm{d}i_L}{\mathrm{d}t} \tag{1}$$

$$C\frac{\mathrm{d}V_0}{\mathrm{d}t} = \frac{-V_0}{R} \tag{2}$$

when the switch is off

$$L\frac{\mathrm{d}i_L}{\mathrm{d}t} = V_{\mathrm{in}} - V_0 \tag{3}$$

$$C\frac{\mathrm{d}V_0}{\mathrm{d}t} = i_L - \frac{V_0}{R} \tag{4}$$

Control block diagram of PFC boost converter

The peak of the AC voltage waveform is detected to generate a sinusoidal reference for the current controller. The voltage controller regulates the output voltage which is followed by the current controller which controls the inductor current and also maintains the sinusoidal wave shape [4].

The reference current I_{ref} and feedback current I_L averaged over the per-switching period can be used to keep the switching frequency constant. Then, I_L is compared with I_{ref}.

- If $I_{ref} > I_L$, then the duty cycle is more than 0.5
- If $I_{ref} = I_L$, then the duty cycle is equal to 0.5
- If $I_{ref} < I_L$, then the duty cycle is less than 0.5.

The inductor current is forced to stay between the maximum and minimum of the triangular waveforms by following the reference sine wave, which is superimposed with a triangle waveform. The reference current I_{ref} is calculated using the error voltage V_e ($= V_{ref} – V_{out}$) and the boost converter's input voltage V_{in}. The error of the I_{ref} and I_L is given to the PI controller which is followed by the limiter. The output of the limiter is given to the PWM generator which generates the pulses for the switch (Fig. 3).

Design of three-phase PFC buck converter

It is not uncommon for two converter stages to be combined to create a three-phase rectifier system with PFC and broad output voltage range. Sinusoidal mains currents are ensured by either an up or down PFC rectifier step, which produces a lower or higher intermediate DC voltage depending on the AC voltage. Three-phase rectifier systems with PFC and wide output voltage ranges are known as full-bridge rectifiers. As a consequence of this, a further DC–DC conversion step is necessary in order to accomplish the desired broad range of regulated DC output voltages. This very high topological complexity is complemented by equally difficult control and modulation techniques (Table 1).

Even in systems with relatively modest power ratings, PFC functionality and potentially even AC-to-DC voltage compatibility are necessary, which is to say below 1 kW, in some

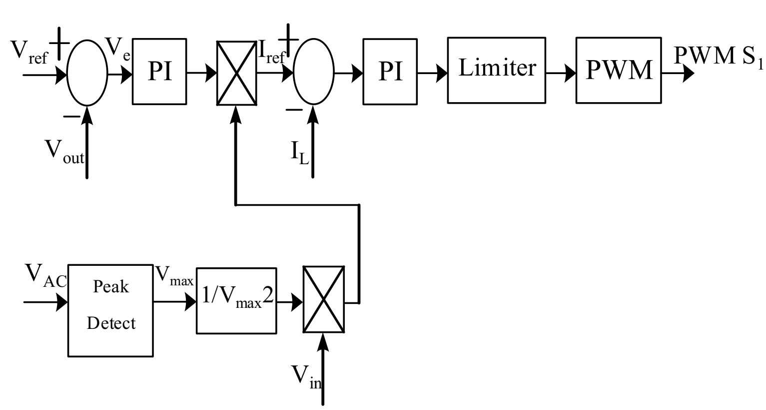

Fig. 3 Controller block diagram of PFC boost converter

Table 1 Parameters of PFC boost converter

Input voltage (Vs)	230 V
Switching frequency	25 kHz
Boost inductor	0.3 mH
Capacitor	2000 μF
Output voltage	400 V

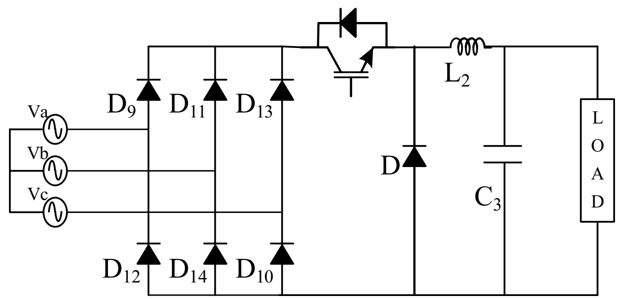

Fig. 4 Three-phase PFC buck converter

new technologies, such as electric planes. This is the case even though the power ratings of these systems are relatively low. For such low-power devices, a two-stage technique would be too difficult and expensive to implement. A high PF, a broad voltage range, and optionally galvanic isolation are all features of these converters—all of which are accomplished with minimal control complexity, i.e. without the need for any current sensors. Additionally, these converters do not require galvanic isolation. In addition, these systems are able to function normally with a broad spectrum of mains frequencies, which is useful for applications such as airborne ones.

It is feasible to construct three-phase rectifiers using either a boost-type topology or a buck-type architecture, which are, in general, equivalent. When compared to boost-type topologies, three-phase buck-type rectifiers, which are capable of maintaining PFC at the input, provide a wide range of output voltage control down to low voltages as well as the ability to restrict current in the event of an output short circuit. The major advantages are reduced load currents on the bus, which means that less cable is needed for transmission, and/or a gain in an overall efficiency of 1 per cent–2 per cent, depending on the application. The provision of effective overcurrent safety in the design of such high-voltage direct current distribution topologies is a difficult challenge to overcome (Fig. 4).

Analysis of buck converter

When the switch is on

$$L\frac{\mathrm{d}i_L}{\mathrm{d}t} = V_{\mathrm{in}} - V_0 \tag{5}$$

$$C\frac{\mathrm{d}V_0}{\mathrm{d}t} = I_L - \frac{V_0}{R} \tag{6}$$

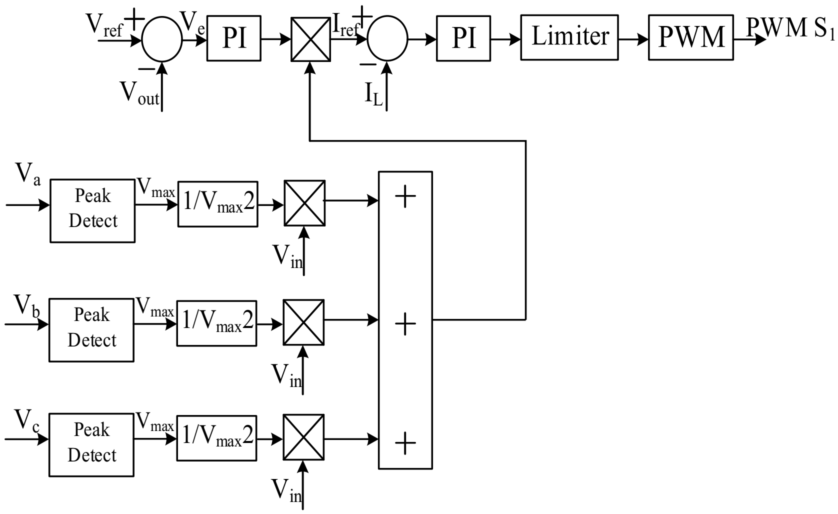

Fig. 5 Controller block diagram of PFC buck converter

Table 2 Parameters of PFC buck converter

Input voltage (Vs)	415 V (ph–ph)
Switching frequency	25 kHz
Boost inductor	0.6 mH
Capacitor	4500 µF
Output voltage	400 V

when the switch is off

$$L\frac{\mathrm{d}i_L}{\mathrm{d}t} = -V_0 \tag{7}$$

$$C\frac{\mathrm{d}V_0}{\mathrm{d}t} = I_L - \frac{V_0}{R} \tag{8}$$

Controller block diagram of three-phase PFC buck converter

The peak of the AC voltage waveform is detected to generate a sinusoidal reference for the current controller. The voltage controller regulates the output voltage which is followed by the current controller which controls the inductor current and also maintains the sinusoidal wave shape (Fig. 5).

The reference current I_{ref} is calculated using the error voltage V_{e} (= V_{ref}–V_{out}) (Table 2).

Design of stand-alone inverter

Working of stand-alone inverter

Stand-alone inverter or off-grid inverter is designed for remote stand-alone application or off-grid power system with battery backup where the inverter draws its DC power from batteries charged by PV array and converts to AC power. Stand-alone

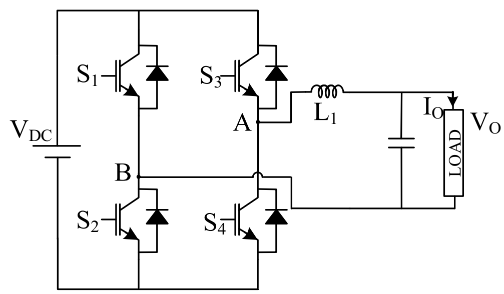

Fig. 6 Circuit diagram of stand-alone inverter

Table 3 Operating modes of stand-alone inverter: operating modes of inverter

MODES	S_1	S_2	S_3	S_4	V_O
1	0	1	1	0	$+V_{DC}$
2	1	0	1	0	0
3	1	0	0	1	$-V_{DC}$
4	0	1	0	1	0

inverters provide variety of size and output waveform depending on your applications. For the best output, the pure sine inverter is required. It suits for solar home system, rural electrification, and village electrification in remote area where the utility grid is not available (Fig. 6).

As the inverter's switching circuit, a full-bridge arrangement with an SPWM unipolar voltage switching technique is used. In the case of unipolar modulation, the switching of each leg occurs in accordance with its respective reference. The legs A and B are switched according to its reference in the case of the technique which we mentioned above (Table 3). The following are the key characteristics of this converter:

- With mirrored sinusoidal reference, leg A and leg B are switched at a high frequency.
- S_1, S_3 = ON and S_2, S_4 = ON are the two possible zero output voltage states.

Mode 1: The power semiconductor switches S_2 and S_3 are turned on in the positive active mode, while the remaining switches are turned off, resulting in an output voltage of V_{DC}. The output current is positive throughout this time.

Mode 2: The power semiconductor switches S_1 and S_3 are turned on in the positive freewheeling mode, while the remaining switches are turned off, resulting in an output voltage of 0.

Mode 3: The power semiconductor switches S_1 and S_4 are turned on in the Negative active mode, while the remaining switches are turned off, resulting in a -V_{DC} output voltage. The output current is negative while this is going on.

Mode 4: The power semiconductor switches S_2 and S_4 are turned on in the negative freewheeling mode, while the remaining switches are turned off, resulting in an output voltage of 0.

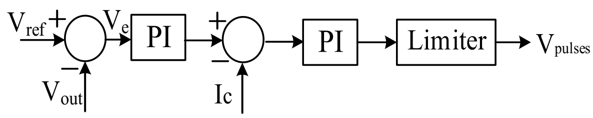

Fig. 7 Controller block diagram of inverter

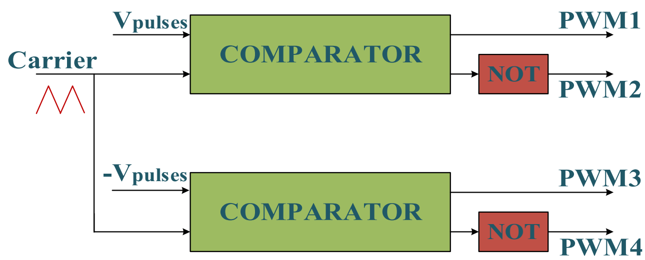

Fig. 8 Unipolar PWM technique

As a result, Mode 1 and Mode 3 are energy delivery stages, with energy from the source fed forward into the load. Modes 2 and 4 are freewheeling phases, and the energy from the AC filter is likewise discharged to the load.

Controller block diagram of inverter

First, we find the difference between the reference voltage (V_{ref}) and the output voltage (V_{out}). We have to properly set the amplitude and frequency of the reference voltage. Now, the difference which is called the error is fed to a PI controller. The output of this gives a capacitor current (Fig. 7). The capacitor current is compared with the actual capacitor current (I_c), and the error is fed to the PI controller which gives a control voltage (V_{pulses}). The reference voltage is given to the PWM generation block. The parameters of both the PI controllers are given below.

Parameters for PI controllers

PI controller (voltage loop)		PI controller (current loop)	
Proportional constant	0.25	Proportional constant	21
Integral constant	35	Integral constant	0.25

The unipolar PWM technique is used for generating the switching pulses. In the unipolar PWM technique, we require two reference voltages that are out of phase with each other. The reference voltage is compared with the triangular carrier wave. The inverted and the non-inverted outputs of each comparator are given to each switch (Fig. 8).

Results and Discussion

Circuit diagram

The topology consists of two inputs single-phase and a three-phase. The single-phase part consists of a PFC boost rectifier with a stand-alone inverter, the three-phase part consists of a PFC buck rectifier and a stand-alone inverter. The outputs of the single-phase part and three-phase part of the inverters are given to the multi-winding

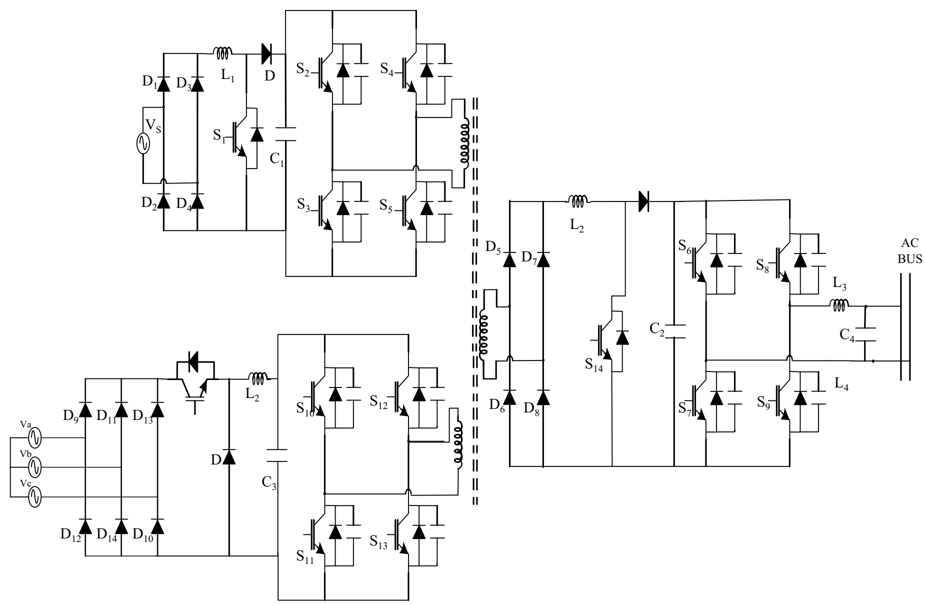

Fig. 9 Circuit diagram of the topology

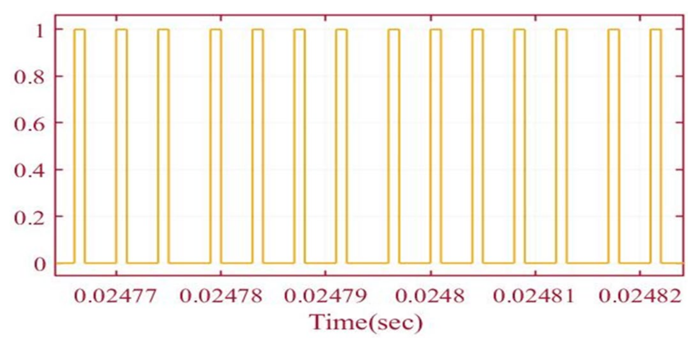

Fig. 10 Switching pulses of PFC boost converter

high-frequency transformer. The multi-winding transformer provides isolation to the circuit and also offers us to connect different ports. The output of the multi-winding transformer is given to the PFC boost rectifier, and the output of the PFC boost rectifier is fed to the stand-alone inverter. The output of the inverter feeds the load. The authors have used linear resistive load for this study; in future, they have extended the work with different types of load (such as RL, RC, RLC, etc.) (Fig. 9).

Figure 10 shows the switching pulses of PFC boost converter which are generated by using controller block diagram (Table 4).

Figure 11 shows the switching pulses of inverter switches (S_1, S_2, S_3, and S_4) which are generated by using the controller block diagram and the unipolar switching scheme.

In accordance with the outcome of the simulation, which is shown in Fig. 12, both the source voltage and source current are in phase with one another. As a result of this, it can be seen that the PF has been enhanced. For better understanding, I have shown the results for three cycles.

Table 4 Parameters of inverter

Input voltage	400 V
Filter inductor	4 mH
Filter capacitor	470 μF
Output voltage	240 V

The PFC boost converter was simulated, and the output voltage is shown in Fig. 13, from the figure, we can observe that the reference voltage given by us is 400 V, and it has been regulated at it.

Figure 14 shows the source current waveform of PFC boost converter without any load variations, and we can observe from the waveform that its sinusoidal.

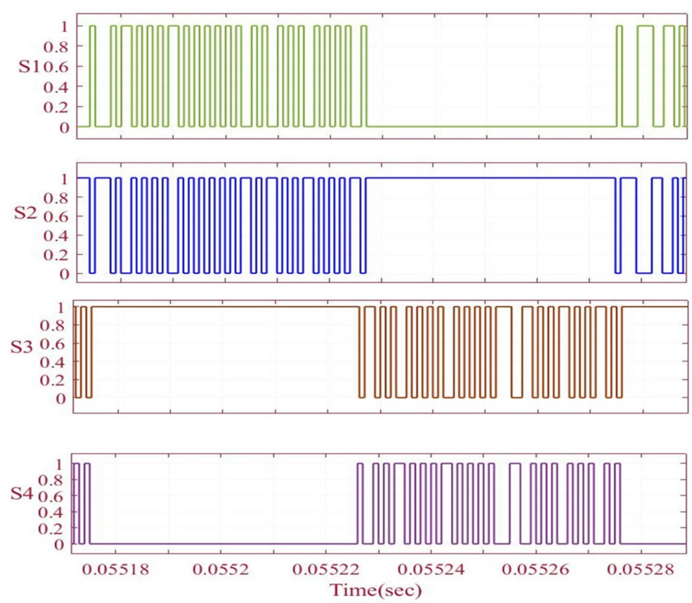

Fig. 11 Switching pulses of inverter

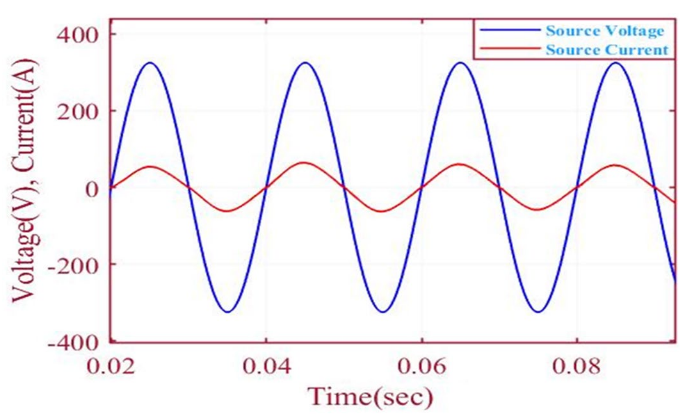

Fig. 12 Voltage and current waveforms of the single-phase input

Figure 15 shows the source current waveform of PFC boost converter with load variation, here I have applied a load from 0.1 to 0.3 s, and the current is being changed with respect to load variations.

Figure 16 shows the output voltage of stand-alone inverter, from which we can observe that the output voltage is symmetrical and sinusoidal in shape irrespective of the load variations.

Figure 17 shows the output current of stand-alone inverter without any load variation in the circuit.

Figure 18 shows the output current of stand-alone inverter with variations in load, the load is varied from 0.2 to 0.5 s in the simulation, and it can be observed from the

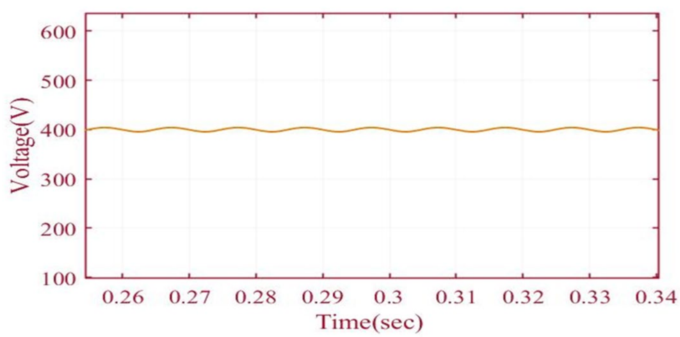

Fig. 13 Output voltage of PFC boost converter

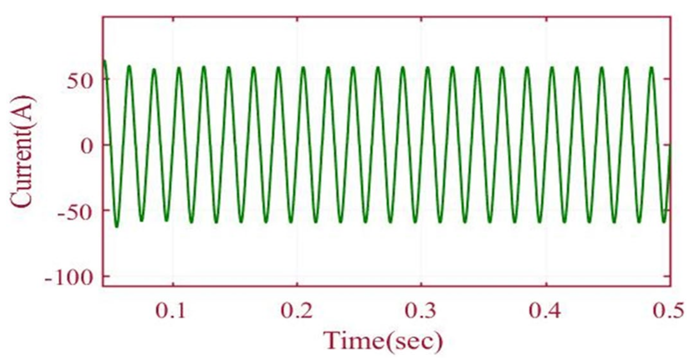

Fig. 14 The source current waveform during constant load

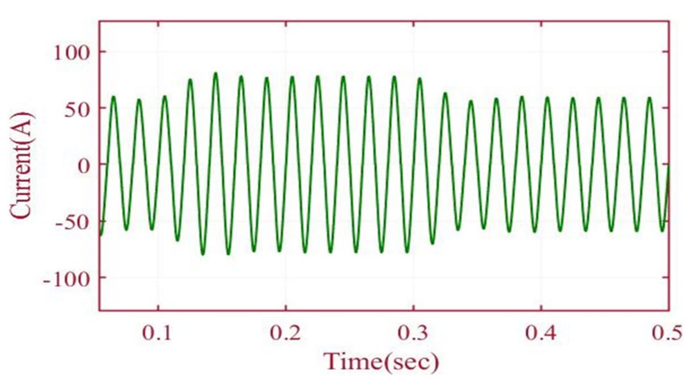

Fig. 15 The source current waveform during load variations

waveform that the current changes with respect to changes in load. Here, the nature of the load is resistive load ($R_L = 100\Omega$). At 0.2 s, the load resistance has increased to 50% (i.e. $R_L = 150\Omega$) and sustained up to 0.5 s. After that, it has decreased to 50% (i.e. $R_L = 50\Omega$). The respective diagram is given in Fig. 18. The other results are given in Fig. 19 to Fig. 23.

Figure 19 shows the output voltage of three-phase PFC buck converter, the reference voltage is given as 400 V, and from the simulation result, we can observe that the voltage is been regulated at reference voltage.

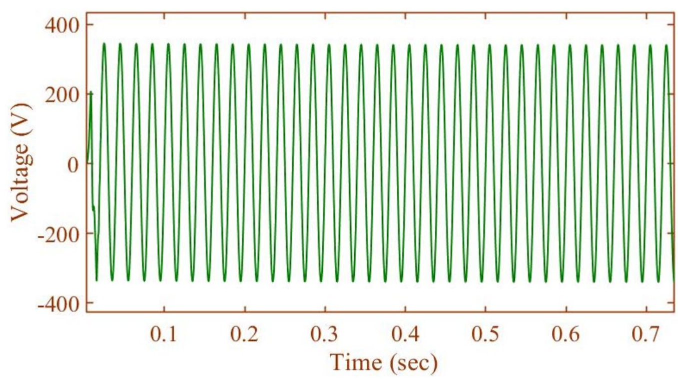

Fig. 16 Output voltage of stand-alone inverter

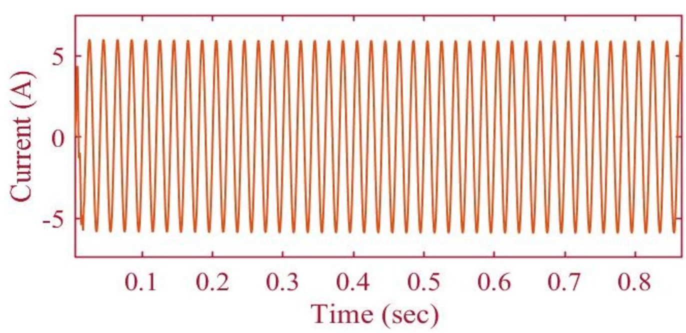

Fig. 17 Output current of stand-alone inverter

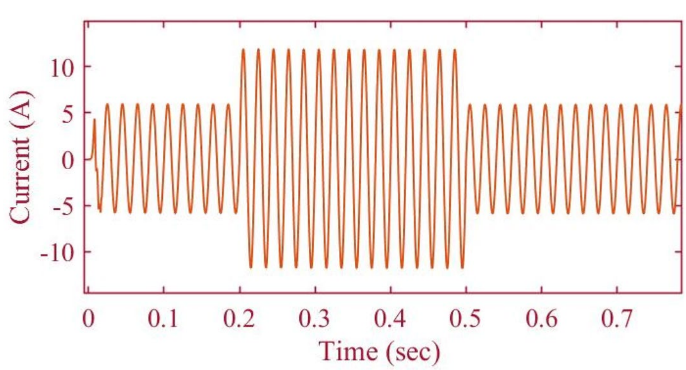

Fig. 18 Output current of stand-alone inverter at ± 50% load variation

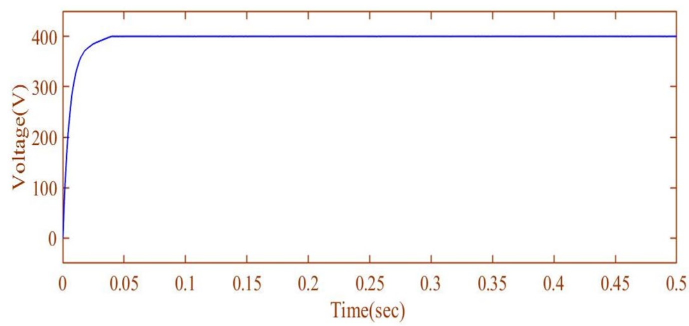

Fig. 19 Output voltage of three-phase PFC buck converter

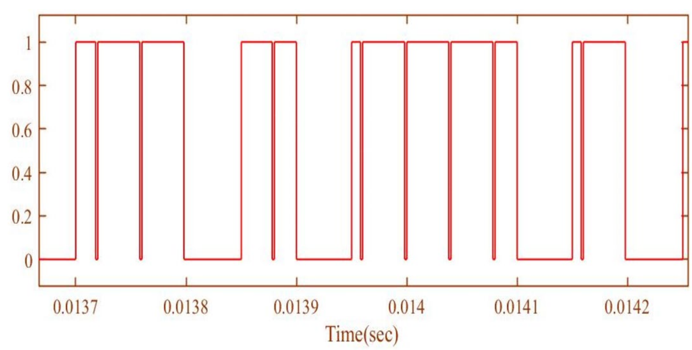

Fig. 20 Switching pulses of PFC buck converter

Figure 20 shows the switching pulses of IGBT of the three-phase PFC buck converter which are generated from the controller block diagram which is shown.

Figure 21 shows the input current of the three-phase supply which is been given to the PFC buck converter; here from the waveform, we can observe that the input current is sinusoidal from which we can say that the PF has been improved.

Figure 22 shows the input voltage of three-phase supply which is been given to the PFC buck converter.

Figure 23 shows the output voltage (port 3) of high-frequency multi-winding transformer; in the circuit, we using a 1:1 transformer which means that all the port voltages are maintained same.

Conclusion

This computational study demonstrates the operation of a single-phase PFC boost converter and a three-phase PFC buck converter in conjunction with a stand-alone inverter, as well as the use of a PFC converters to increase the input PF of the front-end side converter. This study also demonstrates us the study of passive and active PFC methods and the advantage of using active PFC method in the converters. This work explains how the modelling of buck and boost converters are accomplished, the controller approach for both the PFC buck and PFC boost converters is discussed. The building of a self-contained inverter with the purpose of preserving a voltage that is sinusoidally symmetrical throughout the load. This work explains the modelling of a single-phase

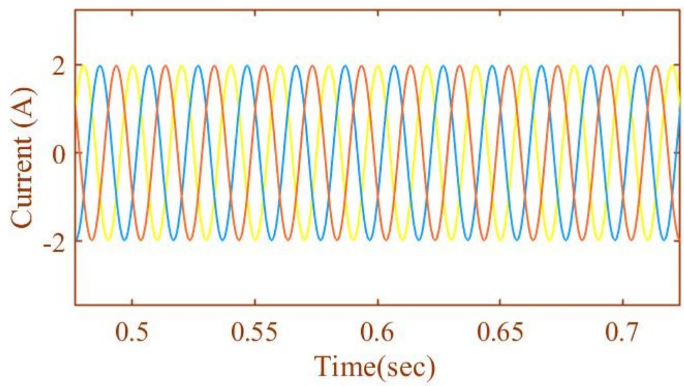

Fig. 21 Input current of three-phase PFC buck converter

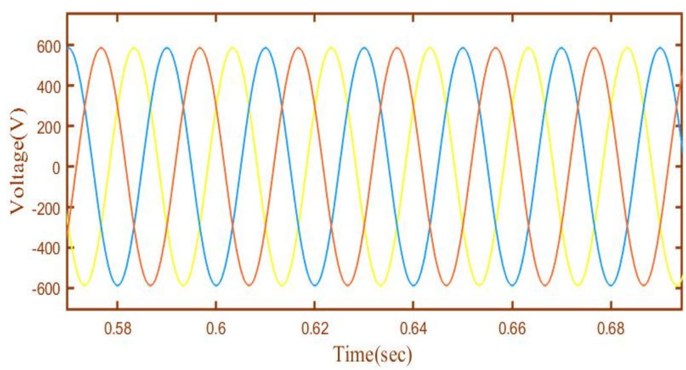

Fig. 22 Input voltage of three-phase PFC buck converter

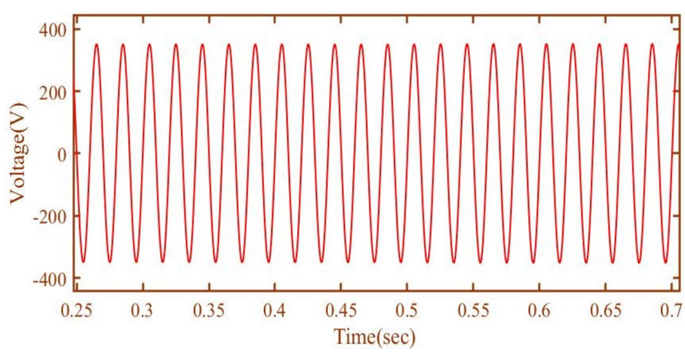

Fig. 23 Output voltage of multi-winding transformer

stand-alone inverter is accomplished as well as how the pulse generation is carried out for the switches of a single-phase inverter by using the sinusoidal pulse width modulation approach. The LC filter is designed in such a manner that the current and voltage harmonics, as well as any losses that may occur inside the filter, are kept to a minimum. In this research, the effects that changes in load have on the voltage and current that are produced by a PFC boost and PFC buck combined with a stand-alone inverter are analysed, and the simulation results are shown, the simulation results prove the efficacy of the systems. In future, the work can be extended by including more number of input sources (renewable sources). By using the multi-winding transformer, the work can be extended to multiple inputs and multiple outputs. The application of the proposed idea is in rural electrification. The experimental work may be performed in future that is future scope of the work.

List of symbols

ACM	Average current mode
CCM	Continuous conduction mode
kHz	Kilohertz
PV	Photovoltaic
PF	Power factor
PFC	Power factor correction
THD	Total harmonic distortion
V_{ref}	Reference voltage
I_c	Capacitor current
I_L	Inductor current
V_s and V_{in}	Input voltage
V_o	Output voltage
I_{ref}	Reference current
D	Duty cycle

Author contributions
Each author contributed significantly to the design and implementation of the proposed work. All authors read and approved the final manuscript.

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Availability of data and materials
On request, authors can provide the data.

Declarations

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Competing interests
There is no conflict of interest.

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