

# Direct Single-stage Power Converter with Power Factor Improvement for Switched Mode Power Supply

R. Kalpana<sup>†</sup>, Bhim Singh\* and G. Bhuvaneswari\*

**Abstract** - This paper presents a direct single-stage power converter using single-phase isolated full-bridge converter modules, with inherent power factor correction (PFC) for a 12 kW switched mode power supply (SMPS). The advantages of the proposed converter are its simple control strategy, reduction in number of conversion stage, low input line current harmonics, and improvement in power factor. Analysis of the single-stage converter is carried out in continuous conduction mode of operation. Steady-state analysis of the proposed converter is conducted to obtain converter parameters. A systematic design procedure is also presented for a 12k W converter with a design example. The effect of load variation on SMPS is also studied in order to demonstrate the effectiveness of the proposed converter for the complete range of load conditions. A set of power quality indices on input ac mains for an SMPS fed from a single-stage converter is also presented for easy comparison of their performance.

**Keywords:** Single-stage, Power factor correction (PFC), Three-phase converter, Full-bridge converter, SMPS

## 1. Introduction

Conventional diode rectifiers are widely used in switched-mode power supplies [1], adjustable speed drives, and process technologies, such as induction and welding units. They draw pulsed current from the utility line, which creates spikes and sags in the line voltage and produces electromagnetic interference. The subsequent propagation of conventional diode rectifiers in utilities is a topic of interest in power quality improvement. Several standard [2]-[3] and review articles in the literature have addressed power quality-related issues in ac-dc converters [4]-[5]. New configurations of power factor correctors are being developed to mitigate the harmonic effects on the input line currents and improve the power factor (PF). International standards and regulations, such as IEEE 519 [2] and IEC 61000-3-2 [3], have been developed to specify the limits of harmonic pollution levels to acceptable levels that can occur in the system. The new configurations of converters conform to international standards.

The use of single-phase converter units in modular form for the three-phase system with high power factor has been reported in related literature [6]-[9]. Such modular development approach has the following advantages and potential:

i) Standard single-phase converter units do not require high-voltage devices that are normally required in specially designed three-phase converters, thereby eliminat-

ing the need for power transformers;  
ii) Reduced number of conversion stages;  
iii) Less need for maintenance and repair of power converter modules because of the use of standard single-phase converter units;  
vi) Inherent power factor correction can be achieved; and  
v) Normally, a simple control strategy is used with a simple design of the converter.

Finally, the other advantage of reducing the stress on the devices using the single-stage PFC converter concept has been discussed in the literature [10]. A three-phase PWM rectifier [11]-[12] is normally used in high-power applications. However, this type of three-phase PFC converter, which causes poor reliability, has complicated controller designs. In contrast, a three-phase converter using single-phase modular rectifier topology has the distinct advantage of having a simple mechanism that can be easily controlled. It is also becoming popular for low-voltage or medium-power supply applications [13]. A single-phase high-frequency transformer-isolated soft-switching single-stage converter with low-line current distortion has been discussed [14]. The input line current THD is between 9%–14% for the wide range of load and supply voltage; in addition, the THD increases with an increase in line voltage but remains almost constant with varying loads. The ease of implementation and the effectiveness of the average current mode controller for medium power converters in forcing the input current to be near sinusoidal for power factor improvement have also been discussed in [15].

In this paper, a direct single-stage converter, consisting of isolated full-bridge DC-DC converter using single-phase modules, is presented for a 12 kW SMPS. The proposed converter system consists of a three-phase supply connected to three single-phase isolated full-bridge converter

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modules with series connection at the final stage of the dc outputs. The analysis and design of a single-stage three-phase ac-dc converter using single-phase full-bridge converter modules, which is based on an average current control technique, are also presented. The proposed converter is operated in Continuous Current Mode (CCM), and the optimal parameters of the converter are estimated in order to achieve the highest power factor. Based on the simulation results, the proposed converter system reduces the input line current harmonics and maintains the power factor close to unity over a wide range of operating conditions.

### 2. Circuit Description

The schematic diagram of the proposed three-phase converter configuration is shown in Fig. 1, which shows three single-phase full-bridge modules connected in a three-phase three-wire system with line-to-line voltage connected to each bridge rectifier. The proposed converter system uses three full-bridge dc-dc converters feeding the SMPS load of 12 kW. A dc link filter ( $L_f, C_f$ ) was placed between the full-bridge converter and single-phase diode

bridge rectifier. Furthermore, a high frequency transformer at the output of the full-bridge converter provided isolation between the input ac mains and output dc load. The secondary windings of the high frequency transformer were connected in series to balance the output dc link currents in the secondary windings. To reduce the conduction losses in the output stage, a center-tapped connection was chosen for the output rectifier. A single-capacitor output  $C_o$  was then connected at the output terminals for filtering the output voltage ripples.

Fig. 2 shows the block diagram of the proposed control scheme of a single-stage three-phase ac-dc converter based on average control technique. An average current mode control is preferred for precise control of the average output voltage because it offers higher commutation noise immunity compared with the peak current control technique. The output voltage was measured and compared with a reference voltage. The resulting error was then fed into an appropriate voltage controller, while the resulting summation signal was multiplied by a signal of rectified input voltage before being compared with the input current. The resulting modulation signal is processed by a suitable inner current control loop, thereby generating the driving signal to control the switches of the PWM bridge converter.

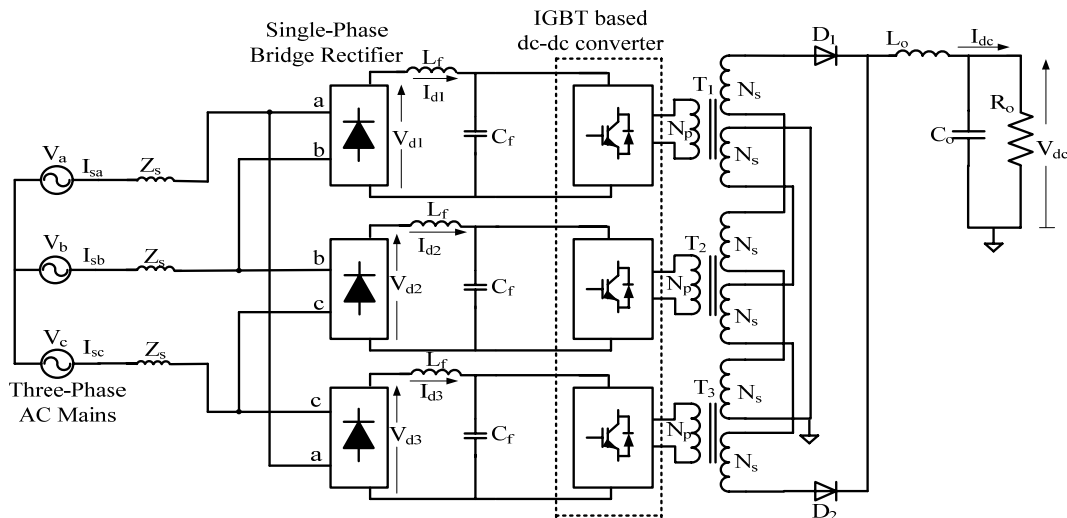


Fig. 1. Schematic diagram of a modular three-phase three-wired full-bridge converter-fed switched mode power supply.

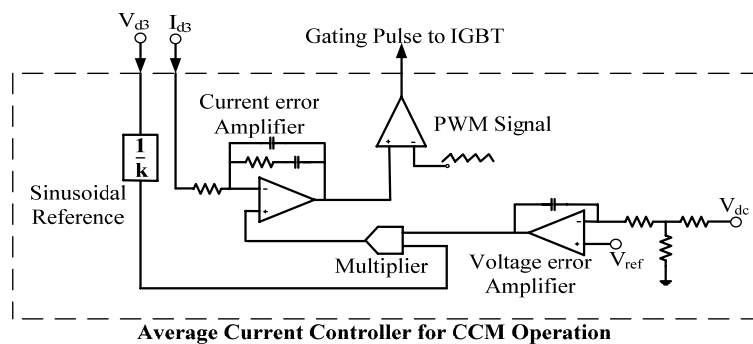


Fig. 2. Schematic of the control strategy for the proposed converter.

### 3. Operation, Analysis, and Design of the Single-phase Full-bridge Converter Module

#### 3.1 Principle of Operation of the Proposed Converter

For the design and analysis of the proposed converter, a single-phase full-bridge converter module was considered with input-output isolation (Fig. 3), which consisted of a single-phase uncontrolled full-bridge rectifier, a dc-dc isolated full-bridge converter, and an output filter. The rectified voltage was filtered by a dc-link filter ( $L_f$ ,  $C_f$ ) before being connected to the dc-dc full-bridge converter. A high frequency transformer with center-tapped secondary winding was connected to the output of the dc-dc converter to provide input-output isolation. The secondary sides of the

high frequency transformer consisted of a series connected to the three-phase converter (Fig. 1).

The operation of the converter can be understood by referring to the gating signals for the switches and other key waveforms (Fig. 4). The diagonal switches in each leg of the dc-dc converter are gated and are complementary to each other. Given that the operation of the converter is symmetric, only one half-cycle is considered. Each half-cycle consists of two main intervals. The equivalent circuits for one half-cycle, along with the devices conducting in each of the intervals, are shown in Fig. 5. The equivalent circuits are shown, with input voltage considered as a constant dc voltage and reflected to the primary winding of the high frequency transformer. The operation of the converter for one half-cycle using the equivalent circuits is explained in the proceeding paragraphs.

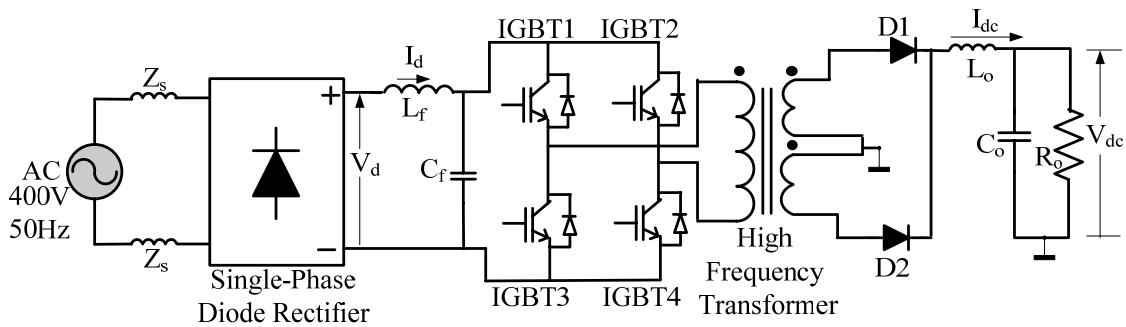


Fig. 3. Schematic of a single-phase module fed switched mode power supply.

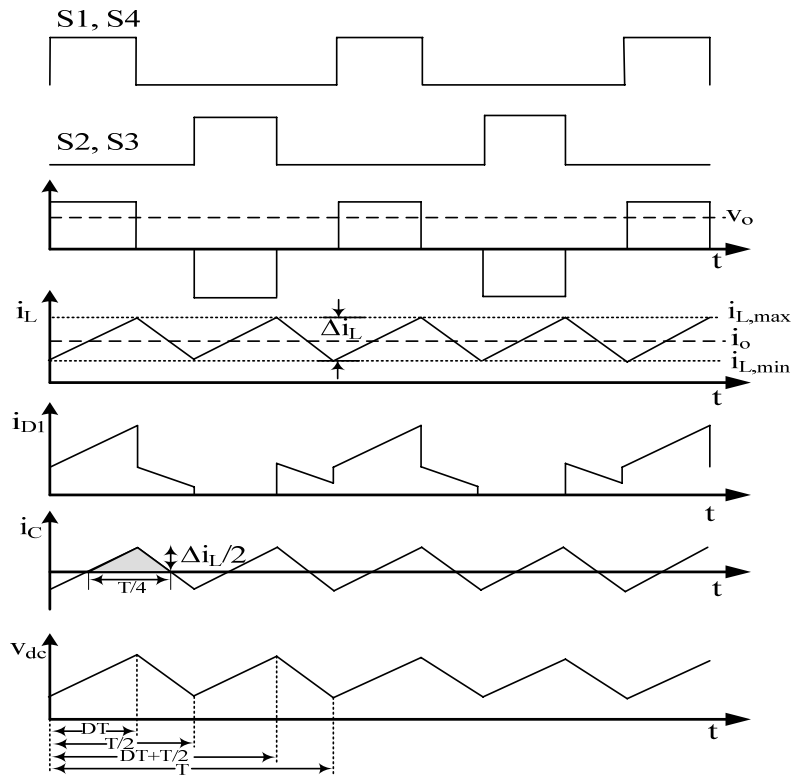


Fig. 4. Key waveforms of full-bridge converter.

### 3.2 Design and Analysis of the Single-phase Full-bridge Converter Module

For the design and analysis of the full-bridge converter, all the switches are considered ideal. The output inductor current is continuous in each switching period. As illustrated in the previous section, the full-bridge converter has two intervals of operation in each half cycle. To operate at CCM, the current should not reach zero at the end of Interval 1. Fig. 6 shows the basic circuit of a full-bridge converter. The converter operates in two intervals in one half-cycle. In Interval 1, S1, and S4 are on. In Interval 2, all the four switches are off. The two intervals of operation are explained in detail below.

#### INTERVAL 1: $T_o < t < DT_s$

In this interval, two diagonal switches, S1 and S4, are on and are providing energy to the load through a high frequency transformer and two diodes. For this purpose, the circuit model is considered (Fig. 5 (a)). From Fig. 6, the following equations can be derived:

$$V_p = V_d \text{ and} \tag{1}$$

$$V_{s1} = (N_{s1}/N_p)V_d; V_{s2} = (N_{s2}/N_p)V_d \tag{2}$$

The voltage across the output inductor is represented by  $V_L$ .  $V_L$  is given by:

$$V_L = (N_{s1}/N_p)V_d - V_{dc}, \tag{3}$$

where  $V_p$  is the voltage across the primary winding of the

high frequency transformer;  $V_{s1}$  and  $V_{s2}$  are the voltages across the secondary windings of the high frequency transformer, respectively;  $V_d$  is the input dc voltage for the full-bridge converter;  $V_L$  is the voltage across the output inductor  $L_o$ ; and  $V_{dc}$  is the dc output voltage across the load.  $N_p$ ,  $N_{s1}$ , and  $N_{s2}$  are the number of turns of the primary winding and secondary windings of the high frequency transformer.

The rate of rise of the inductor current  $i_{L_o}$  is given by:

$$\frac{di_{L_o}}{dt} = \frac{V_L}{L_o} = \frac{(N_{s1}/N_p)V_d - V_{dc}}{L_o} \tag{4}$$

The change in the inductor current during the on period is expressed as:

$$(\Delta i_L)_{ON} = \frac{(n V_d - V_{dc})}{L_o} (\Delta t)_{ON} \text{ and} \tag{5}$$

$$(\Delta i_L)_{ON} = \frac{(n V_d - V_{dc})}{L_o} DT_s, \tag{6}$$

where  $n = \frac{N_{s1} - N_{s2}}{N_p}$  and the duty cycle ratio of the

switch  $D = \frac{T_{ON}}{T_s/2}$ .

#### INTERVAL 2: $DT_s < t < T_s/2$

In this interval, all switches are off during the period  $DT_s < t < (T_s/2)$ , and the load current flows through the diodes. The equivalent circuit can be drawn as in Fig. 5b. The rate

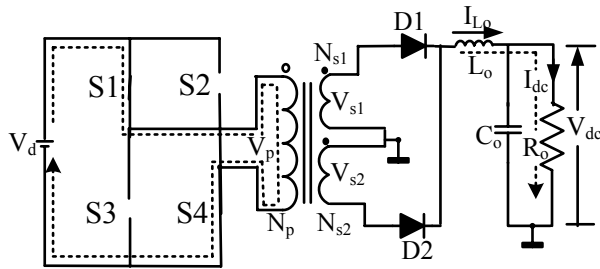


Fig. 5a. INTERVAL 1

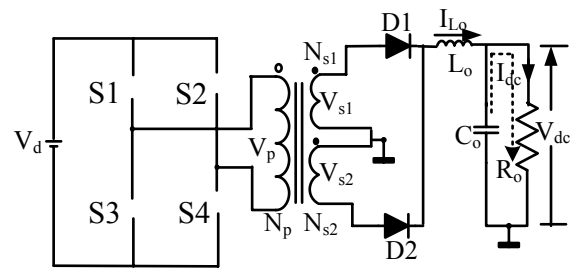


Fig. 5b. INTERVAL 2

Fig. 5. Operation intervals of full-bridge converter.

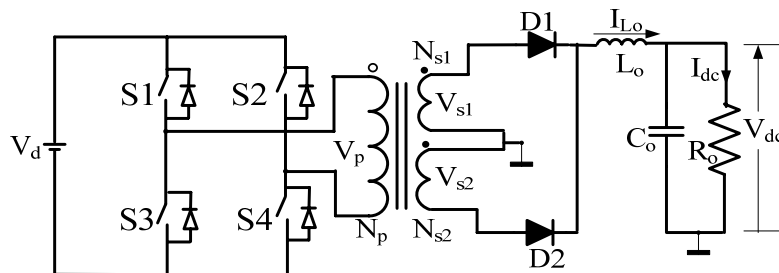


Fig. 6. Schematic for the analysis of a single-phase module full-bridge converter fed by constant dc source.

of change of output inductor current is given by:

$$\frac{di_{L_o}}{dt} = \frac{-V_{dc}}{L_o} \quad (7)$$

The change in inductor current during the off period is given by:

$$(\Delta i_L)_{OFF} = \frac{-V_{dc}}{L_o} (\Delta t)_{OFF}, \quad (8)$$

$$T_{OFF} = \frac{T_s}{2} - T_{ON} = 0.5T_s - T_{ON} \quad \text{and} \quad (9)$$

$$T_{OFF} = (0.5 - D)T_s. \quad (10)$$

Substituting (10) into (8), the change in the inductor current may be obtained using:

$$(\Delta i_L)_{OFF} = \frac{-V_{dc}}{L_o} (0.5 - D)T_s. \quad (11)$$

Under steady state condition the change in the inductor current is zero over a half period  $T_s/2$ .

$$(\Delta i_L)_{ON} + (\Delta i_L)_{OFF} = 0 \quad (12)$$

Substituting (6) and (11) into (12) results in:

$$\frac{(nV_d - V_{dc})DT_s}{L_o} + \frac{-(0.5 - D)V_{dc}T_s}{L_o} = 0. \quad (13)$$

Solving for (13) results in:

$$V_{dc} = 2n - D V_d \quad (14)$$

Using (14), the output voltage may be varied by adjusting the duty ratio of the switch (D) and the high frequency transformer turns ratio (n).

The inductor value  $L_o$  can be calculated for a given value of its ripple current. During the period the inductor current increases linearly as expressed by:

$$(\Delta i_L)_{ON} = \frac{(nV_d - V_{dc})}{L_o} (\Delta t)_{ON}, \quad (15)$$

$$I_{L_o, \max} - I_{L_o, \min} = \frac{(nV_d - V_{dc})}{L_o} T_{ON} \quad \text{and} \quad (16)$$

$$(\Delta i_L)_{ripple} = \frac{(nV_d - V_{dc})}{L_o} T_{ON}. \quad (17)$$

Similarly, during the period when all the switches are off,

the current in the inductor reduces as per (11).

$$I_{L_o, \min} - I_{L_o, \max} = \frac{-V_{dc}}{L_o} (0.5 - D)T_s \quad (18)$$

$$I_{L_o, \max} - I_{L_o, \min} = \frac{V_{dc}}{L_o} (0.5 - D)T_s \quad (19)$$

$$(\Delta i_L)_{ripple} = \frac{V_{dc}}{L_o} (0.5 - D)T_s \quad (20)$$

Therefore, the value of the inductor is given as:

$$L_o = \frac{(0.5 - D)V_{dc}T_s}{(\Delta i_L)_{ripple}}. \quad (21)$$

Fig. 4 shows the output inductor current and amplified output voltage key waveforms in CCM. The ripple voltage across the filter can be calculated from the change in the charge of the output capacitor as expressed by:

$$\Delta Q = C_o \Delta V_o, \quad (22)$$

where  $\Delta V_o$  is the output ripple voltage. Further, this  $\Delta V_o$  can be considered as:

$$\Delta V_o = \frac{\Delta Q}{C_o}. \quad (23)$$

The change in the charge  $\Delta Q$  can be calculated from the area of the triangle representing the positive current (Fig. 4).

$$\Delta Q = \frac{1}{2} * \frac{T_s}{4} * \frac{\Delta i_L}{2} \quad (24)$$

The boundary between the CCM and DCM, by definition the inductor current  $i_L$ , reduces to zero at the end of the off period. At this boundary, the average inductor current becomes:

$$I_L = I_o = \frac{\Delta i_L}{2} \quad (25)$$

Substituting (25) into (24), the change in the capacitor charge is given by:

$$\Delta Q = \frac{1}{2} * \frac{T_s}{4} * I_L. \quad (26)$$

Substituting (26) in (23), the output voltage ripple is given as:

$$\Delta V_o = \frac{T_s I_L}{8 C_o} \tag{27}$$

Therefore, the output capacitor can be found from the ripple voltage as:

$$C_o = \frac{T_s I_L}{8 (\Delta V_o)_{ripple}} \tag{28}$$

As shown above, (28) states the boundary between CCM and DCM.

### 3.3 Design Example of the Single-phase Full-bridge Converter Module

Using a design example, a simple and systematic method for designing the proposed ac-dc converter is presented in this section. The converter can be viewed as a dc-dc full-bridge converter and a buck converter. The converter with the following specifications is designed to illustrate the design procedure:

- Input ac supply voltage is  $V_{LL} = 400$  V (rms), 50 Hz;
- Output voltage  $V_{dc} = 60$  V, output power  $P_{dc} = 12$  kW;
- Switching frequency  $f_s = 40$  kHz,  $T_s = 25$   $\mu$ s;
- Output voltage ripple  $\Delta V_o = 1\%$ , ripple current  $\Delta I_L = 2\%$ , duty ratio of the switch  $D = 0.45$ ; and

Input voltage to the full-bridge converter:  $V_d = 400\sqrt{2} = 566$  V

Using (14), the high frequency transformer ratio is calculated as:

$$n = \frac{V_{dc}}{2 D V_d} = \frac{60}{2 * 0.45 * 566} = 0.12$$

The value of the inductor  $L_o$  can be calculated from (21) as expressed by:

$(\Delta I_L)_{ripple} = 2\%$  of the load current  $I_L = I_o = 200$  A. Therefore  $(\Delta I_L)_{ripple} = 4$  A.

$$L_o = \frac{(0.5 - D) V_d T_s}{4 (\Delta I_L)_{ripple}} = \frac{(0.5 - 0.45) * 60 * 25 * 10^{-6}}{4} = 18.75 \mu H \approx 19 \mu H$$

The value of the capacitor  $C_o$  can be calculated from (28) as expressed by:

$\Delta V_o = 1\%$  of the output voltage  $V_o = 60$  V. Therefore,  $(\Delta V_o)_{ripple} = 0.6$  V.

$$C_o = \frac{T_s I_L}{8 (\Delta V_o)_{ripple}} = \frac{25 * 10^{-6} * 200}{8 * 0.6} = 1042 \mu F$$

These values of various components were considered while modeling the SMPS circuit.

### 4. Simulation Model

To investigate and validate the design, the configuration of the proposed modular converter was simulated in MATLAB environment along with SIMULINK and Sim Power System (SPS). Fig. 7 shows the MATLAB model of the proposed three-phase converter configuration. The de-

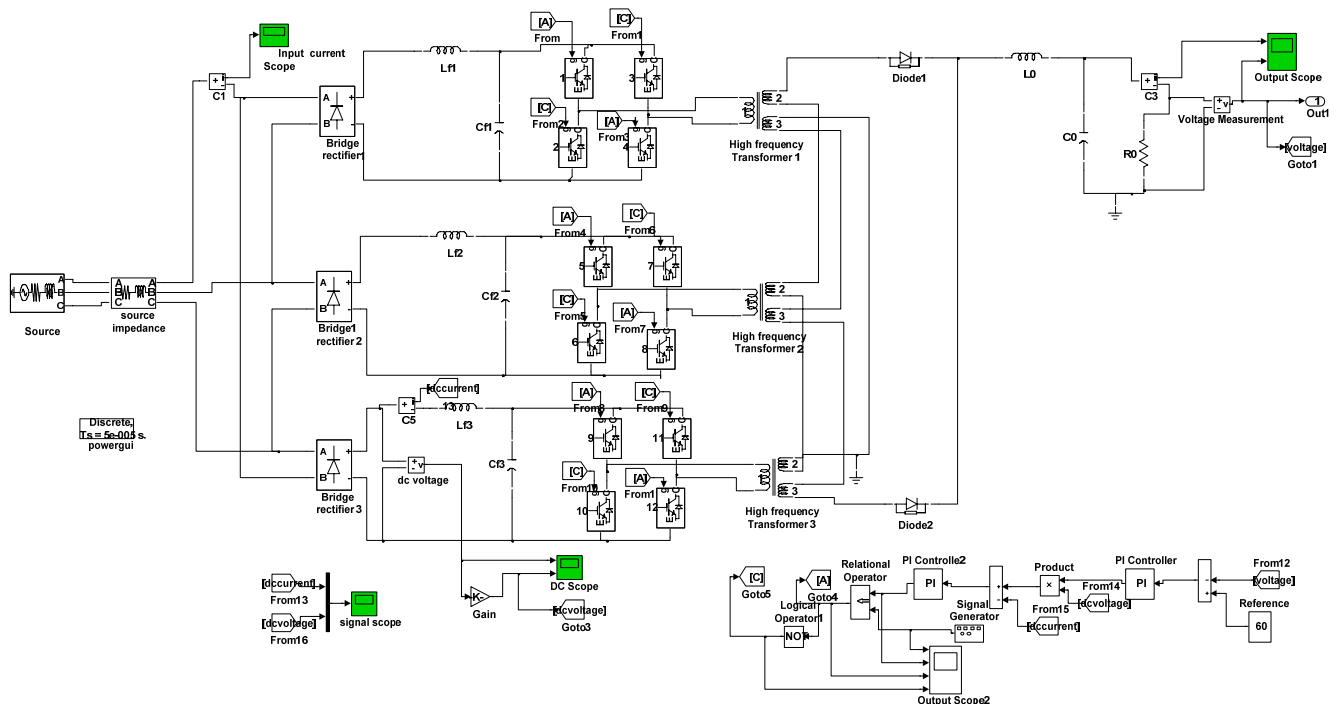
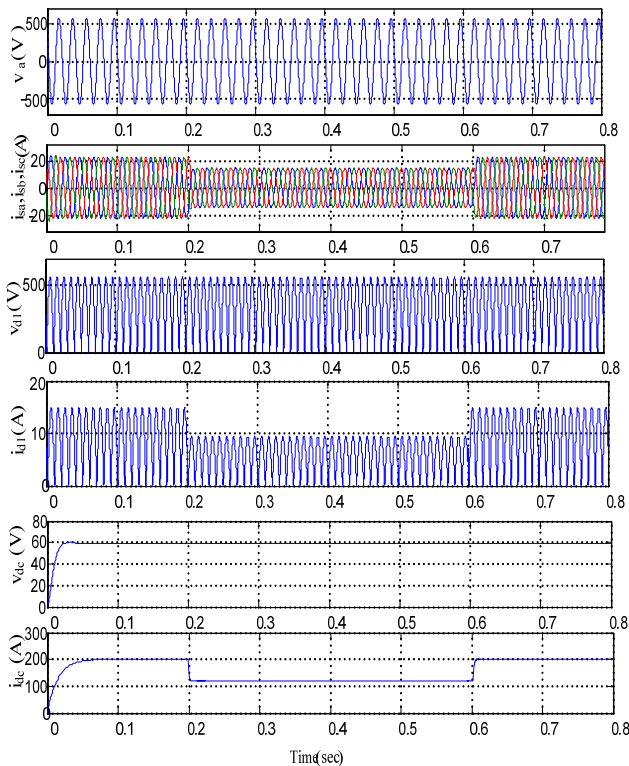


Fig. 7. MATLAB model block diagram for a modular three-phase modular full-bridge converter-fed switched mode power supply.

sign parameters used for the simulation of the proposed converter system are summarized in the Appendix. The modular three-phase ac-to-dc converter (Fig. 7) is operated in continuous conduction mode (CCM), using average current control technique to obtain nearly unity power factor and low THD. For medium power level, CCM operation uses average current control technique to regulate the output voltage, to reduce the input mains current THD as well as to improve the efficiency of the converter at varying load conditions. Simulation was carried out to assess steady state performance from 20%-100% load conditions in the CCM operation. The simulated results for the proposed modular converter are shown in Fig. 8.



**Fig. 8.** Simulation results of the proposed modular three-phase single-stage converter input currents, dc-link voltage, dc-link current, output current, and output voltage waveforms under load variations.

## 5. Results and Discussion

To verify and demonstrate the performance of the SMPS and to achieve various performance indices within the IEEE standard 519 limits, the proposed converter was modeled, designed, and simulated with the following specifications:

Three-phase input voltage: 400 V (rms);

DC output: 60 V/200A;

Output capacitor and inductor:  $L_o = 40 \mu\text{H}$  and  $C_o = 6000 \mu\text{F}$ ; an

Switching frequency:  $f_s$ : 40 kHz.

Fig. 8 shows the simulated waveforms of input volt-

age/current, dc link voltage/current, and the output dc voltage/current at varying load conditions. The results of the simulated performance of the proposed converter for a 12 kW load is presented in Table 1, which shows the quantitative improvement in the power quality indices. The input supply current waveforms at full load and light load (20% of full load), along with their frequency spectrum for proposed modular converter, are shown in Fig. 9. The THD of input ac mains current is 3.6% at full load and 5.2% at light load. These parameters are within IEEE standard limits.

To demonstrate the capability and robustness of the proposed modular converter under varying loads, the load on the SMPS was varied and its effect on various power quality indices were recorded (Table 1). Based on the results, the proposed modular converter results in nearly unity power factor in the wide operating range of the load, and the THD is always less than 5.2%.

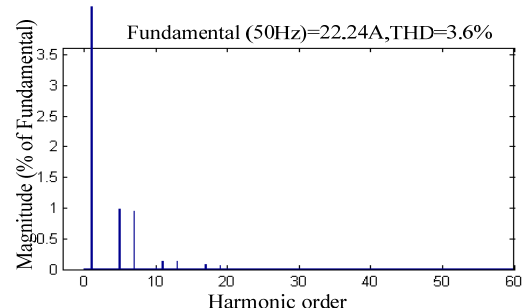
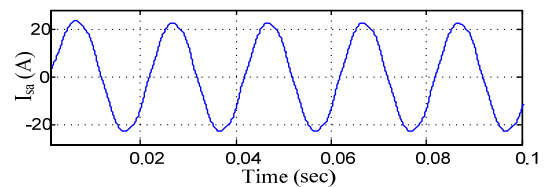


Fig. 9a

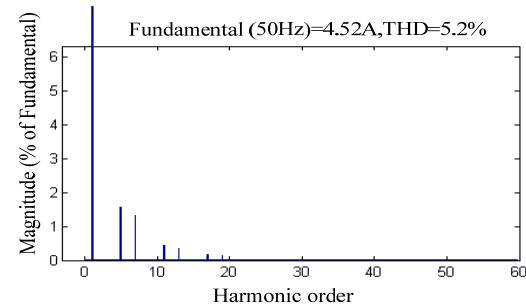
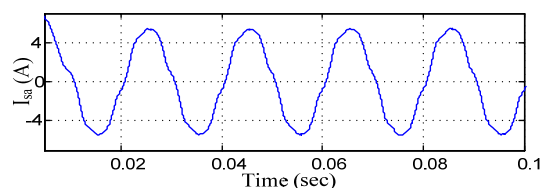


Fig. 9b

**Fig. 9.** Simulation results of input ac mains current ( $i_{sa}$ ) along with its frequency spectrum for the proposed modular three-phase converter-fed SMPS at (a) full load (b) light load conditions.

**Table 1.** Power quality indices for a single stage modular three-phase ac-dc converter fed SMPS under varying loads

Load (%)	THD (%) input current ( $I_{THD}$ )	THD (%) input voltage ( $V_{THD}$ )	DPF	DF	PF
20	5.2	1.2	0.9867	0.9981	0.9849
40	4.9	1.5	0.9883	0.9984	0.9868
60	4.5	1.8	0.9897	0.9987	0.9884
80	4.1	2.1	0.9919	0.9991	0.9913
100	3.6	2.4	0.9949	0.9989	0.9938

## 6. Conclusion

A three-phase single-stage converter using the modular approach was utilized in a simple and convenient way to connect three single-phase converter modules in series at the output to form a medium power three-phase converter. The modular converter was used to convert a three-phase ac power supply into a 60V dc output in a direct single-stage converter with power factor improvement, galvanic isolation, and simple control characteristic. The analysis and design of a single-stage three-phase ac-dc converter, using single-phase full-bridge converter modules, were conducted using an average current control technique. The proposed converter was operated in CCM, from which the optimal parameters of the converter were estimated in order to achieve unity power factor. The effect of load variation on the proposed converter-fed was also studied to demonstrate and validate its performance. According to the results, the THD of the ac mains current lies between 5.7% and 3.9% in the complete range of varying loads, with a nearly unity power factor operation. The observed performance of the modular converter demonstrated the capability of this converter to improve the power quality indices at ac mains, in terms of THD of supply current, THD of supply voltage, and power factor.

## Appendix

### SPECIFICATIONS AND DESIGN PARAMETERS OF THE CONVERTER

Parameters	Values
<i>Converter design:</i>	
Input supply voltage	: 400 V, 50 Hz
Source impedance	: 3%
Load power ( $P_{dc}$ )	: 12 kW (60 V /200 A)
Output dc voltage	: 60 V
Input DC voltage $V_{dc}$	: 566 V
Switching frequency	: 40 kHz
<i>Designed component values:</i>	
DC-link filter components	: $L_f = 2$ mH, $C_f = 1.5$ $\mu$ F
inductor, Capacitor	: $L_o = 2 \times 19$ $\mu$ H, $C_o = 6 \times 1042$ $\mu$ F
HFT turns ratio $N_{s1}/N_p$	: 0.12

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