A Novel FPGA Control Scheme to Improve Power Factor and Reduce The Harmonic Distortion in a Three Phase VIENNA Rectifier

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***Abstract*—Compared with the traditional two-level or three level unidirectional rectifier, VIENNA rectifier is the favorite choice for its advantage such as only half numbers of the switches, simple structure, high power density and ability to realize unity power factor with appropriate control strategy. Vienna rectifier is a kind of power converter with complicated operating constraints. Thus, it is difficult to control with conventional control strategies, especially during transients or under low power factor operation. This paper presents the design of a modified Vienna rectifier for three phase power factor correction (PFC) under R load, also presents a new control scheme system for three phase modified Vienna rectifier which is supposed to control the DC output voltage and almost pure sinusoidal three phase input current to gain almost unity power factor. For switching pulse of the switch in each phase, eight control signals are used, the signals d_{1a}, d_{1b} and d_{1C} are used to determine the positive and negative half-cycle of the current. The simulation of proposed system has been done using MATLAB simulation software. The propose topology provides almost ripple free input current, lower input current THD which is found to be about 3% and improved power factor up to 0.99.**

Keywords—Vienna Converter; Power Factor Correction; Rectifier; Powe Quality; FPGA

I. Introduction

Power electronics are the main application of solid state engineering and control systems which are using for conversing and controlling of electric power. These devices have a poor power quality. These for two reasons have a poor power factor, first It marks source current out of phase (phase displacement) with the source voltage and second It marks source current in a non-sinusoidal waveform [1],[2]. Out of phase current components cannot deliver usable power [3] and non-sinusoidal waveforms have lot of harmonics that are creating huge problems like overheating, circulating currents, high voltage, component failures, cable damaging etc. To overcome these limitations we need power factor correction. [3],[4]. The requirement of improved power quality at ac mains is becoming essential and increasingly important. Hence, this recommends the use of improved power quality converters for achieving a Unity PF (UPF) at ac mains with limited amount of harmonic distortion in the supply current. A front-end Power Factor Correction (PFC) converter is used after the Diode Bridge Rectifier (DBR) for improving the quality of power and achieving a unity power factor at the supply system [5],[6]. A very high Total Harmonic Distortion (THD) of supply current, that is, 65.9% and a very low PF, that is, 0.72 is achieved at ac mains. Two-stage PFC converters have been in wide practice which use two different converters for PFC and dc-link voltage control.

It requires higher number of components and thus has higher losses associated with it and increase the system cost and complexity. Proper selection of a PFC converter is required for achieving high power quality [7].

The Vienna rectifier was introduced in 1993 by Prof. Johann W. Kolar. It is a three phase, three levels and three switch rectifier. It is kind of PWM (Pulse Width Modulation) rectifier with controlled output voltage. The topology of the Vienna Rectifier is a combination of a boost DC/DC converter with a three-phase diode bridge rectifier [8]. Vienna rectifier has the advantage of having a low Total Harmonic Distortion (THD) of the input current [9]–[11]. Besides, compared with other traditional converters, Vienna rectifier is characterized by half numbers of the switches, low voltage stresses, which makes contribution to high power density. Topologies of the switch and control strategies based on Vienna rectifier are proposed and used in various applications, such as, electric vehicles, aviation systems and wind turbine systems [12]. In order to comply with the high requirements for low THD at the input currents, and with the regulation of output and neutral-point voltages, different control methods for Vienna rectifier can be found in literature. Some of them use an average model based on the synchronous d–q frame representation [12],[13]. Moreover, control methods based on pulse width modulation are commonly used as well as those employing space vector-based modulations in spite of the important calculation effort they require. On the other hand, the trade-off between variable switching frequency and simple implementation associated to hysteretic control has been the subject of the first works devoted to this converter as well as the contents of posterior reports. Finally, DC output voltage regulation and PFC based on input–output linearization rendering the system of minimum-phase behavior is the subject reported in, where the theoretical predictions are validated by Matlab simulations [14],[15].

The Vienna rectifier like all the other converters in power electronics has advantages and disadvantages. The pros of this converter are given below: Has continuous sinusoidal input current, No need for a neutral wire, Low number of IGBTs used, Low manufacturing cost, Reduce blocking voltage stress on power semiconductor, Reduction in switching loss of the power semiconductors by almost 40%, Wide voltage range, Higher efficiency, Boosting ability, Production of three levels of voltage with two equal DC voltages [16].

On the other hand, acting as a unidirectional active AC/DC converter and lack of regeneration can be considered as cons. In unidirectional converters power flows in one direction from AC side to DC side and it cannot act as an inverter [16].

In This paper, a Three phase Vienna rectifier is used for improve power quality by a new control method. The proposed rectifier provides improved power quality in terms of low total harmonic distortion (THD) and high power factor. Also it presents an experimental verification of Vienna rectifier improving power quality.

II. MODELING OF THREE-PHASE VIENNA RECTIFIER

A. Description

In Vienna Rectifier configuration, as shown in Fig. 1, the output capacitor is split in two parts as two equal value capacitors, C_1 and C_2 connected in series. Across the output capacitors the $-V_{dc}$ and $+V_{dc}$ are developed as 3-Phase peak detected outputs. A switch for each phase is connected, such that when “ON”, it connects the line phase to the center node of C_1 and C_2 through a series inductance. For a short switching period the capacitors charge linearly.

This offsets $-V_{dc}$ and $+V_{dc}$ The offset depends on the corresponding phase voltage and the switch “ON” time duration. The common node of C_1 and C_2 will have Voltage with triangular wave shape, having three times the mains frequency and its amplitude will be one quarter of the phase voltage. [3]

B. Operation of the Vienna Rectifier

The Vienna rectifier has three switches, and by choosing their (ON/OFF) state considering the polarity of the phase current in each phase, the voltage for each phase will be determined. So, the phase voltage is depending on the direction of phase current and switch position. In this topology, the midpoint N is considered as reference point with zero voltage. Therefore, the phase voltage is described as,

$$L_N \frac{di_k}{dt} = E_N - V_{KN} \tag{1}$$

When the phase current is positive,

$$V_{KN} = \begin{cases} \dfrac{+V_0}{2} & S_k = 0 \\ 0 & S_k = 1 \end{cases} \tag{2}$$

and when the phase current is negative,

$$V_{KN} = \begin{cases} \dfrac{-V_0}{2} & S_k = 0 \\ 0 & S_k = 1 \end{cases} \tag{3}$$

where L_N are the input inductors (N=1,2,3), i_k is the input phase current, V_{KN} is the phase voltage (K =A,B,C), S_k is a controlled switch (S_k = 0 correspond to off state and S_k = 1 to the on state).

If the line current is positive and switch S_A is ON (Fig. 2-a) the current pass through the switch and the phase voltage (V_{AN}) become zero. If the polarity of the current remains as before but the control switch S_A is off, the current flows through diode D_{11}, the voltage V_{AN} is +V0/2, Fig. 2-b illustrates this case. Similarly, the voltage V_{AN} can determined if the line current is negative and switch S_A is ON or OFF, the current path for these two cases is illustrated in Fig. 2-c, Fig. 2-d [3].

If it assumed that the current for phase A is positive and it is negative for both phase B and C. Then eight different switching positions can be considered, given the results is shown in TABLE I. .

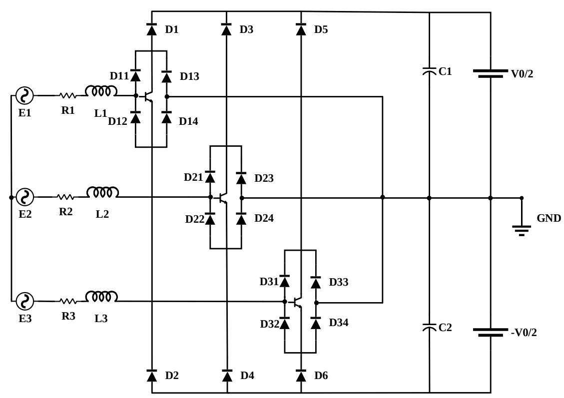

Fig. 1. Three Phase Vienna rectifier

TABLE I. EIGHT DIFFERENT SWITCHING COMBINATION

S_A	S_B	S_C	V_{AN}	V_{BN}	V_{CN}
0	0	0	$+V_0/2$	$-V_0/2$	$-V_0/2$
0	0	1	$+V_0/2$	$-V_0/2$	0
0	1	0	$+V_0/2$	0	$-V_0/2$
0	1	1	$+V_0/2$	0	0
1	0	0	0	$-V_0/2$	$-V_0/2$
1	0	1	0	$-V_0/2$	0
1	1	0	0	0	$-V_0/2$
1	1	1	0	0	0

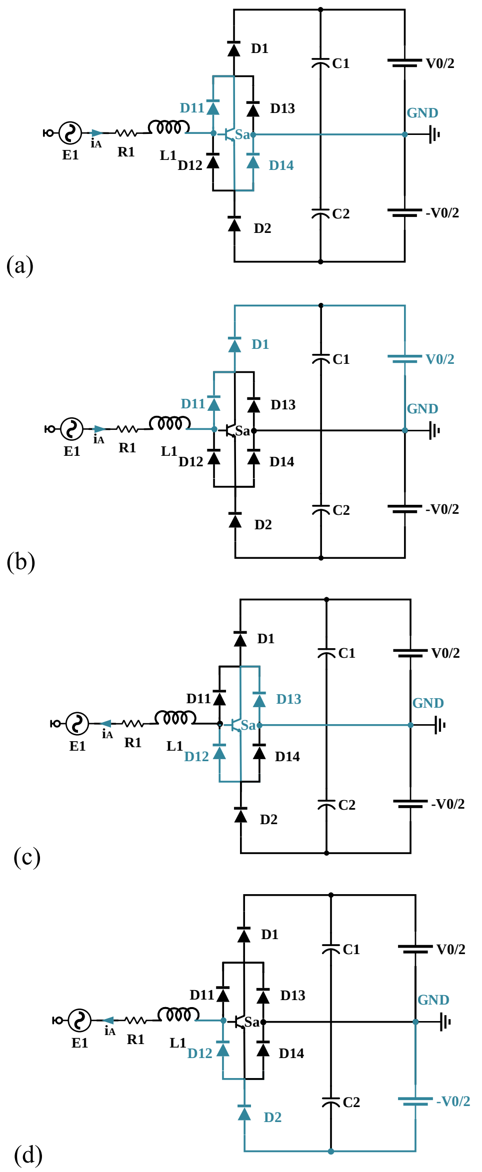

Fig. 2. Conduction path for phase A , (a) I_L>0 , S_a= ON , (b) I_L>0 , S_a= OFF , (c) I_L<0 , S_a=ON , (d) I_L<0 , S_a=OFF

III. THE PROPOSED CONTROL SCHEME

At First, different modes of voltage and current are considered for different switching states. In the next step, all the different states of the signals d_{1a}, d_{1b}, d_{1c} (Related to the current sign), d_{2a}, d_{2b}, d_{2c} (Related to the current hysteresis control), d_3 (Capacitors Voltage), d_4 (Compare amplitude voltage line and capacitor voltage) are checked and for each state the status of each switch is determined, which in total 256 possible states. In the next step Karnaugh table for each switch is extracted. The Flowchart of control strategy is shown in Fig. 3.

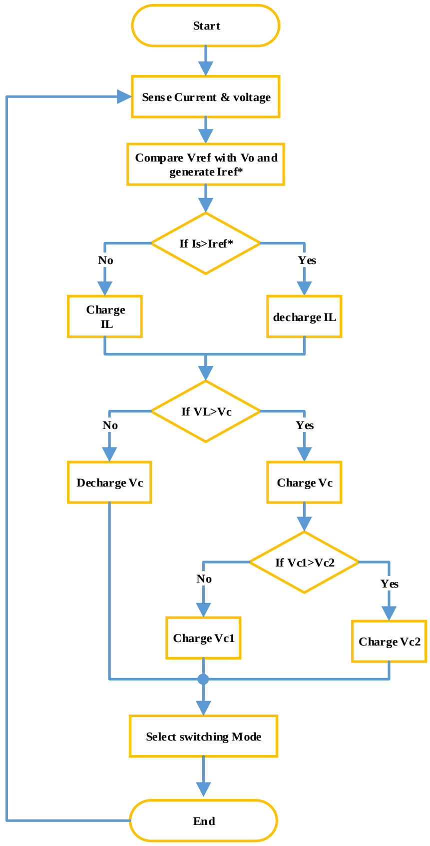

Fig. 3. Flowchart of Control Strategy

A. Control parameters

To achieve optimal parameters, the controller must be properly designed. For this purpose, eight control signals are used, The signals d_{1a}, d_{1b} and d_{1C} are used to determine the positive and negative half-cycle of the current. To generate these signals, the measured flow rate is compared to zero.

$$d_1 = \begin{cases} 1 & i_s < 0 \\ 0 & i_s > 0 \end{cases} \tag{4}$$

TABLE II. VOLTAGES AND CURRENTS FOR DIFFERENT MODES

				i $i_a>0/\ i_b<0/\ i_c<0$			*Ii* $i_a>0/\ i_b>0/\ i_c<0$			*iii* $i_a<0/\ i_b>0/\ i_c<0$		
M	***S1***	***S2***	***S3***	V_{ab}	V_{bc}	V_{ac}	V_{ab}	V_{bc}	V_{ac}	V_{ab}	V_{bc}	V_{ac}
1	0	0	0	$V_{c1}+V_{c2}$	0	$V_{c1}+V_{c2}$	0	$V_{c1}+V_{c2}$	$V_{c1}+V_{c2}$	$-V_{c1}-V_{c2}$	$V_{c1}+V_{c2}$	0
2	0	0	1	$V_{c1}+V_{c2}$	$-V_{c2}$	V_{c1}	0	V_{c1}	V_{c1}	$-V_{c1}-V_{c2}$	V_{c1}	$-V_{c2}$
3	0	1	0	V_{c1}	V_{c2}	$V_{c1}+V_{c2}$	V_{c1}	V_{c2}	$V_{c1}+V_{c2}$	$-V_{c2}$	V_{c2}	0
4	0	1	1	V_{c1}	0	V_{c1}	V_{c1}	0	V_{c1}	$-V_{c2}$	0	$-V_{c2}$
5	1	0	0	V_{c2}	0	V_{c2}	$-V_{c1}$	$V_{c1}+V_{c2}$	V_{c2}	$-V_{c1}$	$V_{c1}+V_{c2}$	V_{c2}
6	1	0	1	V_{c2}	$-V_{c2}$	0	$-V_{c1}$	$-V_{c1}$	0	$-V_{c1}$	V_{c1}	0
7	1	1	0	0	V_{c2}	V_{c2}	0	V_{c2}	V_{c2}	0	V_{c2}	V_{c2}
8	1	1	1	0	0	0	0	0	0	0	0	0

In order to control the input current, signals from d_{2a}, d_{2b} and d_{2c} are used. These signals limit the current due to the hysteresis band defined for the current. If the current has overshoot, the switching should be done so that the inductor is discharged and if the current has undershoot, the inductors must be charged. To make these signals, the output voltage feed is compared to the reference Voltage value and the result is sent to the PI controller to zero its error.

$$d_2 = \begin{cases} 1 & i_s^* - i_s < -h/2 \\ 0 & i_s^* - i_s > h/2 \end{cases} \tag{5}$$

The control signal d_3 compares the voltage capacitors in order to make the switching circuit according to the conditions of the circuit, so that the capacitors can be recharged or discharged.

$$d_3 = \begin{cases} 1 & V_{C_1} < V_{C_2} \\ 0 & V_{C_1} > V_{C_2} \end{cases} \tag{6}$$

In the event that the minimum voltage capacitor are greater than the maximum source voltage, the voltage capacitor must be discharged, which can be achieved by proper switching.

$$d_4 = \begin{cases} 1 & |V_S| > \min(V_{C_1}, V_{C_2}) \\ 0 & |V_S| < \min(V_{C_1}, V_{C_2}) \end{cases} \tag{7}$$

Each control system has a number of parameters that need to be accurately defined to function properly. Because the controller is controlled by FPGA, the control parameters are also 0 and 1.

The controller has four control parameters d_1, d_2, d_3 and d_4. Each of these parameters having two values of 0 and 1. By setting the values of the parameters together, 16 different modes are obtained for these 4 parameters. After reaching 16 states, the 16*16 Karnaugh table is formed. According to the Karnaugh table, different modes for parameters are investigated which can be combined. All of these modes can be used for switching Vienna rectifier. First, the switching functions obtained from the Karnaugh table are extracted and then these functions are used to switching. Finally, each of the functions obtained is applied to a leg of the rectifier to perform a switching based on the functions. The Karnaugh table for Switch s_1 is shown in Table III.

IV. SIMULATION RESULT

A. Study system

The Vienna rectifier is studied in a test system. There is 1kW load at the DC side of Vienna rectifier the total output voltage is 400V. The Short Circuit Ratio (SCR) at AC side is approximately 4, which means the Vienna rectifier has a weak connection to the grid.

B. Vienna rectifier Performance at Steady State

In steady state, the Vienna rectifier performance is given in this section. All DC link capacitor voltages are well balanced and regulated around 0.5 pu is given in Fig. 4. The capacitor energy is evenly distributed among three arms due to the control loop introduced in the previous section, DC Link and capacitors voltage. The waveforms of input currents show that reduce the total harmonic distortion (THD) and it's more important advantage of this converter. Hence, reducing THD improves power quality. THD of current is less than 1.32% that it's acceptable. Waveform of input Current three-phase is shown in Fig. 5.

Another factor that improves the power quality is the power factor that Vienna rectifier increases the power factor by about 1. An improved power quality is achieved for a wide range of speed control. The power factor corrected is shown in Fig. 6.

TABLE III. KARNAUGH TABLE FOR SWITCH S_1

ABCD\EFGH	0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
0000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0001	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0011	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0010	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0110	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0111	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0101	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0100	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1100	1	1	1	1	1	0	0	1	1	0	0	1	1	1	0	1
1101	1	1	1	1	1	0	0	1	0	0	0	1	1	1	0	0
1111	1	1	1	1	1	0	0	1	0	0	0	1	1	1	0	1
1110	1	1	1	1	1	0	0	1	1	0	0	1	1	1	0	1
1010	1	1	1	1	1	0	0	1	0	0	0	1	1	1	0	1
1011	1	1	1	1	1	0	0	0	0	0	0	1	1	0	0	0
1001	1	1	1	1	1	0	0	0	0	0	0	1	1	0	0	0
1000	1	1	1	1	1	0	0	1	0	0	0	1	1	1	0	1

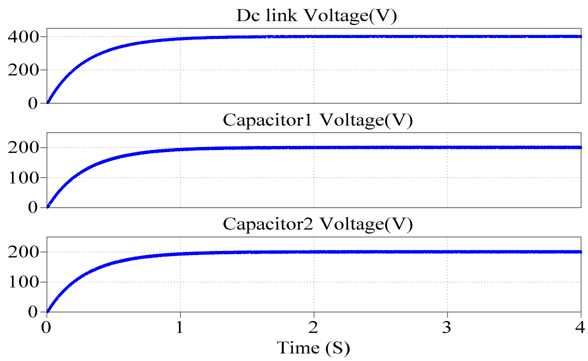

Fig. 4. Output voltage of Vienna rectifier

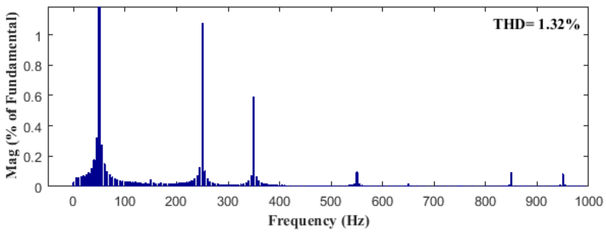

Fig. 5. THD of input current

C. *Vienna rectifier Performance at Variable Voltage*

The Vienna rectifier performance with variable voltage is given in Fig. 7. All DC link capacitor voltages are well balanced and regulated under voltage variations because it maintains stability with the variable voltage. In this case, like in previous mode, the capacitor energy is evenly distributed among three arms due to the control loop.

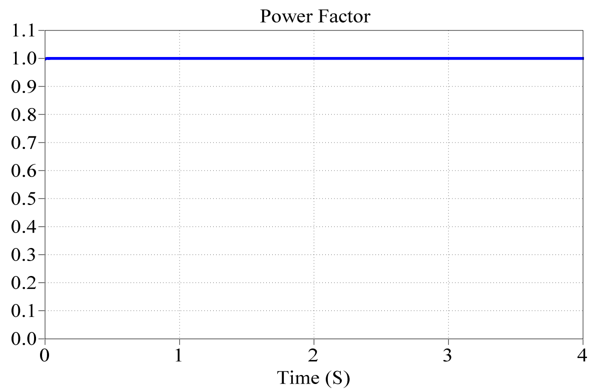

Fig. 6. Power factor of input three phase current

Like the steady state, the waveforms of input currents show that reduce the total harmonic distortion (THD). The current level remains constant at the voltage change. Waveform of input Current three-phase shown in Fig. ٨.

The voltage variation has a negative effect on the power factor. The power factor is reduced by voltage variation unlike the previous mood. However, the power factor is acceptable and improves power factor. The power factor is shown in Fig. 8. Hence, reducing THD improves power quality. In the case, THD of current is less than 1.88% that it's acceptable. THD of input current is shown in Fig. 9.

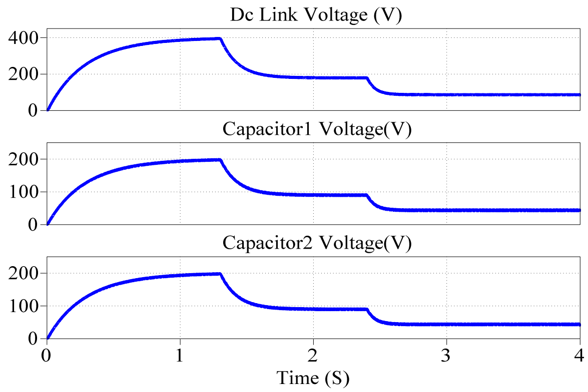

Fig. 7. Output voltage of Vienna rectifier

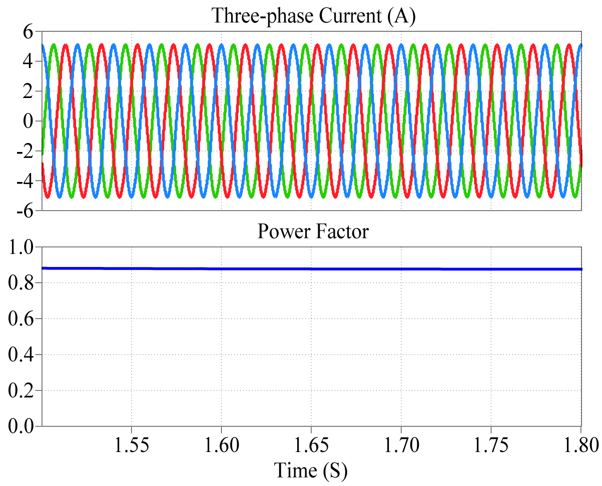

Fig. 8. Power factor of input three phase current

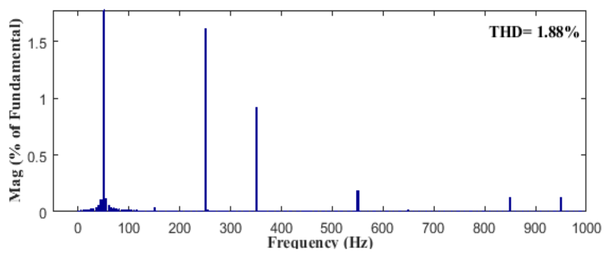

Fig. 9. THD of input current with variable voltage

V. CONCLUSION

In this research, a three phase modified Vienna rectifier with a new control scheme has been proposed. The proposed topology has been designed for acquiring corrected power factor, lower Total Harmonics Distortions (THD), higher efficiency and simple control system. The new controller uses FPGA as its main core. By analyzing the simulation result in MATLAB simulation software of proposed Three-phase Vienna rectifier, we got nearly unity power factor. Here, it is tested that the THD of Three phase input current is found to be about 1% and the efficiency of proposed single-phase PFC system is about 96.8%. This method has the capability to implement on DSP microprocessor.

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