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A Z-Source Network Integrated Buck-Boost PFC Rectifier

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ABSTRACT

This paper presents a wide range of gain buck-boost type PFC rectifiers based on the conventional buck-boost DC-DC converter. This novel rectifier is fed by a buck-type Z-source network at the DC side with the help of an inductor smoothing the AC side input current. The proposed PFC rectifier offers better input and output waveform qualities compared to the conventional buck-boost PFC rectifiers. Maintaining near to unity power factor (PF) and low total harmonic distortion (THD) in a wide range of load variations and also simple single-loop control are the main features of the proposed PFC rectifier. Furthermore, the switching frequency of the proposed rectifier can be chosen much higher than the competitors since it successfully allows increasing the duty cycle for the same voltage gain incredibly compared to the traditional solutions. This leads to a reduced size of passive components and volume of the rectifier. A 250 W prototype circuit is designed and simulated considering most practical issues to evaluate the performance of the proposed PFC in both buck and boost modes. The results that are compared with some well-known conventional PFC rectifiers confirm the superior performance of the proposed topology.

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I. INTRODUCTION

Power factor correction (PFC) rectifiers have attracted attention for feeding most of the industrial DC loads up to hundreds of watts due to their low DC capacitor requirement, low harmonic injection to the grid, high power factor (PF), low electromagnetic interference (EMI), and at the same time, high-quality DC output voltage with minimum ripples. The PFC rectifiers are mainly utilized as the supply of data centers and communication equipment, uninterruptable power supplies (UPSs), electric vehicle (EV) drives, and telecom power supplies [1]-[3]. As is seen in Fig. 1, the main configuration of the PFC rectifiers consists of a diode bridge followed by a PFC circuit including buck, boost, buck-boost or other DC to DC converters. The boost-type PFC rectifier is mostly known as the best solution for power factor correction in many applications due to purely sinusoidal current waveform drawn from the input source and considerably high power factor (PF) [4], [5]. However, its output voltage is higher than the peak AC input voltage while most of the industrial DC loads require lower voltages than the grid voltage. This necessitates employing an additional DC-DC converter to decrease its output voltage for the applications with low voltage operation. This additional DC-DC converter increases the weight and volume, and also decreases the efficiency and power density [6], [7]. Another solution for the aforementioned problem is the buck-type PFC rectifiers. Unfortunately, the buck-type PFC rectifier cannot provide as high-quality waveforms as that of the boost-type one. The input current THD and PF of the buck-type PFC rectifier are drastically worse than the boost-type one resulting in lower practical applications. As shown in Fig. 2, a problem known as the dead angle occurs for buck-type PFC rectifiers, which decreases the quality of the sinusoidal waveform of the AC input current of the buck-type PFC rectifier. In other words, since the output voltage of buck converters decreases to

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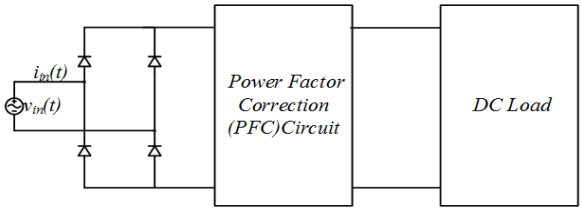

Fig. 1. Conventional PFC rectifier configuration

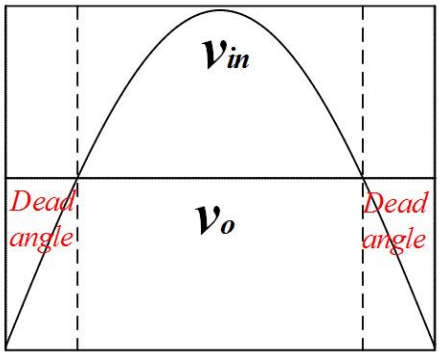

Fig. 2. Dead angle phenomena in a buck-type PFC rectifier.

lower values than the AC input voltage, the series switch of the buck converters cannot be turned on resulting in distortions of the AC input current [8]. In order to improve the input current quality of buck PFC rectifiers, another DC-DC converter, such as a buck-boost, a boost or a flyback connected in series or parallel to the main buck PFC rectifier, can be used [9]-[11]. This additional DC-DC converter improves the quality of input current but uses too many components. In addition to the dead angle problem, the absence of an input inductor significantly increases the input current THD compared to boost-type PFC rectifiers. Conventional buck-boost PFC rectifiers can provide lower or higher voltages than the AC input voltage simultaneously. These PFC rectifiers improve the performance and the quality of the waveforms as compared to other solutions although the lack of an input inductor in these rectifiers still causes AC input current distortions. Moreover, inverse output voltage polarity and the need for a high-side drive circuit for their power switch are the other shortcomings of these PFC rectifiers [5], [12].

This paper proposes an improved buck-boost type PFC rectifier fed from a Z-source network. This new configuration for the PFC rectifier mainly focuses on the improvement of the quality of the input and the output side waveforms. The principles of performance and different modes of operation are presented. Theoretical achievement is backed up with extensive simulations in PSIM software. The simulation results for both buck and boost modes of the proposed PFC rectifier are compared with the results for PFC rectifiers of [3], [13] and [14]. The input inductor helps reduce input

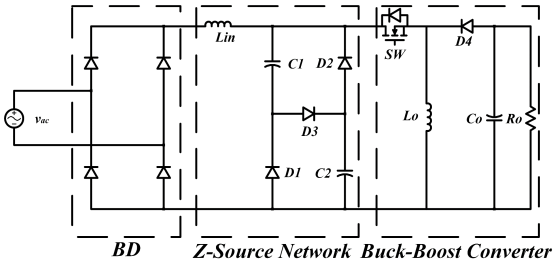

Fig. 3. Proposed Z-Source network integrated buck-boost PFC rectifier.

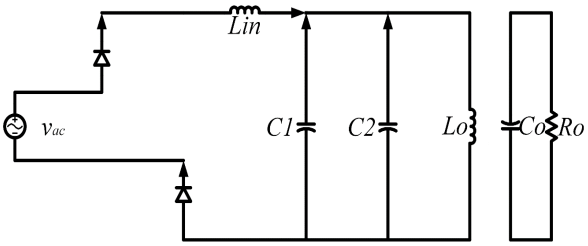

Fig. 4. Mode I of the proposed PFC rectifier operation in positive half cycle.

current THD and increase the power factor. This rectifier produces waveforms with higher quality than conventional rectifiers.

II. Proposed PFC Rectifier

A. Circuit Configuration

The proposed PFC rectifier configuration is composed of a diode bridge, a Z-source network, and a buck-boost type DC-DC converter, as shown in Fig. 3. The Z-source network is composed of an input inductor and a set of diode-switched-capacitors already proposed in [15]. The input inductor of the Z-source network helps reduce input current THD and increase the power factor (PF). Generally, due to the possibility of increasing the switching frequency, the capacitors of the Z-source network are considerably small so as not to contribute to the power loss of the converter. Also, the buck-boost type converter is utilized as the final stage of power conversion to regulate the input current and the output voltage. The performance and operation principles of the proposed PFC rectifier are analyzed below.

B. Operation Principles

Since the operation modes of the proposed PFC rectifier in each half cycle of the input voltage are the same, only the positive half cycle operation modes are discussed here for the sake of simplicity. Also, the DCM operation of the proposed PFC rectifier is analyzed as a general performance analysis since the CCM operation can be derived from it. On the other hand, by operating the rectifier in the DCM, several advantages can be obtained such as the intrinsic near-unity power factor and the zero current switching (ZCS). Thus, the turn-on transients and switching losses and the reverse

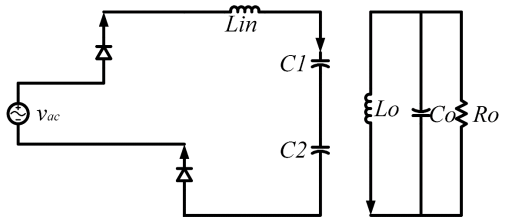

Fig. 5. Mode II of the proposed PFC rectifier operation in positive half cycle.

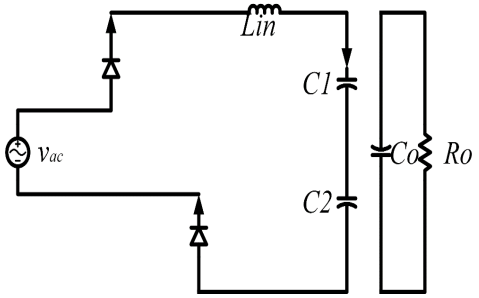

Fig. 6. Mode III of the proposed PFC rectifier operation in positive half cycle.

recovery of the output diode are considerably reduced [8].

1) Mode I [0~DT_s]:

As seen in Fig. 4, the switch *SW* is turned on and the diodes D_3 and D_4 are reverse biased, while D_1 and D_2 conduct. The input and output inductance, i.e. L_{in} and L_o, of the PFC rectifier are charged in this mode and their currents increase with a constant ramp. The voltage and current equations of this mode are written in Eq. (1) as in [15].

$$\begin{cases} \hat{V}_{Lin} = \hat{V}_{in} - \hat{V}_{c_{1,2}} \\ \hat{V}_{Lo} = \hat{V}_{c_{1,2}} \\ \hat{I}_{in} = \hat{I}_{Lin} \\ \hat{I}_{Lo} = \hat{I}_{in} + 2\hat{I}_{c_{1,2}} \\ \hat{I}_{C_o} = -\dfrac{\hat{V}_o}{R_o C_o} \end{cases} \tag{1}$$

2) Mode II [DT_s~$D'T_s$]:

As depicted in Fig. 5, the switch *SW* is turned off and at the same time, the diodes D_3 and D_4 are forward biased and conduct while the diodes D_1 and D_2 block the voltages across the capacitors C_1 and C_2. The inductors L_{in} and L_o are discharged and their currents decrease. The inductor L_o current maintains higher than zero in this mode of operation. The voltage and current equations of this mode are given as Eq. (2).

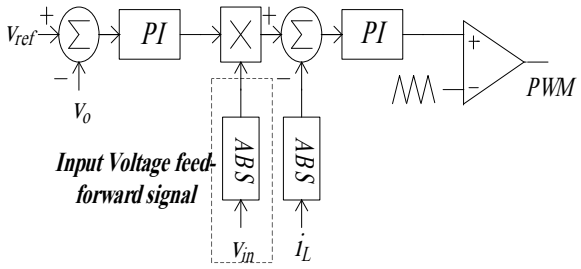

Fig. 7. Conventional average current control method for the PFC rectifiers.

$$\begin{cases} \hat{V}_{Lin} = \hat{V}_{in} - 2\hat{V}_{c_{1,2}} \\ \hat{V}_{Lo} = \hat{V}_o \\ \hat{I}_{in} = \hat{I}_{Lin} = \hat{I}_{c_{1,2}} \\ \hat{I}_{Lo} = -(\hat{I}_{c_o} + \dfrac{\hat{V}_o}{R_o C_o}) \end{cases} \tag{2}$$

3) Mode III [$D'T_s$~T_s]:

The operation is similar to the mode II with the difference that the output inductor L_o current becomes zero, which translate to the DCM operation of the buck-boost-type converter. However, the input inductor L_{in} current decreases to a value higher than zero in this mode. This mode is shown in Fig. 6. According to Fig. 6, one can write Eq. (3).

$$\begin{cases} \hat{V}_{Lin} = \hat{V}_{in} - 2\hat{V}_{c_{1,2}} \\ \hat{V}_{Lo} = \hat{V}_o \\ \hat{I}_{in} = \hat{I}_{Lin} \\ \hat{I}_{Lo} = 0 \\ \hat{I}_{C_o} = -\dfrac{\hat{V}_o}{R_o C_o} \end{cases} \tag{3}$$

The voltage gain equation of the proposed PFC rectifier is obtained by applying the volt-second balance on the voltage across input and output inductors in modes I, II and III. Accordingly, the voltage gain equation, which is the ratio of the output to the input voltages, are given in Eq (4) in terms of the duty cycles (D and D').

$$\begin{aligned} &\frac{\hat{V}_o}{\hat{V}_{in}} = \frac{D}{((D'-D)\times(2-D)} \\ &D'|_{CCM} = 1 \\ &D'|_{DCM} = D + \sqrt{\frac{2L_m}{T_s R}} \end{aligned} \tag{4}$$

III. Control Method

The conventional control method of the boost-type PFC rectifier operation in CCM is shown in Fig. 7. This control scheme known as the average current control (ACC) consists of a double closed-loop control plant. An individual proportional and integral (PI) controller is employed for the output voltage regulation as the outer loop and for the input

Table I.

SIMULATION CONDITIONS AND PARAMETERS.

Description	Values	
	Buck mode	Boost mode
Rated power, P_o	250 W	250 W
Input AC voltage, V_{in}	220 Vrms	220 Vrms
Switching frequency, f_s	50 kHz	50 kHz
Output DC voltage, V_o	48 V_{dc}	400 V_{dc}
Capacitors: C_1, C_2 and C_o	1 µF, 1 µF and 2.5 mF (ESR = 19 mΩ)	1 µF, 1 µF and 540 µF (ESR = 9 mΩ)
Input inductor (L_{in})	2.5 mH, (ESR = 360 mΩ)	1.5 mH, (ESR = 160 mΩ)
Output Inductor (L_o)	10 µH, (ESR = 20 mΩ,)	50 µH (ESR = 45 mΩ)
Diodes, D_1, D_2, D_3	Powerex CS240650	Powerex CS240650
IGBT switch, *SW*	IXGH40N60C2	IXGH40N60C2

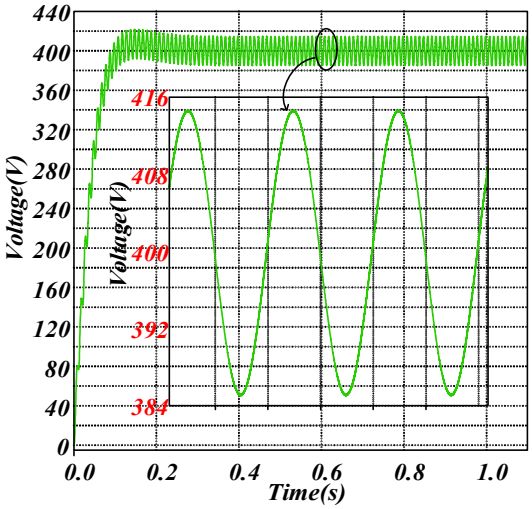

Fig. 8. Output voltage of the proposed rectifier in the boost mode and 250 W load.

AC current regulation as the inner loop. Similar to the SEPIC rectifier of [14], the proposed PFC rectifier can be well operated with only a single loop control scheme for output voltage regulation without requiring any current control loop. In other words, with DCM operation, the input current of the proposed PFC rectifier is maintained as a pure sinusoidal waveform due to the use of an input inductor at the DC side. This allows the input current to be proportional to the input voltage. Thus, the input current can synchronously track the sinusoidal form of the AC input voltage and produce near unity power factor. Also, the single loop control ability translates to two fewer sensors required for the closed-loop control procedure. In fact, only the output voltage sensor is required for the output voltage regulation.

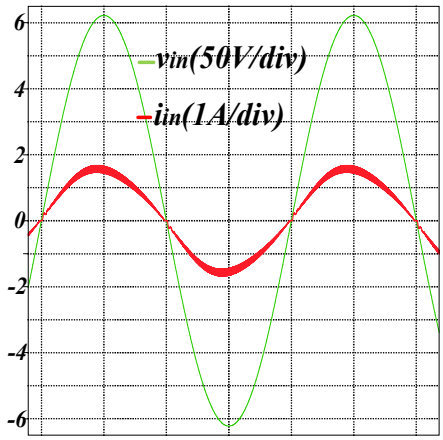

Fig. 9. Input voltage and current of the proposed rectifier in the boost mode and 250 W load.

IV. PERFORMANCE EVALUATION

The theoretically derived operation principles of the proposed buck-boost-type PFC rectifier are investigated in this section through a set of simulations in PSIM software. In order to better simulate the idea, the thermal module of the PSIM software is utilized to model the real and experimental parasitic elements of the proposed rectifier components. The simulations conditions and parameters are listed in Table I. Accordingly, the proposed PFC rectifier is operated so as to feed a DC-load with two different desired voltage profiles, which can be lower or higher than the peak voltage of the grid. Also, to present a fair comparison, the proposed PFC rectifier, the conventional buck-boost PFC rectifier, and the conventional boost PFC rectifier are simulated in the same conditions and component parameters. Fig. 8 shows the output voltage of the proposed PFC rectifier in which a 400 Vdc is obtained by a boost mode operation. As is evident in Fig. 8, even with a load power of as high as 250 W, the proposed PFC rectifier produces output voltage ripple of smaller than 10%, which is a tolerable voltage ripple. In addition, the AC input current of the proposed PFC rectifier is shown in Fig. 9 whose

THD is 5.5%. The input current of the conventional buck-boost PFC rectifier is also displayed in Fig. 10. As depicted in Fig. 10, the input current of the conventional

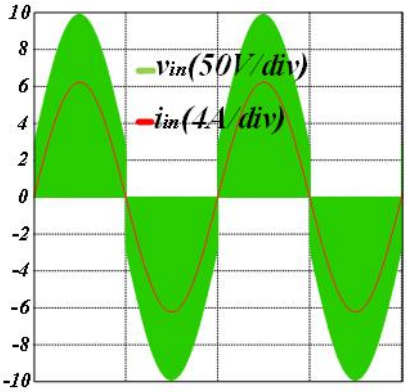

Fig. 10. Input voltage and current of the conventional buck-boost rectifier of [4] in boost mode and 250 W load

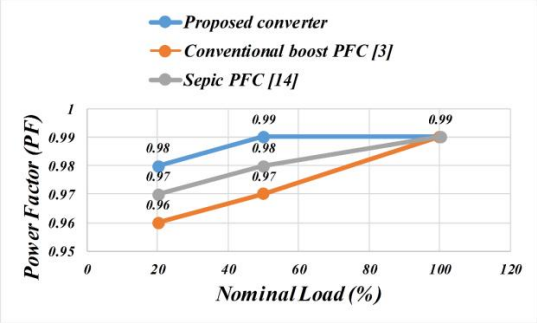

Fig. 11. Power factor comparison among the proposed, conventional boost PFC rectifier of [3] and sepic PFC rectifier of [14] for a 250 W load in boost mode.

buck-boost PFC rectifier absolutely contains switching harmonics, which significantly increases its THD. Consequently, the supremacy of the proposed PFC rectifier upon the conventional one is approved by comparing Figs. 9 and 10. Furthermore, the conventional boost PFC rectifier and the sepic PFC rectifier of [14] are also operated under the same conditions and then, THD and PF results are compared with the proposed PFC rectifier in Figs. 11 and 12. According to these figures, maintaining the input current THD and PF within the range of the standards for power quality from 20% of nominal load to full load is a remarkable feature of the proposed PFC rectifier. In addition to the above analysis, the buck mode operation of the proposed PFC rectifier is also simulated and the results are shown in Figs. 13 and 14. For a fair comparison with the buck-boost PFC rectifier of [5], both proposed and buck-boost PFC rectifier of [5] are operated for a nominal load power of 250 W and 48 Vdc. It should also be noted that the component parameters of the buck mode simulation for both proposed and buck-boost of [5] are

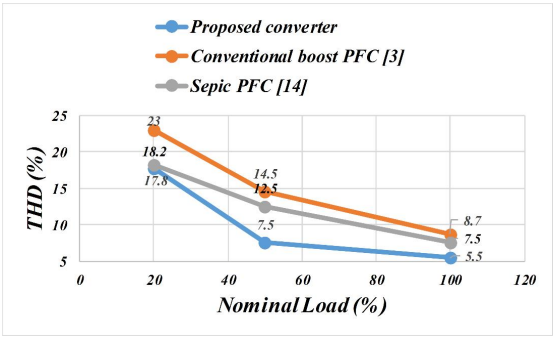

Fig. 12. Input current THD versus load percentage comparison among the proposed, conventional boost PFC rectifier of [3] and sepic PFC rectifier of [14] for a 250 W load in boost mode.

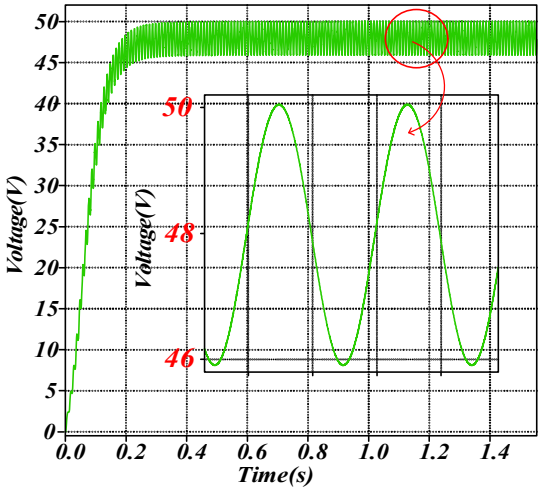

Fig. 13. Output voltage of the proposed rectifier in buck mode and 250 W load.

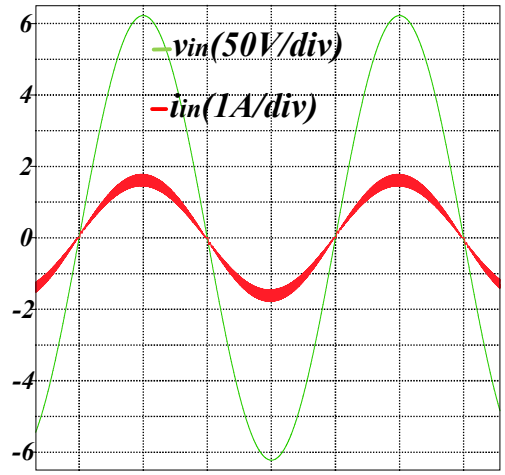

Fig. 14. Input voltage and current of the proposed rectifier in buck mode and 250 W load.

considered the same, where the input inductor Lin = 1.5 mH and output filter capacitor Co = 2.5 mF. As shown in Fig. 13, again the output voltage ripple of the proposed PFC rectifier is

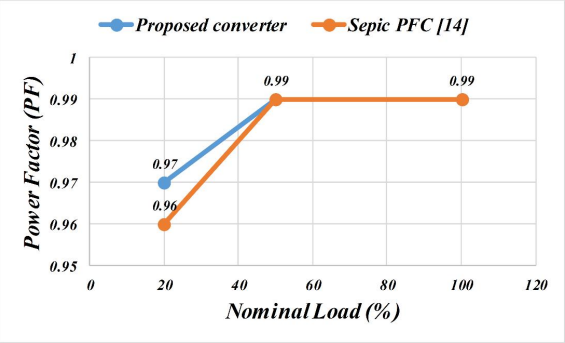

Fig. 15. Power factor comparison among proposed and sepic PFC rectifier of [14] for a 250 W load in buck mode.

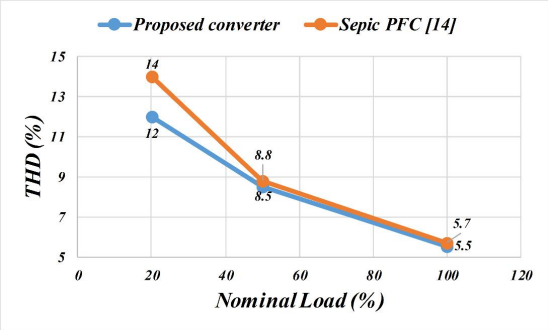

Fig. 16. Input current THD versus load percentage comparison among the proposed and sepic PFC rectifier of [14] for a 250 W load in buck mode.

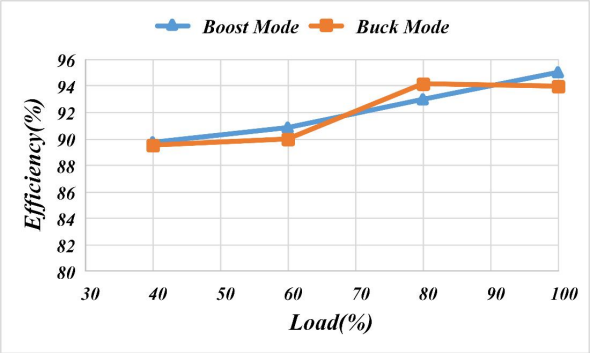

Fig. 17. The efficiency versus the percent of the nominal load

smaller than 10%, which meets the needs of DC-loads. The input current THD of the buck-boost PFC rectifier of [5] is 6.3% while the proposed one offers an input current THD of as low as 5.5%. This low THD input current can be clearly expected from its waveform shown in Fig. 14. Also, the sepic PFC rectifier of [14] is operated under the same conditions and then, the THD and PF results are compared with the proposed PFC rectifier in Figs. 15 and 16. The results show that both rectifiers have good performance with a slightly improved quality of the input current for the proposed one.

The high efficiency of the rectification with the proposed PFC rectifier is verified in Fig. 17. The efficiency is obtained with the various output loads as low as 40% to the nominal output power.

The obtained simulation results and the above analysis show that the proposed PFC rectifier is an improved solution of PFC rectification, which meets the loads and the power quality requirements.

V. Conclusions

This paper introduced an improved buck-boost-type PFC rectifier that brings remarkable advantages for feeding DC-loads directly from the grid. This rectifier produces waveforms with higher quality than its conventional counterparts. The operation principles of the proposed PFC rectifier are presented and analyzed. Then, the simulations are presented in both modes of buck and boost to confirm its performance for two output voltage profiles and load powers. The simulation results confirm the superiority of the proposed converter over the conventional ones in providing high-quality input currents and output voltages without seriously sacrificing other practical concerns, such as the conversion efficiency and circuit simplicity.

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