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Harmonic Optimization by Single Phase Improved Power Quality AC-DC Power Factor Corrected Converters

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ABSTRACT

This paper presents a comparative evaluation of five topologies of single-phase AC-DC boost converters having power factor correction (PFC). These converter topologies are evaluated on the basis of performance and their salient features are discussed to analyze their applicability. The techniques not only help to develop a deeper understanding of these converters but also to evaluate performance and feasibility of control strategies and topological features without fabrication of an actual system. This paper also describes techniques for minimizing the input current distortion of current-controlled single-phase boost rectifiers. Performance of these converters is simulated and conformity of these converters is shown to relevant international standards. This work aims to provide an exposure of PFC converters to researchers and application engineers dealing with power quality issues.

Index Terms

Power electronics, ac-dc power converter; PFC; Power quality improvement; Comparative study

I. INTRODUCTION

Single-phase switch mode ac-dc converters are being used as front-end rectifiers for a variety of applications due to the advantages of high efficiency and power density. These classical converters, however, draw-non-sinusoidal input ac currents leading to low input power factors and injection of harmonics into the utility lines[3]. Research in improved power quality utility interface has gained importance due to stringent power quality regulation and strict limits on total harmonic distortion (THD) of input current placed by standards such as IEC 61000-3-2 and IEEE 519-1992.

This has led to consistent research in the various techniques for power quality improvement. Research into passive and active techniques for input current wave shaping has highlighted their inherent drawbacks. Passive filters have the demerits of fixed compensation, large size and resonance whereas the use of active filters is limited due to added cost and control complexity.

These AC–DC converters provide stable DC voltage at the output with high input power factor. This capability makes PFC converters an extremely attractive choice for offline power supplies and other AC–DC[1] power conversion applications because of increasing concerns about power quality and to meet the guidelines of various power quality regulations and standards. Since these converters cater to the unique requirements of a large number of applications, several control strategies and topologies need to be evaluated and developed to meet the specifications of the target application.

The simplest line-commutated converters use diodes to transform the electrical energy from AC to DC. The use of thyristors allows for the control of energy flow. The main disadvantage of these naturally commutated converters is the generation of harmonics and reactive power.

Harmonics have a negative effect in the operation of the electrical system and therefore, an increasing attention is paid to their generation and control. In particular, several standards have introduced important and stringent limits to harmonics that can be injected to the power supply.

One basic and typical method to reduce input current harmonics is the use of multipulse connections based on transformers with multiple windings. An additional improvement is the use of passive power filters. In the last decade active filters have been introduced to reduce the harmonics injected to the mains. Another conceptually different way of harmonics reduction is the so called Power Factor Correction (PFC)[5]. In these converters, power transistors are included in the power circuit of the rectifier to change actively the waveform of the input current, reducing the distortion. These circuits reduce harmonics and consequently they improve the power factor, which is the origin of their generic name of PFC.

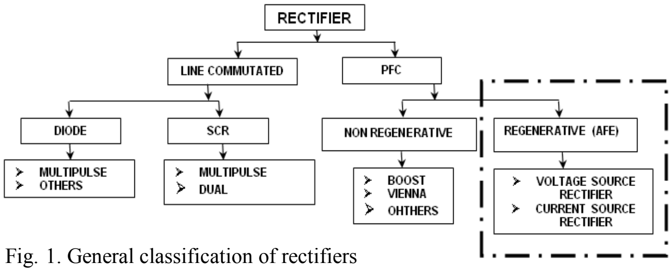

Fig. 1. General classification of rectifiers

II. PWM RECTIFIERS

A. Standard for Harmonics in Single-Phase Rectifiers

The relevance of the problems originated by harmonics in line-commutated single-phase rectifiers has motivated some agencies to introduce restrictions to these converters[2]. The IEC 61000-3-2 International Standard establishes limits to all low-power single-phase equipment having an input current with a "special wave shape" and an active input power P<600W.

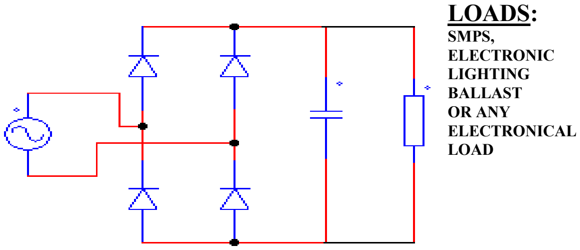

Fig. 2. Standard bridge rectification of line voltage

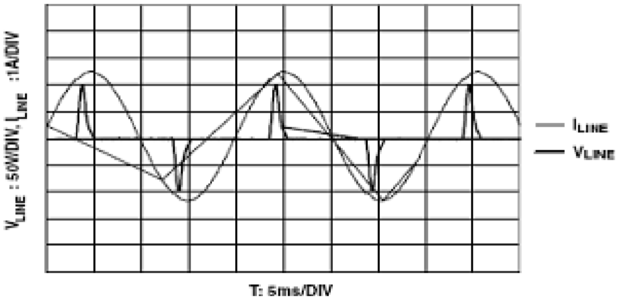

Fig. 3. 20 W Resistive load powered by a circuit like Fig. 2

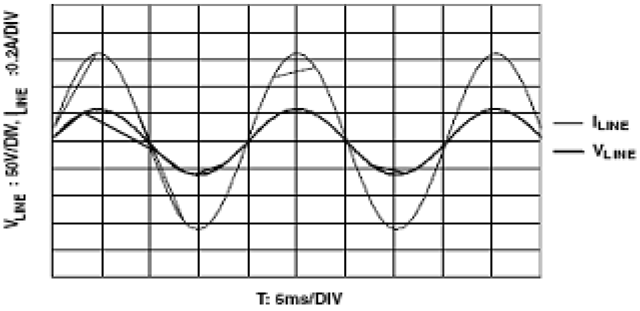

Fig. 4. Same load like Fig.3 but Unity power factor

This class of equipment which is connected with the above circuit must satisfy certain harmonic limits[17]. It is clear that a single-phase line-commutated rectifier shown in Fig.2 is not able to comply with the standard IEC 61000-3-2 Class D [23] as shown in Fig. 5.

For traditional rectifiers the standard can be satisfied only by adding huge passive filters, which increases the size, weight and cost of the rectifier. This standard has been the motivation for the development of active methods to improve the quality of the input current and, consequently, the power factor. PFC converter topologies considered in this work are described in this section.

The single-phase boost converter with uni-directional power flow shown in Figure 6, is realized by cascading single-phase diode bridge rectifier with boost chopper topology. Another topology with unidirectional power flow, semi-boost converter topology is shown in Figures 7 and 8.

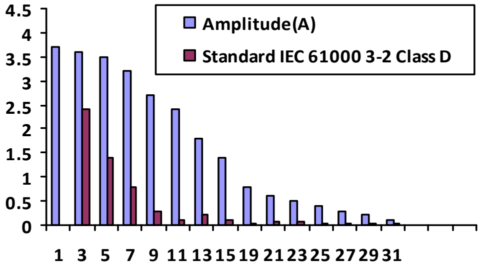

Fig. 5. Harmonics in the input current of the rectifier of Fig.2

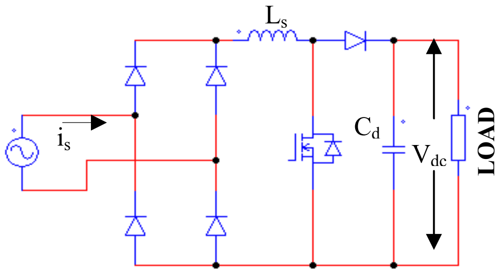

Fig. 6. Boost converter

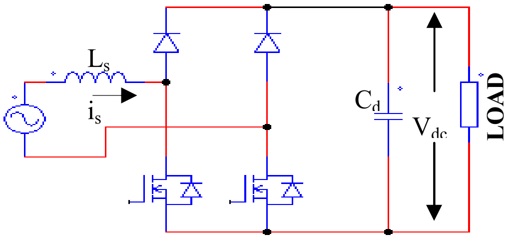

Fig. 7. Symmetrical semi-Boost converter

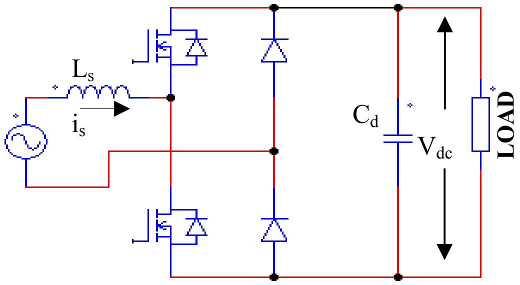

Fig. 8. Asymmetrical semi-Boost converter

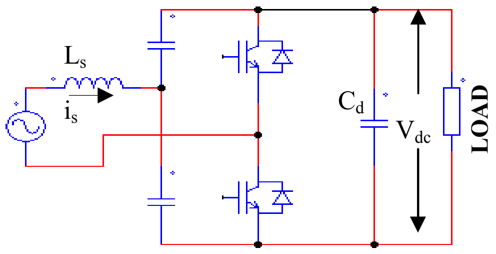

Fig. 9. Half bridge Bridge converter

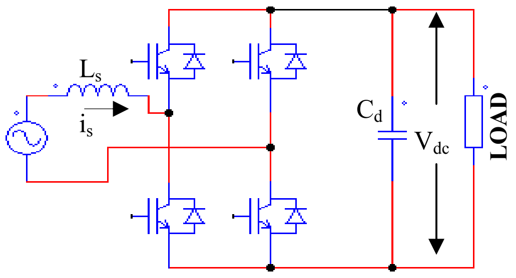

Fig. 10. VS converter

These configurations are implemented with two semi-conductor switches and two diodes. The inductor L is on the input side. Figures 9 and 10 show half-bridge boost converter and voltage source converter based on half-bridge and full bridge topologies, respectively. These two topologies allow bi- directional power flow.

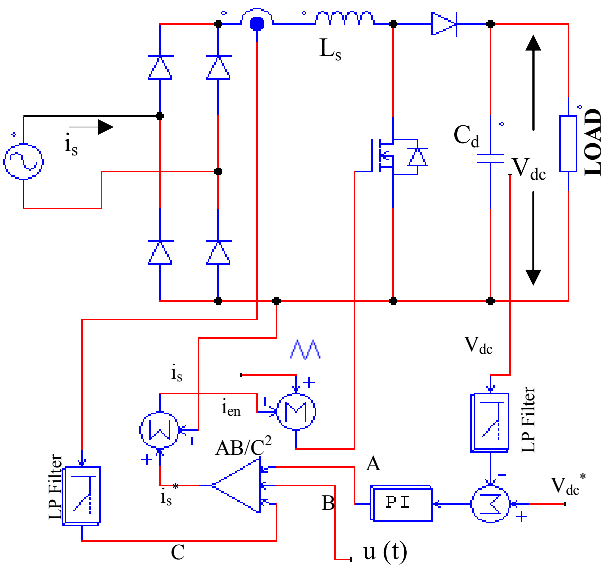

Fig. 11. Control scheme of PFC converter

III. CONTROL SCHEME FOR POWER FACTOR CORRECTION

The objective of the control scheme of the boost converters is to regulate the power flow ensuring tight output voltage regulation as well as unity input power factor. Cascaded control structure shown in Figure 11 is the most extensively used control scheme for these converters and essentially similar control philosophy is applied to all the other topologies of boost converter[5].

In this scheme, the output of voltage regulator, limited to a safe value, forms the amplitude of input reference current. This reference amplitude is then multiplied to a template of input voltage to synchronize the reference with input voltage, as required for unity power factor operation. The inductor current is forced to track its reference current using current controller, which generates appropriate gating signals for the active device(s).

IV. MATHEMATICAL MODELLING OF PFC CONVERTERS

The proposed PFC converter system comprises single-phase AC supply, power converter circuit, and control scheme. In this section modeling equations of various components of the converter system are formulated[6] separately to develop a comprehensive model for their performance simulation. Supply System Under normal operating conditions the supply system can be modeled as a sinusoidal voltage source of amplitude V_m and frequency f_s. The instantaneous voltage is given as,

$$V_s(t) = V_m \sin wt \qquad (1)$$

Where $\omega=2\pi f_s t$ electrical rad./s and t is instantaneous time.
From sensed supply voltage, a template u(t) is estimated for converter topologies with AC side inductor.

$$u(t)=V_s(t)/V_m \qquad (2)$$

u(t) for converter topologies with DC side inductor is obtained from

$$u(t)= \left|V_s(t)\right| / V_m \qquad (3)$$

A.DC Voltage Controller

The objective of dc voltage controller is to maintain the load. A proportional integral (PI) voltage controller is selected for voltage loop for tight regulation of the output voltage. The DC voltage V_{dc} is sensed and compared with set reference voltage V_{dc}*. The resulting voltage error $V_{e(n)}$ at nth sampling instant is

$$V_{e(n)} = V_{dc}^* - V_{dc(n)} \qquad (4)$$

Output of PI voltage regulator $V_{0(n)}$ at nth sampling instant is,

$$V_{0(n)} = V_{0(n-1)} + K_p(V_{e(n)} - V_{e(n-1)}) + K_i V_{e(n)} \qquad (5)$$

where K_p and K_i are the proportional and integral gain constants. $V_{e(n-1)}$ is the error at the (n-1) th sampling instant. The output of the controller $V_{0(n)}$ after limiting to a safe permissible value is taken as amplitude of reference supply current A.

B.PWM Current Regulator

Current regulation loop is required for active wave shaping of input current to achieve unity input power factor and reduced harmonics.

C.Reference Supply Current Generation

The input voltage template B obtained from sensed supply voltage is multiplied with the amplitude of reference source current A in the multiplier-divider circuit. Moreover, a component of input voltage feed forward C is also added to improve the dynamic response of the converter system to line disturbances (Figure 11). The resulting signal forms the reference for input current[21]. The instantaneous value of the reference current is given as

$$i_s^* = AB / C^2 \qquad (6)$$

D.Active Wave-shaping of Input Current

The inductor current error is the difference of reference supply current and inductor current (ien=is*-is). This error signal is amplified and compared to fixed frequency carrier wave to generate gating signals for power devices of the converter[8]. PWM switching algorithm is selected depending on the converter topology.

V. V.MODELLING OF PFC CONVERTERS

The converters are modelled using first order non-linear differential equations[9]. The number of equations is equal to the number of energy storage components in the system.

A. Single-phase Boost PFC Converter

The boost converter is modelled using two differential equations for inductor current i_L and DC link capacitor voltage V_{dc} .

$$P\, i_L=(V_d-V_p)/L-r(i_L/L) \qquad (7)$$

$$P\, V_{dc}=(i_p-V_{dc}/R)/C_d \qquad (8)$$

where P is the differential operator (d/dt); r, the resistance of the inductor L; V_d , the rectified line voltage at diode rectifier output; R, the resistance of the load and V_p is the PWM voltage across the switch and is defined as

$$V_p = V_{dc}\,(1-S) \qquad (9)$$

i_p is the current through the boost diode and is defined as

$$i_p = i_L\,(1-S) \qquad (10)$$

where S is the switching signal obtained from current regulation loop. Its value is 1 (ON) or 0 (OFF) depending upon the state of the switch.

B.Single-phase Semi-boost Converter

Two variants of semi-boost converter topologies are considered, ie., symmetrical and asymmetrical. Both types have identical characteristics. The variations lead to simplified current regulation in the symmetrical variant. The converter is described by two differential equations for inductor current i_L and DC link voltage across capacitor V_{dc} .

$$P\, i_L=(V_s-V_p-riL)/L \qquad (11)$$

$$P\, V_{dc}=(i_p-V_{dc}/R)/C_d \qquad (12)$$

Where PWM voltage and current are ,

$$V_p = V_{dc}\,(S1-S2) \qquad (13)$$

$$i_p=i_L(S1-S2 \qquad (14)$$

where S1 and S2 are switching states of switches S1 and S2.

C.Single-phase Half-bridge Converter

There are three modelling equations describing the model of the converter [12]as:

$$P\, i_L=(V_{s\,+}\,V_{p1}-V_{p2}-r\, i_L)/ L \qquad (15)$$

$$PV_{C1}= -\{i_{p1}+(V_{dc}/R)\}/C1 \qquad (16)$$

$$PV_{C2}=\{i_{p2}-(v_{dc}/R)\}/C2 \qquad (17)$$

DC link voltage is as

$$V_{dc} =(V_{C1}+V_{C2}) \qquad (18)$$

and the PWM voltages and current are as

$$i_{p1} =S1i_L \qquad (19)$$

$$i_{p2} =S2i_L \qquad (20)$$

$$V_{p1} =S1V_{C1} \qquad (21)$$

$$V_{p2} =S2V_{C2} \qquad (22)$$

here S1 and S2 are switching states of respective switches.

D.Single-phase Voltage Source Converter

The converter is described [14]by two differential equations for inductor current i_L and dc link voltage across capacitor V_{dc}

$$P\, i_L=(V_s-V_p-r\, iL)/ L \qquad (23)$$

$$P\, V_{dc}=(i_p-V_{dc}/R)/C_d \qquad (24)$$

where PWM voltage and current are

$$V_p = V_{dc}(S_a-S_b) \qquad (25)$$

$$i_p=i_L(S_a-S_b) \text{ respectively;} \qquad (26)$$

where

$S_a = 1$ if switches S1 and S4 are ON, otherwise $S_a = 0$.

$S_b = 1$ if switches S2 and S3 are ON, otherwise $S_b = 0$.

VI. PERFORMANCE CHARACTERISTICS

The simulation of converters is carried out for different loading conditions at 100-kHz switching frequency. The values of inductor and capacitor are calculated for desired input current ripple and output voltage ripple[10]. A summary of performance evaluation and topology features is presented in Tables 1 and 2, respectively. Steady-State and Dynamic Performance All five topologies considered in this work provide smooth DC voltage at a power factor close to unity and show excellent steady state and dynamic characteristics (Figures 2-5). Input current THD is well below the limits stipulated by IEC61000-3-2 and other standards. These converters exhibit satisfactory voltage regulation at load variations from 325 W to 1625 W of nominal. This makes these converters suitable for applications with significant load variation. Half-bridge converter and voltage source converter exhibit best characteristics in terms of dc voltage regulation and input current THD. Input current distortion at zero crossovers is also non-existent in these converters.

VII.SUMMARY OF PERFORMANCE EVALUATION

Table 1

Summary of performance evaluation

RECTIFIER	THD (%)		POWER FACTOR		RISE/ DIP IN OUTPUT VOLTAGE (%)	SETLINGTIME LOAD APPLICATION / REMOVAL(ms)
	HEAVY LOAD	LIGHT LOAD	HEAVY LOAD	LIGHT LOAD		
BOOST	0.3917	1.0572	1.000	0.999	2.41/3	47/47
SEMI-BOOST	0.4789	1.8680	1.000	0.999	2.41/3	47/47
HALF-BRIDGE	0.4394	1.8137	1.000	0.999	2.8/3.4	27/37
VSC	0.4699	1.9093	1.000	0.999	2.41/3	37/27

Table 2
Summary of topology / efficiency evaluation

RECTIFIER	NUMBER OF POWER SWITCHES	NUMBER OF DIODES	NUMBER OF VOLTAGE DROP ACROSS SEMICONDUCTOR DEVICES	POWER FLOW
BOOST	1	5	3	UNIDIRECTIONAL
SEMI-BOOST	2	4	2	UNIDIRECTIONAL
HALF BRIDGE	2	2	1	BIDIRECTIONAL
VSC	4	4	2	BIDIRECTIONAL

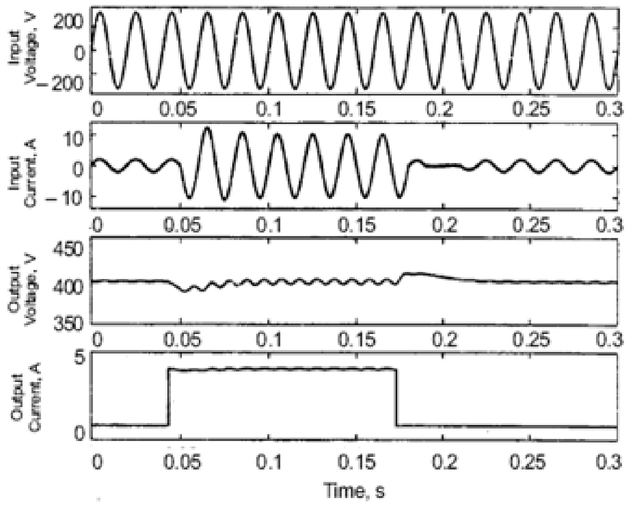

Fig. 12 Dynamic performance of single-phase -boost converter

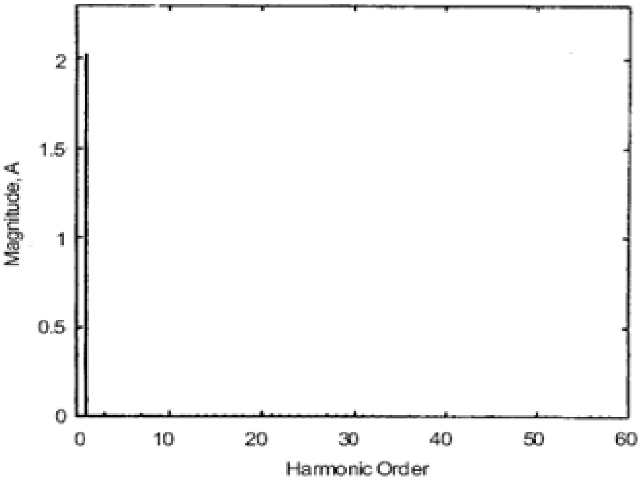

Fig. 13 Harmonic spectrum of input current for single-boost converter at light load (325 W)

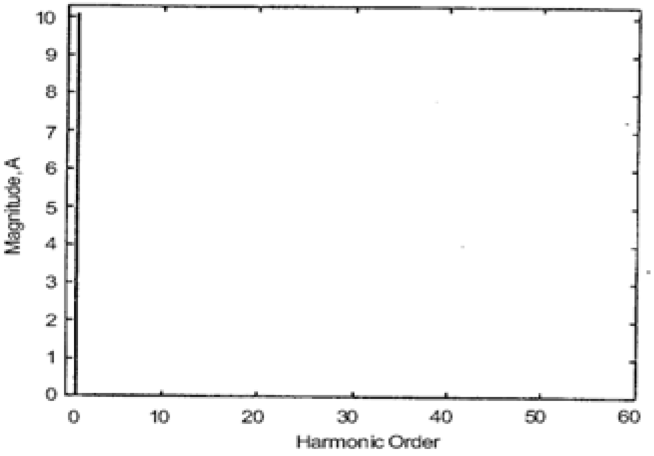

Fig. 14 . Harmonic spectrum of input current for single-phase boost converter at heavy load (1625 W)

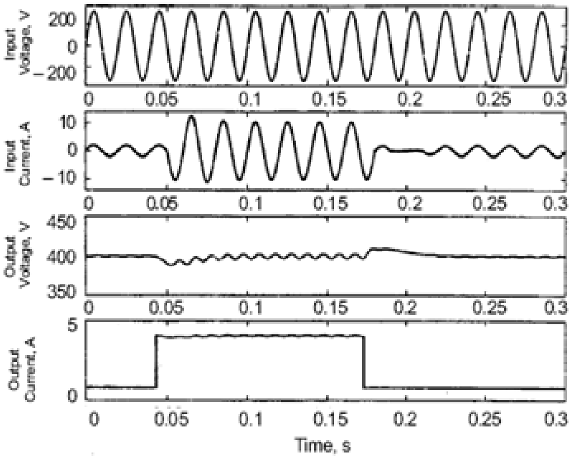

Fig. 15 Dynamic performance of single-phase Semi-boost converter

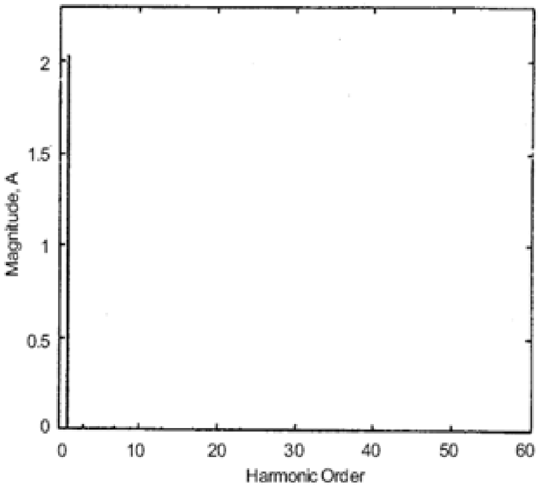

Fig. 16 Harmonic spectrum of input current for single-phase Semi-boost converter at light load (325 W)

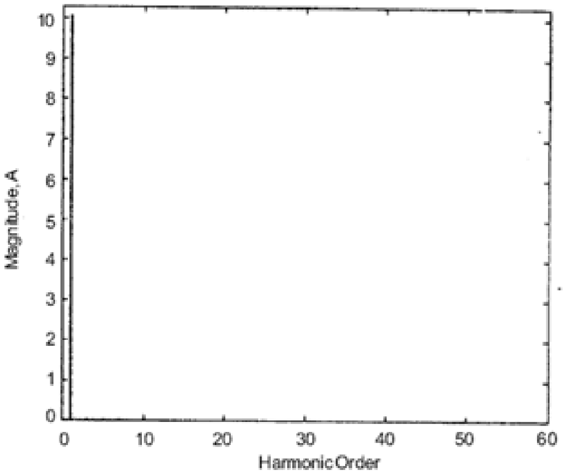

Fig. 17. Harmonic spectrum of input current for single-phase Semi-Boost converter at heavy load (1625 W)

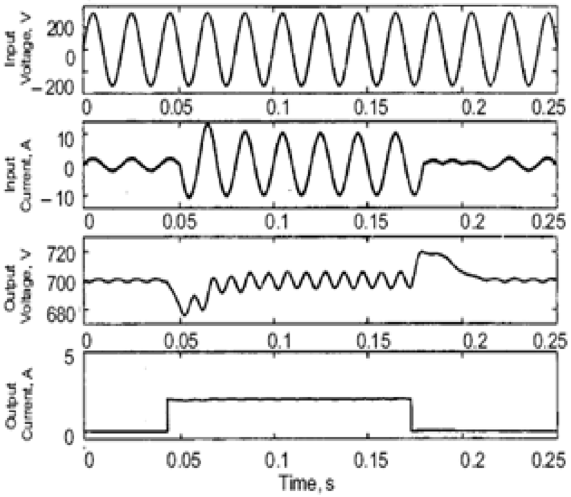

Fig. 18 Dynamic performance of single-phase Half-Bridge converter

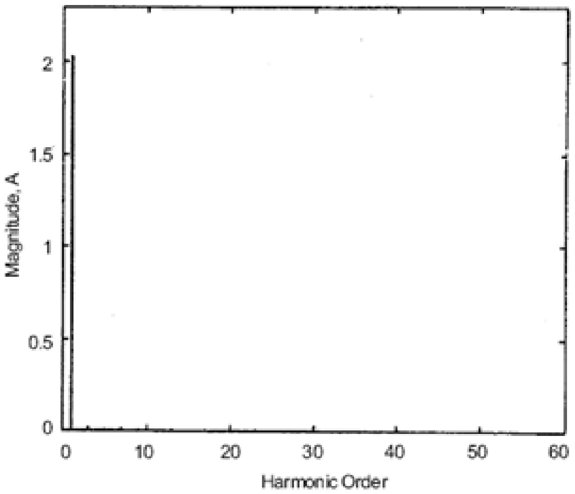

Fig. 19 Harmonic spectrum of input current for single-phase Half-Bridge converter at light load (325 W)

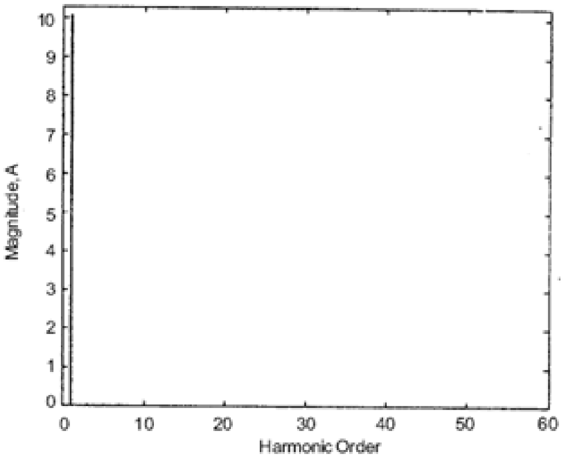

Fig. 20 Harmonic spectrum of input current for single-phase Half-Bridge converter at heavy load (1625 W)

VIII. EFFICIENCY COMPARISION

Several single-phase PWM boost rectifier topologies have been described in the paper[17]. The 1-switch bridge rectifier [see Fig. 6 and 11], has one of the simplest circuit structures. Typical voltage current waveforms for the circuit, using hysteresis current control, are shown in Fig. 12; the hysteresis band is made large in the figure for illustrative purposes. The 2-switch H-bridge rectifier (see Fig. 7), performs the same switching action as the 1-switch rectifier but has the advantage of higher efficiency. The 4-switch H-bridge rectifier [see Fig.10], can produce sinewave currents of a higher quality than the I-switch rectifier. The operation of the 2-switch asymmetrical half-bridge rectifier is described in this paper and can be considered as a 2-switch, and hence low cost, alterative to the 4-switch H-bridge. This new circuit topology [9] can achieve the same performance as the 4-switch H-bridge rectifier, but uses only two switches instead of four. The main disadvantage of the 2-switch asymmetrical half-bridge is the large number of power semiconductor devices placed in series with the line current. This rectifier has four semiconductors in series with the current as opposed to the two semiconductors in the 4-switch H-bridge[22]. This can affect the overall efficiency of the circuit and increase the heat sink size.

IX.EXPERIMENTAL VERIFICATION

The performance of single-phase boost converter is experimentally tested to identify the numerous non-topological factors that can impact the quality of current drawn by these converter as well as to develop greater confidence in the simulation studies carried out in the paper. A universal line input of (80 V-270 V) was fed to the single-phase boost converter. The power circuit is fabricated with CT60AM18B IGBT and MUR460 fast recovery diode with L_s = 1.1 mH and C_d =560μF. The converter is fed from ac lines via an autotransformer followed by an isolation transformer to provide variable input voltage and protection, respectively.

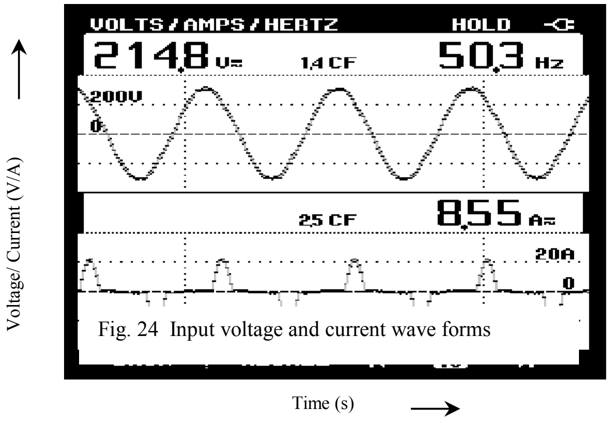

Fig. 24 Input voltage and current wave forms

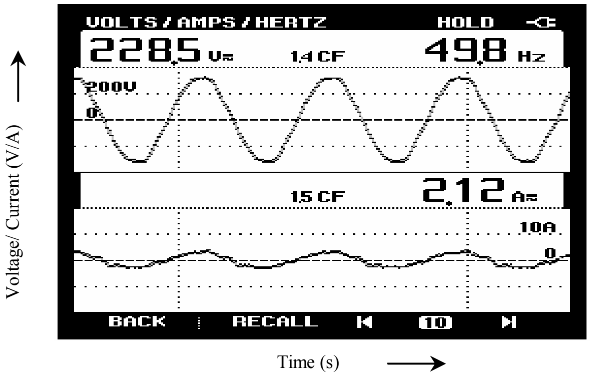

Fig. 25 Input voltage and current wave forms after use of single phase Boost converter

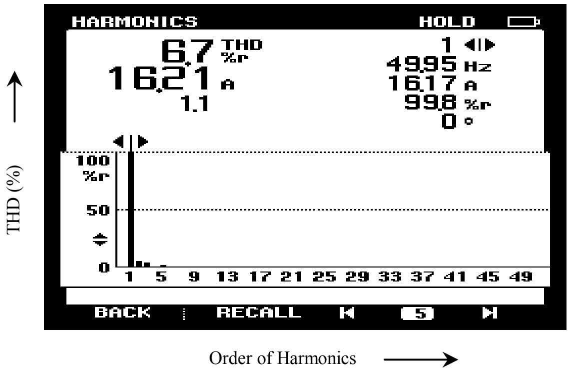

Fig. 26 Harmonic profile after regulation of current

Figure 24. shows the distortion in the input voltage caused by distorted current when the system is operated as an uncontrolled diode bridge rectifier. Harmonic current interacting with the source impedance, primarily due to utility lines and transformers, causes this distortion. This distortion is corrected by triggering the power factor controller[7] and wave shaping the input current into desired sinusoid as shown in Figure 25. The input current and voltage waveforms shown in Figure 25. matches with the simulation results. This validates the mathematical model as well as simulation tools used in the comparative evaluation.

X.CONCLUSION

Modelling and simulation of PFC converters are carried out and single phase boost converter is experimentally tested to verify the simulation results and identify the numerous reasons impacting PFC converters in general. Performance and applicability of these converters are presented on the basis of simulated results under identical line and load conditions. A comprehensive summery of performance indices and topological features are provided. From the study it can be inferred that single-phase boost topology is optimal in terms of performance, efficiency, cost and power density and is therefore suitable for most applications. Half-bridge toplogy is the most efficient topology with excellent performance. Its application is however limited due to restriction on minimum step-up ratio of 2√2 and low efficiency during inverter mode. Semi-boost topologies provide excellent performance and high efficiency for power factor pre-regulator applications for switched power supplies and drives systems albeit at higher cost of implementation and control. Voltage source converters offer bi-directional power flow at high efficiency and variable power factor. The potential applications of VSC can be UPS, static VAR compensator, and battery charging.

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