

Comparative Analysis of Power Factor Correction Converters for Different Topologies



Sanatan Kumar , Devashish , and Madhu Singh

1 Introduction

With the advancement in power electronics equipment, the integration of Power Factor Correction (PFC) into modern motor drives system has developed in the last few years. Today a number of PFC circuits can be built with different operating modes, each having its own set of challenges. As there are different types of load, so it is difficult to create suitable PFC for every load [1].

Harmonic elimination and power factor correction specifications as required by IEC 61000-3-2 stick apart among these developments as one of the most important crucial stage in electrical supply and designs in previous years. Despite increase in power ratings across all electrical appliances and expanding implementation including its harmonic elimination rules, better power supply designs are coming up with integrated power factor correction capability. Engineers are finding difficult to implement the required PFC measures and comply with other requirements of legislation such as power quality improvements, active mode reliability, and EMI constraints [2–3].

Our dedication to the use of many choices for topology and its components is expressed in the design guidance. In this paper, comparison in detail of various PFC implementation options while preserving the overall system requirements has been done.

Choices for power factor compensation approaches vary from varied range of active circuits to narrow range of passive circuits. The suitable solution might change subject to the change in level of power and other system details. The progress that has been made over the last few years in the discrete semiconductor systems and the

S. Kumar (✉) · Devashish · M. Singh
Department of Electrical Engineering, NIT Jamshedpur, Jamshedpur, Jharkhand, India
e-mail: 2015rsee00@nitjsr.ac.in

availability of cheaper controller ICs made the active PFC design more reasonable for a varied choice of uses [4]. It is important to observe at PFC designs in terms of real system price and execution while evaluating such designs.

Power converters typically use a diode correction to transform AC voltage into DC voltage accompanied by a bulk condenser. More than 60% of energy is projected to be consumed by some kind of electronics system by the end of the year 2020. Almost all of the appliances might have a front-end filter DC-DC converter. The capacitor filtration circuit connected to diode rectifier circuit, without any control circuit, draws pulsating currents from the distribution grid, which leads to low power and high harmonics content. These results in increased neutral currents in three-phase network, and heating of rotating motor. This makes some power conditioning. This is necessary, because there is a necessity for the power factor correction to limit the harmonics quality of line currents generated from electrical devices associated with electricity distribution grids [5]. Regulatory bodies across the globe have been brought to notice by the crisis. Governments strengthen rules, set new standards for lower harmonic components of current which eliminate their total harmonic current which may be produced. Consequently, the line current harmonics need to be reduced, and PFC correction and harmonic reduction circuits need to be introduced.

The independence from harmonics often minimizes interference from the same source in other applications. PFCs also have to meet with regulatory requirements in many of the current energy sources. The IEC 61000-3-2 must now be complied with in electrical equipment in Europe, Asia, and Japan [6].

Energy level issues are not a modern trend, Duffey et al. [7] originally proposed an improvement of the power factor for the distribution system back in the 1920s. But the Power Factor Correction (PFC) technique has become increasingly popular in the world of power electronics in the last few years. Lai et al. [8] and Singh et al. [9] defined the power factor and illustrated its significance for the field of power electronic converter.

The growth of DC-DC converter has improved enormously over the past two decades. A detailed analysis of the specifications, design characteristics, device selection, and specification for specific applications of Improved Power Quality Converters (IPQCs) is presented. The objective is to provide scholars, developers, and computer analyst continuing to work on switched-mode AC-DC converter, as suggested by Singh et al. [10] has a broad variety of IPQC application profile.

A boost PFC has been defined by Caneson et al. [11] in which the switch is switched on and off only twice per line. As a result, the losses in di/dt and dv/dt and conversion are smaller, sluggish recovery diodes can be used and heavy EMI filters are avoided. Alternatively, the output voltage may be controlled in a broad load range by simply regulating it. Salmon et al. [12] also implemented a PWM rectifier with a soft-switching unit power factor, which significantly increases the performance of the system by flipping the main switches into a switching system without any auxiliary switches. Thanks to a single-stage converter topology instead of a front-end rectifier followed by a boost converter, the conduction losses can also be greatly decreased. However, this has some pitfalls, as it requires a number of power circuit machines. The modern boost converters impressed primarily with the inductor volume, weight,

and power unit losses; these factors affected the converter’s size, power density, and performance. Zhang et al. [13] suggested the three-level boost converter within only one PFC, with a relatively small inductor and a low power system. It has provided high density, high efficiency, and lower costs.

SEPIC, Cuk, and ZETA converters have been proposed in [14–18] are used for large power applications. But these converters do not reflect the component stresses, the control of output voltage which is leading the distortion of output voltage and noise interference.

Depending on the configuration and specifications of the system, either solution can require the converters to work in DCM or CCM. However, in that article, active PFC converter operation for the AC mains unit power factor is provided.

2 Mathematical Description on Power Factor Correction

The description of power factor is given as proportion of the actual electrical power (defined under W) and the total electrical power is given as (VA): where actual electrical power is the total summation of the continuous product of voltage or current over a cycle and the total electrical power is the combination of current rms and the voltage rms.

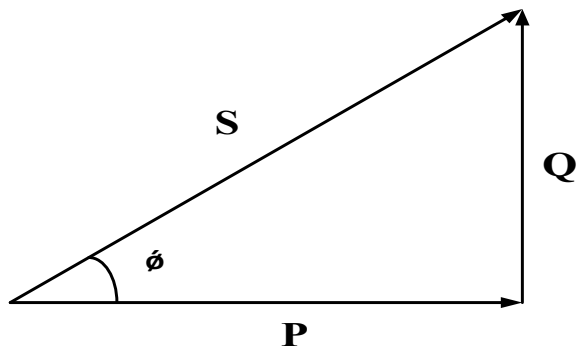
The power ratio is unity when both current curve and voltage curve with respect to time are sinusoidal. All the three powers in electrical system and their relation are shown in Fig. 1. Time

$$S = V \times I(\text{Volt} - \text{Amp}) \tag{1}$$

$$P = S.\text{Cos}\phi(\text{Watt}) \tag{2}$$

$$Q = S.\text{Sin}\phi(\text{var}) \tag{3}$$

Fig. 1 Power triangle for electrical power supply



$$S = \sqrt{(P^2 + Q^2)}(VA) \quad (4)$$

Power factor also is introduced as a result of both the distortion factor as well as the displacement factor as specified in Eqn. 5, the distortion power factor K_θ is the cosine of just the angular position in between simple source reference current and the source reference voltage.

$$Power_Factor = K_d K_\theta \quad (5)$$

$$K_d = \frac{I_{rms}}{I_r} \quad (6)$$

$$K_\theta = \text{Cos}\theta \quad (7)$$

The factor for distortion is defined for sinusoidal voltage only and can be expressed with the total harmonic distortion (THD):

$$DPF = \frac{1}{\sqrt{1 + THD^2}} \quad (8)$$

$$PF = \frac{\text{Cos}\phi}{1 + THD^2} \quad (9)$$

The overall power factor is far below to unit value as only the fundamental component provides true power so another harmonic is introduced to total power. This variance was defined as the effect of distortion, and is primarily responsible for the nonlinear portion. The general balance of actual power and apparent power is presented through

$$P_{in} = V_{inrms} \times I_{inrms} \times \text{Cos}\phi \times \text{Cos}\theta \quad (10)$$

where $\text{cos}\phi$ is indicated as the displacement factor between the source voltage and source current waveforms originating from the phase angle ϕ and where $\text{cos}\theta$ is the factor of distortion. Consequentially, in Fig. 2, power factor correction technique is not implemented for nonlinear load. Harmonic content is injected in the input AC current that's why the power factor of the given power source with the waveform is around 0.6. Harmonic spectrum analysis for different harmonic number is displayed in Fig. 4.

Figure 4 shows the waveform of pure input AC voltage and input current when PFC is implemented with an ideal power factor adjustment between non-linear load and source. It has a current waveform imitating the form as well as the phase of the waveform of the voltage. Notice that their present input harmonics are nearly zero. Harmonic spectrum analysis for different harmonic number is shown in Fig. 5.

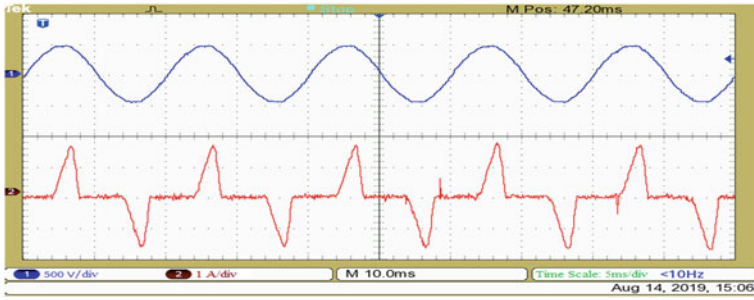


Fig. 2 Source voltage and current waveform without PFC converter

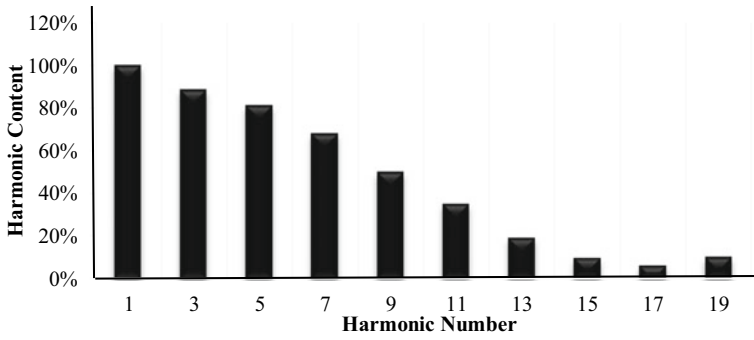


Fig. 3 Harmonic spectrum analysis of the source current waveform shown in Fig. 2

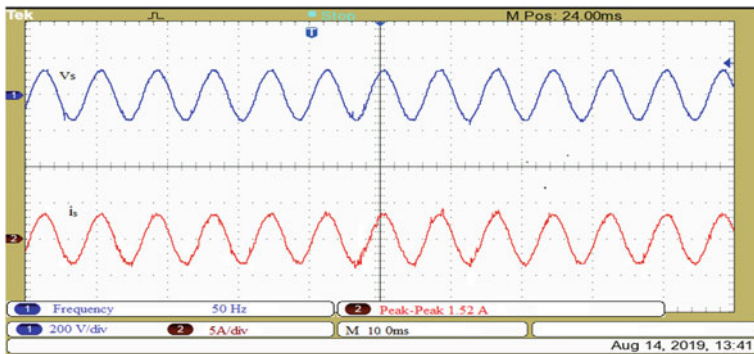


Fig. 4 Source voltage and current waveform with PFC converter

The goal is to increase the displacement factor and distortion factors by using a PFC stage for AC-DC converter in the main phase in directive to decrease the reactive power available from the supply. Acceptable obtained sinusoidal source current I_n

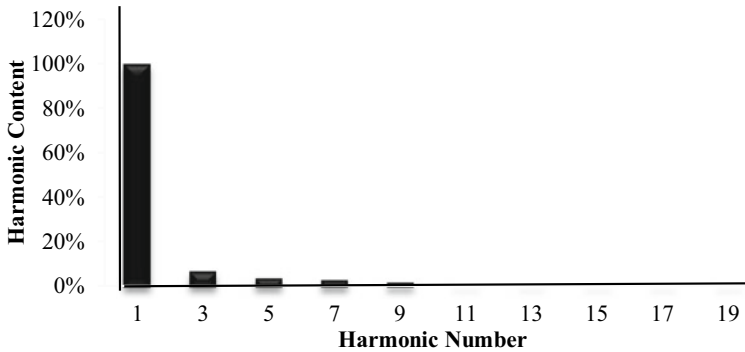


Fig. 5 Harmonic spectrum analysis of the current waveform in Fig. 4

phase with source voltage, the load must be strictly immune from the ac view. This results in better power output and better machine performance.

3 Types of Power Factor Correction

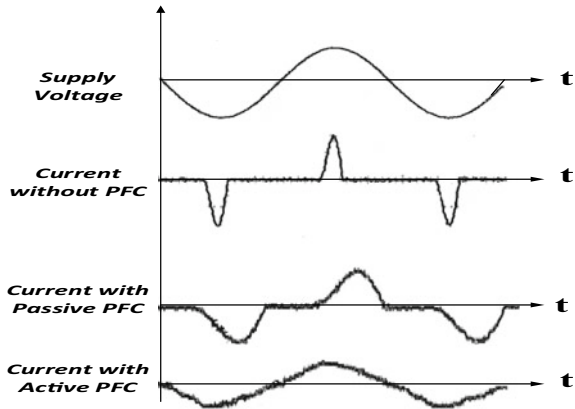
Two major PFC categories are generally available: active and passive PFC. Passive PFC includes basic reactive elements such as inductors and condensers to make up for line voltage and current displacement angle. This process is called correction of passive power factor. Active PFC employs switch and controller circuits for raising the power factor and minimizing the harmonic distortion. Both approaches have their own merits and demerits but a more modern approach appears to be active PFC.

Active PFC is used to mitigate input current distortion, often switch mode power supply (SMPS) are realized in it. Even if they are more complicated than passive PFC circuits, evolving integrated circuits and electronic components made an inexpensive option for active PFCs. Such power systems are capable of reaching a power factor of 99% and a THD of less than 5%. Responsive PFC topologies occur in both low and high-frequency operation.

The scale and weightiness of the passive solution are controversial at higher power levels. Figure 6 shows three distinct power supplies with current waveform with same input characteristics. As seen, the maximum current in passive PFC circuits remains thirty-three percent more than in active circuit maximum currents. Furthermore, although the harmonic rates of the level two that follows the IEC61000-3-2, certain recent regulations may fail to comply with the strict 0.9 PF criterion [19–20].

The market trends (higher copper and metallic core content costs and lower semiconductor prices) have over the past years significantly tipped the difference in terms of active PFC in some of the most price-sensitive applications for consumer use. In combination with the effective action of active PFC circuits [21], it seems that this pattern will continue and make the designers available more advanced active PFC

Fig. 6 Various input Current waveforms with different types of PFC converter



solutions. Therefore, the primary objective of PFC circuit intended for nonlinear load is present to diminish the harmonic value of line current.

3.1 Active Power Factor Improvement Approaches

Active power factor improvement provides a brighter and more effective way to control input side power factor when a power supply configuration is above hundred Watt and it is the preferred form of PFC. Active PFC consists of a high switching regulator which can produce a Quantitative power factor of more than 95% [22]. Effectively power factor correction on AC side of input voltage is automatically corrected and capable of a multiple range of input voltages. The additional costs associated with the increased complexity is needed when implementing Active PFC is a drawback. The following sections will discuss an active PFC circuit which has also improved features and but don't have several of the directly earlier mentioned disadvantages.

Active PFC Based on Boost Converter

The boost converter is widely used with single-phase full-wave diode bridge rectifier for optimizing power efficiency among the various current PFC topologies. It is a high-frequency active PFC system and is most often picked because the boost converter experiences lower transistor stresses than other DC-DC converters like Buck-boost, Cuk, SEPIC, etc.

There are mainly two modes in which the boost converter works that are the continuous mode of conduction and discontinuous mode of conduction, which is the most prevalent power factor improvement architecture. Through changing the switching frequency, the transfer mode power, also termed to as the Critical Conduction form or Barrier Conduction form, keeps the converters at the border stuck in

between CMC as well as DMC. Figure 7 shows the active PFC circuit for Boost converter.

This architecture increases the voltage of the input side. Because the converter can function during the line-cycle, the crossover distortions in the source input current is zero. Across the envelope near source input voltage zero crossing the distortion is zero. Figure 8 shows the current and voltage wave pattern of a PFC circuit centered on a CCM boost converter. The converter switch current is continuous because the boost converter topology is connected in chain sequence through the input and the input power is not interrupted by the high-frequency operation of switch [23]. Therefore, the source current has high-frequency components of harmonics, leading to lower EMI and lower circuits for filtration. The output condenser restricts the turn-off voltage of the switch S_w to approximately the output voltage by diode D and consequently guards the switch.

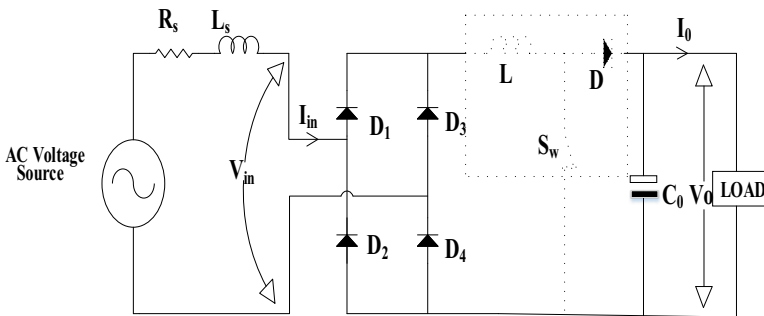
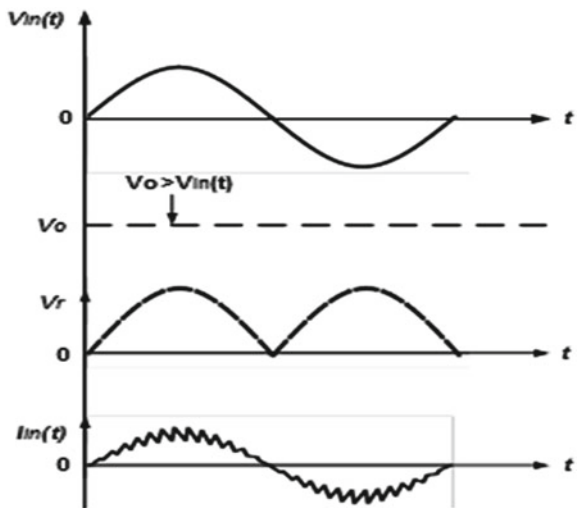


Fig. 7 Active PFC architecture centered on the Boost Converter

Fig. 8 Current and voltage wave pattern of a PFC circuit centered on a CCM boost converter



The regulator controls inductor current and tries to maintain it at a constant value so that it could not fall beyond the permissible limit. In comparison to CCM or CRM, the DCM converter functions in stable frequency and offers current interruptions. Comparison waveform is displayed in Fig. 9. It is seldom or never used because of high peak current and EMI linked to the DCM converter.

The hysteretic control variation is used for CRM converter for the lower limit of zero current on the other pointer. It remains an intrinsically stable variable frequency control technique, which prevents reverse recovery corrective losses. The on time remains the same for a certain constraint of input, but the off time is varied. As a consequence, when the source voltage is lowest instantaneously, and vice versa, the power converter has the highest switching frequency.

Active PFC Buck-Boost Converter

Ultimately, in the figure, you will see the boost buck PFC centered converter circuit with its waveforms Figs. 10 or 11. As even the name indicates, the buck-boost converter is accomplished of creating an inferior or advanced output voltage than the

Fig. 9 Comparison of CCM and CRM operating configurations with inductor current

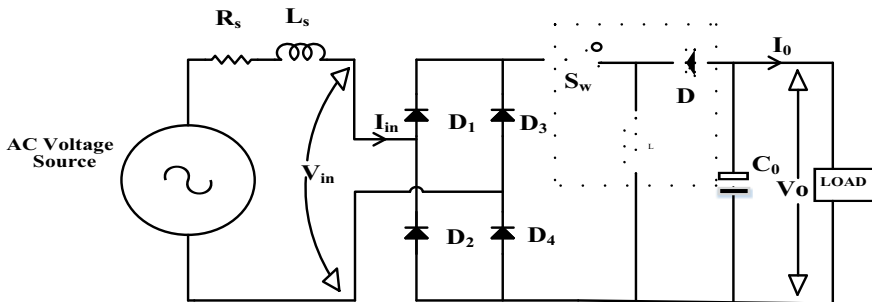
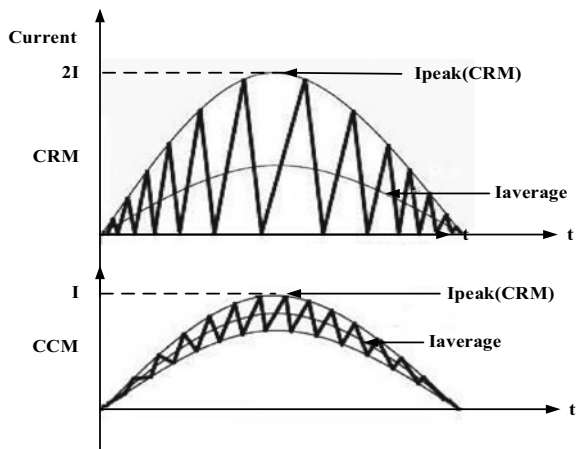
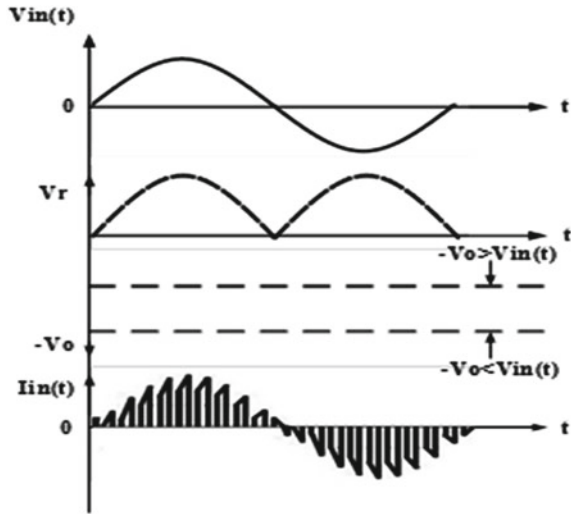


Fig. 10 Active PFC architecture centered as buck-boost converter

Fig. 11 Buck-Boost converter centered PFC circuit current and voltage wave patterns



source voltage. It can be produced as the only cascade attachment between a buck- and a boost converter [24]. As a result, in steady-state, presuming CCM process, its voltage transfer ratio (output-to-input) is the product of the cascading ratio of the attached buck as well as boost converters, supposing that they have a specific duty ratio of D .

The input current takes no crossover distortions since the converter could work during the line cycle. This does not distort the current line envelope across the zero-crossing voltage. Furthermore, even if the inductor current, like that of the buck converter, is constant, since the peak frequency switch S_w stops the source current the converter's input switch is discontinuous [25]. Therefore, the input current is important for high-frequency components which raise the requirement of filtering and EMI.

The production of voltage for the boost-buck converter may be both superior and lesser than the input voltage. In addition, the buck-boost converter can be served to regulate DC voltage and to run the BLDC motor at low speeds, as compared to boost PFC topology.

4 Conclusion

The PFC manufacturer has seen a large rise in the number of choices available in the over few years. All this is because of the growing interest of IEC 61000-3-2 and the vigorous competition among semiconductor providers. As PFC gets better and more cost effective, end-users are going to receive maximum benefits. The through skill of these IC controllers allows power supply manufacturers more opportunities for execution.

Next, the technical context of the power factor correction being defined, such as the fundamentals of the energy usage and the quantity indication. Since the need for an improved power factor was extracted from the illustration of a diode bridge rectifier, PFC circuits were added. Two different topologies of converters are covered: boost and buck-boost converter.

Within this article, topics of power factor correction were discussed, which offered an in-depth knowledge of PFC circuits and extended power electronics understandings.

References

1. T.J.E. Miller, *Brushless Permanent Magnet and Reluctance Motor Drive* (Clarendon Press, Oxford, 1989)
2. A. McEachern, W.M. Grady, W.A. Moncrief, G.T. Heydt, M. McGranaghan, Revenue and harmonics: an evaluation of some proposed rate structures. *IEEE Trans. Power Delivery* **10**(1), 474–480 (1995)
3. I. Batarseh, *Power Electronic Circuits* (Wiley Inc. in press).
4. N. Mohan, T.M. Undeland, W.P. Robbins, *Power Electronics: Converters, Applications and Design* (Wiley, USA, 2003)
5. L. Dixon, Average current mode control of switching power supplies, in *Product & Applications Handbook, Uniprode Integrated Circuits Corporation, U140* (1993–1994), pp. 9–457–9–470
6. Limits for Harmonic Current Emissions (Equipment Input Current ≤ 16 A per Phase). Int. Std. IEC 61000-3-2, 2
7. C.K. Duffey, R.P. Stratford, Update of harmonic standard IEEE-519: IEEE recommended practices and requirements for harmonic control in electric power systems. *IEEE Trans. Indus. Appl.* **25**(6), 1025–1034 (1989)
8. J.S. Lai, D. Hurst, T. Key, Switch-mode power supply power factor improvement via harmonic elimination methods, in *Conference Record of IEEE-APEC'91*, pp. 415–422.
9. B. Singh, S. Singh, A. Chandra, K. Al-Haddad, Comprehensive study of single-phase AC-DC power factor corrected converters with high-frequency isolation. *IEEE Trans. Ind Inform.* **7**(4), 540–555 (2011).
10. B. Singh, B.N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, D.P. Kothari, A review of single-phase improved power quality AC-DC converters. *IEEE Trans. Ind. Electron.* **50**(5), 962–981 (2003)
11. C.A. Caneson, I. Barbi, Analysis and design of constant-frequency peak-current-controlled high-power-factor boost rectifier with slope compensation, in *Conference Record of IEEE-APEC'96*, pp. 807–813.
12. J.C. Salmon, Techniques for minimizing the input current distortion of current-controlled single-phase boost rectifiers. *IEEE Trans. Power Electron.* **8**(4), 509–520 (1993)
13. J. Yang, J. Zhang, X. Wu, Z. Qian, M. Xu, Performance comparison between buck and boost CRM PFC converter, in *Proc. IEEE Control Model. Power Electron. Conf.*, (2010) pp. 1–5.
14. S. Kumar, M. Singh, Improved power quality Cuk converter for variable speed BLDC motor drive. *J. Eng. Appl. Sci.* **13**(5), 1275–1285 (2018)
15. S. Kumar, M. Singh, A fuzzy logic controller based brushless DC motor using PFC Cuk converter. *Int. J. Power Electron. Drive Syst. (IJPEDS)* **10**(4), 1894–1905 (2019)
16. A.R. Prasad, P.D. Ziogas, S. Manias, A new active power factor correction method for single-phase buck-boost AC-DC converter, in *Conference Record of IEEE-APEC'92*, pp. 814–820.
17. C.W. Clark, F. Musavi, W. Eberle, Digital DCM detection and mixed conduction mode control for boost PFC converters. *IEEE Trans. Power Electron.* **29**(1), 347–355 (2014)

18. H.S. Youn, J.S. Park, K.B. Park, J.I. Baek, G.W. Moon, A digital predictive peak current control for power factor correction with low-input current distortion. *IEEE Trans. Power Electron.* **31**(1), 900–912 (2016)
19. IEEE Standards Association. 1076.3-2009, IEEE Standard VHDL Synthesis Packages (IEEE Press, New York, 2009).
20. J.P. Noon, D. Dalal, Practical design issues for PFC circuits, in *Conference Record of APEC'97*, pp. 51–58.
21. K.D. Gusseme, D.M. Van de Sype, A.P.M. Van den Bossche, J.A. Melkebeek, Input-current distortion of CCM boost PFC converters operated in DCM. *IEEE Trans. Ind. Electron.* **54**(2), 858–865 (2007)
22. K. Raggl, T. Nussbaumer, G. Doerig, J. Biela, J.W. Kolar, Comprehensive design and optimization of a high-power-density single-phase boost PFC. *IEEE Trans. Ind. Electron.* **56**(7), 2574–2587 (2009)
23. F. Yang, X. Ruan, Q. Ji, Z.H. Ye, Input differential-mode EMI of CRM boost PFC converter. *IEEE Trans. Power Electron.* **28**(3), 1177–1188 (2013)
24. B. Singh, S. Singh, Single-phase power factor controller topologies for permanent magnet brushless DC motor drives. *IET Power Electron.* **3**(2), 147–175 (2010)
25. Optimizing Inductor Design for Efficient PFC Stage, EDN Asia, 2010 November issue, <https://www.endasia.com/article-27331>.