Buck-Buck/Boost Converter with High Input Power Factor and Non-Floating Output Voltage

[1*]Abdul Hakeem Memon[†], [1]Noor Nabi Shaikh, [1]Mahesh Kumar, [1]Zubair Ahmed Memon,

IICT, Mehran UET, Jamshoro, Sindh, Pakistan

Summary
Buck power factor correction (PFC) converter is widely used for a broad range of AC/DC applications because of its many advantages like protection against short circuit, high efficiency at universal input voltage, low output voltage, less voltage stress on the switch, low inrush current and low component cast. However the inherent dead zone introduces a large harmonic distortion in the average input current, which results a low power factor (PF) and high total harmonic distortion (THD). A constant on-time controlled critical conduction mode (CRM) buck-buck/boost converter is introduced in this paper. It can obtain high PF. The operational principle of the buck and buck-buck/boost converter is discussed and the effectiveness of the topology is evaluated by simulation results.

Key words:
Total harmonic distortion (THD), buck converter, buck/boost converter, power factor (PF)

1. Introduction

Nowadays power electronic technology has bought the revolution in the field of electrical/electronic engineering due to which it is being widely used in various types of modern equipment's which has made our life easier, simpler and luxurious. However, this technology is based on the solid state devices due to which the shape of input current is distorted. So the industries have built various standards such as IEC61000-3-2 limit and IEEE 519 [1-2]. Therefore, various types of power factor correction (PFC) converters are put forward in the literature to improve the shape of distorted current [3-4] and the buck converter is one of them. It has the major advantage of maintaining high efficiency in universal input voltage range. However, its input power factor (PF) is low due to dead zone in the average input current as shown in Figure 1. Thus, it is necessary for the buck converter to propose the technique or topology which can improve its PF.

For modifying the performance of traditional buck converter, various researches have proposed various techniques and control schemes.

The buck converter is proposed in [5] for high PF. The work in [6] has discussed modeling, analysis, and applications of buck converter in discontinuous input voltage mode operation. In [7], a new topology is proposed for reducing the input current harmonics. The performance evaluation of buck converter is presented in [8]. For enhancing the efficiency, a bridgeless buck is put forward in [9]. The study in [10] has presented soft switched buck PFC converter operating with constant on-time control. In order to replace incandescent bulb lamps with HB-LED, a tapped inductor is presented in [11]. In [12], variable on-time control strategy is put forward to enhance the PF of buck converter. The study in [12], has presented an improved buck converter.

In this paper, a critical conduction mode (CRM) buck/boost converter is introduced to work with buck converter. It can obtain high PF.

This paper is divided into six sections. In section 2, the operation states of CRM buck PFC converter are analyzed. A CRM buck/boost converter is introduced in section 3. Then the comparative analysis is discussed in section 4 in terms of input PF and contents of input current harmonics. In section 5, the effectiveness of proposed topology is evaluated by simulation results. Finally, some conclusions are drawn in section 6.

2. Operation analysis of CRM buck PFC converter

Fig. 1 illustrates the schematic diagram of a CRM buck PFC converter.

The instantaneous and rectified input voltage during half line cycle can be given as

$$v_{in} = v_a = V_m \sin\theta \qquad (1)$$

While Q_b is ON, current flows through L, C_o, and R_{Ld}. The rising slope of buck inductor is

$$\frac{di_L}{dt} = \frac{V_m \sin\theta - V_o}{L} \qquad \theta_0 \le \theta \le \pi - \theta_0 \qquad (2)$$

where $\theta_0 = arcsin\ V_{boundary}/V_m$.

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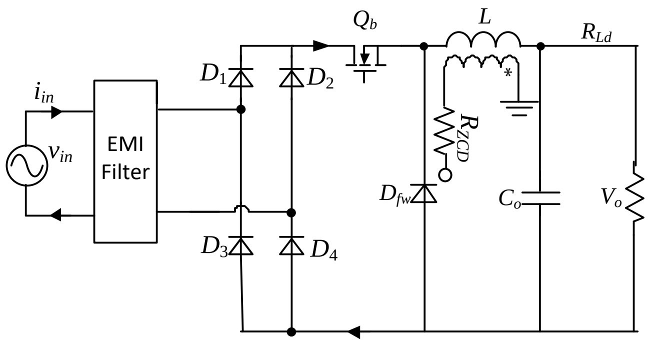

Fig.1 Schematic diagram buck converter

The maximum value of inductor current is

$$i_{L\_pk} = \frac{V_m \sin\theta - V_o}{L} t_{on} \quad (3)$$

When, Q_b is OFF, the path of current is through L, C_o, R_{Ld}, and D_{fw}. The falling time of buck inductor is determined as

$$t_{off} = \frac{L_s}{V_o} i_{L\_pk} \quad (4)$$

By substituting the value of i_{L_pk} in eq. (4), we get

$$t_{off} = t_{on} \frac{V_m \sin\theta - V_o}{V_o} \quad (5)$$

The total time is

$$t_s = t_{on} + t_{off} \quad (6)$$

By putting the (5) into (6) results in

$$t_s = \frac{V_m \sin\theta}{V_o} t_{on} \quad (7)$$

The formula to calculate the average input current of buck converter (i_{in_b}) is

$$i_{in\_b} = \frac{V_o \left(V_m \sin\theta - V_o\right) t_{on}}{2 L V_m \sin\theta} \quad (\theta_0 \le \theta \le \pi - \theta_0) \quad (8)$$

By Fourier analysis, the harmonics of the input current is calculated as

$$I_n = \frac{2}{\pi} \int_0^{\pi} i_{in\_b} \sin n\theta d\theta \quad \left(n = 1, 3, 5 \ldots\right) \quad (9)$$

The average input power can be calculated from (1) and (8) as

$$P_{in\_b} = \frac{t_{on}}{2\pi L} \left[\int_{\theta_0}^{\pi-\theta_0} V_o \left(V_m \sin\theta - V_o\right) d\theta \right] \quad (10)$$

From (10), t_{on} can be determined by assuming the efficiency to be 100% as

$$t_{on} = \frac{2\pi P_o L}{\int_{\theta_0}^{\pi-\theta_0} V_o \left(V_m \sin\theta - V_o\right) d\theta} \quad (11)$$

According to (8), (11) and the specification of the buck converter that are mentioned in section 5, the input current waveforms w.r.t input voltage at 90VAC is depicted in Fig. 2. It shows that input current has dead zone. Therefore, its PF will be low.

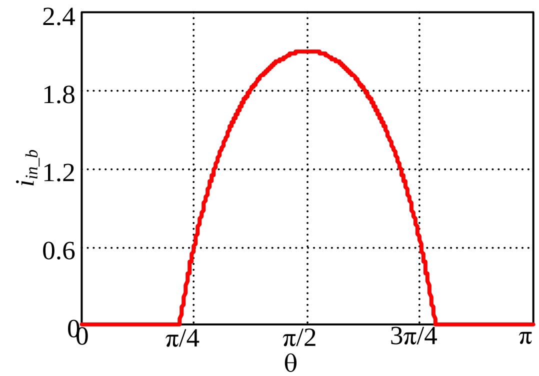

Fig. 2 Input current of CRM buck PFC converter

From (9), the relative harmonic content of the 3rd ,5th, and 7th harmonic along with IEC61000-3-2 class C limit are illustrated in Fig. 3, from which it can be observed that input current does not pass the Class C limits.

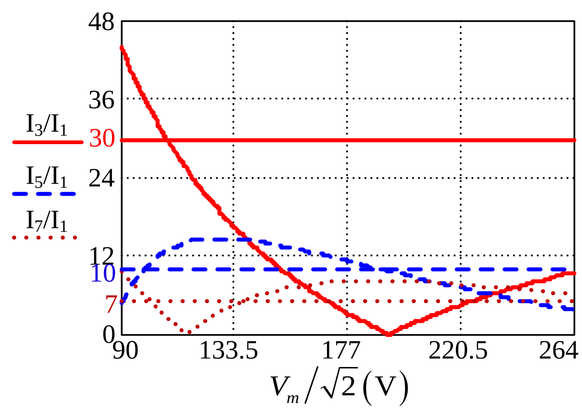

Fig. 3 Contents of input current harmonic along with limits

The input PF of CRM buck converter can be determined as

$$PF = \frac{P_{in}}{\frac{V_m}{\sqrt{2}} I_{rms}} \quad (12)$$

According to (12), the curve of the input PF with respect to universal input voltage range is drawn in Fig. 4, which shows that input PF is low for CRM buck converter. It is low particularly at low input voltage.

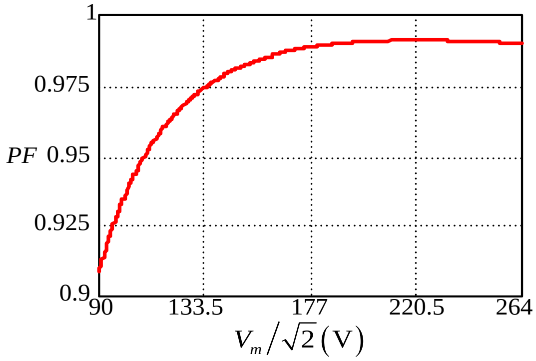

Fig. 4 Input PF for CRM buck converter

3. Operation analysis of CRM buck-buck/boost converter to improve input PF

Fig. 5 illustrates the schematic diagram of a CRM buck-buck/boost PFC converter.

The operating time period between buck and buck/boost converter depends on the boundary voltage, whose value is little more as compared to output voltage (V_o). The introduced converter operates in buck/boost mode as the input voltage (v_{in}) is lower than V_o and in buck mode for opposite condition (i-e $v_{in}>V_{boundary}$). Thus, the operating principle of the converter operating in critical conduction mode (CRM) can be divided into two cases

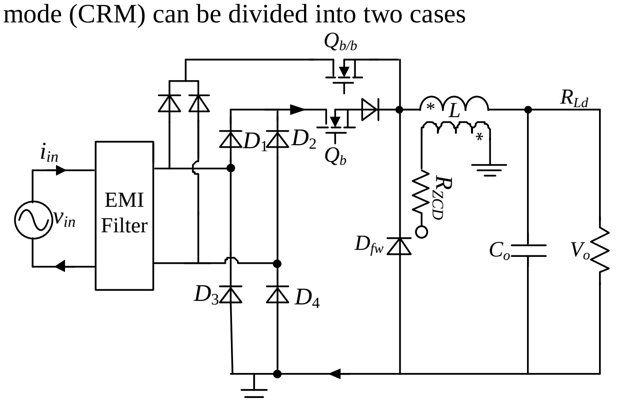

Fig. 5 Schematic diagram of introduced topology

The converter is operating in buck mode when $v_{in}>V_{boundary}$. The buck switch (Q_b) keeps switching, while buck/boost switch ($Q_{b/b}$) remains closed. The operation analysis is same as discussed in section 2.

The converter is operating in buck/boost mode when $v_{in}<V_{boundary}$. The buck/boost switch ($Q_{b/b}$) keeps switching, while buck switch (Q_b) remains closed.

When $Q_{b/b}$ is ON, the current flows through inductor L and the values of peak current is

$$i_{L\_pk2} = M\frac{t_{on}V_m \sin\theta}{L} \qquad (13)$$

Where M is constant whose value can be determined from two parallel resistors R_1 & R_2.

While, $Q_{b/b}$ is OFF, L, C_o, R_{Ld}, D_{fw} conducts and the falling slope is

$$\frac{di_L}{dt} = -\frac{V_o}{L} \qquad (14)$$

Based on volt–second balance, we can get the resulting equation as

$$t_{off} = M\frac{V_m \sin\theta}{V_o}t_{on} \qquad (15)$$

From (15) and (6), following relation is obtained

$$t_s = t_{on}\left(1+M\frac{V_m \sin\theta}{V_o}\right) \qquad (16)$$

The input current of buck/boost converter is

$$i_{in\_b/b} = \frac{V_m \sin\theta}{2L\left(1+M\frac{V_m\sin\theta}{V_o}\right)}t_{on} \qquad (17)$$

By combining (8) and (17), the input current of the put forward converter is expressed as

$$i_{in\_avg} = \begin{cases} \dfrac{t_{on}V_m\sin\theta}{2L\left(1+M\dfrac{V_m\sin\theta}{V_o}\right)} & (0\le\theta<\theta_0)\,\&\,(\pi-\theta_0<\theta\le\pi) \\ \dfrac{t_{on}V_o}{2L}\left(\dfrac{V_m\sin\theta-V_o}{V_m\sin\theta}\right) & (\theta_0\le\theta\le\pi-\theta_0) \end{cases} \qquad (18)$$

The average input power can be calculated from (1) and (18) as

$$P_{in} = \frac{1}{\pi}\left[2\int_0^{\theta_0}\frac{t_{on}\left(V_m\sin\theta\right)^2}{L_p\left(1+\dfrac{\sqrt{L_s}V_m\sin\theta}{\sqrt{L_p}V_o}\right)}d\theta + \int_{\theta_0}^{\pi-\theta_0}\frac{V_o t_{on}\left(V_m\left|\sin\theta\right|-V_o\right)}{L_s}d\theta\right] \qquad (19)$$

From (19), t_{on} can be determined by assuming the efficiency to be 100% as

$$t_{on} = \frac{2\pi P_o}{2\int_0^{\theta_0}\dfrac{\left(V_m\sin\theta\right)^2}{L_p\left(1+M\dfrac{V_m\sin\theta}{V_o}\right)}d\theta+\int_{\theta_0}^{\pi-\theta_0}\dfrac{V_o\left(V_m\sin\theta-V_o\right)d\theta}{L}} \qquad (20)$$

The input PF of the converter can be determined as

$$PF = \frac{P_{in}}{\frac{V_m}{\sqrt{2}}I_{rms}} \qquad (21)$$

According to (21), the curve of the input PF with respect to universal input voltage range for M=1, 1/2, 1/4 and 0 is drawn in Fig. 6, which shows that input PF with M=1/2 is more as compared to other values of M. Thus M=1/2 is finally selected for the converter.

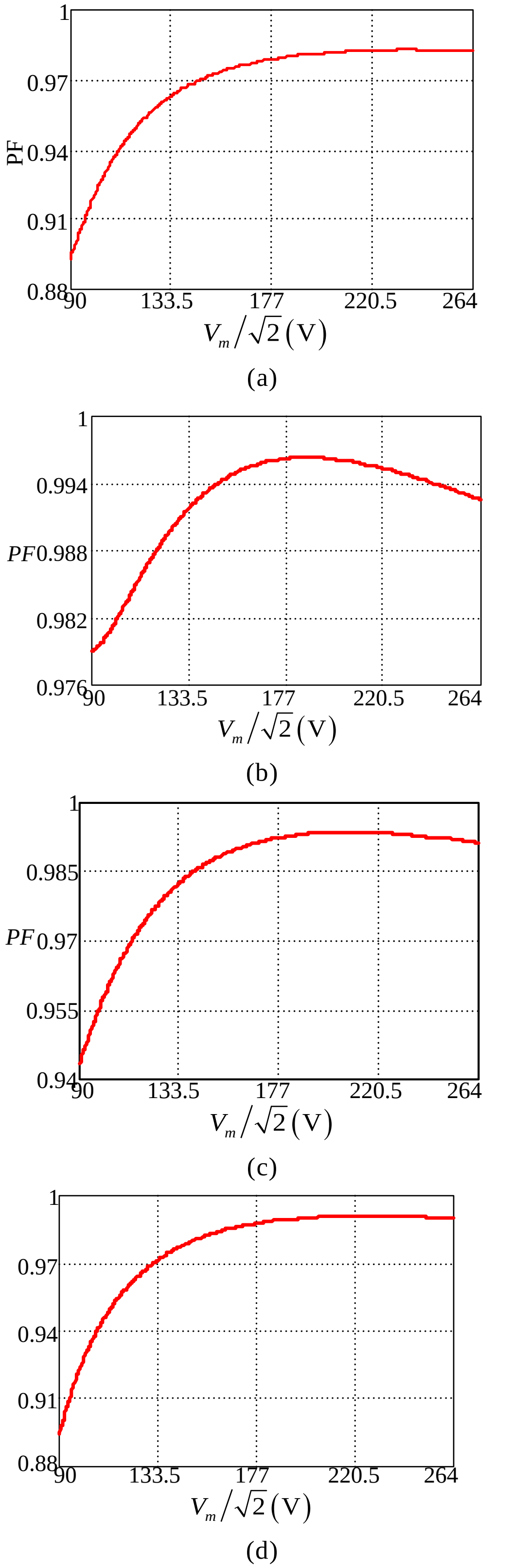

Fig. 6 Input PF for: (a) M=1, (b) M=1/2, (c) M=1/4, (d) M=100

By Fourier analysis, the harmonics of the input current is calculated as

$$I_n = \frac{2}{\pi}\int_0^{\pi} i_{in\_bf} \sin n\theta d\theta \quad (n = 1, 3, 5 \ldots) \qquad (23)$$

From (23), the relative harmonic content of the 3rd ,5th, and 7th harmonic along with IEC class C limits are illustrated in Fig. 7, from which it can be observed that input current passes Class C limits very easily in case of the proposed converter.

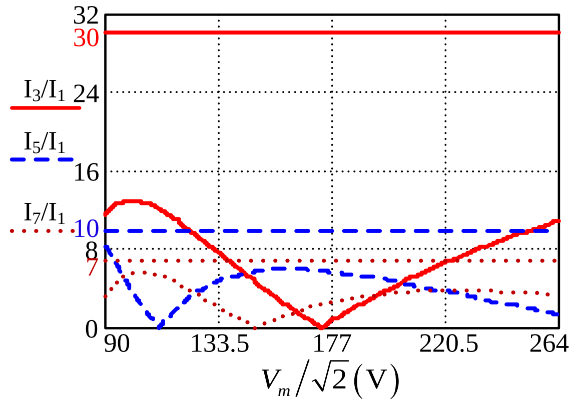

Fig. 7 Contents of input current harmonic along with limits

4. Comparative analysis

The comparative analysis between input PF and contents of input current harmonics between the buck converter and the introduced converter can be seen from Fig. (3-4) & Fig. (6-7), respectively. It can be observed that input PF and contents of input current harmonics are improved in case of introduced converter as compared to traditional converter.

5. Simulation Results

For verifying the effectiveness of the introduced topology, simulations are carried out. The input voltage range is 90-264VAC, and the output is 80V. For ensuring the current to be in CRM, L6561 IC is used. All the components in the circuit are selected as idea.

Fig. 8 and Fig. 9 show the simulation waveforms of v_{in}, i_{in}, and v_o of the buck converter and introduced converter at 110VAC. It can be observed that the buck converter has dead zone as compared to introduced converter. Thus its input PF will be more as compared to traditional converter.

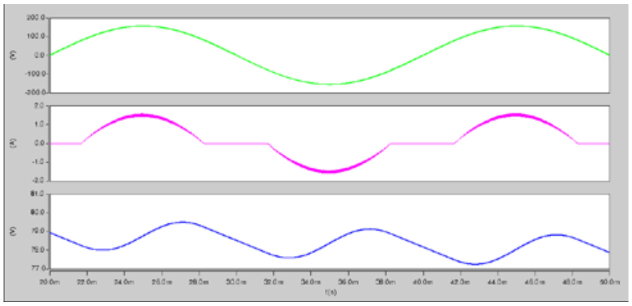

Figure 8 v_{in}, i_{in}, and v_o for buck converter

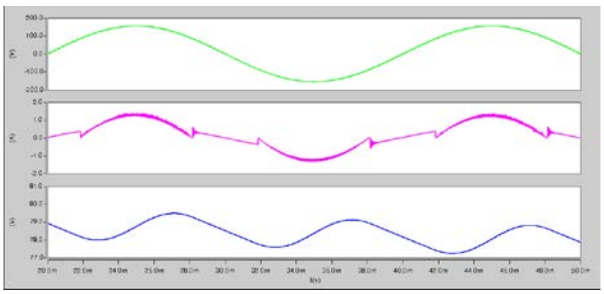

Fig.9 v_{in}, i_{in}, and v_o for buck-buck/boost converter

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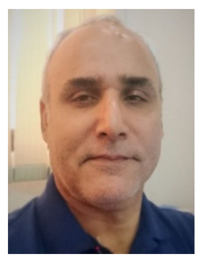
Abdul Hakeem Memon was born in Sindh, Pakistan, in 1987. He received the B.E., M.E., degree in Electrical Engineering from Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan, in 2009 and 2013, respectively. He received the Ph.D. degree from Nanjing University of Science and Technology, Jiangsu, China in 2018. In 2009, he joined Mehran University of Engineering and Technology as a Lecturer. He is currently working as an Assistant Professor in the Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan. His research interests include, Power Converters, Control Engineering and Electric Machine Design.



Noor Nabi Shaikh was born in Sindh, Pakistan, in 1969. He received the B.E., degree in Electrical Engineering from Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan, in 1995. He joined Mehran University of Engineering and Technology as a Demonstrator. He is currently working as an Assistant Professor in the Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan. His research interests include, Power Converters, Power system protection, Electrical Power distribution and Electrical Machines

Mahesh Kumar received his Bachelor and Master of Engineering degree from Mehran University of Engineering and Technology Jamshoro Pakistan from Department of Electrical Engineering in 2008 and 2012 respectively. Dr. Kumar done his Ph.D. degree from universiti Teknologi Petronas Malaysia in the Department of Electrical and Electronics Engineering in 2018. He is currently working as an Assistant Professor in the Department of Electrical Engineering at Mehran university jamshoro. His field of expertise is optimal renewable integration in distribution systems, optimization and smart grid.

Zubair Ahmed Memon was born in Sindh, Pakistan, in 1968. He received the B.E., M.E., and Ph.D. degrees in Electrical Engineering from Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan, in 1991, 2005 and 2012, respectively. He is currently working as a Professor in the Department of Electrical Engineering and Director, Institute of Information and Communication Technologies, Mehran UET, Jamshoro. He has 24 years of teaching experience, both the undergraduate and postgraduate students of Electrical Engineering, with expertise in Electrical Power Engineering. He has supervised/co-supervised around 30 students of Postgraduate level. He has authored and co-authored more than 40 publications in International and National (HEC recognized) journals. Dr. Zubair is a fellow of the Institute of Electrical and Electronics Engineers Pakistan. He is member of International association of Engineers, member of International association of Engineers Society of Artificial Intelligence, member of International association of Engineers Society of Electrical Engineering and member of International association of Engineers Society of Information System Engineering.

His research interests include Renewable Energy Sources, Power Electronic Converters and Control Engineering.