İSTANBUL UNIVERSITY
CERRAHPAŞA

RESEARCH ARTICLE

Electrica 2021; 21(1): 160-167

A New Resonance Based Sıngle-Swıtch Pfc Converter

Hacı Bodur , Erdem Akboy

Department of Electric and Electronic, Faculty of Electrical Engineering, Yıldız Technical University, İstanbul, Turkey

Cite this article as: Bodur H, Akboy E. A New Resonance Based Sıngle-Swıtch Pfc Converter. *Electrica*, 2021; 21(1): 160-167.

ABSTRACT

In this study, a novel resonance-based single-switch and single-stage power factor correction (PFC) converter is proposed. This converter achieves soft switching (SS), thereby minimizing switching losses. The converter draws current from the line in a sinusoidal form during each switching period, which provides high PFC with decreased electromagnetic interference. Furthermore, the proposed converter transfers most of the input energy directly to the output, providing direct power transfer with high efficiency using a forward-flyback converter. The rest of the input energy is transferred to the output via a flyback converter to obtain high output regulation. At this converter, PFC circuit, forward and flyback converters share only one switch. The theoretical analysis of this resonance-based single-switch and single-stage PFC converter is verified by a prototype output of 200 W/120 V with a 100-kHz switching frequency.
Keywords: Soft switching, power factor correction, resonance converter

INTRODUCTION

The usage of AC–DC converters has been increasing in recent years. Conventional AC–DC converters consist of a bridge diode, a high capacitance DC bus capacitor, and a suitable isolated DC–DC converter. These converters have a low power factor (PF) and a high total harmonic distortion, which may lead to operational disruption of sensitive devices. Therefore, standards that limit the harmonic content of the input current have been developed to improve power quality [1-20]. High frequency power factor correction (PFC) converters have been developed to meet these standards. However, most PFC converters draw linear current from the line during a single switching period, which increases its electromagnetic interference (EMI).

There are two types of PFC converters, two-stage and single-stage. In two-stage PFC converters, the output voltage regulation and PFC operations are achieved using separate controllers and switches. This separation allows the achievement of tight voltage regulation of the output and high PF of the input. However, these converters have low efficiency, high cost, and a complex circuit structure. To overcome the disadvantages of two-stage converters, single-stage PFC converters have been developed for low power applications.

In single-stage PFC converters, the PFC and DC–DC converter stages can be operated through a single switch and a single controller. In this process, some or all of the input power is initially transferred to a storage capacitor. Then, the output voltage regulation is provided by using the filtered voltage across the capacitor. Single-stage PFC converters aim to provide high PF by drawing current impulses proportional to the instantaneous input rectified voltage [10]. The main disadvantages of single-stage PFC converters are its high storage capacitor voltage, additional current stress on the switch, and its low efficiency [11]. To overcome these drawbacks, different single-stage PFC converter designs have been presented, which provide direct power transfer (DPT) [3-10].

In principle, DPT works by transferring a large amount of the input power directly to the output and using the remaining part of the input power to regulate the output voltage as shown in Figure 1. In this way, the switch current stress and the storage capacitor voltage are reduced, and the efficiency of the converter is increased.

Flyback converters and forward converters are used for isolated DC–DC converters. Flyback converters cannot be used for high power applications due to leakage inductance and snubber losses. Despite these disadvantages, they are suitable for DPT applications. Forward converters have additional winding to reset magnetizing energy. Furthermore, to achieve high

Corresponding Author:
Erdem Akboy

E-mail:
eakboy@yildiz.edu.tr

Received: 10.11.2020

Accepted: 09.12.2020

DOI: 10.5152/electrica.2021.20090

efficiency and soft switching (SS), Discrete Current Mode (DCM) is preferred for low power applications, because at Continuous Current Mode (CCM) operations, diode reverse-recovery losses decreases efficiency. [17-20].

In this study, a new resonance-based single-switch single-stage PFC converter is proposed. This converter improves upon the converter, which is described in [10]. The referenced converter has two active switches and a low power level. In contrast, the proposed converter removes one active switch such that the resonance, flyback, and forward converters are combined into only one active switch. This allows for an increased power level and achievement of SS as in [10]. The theoretical analysis of the converter is the same as in [10]. The detailed theoretical analysis was confirmed by an application circuit with an input voltage of 220 VAC, an output voltage of 120 VDC, an output power of 200 W, and a switching frequency of 100 kHz.

THEORETICAL METHOD

Definitions and Assumptions

In this converter, the resonance switch, which is given in [10] and shown in Figure 2, is canceled. The resonance circuit, flyback converter, and forward converters all share a single switch.

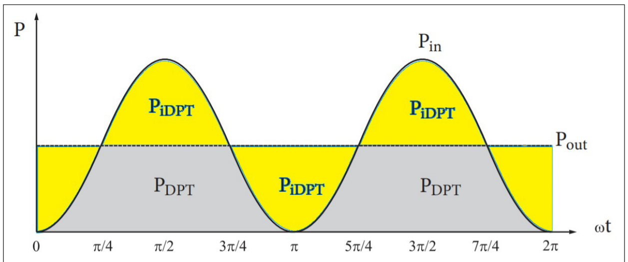

Figure 1. Power relationship for DPT operation

The resonance-based single-stage single-switch PFC converter circuit diagram is given in Figure 3. In this converter, the resonance PFC cell is combined both L_r and C_r. T_1 and T_2 are the forward and flyback transformers, respectively. C_b is the bulk capacitor, and C_o is the output capacitor. L_f is the forward inductance.

In this proposed converter, the resonance circuit provides SS and a sinusoidal line current for each switching cycle. The T_1 transformer can be operated as the forward transformer or the flyback transformer according to the value of the line voltage. If the line voltage is greater than the bulk capacitor voltage, the transformer will operate as a forward transformer. During this operation, a part of the input power is transferred to the output, while the rest of the power is transferred to the bulk capacitor. If the line voltage is lower than the bulk capacitor voltage, the transformer will operate as a flyback transformer. During this operation, all input power is transferred to the output. As a result, the magnetizing energy is transferred to the output directly in both operation modes, and DPT is achieved.

The following assumptions were made to facilitate steady-state analysis during a switching period.

- The rectified input voltage V_i is constant.
- The output capacitor C_o is large enough to accept the output voltage V_o as constant.
- The resonance circuit and semiconductor elements are ideal.
- All transformers are ideal.

Operation Stages

In the proposed resonance-based single-stage single-switch PFC converter, nine different intervals occur during a switching period, as shown in Figure 4. At high values of the input

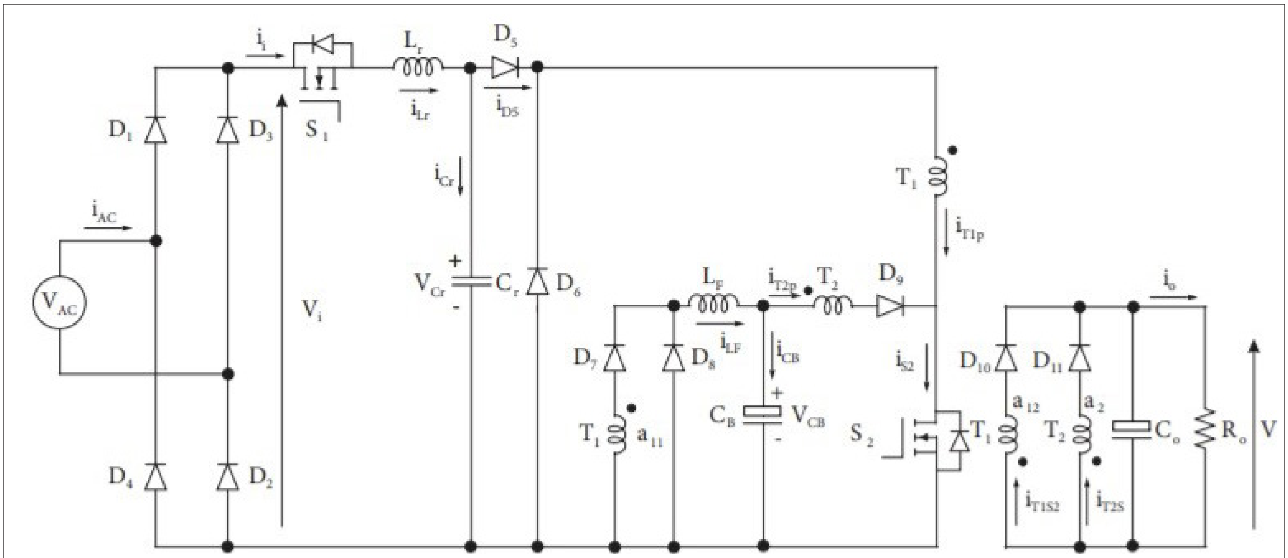

Figure 2. Proposed converter which is given in [10]

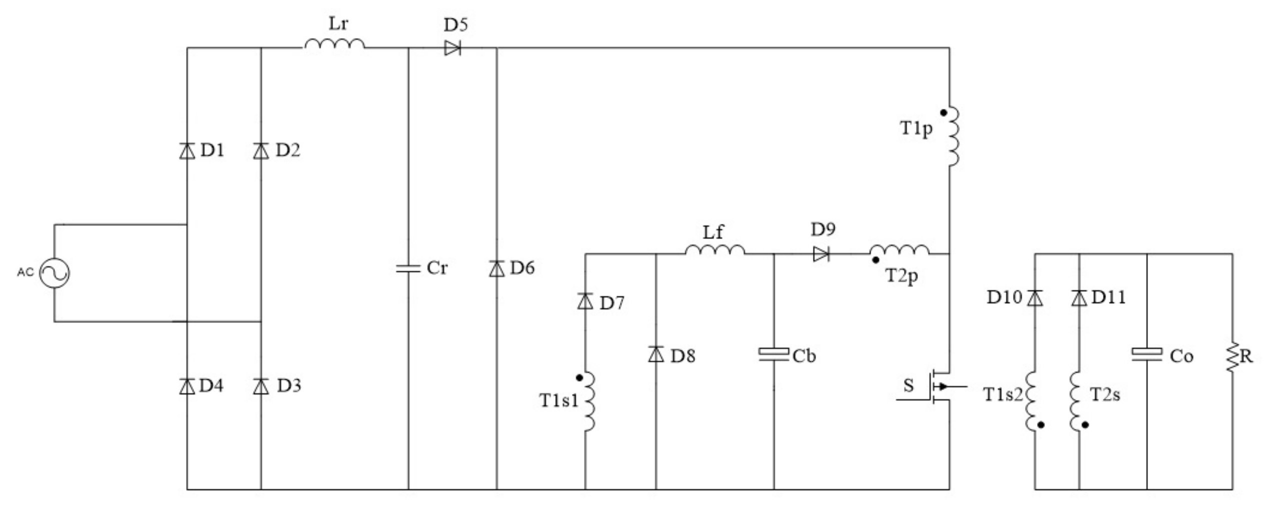

Figure 3. The proposed resonacnce based single-switch single-stage PFC converter

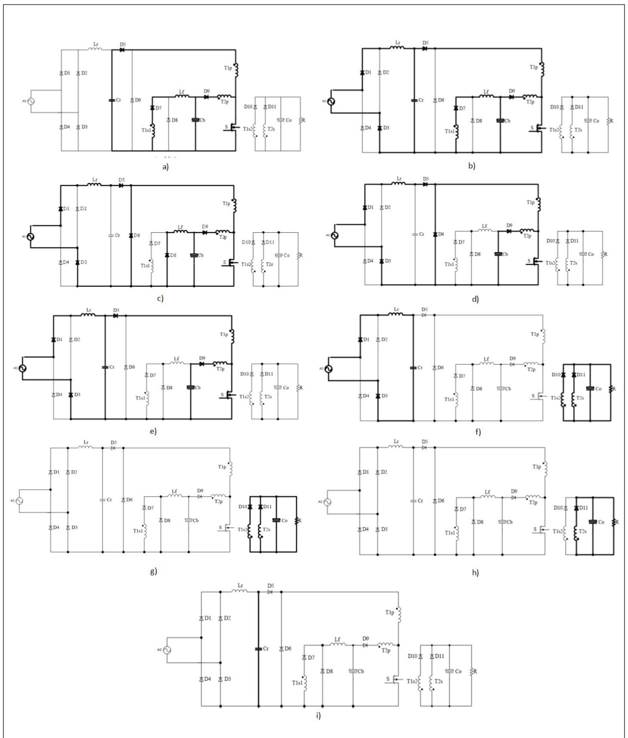

Figure 4. The equivalent circuit diagrams of the stages of the proposed resonance based single-switch single-stage PFC converter

voltage, the T_1 transformer operates as the forward transformer and it operates as the flyback transformer at low input voltage values. At this study, only high values of the input voltage situations will be discussed, and the other situation is similar.

Initial Status

During this interval, all transformers and inductances are reset.

Stage 1 ($t_0<t<t_1$)

This interval begins with a signal to the switch. In this stage, T_1 operates as a forward transformer. The C_r capacitor, which is fully above the line voltage, transfers its energy to L_f and C_b over T_1, according to the magnetization inductance of T_1 (L_{1P}) and the resonance formed due to L_f. Simultaneously, T_2 acts as a flyback transformer. This interval ends when the capacitor voltage decreases to the line voltage and the bridge diodes turn on with zero-voltage switching (ZVS). Depending on the resonance occurring in this interval, the S switch enters the transmission with zero-current switching (ZCS).

$$i_{Lr} = \frac{V_i}{Z}\sin(\omega t) \tag{1}$$

$$v_{Cr} = V_i\left(1-\cos(\omega t)\right) \tag{2}$$

where,

$$Z = \sqrt{\frac{L_r}{C_r}} \tag{3}$$

Stage 2 ($t_1<t<t_2$)

This interval starts with the reduction of the capacitor voltage to the line voltage, and the rectifier diodes turn on with ZVS. In this interval, resonance occurs over L_r, C_r, L_{1P}, L_f, and C_b. A sinusoidal current is drawn from the line depending on the resonance that occurs as in Eq.1. At the same time, the capacitor continues to discharge as in Eq. 2. This stage ends when the capacitor voltage becomes zero, and the D_6 diode turns on with ZVS.

Stage 3 (t_2<t<t_3)

This stage begins with D_6 turning on. In this interval, L_{1P} acts as a current source. At the same time, L_r inductance causes a linear current to be drawn from the line under constant V_{AC} voltage. In this stage, the inductance L_f transfers its energy to the storage capacitor. This interval ends when the current of L_f is zero.

Stage 4 (t_3<t<t_4)

In this interval, the linear current continues to be drawn from the line, and this interval ends when the current of L_r is equal to the current of L_{1P}, and the diode D_6 turns off with ZCS. The total duration of Stage 3 and Stage 4 is very short (500 ns), and a sinusoidal current is drawn from the line for most of the period.

Stage 5 (t_4<t<t_5)

This interval starts with the D_6 diode being turning off with ZCS. In this interval, resonance occurs between L_r, C_r, and L_{1P}. The capacitor voltage and current of L_{1P} begin to increase depending on the resonance that occurs. This interval ends when the signal of the switch is cut.

Stage 6 (t_7<t<t_8)

This interval begins with the switch's signal being cut off. In this stage, resonance occurs between the L_r inductance and C_r capacitor depending on the line voltage. Depending on the resonance that occurs, while the capacitor voltage increases, the inductance current decreases. This stage ends with the inductance current becoming zero. In this stage, the sinusoidal current continues to be drawn from the line. At the same time, the energies in the magnetizing inductances of the T_1 and T_2 transformers are transferred to the output.

Stage 7 (t_8<t<t_9)

Energies in the magnetizing inductances of T_1 and T_2 transformers are transferred to the output at this stage. This interval ends with the D_{10} diode being turning off with ZCS.

Stage 8 (t_9<t<t_{10})

At this stage, the energy in the magnetizing inductance of the T_2 transformer is transferred to the output.

Stage 9 (t_9<t<t_{10})

This interval starts when T_1 and T_2 completely transfer the energies in the magnetizing inductances, and the interval continues until the switch is turned on. The capacitor voltage is above the line voltage.

3. Design Procedure

Resonance Inductance L_r and Resonance Capacitor C_r

The PFC circuit is a fully resonant circuit, so L_r and C_r are chosen with consideration to the following factors: output power, switching frequency, root mean square (rms) value of the line voltage, and resonance period.

$$P_{avg} = f_s \frac{1}{2} C_r \left(2V_{AC\_RMS}\right)^2 \tag{4}$$

$$T_{r1} = 2\pi\sqrt{L_r C_r} \tag{5}$$

Transformer T_1

In the proposed novel converter, T_1 processes the majority of the input power to the output based on DPT idea by operating as a flyback converter. C_b is supplied by the remaining energy when T_1 operates as a forward converter.

$$t_{43} = \frac{\pi}{2}\sqrt{L_{1P} C_r} \le DT_S \tag{6}$$

Here in Eq. 6, D is the duty cycle of the switch, and T_s is the switching period.

$$V_o t_{off} a_{12} = L_{1mp} i_{L1P\_max} \tag{7}$$

$$L_{L1S2} = L_{1P}\left(\frac{1}{a_{12}}\right)^2 \tag{8}$$

In Eq. 8, a_{12} is the turn ratio between the primary and first secondary windings.

Transformer T_2

At the proposed circuit, T_2 is used for processing the part of the input power (P_b), which is indirect, to the output. T_2 operates as a flyback converter under DCM. When S is on, the energy that is charged in the magnetizing inductance of T_2 should be processed through to the output by secondary winding of T_2 when S is off. Hence, the power which is transferred to the output via T_2 is defined in Eq. 9 as follows.

$$P_B = \frac{1}{2} f_s L_{2P} i^2_{T2p\_max} \tag{9}$$

are obtained. For DCM operation of the flyback converter, we can choose the time of conduction of secondary winding so that a_2 can be calculated easily.

$$V_o = L_{2S} \frac{i_{T2S\_max}}{t_{off}} \tag{10}$$

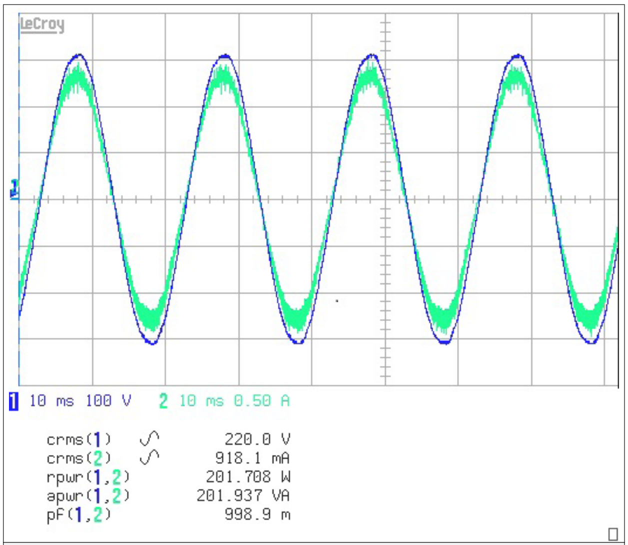

Figure 5. The input voltage and current waveforms of the proposed converter

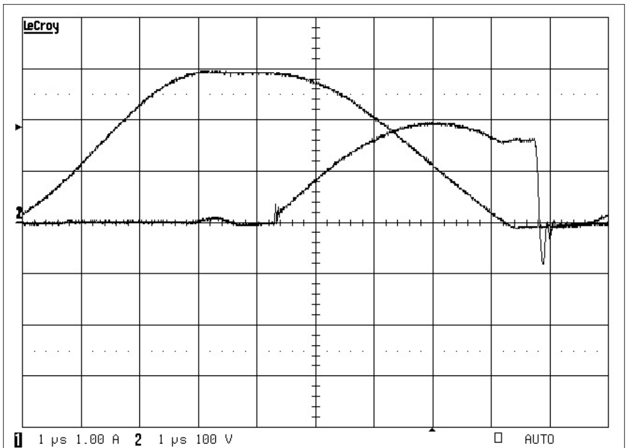

Figure 6. The switch current waveform with snubber capacitor voltage waveform

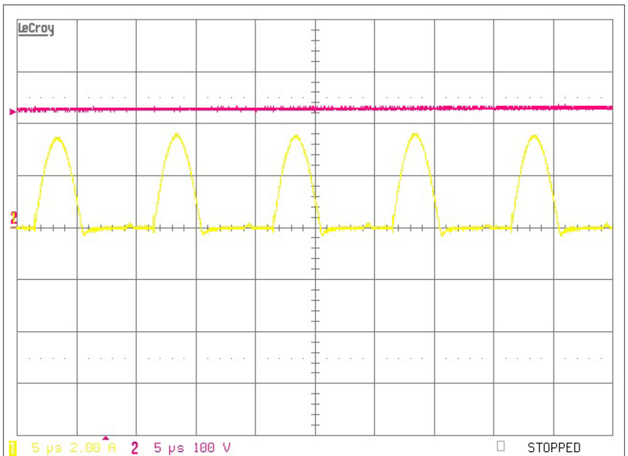

Figure 7. The forward inductance current waveform with bulk capacitor voltage waveform

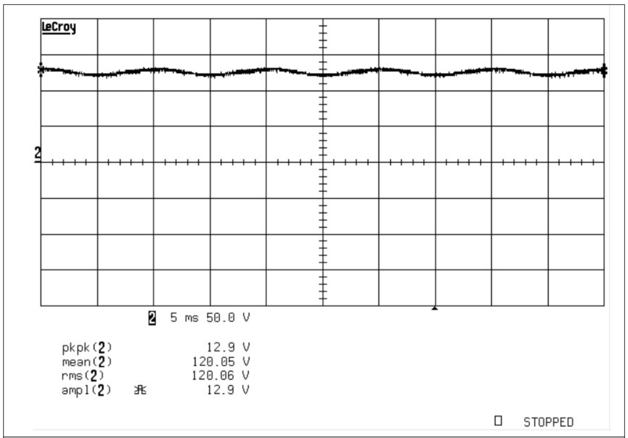

Figure 8. The output voltage waveform

$$a_2 = \frac{V_{Cb} t_{on}}{V_o t_{off}} \quad (11)$$

$$L_{2S} = \left(\frac{1}{a_2}\right)^2 L_{2P} \quad (12)$$

EXPERIMENTAL RESULTS

The prototype of the proposed resonance-based single-stage single-switch DPT-PFC converter is achieved for 120 V DC–200 W output with a 100-kHz switching frequency. The parameters based on the aforementioned analysis and design procedure are given in Table 1.

In Figure 5, the input voltage and input current measurements are given. Figure 5 shows that the input current follows the input voltage in a healthy way at full load (200 W). Furthermore, the power factor is measured as 0.998.

In Figure 6, the switching current with the snubber capacitor is given. It can easily be seen that the resonance is perfectly achieved.

In Figure 7, the forward current and bulk capacitor voltage waveform measurements are given. It is known that the bulk capacitor is charged with this forward inductance current. This current is purely a sinusoidal waveform, and the diodes can turn on and turn off with SS.

In Figure 8, the output voltage waveform is given. It can be seen that the output voltage is tightly regulated.

In Figure 9, the efficiency curve of the proposed converter and the converter in [10] are given. It can be seen that the efficiency is increased.

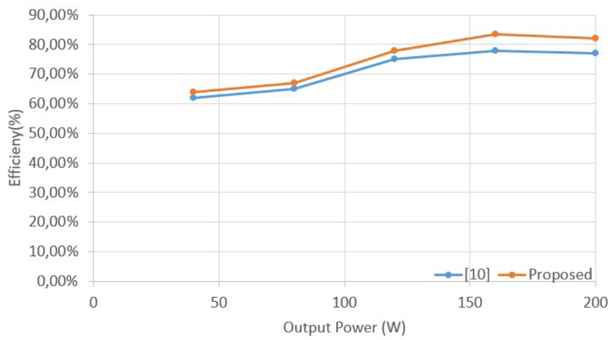

Figure 9. The efficiency curve of the proposed converter and the converter in [10]

Table 1. Parameters of the proposed PFC Converter

Parameter	Symbol	Values	Model
Input Voltage	V_{AC}	220 VAC	-
Output Voltage	V_o	120 VDC	-
Output Power	P_o	200 W	-
Switching Frequency	f_s	100 kHz	-
Resonance Inductance	L_r	80 µH	EE20 core
Resonance Capacitor	C_r	20 nF	MKP
T1	L_{1P}	325 µH	EE 42 core
	L_{1S1}	81 µH	
	L_{1S2}	88 µH	
Bulk Capacitor	C_B	220 µF-450V	Electrolytic
Output Capacitor	C	2.2 mF-220V	Electrolytic
T2	L_{2P}	1 mH	EE 42 core
	L_{2S}	81 µH	
Switch	S	1000V – 15 A	IXFH15N100Q

DISCUSSION

In this study, we present a novel resonance-based single-stage single-switch PFC converter. In this converter, the PFC resonant circuit, forward converter, and flyback converter share only one switch. The current, which is drawn from the line, has a pure sinusoidal waveform at each switching period and thus, allows low EMI to be achieved. Moreover, DPT is provided by a forward-flyback-based converter, leading to high efficiency. Furthermore, there is isolation between input and output for electrical safety. Theoretical analyses have been confirmed with the application of a PFC converter with an input of 220 VAC, an output of 120 VDC, a switching frequency of 100 kHz, and an output power of 200 W. Due to the resonance operations, all the semiconductor elements are operated with soft switching. The total efficiency of the applied PFC amplifier converter is improved from [10].

Peer-review: Externally peer-reviewed.

Conflict of Interest: The authors have no conflicts of interest to declare.

Financial Disclosure: The authors declared that the study has received no financial support.

References

1. H. Bodur, H. Yesilyurt, E. Akboy, "Passive Lossless Snubber for PFC AC-DC Converters", Electrica, vol.20, no.1, pp. 98-107, 1998, Jan. 2020. [Crossref]
2. M. Nagao, "A novel one-stage forward-type power-factor-correction circuit", IEEE Trans. Ind Electron; vol.15, pp. 103-110, Jan. 2000. [Crossref]
3. X. Xie, J. Li, C. Zhao, Q. Lu, "Study on the single-stage forward-flyback PFC converter with QR control", IEEE Trans. On Power Electron., vol.31, no.1, pp. 430- 442, Feb. 2016. [Crossref]
4. H. Bodur, S. Yıldırmaz, "A new ZVT snubber cell for PWM-PFC boost converter", IEEE Trans. Ind. Electron., vol.64, no.1, pp. 300-309, Sep. 2017. [Crossref]
5. L. Chen, H. Hu, Q. Zhang, A. Amirahmadi, I. Batarseh, "A boundary-mode forward-flyback converter with an efficient active LC snubber circuit", IEEE Trans. Power Electron. vol. 26, no.6, pp. 2944-2958, Jul. 2014. [Crossref]
6. H. S. Athab, D. D-C. Lu, K. Ramar, "A single-switch AC/DC flyback converter using a CCM/DCM quasi-active power factor correction front-end", IEEE Trans. Ind. Electron. vol. 59, no.3, pp. 1517- 1526, June, 2012. [Crossref]
7. S. Gangavarapu, K. Rathore, V. Khadkikar, "High efficiency three-phase single-stage isolated flyback-based PFC converter with a novel clamping circuit", IEEE Trans. Ind. Electron. vol. 56, no.1, pp. 718-729, Sep. 2020. [Crossref]
8. S. Gangavarapu, K. Rathore, "A three phase single stage isolated flyback-based PFC converter with leakage energy recovery clamping circuit", IEEE Trans. Transportation Electrification, vol. 5, no. 4, pp. 1155-1168, Oct. 2019. [Crossref]
9. K. Yao, C. Mao, K. Chen, L. Li, H. Tang, "Adequate usage rate control of switching cycles for DCM buck PFC converter", IEEE J of Emerging and Selected Topics Power Electron. vol. 8, no.1, pp. 732- 748, Nov. 2020. [Crossref]
10. H. Bodur, E. Akboy, I. Aksoy, "A new single stage single phase power factor corrected and isolated AC-DC converter based on resonance and soft switching", Turkish J. Elec. Eng & Computer Sciences, vol.24, pp. 1487-1501, Mar. 2016. [Crossref]
11. W. Qi, S. Li, H. Yuan, S-C Tan, S-Y. Hui, "High power-density single-phase three-level flying-capacitor buck pfc rectifier". IEEE Trans Power Electron. vol. 34, no. 11, pp. 10833-10844, Jan. 2019. [Crossref]
12. A. R. Ghanbari, E. Adib, H. Farzanehfard, "Single-stage single-switch power factor correction converter based on discontinuous capacitor voltage mode buck and flyback converters", IET Power Electron, vol. 6, no.1, pp. 146-152, June, 2019. [Crossref]
13. H.Bodur, A. F. Bakan, M. Baysal, "A detailed analytical analysis of a passive resonant snubber perfectly constructed for pulse width modulated d.c-d.c buck converter", Electrical Enginnering, vol.85, pp. 45-52, Jan. 2003. [Crossref]

14. G. Moshcolopolus, P. Jain, "Single-phase single-stage power-factor-corrected converter topologies", IEEE Trans Ind Electron. vol. 52, pp. 35, Feb. 2005. [Crossref]
15. J. Y. Lee, M. J. Youn, "A single-stage power-factor-correction converter with simple link voltage suppressing circuit", IEEE Trans Power Electron. vol. 48, pp. 572-584, June, 2001. [Crossref]
16. Y-C. Li, C-L Chen, "A novel single-stage high-power-factor ac-to-dc led driving circuit with leakage inductance recycling", IEEE Trans. Industrial Electron., vol. 59, no. 2, pp. 793-802, May, 2012. [Crossref]
17. Q. Luo, J. Huang, Q. He, K. Ma, L. Zhou, "Anaysis and design of a single-stage isolated ac-dc led driver with a voltage doubler rectifier", IEEE Industial Electron. vol. 64, no. 7, pp. 5807-5817, May, 2017. [Crossref]
18. X. We, J. Zhang, Z. Qian, "A simple two-channel led driver with automatic precise current sharing", IEEE Trans. Industrial Electron., vol.58, no.10, pp. 4783-4788, Jan. 2011. [Crossref]
19. J. C. W. Lam, P. K. Jain, "Isolated AC/DC offline high power factor single-switch led drivers without electrolytic capacitors", IEEE J Emerg. Sel. Topics Power Electron., vol. 3, no. 3, pp., 679-690, Mar. 2015. [Crossref]
20. Z. Zhiguo, Z. Lin, "Analysis and design of isolated flyback voltage multipler converter for low-voltage input and high voltage output applications", IET Power Electron. vol. 6, no. 6, pp. 1100-1110, Aug. 2013. [Crossref]

Haci Bodur (M'00) was born in Ordu, Turkey, in 1959. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Yildiz Technical University, Yildiz, Turkey, in 1981, 1983, and 1990, respectively.
He was employed as a Research Assistant from 1982 to 1986, a Lecturer from 1986 to 1991, an Assistant Professor from 1991 to 1995, and an Associate Professor from 1995 to 2002, in the Department of Electrical Engineering, Yildiz Technical University, Turkey, where, since 2002, he has been a Professor. He has published over 50 journal and conference papers in the area of power electronics. He also took part in more than 10 research projects concerning power electronics. His research has been concentrated on the areas of motor drives, power factor correction, uninterruptable and switching power supplies, high frequency power conversion, and active and passive snubber cells in power electronics

Erdem Akboy was born in Istanbul, Turkey, in 1987. He received B.S. degree in electrical-electronics engineering from Sakarya University, Sakarya, Turkey, in 2009, M.S., and Ph.D. degrees in electrical engineering from Yildiz Technical University, Esenler, Turkey, in 2012 and 2018, respectively, where he is currently a research assistant. His current research interests include soft switching,grid connected converter, power factor correction (PFC), inverters, energy storage systems and DC-DC converters.