A New Resonance Based Single-Switch PFC Converter

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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
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.

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
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).

\[
i_{L_f} = \frac{V_i}{Z} \sin(\omega t) \tag{1}\]

\[
v_{C_r} = V_i \left(1 - \cos(\omega t)\right) \tag{2}\]

where,

\[
Z = \sqrt{\frac{L_f}{C_r}} \tag{3}\]

**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 $L_f$, $C_r$, $L_{1p}$, $L_f$, 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, \(L_{ip}\) acts as a current source. At the same time, \(L_1\) 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 \(L_1\) is equal to the current of \(L_{ip}\) 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 \(L_{ip}\). The capacitor voltage and current of \(L_{ip}\) begin to increase depending on the resonance that occurs. This interval ends when the signal of the switch is cut.

Stage 6 \((t_5 < t < t_6)\)

This interval begins with the switch’s signal being cut off. In this stage, resonance occurs between the \(L_1\) inductance and \(C\), 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 is drawn from the line for most of the period.

Stage 7 \((t_6 < t < t_7)\)

Energies in the magnetizing inductances of \(T_1\) and \(T_2\) transformers are transferred to the output.

Stage 8 \((t_7 < t < t_8)\)

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

Stage 9 \((t_8 < t < t_9)\)

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.

\[
P_{avg} = \frac{1}{2} f_s \left( \frac{1}{2} V_{AC\_rms} \right)^2
\]

\[
T_{r1} = 2\pi \sqrt{L_t C_t}
\]

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.

\[
t_{43} = \frac{\pi}{2} \sqrt{L_{ip} C_t} \leq DT_s
\]

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

\[
V_{o\_off} a_{12} = \frac{L_{amp} n_{12}}{i_{LIP\_max}}
\]

\[
L_{L1S2} = L_{ip} \left( \frac{1}{a_{12}} \right)^2
\]

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.

\[
P_B = \frac{1}{2} f_s L_{2p} a_{12}^2
\]

are obtained. For DCM operation of the flyback converter, we can choose the time of conduction of secondary winding so that \(a_{12}\) can be calculated easily.

\[
V_o = \frac{L_{2S} i_{T2S\_max}}{t_{off}}
\]
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 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.

\[
a_2 = \frac{V_{CB \, on}}{V_{CB \, off}}
\]

(11)

\[
L_{2S} = \left( \frac{1}{a_2} \right)^2 L_{2P}
\]

(12)
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].

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