Voltage tracking of bridgeless PFC Cuk converter using PI controller

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ABSTRACT

This paper proposes a Proportional-Integral (PI) control voltage tracking of Bridgeless Power Factor Correction (BPFC) Cuk converter. In order to investigate the behaviour of different output voltages during overshoot, steady state and step response, P.I controller is designed to set the -42 V, -48 V, -54 V output voltages. The simulation results show that the proposed PI controller able to control the output voltage and achieve fast steady state and step response of BPFC Cuk converter. When the value of output voltage increase, the overshoot voltage will become higher but the steady state respond will be faster. Furthermore, BPFC Cuk converter with P.I controller have low output voltage ripples.

Keywords: Bridgeless, Power factor correction, Cuk converter, Control system, Proportional-Integral

1. INTRODUCTION

Power electronic equipment with an active power factor correction (PFC) for telecom, datacom, and automotive electrical system are becoming necessary nowadays [1-5]. There are several types of DC-DC BPFC converters were developed for PFC applications such as boost, buck, buck-boost, SEPIC and Cuk converters [6]. However, for low power application, BPFC Cuk converter is the most reliable converter because it offers low THD of input current, good power factor, easy to implement in transformer isolation, and natural protection against inrush current from start-up or overload current [7-11]. This converter acts similar to the buck-boost converter since it able to step up and step-down the output voltage by controlling the duty cycle [11, 12]

Basically, the DC-DC converter used power semiconductor devices that operated as the electronic switches which are refer as switched mode power supply [SMPS] [13, 14]. The operation of this switching devices may cause inherently nonlinear characteristic of the BPFC Cuk converter [15]. Pulse width modulation (PWM) is the most popular method for the various switching technique [15, 16]. Switch-mode PWM dc–dc converters used to provide a constant output voltage[17]. Proportional-Integral (PI)
controller often to use as the control method for PWM switching due to the simple design and easy to implement [18, 19].

The proposed system bridgeless PFC Cuk converter is shown in Figure 1 where, a single MOSFET switch replacing the two MOSFETs, which helps to reduce high conduction loss and size of the structure [20, 21]. In this case, the structure proposed to reduce the complexity of controller circuit. Basically, bridgeless PFC structure suffer from the difficulty of implementation of control circuit because of two switches. Nevertheless, this structure can reduce conduction losses form bridgeless. In this paper, the output voltage was selected to -42 and -54 V for the electric vehicle application [22-24]. Meanwhile -48 V is used in telecommunication application [7, 25].

The remainder of this study is organized as follows: operation of BPFC Cuk converter will be shown in section II. Then the parameter design for PFC converter is presented in section III. Section IV describe about the P.I controller for BPFC Cuk converter. Simulation result and analysis in section V, followed by conclusion in section VI.

2. OPERATION OF BPFC CUK CONVERTER

The proposed BPFC Cuk structure as shown in Figure 1. When the MOSFET M is turned-on during positive cycle, $D_p$, $D_1$ are on-state and $D_{out}$ is off-state as shown in Figure 2. There are two modes for this operation. For the first mode, the inductors $L_1$ and $L_2$ are charging. Meanwhile, the capacitor $C_1$ and capacitor $C_2$ are discharging. Then output inductor $L_o$ is charging and capacitor $C_{out}$ is discharging. In mode 2 condition, capacitor $C_1$ and capacitor $C_2$ are charging through inductors $L_1$ and $L_1$. Then, the inductor $L_{out}$ recharges the capacitor $C_{out}$.

When the MOSFET M is turned-on during negative cycle, $D_n$, $D_2$ operate in on-state and $D_{out}$ is off-state as shown in Figure 3. There are two modes for this operation. First, the inductors $L_1$ and $L_2$ are charging, the capacitor $C_1$ and capacitor $C_2$ are discharging, the output inductor $L_o$ is charging and capacitor $C_{out}$ is discharging. For the next condition, capacitor $C_1$ and capacitor $C_2$ are charging through inductors $L_1$ and $L_1$. Then, the inductor $L_{out}$ recharges the capacitor $C_{out}$ and power supplied to the load.

When the MOSFET M is turned-off, $D_p$, $D_1$ are off-state and $D_{out}$ is on-state as shown in Figure 4. There are four conditions for this mode. In the first condition, capacitor $C_1$ and capacitor $C_2$ are charging. Inductors $L_1$ and $L_2$ are discharging. Then, the output inductor $L_{out}$ is discharging while capacitor $C_0$ is charging and the power is supplied to the load. For the second condition, inductor $L_1$, inductor $L_2$ and capacitor $C_2$ are discharging. Then, inductor $L_1$, inductor $L_2$ and capacitor $C_2$ are discharging, while capacitor $C_1$ is charging. Output inductor $L_{out}$ is discharging and capacitor $C_{out}$ is charging and the power is supplied to the load. For the third condition, inductor $L_1$, inductor $L_2$ and capacitor $C_2$ are discharging. Meanwhile capacitor $C_1$ is charging. Then, capacitor $C_{out}$ is discharging through output inductor $L_{out}$ and the power is supplied to the load. For the fourth condition, capacitor $C_1$ and capacitor $C_2$ are discharging through inductors $L_1$. Then, $L_2$ are charging and output inductor $L_{out}$ recharges capacitor $C_{out}$. Then, the power is supplied to the load.

When the MOSFET M is turned-off, $D_n$, $D_2$ are in off-state while $D_{out}$ is on-state as shown in Figure 5. There are four modes at this condition. First, capacitor $C_1$ and capacitor $C_2$ are charging, at the same time inductors $L_1$ and $L_2$ are discharging. Then, the output inductor $L_{out}$ is discharging, capacitor $C_0$ is charging and the power is supplied to the load. In the second mode, inductor $L_1$, inductor $L_2$ and capacitor $C_2$ are discharging. Then, inductor $L_1$, inductor $L_2$ and capacitor $C_2$ are discharging while capacitor $C_1$ is charging. Output inductor $L_{out}$ is discharging. Capacitor $C_{out}$ is charging and power is supplied to the load. For the third mode, inductor $L_1$, inductor $L_2$ and capacitor $C_2$ are discharging, but capacitor $C_1$ is charging. Meanwhile, capacitor $C_{out}$ is discharging through output inductor $L_{out}$ and the power is supplied to the load. In the fourth mode, capacitor $C_1$ and capacitor $C_2$ are discharging through inductors $L_1$. Then, $L_2$ is in charging mode. However, inductor $L_{out}$ recharges the capacitor $C_{out}$ and the power is supplied to the load.

![Figure 1. BPFC cuk structure](image_url)
3. PARAMETER DESIGN FOR BPFC CUK CONVERTER

3.1. Voltage conversion ratio, M

The voltage conversion ratio \( M = \frac{V_o}{V_m} \) in terms of circuit structure parameters can be obtained by applying the power-balancing principle where \( P_{in} = P_{AC} \) by assuming a lossless converter.

\[
P_{AC} = \frac{2}{T} \int_{0}^{T} V_{AC}(t) \cdot I_{AC}(t) \, dt
\]

The average AC supply current is given as (2),

\[
I_{AC}(t) = \frac{V_{AC}(t)}{R_e}
\]

Where the \( R_e \) is defined as the effective input resistance of the converter and given by (3)

\[
R_e = \frac{2 \cdot R_e}{D_{ton} \cdot T_s}
\]

The \( D_{ton} \) is the summation of \( D_{1TS} \) and \( D_{2TS} \). On the other hand, the average output current of diode during one-line cycle is equal to the average current, \( I_o \) through to the load, \( R \)

\[
I_o = \frac{V_{out}}{R}
\]

Thus, it can be simplified by evaluating (2) by using (3) and applying the power-balancing between the AC supply and DC output, the voltage conversion ratio is equal to:

\[
M = \frac{V_{out}}{\sqrt{2} V_{AC}} = \frac{R}{\sqrt{2} R_e} = \frac{D_{ton}}{\sqrt{2} R_e}
\]

3.2. Gain ratio as function of duty cycle, D

DCM operation mode requires that the sum of duty cycle and the normalized MOSFET-off time length to be less than one. Following inequality must be satisfied:

\[
D_{toff} < 1 - D_{ton}
\]
Where the $D_{\text{off}}$ is the summation of $D_3T_s$ and $D_4T_s$. The worst situation occurs at $\omega t = 90^\circ$. Therefore, to operate in DCM operation

$$D = \frac{M}{M+1} \quad (7)$$

### 3.3. Design of input inductor L1 and L2

The input inductance is calculated by using inductor current ripple:

$$\Delta I_{L1} = \frac{\sqrt{2}V_{AC}}{2L_1} \cdot D \cdot T_s \quad (8)$$

The maximum inductor current ripple calculated from the peak input current is given by (9)

$$\Delta I_{AC, \text{peak}} = \left(\frac{2P_{AC}}{\sqrt{2}V_{AC}}\right)_{L1, \text{max}} \quad (9)$$

By substituting (9) into (10), the input inductance $L_1$ can be calculated. Noted that, the $L_1$ is equal to $L_2$, thus the same formula can be used. The value of input inductance can be found as:

$$L_1 = \frac{V_{AC}}{2I_{L1, \text{fsw}}} \quad (10)$$

### 3.4. Design of output inductor, $L_o$

From (1), the average output current of diode, $I_{Do}$ during one line-cycle of the AC supply can be determined by (11)

$$I_{AC, \text{Avg}} = \frac{I_{Do} T_s V_{AC}^2}{2L_e V_o} \quad (11)$$

$K_e$ is dimensionless parameter are defined and can be expressed by (12)

$$K_e = \frac{D^2}{2M^2} \quad (12)$$

The average output current is the average diode current, $L_o$ from can be found by (13)

$$L_o = \frac{R T_s K_e}{2} \quad (13)$$

Therefore, the output inductor can be determined by applying (10) and (13):

$$L_o = \frac{L_1 L_e}{L_1 - L_e} \quad (14)$$

### 3.5. Design of input capacitor, $C_1$ and $C_2$

The input capacitor, $C_1$ is an important component in the Cuk topology since it may distort the quality of AC supply current. The $C_1$ must be designed properly by considering resonant frequency, $f_r$ not close to line frequency $f_L$ and switching frequency $f_{sw}$. Hence, the energy transfer to capacitor $C_1$ is determined based on inductors $L_1$, $L_2$, and $L_o$ values. In addition, a better initial estimation for choosing the resonant frequency, $f_r$ is given by (15). Noted that, the $C_1$ is equal to $C_2$ which the same formula can be used, thus the design $C_1$ (16) is:

$$f_L < f_r < f_{sw} \quad (15)$$

$$C_1 = C_2 = \frac{1}{(2\pi f_r)^2 (L_1 + L_o)} \quad (16)$$

### 3.6. Design of output capacitor, $C_o$

Since the input of converter is AC supply, the output capacitor must be large enough to reduce the output voltage ripple. Thus, the output ripple frequency of the converter is two times of the input frequency, given in (15). In the worst case, the output current during half-period of the ripple frequency is provided by
the output capacitor. Therefore, the output voltage ripple must be selected based on the application requirement and $C_o$ can be obtained as follows:

$$2\Delta f_{out} = f_L$$

$$C_o = \frac{P_{out}}{4f_LV_o\Delta V_o}$$

4. PI CONTROLLER FOR BPFC CUK CONVERTER

Figure 6 illustrate the simulation diagram of proposed design of P.I controller for BPFC Cuk converter by using Maltab software. The reference voltage for P.I controller is set to -48V with 2/50 gain value. The value of $P$ is 1.0 while the value of $I$ is 3.34. The output of the P.I control is a power value and in order to convert it to a quantity that is comparable to that of the control signal, it goes through a power to PWM signal converter.

Figure 6. Simulation diagram of proposed BPFC Cuk with PI controller

5. SIMULATION RESULT

The performance of BPFC Cuk converter is verified by the simulation results by using MATLAB software. The converter is designed by the following specifications:

- Input voltage, $V_{AC} = 230$ V
- Output voltage, $V_{DC} = -42$ V, -48 V, -54 V
- Output power, $P_{out} = 200$ W
- Switching frequency, $f_{sw} = 50$ Hz
- Maximum output voltage ripple, $\Delta V_{out}\leq 2$ V

Figure 7 show the characteristic of BPFC Cuk converter output voltage with P.I controller when the reference voltage is set up to -42V output voltage. The result shows the P.I controller functional well since the BPFC Cuk converter produce -42 V output voltage by following the reference voltage command. The overshoot voltage is -56 V. At 0.6 seconds, the system achieved steady state condition.

When the reference voltage for P.I controller is set to -48 V, the BPFC Cuk converter will produce -48 V output voltage as shown in Figure 8. The overshoot voltage is -59 V. The steady state condition achieved at 0.5 seconds.

Figure 9 illustrate the -54 V output voltage with P.I controller. The overshoot voltage is -63 V. For -54 V output voltage, the system starts to achieve stability at 0.41 seconds (Figure 10).

Figure 1 show the result for the output voltage ripple value with P.I controller. As increase the output voltage, the ripple will be increase too. P.I control is functioning well in order to reduce the output voltage ripples.
6. CONCLUSION

In this paper, a proportional-integral control for bridgeless PFC Cuk converter is discussed. Various output voltage was set up to observe the characteristic of output voltage during steady state and step response. The proposed design of P.I controller able to control the output voltage of BPFC Cuk converter. As increase the output voltage value, the overshoot voltage will increase too but the steady state time will be faster. Furthermore, the performance of BPFC Cuk converter become better since the output voltage able to achieve fast steady state condition. The output voltage ripples are affected toward the output voltage value. However, the P.I controller able to reduce the output voltage ripples.

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