A Novel Single-Stage Push–Pull Electronic Ballast
With High Input Power Factor
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Abstract—A novel single-stage push–pull electronic ballast with high input power factor is presented in this paper. The proposed electronic ballast combines the front-end power-factor corrector and push–pull converter into a single-stage converter. Compared to the single-stage class-D electronic ballast, the proposed circuit does not require an isolated driver. The control of the circuit is easier and the cost less. The circuit of the ballast is analyzed and the designed guidelines are listed. The experimental results verify the theoretical derivation.

Index Terms—Electronic ballast, power factor, push–pull, single stage.

I. INTRODUCTION
IN RECENT years, electronic ballast has played a very important role in lighting gears. The electronic ballast has high efficiency and efficacy when driving fluorescent lamps at a high frequency. Its size is smaller and weight lighter when compared with the traditional ones. The bulk capacitors in the electronic ballast cause a large and sharp input current when source voltage reaches its peak. The input current with rich harmonics is harmful for other home electrical appliances, such as TV sets, computers, and radios. For the purpose of reducing the input line current harmonics, a power-factor-correction (PFC) circuit is attached to the electronic ballast. The cost will be higher when the PFC and the dc-to-ac converter are cascaded for one set of the electronic ballast. To reduce the cost of the electronic ballast, one single-stage converter is used to perform both functions of the PFC and the dc-to-ac conversion simultaneously. For single-stage electronic ballasting, several circuit topologies are presented [1], [2]. These ballast circuits are based on the class-D converters, as shown in Fig. 1. In this paper, a new type of circuit of a single-stage electronic ballast is proposed. It is a push–pull converter with a front-end power-factor corrector. The proposed circuit is depicted in Fig. 2. The control signals for switches \( S_1 \) and \( S_2 \) are constant duty cycle pulses. The reference grounding of the control signal and the two switches \( S_1 \) and \( S_2 \) are at the same level. The push–pull electronic ballast does not need the photocoupler or the pulse transformer as the isolated driver to control the cascade switches as do the class-D converters. In this way, the control circuit is simpler, and low-cost commercial ICs are available. A single-stage push–pull-type electronic ballast with high input power factor had been proposed by Lee, Joung, and Cho [3]. However, the input current is not sinusoidal and the fluorescent lamps would dim when the input voltage crosses zero. In this paper, two fast-recovery diodes and an energy storage capacitor are added, and the input current and the output performance are improved. The proposed ballast circuit is analyzed and the design rules are listed, and the experimental results verify the analysis.

II. CIRCUIT DESCRIPTIONS
The circuit in Fig. 2 can be functionally explained as follows.

1) Line filter \( E_1 \)—The electromagnetic interference (EMI) filter blocks the high-frequency switching noise from the ballast to the source.
2) Diode bridge \( B_1 \)—The diode bridge rectifies the ac input voltage into dc.
3) Input inductor \( L_1 \)—The front-end power-factor corrector is added to the ballast, and the discontinuous inductor current mode control makes the input current approaching sinusoidal waveforms.
4) PFC diode \( D_1 \)—When the diode is on, \( L_1 \) is charged by the source, the diode blocks the reverse current of the inductor \( L_1 \) when it is in discontinuous current conduction mode.
5) PFC diode \( D_2 \)—While the diode is on, \( L_2 \) discharges energy to \( C_3 \). The diode also blocks the reverse current of the inductor \( L_2 \).
6) Switch \( S_1 \)—The switch controls the high-frequency output and shapes the input current (PFC).
7) Switch \( S_2 \)—The switch only controls the high-frequency output.
8) **Main transformer \( T_x \)**—This provides electrical isolation between the source and the output.

9) **Resonant tank \( L_f \) and \( C_f \)**—The \( L_f \) and \( C_f \) resonate with the lamp \( (R_L) \) and, hence, sinusoidal output current can be generated.

10) **Fluorescent lamp \( R_L \)**—It is the load of the ballast.

11) **Starting capacitor \( C_S \)**—It is used only when the fluorescent lamps start.

12) **Energy storage capacitor \( C_1 \) and \( C_f \)**—stores energy when the input voltage is low.

13) **Soft-switching capacitors \( C_{P1} \) and \( C_{P2} \)** are parallel with the switches \( S_1 \) and \( S_2 \), respectively, to reduce the switching spikes.

The notations of the circuit parameters in this paper are defined as follows:

- \( D \) duty cycle of the control pulses of the two switches;
- \( D_{S1} \) body diode of \( S_1 \);
- \( D_{S2} \) body diode of \( S_2 \);
- \( F.G. \) functional ground;
- \( f_m \) line frequency;
- \( f_s \) switching frequency;
- \( i_{L1} \) current of inductor \( L_1 \);
- \( i_{S1} \) drain current of \( S_1 \);
- \( i_{S2} \) drain current of \( S_2 \);
- \( i_o \) lamp current;
- \( I_P \) charging current of the soft-switching capacitors;
- \( i_s \) input current;
- \( M \) ratio of the voltage of \( C_1 \) and the rms of the input voltage;
- \( P_m \) average input power of the ballast;
- \( Q \) quality factor of the resonant network;
- \( R_L \) equivalent resistance of fluorescent lamp;
- \( T_D \) switching time;
- \( V_{gs1} \) gate control signal of \( S_1 \);
- \( V_{gs2} \) gate control signal of \( S_2 \);
- \( V_{DC} \) voltage of the energy storage capacitor \( C_f \);
- \( V_{DC} \) peak-to-peak voltage ripple of \( C_f \);
- \( V_m \) rms of the input voltage;
- \( V_S \) source voltage;
- \( V_{S1} \) drain-to-source voltage of \( S_1 \);
- \( V_{S2} \) drain-to-source voltage of \( S_2 \).

### III. Circuit Operation

The operation of the proposed electronic ballast is described in the following seven modes, denoted \( M_1 - M_7 \).

1) \( M_1, S_1 \) on—When the switch \( S_1 \) is on and \( S_2 \) off, the input inductor \( L_1 \) is charged by the source \( V_S \) through \( D_1 \). The output voltage of the transformer \( T_x \) is positive. The lamp voltage and current is sinusoidal through the resonant tank filter. The current through \( S_1 \) is the sum of \( L_1 \) current (PFC) and the primary current of \( T_x \) (inverter).

2) \( M_2, S_1 \) off—When the switch \( S_1 \) is off, the current of inductor \( L_1 \) discharges through \( D_2 \) to \( C_f \). The sinusoidal lamp current lasts through the secondary winding of transformer \( T_x \). In this mode, the resonant current charges the soft-switching capacitor of \( S_1 \) \( (C_{P1}) \) and discharges capacitor of \( S_2 \) \( (C_{P2}) \). It helps \( S_2 \) perform ZVS at \( M_3 \) because the drain-to-source voltage of \( S_2 \) \( (V_{S2}) \) becomes zero at the end of this mode. In practice, a switching spike is found on the voltage waveform of \( S_1 \) when it is off. It is due to the leakage inductance of \( T_x \).

3) \( M_3, D_{S2} \) off—When \( V_{S2} \) goes zero, the resonant current passes through the body diode of \( S_2 \) \( (D_{S2}) \).

4) \( M_4, S_2 \) on—The switch \( S_2 \) is on with ZVS soft switching at the beginning of this mode as expected in \( M_2 \). In this mode, the direction of the lamp current changes because the voltage on the transformer \( T_x \) turns to negative. The PFC current of inductor \( L_1 \) also discharges energy through \( D_2 \) to \( C_f \).

5) \( M_5, D_2 \) off—When the current of inductor \( L_1 \) discharges to zero, \( D_2 \) turns off to block the reverse current.

6) \( M_6, S_2 \) off—When \( S_2 \) is off, as the transition in \( M_2 \), the resonant current changes the capacitor of \( S_2 \) \( (C_{P2}) \) and discharges the capacitor of \( S_1 \) \( (C_{P1}) \). It also helps ZVS soft switching of \( S_1 \). A switching spike is also found on the voltage waveform of \( S_2 \) when it is off.

7) \( M_7, D_{S1} \) on—When \( V_{S1} \) goes zero at the end of \( M_6 \), the resonant current passes through the body diode of \( S_1 \) \( (D_{S1}) \). Then, the switch \( S_1 \) turns on and recycles to \( M_1 \).

The key waveforms of the ballast are depicted in Fig. 3. The two switches \( S_1 \) and \( S_2 \) are soft turned on and hard off. The
Fig. 3. Key waveforms of the proposed electronic ballast.

The circuit operations of the seven modes are shown in Fig. 4(a)–(g), respectively.

IV. ANALYSIS

The circuit can be analyzed as follows.

1) PFC: Inductor $L_1$ is operated in discontinuous mode. The maximum duty cycle is 0.5. The value of the component $L_1$ must be lower than the critical value that is operated at the boundary of the continuous mode and the discontinuous mode. The input inductor can be derived as [4]

$$L_1 \approx \frac{M}{M-1} \frac{D^2 V_m^2}{4 f_s P_m}$$

$$M = \frac{V_{DC}}{V_m}.$$  \hspace{1cm} (1)

$V_m$ is the rms input voltage and $P_m$ is the average input power. $V_{DC}$ is the voltage of the energy storage capacitor $C_A$.

2) Push–pull converter: The push–pull converter can be classified as a voltage-fed and current-fed push–pull converter. Due to the unbalance problem of both push and pull voltage, the transformer may be saturated after a period of running time. The current-fed push–pull converter is commonly used in the ballast circuit because the transformer will not be saturated by the current source driving. A voltage-fed push–pull converter can also be used in the ballast circuit with the current-mode control. The control circuit is shown in Fig. 5. The commercial IC TL598 is used to control the ballast. The current of switch $S_2$ is monitored because switch $S_1$ is used for PFC, and the current of $S_1$ is not a constant. The current flow through $S_1$ is larger than $S_2$, with the same $R_{ds(sat)}$ of the two switches, when $S_1$ is on, its voltage across the transformer will be less than that of $S_2$. Overcurrent usually occurs at $S_2$ when the transformer is saturated. The current-mode control of $S_2$ prevents it from the saturation problem.

3) Resonant filter: The series resonant parallel-loaded filter circuit is the same as the class-D converter. The turns ratio of $T_r$ can be adjusted to fit different types of fluorescent lamps. The resonant components $L_r$ and $C_r$ should be traded off with the size of $L_r$ and the resonant quality $Q$. The following equation can be used for inductor design:

$$L_r = \frac{QR_r}{2 \pi f_s}.$$  \hspace{1cm} (2)

The value of the resonant capacitor $C_r$ is designed to avoid exciting the resonant tank at switching frequency $f_s$ [5], [6]

$$C_r \geq \frac{1}{\pi^2 f_s^2 L_r}.$$  \hspace{1cm} (3)

4) Dimming control: The proposed electronic ballast with pulsewidth modulation (PWM) control has two dimming control methods: PWM and variable frequency. To maintain the low crest factor of the lamp waveforms, variable frequency is superior to the PWM method. When the duty cycle of the switch control is 0.5, its lamp waveforms are sinusoidal. If the PWM dimming control is used in low duty cycle $D$, the lamp waveforms have distortions.

5) Proper conditions to choose push–pull topology: The voltage stress of $S_1$ and $S_2$ is twice the dc-bus voltage; it is higher than the class-D converter. On the other hand, the current stress of the switch is lower than any other topology. When the input voltage is low and output loading is not heavy, the choice of push–pull ballast is considerably reasonable. For example, the push–pull ballasts are commonly used in 24/48-V battery systems. For a 110-V ac system, the dc-bus is lower than 250 V, and the switch stress is 500 V. If the output power is 40 W, the current stress is 1.5 A (include the PFC current). 500-V/2-A MOSFET switches are low cost. However, for a 220-V ac system, 1-kV switches are not commonly available. The push–pull converter provides electrical isolation between the source and the output. The cost is low to choose a push–pull converter, especially when the ballasts need electrical isolation [7], [8].

V. DISCUSSION

Three important topics of the proposed ballast are discussed.

1) Ignition Process: The starting capacitor $C_5$ helps the fluorescent lamp warm up before ignition. When the circuit starts, the impedance of the lamp is extremely high. The filaments of the lamp, as shown in Fig. 2, are in series with the $L_r$–$C_r$–$C_5$ loop. They become hot rapidly as the load
of the ballast. At the end of the warmup time, as the starting voltage of the lamp decreases, a high voltage across $C_S$ ignites the fluorescent lamp. After the lamp is lit, the voltage across $C_S$ decreases. The warmup current also decreases to prevent filaments from overheating.

2) Soft Switching and Snubbers: As seen in the analysis in Section III, the push–pull inverter with resonant load network can perform ZVS soft switching. The capacitors $C_{P1}$ and $C_{P2}$ for $S_1$ and $S_2$ are used at the switching transition, respectively. These snubbers increase switching time and eliminate the voltage spikes. However, a large snubber capacitor ZVS deteriorates the function of soft switching. The following equation estimates the limit:

$$\left( C_{P1} + C_{P2} \right) \leq \frac{T_D I_P}{2V_{DC}}$$  \hspace{1cm} (4)
3) Comparison With the Other Discontinuous Conduction Mode Power Factor (DCMPF) Ballast: The proposed ballast is suitable for low-voltage and low-power cases. According to the above analysis and discussion, Table I lists a comparison with the class-D DCMPF ballast. Generally, the proposed ballast has higher voltage stress than the class D. One of the two switches affords high current stress of PFC and the inverter, but the other does not. This unbalance can possibly saturate the main transformer. Unlike the class-D circuit, the push–pull does not need an isolated driver to control the switches. The two topologies have the advantage of the ZVS soft switching.

For the class-D ballast, it is not necessary to have an isolation transformer.

VI. DESIGN GUIDELINES

The design rules are listed as follows.

1) The design of the discontinuous-mode PFC can follow the class-D converter design. The PFC inductor $L_1$ can be designed according to (1).

2) The voltage stress of switch $S_1$ or $S_2$ is twice the dc bus; for 110-V input, it is about 250 V. The rating of the switches is 500 V, but the current rating can be smaller than the class-D converter for $S_2$. The current rating of $S_1$ is the total peak current of inductor $L_1$ and output primary current transformer $T_x$. Even if the current ratings of the two switches $S_1$ and $S_2$ are not the same, it is better to choose the same type of switch device for the same value of $R_{ds(on)}$.

3) The voltage ratings of $D_1$ and $D_2$ are the same as $S_1$; the current ratings of these diodes are the same as the peak current of inductor $L_1$.

4) The design of the resonant inductor $L_r$ can refer to (2). To prevent the transformer from saturation, a small gap is usually used on the core of the transformer $T_x$. However, it will increase switching spikes because the leakage inductance of $T_x$ also increases.

5) The resonant capacitor $C_r$ is usually determined as the nature resonant frequency $L_r^{-1}C_r$ that is much lower than switching frequency. Equation (3) will help us choose the proper value of $C_r$.

6) The minimum capacity of $C_1$ is

$$C_1 \geq \frac{P_{\text{in}}}{2\pi f_{\text{in}} \Delta V_{\text{DC}} V_{\text{DC}}}$$

where $f_{\text{in}}$ is the frequency of the input power source. $\Delta V_{\text{DC}}$ is the peak-to-peak ripple voltage at $C_1$.

VII. EXPERIMENTAL RESULTS

To experimentally verify the theoretical derivation, an electronic ballast for 100-Vac input and a 40-W fluorescent lamp was implemented. The detailed ballast circuit is shown in Fig. 6. The circuit parameters are as follows:

$L_1$: 600 $\mu$H,
$L_r$: 1.8 mH,
$C_r$: 100 $\mu$F
$C_b$: 47 nF,
$R_{s1}$, $R_{s2}$: 0.33 $\Omega$

turn ratio of $T_x$: 1 : 1,
$S_1$, $S_2$: 300 V/5.5 A

$D_1$, $D_2$: 600 V/2 A,
$C_{p1}$, $C_{p2}$: 1 nF

The switching frequency $f_s$ is 48 kHz.

The components of the EMI filter are as follows:

$L_{x1} = L_{x2} = 2$ mH
$L_{y1} = L_{y2} = 1.4$ mH
$C_{x1} = C_{x2} = 1$ $\mu$F
$C_{y1} = C_{y2} = 4.7$ nF.

The input voltage and current waveforms are shown in Fig. 7. The current is like a triangle, while the input voltage has a sine waveform. This distortion usually occurs in discontinuous-mode boost PFC [9], but the input power factor of the ballast was 0.99. The waveforms of switch $S_1$ are shown in Fig. 8 on different input voltages. The waveforms of switch $S_2$ are shown in Fig. 9. The two switches are turned off under hard-switching conditions. The lamp voltage and current waveforms are shown in Fig. 10. The measured efficiency of the ballast was 0.81 if the filament and control circuitry losses are included.
Fig. 6. Design example of the proposed electronic ballast.

Fig. 7. Measured input voltage and current waveforms of the proposed ballast.

Fig. 8. Measured voltage and current waveforms of switch $S_1$.

Fig. 9. Measured voltage and current waveforms of switch $S_2$.

Fig. 10. Measured lamp voltage and current waveforms of the proposed ballast.
VIII. CONCLUSION

In this paper, a new single-stage push–pull electronic ballast with high input power factor has been proposed. The control of the circuit is easier and costs less. Low-cost commercial ICs are available for the ballast. The input and output performance is better than that of the traditional push–pull ballast. The proposed circuit has less output crest factor than the other DCMPF push–pull ones because it has an energy storage capacitor.

A comparison of the proposed topology and the DCMPF half-bridge ballast was discussed. Although the voltage stress of the switches is twice as high as the half bridge, the proposed ballast does not need an isolated driver. It can be utilized in low-voltage and low-power output lighting gears which need electrical isolation.

REFERENCES


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