Abstract – This paper presents an efficient, small-sized, and cost-effective single-switch power-factor-correction (PFC) scheme for high-frequency electronic ballasts. The circuit topology originates from the integration of a buck-boost power-factor-correction converter and a class-E electronic ballast. Only one active power switch is commonly used by both power stages to save the cost of active switches and control circuits. The active switch is controlled by pulse-width-modulation (PWM) at a fixed switching frequency and constant duty cycle. The electronic ballast can achieve nearly unity power factor by operating the buck-boost converter at discontinuous conduction mode (DCM). With carefully designed circuit parameters, the active power switch can be operated at zero-voltage switching, leading to a high circuit efficiency. A prototype circuit designed for a PL-27W compact fluorescent lamp is built and tested to verify the theoretical predictions. Satisfactory performance is obtained from the experimental results.

I. INTRODUCTION

Fluorescent lamps have been increasingly accepted in residential, industrial, and commercial lighting applications. However, these lamps require high striking voltage for starting and limiting currents after ignition because they have negative incremental impedance characteristics. Traditional electromagnetic ballasts, operating at line frequency, have been used to solve these problems. In spite of their low cost, these ballasts present flickering, large size, heavy weight, and hum. Therefore, high-frequency electronic ballasts for fluorescent lamps have received great attention in recent years owing to their merits of light weight, small size, high luminous efficiency, and long lamp life. Most electronic ballasts are realized with load resonant inverters since they can provide an appropriate ignition voltage and then a stable lamp current with a low crest factor for fluorescent lamps. The use of class-E resonant inverters as fluorescent lamp ballasts presents several advantages such as less component count, low cost, and high power density. These features, in addition to the fact that the class-E resonant inverter uses only one active power switch, result in the electronic ballast with very simple structure, low switching losses, small volume and light weight. Furthermore, since the commutations in the switch of the resonant inverter are accomplished at zero voltage, the switching losses of the electronic ballast are very low, resulting in a very high efficiency.

In order to obtain a compact electronic ballast and eliminate undesirable characteristics like audible noise, flickering and stroboscopic effects, the operating frequency must be raised. In the case of a fluorescent lamp operating at high frequency, the luminous efficiency increases by about 20% [1,2], which saves the energy consumption of the system. Conventionally, high-frequency electronic ballasts, when consuming power from the AC line voltage source, often use a diode-bridge rectifier with a bulk electrolytic capacitor to convert the AC voltage to a smoothed dc-link voltage for the high-frequency electronic ballasts. Such a rectifier circuit inevitably draws an input current of narrow pulses, which is notorious for very poor power factor and serious harmonic distortion. The power factor (PF) is typically less than 0.6 and the total harmonic distortion (THD) can be greater than 100%. The widespread use of high-frequency electronic ballasts for fluorescent lamps in lighting applications is a significant source of power pollution. However, the benefits of high power factor, including reductions in the rms line current and the line current harmonic distortion can cause the utility line to be more efficiently utilized and less polluted. Therefore, a filter circuit becomes necessary in the design of the high-frequency electronic ballast.

The general solution to reducing the input current harmonic and improving the power factor of the AC line source is the addition of a second power processing stage, called the PFC stage. Normally employing the discontinuous current dc-to-dc converter, these stages make the line current naturally follow the sinusoidal line voltage waveform [3]. However, the two-stage approach increases the cost, besides reducing reliability and efficiency, since the power is processed twice. This problem can be solved by integrating the PFC circuit into the load resonant inverter stage [4]. By sharing the active power switch and the control circuit, the component count can be effectively reduced. However,
in compliance with the operation of the load resonant inverter stage, the active power switch has to be switched at the desired frequency with the specified duty cycle. Under this constrain, the PFC circuit with buck-boost topology is preferable since the high power factor for the PFC with boost topology resorts to an excessively high dc-link voltage.

Load resonant inverters are considered to be the most effective way for the miniaturization of electronic ballasts. They can operate at very high switching frequency because of low switching losses and electromagnetic interference. Furthermore, since the commutations in the switch of the inverter are accomplished at zero voltage, switching losses are very low, resulting in a very high efficiency. Therefore, one of the ways to reduce the cost in high power factor electronic ballasts is the integration of two stages, a buck-boost converter and a class-E resonant inverter, in a single-stage electronic ballast with only one active power switch. Usually, in order to achieve high circuit efficiency, the buck-boost converter is operated in a discontinuous conduction mode at a fixed frequency with a constant duty cycle. Thus, the electronic ballast provides simultaneously a unity power factor to the utility line and high-frequency voltage to the fluorescent lamp, as well as offers high efficiency, low cost and high reliability compared to conventional high-power-factor electronic ballasts. Experimental results based on a PL-27W compact fluorescent lamp is built and tested to verify the computer simulations and analytical predictions.

II. CIRCUIT CONFIGURATION AND OPERATION

A. Circuit Configuration

The circuit configuration of the proposed single-stage single-switch high-power-factor electronic ballast is illustrated in Fig. 1. The electronic ballast is mainly composed of a class-E load resonant inverter for driving the fluorescent and a buck-boost converter for input current shaping. The buck-boost converter is formed by diodes \(D_1, D_2\), inductor \(L_p\), dc-link capacitor \(C_{dc}\), and active power switch \(S\). The class-E resonant inverter is composed of dc-link capacitor \(C_{dc}\), inductor \(L_1\), diodes \(D_3, D_4\) and load resonant circuit. The diodes \(D_1\) and \(D_3\) are used for isolating the dc-link voltage and class-E resonant inverter. The diode \(D_4\) has the purpose of providing a path for the resonant current of the class-E inverter. The fluorescent lamp is connected in parallel with a capacitor \(C_f\), which is in series with an inductor \(L_s\), and a capacitor \(C_s\). The capacitor \(C_f\) is used to provide a sufficiently high ignition voltage on the lamp during starting transient and then a proper filament heating at steady state. A resonant energy tank, \(L_s\), and \(C_s\), in series with the lamp network forms the load resonant circuit of the class-E resonant inverter. The load resonant circuit of the class-E inverter is formed by the fluorescent and the reactive components \(L_s, C_s, C_p\), and \(C_f\).

In order to reduce switching losses, the buck-boost converter can deliberately be operated at DCM. Hence, the switching--on losses of the active power switch can be eliminated. Since the active power switch \(S\) is turned on and off at a high frequency with fixed frequency and constant duty cycle, the input current becomes a pulsating waveform at the same frequency. By properly controlling the amplitude and duration of the pulsating current, the average of the input current can be made to be sinusoidal and in phase with the input voltage. The high-frequency harmonics in the input current can simply be removed by a small low-pass filter at the input terminal. Consequently, a nearly unity power factor and very low harmonic distortion can be achieved.

To improve the efficiency of the high-frequency electronic ballasts, many types of soft-switching technologies have been proposed. However, the class-E resonant inverters are the most efficient inverters known so far [5,6]. In this paper, we choose the class-E resonant inverter with simple circuit configuration because less component count can achieve high efficiency and low cost. Also, it is a single-switch topology that produces a sinusoidal output current. With carefully designed circuit parameters, the active power switch can be operated at zero-voltage switching, leading to high circuit efficiency.

B. Circuit Operation

The single-stage single-switch high-power-factor electronic ballast, shown in Fig. 1, integrates the buck-boost PFC stage and the class-E resonant inverter stage. The active power switch of the proposed electronic ballast is excited by the driving signal \(V_{gs}\). The duty cycle of the driving signal is \(d\). The circuit operation can be divided into five modes in accordance with the conducting power switch within one high-frequency cycle.

Mode I (t0<t1):

Prior to \(t_0\), the active power switch \(S\) is off, and the freewheeling diode \(D_4\) is conducting. The current of \(D_4\) is the difference between inductor current \(I_{dc}\) and the load resonant current \(I_r\). At the beginning of this mode, a
turn on signal is applied to the gate of the switch $S$. The equivalent of this mode is depicted in Fig. 2. Once $S$ has been turned on, the line voltage is imposed on the inductor $L_p$. At DCM operation, the inductor current $I_p$ of the buck-boost converter increases linearly from zero. Hence the turn-on of the switch $S$ occurs at zero current switching condition. The slope of $I_p$ is proportional to the line voltage. In the interval of this mode, the input current $I_{in}$ is equal to $I_p$. When the difference between $I_{dc}$ and $I_r$ becomes positive, the diode $D_4$ turns off and Mode I ends.

Mode II ($t_1 < t < t_2$):

During this period, the switch $S$ is kept at the on state. The equivalent circuit is shown in Fig. 3. The line voltage is applied on $L_p$, and $I_p$ increases continuously. In this mode, the current $I_{dc}-I_r$ naturally commutates from diode $D_4$ to the switch $S$. Both the currents $I_{dc}-I_r$ and $I_p$ pass through switch $S$.

Mode III ($t_2 < t < t_3$):

At the beginning of mode III, the inductor $I_p$ reaches its peak value and the switch $S$ is turned off. The inductor current $I_p$ freewheels through $D_2$ to charge the dc-link capacitor $C_{dc}$. The equivalent of this mode is depicted in Fig. 4. In this time interval, the voltage across $L_p$ is equal to $V_{dc}$. Therefore, the inductor current $I_p$ decreases linearly. The capacitor current $I_{c1}$ becomes $I_{dc}-I_r$. The capacitor voltage $V_{c1}$ rises from zero to a maximum value and falls again.

Since the peak of $I_p$ is proportional to the rectified input voltage $V_{rec}$, the duration for $I_p$ declining to zero is not constant but varies with the rectified input voltage. Thus, there are two possible modes following mode III, depending on which of the current $I_p$ and the voltage $V_{c1}$ reaches zero first.

Mode IV-a ($t_3 < t < t_4$):

When the line voltage is high, $V_{c1}$ declines to zero before $I_p$ does. Mode III finishes at the time when $V_{c1}$ becomes zero, and then, the operating mode enters mode IV-a. The equivalent circuit is illustrated in Fig. 5. At this instant, the current $I_{dc}-I_r$ naturally commutates from the capacitor $C_1$ to the diode $D_4$. In this operating mode, the inductor current $I_p$ decreases continuously. This mode ends when $I_p$ decreases to zero.

Mode IV-b ($t_3 < t < t_4$):

At lower line voltage, the peak of $I_p$ is small and declines to zero faster. In case that $I_p$ decreases to zero, mode IV-b instead of mode IV-a, follows mode III. Then, the diode $D_2$ is turned off. The equivalent circuit is shown in Fig. 6. During this mode, the current $I_{dc}-I_r$ flows through $C_1$ continuously. This mode finishes at the time when $V_{c1}$ resonates to zero.

Mode V ($t_4 < t < t_5$):

The diode $D_4$ turns on at the beginning of mode V, and carries the freewheeling current which is equal to the difference between $I_{dc}$ and $I_r$. The equivalent circuit is depicted in Fig. 7. When the active power switch $S$ is excited again by the driving signal $V_{gs}$, this mode ends and the operation returns to mode I of the next cycle.
Fig. 7 Equivalent circuit of Mode V

Fig. 8 and Fig. 9 illustrate the theoretical waveforms for the proposed high-power-factor electronic ballast operating at the high voltages and the low voltages of the rectified line source, respectively. As illustrated in these two figures, the buck-boost PFC stage is operated at DCM in order to provide an average input current proportional to the sinusoidal input voltage, thus achieving high input power factor.

Fig. 8 Theoretical waveforms (at high rectified line voltage)

Fig. 9 Theoretical waveforms (at low rectified line voltage)

III. CIRCUIT ANALYSIS

To facilitate the analysis of the single-stage single-switch high-power-factor electronic ballast, the following assumptions are made.

1) All the circuit components are ideal.
2) The switching frequency is designed to be much higher than the AC line frequency; therefore, input voltage can be considered as constant during a switching cycle.
3) The dc-link capacitor $C_{dc}$ is assumed to be sufficiently large so that the dc-link voltage $V_{dc}$ can be considered as an ideal dc voltage source.
4) The inductor $L_1$ is large enough that the inductor current $I_{dc}$ can be approximated as a dc current source.
5) The loaded quality factor of the class-E resonant inverter is high enough so that the load current, $I_r$, is sinusoidal.
6) The lamp is regarded as an open circuit before ignition, and a resistance at the steady state.

Based on the above assumptions and considering a single switching period, this electronic ballast can be treated as two simplified independent stages, the buck-boost PFC and the class-E resonant inverter.
fluorescent lamp are usually very small; therefore, they are neglected in the analysis. Then, the parallel combination of $C_p, C_f,$ and lamp of Fig. 1 is converted into a series combination of $C_{SS}$ and $R_{eq}$, as shown in Fig. 10.

Referring to Fig. 10, the equivalent resistance $R_{eq}$ is represented by

$$R_{eq} = \frac{R_{lamp}}{1 + \omega_f^2 R_{lamp}^2 (C_p + C_f)^2}$$

and the equivalent capacitance $C_{SS}$ is

$$C_{SS} = \frac{C_s [1 + \omega_f^2 R_{lamp}^2 (C_p + C_f)^2]}{1 + \omega_f^2 R_{lamp}^2 (C_p + C_f)^2 + \omega_f^2 R_{lamp}^2 C_s (C_p + C_f)}$$

The inductance $L_I$ is assumed to be high enough so that the ac ripple on the dc-link current $I_{dc}$ can be neglected.

$$V_{dc} \rightarrow I_{dc} \rightarrow S \rightarrow \frac{R_{lamp}}{C_f} \rightarrow R_{eq} \rightarrow C_p \rightarrow L_s \rightarrow C_f$$

Fig. 10 Derivation of the equivalent circuit for electronic ballast with class-E inverter

To achieve zero-voltage switching of the active power switch $S$, the operating frequency $f_s$ should be greater than the resonant frequency $f_{rl} = 1/(2\sqrt{L_s C_{SS}})$. The shape of the waveform of the load current $I_r$ depends on the loaded quality factor $Q_L$. If the loaded quality factor is high, the shape of the waveform of the load current $I_r$ is approximately sinusoidal. Then, the combination of the inductor $L_1$ and the $L_s-C_{SS}-R_{eq}$ resonant circuit acts as a current source whose current is $I_{dc}-I_r$. When the active power switch is on, the current $I_{dc}-I_r$ flows through the active power switch $S$. When the active power switch is off, the current $I_{dc}-I_r$ flows through the capacitor $C_f$. Therefore, the shunt capacitor $C_f$ shapes the voltage across the active power switch. Since the active power switch current and voltage waveforms do not overlap during the switching time intervals, switching losses are virtually zero, yielding high efficiency.

B. The Buck-Boost PFC Stage

The buck-boost PFC stage is supplied from the ac line voltage source.

$$v_s(t) = V_m \sin(2\pi f_L t)$$

where $V_m$ is the amplitude of the ac line voltage source and $f_L$ is the line frequency.

During mode I and mode II, the line source supplies current to the buck-boost stage. The unfiltered input current $I_{in}$ is equal to $I_p$. Because the buck-boost PFC stage is operated at DCM over an entire line frequency cycle, $I_p$ increases from zero at the beginning of mode I and reaches its peak at the end of mode II. Then, it decreases to zero before the end of mode IV. The current waveform of inductor $I_p$ in a completed utility line cycle is conceptually illustrated in Fig. 11. Its peak values follow a sinusoidal envelope and can be represented as

$$I_{p, peak}(t) = \frac{d \int V_m \sin(2\pi f_L t) dt}{2L_p f_s}$$

where $|V_m \sin(2\pi f_L t)|$ represents the instantaneous line voltage, which can be considered constant within each switching cycle.

The average value of input current $I_{in}$ within a high frequency switching period can be calculated as

$$I_{in, avg}(t) = \frac{1}{T_s} \int_{0}^{T_s} I_p(t) d(t)$$

$$= \frac{d^2}{2L_p f_s} V_m \sin(2\pi f_L t)$$

Equation (5) reveals that the input current is sinusoidal and in phase with the ac line voltage. Therefore, as the buck-boost PFC stage is designed to operate at DCM with fixed switching frequency and constant duty cycle, the input current naturally follows the sinusoidal waveform of the ac line source. As a result, a high power factor of the utility line can be obtained.

Fig. 11 Buck-boost inductor current waveform

IV. EXPERIMENT RESULTS

To verify the predicted operation principles and theoretical analysis of the proposed new single-stage single-switch high-power-factor electronic ballast for fluorescent lamps, a laboratory electronic ballast of Fig. 1 is designed and built to drive a compact fluorescent lamp of PL-27W. The circuit parameters are listed in Table 1. Figs. 12 and 13 show the measured experimental waveforms of the experiment circuit,
which are quite consistent with simulated. The experimental results shown in Figs. 12 and 13, demonstrate that zero-voltage switching is achieved at constant frequency for the active power switch. It should be noticed that the active power switch $S$ and the capacitor $C_f$ were also softly commutated under zero-voltage-switching. Therefore, the switching losses for this new electronic ballast are practically zero. The experimentally obtained efficiency from the single-stage single-switch high-power-factor electronic ballast is equal to 92.1%. Fig. 14 shows the measured input line voltage and current waveforms when the PFC circuit is supplied from an input voltage of 110V. At this operating point, the new design can achieve a high power factor greater than 0.99 and a low total harmonic distortion less than 9.8%. The high-frequency fluorescent lamp voltage and current waveforms are illustrated in Fig. 15. The crest factor (CF) of the lamp current equals 1.42.

<table>
<thead>
<tr>
<th>Table 1 Circuit parameters</th>
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<tr>
<td>Input voltage $V_s$</td>
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<tr>
<td>Switching frequency $f_s$</td>
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<tr>
<td>Duty cycle $d$</td>
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<tr>
<td>DC-link voltage $V_{dc}$</td>
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<tr>
<td>DC-link Capacitor $C_{dc}$</td>
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<tr>
<td>Inductor $L_p$</td>
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<td>Inductor $L_s$</td>
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<td>Inductor $L_1$</td>
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<td>Capacitor $C_f$</td>
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V. CONCLUSIONS

A single-stage single-switch high-power-factor electronic ballast has been presented in this paper. The proposed single-stage ballast is the combination of a buck-boost PFC stage and a class-E resonant inverter output stage. The buck-boost stage is used to provide unity power factor and the class-E resonant inverter ignites and supplies the fluorescent lamp at the nominal operating point. This topology was accomplished by allowing both stages to share the only one switch of the electronic ballast. When the active power switch is designed to be softly switched at zero voltage and DCM, the switching losses can be completely eliminated and
leading to high efficiency. In addition, the power losses can also be reduced with fewer circuit components. As a result, the ballast efficiency can be as high as 92.1%. Theoretical analysis and experimental results prove that almost unity power factor and very low THD can be achieved.

A prototype of the proposed ballast for a PL-27W compact fluorescent lamp has been successfully implemented. The current waveform with low crest factor is obtained as expected. The proposed topology works as a good solution to implement low-cost high-power-factor electronic ballasts.

REFERENCES


