

Hybrid Source Driven E-Ballasts by using Microprocessor-Controlled Switching Technique

Priyanka Sahni & Nonika Sharma

Information Technology

Dronacharya College of Engg, Gurgaon, Haryana, India

priyanka.sahni@yahoo.com.au Nonikasharma1@gmail.com

Abstract—

A novel microprocessor-controlled electronic ballast with a class-E resonant inverter for illumination applications is employed to link a photovoltaic (PV)-powered battery energy storage system (BESS) as a main power source with a utility ac power as a complementary source. The proposed strategy aims to control power flow either from the PV-powered BESS or from the utility ac power line to the electronic ballast. This novel design has lower loss, easier control, and higher efficiency than the traditional photovoltaic panel has. A 27W fluorescent lamp is ignited by electronic ballast with a class-E topology to validate the proposed theoretical analyses. When the electronic ballast is driven by the PV-powered BESS and the utility ac power, overall efficiency of the proposed system is 94.2% and 91.1%, respectively. Experimental results demonstrate the functionality of the overall system, indicating that it is a good solution for several hybrid source applications.

Keywords:

Electronic ballast; hybrid source; microprocessor; battery energy storage system; class-E resonant inverter.

INTRODUCTION

Giving growing public concern over the exhaustion of fossil fuel reserves and pollution problems incurred by conventional power generation, renewable energy sources such as solar, wind, micro-hydraulic, biomass, geothermal, hydrogen, and tidal are extensively adopted in industrial, commercial and military applications [1-6]. Moreover, fluctuations and increases in oil prices have negatively impacted the world economy, particularly economies in developing countries. Photovoltaic (PV) energy as an alternative energy source has been widely investigated as it is pollution-free, abundant and widely available. The PV energy applications can be divided into grid-connection systems and stand-alone systems. In grid-connection systems, an inverter stage plays an important role as the interface device between the PV power generation system and the utility. To connect to a utility, an inverter stage must be operated in grid-connection mode. Notably, an inverter stage can synchronize with utility ac sources. Additionally, inverters must be operated in switching mode when connected to a grid, and the current transferred onto a grid must be regulated to follow the reference signal. At the same time, active power switches of the inverter must be driven properly to generate a series of sinusoidal pulse width modulation (SPWM) waveforms. Then, through a LC lowpass

filter, this inverter can generate sinusoidal voltage along with the utility to supply power to loads [7,8]. However, such PV systems are typically idle at night or during cloudy days. However, system components have not been used optimally. Conversely, traditional stand-alone systems have advantages of a simple system configuration and control scheme. To draw electrical power from PV arrays and store excess energy, a BESS is required. When output of a PV power generation system is insufficient, a BESS can provide backup energy; that is, a BESS works as an energy buffer. Furthermore, by using power electronic converters, stand-alone operation can be achieved easily and load-independent, high-quality voltage can be generated. Utilizing PV electricity to drive electronic ballasts may be one of the most appropriate applications of PV arrays with a BESS. Consequently, stand-alone systems have

become the focus of research investigating PV-powered lighting applications.

The conventionally stand-alone PV-powered BESS for lighting applications has two power processing stages—an inverter stage and bridge rectifier stage. The inverter stage provides a low-frequency ac source of 50 or 60Hz, which is transferred to the downstream load, and the bridge rectifier stage generates a dc voltage for the electronic ballast which ignites a lamp and stabilizes lamp current during steady-state operation. However, the two-stage approach is costly, and reduces system reliability and efficiency, as energy is converted twice (Fig. 1). Moreover, this approach requires numerous components, thereby increasing final cost of the electronic lighting system and reducing system energy conversion efficiency.

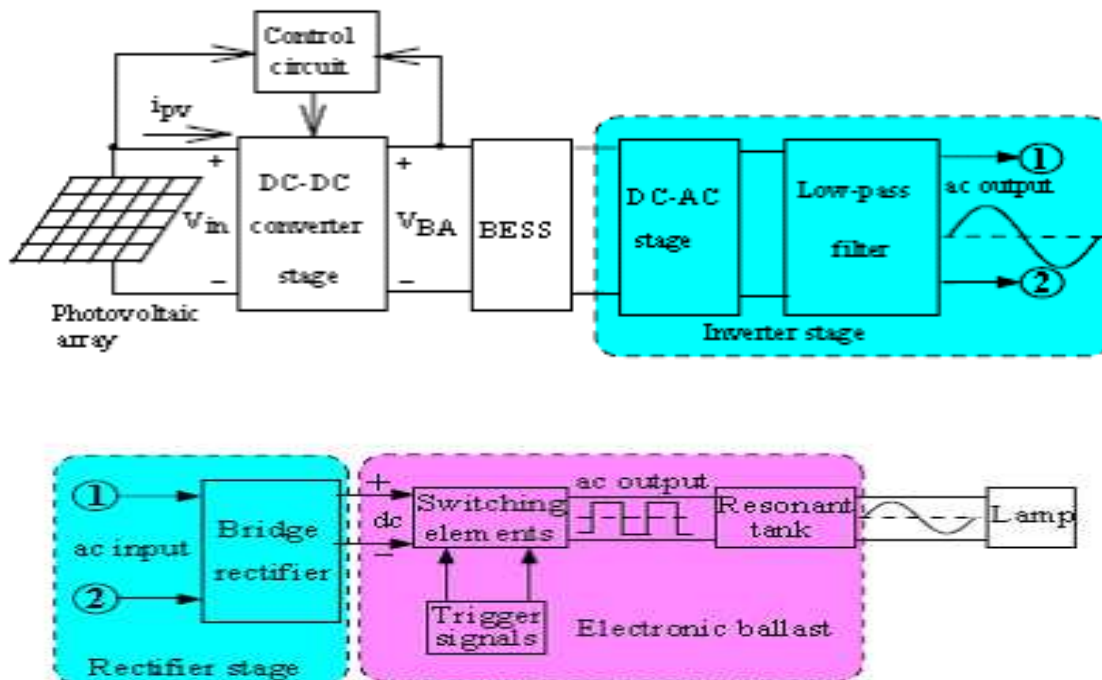


Fig. 1. Block diagram of a traditional PV-powered battery system for storing energy for lighting applications

These problems have promoted the use of high-frequency energy converters that convert dc electrical energy into energy for lighting. The simplest and least expensive method for converting PV power to dc electricity is to store energy in a BESS. The

electronic ballast is directly connected to the BESS without an inverter stage or rectifier stage to improve conversion efficiency and decrease cost. Directly driven electronic ballast is then obtained that employs a PV-powered BESS (Fig. 2).

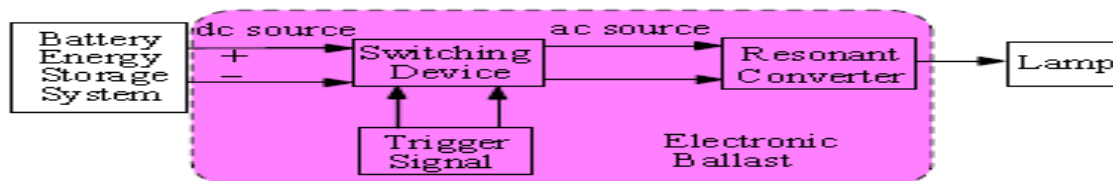


Fig. 2. Simplified block diagram of direct-driven electronic ballast by a PV-powered battery system for storing energy

Several lighting fixtures typically exist in lighting applications. Incandescent lamps and florescent lamps are the most common in lighting. Incandescent lamps and florescent lamps generate light via two physical mechanisms that convert electrical energy into light energy. Incandescent lamps exploit Joule-heating by electrically heating high-resistance tungsten filaments to an extreme brightness. The electrical behavior of incandescent lamps is simple. Lamp current is based on the applied voltage and the resistance of tungsten filament, whose $v-i$ characteristic is close to that of a linear resistor. However, only about 10% of the electricity flowing through incandescent lamps is converted to light; thus, luminous efficiency of incandescent lamps is poor. Florescent lamps convert electrical energy into light by transforming electrical energy into the kinetic energy for moving electrons, which in turn produce radiation when they collide. Modifying the gas composition in florescent lamps can considerably alter luminous efficiency.

This study focuses on florescent lamps, which are utilized extensively in general lighting applications and have high luminous efficiency [9,10]. However, florescent lamps depend on a high striking

voltage to generate and limit currents following ignition as they utilize negative incremental impedance. Thus, florescent lamps cannot be connected directly to a voltage source. Without limiting current, a lamp would be destroyed quickly, because of the negative resistance of florescent lamps. Consequently, some impedance must exist between a florescent lamp and the voltage source to limit lamp current. Most florescent lamps are operated using an ac source such that inductive impedance can be employed to limit current. AC operation also balances wear to the two electrodes and increase lamp life. Inductor ballasts are conventional ballasting, known as electromagnetic ballasts. Traditional electromagnetic ballasts are used to overcome these problems. Despite their low cost, ballasts cause bulbs to flicker are large, heavy and hum. Therefore, high-frequency electronic ballasts for florescent lamps have garnered considerable attention in recent years due to their light weight, small volume, high luminous efficiency and long lamp life. When a florescent lamp operates at a high frequency, luminous efficiency increases to about 20% higher than that achieved with conventional electromagnetic ballast operated at utility line frequency,

thereby reducing the amount of energy consumed by the input power source.

Most high-frequency electronic ballasts have load resonant inverters that provide ignition voltage and a stable lamp current with a low crest factor for fluorescent lamps. Furthermore, load resonant inverters can operate at very high switching frequencies and have low switching losses and electromagnetic interference (EMI). To enhance the efficiency of high-frequency electronic ballasts, many soft-switching technologies have been developed [11-15]. The class-E zero voltage-switching (ZVS) resonant inverters have the highest efficiency of all existing resonant inverters. The class-E ZVS resonant inverter has a single-ended structure and, thus, is unlike class-D ZVS inverters, which have a double-ended output and, thus requires two separate gate trigger signals and an upper trigger signal that has an isolated circuit. Additionally, the trigger circuit in the class-E topology, which has a single end, is simple. Consequently, the class-E ZVS resonant inverter has recently become common in switchmode power applications. The use of a class-E ZVS resonant inverter as a fluorescent lamp ballast has such advantages as few components, low cost and high power density. These characteristics, combined with the fact that the class-E ZVS resonant inverter has only one active power switch, result in electronic ballast with a very simple structure, low switching losses, small volume and light weight. Additionally, as commutations in the active power switch of the class-E resonant inverter are performed at zero voltage, electronic ballast switching losses are extremely low, resulting in very high efficiency.

This work presents a novel application of electronic ballasts driven by a hybrid source. In contrast to the conventional topology, the

proposed configuration has no inverter stage for the main power source; rather it has a powerfactor-correction (PFC) circuit and rectifier stage as the auxiliary power source. The PV arrays convert solar energy into dc electrical power, which can be used directly by electronic ballasts, where energy is stored in a BESS, and transformed to high-frequency ac power source using a highfrequency resonant inverter for fluorescent lamps. However, when a preset discharge threshold is attained, the load is disconnected from the BESS. A novel hybrid-source-powered energy-saving lighting system is then employed for optimal use of the electronic ballast via microprocessor-controlled digital switching. Fig. 3 shows a typical configuration of proposed hybrid-source-powered lighting system with a digital switching feature. The proposed system is particularly suited to typically lighting applications. During daytime this system effectively extract electrical power from PV arrays, while during nighttime, the system draws power from the utility for the lighting system with a high power factor (HPF) and high efficiency. The proposed system also requires a highly efficient illumination device such as a fluorescent lamp. To implement the two different energy control schemes and control the relay for switching operation modes, the proposed system has a microprocessor. Figure 4 shows a simplified block diagram of electronic ballast driven by using the microprocessor-controlled digital switching technique. In the proposed hybrid sources lighting system, circuit components must be designed carefully to reduce cost and improve reliability and efficiency. One benefit of the proposed topology of the electronic ballast is that it only requires one power processing stage, which makes it highly efficient, low-cost, reliable and simple. Hence, this study applies the power electronic load to a fluorescent lamp lighting

system. The following sections present a detailed analysis and elucidate the function

of the PV-powered electronic ballast.

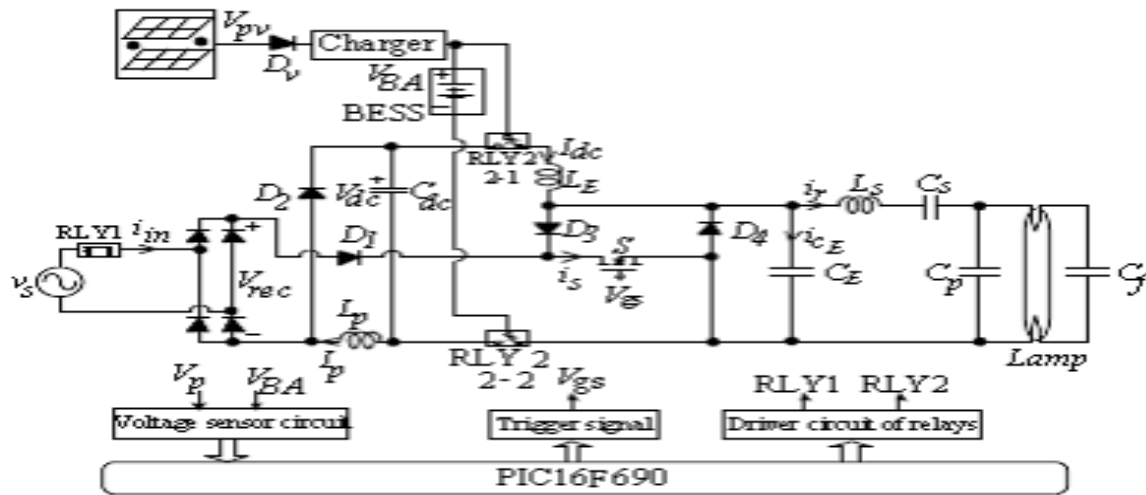


Fig. 3. Typical configuration of proposed hybrid-source-powered lighting system with a digital switching technique

The remainder of this paper is organized as follows. Section II describes the operating principle of electronic ballast with a class-E resonant inverter. Section III presents assumptions in analysis and the analytic results for the single-stage high power-factor electronic ballast for fluorescent

lamps. Section IV presents applications of the proposed electronic ballasts driven by a hybrid source using a microprocessor-controlled digital switching technique. The most important study results are also given in this section. Conclusions are presented in Section V.

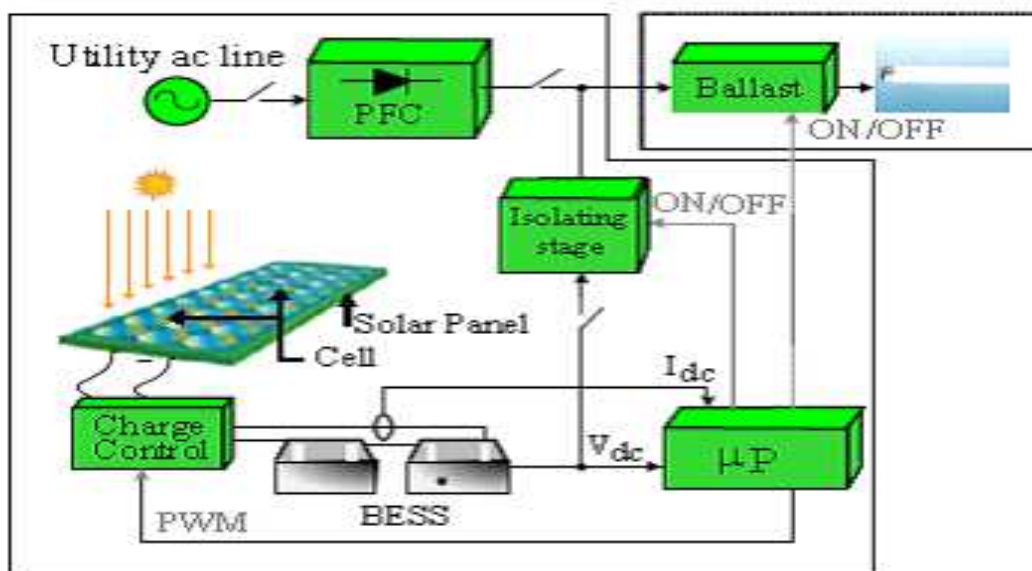


Fig. 4. Simplified block diagram of electronic ballast driven by using the microprocessor-controlled digital switching technique

OPERATING PRINCIPLE OF ELECTRONIC BALLAST WITH CLASS-E RESONANT INVERTER

Unlike traditional ballast (Fig.1), this electronic ballast, which is driven by dc voltage, does not require an inverter stage with a large and heavy transformer with a filter circuit. Figure 5 schematically shows the circuit in the proposed single-switch electronic ballast for solar energy applications. The input terminal has a choke inductor L_E , which is generally large for the small ripple at the input dc current. The electronic ballast uses a class-E ZVS load resonant inverter to drive the fluorescent lamp. The diode D provides a path for the resonant current of the class-E ZVS resonant inverter. Metal-oxide- semiconductor field-effect transistors (MOSFETs) are preferred

because their body diodes can be used as antiparallel diodes for operation beyond resonance. The fluorescent lamp is connected in parallel with a preheating capacitor C_f , which is in series with an resonant inductor L_s and a resonant capacitor C_s . The capacitor C_f provides a sufficiently high ignition voltage to the lamp during the initial start-up and then appropriate filament heating at a steady state. A resonant energy tanks, L_s and C_s , which are in series with the lamp network, comprise the load resonant circuit of the class-E ZVS resonant inverter. The load resonant circuit of the class-E resonant inverter is formed by the fluorescent lamp and reactive components L_s , C_s , C_p , and C_f . In this investigation, the dc voltage V_{dc} is obtained from the BESS, which is fed by a PV array.

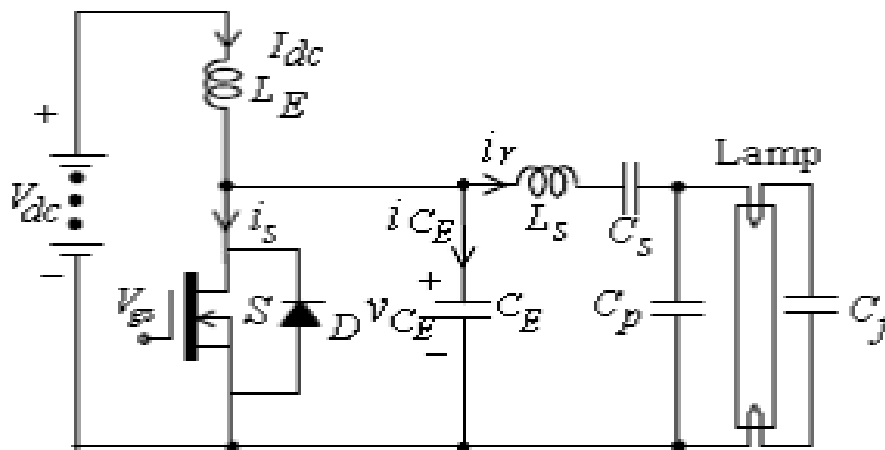


Fig. 5. Electronic ballast powered by a BESS

The electronic ballast with a class-E ZVS resonant inverter has an active power switch S , shunt capacitor C_E , an L_s - C_s - C_p resonant circuit, preheating capacitor C_f and fluorescent lamp. When operated at high

frequency, the fluorescent lamp can be modeled as a resistance R_{lamp} and filament resistance r_f for each cathode. In practice, filament resistances of the fluorescent lamp are typically extremely small; therefore, they

are not analyzed in this work. Then, the combination of C_p , C_f and the lamp (Fig. 5) connected in parallel is converted into a series combination of C_{ss} and R_{eq} (Fig.

5). Equation (1) derives equivalent resistance R_{eq} and Eq. (2) derives equivalent capacitance C_{ss} (Fig.6).

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

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

Inductance L_E is assumed to be sufficiently large, such that the ac ripple on the dc-link current I_{dc} can be neglected.

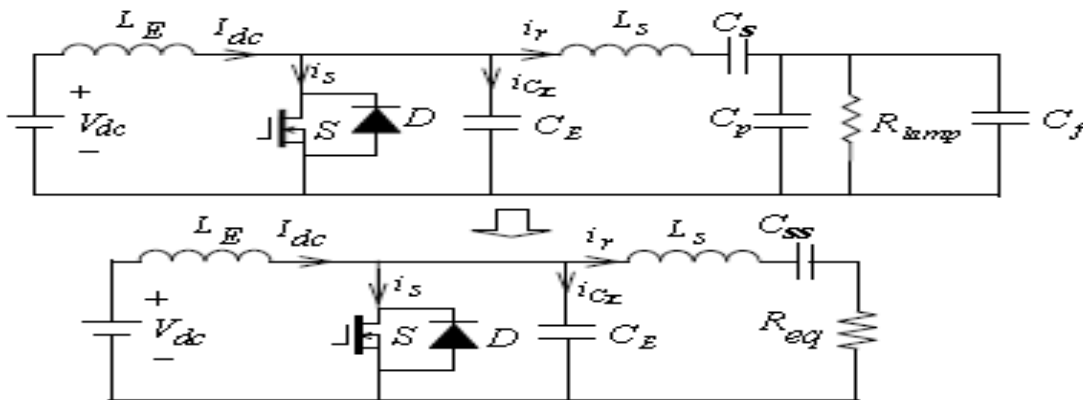


Fig. 6. Derivation of the equivalent circuit for the electronic ballast with the class-E resonant inverter

The PV-powered system is generally equipped with a BESS, which stores energy from a PV array during periods of high irradiation and provides electrical energy to the load during periods of low irradiation and at night. The charger circuit in the BESS is not analyzed. Since a BESS is a voltage source, using a voltage source converter simplifies system configuration. Figure 7 presents simplified schematics of a class-E ZVS resonant inverter. The following assumptions are used to elucidate the operation of a Class-E ZVS resonant inverter:

- All circuit components are ideal.

2) The loaded quality factor of the class-E resonant inverter is sufficiently high, such that load current, i_r , is sinusoidal.

- Inductance of the input inductor L_E is sufficiently high, such that input current is constant during each switching cycle.
- The lamp is an open circuit before ignition, and a resistor in the steady state.

The driving signal V_{gs} first excites the active power switch of the proposed class-E electronic ballast. The duty cycle of the driving signal is d . Circuit operation can be

divided into three modes based on the conducting power switch in a high frequency cycle. Figure 8 displays the theoretical waveforms of the Class-E ZVS resonant inverter.

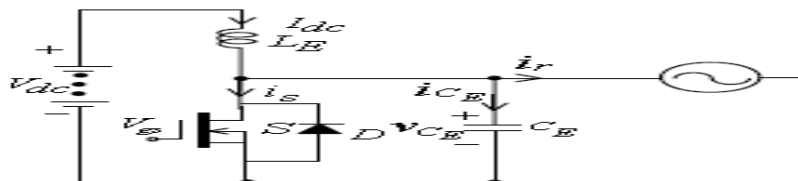


Fig. 7. Simplified equivalent circuit of the electronic ballast with the class-E ZVS resonant inverter

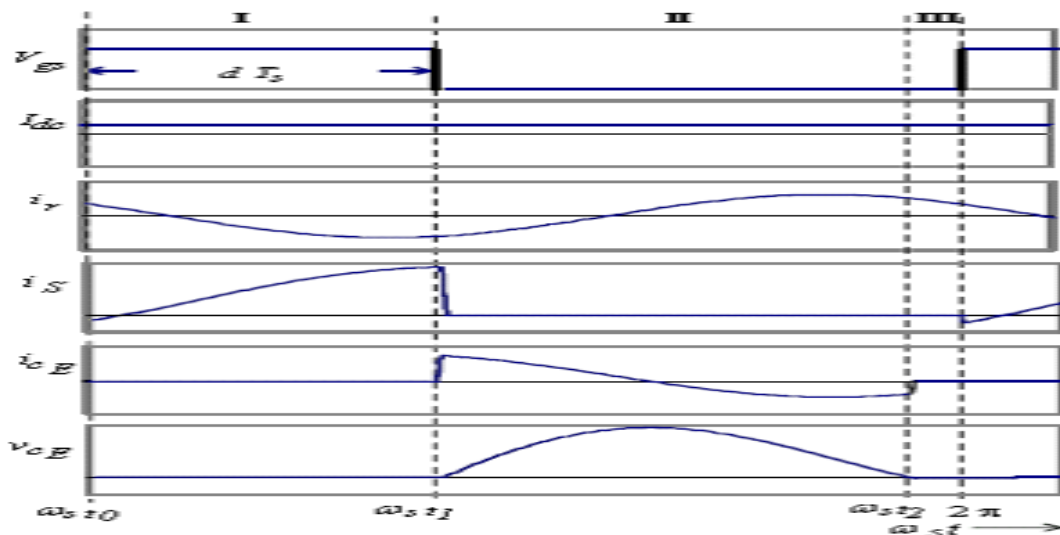


Fig. 8. Theoretical waveforms of the Class-E ZVS resonant inverter

SINGLE-STAGE HIGH-POWER-FACTOR ELECTRONIC BALLAST FOR FLUORESCENT LAMPS

Conventionally, when high-frequency electronic ballasts consume ac power from a utility, a diode-bridge rectifier with a bulk electrolytic capacitor is often utilized to convert ac voltage into smoothed dc-link voltage for high-frequency electronic ballasts. Such a rectifier circuit inevitably draws an input current with narrow pulses, which is notorious for having a very poor

power factor and serious harmonic distortion. The power factor (PF) is typically ≤ 0.6 and total harmonic distortion (THD) can exceed 100%. The widespread use of high-frequency electronic ballasts for fluorescent lamps is a significant source of power pollution. However, a high power factor, including reductions in the rms line current and line current harmonic distortion, can cause a utility to increase its efficiency and reduce pollution. Therefore, high-frequency electronic ballast requires a filter circuit.

The most common solution for reducing input current harmonic distortion and improving the power factor of the utility ac source is to add a second power processing stage, called the PFC stage. Such stages normally employ a discontinuous current dc-to-dc converter to make the line current follow the sinusoidal line voltage waveform. However, this two-stage approach increases cost, and reduces reliability and efficiency as power is processed twice. This problem can be solved by integrating the PFC circuit into the load resonant inverter stage. As a result of sharing the active power switch and control circuit, component count can be reduced. However, based on operation of the load resonant inverter stage, the active power switch must be switched at the desired frequency with the specified duty cycle. Under this constraint, the PFC circuit with a buck-boost topology is preferable as the high power factor for the PFC with a boost topology uses an excessively high dc-link voltage.

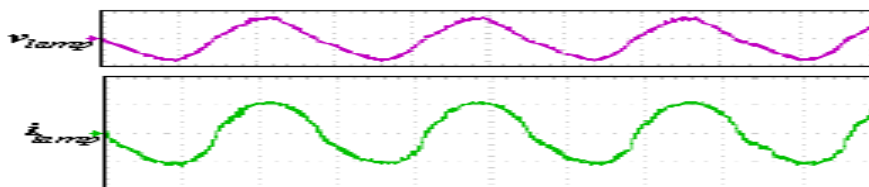
EXPERIMENT RESULTS

The proposed system (Fig.3) connects two different sources and two power relays. A

programmable intelligent computer (PIC) microprocessor senses and controls the operation of peripheral interface devices such as the terminal voltage of the BESS, relay operational status, pulse-width-modulated (PWM) signal generation, and duty cycle control. Further more, the computer microprocessor controls energy management, including battery charging/discharging. The entire control system (Fig. 3) optimizes the energy performance of the hybrid system based on system state information, the BESS and the utility ac line. If the BESS operates at an output power condition (when providing energy to the electronic ballast, the terminal voltage of the BESS gradually declines), the microprocessor system only supervises the BESS policy of the hybrid source system. Once the terminal voltage of the BESS drops to the preset value, the utility ac line source supplies power to the single-stage high-power-factor electronic ballast. The microprocessor-controlled system controls energy management of the BESS energy system and output power of the utility ac line source system.

Table 1 Circuit parameters

DC-link Capacitor C_d	200 μ F
Inductor L_p	0.68mH
Inductor L_E	10mH
Inductor L_s	1.97mH
Capacitor C_E	9.35nF
Capacitor C_s	32.8nF
Capacitor C_p	6.5nF
Capacitor C_f	12nF



v_{lamp} : 100V/div, i_{lamp} : 0.5A/div, Time: 10 μ s/div

Fig. 13. The measured waveforms of lamp voltage and lamp current

CONCLUSIONS

This work presents novel electronic ballast with a simple structure, small volume, light weight, and low energy transfer losses. The electronic ballast circuit utilizes only a single active power switch and, unlike the traditional electronic ballast driven by a PV-powered BESS, does not require any output transformer. No power loss occurs between the BESS and electronic ballast without an additional power processing stage. Moreover, since commutations in the active power switch of the resonant inverter are achieved at zero voltage, electronic ballast switching losses are very low, resulting in extremely high efficiency. Consequently, ballast efficiency can be as high as 94.21%. A prototype of the proposed ballast for a 27W fluorescent lamp was implemented. As expected, a lamp current waveform with a low crest factor is obtained. The proposed topology is a viable solution for implementing low-cost high-efficiency electronic ballasts for PV-powered BESS applications.

Further more, when the voltage of the BESS declines to the preset discharge point, the microprocessor-controlled relays will automatically switch to the utility ac line that continuously supplies power for the electronic ballast. Under this operating condition, the single-stage structure is obtained by integrating a buck-boost converter for PFC and a class-E resonant inverter for the electronic ballast. Only one active power switch is commonly used by both power stages to reduce the cost of active switches and control circuits. When the active power switch is softly switched at zero voltage and DCM, switching losses can be eliminated completely leading to high efficiency. Moreover, power losses are also be reduced by using few circuit components.

Consequently, ballast efficiency is as high as 92.1%. Theoretical analysis and experimental results prove that a near-unity power factor and very low THD can be achieved. The proposed electronic ballast with microprocessor controlled digital switching is a good solution for hybridsource applications.

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