A Single-Switch Soft-Switching Electronic Ballast With High Input Power Factor

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Abstract - Design and analysis of a new single-switch soft-switching class E electronic ballast with high input power factor is presented. Design equations for the optimum operating condition are derived and complete computer analysis is performed. It is shown that low duty cycle control of the class E ballast can reduce the voltage stress of the controlled switch. A 40-W fluorescent lamp ballast is implemented and the experimental recordings verify the analytical results.

I. INTRODUCTION

High-frequency electronic ballasts have attracted much attention in recent years. Electronic ballasting for fluorescent lamps greatly improves efficacy, efficiency and compactness. Moreover with the goal of alleviating problems of noises, line-voltage distortion, and enforcement of new harmonic regulations on the utility line, there is a growing need for electronic ballasts with high input power factor. For this purpose, an input current shaper, power factor corrector (PFC), can be used in the input stage in place of the usual diode rectifier followed by a bulk capacitor. This solution, however, may result in unacceptable cost for ballast applications.

Single switch high input power factor electronic ballasts have been proposed [1,2] to improve efficiency, reliability, size, and weight. The input current shaper and the output high-frequency inverter are combined into one stage. Only one active switch is used. Yet, the single-switch ballast presented by Licitra, etc. [1] would dim when the input sinusoidal voltage crosses zero. Flickering of twice line frequency might appear. Deng and Cuk presented a family of class-E ballasts [2]. Simple structure and high performance are achieved. However with fixed 50% duty cycle control, the maximum voltage stress on the controlled semiconductor switch is 3.56 times the peak AC input voltage [3,4]. This peak stress would reach 604/1108V for 120/220V AC input.

In this paper, a new single-switch soft-switching electronic ballast with high input power factor is presented. Low duty cycle control is proposed for this class E ballast to reduce the maximum switch voltage stress. Design equations for the optimum operating condition to facilitate soft switching are derived and complete computer analysis is performed.

II. CIRCUIT DESCRIPTION

The proposed circuit topology is shown in Fig. 1. The basic functions of the sub-circuits are:

- BD1** :bridge rectifier, converting line-frequency AC power into DC;
- L_f - C_f** :EMI filter, filtering high-frequency noises;
- L_1 - D_1** :current shaper, shaping the input current wave form;
- S_1** :controlled active switch, controlling charging/discharging of L_1 ;
- C_1 - D_2** :soft switching components, facilitating soft switching of S_1 ;
- C_2** :energy storage capacitor, reducing output ripples;
- T_x** :transformer, isolating the lamp load from the source;
- L_r - C_r** :resonant tank, the correct load angle [5] for soft switching must under proper design of L_r and C_r ;
- C_s** :start-up capacitor, preheating the lamp filament and starting up the lamp;
- R_{lamp}** :equivalent resistor of the lamp.

III. ANALYSIS

1) *Equivalent circuit*: For convenience, the ballast can be studied as the equivalent circuits shown in Fig. 2(a). V_{DC} represents the rectified and filtered DC voltage before

Fig. 1. The circuit diagram of a class E electronic ballast

Fig. 2 The equivalent circuit of the ballast.

L_1 , L_m is the magnetizing inductance of Tx. Since the voltage source V_{DC} is shorted at high frequency analysis. To simplify analysis, we can make a dummy inductor L_1' which is equivalent to L_1 paralleling L_m in the high frequency circuit model. R represents the equivalent lamp resistance R_{lamp} . The bulk capacitor C_2 does not affect the high frequency operation, so it is shorted in the simplified equivalent circuit, Fig. 2(b). It is exactly a class E inverter. Before the analysis, the basic conditions must be mentioned:

1. Assume the main switch and all other components of the circuit are all ideal without any loss, so the efficiency of the converter is 100%.
2. The load quality factor of the resonant tank must be high enough to generate a pure sinusoidal output current [6-8].
3. The damping ratio of the circuit is small enough so that the damping of the switching wave forms can be neglected.
4. The inductor L_1' need not be infinity to act as a constant current source. The inverter can be operated with a finite dc-feed inductor [9,10].

2) *Circuit Operation*: There are two stages of operations in the class E simplified equivalent circuit :

Stage 1.) S_1 is turned off, L_1' discharged: The equivalent circuit of this stage is depicted in Fig. 3(a). The supply current I_{DC} and the output current I_o pass

(a) stage 1 - S_1 off

(b) stage 2 - S_1 on

Fig. 3 Equivalent circuits representing circuit operations

Fig. 4 The waveforms of the class E inverter.

through C_1 . The voltage across C_1 , V_{C1} , forms a tilted sine wave as shown in Fig. 4.

Stage 2.) S_1 on, L_1' charged: The equivalent circuit of this stage is depicted in Fig. 3(b). In this stage the supply current I_{DC} and the output current I_o pass through S_1 . The current across S_1 form a tilted sine wave as shown in Fig. 4.

3) *Circuit analysis*: Two differential equations can be used to describe the wave form of V_{C1} and $i_{L1'}$ in stage 1:

$$\begin{cases} V_{C1} = V_{DC} - L_1' \frac{di_{L1'}}{dt} \\ C_1 \frac{dV_{C1}}{dt} = i_{L1'} - I_o \sin(\omega t + \phi) \end{cases} \quad (1)$$

With the boundary conditions for V_{C1} :

$$V_{C1}|_{t=0} = 0, \quad V_{C1}|_{t=t_{on}} = 0, \quad \frac{dV_{C1}}{dt}|_{t=t_{on}} = 0 \quad (2)$$

Where $\omega = 2\pi f_s$ and f_s is the switching frequency. ϕ is the legged load angle when the output current passes through the resonant network L_r - C_r - R . $t_{on} = (1-D)T$, T and D are

the switching period and duty cycle, respectively. The V_{C1} wave form can then be solved as:

$$V_{C1}(t) = k_1 \sin(\omega_1 t) + k_1 \cos(\omega_1 t) + \frac{\omega}{C_1(\omega^2 - \omega_1^2)} I_o \cos(\omega t + \varphi) + V_{DC} \quad (3)$$

The load angle φ can be found numerically from (4) when the duty cycle is not 50%:

$$(1-D) \sin(\omega t_{on} + \varphi) + \frac{1}{2\pi} [\cos(\omega t_{on} + \varphi) - \cos \varphi] = 0 \quad (4)$$

The output current I_o can be calculated by solving:

$$I_o \sin(\omega t_{on} + \varphi) - (I_{DC} - \frac{D^2 TV_{DC}}{2L_1'}) = 0, \quad I_o \geq 0 \quad (5)$$

The output lamp resistor R can be determined from the assumption of input/output power equality, as a first-cut estimate.

$$P = V_{DC} * I_{DC} = \frac{V_o I_o}{2} = \frac{R I_o^2}{2} \quad (6)$$

C_1 can be found by observing no DC voltage across L_1'

$$\frac{1}{T} \int_0^{t_{on}} V_{C1} dt = V_{DC} \quad (7)$$

Once the circuit parameter has been determined, the voltage stress of S_1 can be found by solving the instant when the maximum V_{C1} occurs.

$$\left. \frac{dV_{C1}}{dt} \right|_{t=t_{V_{max}}} = 0, \quad 0 < t_{V_{max}} < t_{on} \quad (8)$$

Then the peak voltage stress is derived:

$$V_{S1_{max}} = V_{C1}|_{t=t_{V_{max}}} \quad (9)$$

In the second stage, the current passes through $S1$ can be mathematically expressed as:

$$i_{S1} = i_{L1'} - i_o = I_{L1'}(t_{on}) + \frac{V_{DC}}{L_1'}(t - t_{on}) - I_o \sin(\omega t + \varphi) \quad (10)$$

The instant when the maximum switch current occurs is obtained by solving:

$$\left. \frac{di_{S1}}{dt} \right|_{t=t_{i_{max}}} = 0, \quad t_{on} < t_{i_{max}} < T \quad (11)$$

or the maximum current occur at $t=t_{on}$ when (11) has no solution. Thus the maximum current is:

$$I_{S1_{max}} = i_{S1}|_{t=t_{i_{max}}} \quad (12)$$

Fig. 5 shows an electronic ballast design for 110VAC input. The switch stresses versus duty cycle D from 0.5 to 0.2 when L_1' is infinite and 0.9mH, respectively. We can see that the low duty cycle operation of the circuit can reduce the voltage stress and increase the current stress. In low power electronic ballasts design, there is a slight voltage safety margin but a large current safety margin for the switch. For example, the voltage and current rating of IRF740 is 400V/5.5A. If the output power is 40W, usually the peak current of the switch is 1A, much lower than 5.5A. Thus in class E ballasts we can transfer the voltage stress to the current stress by low duty cycle operation.

IV. POWER FACTOR CORRECTION

For single-stage electronic ballasts, a front-ended discontinuous inductor current mode (DICM) power factor correction is needed. The discontinuous inductor can be considered as L_1 in the class E electronic ballast in Fig. 1. The inductor L_1 has a critical value when operating at the boundary of continuous and discontinuous mode:

$$L_{Cr} = \frac{DTV_{S_m}}{2I_{S_m}}, \quad L_1 < L_{Cr} \quad (13)$$

The voltage conversion ratio:

$$M = \frac{V_{boost}}{V_{S_m}} \quad (14)$$

where V_{sm} is the maximum value of input AC voltage. V_{boost} is the boost power factor corrector output DC voltage. In this circuit V_{boost} is the DC component of V_{C1} in stage 1.

$$V_{boost} = \frac{1}{t_{on}} \int_0^{t_{on}} V_{C1} dt = \frac{1}{1-D} V_{DC} \quad (15)$$

then

$$V_{DC} = M(1-D) V_{S_m} \quad (16)$$

Fig. 5 The voltage and current waveforms of S1 versus D.

In Fig. 1 C_2 blocks the DC component of V_{C1} , so

$$V_{C2} = \frac{1}{T} \int_0^T V_{C1} dt = V_{DC} = M(1-D)V_{Sm} \quad (17)$$

C_2 must be large enough to hold up the power while input power decrease. The minimum value of V_{C1} can be determined by:

$$C_2 = \frac{P}{\omega_L V_{C2} \Delta V} \quad (18)$$

where ΔV is the peak to peak ripple of V_{C2} and ω_L is the AC source angular frequency. Fig. 6 and Fig. 7 shows the ballast output current with large C_2 and small C_2 , respectively. Obviously, a large C_2 can avoid the twice line-frequency flickers which cause the low quality lighting and shorten lifetime of the lamps.

At the discontinuous operation, neglecting the high order terms, the approximate average input current can be expressed as:

$$i_{SL} = I_{Sm} \sin(\omega_L t) \frac{MD}{M - |\sin(\omega_L t)|} \quad (19)$$

where I_{Sm} is the maximum value of input current I_s . The plot of average input current versus duty cycle is shown in Fig. 8. The power factor varies with duty cycle is given in

Fig. 6 The output current with large C_2 .

Fig. 7 Line-frequency flickers caused by small C_2

Fig. 9. The low duty cycle slightly deteriorates the power factor, but still higher than 0.95.

V. EXPERIMENTAL RESULTS

A 40W fluorescent lamp ballast adopting the proposed circuit is developed. Circuit parameters of the experimental ballast are:

$$\begin{aligned} L_1 &= 0.9\text{mH}, & C_1 &= 14.7\text{nF}, \\ L_m &= 2\text{mH}, & L_r &= 4\text{mH}, \\ C_r &= 100\text{nF}, & R_{\text{lamp}} &= 250\Omega, \\ C_s &= 3.3\text{nF}, & C_2 &= 68\mu\text{F}, \\ T_x \text{ turn ratio} &= 1:1.25, & V_s &= 110\text{VAC}, \\ S_1 &: \text{IRF830}, & f_s &= 50\text{kHz}, \\ D &= 0.3. \end{aligned}$$

The recorded voltage and current wave forms of S_1 are shown in Fig. 10(a). The discontinuous current wave form of inductor L_1 is shown in Fig. 10(b). The input and output voltage/current wave forms of the ballast are shown in Fig. 10(c) and 10(d), respectively. The maximum voltage stress for S_1 is about 400V. The measured input power factor is 0.97.

Fig. 8. The input current versus D

Fig. 9. The power factor versus D

VI. CONCLUSIONS

A single-stage single-switch high-power-factor electronic ballast is presented. It has no line flickers by adding the energy storage element. The major problem of class E type ballasts is the high voltage stress. The problem can be relieved by the low duty cycle operation of the switch. While the duty cycle is not 0.5, Circuit parameters are difficult to be determined due to nonlinearity of the circuit operations. This paper proposes the design equations and rules to determine the circuit parameters.

VII. REFERENCES

- [1] C. Licitra, L. Malesami, G. Spiazzi, P. Tenti, and A. Testa, "Single-Ended Soft-switching Electronic Ballast with Unity Power Factor", IEEE Transactions on Industry Applications, Vol. 29, NO. 2, pp. 382-388, March/April 1993.
- [2] E. Deng and S. Cuk, "Single Switch, Unity Power Factor, Lamp Ballasts", IEEE Applied Power Electronics Conference 1995, pp. 670-676.
- [3] G. Lutteke and H. C. Raets, "High Voltage High Frequency Class E Converter Suitable for Miniaturization", IEEE Transaction on Power Electronics, Vol. PE-1, No. 4, pp. 193-199, October 1986.
- [4] G. Lutteke and H. C. Raets, "220-V Mains 500-kHz Class E Converter Using a BiMos", IEEE Transaction on Power Electronics, Vol. PE-2, No. 3, pp. 186-193, July 1987.
- [5] N. O. Sokal, A. D. Sokal, "Class E-A New Class of High-Efficiency Tuned Single-ended Switching Power Amplifiers", IEEE Journal of Solid-State Circuits, Vol. SC-10, NO. 3, pp. 168-176, June 1975.
- [6] F. H. Raab, "Ideal Operation of the Class E Tuned Power Amplifier", IEEE Transactions on Circuits and Systems, Vol. CAS-24, No. 12, pp. 725-735, December 1977.
- [7] F. H. Raab, "Effects of Circuit Variations on the Class E Tuned Power Amplifier", IEEE Journal of Solid-State Circuits, Vol. SC-13, NO. 2, pp. 239-247, April 1978.
- [8] M. K. Kazimierczuk and K. Puczek, "Exact Analysis of Class E Tuned Power Amplifier at any Q and Switch Duty Cycle", IEEE Transaction on Circuits and System, Vol. CAS-34, No. 2, pp. 149-159, February 1987.
- [9] R. Zulinsky and J. W. Steadman, "Class E Power Amplifiers and Frequency Multipliers with Finite DC-Feed Inductance", IEEE Transaction on Circuits and Systems, Vol. CAS-34, No. 9, pp. 1074-1087, September 1987.
- [10] R. Zulinsky, "A High-Efficiency Self-Regulated Class E Power Inverter/ Converter", IEEE Transaction on Industrial Electronics, Vol. IE-33, No. 3, pp. 340-342, August 1986.

Fig.10(a) The voltage and current waveform of S1.

Fig. 10(b) The discontinuous current of L1.

Fig. 10(c) The input voltage and current of the ballast.

Fig. 10(d) The output voltage and current of the ballast.