Solution to Some Key Problems of Self-exciting Electronic Ballast

Peng Mao and Weiping Zhang
School of Information and Electronics, Beijing Institute of Technology and School of Information Engineering, North China University of Technology, Beijing 100144, China

Mao Zhang
School of Information and Electronics, Beijing Institute of Technology, Beijing 100081, China

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Self-exciting electronic ballast, of small size, and low cost, and high power, with no stroboscopic effect, no noise, is widely used in the general lighting market. This paper describes the cause of high switching loss of self-exciting electronic ballast, based on its operational principle; then, to reduce the switch temperature and increase the reliability of the product, the drive circuit has been improved, to achieve soft-switching. The theory analysis, simulation and experimental result prove the feasibility and compatibility of this new method in practice. Finally, the design procedure and winding method of the self-exciting current transformer are introduced.

**Keywords:** Self-exciting electronic ballast, Operation principle, Soft switching, Self-exciting current transformer

1. INTRODUCTION

Ballast is a device intended to limit the amount of current in an electric circuit. A familiar and widely used example is the inductive ballast used in fluorescent lamps, to limit the current through the tube, which would otherwise rise to destructive levels, due to the fluorescent tube’s negative resistance characteristic. Generally speaking, ballast can be categorized into two major types: electromagnetic ballast and electronic ballast. Compared with electromagnetic ballast, electronic ballast has some advantages, such as higher luminous efficacy, lighter weight, and the elimination of flicker and audible noise.

Electronic ballast usually supplies power to the lamp at a frequency of 20 kHz or higher, rather than the mains frequency of 50–60 Hz [1]; this substantially eliminates the stroboscopic effect of flicker, a product of the line frequency associated with fluorescent lighting. The high output frequency of the electrical ballast refreshes the phosphors in a fluorescent lamp so rapidly that there is no perceptible flicker. With the higher efficiency of the ballast itself, and the higher lamp efficacy at higher frequency, electronic ballast offers higher system efficacy for low pressure lamp, like the fluorescent lamp.

Electronic ballast is often based on switch mode power supply (SMPS) topology, such as (m1) the ringing choke converter (RCC), push-pull inverter, half-bridge inverter and full-bridge inverter, which first rectify the input power, and then chop it at a high frequency. The gate–drive methods used for electronic ballast can be further categorized into two major types: self-exciting and IC-controlled versions. The self-exciting converters have a long history of more than 45 years, and find many applications in power supplies, such as dc-to-dc converters, and electronic ballast. The major advantages of self-exciting converters are circuit simplicity and robust operation. In electronic ballast application, the self-exciting inverter is regarded as one of the simplest and most cost-effective topologies. Disadvantageously, however, the operating frequency of the self-exciting circuit is, by the nature of its operation, load dependent; and thus is very difficult to control, and the driver waveform is affected by the power switch and self-exciting current transformer, causing high switching loss and
high temperature, leading to the increase of heat dissipation area, and reduction of product reliability [1,2].

In this paper, a novel drive circuit of the self-exciting electronic ballast is proposed. The circuit employs BJT as a power switch, and a linear core for the current transformer. Firstly, the operation principle of the BJT-based typical self-exciting electronic ballast is analyzed, and the cause of high switching loss was found; meanwhile, experiment and simulation results are presented to validate the analysis. Then, the novel self-exciting electronic ballast is proposed. All switches in the novel circuit are soft switching, which is verified by the experimental and simulation results. Finally, based on the operational principle of novel self-excitation electronic ballast, how to choose and wind the magnet ring, and the design procedure, were provided in this paper.

2. TYPICAL SELF-EXCITING ELECTRONIC BALLAST

2.1 Operation principle

Figure 1 shows a typical circuit of BJT-based self-exciting electronic ballast. D₁, D₂, Q₁, Q₂, C₁, and C₂ make up a half-bridge topology. Two BJTs form a half-bridge inverter stage, to output a square voltage wave. The self-exciting drive circuitry is composed of a current-transformer, T₁, with three windings (N₁p, N₁s, and N₂s), and gate resistors R₁ and R₂. The resonant inductor current is fed back through the T₁, and converted into a complementary voltage, to drive the two BJTs Q₁ and Q₂. The T₁ is in series with the inductor L₁. The polarities of the T₁ are chosen in such a way that inductor current, flowing through the primary side of T₁, will generate complementary gate drive voltages to the BJTs Q₁ and Q₂, causing the circuit to oscillate. An inductive appearance of the tank is naturally obtained by this configuration, so that zero-voltage switching (ZVS) is achieved for both BJTs. The inductor L₁ limits the output current, and its coupling coil L₂, D₃ and D₄ are employed, to reject the unbalancing problem of neutral-point voltage, due to the inconsistency of capacitors C₁ and C₂ in the half-bridge circuit [3-5].

The key waveforms concerned are shown in Fig. 2, and the trajectory of the current-transformer T₁ is shown in Fig. 3. The operational principle of the circuit is as follows:

1) Stage [a, b]: In this stage, the current injecting collector of Q₂ becomes lower; meanwhile, C₁ begins to discharge, and the junction capacitance CQ₂ce of Q₂ to be charged. At the end of this stage, as a result of the current injecting collector of Q₂ quick declining, and the larger value of C₁ and CQ₂ce in parallel, the voltage across C₁ is almost unchanged. It is assumed that the current of the inductor L₁ remains unchanged, because of small time-interval. The voltage of UQ₁b-e and UQ₂b-e are almost zero, since the current-transformer T₁ is in deep saturation state, so the currents flowing from the windings N₁s and N₂s are close to zero. According to Ampere law,

\[ N₁p\frac{di}{dt} = Hl \]

(2.1)

where, H and l are the magnetic field intensity, and the circumference of magnet ring T₁, respectively. As a result, the absolute value of the magnetic field intensity reduces, and the corresponding operating point of magnet ring T₁ moves from a to b.

2) Stage [b, c]: In this stage, C₁ discharges, and the CQ₂ce is charged by the current of inductor L₁. At the end of this stage,
the voltage across $C_1$ is almost zero, and the voltage across $C_{Q2ce}$ is equal to $U_{in}$. During this time-interval, magnet ring $T_1$ is still saturated, but begins to withdraw from deep saturation, and the absolute value of the magnetic field intensity continues to reduce, just like stage [a, b]. Hence, the corresponding operating point of the magnet ring $T_1$ moves from b to c.

3) Stage [c, d]: At $t=c$, the inductor $L_1$ remains discharged, and the current reduces to zero at the end. If assuming that $D_1$ starts to conduct, $U_{Q1b-e}$ is about 1.2 V. However, the magnet ring $T_1$ is still saturated, $U_{Q2be}$ is almost zero, and the on-state voltage drop of p-n junction of $Q_1$ is only 0.7 V. Obviously, the diode $D_1$ is clamped, but the p-n junction provides a free-wheeling path, instead. During this time-interval, according to Ampere’s law, it is obtained that

$$N_{d}l_{b1} + N_{a}l_{abs} = Hl_1$$

Therefore, the absolute value of magnetic field intensity increases suddenly at the time of point c; then, with the current reduction of $L_1$, the absolute value of the magnetic field intensity gradually decreases. According to Faraday’s law,

$$U_{Qbe} = -N_{a} \frac{d\Phi}{dt}$$

$U_{Qbe}$ is negative at the time of point c, and $U_{Qbe}$ is positive at the end, but $U_{Qbe}$ is opposite to $U_{Qbe}$ which causes the sudden conduction of $Q_1$. It is probable that the reverse recovery surge current flows through $Q_1$ in several microseconds in this time-interval; meanwhile, $Q_1$ withstands the high dv/dt voltage [6] Therefore, it causes high switching loss of BJT.

4) Stage [d, e]: At $t=d$, $Q_1$ starts to conduct. The magnet ring $T_1$ withdraws from deep saturation quickly, and operates in the linear area, due to the positive feedback effect. During this time-interval, $U_{Q1b-e}$ is about 0.6 V, $U_{Q1be}$ divided by $R_{b1}$ equals $i_{Rb1}$, and $i_{Rb1}$ is about zero, and so is $i_{Rb2}$. According to Ampere’s law, it is obtained that

$$N_{p}l_{y1} - N_{d}l_{abs} = Hl_1 = 0$$

$$i_{abs}/i_{y2} = N_{p}/N_{a} = 1/(h_{ef} + 1)$$

where, $h_{ef}$ is the current gain of the transistor.

Meanwhile,

$$U_{Qbe} = N_{a}d\Phi/dt > 0$$

it is indicated that the magnetic flux increase linearly, until point e.

5) Stage [e, f]: In this stage, the magnet ring $T_1$ becomes saturated, so that $U_{Qbe}$ is about zero. Nevertheless, $Q_1$ is still in the conduction state, because of the charge storage effect. At the time of point f, $Q_1$ is off.

2.2 Simulation and experiment results

Take a fluorescent lamp GE F40/T12 for example. The output current is about 1.2 A, the output voltage is about 70 V, and the self-exciting frequency is about 22 kHz, applying the rated voltage of 220 Vac. The circuit parameters are:

- DC link voltage $U_{in}=300$ V;
- Tank components: $L_1=1$ mH, $C_3=C_4=100$ uF;
- $T_1$ (TDK PC40 E116 Core): $N_{p}=3$ T, $N_{s}=N_{e}=4$ T;
- Power transistor $Q_1$ and $Q_2$: BJT48A;
- Rated lamp power: 75 W;

Switching waveforms are as shown in Fig. 4 using OrCAD10.5 software, and the experimental results are shown in Fig. 5 and Fig. 6, respectively.

It is proved true that the p-n junction of the transistor provides a free-wheeling path, and the transistor is suddenly turned on,
causing high switching losses of the transistor.

3. NOVEL SELF-EXCITING ELECTRONIC BALLAST

3.1 Operation principle

Based on the above analysis and results, high switching loss and high temperature cause the increase of heat dissipation area and reduction of product reliability, owing to the coupling of gate-drive signals of upper and lower bridge arm, produced by the self-exciting transformer. To solve the above key problems, a novel circuit of electronic ballast is proposed in this paper.

Figure 7 shows the circuit of novel self-exciting electronic ballast, and the key waveforms concerned are shown in Fig. 8, and the trajectory of the current-transformer T1 is almost the same as Fig. 3. The operational principle of the circuit is as follows:

The operational principle of the novel ballast in stage [a, b] and [b, c] are the same as typical self-exciting electronic ballast.

1) Stage [c, d]: Compared with the typical self-exciting electronic ballast, thanks to series resistance $R_{b1}$, both the diode $D_1$ and p-n junction of $Q_1$ provide a free-wheeling path in this stage. It can be seen that

\[
\begin{align*}
-I_{PS1} &= I_{PS1} + I_{PS1} \\
\frac{U_{PS1} - U_{PS1} - U_{PS1}}{R_{b1}} &= \frac{U_{PS1} - U_{PS1} + U_{PS1}}{R_{M}} \\
I_{PS1} &= -I_{PS1} 
\end{align*}
\]  

(3.1)

At $t=c$, $D_1$ is turned on, $U_{PS1}$ is about 1.2 V, and magnet ring $T_1$ is still saturated. According to Ampere’s law and Faraday’s law, the same conclusions can be obtained that $U_{PS1}$ is negative at the time of point c, $U_{PS1}$ is positive at the end, and the current $I_{PS1}$ increases. Owing to the placement of series resistance $R_{b1}$, the base current of $Q_2$ is relatively small, and $Q_2$ is kept off. In addition, thanks to the introduction of the two Schottky barrier diodes $D_5$ and $D_6$, as shown in Fig. 7, low impedance passes are provided for the flow of reverse base current, when the transistor is off [3]. It loosens the coupling between the gate-drive of each transistor, and makes the self-exciting magnet ring not very deeply saturated, resulting in easy commutation at the knee point of magnet ring [6].

2) Stage [d, e]: At $t=d$, $Q_1$ starts to conduct. The magnet ring $T_1$ withdraws from deep saturation quickly, and operates in the linear area, due to the positive feedback effect. During this time-interval,

\[
\begin{align*}
N_{PS1}I_{I1} - N_{PS1}I_{I1} - N_{PS1}I_{I1} = HIL &= 0 \\
N_{PS1}I_{I1} &= N_{I}\left(I_{PS1} + I_{PS1}\right) 
\end{align*}
\]  

(3.2)

Assuming that $I_{PS1}$ and $I_{PS1}$ satisfy the following equation,

\[
I_{PS1} / I_{PS1} = 1/2 
\]  

(3.3)

it is obtained that

\[
N_{PS1} / N_{I} = 3I_{PS1} / I_{PS1} = 3/(h_{fe} + 1) 
\]  

(3.4)

3) Stage [e, f]: During this time-interval, for the sake of saturation of the magnet ring, $U_{PS1}$ is near zero, and the IRB1 current is given by

\[
I_{PS1} = -U_{PS1}/R_{b1} 
\]  

(3.5)

3.2 Simulation and experiment results

The simulation of switching waveforms of novel self-exciting electronic ballast are as shown in Fig. 9, and the experimental results are shown in Fig. 10 and Fig. 11, respectively.

Compared with Fig. 5, the collector current spike of the tran-
sistor is eliminated, as shown in Fig. 10; meanwhile, all switches in the novel circuit are soft switching, and the losses of the power switches are reduced, as shown in Fig. 11.

It is shown in the experiment that without a heat-sink, the collector temperature of the transistor is just 25°C higher than the ambient temperature, meeting the project requirement.

4. DESIGN PROCEDURE AND WINDING METHOD OF THE SELF-EXCITING TRANSFORMER IN THE NOVEL ELECTRONIC BALLAST

Some assumptions are made, as follows [7-9]:

1) The self-exciting frequency is about 20 kHz.

2) The waveform of the tank current is a pure sine wave, and the rms is I.

3) The waveform of UNs1 is a pure sine wave.

It can be seen that:

\[
\begin{align*}
V_{\text{tot}} &= I_{\text{tot}} [R_s + (1 + h_f) R_e] + V_{\text{sat}} \\
I_{\text{tot}} &= \frac{I}{h_f + 1}
\end{align*}
\]

(4.1)

According to Faraday’s law, the winding turns of secondary coils can be expressed by the following formula [10]:

\[
N_{s2} = \frac{V_{\text{sat}}}{K_f B_{ms} A_e}
\]

(4.2)

where, \(K_f\) is the wave coefficient, and equal to 4.44 as a pure sine-wave, \(u\) is the core material permeability, \(A_e\) is the effective cross-section area, \(B_{ms}\) is the operation magnetic flux density, and \(f_s\) is the self-exciting frequency. Thus, the windings turns of primary coils can be calculated by
The following addresses the method of winding the self-excit- ing transformer, and three winding methods are shown in Fig. 12, Fig. 13, and Fig. 14.

The problem with the single-ring, as shown in Fig. 12, is that the turn-on waveform of one transistor is the exact inverse of the turn-off waveform of the other, so there is no possibility of driving them appropriately and differently and efficiently.

To conquer the limitations of the single-ring drive, the double-ring approach could be used, as shown in Fig. 13. However, if the permeability and dimension of the two rings are not well matched, discrepancies during the crossover result in losses. It is advisable to use a balun-ring core to drive the transistors, as shown in Fig. 14 [11].

In addition, it is sensible not to select high relative permeability (greater than 6000) in the power ferrite material, which has poor performance in permeability under the temperature change [11].

5. CONCLUSIONS

A novel self-exciting electronic ballast is proposed, implemented and tested in this paper, and all power switches in this circuit are soft-switching. Moreover, how to choose and wind the magnet ring and the design procedure are provided in this paper. The proposed circuit is very simple, and ideal for low cost and high reliability self-exciting electronic ballast.

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