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Solution to Some Key Problems of Self-exciting Electronic Ballast

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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

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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. D_1, D_2, Q_1, Q_2, C_3 and C_4 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, T_1, with three windings (N_{p1}, N_{s1}, and N_{s2}), and gate resistors R_{bl} and R_{b2}. The resonant inductor current is fed back through the T_1, and converted into a complementary voltage, to drive the two BJTs, Q_1 and Q_2. The T_1 is in series with the inductor L_1. The polarities of the T_1 are chosen in such a way that inductor current, flowing through the primary side of T_1, will generate complementary gate drive voltages to the BJTs Q_1 and Q_2, 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 L_1 limits the output current, and its coupling coil L_2, D_3 and D_4 are employed, to reject the unbalancing problem of neutral-point voltage, due to the inconsistency of capacitors C_3 and C_4 in the half-bridge circuit [3-5].

The key waveforms concerned are shown in Fig. 2, and the trajectory of the current-transformer T_1 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 Q_2 becomes lower; meanwhile, C_1 begins to discharge, and the junction capacitance C_{Q2ce} of Q_2 to be charged. At the end of this stage, as a result of the current injecting collector of Q_2 quick declining, and the larger value of C_1 and C_{Q2ce} in parallel, the voltage across C_1 is almost unchanged. It is assumed that the current of the inductor L_1 remains unchanged, because of small time-interval. The voltage of $U_{Q1b\text{-}e}$ and $U_{Q2b\text{-}e}$ are almost zero, since the current-transformer T_1 is in deep saturation state, so the currents flowing from the windings N_{s1} and N_{s2} are close to zero. According to Ampere law,

$$N_{p1} \cdot i_{L1} = H \cdot l_c \tag{2.1}$$

where, H and l_c are the magnetic field intensity, and the circumference of magnet ring T_1, respectively. As a result, the absolute value of the magnetic field intensity reduces, and the corresponding operating point of magnet ring T_1 moves from a to b.

2) Stage [b, c]: In this stage, C_1 discharges, and the C_{Q2ce} is charged by the current of inductor L_1. At the end of this stage,

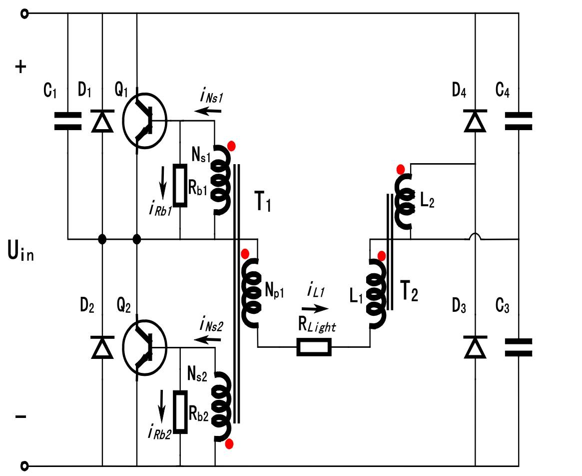

Fig. 1. Schematic diagram of typical self-exciting electronic ballast.

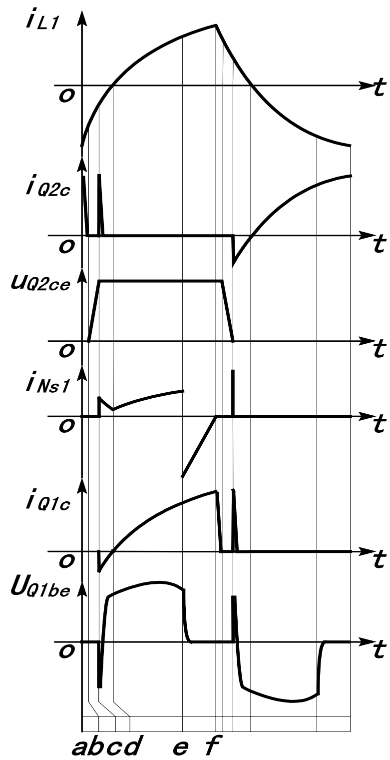

Fig. 2. Key waveforms of typical self-exciting electronic ballast.

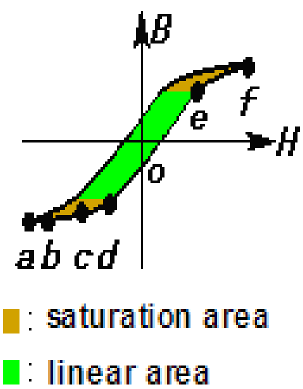

Fig. 3. Trajectory of the current-transformer T_1.

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_{D1on} is about 1.2 V. However, the magnet ring T_1 is still saturated, $U_{Q1b\text{-}e}$ 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

$$N_{p1}i_{L1} + N_{s1}i_{Ns1} = Hl_c \tag{2.2}$$

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,

$$U_{Q1be} = -N_{s1}\frac{d\Phi}{dt} \tag{2.3}$$

U_{Q1be} is negative at the time of point c, and U_{Q1be} is positive at the end, but U_{Q2be} is opposite to U_{Q1be}, which causes the sudden conduction of Q_2. It is probable that the reverse recovery surge current flows through Q_2 in several microseconds in this time-interval; meanwhile, Q_2 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, $U_{Q1b\text{-}e}$ 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

$$N_{p1}i_{L1} - N_{s1}i_{Ns1} \approx Hl_c \approx 0 \tag{2.4}$$

$$i_{Ns1}/i_{L1} = N_{p1}/N_{s1} = 1/(h_{ef}+1) \tag{2.5}$$

where, hef is the current gain of the transistor.

Meanwhile,

$$U_{Q1be} = N_{s1}d\Phi/dt > 0 \tag{2.6}$$

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 $U_{Q1b\text{-}e}$ 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_{p1} =3 T, N_{s1}=N_{s2}=4 T;
Power transistor Q_1 and Q_2: BUV48A;
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,

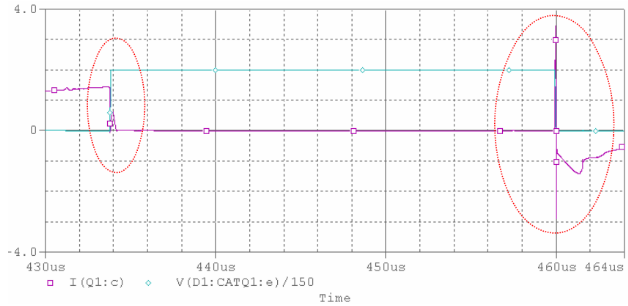

Fig. 4. Voltage and current waveforms of the transistor.

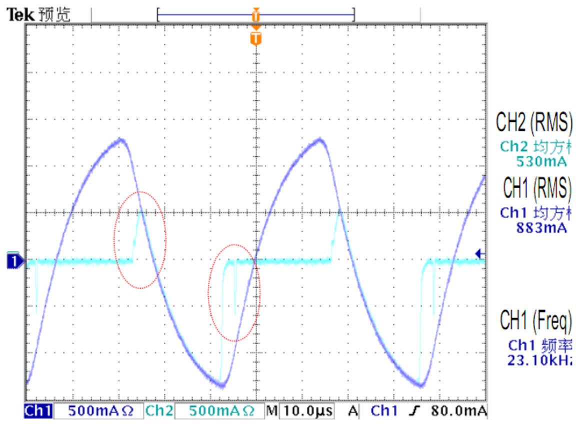

Fig. 5. Current of the transistor and tank current.

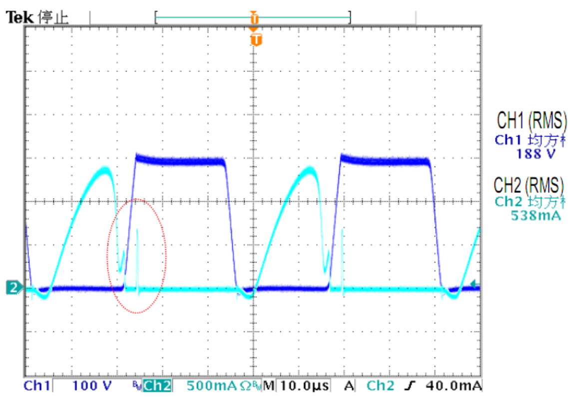

Fig. 6. Voltage and current waveforms of the transistor.

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 T_1 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

$$\begin{cases} -I_{Q1c} = I_{D5} + I_{Rb1} \\ \qquad = \dfrac{U_{D1} - U_{Q1bc} - U_{D5}}{R_{e1}} + \dfrac{U_{D1} - U_{Q1bc} + U_{Ns1}}{R_{b1}} \\ I_{D1} - I_{Q1c} = -I_{L1} \end{cases} \tag{3.1}$$

At t=c, D_1 is turned on, U_{D1} 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_{Ns1} is negative at the time of point c, U_{Ns1} is positive at the end, and the current I_{Rb1} 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,

$$\begin{aligned} &N_{p1} i_{L1} - N_{s1} i_{Rb1} - N_{s2} i_{D6} = H l_c \approx 0 \\ &N_{p1} i_{L1} = N_{s1}(i_{Rb1} + i_{D6}) \end{aligned} \tag{3.2}$$

Assuming that i_{Rb1} and i_{D6} satisfy the following equation,

$$i_{Rb1} / i_{D6} = 1/2 \tag{3.3}$$

it is obtained that

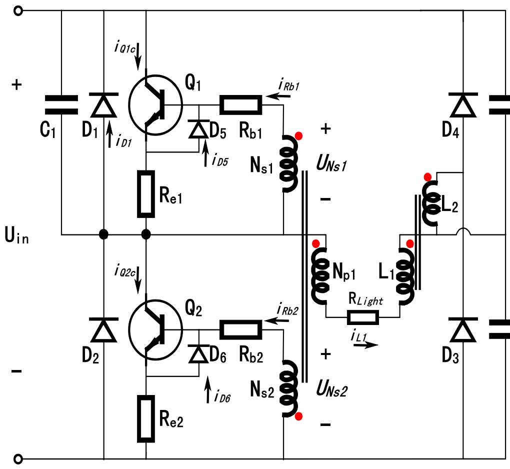

Fig. 7. Schematic diagram of novel self-exciting electronic ballast.

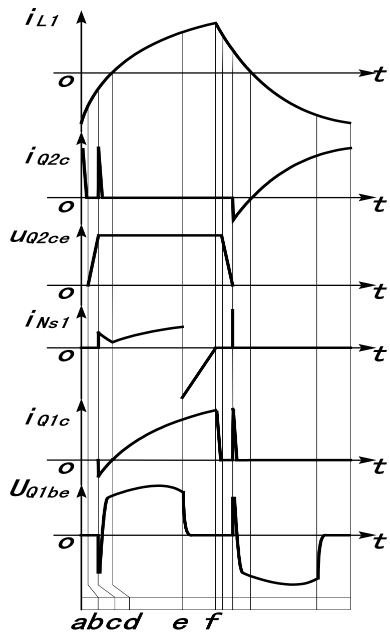

Fig. 8. Key waveforms of the novel self-exciting electronic ballast.

$$N_{p1} / N_{s1} = 3 i_{Rb1} / i_{L1} = 3/(h_{ef} + 1) \tag{3.4}$$

3) Stage [e, f]: During this time-interval, for the sake of saturation of the magnet ring, U_{Ns1} is near zero, and the IRb1 current is given by

$$I_{Rb1} = -U_{Q1be(sat)} / R_{b1} \tag{3.5}$$

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-

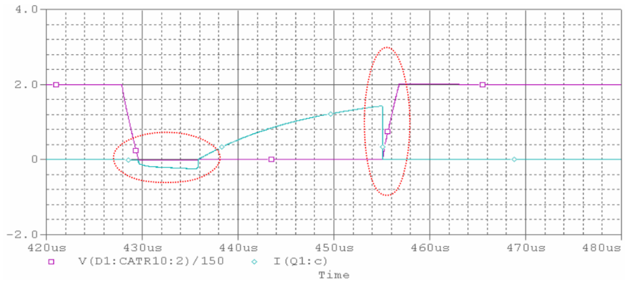

Fig. 9. Voltage and current waveforms of the transistor.

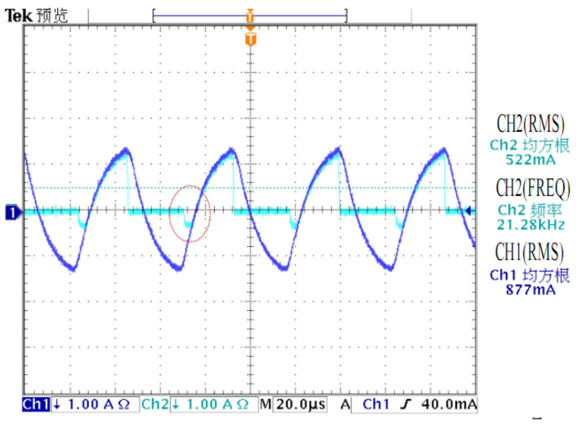

Fig. 10. Current of the transistor and tank current.

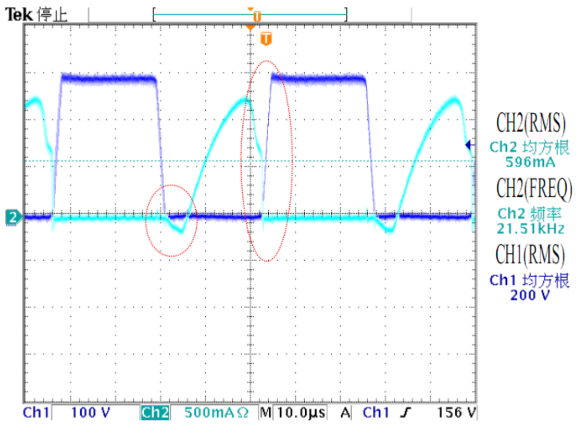

Fig. 11. Voltage and current waveforms of the transistor.

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℃ 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]:

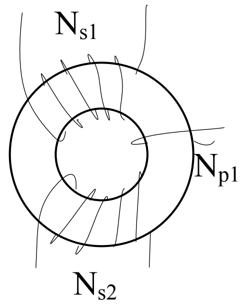

Fig. 12. Wind diagram of a single magnet ring.

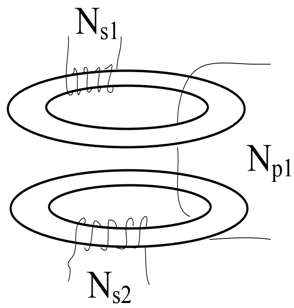

Fig. 13. Wind diagram of a double magnet ring.

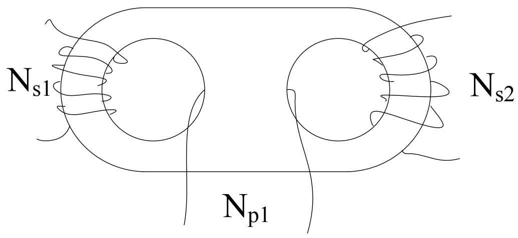

Fig. 14. Wind diagram of a magnet balun-ring.

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 U_{Ns1} is a pure sine wave.

It can be seen that:

$$\begin{cases} V_{Ns1} = \{I_{Rb1}[R_{b1} + (1+h_{ef})R_{e1}] + V_{be(sat)} \\ I_{Rb1} = \dfrac{I}{h_{ef}+1} \end{cases} \tag{4.1}$$

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

$$N_{s1} = N_{s2} = \frac{V_{Ns1}}{K_f f_s B_{ms} A_e} \tag{4.2}$$

where, K_f is the wave coefficient, and equal to 4.44 as a pure sinewave, 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

$$N_{p1} = \frac{3N_{Ns1}}{h_{ef}+1} \tag{4.3}$$

The following addresses the method of winding the self-exciting 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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