Regenerative Signal Amplifying Gate Driver of Self-Excited Electronic Ballast for High Pressure Sodium (HPS) Lamp

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Abstract - A regenerative signal amplifying gate driver of self-excited electronic ballast is presented. It can be used for high pressure sodium (HPS) lamp without auxiliary external ignitor. Since the HPS lamp requires very high ignition voltage at start up, the resonant frequency of the circuit must be increased to obtain high voltage oscillations in spite of relatively small resonant current. The presented gate driver amplifies the current of gate drive transformer and raises the gate-source voltage quickly to turn on the MOSFET switches. Hence, the resonant frequency can be increased more than 100kHz for large size switching devices. Besides, to protect the ballast from being destroyed, over-voltage/current protection and trigger delay circuits are designed. The HPS lamp used in the simulation and experiment has the rating of 400W input power at 220V input ac voltage source. The experiments show that the resonant frequency is above 150kHz at start up and the inverter stops its operation by the over-voltage/current protection at nearly 3000V.

I. Introduction

The discharge lamp is today's one of the most popular lighting choice because of its high luminous efficacy (lm/W) [1]. A ballast is needed for the discharge lamp because this has negative resistance characteristic in the desired region of operation. The ballast plays the roles of providing sufficiently high starting voltage, current limiting after starting and probably raising input power factor.

Traditional electromagnetic ballasts used at 50-60 Hz suffer from noticeable lamp flicker as well as hum, high loss and heavy weight. The electronic ballast operated at frequency higher than audio frequency (more than 20kHz) reduces aforementioned undesired phenomena [2,3]. At the high frequency the flicker falls to unnoticeable levels and the hum is eliminated. Also, inductors and capacitors can be much smaller to realize the needed current limiting impedance, and thus a substantial weight saving is possible. Besides, for the same input power the lumen output of a lamp operated at high frequency is about 10% more than 50-60Hz operation. Therefore, the electronic ballast for the discharge lamp is used widely in house and office lighting systems, street lights, etc., and this is increasing more and more.

Generally, resonant inverters are utilized as the power stage of the electronic ballast because of their load dependent characteristics [4]. There are two types of resonant inverters according to driving methods; the self-exciting and the external-exciting. The self-excited driving circuit using gate drive transformer are simpler and cheaper than the external-excited one. At start up, however, the self-exciting gate driver without auxiliary ignitor has such a constraint as resonant frequency (f_O) limit since it is not easy to turn on the switching transistors alternately in case of high f_O.

The high pressure sodium (HPS) lamp is one of the lamps which require very high ignition voltage [5,6], that is, very high f_O. So it is impossible to drive the switching transistors using the typical gate driver as shown in Fig. 1. These will be explained in the next chapter.

In this paper, therefore, the regenerative signal amplifying gate driver of self-excited electronic ballast for the HPS lamp is presented and tested. Using this gate driver, the switching frequency can be increased more than 150kHz at start up. Also, to protect the ballast from being destroyed, the over-voltage/current protection and the trigger delay circuits are designed and tested. The former is to prevent retrigger when the HPS lamp has done its life time or is not inserted. The latter is to delay the trigger time under instantaneous interruption of electric power.

II. Regenerative Signal Amplifying Gate Driver

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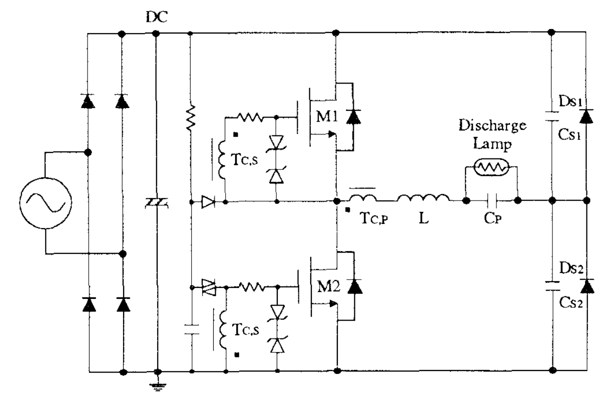

Figure 1: Typical self-excited half-bridge series resonant electronic ballast for discharge lamps

The schematic of a typical self-excited half-bridge series resonant electronic ballast for discharge lamps is shown in Fig. 1. Input ac supply (50 or 60Hz) is rectified and filtered to obtain a dc input voltage for resonant inverter. By using a gate drive transformer Tc, MOSFET transistors are switched alternately at high frequency (more than 20kHz) during normal operation. This generates a square-wave voltage supplied to the discharge lamp through a resonant LCC network.

At start up, the resonant frequency (f_O) and characteristic impedance (Z_O) of the resonant LCC network can be approximated by (1). Here we assume that a lamp impedance is quite large (almost open circuit) before ionization and series capacitors $C_{S1,S2}$ are much larger than parallel capacitor C_P.

$$f_o \cong \frac{1}{2\pi\sqrt{L*C_P}} \ , \qquad Z_o \cong \sqrt{\frac{L}{C_P}} \qquad (1)$$

The high voltage peak required for ignition is obtained using inductor L resonating with the capacitor C_P, and applied across the lamp. The resonant current (I_L) of L increases steadily as the resonance goes on. The resonant voltage (V_{Cp}) across C_P is expressed as (2). As soon as the V_{Cp} reaches ignition voltage, the discharge lamp is ionized and starts emitting light.

$$V_{C_P} = I_L * Z_o = I_L * \sqrt{\frac{L}{C_P}} \qquad (2)$$

The HPS lamp requires very high ignition voltage (about 2000V) i.e. large I_L or large Z_O from (2). The large current I_L results in increased inductor/capacitor size and expensive switching devices. Hence, the high ignition voltage has to be obtained by increasing Z_O. In (2), L can not be adjusted because it determines the desired output power in the steady state. So instead of L, C_P must be minimized to obtain the voltage spike as high as possible.

But we can not reduce C_P arbitrarily because f_O becomes very high. High f_O has a difficulty in turning on the MOSFET switches alternately as shown in (3). Eq. (3) shows that the variation of gate-source voltage (ΔV_{GS}) of MOSFET is inversely proportional to f_O.

$$\Delta V_{GS} \propto \frac{1}{C_{GS}} \frac{I_{Tc,S}}{f_o} \qquad (3)$$

In (3), C_{GS} is the gate-source capacitance of MOSFET, and $I_{Tc,S}$ is the secondary current of gate drive transformer. C_{GS} is large constant value because relatively high power HPS lamp requires large size MOSFET. And $I_{Tc,S}$ which is adjusted to be minimum value for reducing the power loss in the steady state, is almost zero at initial trigger. As a result, only f_O determines ΔV_{GS} dominantly, and the higher f_O, the smaller ΔV_{GS} becomes.

In practice, if f_O is above 100kHz, ΔV_{GS} is too small to reach the threshold voltage. So it is impossible to turn on the MOSFET switches alternately. Hence, f_O can not be increased more than 100kHz in case of using a self-excited driving circuit without auxiliary ignitor as shown in Fig. 1.

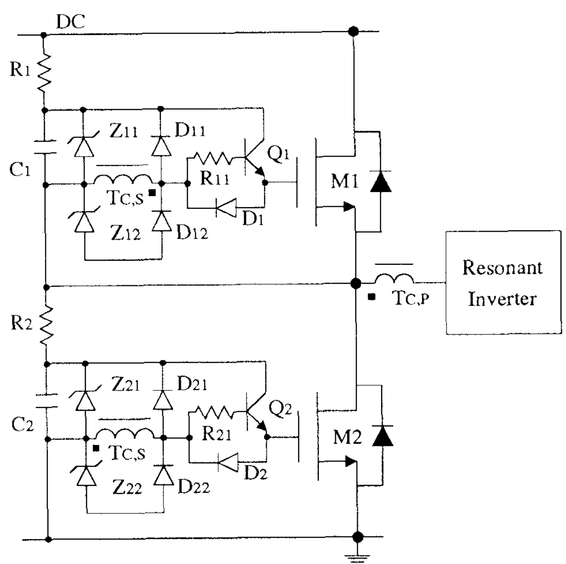

Figure 2: Regenerative signal amplifying gate driver

Fig. 2 shows the designed regenerative signal amplifying gate driver. This gate driver, however, is so successful to operate more than 150kHz regardless of the small C_P. The operation of Fig. 2 is as follows:

Before initial trigger, $C_{1,2}$ are precharged up to the zener breakdown voltage (Vz) by the current flowing through $R_{1,2}$. Then, initial trigger turns on M2 and I_L starts to flow into the M2. When the direction of I_L is changed by resonance, Q_1 amplifies $I_{Tc,S}$ by using the precharged C_1 as voltage source. This amplified $I_{Tc,S}$ raises V_{GS1} quickly up to the threshold voltage to turn on M1. At the same time, $I_{Tc,S}$ pulls down V_{GS2} through D_2 to turn off M2. Once M1 is turned on, the surplus current of $I_{Tc,S}$ feeds C_1 through D_{11} for regenerative operation.

As resonance goes on, M1,M2 are turned on and off alternately, and the operations mentioned above are applied to both M1 and M2 gate drive circuits. $Z_{11,12,21,22}$ clamp $V_{GS1,2}$ to Vz since power MOSFET transistors have maximum ΔV_{GS} limit. $D_{12,22}$ pass the remaining current of $I_{Tc,S}$ to $Z_{12,22}$.

III. Protection Circuits

A. Over-voltage/current protection

In case that the HPS lamp has done its life time or is not inserted, high voltage spike and large resonant current increases more and more, resulting in destruction of the resonant inverter during start up interval. Thus, over-voltage/current protection is indispensable to the resonant inverter. An over-voltage/current protection circuit is designed as shown in Fig. 3.

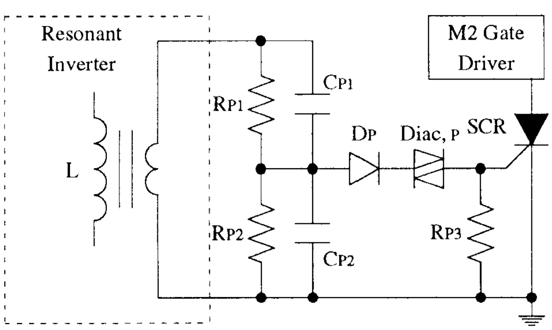

Figure 3: Over-voltage/current protection circuit

By using series connected RC network, the secondary winding of Inductor L senses the voltage across L i.e. approximately V_{Cp}. Because the amplitude of the voltage is proportional to that of the current in resonance, it is sufficient to sense the inductor voltage only. At over-voltage/current, $Diac_{,P}$ is shorted and SCR is turned on to stop the operation of M2 gate driver. Once SCR is turned on, the resonant inverter can not be retriggered.

B. Trigger delay circuit

The ignition voltage has an unique characteristic dependent on the HPS tube temperature. In the steady state, the HPS tube temperature is usually 500~1000°C. If the instantaneous interruption of electric power takes place, the HPS lamp requires very high voltage spike more than the rated ignition voltage as shown in Fig. 4.

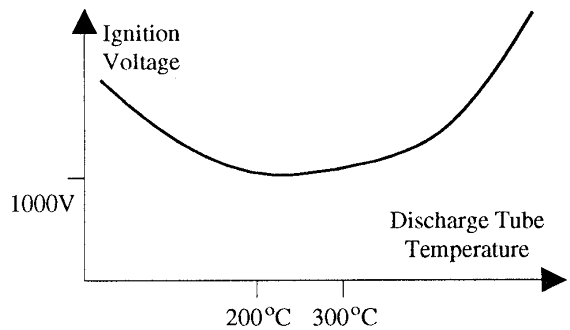

Figure 4: Ignition voltage vs. Discharge tube temperature

In this case, it is impossible to retrigger until the HPS tube temperature falls below nearly 500°C. Thus we designed a trigger delay circuit adding R_{T2} and C_{T2} to the typical trigger circuit in Fig. 5. The delay time is determined dominantly by R_{T1} and C_{T2}. R_{T2} limits the current flowing to the gate drive circuit of M2 at trigger.

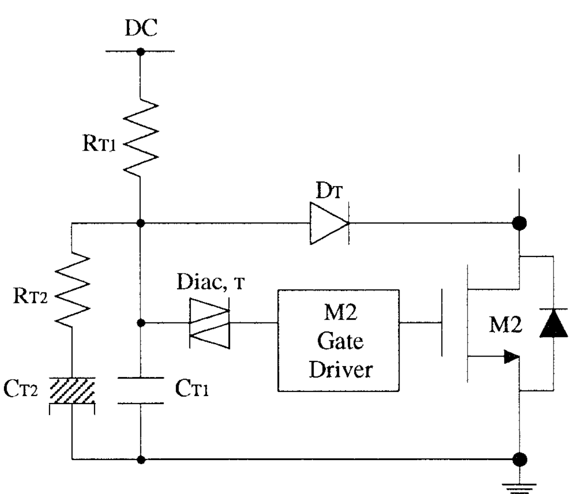

Figure 5: Trigger delay circuit

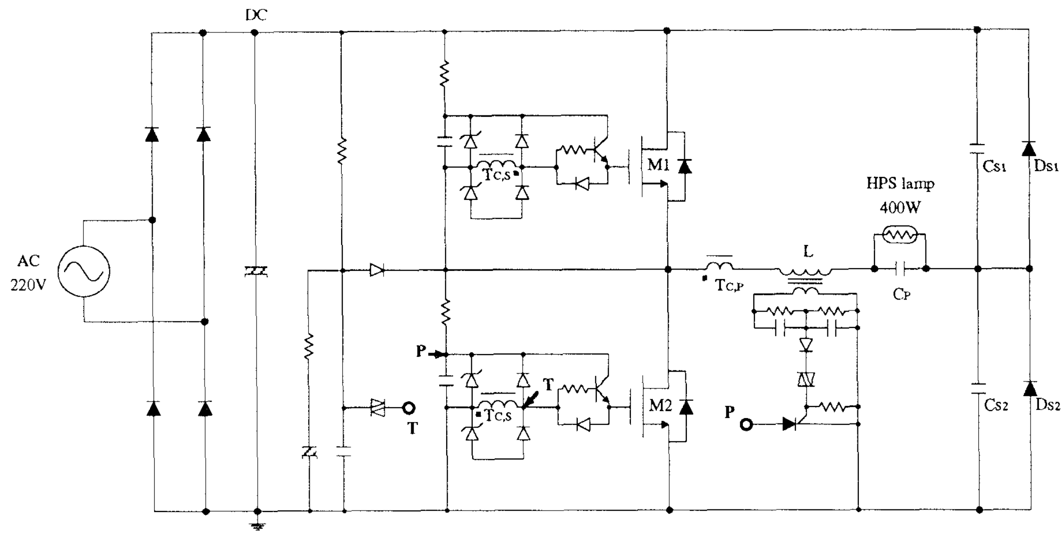

Figure 6: The overall schematic of the presented electronic ballast for the HPS lamp

IV. PSPICE Simulation & Experimental Results

An electronic ballast using the half-bridge series resonant inverter for the HPS lamp is simulated and constructed in the laboratory. The half-bridge series resonant inverter has a self-excited gate driver without any additional auxiliary ignitor. Fig. 6 shows the overall schematic including all of the circuits mentioned above. The HPS lamp used in the simulation and experiment has 400W rated power. Input ac voltage source is 220V, and IRFP350 MOSFET's are used.

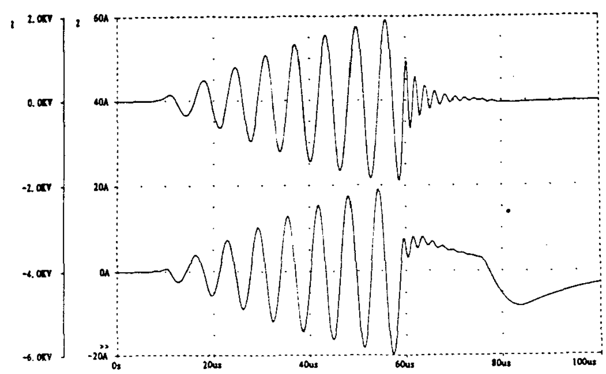

Figure 7: Simulation waveforms at start up
upper - resonant voltage (V_{Cp})
lower - resonant current (I_L)

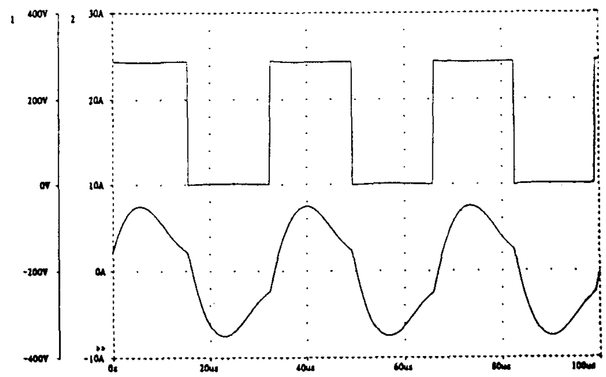

Figure 8: Simulation waveforms in the steady state
upper - half-bridge center voltage (V_{HB})
lower - HPS lamp current (I_{Lamp})

The 400W HPS lamp is modeled on open circuit at start up, and equivalently 20 ohm in the steady state under simulation. Besides, we assumes that the ignition votage is about 2000V, and the HPS lamp is equivalently series connected 5ohm+10uH right after the ignition Through PSPICE simulation, the values of the resonant inverter components C_P, $C_{S1,S2}$ and L are determined, which are 10nF,100nF and 100uH, respectively. Fig. 7 shows the simulation waveforms of resonant voltage (V_{Cp}) and current (I_L) at start up. Fig. 8 shows the simulation waveforms of the half-bridge center voltage (V_{HB}) and HPS lamp current (I_{Lamp}) in the steady state.

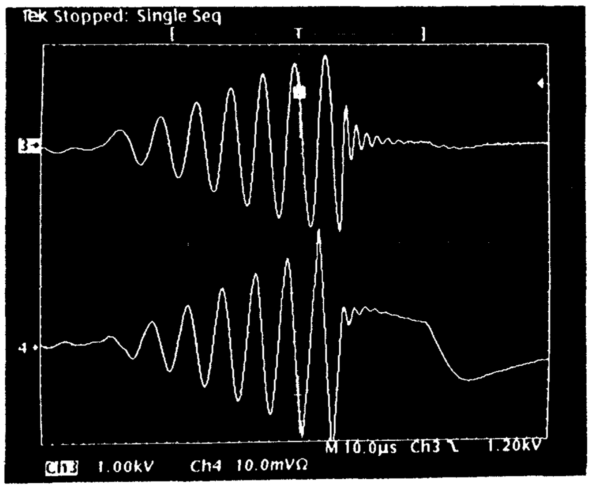

Figure 9: Experimental waveforms at start up
upper - resonant voltage (V_{Cp})
lower - resonant current (I_L) [10A/div]

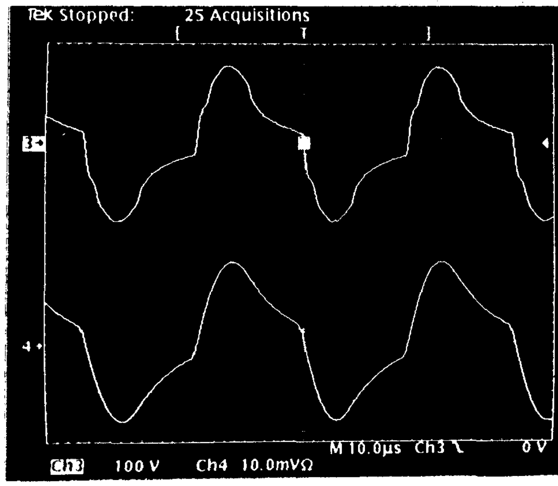

Figure 11: Experimental waveforms in the steady state
upper - HPS lamp voltage (V_{Lamp})
lower - HPS lamp current (I_{Lamp}) [5A/div]

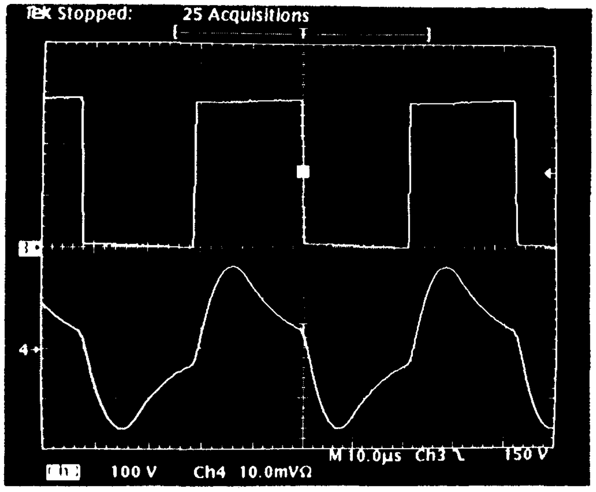

Figure 10: Experimental waveforms in the steady state
upper - half-bridge center voltage (V_{HB})
lower - inductor current (I_L) [5A/div]

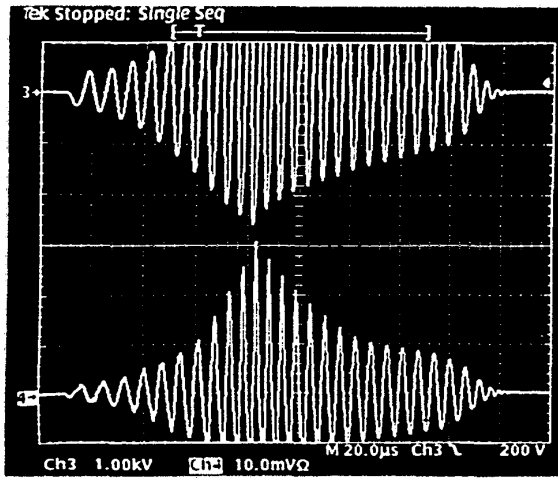

Figure 12: Over-voltage/current protection
upper - resonant voltage (V_{Cp})
lower - resonant current (I_L) [20A/div]

We confirmed by experiments that the newly designed circuitry has the performances stated previously and operates to the desired results. Fig. 9 shows the experimental waveforms of resonant voltage (V_{Cp}) and current (I_L) at start up. The resonant frequency (f_O) is about 160kHz by using the presented regenerative signal amplifying gate driver, and the ignition voltage reaches approximately 1800V. In the steady state, half-bridge center voltage (V_{HB}) and inductor current (I_L) waveforms are shown in Fig. 10, and Fig. 11 shows the waveforms of HPS lamp voltage (V_{Lamp}) and current (I_{Lamp}). Fig. 11 shows that the equivalent resistance of the 400W HPS lamp is not 20 ohm but neary 10 ohm when the resonant current freewheels M1,M2-L-Lamp-$D_{S1,S2}$ path in Fig. 6. Thus, the switching frequency decreases to about 23kHz in the steady state because the reduced lamp resistance increases the time constant (L/R_{Lamp}) of L-Lamp freewheeling path. The experimental waveforms of over-voltage/current protection circuit is shown in Fig. 12. The resonant inverter stops its operation at nearly 3000V by this over-voltage/current protection.

V. Conclusion

In this paper, we presented a regenerative signal amplifying gate driver for self-excited electronic ballast. It can be used for the high pressure sodium (HPS) lamp without auxiliary external ignitor. Using this gate driver we can drive the switching transistors more than 150kHz at start up, which can not be obtained in the typical gate driver such as in Fig. 1. It should be noted that the higher the switching frequency, the higher the ignition voltage is in spite of small resonant current. Besides, to protect the electronic ballast from being destroyed, we designed the over-voltage/current protection circuit and the trigger delay circuit. The former is to prevent retrigger in such a case when the HPS lamp has done its life time or is not inserted, and the latter is to delay the trigger time under an unexpected interruption of electric power.

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