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Close Loop Solution for Electronic Ballast of Metal Halide Lamps with Power Factor Correction

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Abstract: This paper presents a close loop three stages Electronic Ballast for Metal Halide (MH) High Intensity Discharge (HID) Lamps. Normally Electronic Ballast consists of power factor correction stage to achieve unity power factor, buck converter to lower the input voltage according to lamp requirement and half bridge inverter to supply the lamp with high frequency sinusoidal voltage and current. LCC resonant tank is used to provide the ignition and normal running requirements of lamp. Since MH lamps are categorised under high intensity discharge lamps, no of electrons in discharge tube reduces as lamp becomes older and lamp resistance increases ultimately. This variation in lamp resistance will affect the lamp power very much that draws the safety issue for end user. To overcome this problem a close loop design of Electronic Ballast is proposed in this paper. So aging protected electronic ballast is modelled ultimately. Proposed circuit is verified with analytical and simulation results.

Keywords: Metal Halide Lamp, Power Electronics Converter, Controller, PSIM.

I. INTRODUCTION

Metal Halide (MH) Lamps are well known due to its high luminous efficacy [1]-[2].Since operation of these lamps are very complex as MH lamps have several phases of operation. Very high voltage approximately (1500V - 3000V) is required during starting of lamps and at normal running condition low voltage is required i.e. approximately 100V - 200V for 60W MH lamp [3]-[4].

Therefore control system is essential to provide these requirements. With the recent development in power electronics, electromagnetic ballast are totally replaced by Electronic Ballast (EB) due to its less weight, reduce size and high efficiency [5]. With a continuous growth rate of 20% per year, electronic ballasts are widely spread over the world [6].

The growing electric energy consumption worldwide, day by day, is stimulating research and development of energy efficiency technique. Considering that the artificial lighting systems represent a great amount of consumption, the development in this field making possible saving energy to produce light. This will make a significant contribution on total electric energy consumption. This work propose a saving energy solution for lighting systems, using electronic ballast operating at high-frequency to supply MH lamps. Some electric advantages can be observed in the use of high-frequencies electronic ballast comparing to electromagnetic one, like audible noise, flicker absence, and better lighting efficacy (lm/W).

Conventional ballasts, which operate at low frequencies (50 or 60 Hz) are not the most practical solution, due to their large size, excessive weight and low efficiency. In order to reduce the size of the ballasts for HID lamps, high frequency ballasts have been developed. However, the arc in the HID lamp tends to be unstable at specific frequency operation ranges. This phenomenon is called acoustic resonance. So MH lamps driven by high-frequency electronic ballast may suffer from problematic acoustic resonance that may lead to arc instability, light fluctuation, or extinguishment, and even cracking the arc tube. One method for avoiding this phenomenon is to operate at a frequency above this range.

However, the switching loss on the ballast becomes greater as the operating frequency increases. In order to reduce the switching loss, a resonant-type inverter is used to provide electronic ballast for a HID lamp.

Various Types of Electronic Ballast is proposed in literature [7]-[8]. Since Electronic Ballast has different stages as shown in Fig.1, therefore input power factor of the circuit is worthly affected. Hence a power factor correction circuit is required to maintain the input power factor unity.

Active Power Factor Correction (PFC) Technique is preferred to serve as a PFC due to its simple working and good performance over passive PFC technique [9].

In this paper bridge rectifier with boost converter is used as PFC. The PFC circuit works in such a manner that it keeps output voltage constant in spite of input voltage fluctuates between 110V to 300V.

So output power of the lamp does not affected by input voltage fluctuation as per IEC-61000-3-2 class C requirements [10].

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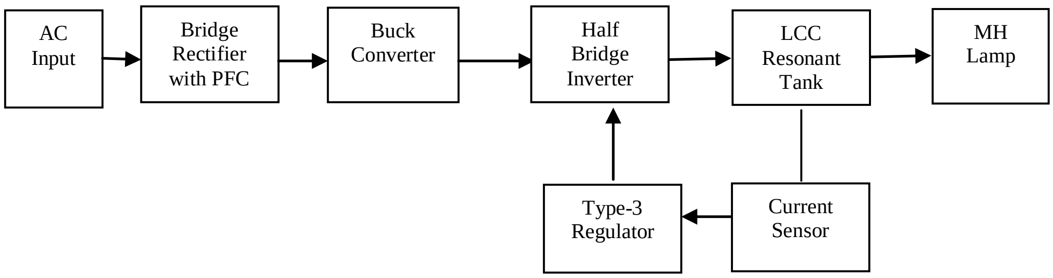

Fig.1 Block Diagram of Electronic Ballast

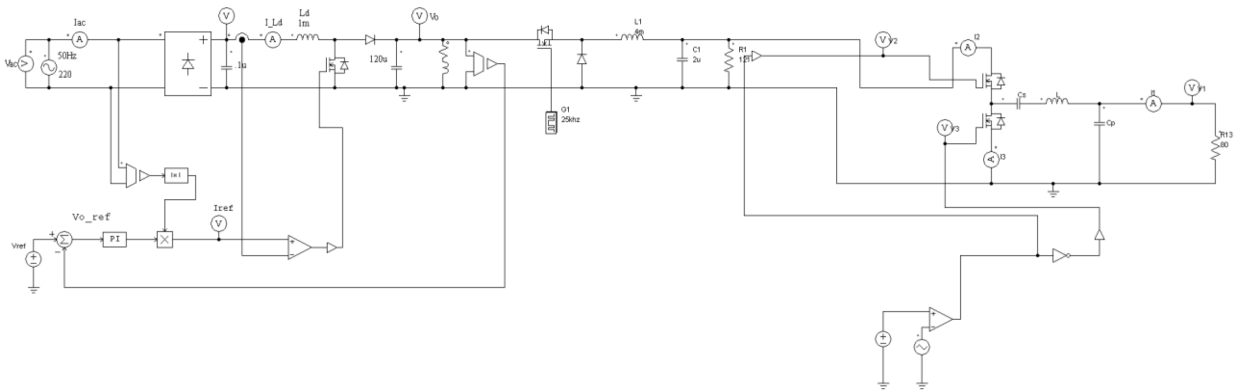

Fig.2 Schematic of Open Loop Electronic Ballast

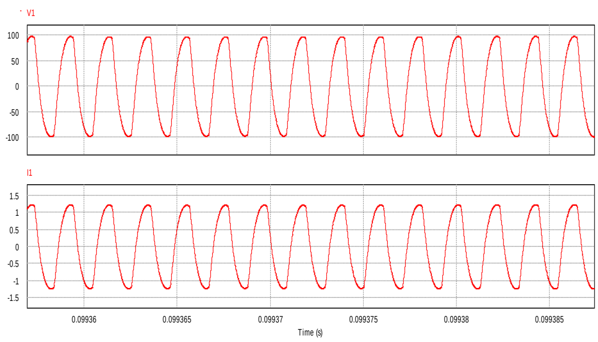

Fig.3(a) Output Voltage and Output Current of open loop Electronic Ballast at 80ohm

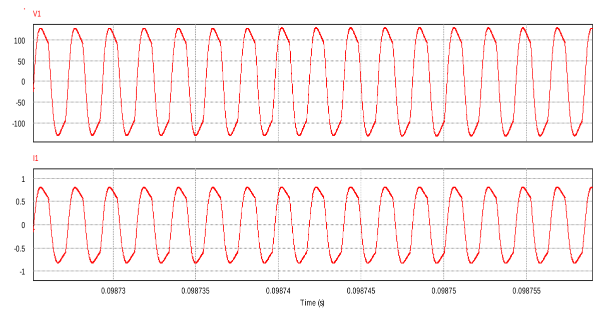

Fig3(b) Output Voltage and Output Current of Open loop Electronic Ballast at 160ohm

Since the dc voltage of boost PFC is greater than the operating voltage of an MH lamp, a buck converter is added after the PFC to comply with the lamp voltage.

After dc output of buck converter, a half bridge inverter is used to convert dc signal into high frequency ac signal. LCC resonant tank is popularly used in Electronic Ballast because no additional circuitry such as transformer is required to ignite the lamp. Close Current Loop is used to maintain lamp power constant when lamp resistance changes due to aging effect [11]. Type-3 Regulator is used to regulate the overall performance of feedback loop. In this close loop inner current loop is used and output of current loop is connected to Type-3 Regulator which regulate the duty cycle of the square wave that is given to switches of Half Bridge Inverter. Power Factor Correction Circuit and LCC Resonant Tank is designed for operating 60W MH lamp and simulation results are analysed. Good performance is obtained from the simulation results.

This paper is organized as following: In Section 2 the working of Electronic Ballast is described with power variation results. Section 3 gives the model of Electronic Ballast under normal operating condition. In Section 4 Active Power Factor Correction is discussed with simulation results followed by the working of Buck Converter with simulation results in Section 5. Section 6 gives LCC resonant inverter configuration and operation. Novel part of this article i.e. Control strategy and stability analysis of open loop and close loop Electronic Ballast is presented in section 7. In section 8 results are discussed.

II. WORKING OF ELECTRONIC BALLAST

The schematic of simulated circuit diagram for Electronic Ballast in open loop is shown in Fig.2.Boost Power Factor Correction Circuit is used to improve the power factor of the Electronic Ballast and provide safety to the circuit from input voltage fluctuations. Buck Converter is used to

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step down the output voltage obtained from the Boost PFC [9]. The half bridge inverter is used to give high frequency ac supply to the lamp while LCC Resonant Tank is used to fulfil the normal running and ignition requirements of the lamp. At high frequency the problematic phenomenon i.e. Acoustic Resonance is avoided also the size of component is reduced largely. This LCC tank is used as a series and parallel resonant tank. The lamp is simulated as resistance. During ignition state the resistor is chosen as a very high value and during the normal operation it is chosen to give 60W lamp power. The value of parallel capacitor Cp and series capacitor Cs are chosen such that the effect of Cp remains during ignition stage only. Once the lamp reaches to steady state the frequency of half bridge inverter is reduced and the Cp behaves like anopen circuit. The effective circuit will have Cs, L and load resistance. The operating frequency chosen during ignition stage is 1020 kHz and normal running condition is 450 kHz. These frequencies may vary with design along with the LCC resonant tank and lamp power. The care is required to be taken while choosing the operating frequency, lamp power and LCC resonant tank is the switching should not occur in the capacitive region. Fig.3 shows the variation in lamp voltage and lamp current at 80 ohm and 160ohm. From Table1, it is clear that lamp power varies significantly in open loop Electronic Ballast when lamp resistance changes due to aging effect.

III. MODEL OF ELECTRONIC BALLAST

Under normal running condition LCC Resonant Tank act as a series Resonant Tank. Equivalent model is shown in Fig.4 in which inductor and capacitor are changed to their s domain equivalent. Transfer Function of Electronic Ballast is given by eq. 1.
Since the Electronic Ballast is operating in open loop mode, the lamp power varies with the change of its impedance.

$$\frac{V_{out}}{V_{in}} = \frac{sCR}{s^2LC + sCR + 1} \quad (1)$$

TABLE I: VARIATION IN LAMP POWER

Configuration	Power @ 80ohm	Power @ 160ohm	% Variation
Open Loop Electronic Ballast	70Watt	60 Watt	18%

TABLE II: SIMULATION PARAMETER OF BOOST PFC

Input Voltage (V_{DC})	220V
Output Voltage (V_o)	400V
Duty Ratio(D)	0.45
Inductor (L)	1mH
Capacitance(C)	120uF
Load Resistance(R)	1000ohm
Switching Frequency(f)	68Khz

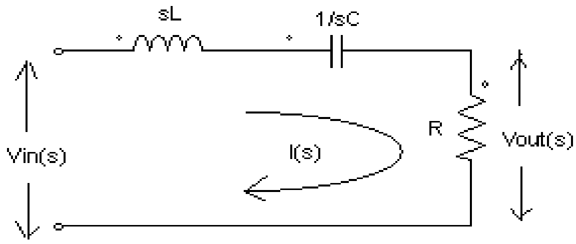

Fig.4. Model of Electronic Ballast at Normal Running Condition

IV. ACTIVE POWER FACTOR CORRECTION

An active power factor correction technique is the most effective way to achieve unity power factor. Here boost converter is placed between bridge rectifier and load. Also the circuit maintains the DC output constant.Fig.5 shows the schematic diagram of active power factor correction circuit using boost converter maintains the capacitor voltage at a set reference value using feedback action. The error at the DC output is regulated by a PI controller (voltage compensator or Integrator) and the PI controller

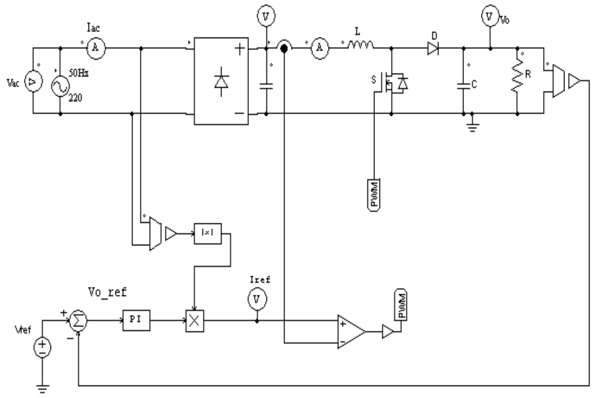

Fig.5. Schematic of Active Power Factor Correction Circuit using Boost Converter

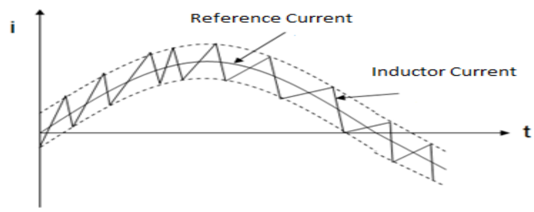

Fig.6 Average Current Control Technique [9]

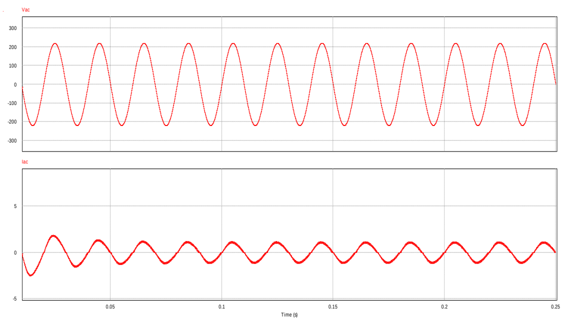
Fig.7 Input Voltage along with input Current of PFC

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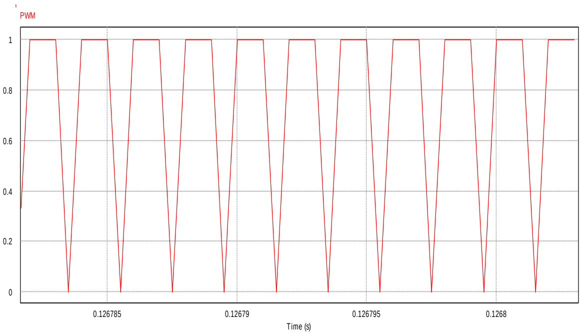

Fig.8 Gate Signal for Switch S of PFC

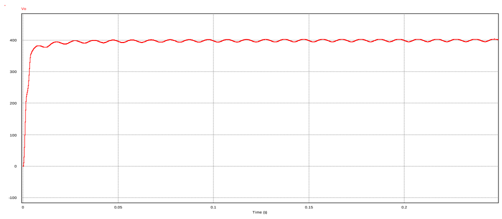

Fig.9 Output Voltage of Boost PFC

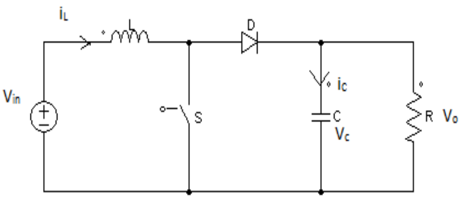

Fig.10 State Space Model of PFC

output is added to the current control loop to vary the duty ratio to maintain the DC output voltage constant. The current control techniques have gained importance in ac to dc converters used for high performance applications, where fast response and high accuracy are important. But user has to pay more cost for this. Various current control methods have been proposed and classified as hysteresis control, predictive control, average control and timer controller with constant switching frequency. Here average control method is used for current control loop.

A. Average Current Control Technique

The control technique is designed so that the inductor current follows the shape of the rectified ac line voltage. To regulate the load, comparator senses the variation between the output voltage and the fixed dc reference. This error voltage is multiplied with the sensed line voltage known to control the inductor current amplitude. The advantages of the control are that one has no need of compensation ramp, converting a voltage source into a fast-acting current source, the inductor is easy to design, operating switching frequency is high and low distorted input current waveforms with fixed load.Fig.6 shows Average current control technique to generate the switching pulse [9]. Fig.7 shows the input voltage and input current waveform of the PFC while Fig.8 shows the gate driver signal or switching pulse given to the single switch of PFC.Output waveform of the PFC is shown in Fig.9. Key feature of the circuit is that output remain constant irrespective of input signal varies between 110 to 330 volts. Table.2 shows the design parameter of Boost Converter.

B. State Space Model of PFC

Choosing the inductor current and capacitor voltage as natural state variables and picking the resistor voltage as the output shown in Fig.10, it is easy to see that the state-space model describe the idealized boost converter in that figure. The State Space Equation is stated as under.

$$\begin{bmatrix}\dot{i}_L\\ \dot{v}_C\end{bmatrix}=\begin{bmatrix}0 & \frac{q-1}{L}\\ \frac{1-q}{C} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}i_L\\ v_C\end{bmatrix}+\begin{bmatrix}1/L\\ 0\end{bmatrix}[V_{in}] \qquad (2)$$

$$[V_0]=[0 \quad 1]\begin{bmatrix}i_L\\ v_C\end{bmatrix} \qquad (3)$$

Where i_L, v_C are the inductor current and capacitor voltage.

q = 0 when switch is off.
q = 1 when switch is on.

V. BUCK CONVERTER

Buck Converter is a Power Electronics converter that converts applied dc voltage into lesser dc voltage. Fig.11 shows the schematic diagram of Buck Converter. Input voltage is 220V while output voltage is 110V as shown in Fig.12. Table.3 shows the design parameter of Buck Converter.

A. Design Consideration of Buck Converter

TABLE.III: SIMULATION PARAMETER OF BUCK CONVERTER

Input Voltage (V_{DC})	220V
Output Voltage (V_o)	110V
Duty Ratio(D)	0.5
Inductor (L)	7.5mH
Capacitance(C)	2uF
Load Resistance(R)	121ohm
Switching Frequency(f)	25Khz

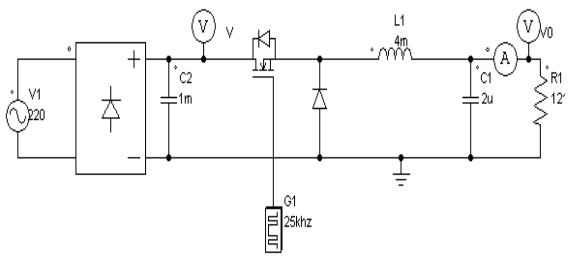

Fig.11 Schematic of Buck Converter

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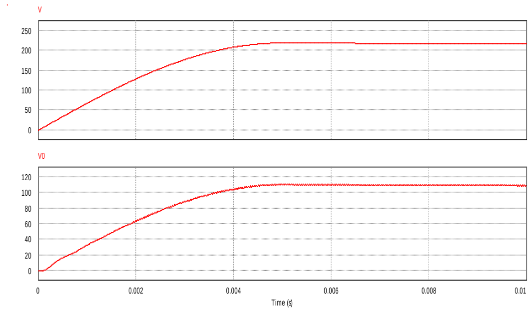

Fig.12 Input Voltage and Output Voltage of Buck Converter

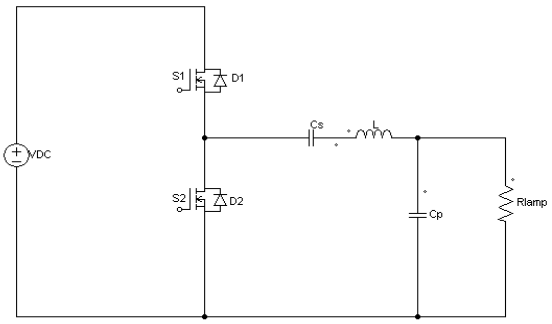

Fig.13 Circuit Diagram of LCC Resonant Inverter

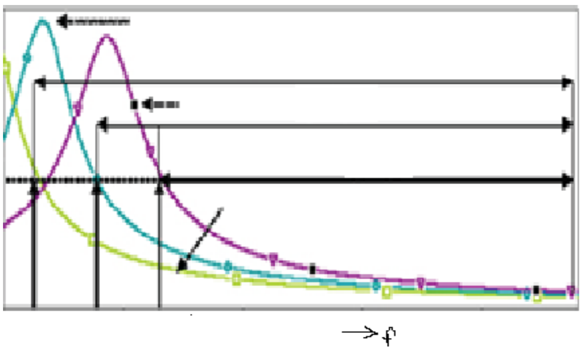

Fig.14 Schematic of Frequency Sweeping Technique [13]

TABLE.IV: PARAMETER OF RESONANT INVERTER

Input Voltage V_{DC}	220V
Line Frequency	50Hz
Lamp Voltage V_{out}	135V
Lamp Current I_{out}	0.52A
Lamp Power P_{out}	61Watt
Series Inductance L_s	36µH
Series Capacitance C_s	13nf
Parallel Capacitance C_p	0.7nf
Lamp Resistance R_{lamp}	80Ω

If output voltage is represented as V_o and input voltage is represented as V_{in}, the duty ratio (D) of a typical buck converter is given by-

$$D = \frac{V_o}{V_{in}} \qquad (4)$$

The inductor can be designed using the equation (5).

$$L > \frac{V_{in}.D.(1\text{-}D)}{2.f.I_L} \qquad (5)$$

The value of capacitance is given by in equation (6).

$$C > \frac{(1\text{-}D)}{16.L.f^2} \qquad (6)$$

Where

f = Frequency of operation
I_L = Inductor Current

VI. LCC RESONANT INVERTER CONFIGURATION AND OPERATION

In this section, the behaviour of LCC Resonant Inverter is explained, as shown in Fig.13. The resonant tank circuit consists of C_s, L and C_p. The MH Lamp is represented by resistor R_{lamp}.To analyse the steady state or normal running circuit behaviour, the capacitor C_p can be neglected and the resonant tank acts as a series resonant tank. Also the operational frequency is greater than the resonant frequency.

Design procedure of LCC Resonant Inverter is discussed in R.Sharma et al [11]. In this design Q=0.72 and f = 450 KHz, so the design results are L=36uH, C_s=13nf and C_p=0.7nf.Table 4 shows the design parameter of Resonant Inverter.

VII. CONTROL STRATEGY AND STABILITY ANALYSIS

The gas deterioration in the discharge tube, decreases the free electrons hence the lamp resistance increases. After one year the equivalent lamp resistance may double. In open loop configuration lamp power varies drastically, therefore the inner current loop is necessary to regulate the increment of lamp equivalent resistance [12].Inner Current loop is used and inductor current of resonant inverter is given to Type-3 Regulator. The output coming from Type-3 Regulator is utilised as an input to non inverting terminal of op-amp comparator, while high frequency triangular wave is given to the inverting terminal of the comparator. The frequency of triangular wave is adjusted according to voltage requirement of the lamp. At transient stage frequency of triangular wave is high comparison to normal running state. This phenomenon is called frequency sweeping shown in Fig.14 i.e. between frequency vs. voltage gain. In this design ignition frequency is 540 KHz while steady state frequency is 450 KHz.

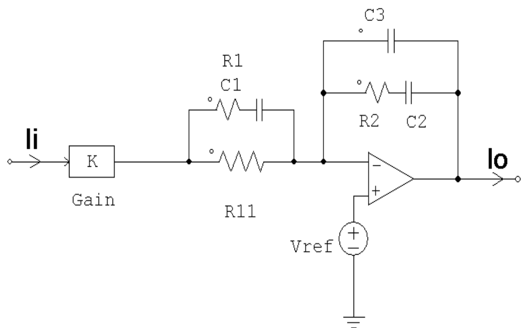

Fig.15 Implementation of Type-3 Regulator

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A. Design Procedure of Type-3 Regulator

Determine the open loop transfer function of the Electronic Ballast.

Choose the gain crossover frequency and required phase margin.

A regulator that has gain equal to the reciprocal of the plant gain at desired crossover frequency and phase margin is designed by smartctrl feature of powersim simulator.

Fig.15 shows the implementation of Type-3 regulator, Current Transfer function of Type-3 Regulator is given in “Equation. (7)”. Table.5 shows the design specification of Type-3 Regulator.

$$\frac{I_o}{I_i} = -\frac{K}{s.R_{11}.(C_1+C_2)} \frac{(1+s.C_2.R_2)}{(1+s.R_2.\frac{C_3.C_2}{C_3+C_2})} \frac{(1+s.C_1.(R_{11}+R_1))}{(1+s.C_1.R_1)} \qquad (7)$$

B. Stability Analysis

For overall Power electronics converters the minimum values of the gain margin and phase should be 5 db and 45 degrees respectively [14].

The Bode Plot of Electronic Ballast without regulator or open loop Electronic Ballast is shown in Fig.16 while Bode Plot of Electronic Ballast with Regulator or close loop Electronic Ballast is shown in Fig.17.

TABLE V: DESIGN SPECIFICATION OF TYPE-3 REGULATOR

R_1	17KΩ/0.25W
R_2	585Ω/0.25W
R_{11}	10kΩ/0.25W
C_1	16pF
C_2	758pF
C_3	1.2nf
G_{mod}	0.05
V_{ref}	2V
Gain(K)	120Ω
Switching Frequency	450Khz

One can note that the response of close loop Electronic Ballast is stable, with a gain crossover frequency equal to 426 KHz, phase margin around 51° and gain margin around 40dB.

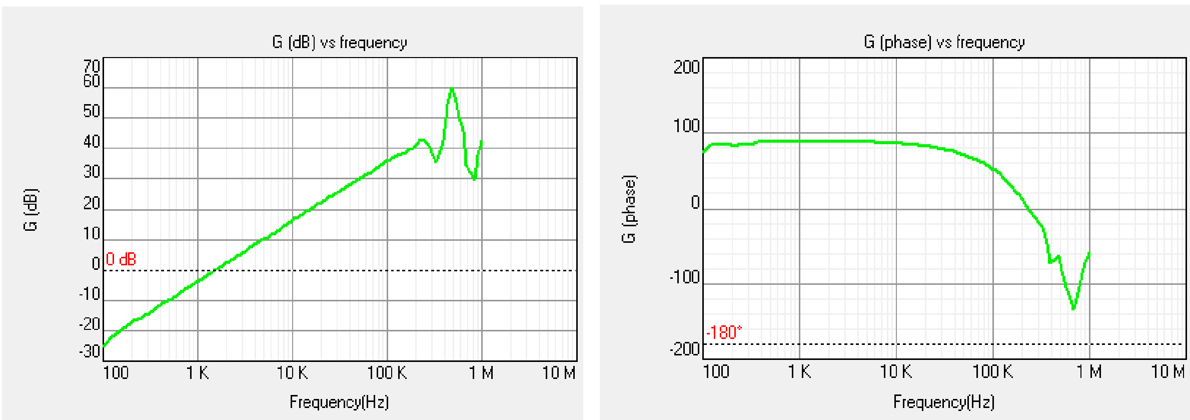

Fig.16 Bode Plot of Open Loop Electronic Ballast

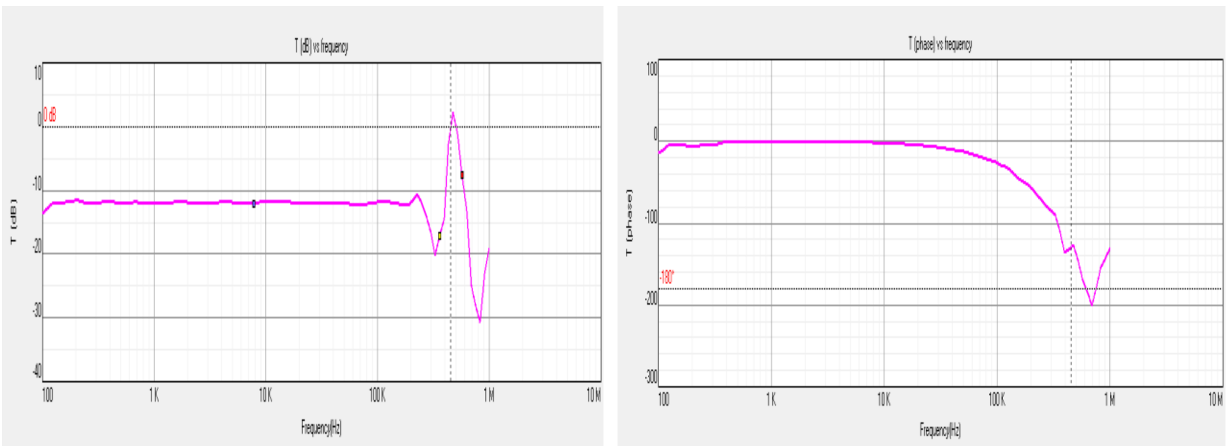

Fig.17 Bode Plot of Close loop Electronic Ballast

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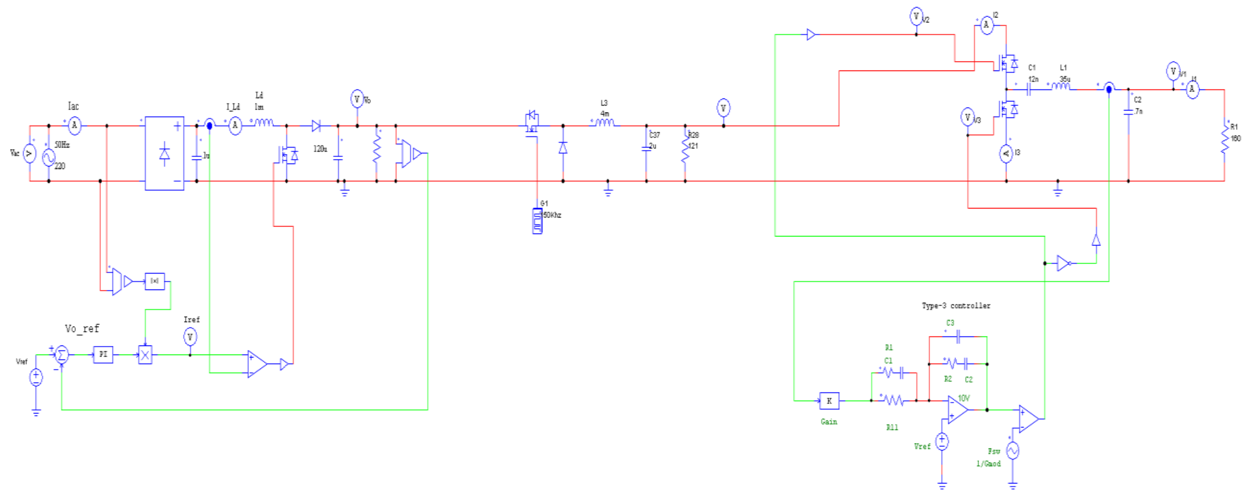

Fig.18 Simulated Circuit Diagram of Close Loop Electronic Ballast

VIII. CIRCUIT SIMULATION AND SIMULATION RESULTS

As lamp becomes older its internal resistance doubles that creates hurdles for the manufacturer as well as end-user. Main contribution of this paper is to provide aging free solution for electronic ballast. A simulation model with close current loop is shown in Fig.18 for 60W MH lamp in the PSIM simulation environment. In this figure other parts i.e. Active power factor correction, buck converter, half bridge resonant inverter are used for normal lamp operation but Type-3 regulator is proposed to save the lamp from aging effect. Steps to design this regulator are already mentioned in section7.

Fig.19 shows the power variation in close loop electric control system when load changes from 80 ohm to 160 ohm. Fig.20 shows the lamp voltage during the starting transient. Fig.21 shows the input power factor of Electronic Ballast without power factor correction while Fig.22 shows the input power factor using power factor correction stage. In case of electronic ballast without PFC the power factor is only 0.1 while in second case power factor is significantly improved to 0.985.

Fig. 23 shows the waveforms of the lamp voltage and current along with the switches current I2 and I3 at steady state operation. The lamp is resistive, and the current and voltage is nearly sinusoidal.

Table 6 shows the voltage and current across the components of electronic ballast at normal running condition while Table 7 shows the % lamp power variation in open loop and close loop configuration of electronic ballast.

Simulation Result shows that in close loop electronic ballast power variation across lamp is 2% when load resistance is double due to aging effect but in case of open loop or Electronic Ballast without regulator the same lamp power variation is 18%. Thus power variation reduces when load is dynamically changes.

IX. CONCLUSION

In this paper a closed current loop solution is proposed for an electronic ballast to supply 60W M.H lamp. A complete topology modelling of proposed electronic ballast is shown and confirmed in simulation. Due to the frequency sweeping technique used in this paper, no extra circuitry is required to ignite the MH Lamp. Frequency response of electronic ballast shows the stability consideration at open loop and close loop configuration.

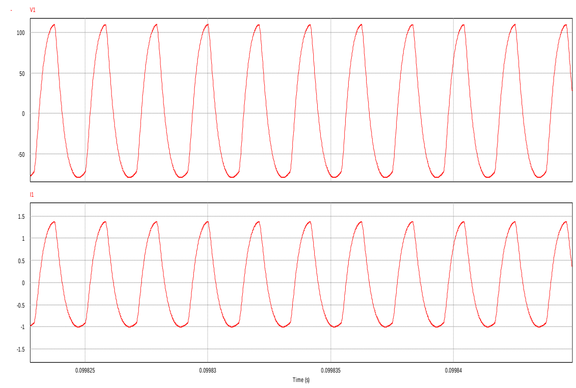

Fig.19 (a) Output Voltage and Output Current of Close Loop Electronic Ballast at 80ohm

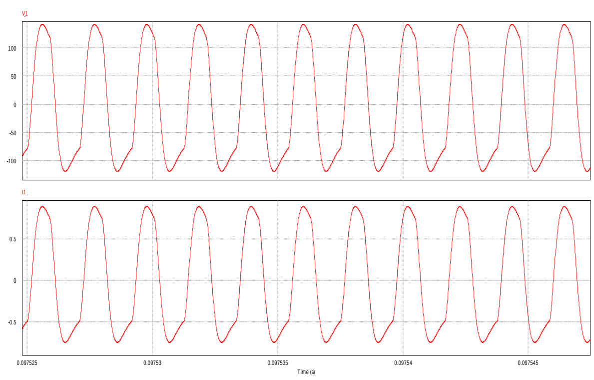

Fig. 19(b) Output Voltage and Output Current of Close Loop Electronic Ballast at 160ohm

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TABLE VI: COMPONENT STRESS

Component	Voltage(Volt)	Current(Amp)
Inductor(L_s)	105	0.84
Capacitor(C_s)	81	0.86
Capacitor(C_p)	67	0 .154
MOSFET(S_1)	172	0.63
MOSFET(S_2)	124	0.62

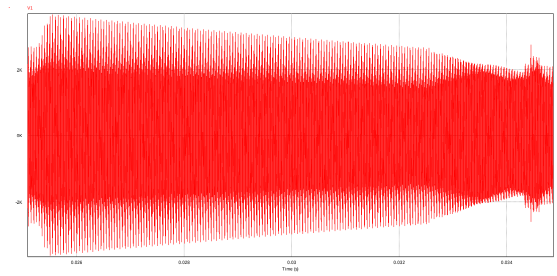

Fig.20 Lamp Voltage during Stating Transients

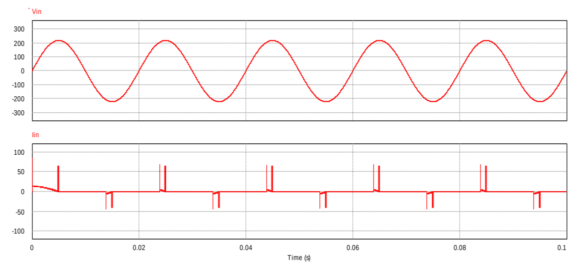

Fig.21 Input Voltage and Input Current of Electronic Ballast without PFC

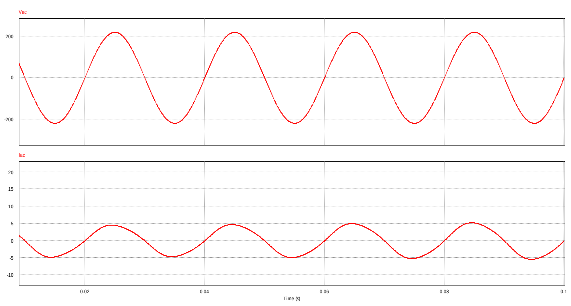

Fig.22 Input Voltage and Input Current of Electronic Ballast with PFC

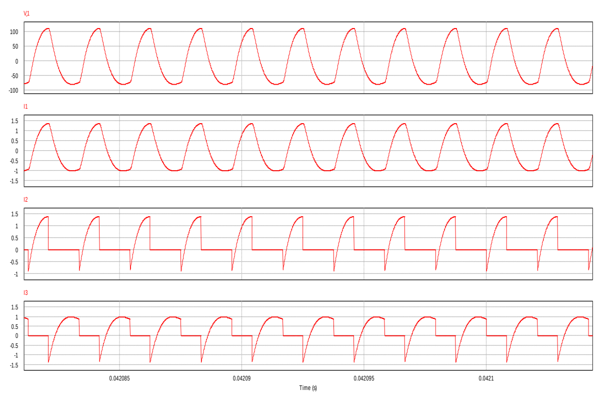

Fig.23 Waveforms of lamp voltage and current along with switches current I2 and I3 at normal running condition

TABLE VII: SIMULATION RESULTS

Configuration	Power@ 80Ω load	Power@ 160Ω load	%Variation
Open Loop	70W	60W	18%
Close Loop	62W	61W	2%

From the result obtained after simulation shows that the system can be ignited reliably, transit smoothly and the lamp power can be kept constant accurately. Current fluctuation of the proposed Electronic Ballast has been compared with the IEC-61000-3-2 class C requirement. Also input power factor of the circuit maintained nearly unity that increases efficiency of the circuit. Although in this paper only simulation results are discussed but the discussed type-3 controller can be easily implemented with microcontroller during hardware implementation. So these results are very useful during that time.

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