Modelling of 200W LED Driver Circuit Design with LLC Converter

Boyapati Chandrasekhar
PG Scholar
Department of Electronics and Electrical Engineering
MIT, Manipal University, Manipal, INDIA

Anjan Padmashali
Assistant Professor
Department of Electronics and Electrical Engineering
MIT, Manipal University, Manipal, INDIA

Abstract

LED is a recent technology, which has replaced all other conventional light sources in the past few years and since it is current controlled, accurate driver design is necessary. The LED driver should have the capability of providing constant current regardless of the LED forward voltage variations. The LLC converter is controlled to operate as a constant current mode LED driver. A 100 kHz, 200W LLC LED driver is designed and calculated to verify the proposed circuit and design method. This paper proposes mathematical model of 200W LED driver circuit design with LLC resonant converter. The proposed circuit uses a full bridge rectifier to convert AC to DC and increases the rectified output voltage using boost converter which is operated in continuous conduction mode and a quasi-half bridge resonant converter to drive the LED lamp load with coupling transformer. The LLC converter is designed such that solid state switches of quasi half bridge are working under zero switching scheme to reduce switching losses. The analysis, design and modelling of 200 W LED driver is carried out by mathematical model and stability analysis for universal AC mains.

Keywords: LED (Light Emitting Diode), Constant current (CC), Pulse width modulation (PWM), Continuous conduction mode (CCM), Discontinuous conduction mode (DCM), Series Resonant Converter (SRC), Parallel Resonant Converter (PRC), Zero voltage switching (ZVS), Electromagnetic interface (EMI), Gain Margin (GM), Phase Margin (PM), Voltage gain (M), Coupling factor (K), Primary side turns (Np), Secondary side turns (Ns)

I. INTRODUCTION

LEDs are the future of lighting systems as they consume less energy and are efficient. LEDs have greater longevity. LEDs do not contain any toxic substance and do not emit UV rays which are harmful. In papers [1] and [2] authors have concluded that the LEDs are the best fixtures for streetlight applications. [1]-[2].

In order to enhance the performance of LEDs, nowadays the design of electronic drivers has gained importance. To design the drivers capable of handling high power, achieving accurate current control and to enhance the life of LEDs are the challenges before the researchers. Light output of an LED depends on the amount of current flowing through it. The forward voltage is determined by the characteristics of LEDs which in turn determines the required current. Due to the variations in the voltage versus current characteristics of the LED, controlling only the voltage across them would lead to variations in the light output. Hence to achieve brightness control, many LED drivers make use of current control technique [3]-[4].

Literatures have proposed many circuit topologies for the LED drivers like single stage converters with power factor correction and with passive elements without power switches are used [5]. But for high power applications both power factor correction and DC to DC converter is required. In this paper, the first stage is converting A.C. supply to pulsating D.C. using full bridge rectifier and boosting the output voltage of rectifier using boost converter up to 400V to feed the LLC section and design transformer to isolate the driver and load. The LLC resonant converter stands out among those types of resonant topologies and is widely used as power supply for high power applications. It is because the LLC resonant converter has simple structure to maintain constant current and higher efficiency [6].

In this paper after rectification from AC to DC the DC to DC stage begins, where it undergoes two-stage improvement using the LED driver, the first stage being the Boost converter stage.
The basic circuit of boost converter is shown in Fig (1) where it can be observed that, when the switch is ON, the source is connected to the inductor thereby charging the inductor. When the switch is OFF, the inductor discharges through the load and the power is fed to the load from source, inductor and capacitor. If the switch is turned ON again, before the inductor discharges completely, the mode of operation is called as continuous conduction mode. If the inductor completely discharges before next turn ON, the capacitor alone feeds power to the load and such a mode is called discontinuous conduction mode [7]-[8]. In the second stage by using boost converter the output voltage is increased up to 400V which is fed to LLC section. The two major and desirable objectives of DC to DC converters are high power density and high efficiency. This can be achieved by operating the converter at a higher switching frequency with high efficiency. However, in resonant converters, the switching losses are inherently low even at higher frequency [9].

In resonant topology there are different type of converters are there like series resonant converter (SRC), parallel resonant converter (PRC) and LLC resonant converter. Both SRC and PRC can’t be used for high power application because of its own limitations. But because of many advantages over SRC and PRC topologies, such as high efficiency, high switching frequency, ZVS turn on over entire load range, low level of EMI emissions and so on of LLC resonant converter become the most popular topology for many applications [10]. The proposed design converter is a constant current converter ensure a high efficiency over wide output voltage range. It can be proved that LLC is an excellent topology selection for LED driver [11].

II. BOOST CONVERTER DESIGN

Here, the continuous conduction mode inserts discussed. The average voltage across the inductor in either case is zero due to charging and discharging process. Therefore from steady state analysis of Fig (1) Boost converter, we get Equations 1 and 2

\[
\frac{V_s}{(V_s)DT_s+(V_s-V_o)(1-D)/Ts=0} \quad -(1) \quad V_o=1-D \quad -(2)
\]

The change in inductor current in each interval is the same. Applying the voltage-current relation of inductor, we obtain expression for ripple content in the inductor. It’s given by Equation 3

\[
\Delta i_l=\frac{V_{sD}}{R_L} \quad -(3)
\]

The capacitor voltage ripple content is yet another feature which decides the quality of output. Applying the basic charge current relationship, we get the expression for output ripple and is given by Equation 4

\[
\frac{\Delta V_o}{V_o}=\frac{D}{R_Cf_s} \quad -(4)
\]

A. Continuous conduction Boost converter mode

\[
\frac{V_s-V_d(1-D)R}{V_o=D_{rsf}+r_l+R(1-D)+0.5C_{sw}R^2 f_s(1-D)^2+R(1-D)^2} \quad -(5)
\]

From Equation (5) the output voltage of the boost converter is a function of input voltage, duty cycle, all parasitic elements and load resistance (r_{load}) because of non-ideality of the converter. Using the relationship of inductor volt current, expression for current ripple can be derived. When switch is ON,

\[
\Delta i_{lmax}=\frac{V_{sD}}{L_f s+(r_l+r_{sw})D} \quad -(6)
\]

From Equation (6), it is clear that inductor ripple depends on ESR of inductor and switch and they help in minimizing the ripple. Maximum and minimum inductor currents depend on the inductor current and the expressions are given by Equations (7) & (8).

\[
\frac{\Delta i_{lmax}}{2}=i_l+1 \quad -(7)
\]

\[
\frac{1}{R(1-D)}+\frac{D(1-D)}{2L_f s}\quad \frac{\Delta i_{lmax}}{2}=i_lmin \quad -(9) \quad -(8)
\]

By using Equation (6) and Equation (9), we get
To calculate minimum inductance requirement set $i_{lmin} = 0$, and solve for Inductance. Expression for $L_{min}$ is given in Equation (11)

$$L_{min} = \frac{D(1-D)R - D(rL + rW)}{2Rfs}\left[R(1 - D)\right]$$

Applying charge balance we get,

$$\Delta V_o(Ideal) = \frac{D}{RCfs}$$

$$\Delta V_o(esr) = \Delta i_c * r_c = il_{max} * r_c$$

The Expression for output voltage ripple is given by Equation (14)

$$\Delta V_o(nonideal) = V_o$$

Equation (14) represents that the ripple is directly proportional to $r_c$. Hence by choosing lower value of $r_c$ ensure lower ripple.

Therefore, the transfer function of open loop Boost converter is as follows.

$$\frac{I(s)}{D} = \frac{V_s}{R(1-D)^2s^2 + \frac{(2+SCR)}{SL} + \frac{S^2LC}{1(1-D)^2s + (1-D)^2}}$$

The Simulation result of Open loop transfer function is

![Bode plot of Open loop Boost Converter](image)

From the Fig. 3 Bode plot it is clear that the system is unstable. So, Because of Instability of this we have to design compensator to become a stable system.

A. Compensator Design

To have a stable Boost converter, a properly designed compensator is required. The compensation type and the output capacitor as shown in Table 1. to become the stable system.

<table>
<thead>
<tr>
<th>Type of Compensator</th>
<th>Location of crossover frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-II (PI)</td>
<td>FLC &lt; FESR &lt; Fo &lt; Fs/2</td>
</tr>
<tr>
<td>Type-III (PID)</td>
<td>FLC &lt; Fc &lt; FESR &lt; Fs/2</td>
</tr>
<tr>
<td>Type-III (PID)</td>
<td>FLC &lt; Fo &lt; Fs/2 &lt; FESR</td>
</tr>
</tbody>
</table>

Therefore, the cross frequency values of Boost converter is

$$F_{LC} = \frac{1}{2\pi \sqrt{LC}} = 868ZH$$

$$F_{ESR} = \frac{1}{2\pi rfc} = 189KHZ$$

$$\frac{Fs}{2} = 30 KHz$$

From the equations (16), (17) & (18) it is clear that the compensator model is a Type-3B compensator.

B. DESIGN OF TYPE III Compensator:

The designed parameters of Type-III compensator has follows, it has two zeros and three poles.

$$F_{Z2} = F_0 \sqrt{\frac{1-Sin\theta}{1+Sin\theta}} = 2.12KHZ$$
\[
F_{P2} = F_0 \cdot \sqrt{\frac{1 + \sin \theta}{1 - \sin \theta}} = 68.1 \text{ KHz} - (20)
\]

\[
F_{z1} = 0.5 \cdot F_{z2} = 1.06 \text{ KHz} - (21)
\]

\[
F_{P3} = \frac{F_5}{2} = 6 \text{ KHz} - (22)
\]

Based on the resistors and capacitors for the selected compensator the desired poles and zeros are achieved. When \( F_0 > F_{ESR} \) the Type-II compensator is not preferred because of large real parameters for that the Type-III compensator is preferred. The transfer function of Type-III compensator is

\[
H(s) = \frac{\sum_{i=1}^{n} r_{i}}{s^{n} + \sum_{i=1}^{n} r_{i} s^{n-1} + \cdots + \sum_{i=1}^{n} r_{i} s + r_{n} s^{n}}
\]

Here \( C_3 \ll C_1 \). Therefore

\[
H(s) = \frac{(1 + sR2 + C1)(1 + sC2)(R1 + R3)}{sR1(C1 + C3)(1 + sR2)(C1 + C3)} - (23)
\]

The compensator values i.e. \( R \) and \( C \) values are defined using following equations.

\[
R_3 = \frac{1}{2 \pi C_2 F_{P2}} = 1.06 \text{K}\Omega - (25)
\]

\[
R_1 = \frac{1}{2 \pi C_2 F_{z2}} - R_3 = 33.06 \text{K}\Omega - (26)
\]

\[
C_1 = \frac{1}{2 \pi R_2 F_{z1}} = 4.65 \text{nF} - (28)
\]

\[
C_3 = \frac{1}{2 \pi R_2 F_{P3}} = 822 \text{PF} - (29)
\]

Substitute equations (25) to (29) in equation 20, we get the compensator transfer function.

\[
H(s) = \frac{(11.27 \times 10^{-9})s^2 + (225.2 \times 10^{-6})s + 1}{(9.51 \times 10^{-15})s^3 + (4.44 \times 10^{-9})s^2 + (153.73 \times 10^{-6})s} - (30)
\]

C. Closed loop Boost converter Design

The Simulation result of compensator is From the fundamental approximation assumes that only the

The overall transfer function of closed loop Boost converter fundamental square wave voltage input contributes in the with compensator is power transfer to obtain the voltage gain. The equivalent load T.F resistance and actual load resistance are different. So, this = equivalent load resistance is derived using Equation (32).

\[
R_{ac} = \frac{4V_{o1}}{V_{ref}n} = \frac{V_{o}}{\pi^2 I_o} = \frac{8V_o}{\pi^2 I_o} = \frac{8R_o}{\pi^2} - (31)
\]

\[
R_{ac} = \frac{8n^2 R_o}{\pi^2} - (32)
\]

equivalent load resistance with respect to the primary side is

The Simulation result of closed loop Boost converter is

\[
M = \frac{2nV_o}{V_{s}} - (33)
\]

the voltage gain (\( M \)) is obtained as

\[
M = \frac{2nV_o}{V_{s}} - (34)
\]

The minimum and maximum voltage gain (equation (35) and (36)) can be obtained by choosing suitable \( k \) value.
From Fig. 8. It is clear that the closed loop Boost converter system is stable.

III. DESIGN ANALYSIS OF LLC CONVERTER

In the Fig. 6, it shows the simplified schematic of halfbridge LLC resonant converter and this topology consists of three stages as Switching network, resonant network and rectifier network. In first stage, the switching network produces a square wave voltage from output of Boost converter. In second stage, the resonant network consists of $C_r$, $L_r$ and $L_m$ of the transformer which eliminates the higher harmonic currents and a pure sinusoidal current output is obtained across $L_m$. In third stage, the rectifier network is implemented as a half bridge rectifier configuration with capacitive output filter to maintain constant voltage. Therefore, the turns ratio of transformer is

$$n = \frac{V_{in(max)} \cdot M_{min}}{2(V_o+2V_f)}$$  

(38)

Where, $V_f$ is the secondary side diode voltage drop. From Equation (38), the equivalent load resistance is obtained as

$$R_{ac} = \frac{8n^2V_o^2\eta}{\pi^2 P_o}$$  

(39)

With the $k$ value and proper Quality factor ($Q$), the resonant parameters are obtained as

$$C_r = \frac{1}{2\pi Q f_o R_{ac}}$$  

(40)

$$L_r = \frac{1}{(2\pi f_0)^2 C_r}$$  

(41)

$$L_p = \frac{(K+1)^2 \cdot L_r}{2K+1}$$  

(42)

IV. DESIGN PROCEDURE OF TRANSFORMER

The worst case for the transformer design is the minimum switching frequency condition. The minimum number of turns for the primary side of transformer is obtained as

$$N_p = \frac{n(V_o+2V_f)}{2f_o(min) \cdot 2\pi E \cdot A}$$  

(43)

By choosing proper $N_s$, the $N_p$ is obtained as

$$N_p = nN_s > N_p(min)$$  

(44)

$$N_s = N_p/n$$  

(45)

In LLC resonant converter, the transformer can be designed by a single magnetic core to reduce the magnetic losses. Because of difficulty of $L_r$ in transformer design, the iteration is required with an actual $L_r$ value after the transformer is design. In the resonant network, the RMS current through the resonant capacitor in steady state condition is

$$I_{cr(rms)}^2 = \frac{m_l}{2 \cdot 1.44 \cdot n} + \frac{n(V_o+2V_f)}{4 \cdot 1.44 \cdot f_o \cdot L_m}$$  

(46)

Thus, the maximum RMS voltage across the resonant capacitor in steady state condition is

$$V_{cr(rms)} = \frac{V_{in(max)}}{2} + \frac{1.44 \cdot I_{cr(rms)}}{2\pi f_o \cdot C_r}$$  

(47)
V. RESULTS

A. Boost converter Results:

According to Table 2. The Open loop Boost converter is designed for 60 KHz switching frequency and based on these values the Gain margin is infinity. So, because of infinity of gain margin, the system is unstable. For this, we have to design Compensator.

B. Compensator Results:

According to Table 3. The compensator is designed to compensate the open loop Boost converter and based on these, the real parameter values such as R and C calculated. From the transfer function of compensator, the Gain margin is infinity and bode plot shows as Low pass filter. So, because of low pass filter, the frequency response of open loop Boost converter will improve with suitable reference voltage and system will become stable.

C. Closed loop Boost converter Results:

According to Table 4. The Closed loop Boost converter is stable with proper reference voltage and the gain margin of closed loop boost converter is 11dB and phase margin is stabilized at 180deg. So, the overall boost converter always become stable irrespective of input by proper choosing of reference voltage.

LLC Converter Results:

According to Table 5. The LLC converter is designed for 100 KHz switching frequency. The Quality factor (Q) and coupling factor (K) always maintained as proper ratio. So that, the minimum and maximum voltage gain are always in between the range.
Therefore, because of proper ratio of Q and K, the stress on resonant parameters like Lr, Lm and Cr will be reduced and switching losses are less.

D. Transformer Design:

According to Table 6. By calculating primary and secondary winding turns of transformer, the transformer is maintained at constant voltage at secondary side. Because of large cross sectional area the core losses are very less. Therefore, the efficiency will be improved up to 95% of the converter.

VI. OUTPUT RESULTS

According to Table 7. The output R.M.S. current is maintained at 1.4A. So, the current is maintained constant at particular voltage of 143V to flow through the load. Then because of constant voltage and current, both input and output power is maintained as equally. Therefore, the efficiency will be more than 95% of the overall converter.

VII. CONCLUSION

The proposed 200W LED driver circuit is suitable for street lighting and industrial applications, because of lesser switching losses and the wide input range operation. From this analysis the LLC resonant converter has become more attractive for front end AC to DC converters. In this paper, the theoretical analysis is done on the circuit operation at Mmax and Fr point and the relationship between the converter loss and the operation range has been observed. Moreover, by choosing Lr, Lm, Cr, Q and M, the operation range of the LLC resonant converter can be ensured. The proposed 200W LED driver has demonstrated cost effectiveness because of single stage, high circuit efficiency (>95%), constant voltage (143V) and constant current (1.4A) output to improve the life of driver and LED’s. The driver circuit is modelled using Mat lab, for Boost converter, for stability analysis and calculated the output parameters required for the circuit design.

REFERENCES