ASSIGNMENT OF DESIGN OF POWER CONVERTERS

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5KW LED DRIVER

High Power White LED

Enormous energy can be saved by using efficient equipments along with effective control and careful design. The use of energy efficient lighting has been gaining popularity and LED offer one of the alternatives owing to their low power consumption. Particularly white LED’s are suitable for lighting as they provide lighting condition similar to the conventional light sources. The lighting intensity produced by it depends on the current through it at a specified forward voltage.

LED Driver Requirement

LED driver is a regulated power supply designed to match the electrical characteristics of an LED or an array of LED's in the application. Its primary function is to maintain consistent forward current and forward voltage required for operation of the LEDs over varying conditions. Change of current changes the brightness / luminosity of the LED hence it is important for the driver to provide a constant current even in the presence of disturbance and parameter variation which can be obtained through using feedback compensation. However the LED can also be fed with pulsating current due to its fast light to current response, neglecting the small color shift.

Topology selection:

Various topologies can be used, buck, boost, buck-boost for LED driver circuit but the flyback converter are the favorites for the power levels below 100W for all kind of applications and also preferred due to following advantages:

a. LED driver based on flyback converter is simple and cheap (number of component is less)
b. Provide isolated output for safety of LED lamps (LED’s and AC line are electrically isolated)
c. Can add PFC function without greatly increasing the cost of the system.
d. Addition of TRIAC can enable dimming function of LED light.
e. Inherits the advantages of isolated DC-DC converters over non-isolated(

Design Specifications

The LED’s are non linear and have electrical characteristics similar to diode. White LED operates at a minimum forward voltage and through driver a constant current has to be maintained.

The forward voltage drop of white LED ($V_f$) = 3V

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>$V_{in}$</td>
<td>220 V(RMS) at 50 Hz</td>
</tr>
<tr>
<td>Output Power</td>
<td>$P_{out}$</td>
<td>5 W</td>
</tr>
<tr>
<td>LED string average current</td>
<td>$I_{LED}$</td>
<td>300 mA</td>
</tr>
</tbody>
</table>

The LED devices can be connected in parallel, series and parallel/series arrangements. However the series connection has certain advantages over parallel connection as it does not require current limiting resistors/functions in each branch. Constant current driver to provide constant load current at required output voltage would do the task.
Let the LED’s are connected in series with same current and sharing the output voltage among them.

Output Voltage = \( V_{\text{out}} = \frac{P_{\text{out}}}{I_{\text{LED}}} = \frac{5W}{0.300\,\text{A}} \)

= 16.66 V

There will be the limitation in the number of LED’s that can be connected in series.

Number of LED’s in the string = \( n = \frac{V_{\text{out}}}{V_f} = \frac{16.66}{3} \)

≈ 5

With these specifications we design the fly back converter with proper devices and components suitable for the said application.

**FLYBACK CONVERTER**

The isolated Flyback converter is a Buck-Boost Derived topology with an isolation winding. Hence it has a transfer function of the form

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{D \cdot N_s}{I - D \cdot N_p}
\]

The topological structure of flyback converter consists of a flyback transformer or coupled inductor. When the switch is ON the energy is stored in the primary side (magnetizing inductor) and when the switch is OFF the energy is transferred to the secondary side by mutual induction. However the input and output currents have high ripple content.

A flyback transformer is actually an inductor with multiple windings having characteristics of both inductor (store and release energy) and transformer (isolation/change of voltage level). It stores energy taken from input during one switching instant and releases/delivers to the output in the subsequent interval. Energy is stored in the gapped core and the air gap (higher reluctance) inductance represents most of the magnetization inductance. Hence the flyback transformer is modeled as a magnetizing inductance in parallel to an ideal transformer. The leakage inductance of the flyback
transformer is unwanted parasitic component and is neglected. So the main aim is designing features of core, gap and winding considering the problems associated due to saturation and loss (core/hysteresis).

**Selection of Switching Frequency:**

Various performance criteria are affected by the selection of switching frequency. Though higher switching frequency reduces improves the transient response and reduces the size of converter but that comes with a trade in decrease in efficiency and increase of heat production. Hence a optimum switching frequency has to be used and for this case it is selected as 100 KHz.

\[ T_s = \frac{1}{f_s} = 0.00001 \text{sec} \]  

**FLYBACK CONVERTER DESIGN:**

The input AC voltage is fed to a diode bridge rectifier and the output through the DC link capacitor or smoothing capacitor is given to the flyback converter.

The circuit can be divided into 2 converters AC-DC/rectifier and DC-DC converter. If the overall efficiency

If the overall efficiency of the converter is assumed to be 90% then the input power drawn from AC source is:

\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \]  

\[ P_{\text{in}} = \frac{5W}{0.9} = 5.5 \text{ W} \]  

**AC-DC Converter**

The DC value of the rectified voltage using full bridge diode rectifier is given as:

\[ V_{\text{dc}} = \left( 1 - \frac{1}{2 fR_L C} \right) V_{pk(\text{rect})} \]

\[ V_{\text{peak}} = \sqrt{2} \times V_{\text{rms}} \quad \text{and} \quad V_{pk(\text{rect})} = V_{\text{peak}} - V_{\text{diode}} \]

If the capacitor filter component is very large the dc voltage at the filter end is equal to the peak voltage of the supply as the capacitor gets charged and cannot discharge in small time period due to large time constant associated with equivalent load resistance and capacitance. Generally the capacitor is selected on the basis of 2-3\( \mu \)F /watt of input power. However, to simplify the Flyback converter design the DC Link Capacitor is selected to 0.01F such that the voltage input to DC-DC converter would be constant i.e the ripple voltage would be negligible.

\[ C_{\text{f,inp}} = 0.01 \text{F} \]  

---------------------------------------(3)
DC-DC Converter

Operating Mode of Converter:

Both the CCM and DCM mode have their share of advantages and disadvantages and the component and control design depends on the operating mode of the converter. The advantages of CCM are higher efficiency and lower current stress while the DCM mode does not have RHP zero which simplifies control procedure. The CCM mode will be used and the issues with it will be discussed.

CCM Mode of Operation:

The design of flyback transformer consists of the main work in the flyback converter design. Let us make following assumptions as specifications for the flyback transformer design.

- Magnetizing current ripple \((I_{mr}) = 20\% \text{ of DC component of magnetization current.}\)
- Duty cycle \((D) = 0.4 \) (has to be selected carefully to not to cause high voltage stress on Switching Devices)
- Copper loss \((Cu_{loss}) = 1.5 \text{ W} \) (Core loss and other losses are neglected)
- Maximum flux Density \((B_{max}) = 0.25 \text{ T} \) (To prevent transformer from being driven to saturation).

\[
\frac{V_o}{V_{in}} = \frac{N_s \cdot D}{N_p \cdot (1-D)}, \text{ where } N_s / N_p, \text{ is the secondary to primary turns ratio.}
\]

\[\mathcal{E} N_p / N_s (n) = 12.4:1 \]  

\[\frac{V_{out}}{V_{in}} = \frac{1}{1-D \cdot R_{eq}}, \quad (V_{out} / R_{eq} \approx I_{out})\]

\[= 0.040 \text{ Amp}\]

The magnetizing current ripple is \(\Delta I_m = 20\% \text{ of } I_m\)

\[= 0.008 \text{ Amp}\]

Maximum value of magnetizing current \(I_{m,max} = I_m + \Delta I_m\)

\[= 0.048 \text{ Amp}\]

The magnetizing inductance \((L_m)\) required producing the given ripple inductor current is as:

\[L_m = \frac{V_{in} DT_s}{2 \Delta I_m} = 0.0775 \text{ H}\]
The RMS value of the primary winding current is given

\[ I_p = I_M \sqrt{1 + \frac{1}{3} \left( \frac{\Delta I_M}{I_M} \right)^2} \]

\[ = 0.02546631762414 \text{ Amp} \]

Similarly the secondary winding RMS current is,

\[ I_s = \frac{N_p}{N_s} I_M \sqrt{1 + \frac{1}{3} \left( \frac{\Delta I_M}{I_M} \right)^2} \]

\[ = 0.38675279960201 \text{ Amp} \]

Total RMS winding current is equal to

\[ I_{tot} = I_p + \frac{N_s}{N_p} I_s \]

\[ = 0.05665605952 \text{ Amp} \]

The output capacitor required is larger in case of flyback converter due to absence of inductor this is the only filter/energy storage component present in the output side. The value of capacitor is based on the ripple requirement on output voltage and the output ripple is determined by the ESR of the capacitor. For an aluminum electrolytic capacitor we have

ESL of the capacitor is zero (\( \therefore \) below 300 kHz) and ESR is \( r_C \)

Let the output ripple voltage be \( V_{rr} = 0.25 \)

ESR capacitance product \( (C_0r_C) = 60 \times 10^{-6} \text{ FΩ} \) \[ \text{-----------------------------------(5)} \]

\[ V_{rr} = I_{rr} \times r_C \]

\[ \Delta V_0 = \frac{I_0 D}{C_0 f_s} + I_{ds \text{ peak}} V_{R0} r_C, \text{ where (} \because \text{VF is voltage drop across secondary diode=0V)} \]

\[ V_{R0} = \frac{D_{\text{max}} V_{DC \text{ min}}}{1 - D_{\text{max}}} \text{ and } I_{ds \text{ peak}} = \frac{I_{\text{in}}}{V_{DC \text{ min}} \times D_{\text{max}}} \]

Using the above equation along with the values we have...

\[ V_{R0} = \frac{0.4}{0.6} \times 310 = 206 \text{V} \] the, voltage reflected on the primary side during switch off time.

\[ I_{ds \text{ peak}} = \frac{5.5}{310 \times 0.4} = 0.04435\text{A} \] the maximum peak drain current of the switch.
0.25 = \frac{1.2 \times 10^{-6}}{C_0} + \frac{32.90 \times 10^{-6}}{C_0}

\text{hence} C_0 = 1.3641 \times 10^{-5} \approx 136 \mu F

And the ESR will be, \[ r_c = \frac{60 \times 10^{-6}}{136 \times 10^{-6}} \approx 0.44 \Omega \]

Load Side calculations

The load in this case is LED string with a current sensor in series with the unit. The sensor resistor will form a dual purpose as a current limiting resistor in case of fault in the circuit. In MATLAB we can use a single Diode with a turn ON voltage of 5 LED or a DC voltage source of equivalent value. If the converter is designed for 16.6 V output and LED string requiring 15.5 V to fully turn ON.

Voltage drop on resistance of LED and Sensor \[ V_R = V_{out} - V_{F, LED} = 16.6 - 15.5 \]

\[ = 1.1 \text{ V} \]

Let the turn on resistance of LED be 0.01 Ω,

\[ I_{out} \times R_{Tot} = V_R \]

\[ \bar{I} R_{Tot} = 3.6666 \Omega \]

\[ R_{Tot} = R_{ON} + R_{sen} = 3.666666 \Omega \]

Hence the sensor resistor is \[ R_{sen} \approx 3.6166 \Omega \]

Design of Core

The presence of core in flyback transformer will cause to concentrate the magnetic field. The cores of flyback transformer must be able to allow large primary currents to flow without saturating the core. To prevent magnetic saturation of core we need to use either a gapped core or powdered permalloy core. In this design we will be using a gapped core which will increase number of ampere turns though on the cost of reduced permeability.

The core geometrical constant is a figure of merit that describes the effective electrical size of the core and is a function various geometrical parameters and given as:

\[ K_g = \frac{A_c W_A}{(\text{MLT})} \geq \left( \frac{\rho L^2 I^2_{m,\text{max}}}{B_{\text{max}}^2 \rho_{\text{cu}} K_u} \right) \]

The above relation shows the dependence of core size on the system specifications and is used to design a core to attain a given copper loss.

The given specifications are tabulated below used for calculation of the \( K_g \)
### Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire resistivity ($\rho$)</td>
<td>$1.724 \times 10^{-6} \Omega \text{ cm}$</td>
</tr>
<tr>
<td>Peak winding current ($I_{\text{max}}$)</td>
<td>0.048 A</td>
</tr>
<tr>
<td>Magnetizing Inductance ($L_m$)</td>
<td>0.0775 H</td>
</tr>
<tr>
<td>Copper Loss ($P_{\text{cu}}$)</td>
<td>1.5 W</td>
</tr>
<tr>
<td>Winding fill factor ($K_u$)</td>
<td>0.3</td>
</tr>
<tr>
<td>Maximum operating flux Density ($B_{\text{max}}$)</td>
<td>0.25 Tesla</td>
</tr>
</tbody>
</table>

\[ K_g \geq \frac{1.724 \times 10^{-6} \times (0.0775)^2 \times (0.05666)^2 \times (0.048)^2}{(0.25)^2 \times 1.5 \times 0.3} \times 10^8 \]

\[ =0.00027232264107 \text{ cm}^5 \]

The smallest EE core along which satisfies the given inequality has the dimension is obtained from the table below:

![EE CORE DATA](image)

<table>
<thead>
<tr>
<th>Core type</th>
<th>Geometrical constant</th>
<th>Geometrical constant</th>
<th>Cross-sectional area</th>
<th>Bobbin winding area</th>
<th>Mean length per turn</th>
<th>Magnetic path length</th>
<th>Core weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($A$ mm)</td>
<td>($K_s$ cm$^2$)</td>
<td>($K_{sfr}$ cm$^2$)</td>
<td>($A_c$ cm$^2$)</td>
<td>($W_A$ cm$^3$)</td>
<td>($MLT$ cm)</td>
<td>($\ell_m$ cm)</td>
</tr>
<tr>
<td>EE12</td>
<td>0.731 $\times 10^{-3}$</td>
<td>0.458 $\times 10^{-2}$</td>
<td>0.14</td>
<td>0.085</td>
<td>2.28</td>
<td>2.7</td>
<td>2.34</td>
</tr>
</tbody>
</table>
The air gap length in the core is calculated as:

\[ l_g = \frac{\mu_0 l_M l^2_{m,max}}{B^2_{max} A_c} \times 10^4 \]

\[ = \frac{4\pi \times 10^{-7} \times 0.0775 \times (0.048)^2}{(0.25)^2 \times (0.14)} \times 10^4 \]

\[ = 0.25644 \times 10^{-3} \text{ cm} \]

With the chosen core the minimum number of turns for the transformer primary side to avoid the core saturation is given as:

\[ N_p = \frac{L_m}{B_{max} A_c} \times 10^4 \]

\[ = 0.0775 \times 0.048 \]

\[ = \frac{0.25 \times 0.14}{25644 \times 10^{-3} \text{ cm}} \]

\[ = 1063 \text{ turns (on rounding off)} \]

Then using the desired turns ratio required turns in secondary side is as: \( N_s = \frac{N_p}{12.4} \)

\[ \approx 86 \text{ turns} \]

For calculating the window area allocated to each winding,

\[ \alpha_p = \frac{N_p l_p}{N_p l_{tot}} = \frac{0.02546631762414}{0.05665605952} = 0.4495 \]

Similarly for secondary side

\[ \alpha_s = \frac{N_s l_s}{N_s l_{tot}} = \frac{86 \times 0.38675279960201}{1063 \times 0.05665605952} = 0.55227 \]

The wire gauge determining the size of wire in terms of cross sectional area is required as:

\[ A_{wp} \leq \frac{\alpha_p K_a W_A}{N_p} = \frac{0.4495 \times 0.3 \times 0.085}{1063} = 1.0783 \times 10^{-4} \text{ cm}^2 \]

And for the secondary side winding
The AWG value for primary side is smaller and hence the conductor's physical size is smaller and the value for primary side AWG is below the lowest AWG value available.

<table>
<thead>
<tr>
<th>AWG#</th>
<th>Bare area, $10^{-3} \text{ cm}^2$</th>
<th>Resistance, $10^{-6} \Omega/\text{cm}$</th>
<th>Diameter, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>43</td>
<td>0.02452</td>
<td>70308</td>
<td>0.00685</td>
</tr>
<tr>
<td>44</td>
<td>0.0202</td>
<td>85072</td>
<td>0.00635</td>
</tr>
</tbody>
</table>

Based on the value obtained above for secondary side winding area the suitable AWG is

<table>
<thead>
<tr>
<th>AWG#</th>
<th>Bare area, $10^{-3} \text{ cm}^2$</th>
<th>Resistance, $10^{-6} \Omega/\text{cm}$</th>
<th>Diameter, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>0.1589</td>
<td>10849</td>
<td>0.0170</td>
</tr>
<tr>
<td>36</td>
<td>0.1266</td>
<td>13608</td>
<td>0.0152</td>
</tr>
<tr>
<td>37</td>
<td>0.1026</td>
<td>16801</td>
<td>0.0149</td>
</tr>
</tbody>
</table>

**CONTROLLER DESIGN**

The feedback compensation is required to maintain stable operation and prescribed operating condition/regulate output and respond fast enough in the event of disturbance and parameter variation.

The load (LED) requires specified amount of current as the change in current causes various characteristics of load to change. Voltage mode control will be used to maintain a specified voltage across a fixed sensor resistor which will ensure a constant current through LED. VMC is a single loop controller which will act to change the duty cycle based on error between the observed voltage and desired voltage at the sensor.

**Small Signal Analysis**

The small signal dynamic characteristics of PWM flyback converter can be derived using the small signal model:

The control to output transfer function is given as:

\[
\frac{V_o(s)}{d(s)} = -\frac{nV_0 r C \omega_n \omega_p \left(1 + \frac{s}{\omega_n}\right)\left(1 - \frac{s}{\omega_p}\right)}{(1 - D)(R + rC)\omega_0^2 \left(1 + \frac{s}{\omega_0 Q} + \frac{s^2}{\omega_0^2}\right)}.
\]
Where, \( \omega_m = \frac{1}{Cr} \), \( \omega_p = \frac{1}{LD} \left( \frac{n-2D(n-1)}{n-D(n-1)} \right) \times \left[ \left( \frac{n(1-D)}{V_0} \right)^2 + n(1-D) \right] - Dr \)

\[ \omega_0 = \sqrt{\frac{n^3(1-D)^2R + [n-D(n-1)]r}{LC(R+rC)\{n-D(n-1)\}}} \] and damping ratio \( (\zeta) = \frac{\tau}{2\sqrt{\rho \times \gamma}} \)

\[ \tau = n^3(1-D)^2CRrC + \{Cr(R+rC) + L\}[n-D(n-1)] \]

\[ \rho = LC(R+rC)[n-D(n-1)] \]

\[ \gamma = n^3(1-D)^2R + [n-D(n-1)] \]

Using MATLAB to calculate the control to output transfer function, we have

Controller Design Using SISOTOOL

The control to output transfer function is a second order with 2 zeros one of which lies in RHP. The open loop gain has a resonant peak at \( \omega_0 = 2853.2 \text{ rad/sec} \). The phase plot starts from 360° which is equivalent to 0°, just the difference in the phase offset.
Voltage across the sensor will be measured and compared with the reference voltage. For output current of 300 mA at load branch (through LED) the voltage drop at sensor resistor should be

$$V_{sens,\text{ref}} = 0.3A \times \frac{3.616667}{\Omega}$$

$$= 1.085 \text{ V}$$

The voltage across the sensor resistor will be compared and the error will be passed through the compensator which will be modulated by a sawtooth carrier to form a suitable gating signal to force sensor resistor voltage to reference value which will ensure desired current to flow through the LED.

The Compensator is designed using SISOTOOL. Since the RHP zero is present near the resonant frequency it complicates the feedback compensation. The crossover frequency has to be limited below the theoretical limit available even in the case with RHP zero ($1/5^{\text{th}}$ of RHP zero location). An integrator and a high frequency pole at ESR zero are added to obtain the desired shape of compensated loop gain ensuring stability and best available accurate tracking.

The compensator transfer function in the Zero/Pole/Gain Format
The Crossover Frequency is very low and hence the settling time/time response of the closed loop system is not fast enough during disturbance.

**Step Response Settling Time** ($t_s$) = 0.0175 seconds.

**SIMULATION RESULTS:**

The simulation and verification of above design is done using MATLAB/SIMULINK. Both the open loop and closed loop simulation is done. A Universal Diode Bridge rectifier is used for rectification of AC and output of which is fed to the flyback converter. The fly back transformer is implemented using the linear transformer and an inductor (magnetization) in parallel to it. The LED is modeled as a diode of turn ON voltage 15.5 V can also be modeled as a voltage source. The average value of the output current and voltage is measured with the help of simulink block MEAN VALUE.

The gating signal is provided through PULSE GENERATOR block in open loop simulation and PWM block using sawtooth carrier is used for the closed loop simulation. A disturbance voltage signal (step up/down voltage) is added in series with capacitor to check the closed loop response/performance in the event of disturbance.
OBSERVATIONS/CONCLUSIONS

Converter Design

- The duty cycle has to be selected carefully such that the turn’s ratio should be small which determines the voltage stress on the power transistor.

\[ V_{\text{max}} = V_{\text{dc, max}} + \frac{N_p}{N_s} (V_{\text{out}} + V_{\text{diode}}) \quad V_{\text{ds, nom}} = V_{\text{DC, max}} + V_{R_0} \]

So, the maximum voltage stress in the switch is around \( \approx 530 \, V \), which can also be verified by the voltage waveform across the windings during simulation.

- Unlike other converters there is only capacitor in the output side (no inductor) so its value should be carefully selected, infact larger capacitor is used to ensure that it can supply the requirements of load during switch ON time.

- The output voltage and current are discontinuous due to ESR of the capacitor, however the average output voltage and current are approximately 16.6V and 300 mA.

- Pulsating current can also be fed to LED (without output capacitor) as mentioned in the beginning but would increase load peak and RMS current and may cause EMI problems.

- The voltage across the winding obeys the turn’s ratio relation while the instantaneous winding current does not obey. \( V_p / V_s = N_p / N_s \)

- The output current starts to flow after several switching cycle and for some initial cycles the current is 0 and voltage rises steadily.

Controller Design

- Control to output transfer function is a second order with 2 zeros one of which lies in RHP. Hence the flyback converter’s power stage is a non-minimum phase system.

- The crossover frequency of closed loop system is limited due to RHP zero. The \( f_c \) should be within one fifth of the position of RHP zero. However due to closeness of the RHP with the resonant poles the full available theoretical bandwidth could not be attained.

- For better performance the Current mode control can be used which uses dual loop and the problem of RHP zero can be negated and a faster responsive system can be attained.

- The flyback can be operated in the DCM mode which is also the preferred mode of operation for low powered applications and provides simplified feedback compensation/higher bandwidth due to absence of RHP zero. Furthermore core size is also reduced and is suitable for high voltage low current application like LED Driver.