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A New Procedure for High-Frequency Electronic Ballast Design

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***Abstract* - A new and simple procedure has been developed which allows for rapid design and component selection for the output stage of high-frequency electronic ballasts. The procedure predicts pre-heat, ignition and running conditions based on fluorescent lamp manufacturer's specifications. This approach has been used to design commercial high-frequency electronic ballasts.**

I. INTRODUCTION

Designing a high-frequency electronic ballast output stage and choosing component values for various lamp types can be a difficult engineering challenge with many hidden pitfalls. As new lamp types emerge on the market, with virtually no high-frequency lamp data available, the task of designing the output stage becomes even more difficult. The purpose of this paper is to present a design procedure that solves for the operating points based on given lamp data. The paper includes the design approach, the model, lamp requirements and actual ballast design. The designer will obtain an understanding of the relative and absolute locations of the operating points and gain further insight to the nature of this deceptively simple-appearing circuit.

II. DESIGN APPROACH

The functions performed by present day electronic ballasts include electromagnetic interference (EMI) filtering to block ballast generated noise, rectification, power factor correction (PFC) for sinusoidal input current, undervoltage lockout (UVLO) and fault protection, half-bridge switches with driver and timing for high-frequency operation, and final output stage to power the lamp (Figure 1). The focus of this paper is on the design of the output stage using a simplified model (Figure 2). This is presently one of the most popular approaches to powering a fluorescent lamp at high-frequency [1].

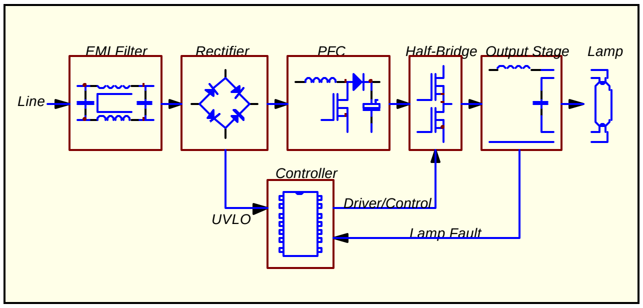

Figure 1, Ballast functional block diagram.

The lamp requires a current for a specified time to preheat the filaments, a high-voltage for ignition, and running power. These requirements are satisfied by changing the frequency of the input voltage and properly selecting Vin, L and C. For preheat and ignition, the lamp is not conducting and the circuit is a series L-C. During running, the lamp is conducting, and the circuit is an L in series with a parallel R-C.

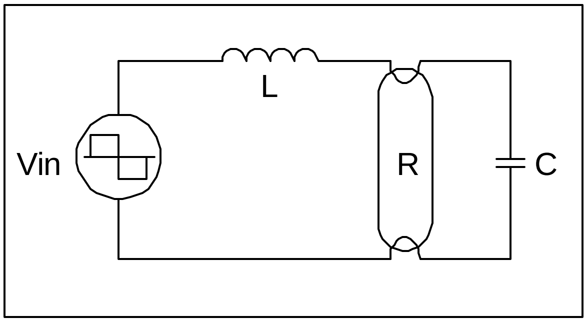

Figure 2, Output stage simplified model.

The magnitude of the transfer function (lamp voltage divided by input voltage) for the two circuit configurations, illustrates the operating characteristics for this design approach (Figure 3). The currents and voltages corresponding to the resulting operating frequencies determine the maximum current and voltage ratings for the

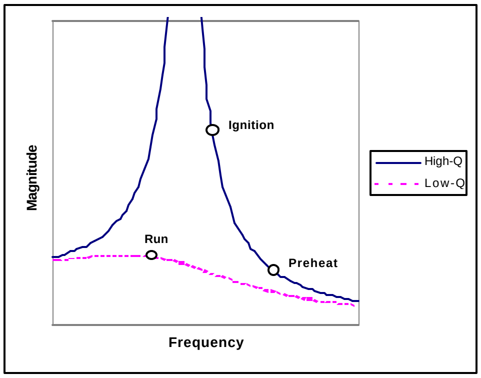

Figure 3, Transfer function of RCL circuit with typical operating points.

inductor, capacitor and the switches, which, in turn, directly determine the size and cost of the ballast.

III. THE MODEL

The model consists of a set of equations for each operating frequency and the corresponding lamp voltage and circuit currents. These operating frequencies are a function of L, C, input voltage, filament pre-heat current, ignition voltage, lamp running voltage and power. During preheat, the resistance of the lamp is assumed to be infinite and the filament resistance negligible, resulting in an L-C series circuit. Using the impedance across the capacitor, the preheat frequency is:

$$f_{ph} = \frac{I_{ph}}{2pCV_{ph}} \text{ [Hz]} \tag{1}$$

and the transfer function is,

$$\frac{V_{ph}}{\frac{4V_{in}}{p}} = \frac{1}{\left|1 - 4LCp^2 f_{ph}^2\right|} \tag{2}$$

Solving **(1)** and **(2)** simultaneously yields,

$$V_{ph} = -\frac{2V_{in}}{p} + \sqrt{\left(\frac{2V_{in}}{p}\right)^2 + \frac{L}{C} I_{ph}^2} \tag{3}$$

where,

V_{in} = Input square-wave voltage amplitude [Volts]
V_{ph} = Lamp preheat voltage amplitude [Volts]
I_{ph} = Filament preheat current amplitude [Amps]
L = Output stage inductor [Henries]
C = Output stage capacitor [Farads]

Note that the linear analysis uses the fundamental frequency of the square-wave produced by the half-bridge switches. Square-wave harmonics are assumed negligible and the practical implementation of the square-wave which includes switching deadtime, current circulation paths and snubbing has been considered in selecting the fundamental frequency for the model.

During ignition, the frequency for a given ignition voltage can be found using **(2)**, since the lamp is still an open circuit,

$$f_{ign} = \frac{1}{2p}\sqrt{\frac{1 + \frac{\frac{4}{p}V_{in}}{V_{ign}}}{LC}} \text{ [Hz]} \tag{4}$$

where,

V_{ign} = Lamp ignition voltage amplitude [Volts]

The associated ignition current amplitude [Amps] flowing in the circuit that determines the maximum current ratings for the L and half-bridge switches, becomes:

$$I_{ign} = f_{ign} C V_{ign} 2p \tag{5}$$

Once the lamp has ignited, the resistance of the lamp is no longer negligible, and the system becomes a low-Q RCL series-parallel circuit with a transfer function,

$$\frac{V_{run}}{\frac{4V_{in}}{p}} = \frac{1}{\sqrt{(1 - LCw^2)^2 + \frac{L^2}{R^2}w^2}} \tag{6}$$

The running frequency [Hz] becomes:

$$f_{run} = \frac{1}{2p}\sqrt{\frac{1}{LC} - \frac{1}{2R^2C^2} + \sqrt{\left[\frac{1}{LC} - \frac{1}{2R^2C^2}\right]^2 - \frac{1 - \left(\frac{4V_{in}}{V_{run}p}\right)^2}{L^2C^2}}} \tag{7}$$

where R is assumed to be the linearized lamp resistance determined from the running lamp power and voltage at a single operating point:

$$R = \frac{V_{run}^2}{2P_{run}} \text{ [Ohms]} \tag{8}$$

where,

P_{run} = Lamp running power [Watts]

V_{run} = Lamp running voltage amplitude [Volts]

IV. LAMP REQUIREMENTS

The procedure is used to design a ballast output stage based on preheat, ignition and running lamp requirements. For preheat, a current must be defined, I_{ph}, which adequately heats the lamp filaments to their correct emission temperature within a defined time. The series connection of the lamp filaments with the capacitor defines the preheat mode as *current-controlled*. The model therefore calls for a constant current flowing through the filaments as opposed to a constant voltage over the filaments as in *voltage-controlled* preheat mode. Because of the lamp life sensitivity to preheat current, this value is not commonly listed in the lamp manufacturers data sheet. Because of tolerances from lamp to lamp and differences in the electron-emitting filament coating mix from manufacturer to manufacturer for the same lamp type, the author highly recommends that the designer choose the preheat current experimentally and verify it over all lamp manufacturers with lamp life switching cycle tests. The preheat current should heat the filaments to a warm to cold resistance ratio of 3:1 within an acceptable preheat time.

The maximum allowable voltage over the lamp during preheat, V_{ph}, must be less than the minimum voltage required to ignite the lamp. Should the lamp voltage exceed this value during preheat, the lamp can ignite before the filaments have been sufficiently heated, affecting the life of the lamp. This voltage is a function of ambient temperature, frequency and distance from the lamp to the nearest earth plane (usually the fixture).

The minimum voltage required to ignite the lamp, V_{ign}, increases with decreasing lamp temperature and/or insufficient preheating, and increases with increasing distance from the lamp to the nearest earth plane.

During running, the lamp should be driven at the manufacturer's recommended lamp power, P_{run}, and voltage, V_{run}.

For a 36W/T8 linear lamp type, the lamp requirements are determined to be:

I_{ph} = 0.85 [Amps]
V_{ph} = 300 [Volts]
V_{ign} = 550 [Volts]
P_{run} = 32 [Watts]
V_{run} = 141 [Volts]

With each operating point now bounded for the given lamp type, the procedure can be used to calculate frequencies and component values.

V. BALLAST DESIGN

A breadboard was designed, built and tested for performance. The input stage was designed for universal input, high PF and low total harmonic distortion (THD) using a generic PFC IC. The International Rectifier IR21571 Ballast Controller IC [2] was used to program the operating frequencies. The IR21571 is a crucial block that provides a flexible control sequence (Figure 4) for the preheat time and a smooth transition to each operating point, as well as over-current protection against failure to strike and lamp presence detection for open-filament protection or lamp removal. The procedure was used to choose the L, C and frequencies of the output stage for a 36W/T8 lamp and they were used to select the component values comprising the programmable inputs of the IR21571 (Figure 5). Choosing an L and a C for a given lamp type entails a careful inspection of the operating frequencies and where they lie with respect to one another. The procedure may require some iterations until the operating points are acceptable.

The first step is to calculate an L based on the power in the lamp during running. For an optimum transfer of energy to the low-Q RCL circuit, an optimal dimensioning of L and C would set their physical size to just match the maximum power requirement. This occurs at the resonant frequency of the low-Q circuit, and at maximum power transfer half of the input voltage (half of Vin) will be across L, where the output stage input power [Watts] is:

$$P_{in} = \frac{4V_{in}}{\sqrt{2}\pi} I_{in} = \frac{4V_{in}}{\sqrt{2}\pi}\left(\frac{V_{in}}{2L\omega}\right) = \frac{P_{run}}{\eta} \qquad \textbf{(9)}$$

The output stage efficiency, η, takes into account switching and conductive losses in the half-bridge switches and resistive losses in L and the filaments. Solving for L as a function of lamp power yields:

$$L = \frac{V_{in}^2 \eta}{f_{run}\sqrt{2}\pi^2 P_{run}} \quad \text{[Henries]} \qquad \textbf{(10)}$$

Selecting a reasonable running frequency of about 35kHz, assuming an efficiency of 0.95, and setting the DC bus to 400VDC for universal input (Vin = 200V), gives an L = 2.5mH for a lamp power of 32W. How good this value is for L depends on the dimensioning of C (discussed below) and how well the other operating conditions are fulfilled.

To select C, the model was used to generate a set of curves for frequency versus C for the preheat, ignition and running operating points (Figure 6). The open-loop control sequence of the IR21571 (Figure 4) consists of starting at a high frequency for a flash-free start during the first few pulses of the half-bridge before ramping quickly to the preheat frequency for the duration of the preheat time. After preheat has ended, the frequency is ramped down further to the ignition frequency for the duration of the ignition ramp, after which the frequency is increased to the final run frequency. Should the lamp fail to strike, the voltage across the current sensing resistor will exceed an internal threshold voltage during the ignition ramp mode, and the internal high and low-side driver will turn both half-bridge switches off. Automatic restart is achieved by cycling the voltage on the shutdown pin above and below 2V. This control sequence places a design constraint on the values for L and C of $f_{ph} > f_{ign}$.

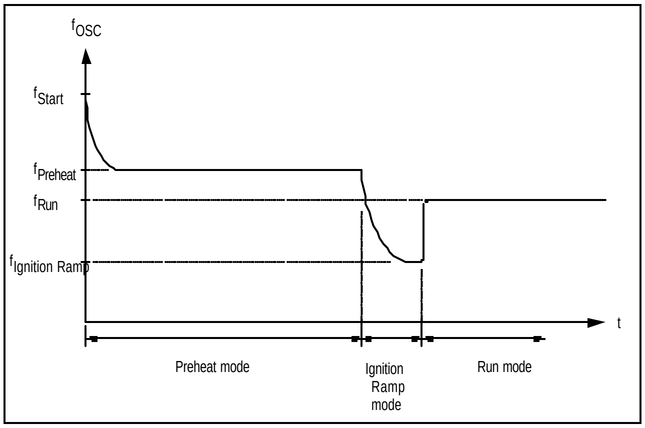

Figure 4, IR21571 ballast control sequence.

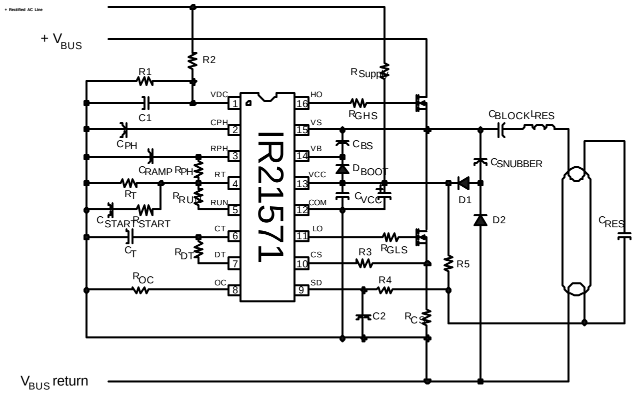

Figure 5, IR21571 Ballast Control IC typical application schematic.

From the plot, it can be seen that there exists several values of C which fulfill the control sequence constraint, however, the lower the value of C, the narrower the range of frequency between preheat and ignition. These narrow ranges may give tolerance problems during production. A higher C value such as 10nF gives a larger frequency range between operating points. Another trade-off associated with C is that the higher the C value, the lower the lamp voltage during preheat, but, the ignition current associated with the defined worst-case ignition voltage increases. All of these parameters should be carefully checked with each new L and C combination, as summarized in a chart consisting of six design steps for the selection procedure (Figure 7).

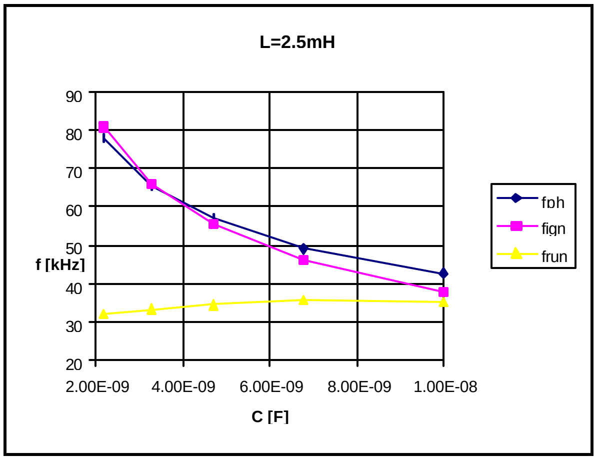

Figure 6, Frequency vs. C for different operating points.

With a chosen L and C of 2.5mH and 10nF, and the operating frequencies calculated, the corresponding programmable inputs of the IR2157 are calculated with the following design equations:

$$R_T = \frac{1.33}{C_T}\left(\frac{1}{2 f_{ign}} - 0.56 \cdot R_{DT} \cdot C_T\right)[\text{Ohms}] \qquad \textbf{(11)}$$

$$R_{run} = \frac{\frac{1}{C_T}\left(\frac{1}{2 f_{run}} - t_{deadtime}\right)}{1 - \frac{1}{R_T C_T}\left(\frac{1}{2 f_{run}} - t_{deadtime}\right)}[\text{Ohms}] \qquad \textbf{(12)}$$

$$C_{PH} = \frac{t_{ph}}{5.15E6} \qquad [\text{Farads}]$$

(13)

$$R_{PH} = \frac{\frac{1.33}{C_T}\left(\frac{1}{2 f_{ph}} - 0.56 \cdot R_{DT} \cdot C_T\right)}{1 - \frac{1.33}{R_T C_T}\left(\frac{1}{2 f_{ph}} - 0.56 \cdot R_{DT} \cdot C_T\right)} \qquad [\text{Ohms}] \qquad \textbf{(14)}$$

$$R_{DT} = \frac{1.79 t_{deadtime}}{C_T} \qquad [\text{Ohms}] \qquad \textbf{(15)}$$

$$C_{IGN} = \frac{t_{ign}}{3R_{PH}} \qquad \text{[Farads]}$$

(16)

$$R_{CS} = \frac{R_{OC} \cdot 50uA}{I_{ign}} \qquad \text{[Ohms]} \qquad \textbf{(17)}$$

1. Select lamp and specify $P_{run}, V_{run}, V_{ph_{\max}}, V_{ign_{\max}}, I_{ign_{\max}}$
2. Select $f_{run\,\min}$
3. Select Vin
4. Calculate L
5. Calculate $f_{ph}, f_{ign}, f_{run}, V_{ph}, I_{ign}$
6. Select C such that:
   - $\exists\, f_{ph} - f_{ign} > 5kHz$
   - $\exists\, I_{ign} < I_{ign_{\max}}$
   - $\exists\, V_{ph} < V_{ph_{\max}}$

Figure 7, Summary of design steps for selection of L and C.

Choosing $t_{ph} = 2.0s, t_{deadtime} = 1.2E-6s, t_{ign} = 0.05s$ and $C_T = 1E-9F$ yields $R_{DT} = 2000\Omega, R_T = 20000\Omega, R_{PH} = 56000\Omega,$ $R_{CS} = 0.8\Omega, C_{PH} = 470E-9F$ and $C_{IGN} = 330E-9F$. All other diodes, capacitors and resistors shown (Figure 5) are needed for such standard functions as IC power-up, snubbing, bootstrapping and DC blocking. Should the final run frequency need to be greater than the ignition frequency, resistor Rrun can be added which is connected in parallel with RT after the lamp has ignited, therefore raising the frequency back up above the ignition frequency to the final run frequency.

The breadboard was measured and compared with the predicted model values. Figures 8, 9 and 10 show operating frequency, lamp voltage and inductor current for preheat, ignition and running conditions. During preheat and ignition, the voltage and current waveforms are sinusoidal. During running, the effects of the non-linear resistance of the lamp can be seen on the lamp voltage. To measure the maximum voltage and current available for ignition (Figure 9), the lamp was removed and substitute filament resistors were inserted to simulated a deactivated lamp. This allows the frequency to ramp down from preheat to ignition along the high-Q transfer function (Figure 3) until the current limit of the IR21571 is reached and the half-bridge switches turn off.

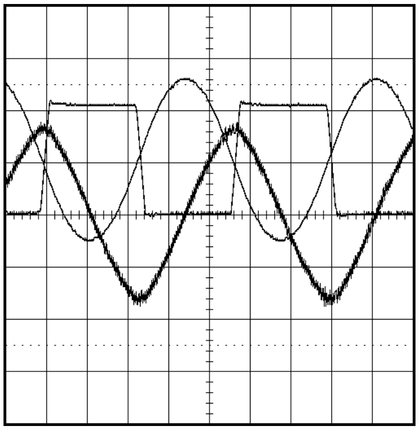

Figure 8, Preheat current (lower trace, 500mA/div), preheat lamp voltage (upper trace, 200V/div) and input voltage (middle trace, 200V/div). Timescale = 5us/div.

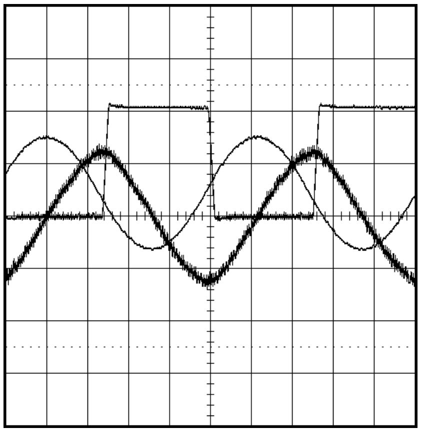

Figure 9, Ignition current (lower trace, 1A/div), ignition lamp voltage (middle trace, 500V/div) and input voltage (upper, 200V/div). Timescale = 5us/div.

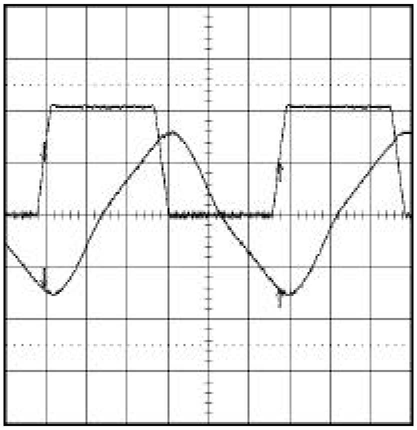

Figure 10, Running voltage (lower trace, 100V/div) and input voltage (upper, 200V/div). Timescale = 5us/div.

The measured and predicted frequencies match within 3% (Table 1), while other lamp types and component selections can deviate as much as 10%. Such deviations are expected due to the neglected harmonics, non-linear lamp resistance, filament resistance, inductor losses and tolerances in lamp manufacturing, Vin, L and C. Another iteration in the component selection process may be necessary.

Parameter	Model	Measured
f_{ph}	42.8 kHz	42.6 kHz
f_{ign}	38.5 kHz	38.8 kHz
f_{run}	35.3 kHz	34.4 kHz
V_{ph}	632 V	625 V
I_{ign}	1.5 A	1.2 A

Table 1, Predicted and measured values for F36T8 ballast output stage.

An IR21571 ballast demonstration board (Figure 11) was constructed using the above approach, and the output stage was dimensioned for single lamp operation. Temperature, lifetime, performance margins, packaging, layout, manufacturablity and cost were all considered during the design process.

VI. CONCLUSIONS

This procedure has yielded good results in predicting the operating points for several different lamp types ranging in both geometry (linear and compact types) and power (all wattages). This procedure has greatly reduced the time needed to dimension the ballast for different lamp types on the market and has been an effective and useful tool for optimizing ballast size and cost. This procedure has also helped to reduce the number of ballast product families and increase manufacturablility. Improvements are being done on the model to include non-linear lamp characteristics [3] and dimming for upcoming ballast ICs: IR2158 (closed-loop, non-dimming) and IR2159 (dimming) [4].

Defining lamp requirements can be more of an art rather than a straight forward process. However, the International Electrotechnical Commission (IEC) is currently working on IEC 81, which includes data sheets intended for use in designing high-frequency ballasts.

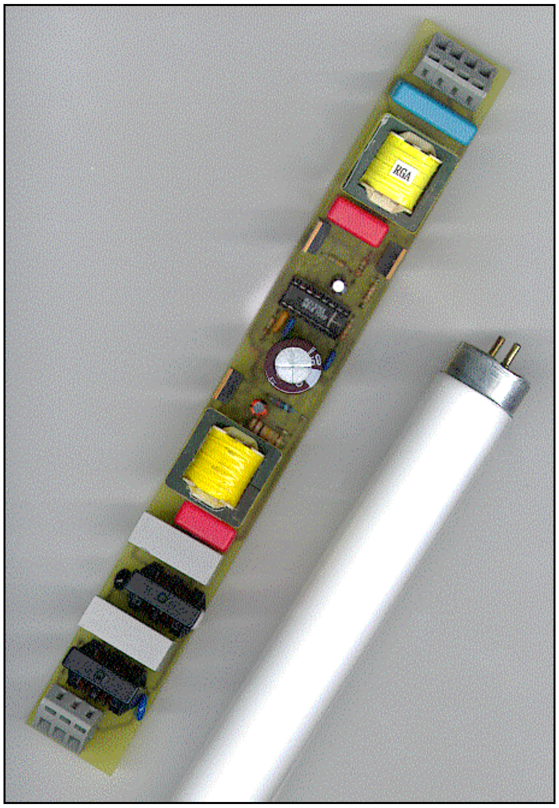

Figure 11, IRPLLNR2E 36W/T8 ballast demonstration board.

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