

## Time Domain Modeling of Ballast Resonant Converters

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**Abstract** - A simple time-domain model has been developed which allows for rapid design and component selection for the resonant output stage of high-frequency electronic ballasts. The model predicts ballast pre-heat, ignition and running modes based on fluorescent lamp requirements. This approach has been used to design commercial high-frequency electronic ballasts.

### I. INTRODUCTION

Many methods exist for designing the resonant output stage of electronic ballasts. These include running computer simulations, solving closed-form equations, trial-and-error prototyping of the actual circuit, or (usually the reality) a mixture of all three. Computer simulations are very convenient for generating time and frequency domain waveforms, but many simulations are necessary for scaling component values, simulation time is necessary for each run, and the cost and learning of the software can be significant. Closed-form equations can be difficult to solve and time consuming such that it becomes impractical. Building prototypes on the bench is inevitable regardless of the method used because the design has to be verified for functionality and manufacturability. The model presented in this paper is a simple and fast design method that can be implemented using a simple spreadsheet program and gives time-domain solutions that can be compared to actual bench measurements.

### II. BALLAST OUTPUT STAGE

The focus of this paper is on the design of the output stage using a simplified model (Figure 1). The circuit consists of an input square-wave voltage source (VIN), a resonant inductor (L), a DC blocking capacitor (CDC), a lamp (R) and a resonant capacitor (C).

The lamp requires current to preheat the filaments, high-voltage for ignition, and current during running. These requirements are satisfied by properly selecting L, C and the amplitude and period of VIN. During preheat and ignition modes, the lamp is not conducting and the circuit is a series L-C. During running mode, the lamp is

conducting, and the circuit is an L in series with a parallel R-C. The capacitor CDC is necessary for blocking the DC component of VIN and is typically  $\gg C$ .

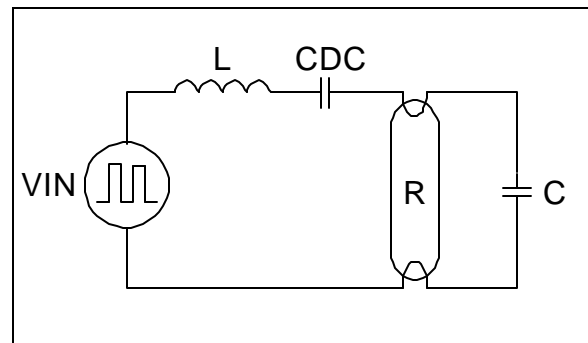


Figure 1. Ballast output stage simplified model.

### III. THE MODEL

The model consists of a set of differential equations for the circuit voltages and currents during each ballast operating mode. A simple numerical analysis approach is then used where the equations are solved iteratively at small increments of time. The resulting waveforms are a function of VIN, L, CDC, R and C.

During preheat and ignition modes, the resistance of the lamp is assumed to be infinite and the filament resistance negligible, resulting in an LC series circuit. Applying Kirchoff's Voltage Law around the loop gives:

$$V_{IN} \approx L \frac{di_L}{dt} \approx \frac{1}{CDC} \int i_L dt \approx \frac{1}{C} \int i_L dt \quad (1)$$

Solving for the various voltages and currents gives:

$$i_{L_n} \approx \frac{dt}{L} \int V_{IN_{n+1}} \approx V_{CDC_{n+1}} \approx V_{C_{n+1}} \int i_{L_{n+1}} \quad (2)$$

$$V_{L_n} \approx \frac{L}{dt} \int i_{L_n} \approx i_{L_{n+1}} \quad (3)$$

$$V_{CDC_n} \approx \frac{dt}{CDC} \int i_{L_n} \approx \frac{i_{L_n} \int i_{L_{n+1}}}{2} \approx V_{CDC_{n+1}} \quad (4)$$

$$V_{C_n} \approx \frac{dt}{C} \int i_{L_n} \approx \frac{i_{L_n} \int i_{L_{n+1}}}{2} \approx V_{C_{n+1}} \quad (5)$$

During running mode, the resistance of the lamp is no longer negligible, and the circuit becomes a series-L/parallel-RC. Applying Kirchoff's Voltage Law around both loops gives:

$$V_{IN} \approx L \frac{di_L}{dt} \approx \frac{1}{CDC} \int i_L dt \approx i_R \approx R \quad (6)$$

$$i_R \approx R \approx \frac{1}{C} \int i_C dt \quad (7)$$

Applying Kirchoff's Current Law at the common node gives:

$$i_L \approx i_R \approx i_C \quad (8)$$

Solving for the various voltages and currents gives:

$$i_{L_n} \approx \frac{dt}{L} \int V_{IN_{n+1}} \approx V_{CDC_{n+1}} \approx V_{R_{n+1}} \int i_{L_{n+1}} \quad (9)$$

$$V_{L_n} \approx \frac{L}{dt} \int i_{L_n} \approx i_{L_{n+1}} \quad (10)$$

$$V_{CDC_n} \approx \frac{dt}{CDC} \int i_{L_n} \approx \frac{i_{L_n} \int i_{L_{n+1}}}{2} \approx V_{CDC_{n+1}} \quad (11)$$

$$i_{R_n} \approx \frac{i_{L_n} \int dt}{2C} \approx V_{R_{n+1}} \quad (12)$$

$$R \approx \frac{dt}{2C} \quad (13)$$

$$i_{C_n} \approx i_{L_n} \approx i_{R_n} \quad (13)$$

To plot the various waveforms, the equations are calculated at each iteration of  $n$  which corresponds to each new  $dt$  increment of time.

#### IV. BALLAST DESIGN

An electronic ballast prototype was designed, built and measured against the model. The IR2520D Adaptive Ballast Control IC (Figure 2) was used to control the ballast. The IR2520D is a new IC that provides a simple control sequence (Figure 3) for preheat, ignition and running modes, as well as protection against brown-out, lamp non-strike, open-filament and lamp removal fault modes.

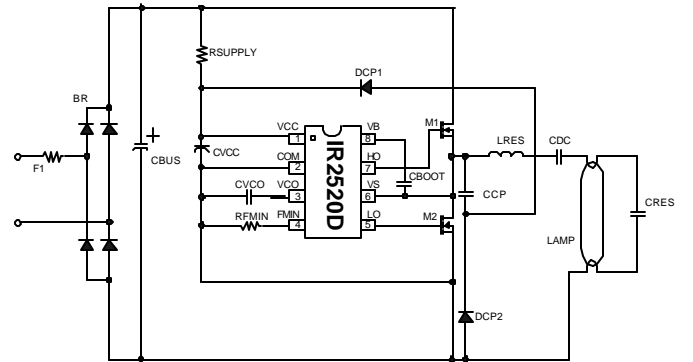


Figure 2. IR2520D ballast schematic.

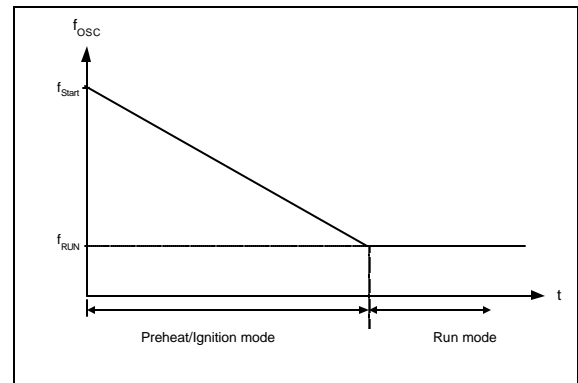


Figure 3. IR2520D ballast control sequence.

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

$$\begin{aligned}
 I_{ph} &= 0.85 \quad \text{Amps Peak} \\
 V_{ph_{max}} &= 300 \quad \text{Volts Peak} \\
 V_{ign_{max}} &= 550 \quad \text{Volts Peak} \\
 R &= 310 \quad \text{Ohms}
 \end{aligned}$$

The additional ballast specifications are chosen to be:

$$\begin{aligned}
 f_{run} &= 35 \quad \text{kHz} \quad (\text{Running frequency}) \\
 V_{IN} &= 400 \quad \text{Volts} \quad (\text{DC Bus voltage}) \\
 t_{ph} &= 1.0 \quad \text{Seconds} \quad (\text{Preheat time})
 \end{aligned}$$

Using the model equations and waveforms directly, L and C are then adjusted until the lamp and ballast requirements are fulfilled. The inductor (L) primarily sets the nominal lamp power at the desired running frequency. The capacitor (C) primarily sets the preheat frequency and current while keeping the preheat voltage below the maximum. The combination of both sets the resonance frequency for ignition. The waveforms for preheat, ignition and running modes should all be carefully inspected and iterations on L, C and frequency are usually required to meet the desired specifications. The final component values from the model are determined to be:

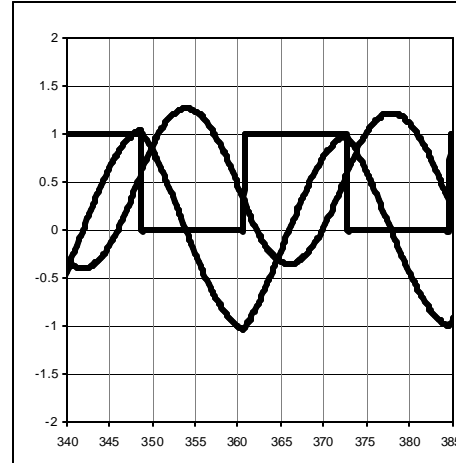
$$\begin{aligned}
 L &= 2.5 \text{ mH} \\
 C &= 10 \text{ nF} \\
 C_{DC} &= 0.1 \mu\text{F}
 \end{aligned}$$

The programmable components for the IR2520D Control IC are then set as:

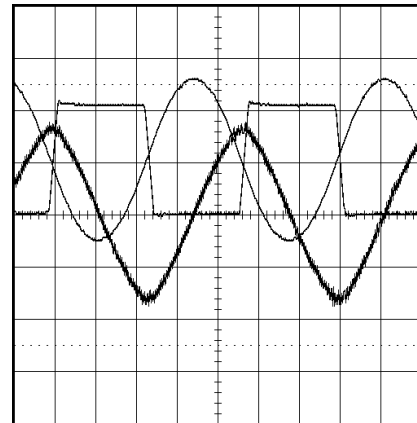
$$\begin{aligned}
 R_{FMIN} &= 75 \quad \text{kOhm} \quad (\text{Sets run frequency}) \\
 C_{VCO} &= 0.33 \quad \mu\text{F} \quad (\text{Sets preheat time})
 \end{aligned}$$

All other diodes, capacitors and resistors shown (Figure 2) are needed for such standard functions as AC line rectification, IC micro-power start-up, EMI snubbing and VCC supply.

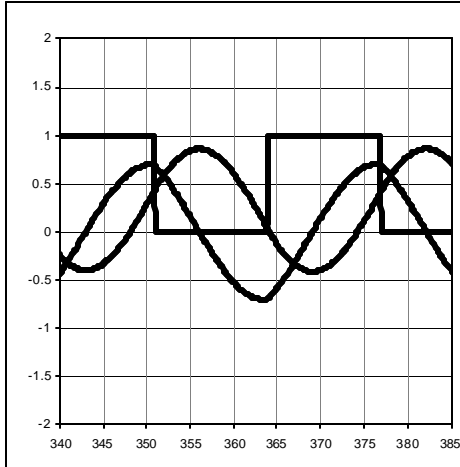
The prototype was measured and compared with the simulated model values. Figures 4, 5, 6, 7, 8 and 9 show the input voltage (VIN), lamp voltage (VC) and inductor current (IL) for preheat, ignition and running modes for both the simulated and measured results.



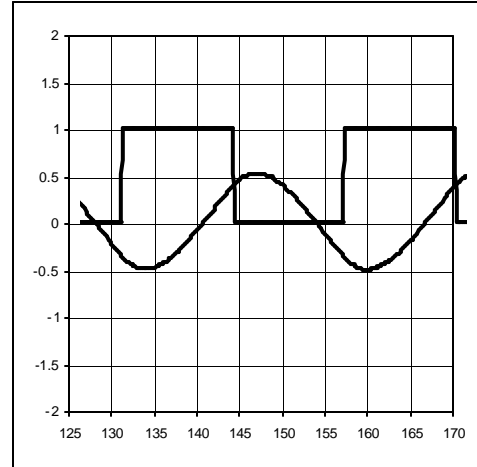
**Figure 4.** Simulated preheat waveforms.  
 Filament current IL (lower trace, 0.5A/div)  
 Lamp Voltage VC (upper trace, 200V/div)  
 Input voltage VIN (middle trace, 200V/div)  
 Timescale = 5us/div.



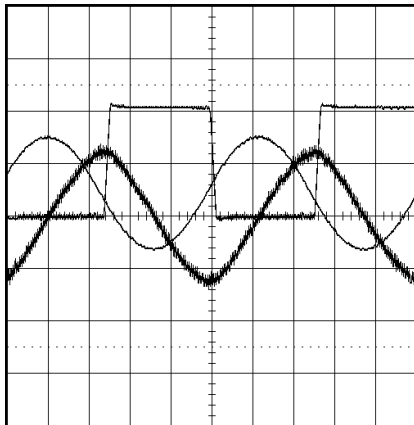
**Figure 5.** Measured preheat waveforms.  
 Filament current IL (lower trace, 0.5A/div)  
 Lamp Voltage VC (upper trace, 200V/div)  
 Input voltage VIN (middle trace, 200V/div)  
 Timescale = 5us/div.



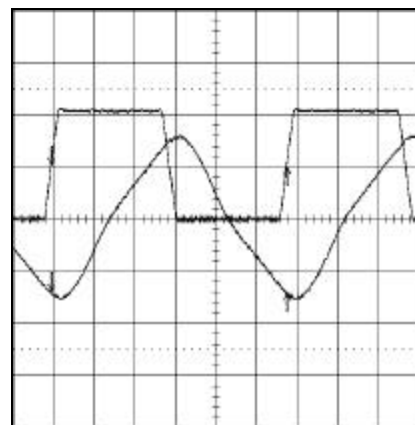
**Figure 6.** Simulated ignition waveforms.  
 Inductor current  $I_L$  (lower trace, 1A/div)  
 Lamp Voltage  $V_C$  (upper trace, 500V/div)  
 Input voltage  $V_{IN}$  (middle trace, 200V/div)  
 Timescale = 5 $\mu$ s/div.



**Figure 8.** Simulated running waveforms.  
 Lamp Voltage  $V_R$  (lower trace, 100V/div)  
 Input voltage  $V_{IN}$  (upper trace, 200V/div)  
 Timescale = 5 $\mu$ s/div.



**Figure 7.** Measured ignition waveforms.  
 Inductor current  $I_L$  (lower trace, 1A/div)  
 Lamp Voltage  $V_C$  (upper trace, 500V/div)  
 Input voltage  $V_{IN}$  (middle trace, 200V/div)  
 Timescale = 5 $\mu$ s/div.



**Figure 9.** Measured running waveforms.  
 Lamp Voltage  $V_R$  (lower trace, 100V/div)  
 Input voltage  $V_{IN}$  (upper trace, 200V/div)  
 Timescale = 5 $\mu$ s/div

The measured and predicted frequencies match within 5% (Table 1), while other lamp types and component selections can deviate as much as 10%. Such deviations are expected due to the non-linear lamp resistance, filament resistance, inductor losses and tolerances in R, VIN, L, C and frequency.

| Parameter | Model    | Measured |
|-----------|----------|----------|
| $I_{ph}$  | 0.85 Apk | 1.0 Apk  |
| $V_{ph}$  | 310 Vpk  | 300 Vpk  |
| $V_{ign}$ | 625 Vpk  | 550 Vpk  |
| $I_{ign}$ | 1.4 Apk  | 1.2 Apk  |
| $V_{run}$ | 110 Vpk  | 150 Vpk  |

Table 1, Modeled and measured values for F36T8 Ballast prototype.

## VI. CONCLUSIONS

The new model has given good results for predicting the measured ballast parameters. This model is a more simple and direct method for generating the final ballast waveforms and will greatly decrease design time. Modeling of the actual time domain waveforms allows the designer to better understand the nature of the circuit and matches better the final design environment on the bench. This method is easily implemented into a simple spreadsheet program and results are obtained instantly as component values are adjusted.

Future improvements include modeling of the half-bridge switches, dimming and non-linear lamp characteristics.

## REFERENCES

- [1] Elenbaas, W., ed., *Fluorescent Lamps*, Second Edition, Philips Technical Library, Eindhoven, The Netherlands 1971.
- [2] International Rectifier, *IR2520D Adaptive Ballast Control IC*, Data Sheet, 2003, [www.irf.com](http://www.irf.com)
- [3] T. Ribarich, J. Ribarich, *A New High-Frequency Fluorescent Lamp Model*, in *IEEE-IAS Conf. Rec.*, 1998.
- [4] T. Ribarich, J. Ribarich, *A New Control Method for Dimmable High-Frequency Electronic Ballasts*, in *IEEE-IAS Conf. Rec.*, 1998.
- [5] U. Mader and P. Horn, "A Dynamic Model for the Electrical Characteristics of Fluorescent Lamps", *IEEE IAS 1992*, pp. 1928-1934
- [6] S.L. Salas and Einar Hille, "Calculus: One and Several Variables", John Wiley and Sons, Canada, 1982.