

# How to design a dimming fluorescent electronic ballast

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Dimming fluorescent lamps is an attractive feature that provides mood and brightness effects as well as having tremendous energy savings potential. Designing a dimmable electronic ballast, however, is a complicated and challenging task. This paper presents an overview for designing a dimming electronic ballast for a T5 35W lamp. Lamp requirements, dimming control methods, and resonant output stage design are all discussed in this paper. A new ballast design software program is also demonstrated which greatly aids with the design of the dimming ballast and generates the necessary schematic and bill of materials for prototyping. Finally, a fully-functional prototype is built, tested and compared against original design results.

## Lamp Requirements

A fluorescent lamp requires preheating of the filaments, a high ignition voltage to strike, current or power control for dimming, and additional filament heating during low dimming levels. To understand how a dimming fluorescent lamp works, a simple resistive model for the lamp is used (Figure 1). The lamp resistance ( $R_{lamp}$ ) is connected between each filament resistor pair ( $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$ ).

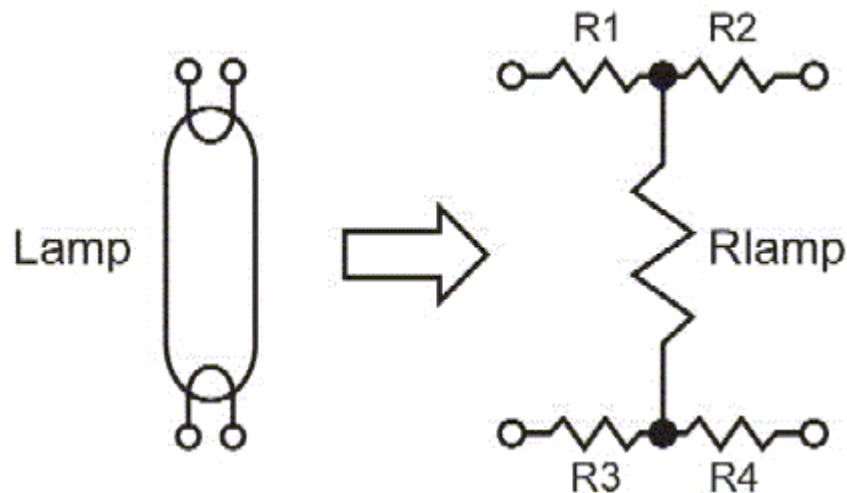


Figure 1, Resistive lamp model

During dimming, the current flowing through the lamp resistance determines the lamp power and brightness. At low brightness levels (typically below 20%), the lamp requires additional heating current through the filament resistors for maintaining the arc. To calculate the equivalent lamp resistance some basic electrical lamp parameters must first be known (Table I).

Parameter	Value	Units	Description
$t_{ph}$	1.0	sec	Filament preheat time
$V_{ign}$	900	Volts	Ignition voltage amplitude to strike the lamp
$P_{100\%}$	35	Watts	Lamp power at 100% brightness
$V_{100\%>}$	310	Volts	Lamp voltage amplitude at 100% brightness
$P_{5\%>}$	0.7	Watts	Lamp power at 5% brightness
$V_{5\%}$	425	Volts	Lamp voltage amplitude at 5% brightness
$R_{Lamp100\%}$	1.4	k $\Omega$	Equivalent lamp resistance at 100% brightness
$R_{Lamp5\%}$	129	k $\Omega$	Equivalent lamp resistance at 5% brightness
$R_{1,2,3,4}$	10	&Omega;	Cold filament resistances

Table I, Typical 35W/T5 lamp requirements

The lamp resistance [Ohms] at the corresponding % dimming level is determined from the running lamp power and voltage:

$$R_{Lamp\%} = \frac{V_{\%}^2}{2P_{\%}} \quad (1)$$

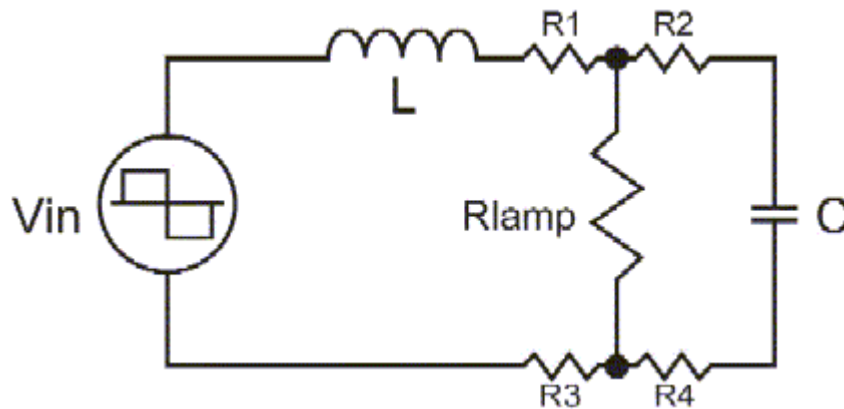
where,

$P_{\%}$ = Lamp power at % dimming level [Watts]  $V_{\%}$ = Lamp voltage amplitude at % dimming level [Volts]

The lamp manufacturer does not typically specify the filament resistor values so they must be measured directly on the bench across one end of the lamp. The exact location where the arc leaves the filament (hot spot) is not known. For purposes of the model, the hot spot is assumed to be exactly in the middle of each filament, therefore,  $R_1=R_2=R_3=R_4= 1/2 \times$  (total resistance measured across one filament). Also, the filament resistance is a strong function of temperature so the values given are measured at cold.

## Resonant output stage

A resonant RCL output stage is used to control the fluorescent lamp (Figure 2). The resonant behavior of the circuit is used to preheat, ignite and dim the lamp. During preheat, the lamp is not conducting and the circuit is a high-Q series L and C. The frequency is held constant and above resonance for a fixed time to preheat the filaments with a given current.



*Figure 2, Resonant lamp output stage simplified model*

After preheat, the frequency is swept down smoothly towards resonance to generate a high voltage for ignition (Figure 3). After ignition, the lamp is conducting and the circuit is an L in series with a parallel R and C. The frequency continues to decrease to the final frequency where 100% brightness is achieved. By properly selecting the amplitude and frequency of  $V_{in}$ , and the values of L and C, all of the lamp requirements can be satisfied. For dimming, the frequency is increased to decrease the lamp current and the Q-factor of the circuit changes depending on the lamp resistance.

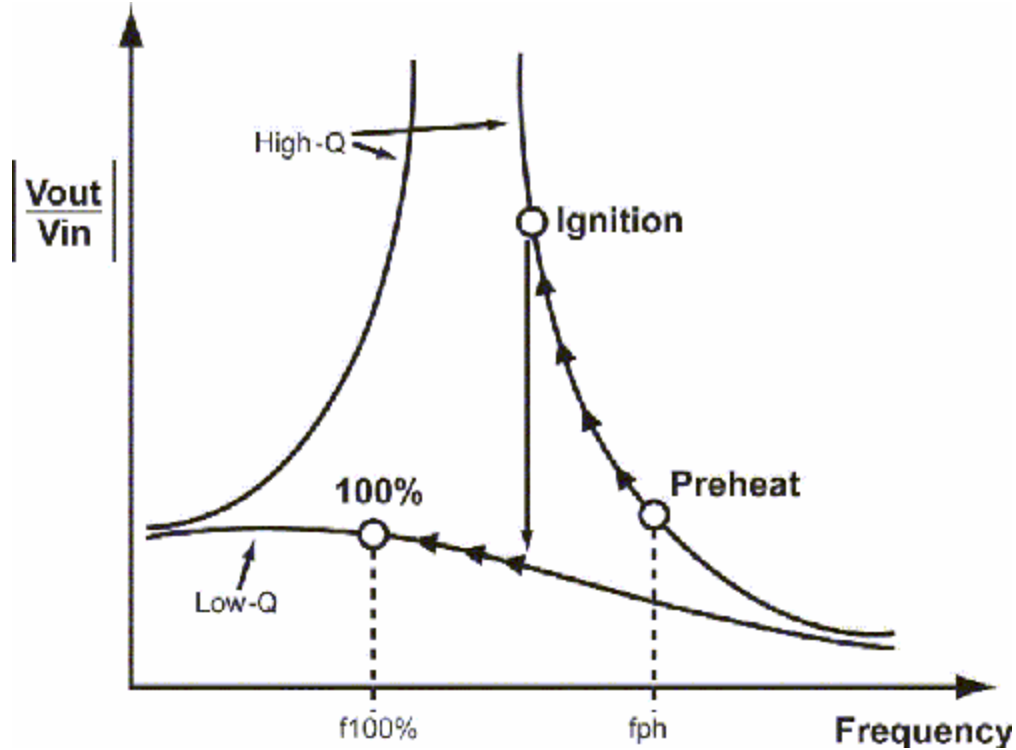


Figure 3, Resonant tank Bode plot with lamp operating points

To design the output stage for a specific lamp type, it is necessary to calculate the preheat, ignition and dimming operating frequencies. The frequency [Hertz] as a function of lamp power is derived from the output to input voltage transfer function of the ballast output stage [3] and is given as,

$$f_{\%} = \frac{1}{2\pi} \sqrt{\left[ \frac{1}{LC} - 2 \left( \frac{P_{\%}}{CV_{\%}^2} \right)^2 + 1 \right] \left[ \left[ \frac{1}{LC} - 2 \left( \frac{P_{\%}}{CV_{\%}^2} \right)^2 \right]^2 - \frac{1 - \left( \frac{4V_{in}}{V_{\%}\pi} \right)^2}{L^2 C^2} \right]} \quad (2)$$

Where,

L = Output stage inductor [Henries]

C = Output stage capacitor [Farads]

P<sub>%</sub> = Lamp power at % dimming level [Watts]

V<sub>%</sub> = Lamp voltage amplitude at % dimming level [Volts]

f<sub>%</sub> = Frequency corresponding to lamp power at % dimming level [Hertz]

The values for L and C, and the amplitude of V<sub>in</sub> can be varied or iterated until the lamp preheat, ignition and dimming operating points are set at the desired frequencies.

## Dimming Control Method

Deriving the phase angle [degrees] as a function of lamp power from the output voltage to input current transfer function of the ballast output stage [4] yields,

$$\varphi = \frac{360}{2\pi} \tan^{-1} \left[ \left( \frac{V_{\%}^2}{2P_{\%}} C - \frac{2P_{\%}}{V_{\%}^2} L \right) 2\pi f_{\%} - 4 \frac{V_{\%}^2}{P_{\%}} LC^2 \pi^3 f_{\%}^3 \right] \quad (3)$$

Plotting equation (3) versus lamp power (Figure 4) results in a linear dimming curve for the given dimming range, even down to ultra-low light levels where the resistance of the lamp can change by orders of magnitude. This patented relationship between the phase angle of the input current and running lamp power allows for closed-loop dimming control of the lamp.

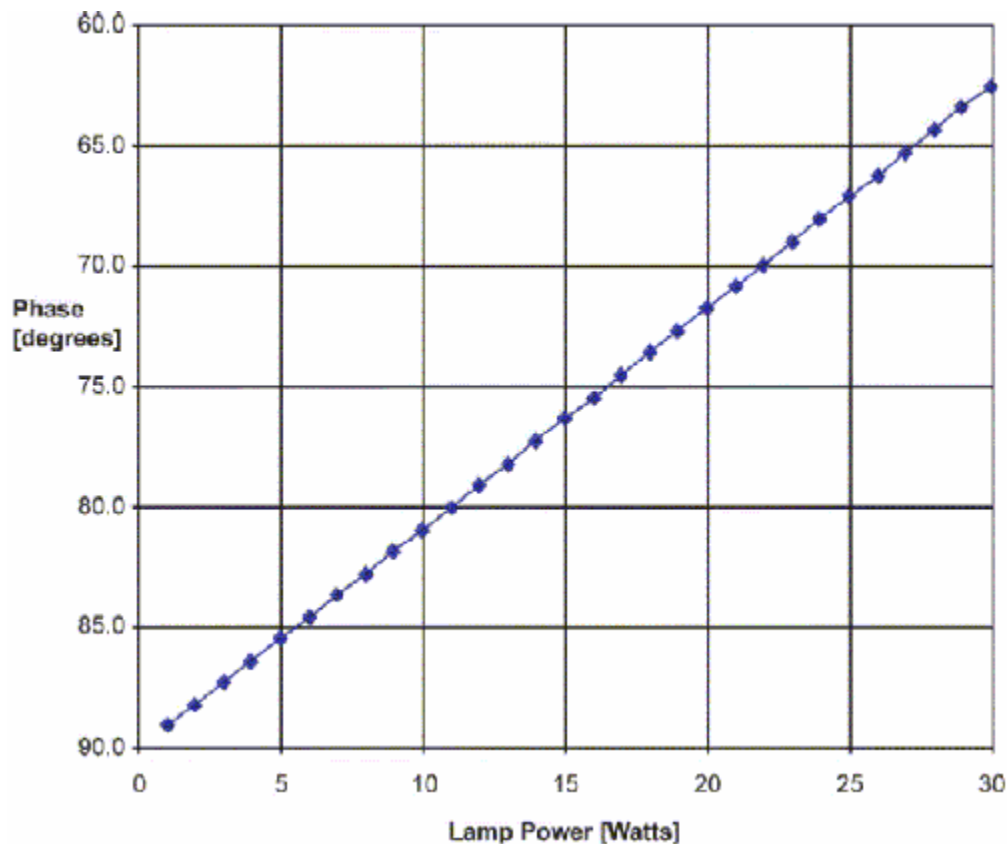
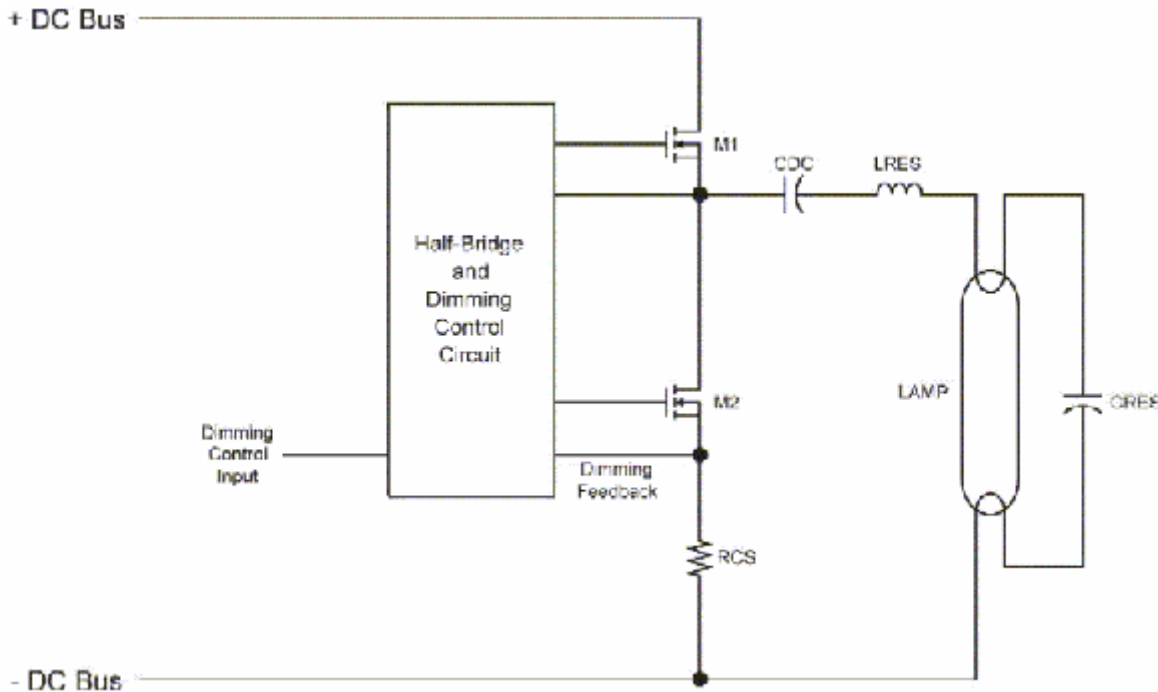


Figure 4, Lamp power vs. phase of output stage current showing patented linear dimming method

The phase angle of  $I_{in}$  is measured and fed back to a control circuit. The control circuit continuously adjusts the operating frequency to keep the phase angle equal to the

reference phase angle corresponding to the desired dimming level. The control circuit should also contain the necessary frequency control functions for preheating and igniting the lamp. The actual dimming circuit (Figure 5) includes a DC bus capacitor, two MOSFETs connected in a half-bridge configuration for generating the  $V_{in}$  square wave, the resonant output stage with an additional DC blocking capacitor, and a control circuit for driving the half-bridge MOSFETs, preheating, igniting and regulating the phase angle for dimming.



*Figure 5, Dimming control circuit*

With the lamp requirements defined, the output stage circuit modeled, and the dimming control method defined, the dimming ballast circuit parameters can be determined. However, because of the many variables involved and the lack of adequate lamp data available, this procedure can still be a very difficult task to perform. Many design iterations can be needed to fulfill the lamp requirements. The frequency and phase equations are complex and difficult to use, and many other details of the complete ballast circuit still need to be designed. Some of the lamp data will have to be empirically determined from actual bench measurements that require a dimming ballast to begin with! To avoid long design cycle times, a ballast design software program exists to help facilitate the process. The program incorporates the model and the calculations discussed, includes a complete library of many popular lamp types, and generates a schematic and bill of materials to help the designer prototype a working ballast quickly.

## Ballast design assistant (BDA) Software

A software program (BDA V4.0) has been developed for easy design and prototyping of electronic ballasts. This program includes a graphical interface with a 5-step design procedure. The steps include selecting the control IC, the ballast input configuration, the lamp type, and the lamp configuration. The final step will calculate the ballast parameters and output the schematic, bill of materials and inductor specifications.

An advanced display is also available (Figure 6) that provides all input and output data and allows the user to modify parameters and view the calculation results. An operating points Bode diagram and time-domain graph are also generated so the actual ballast operating points and actual time-domain waveforms can be analyzed in more detail.

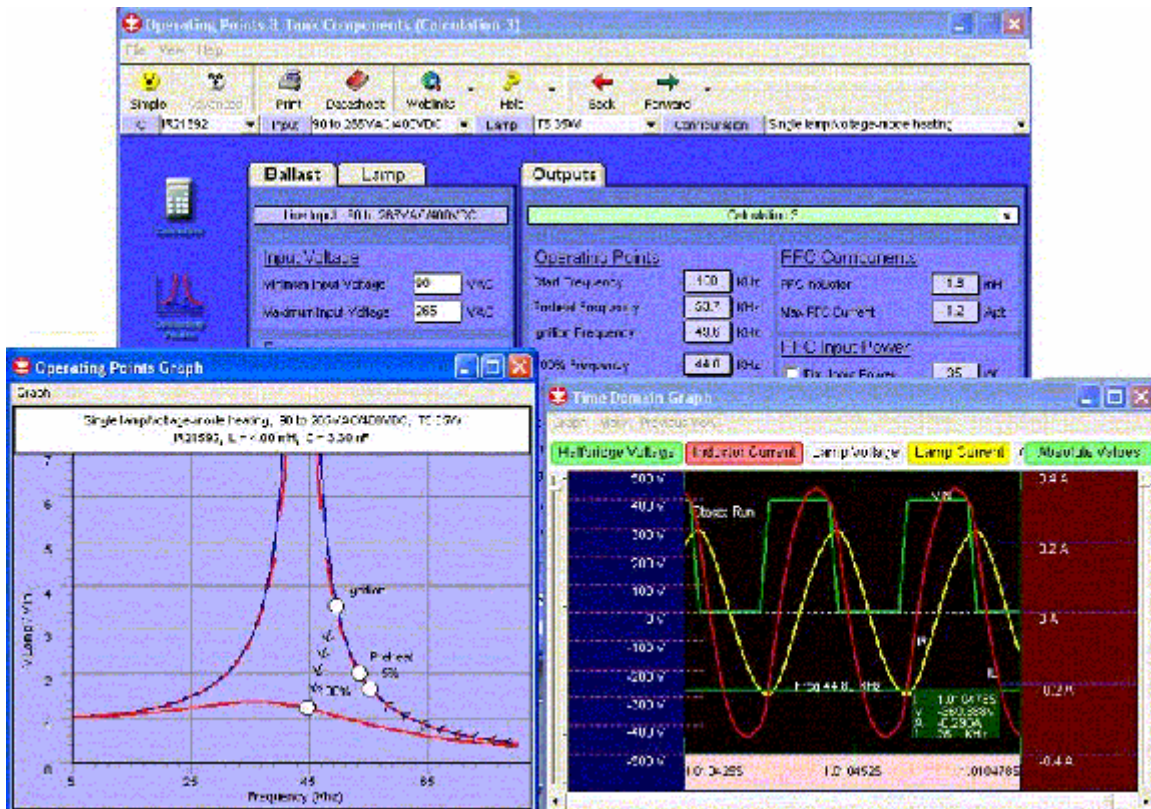


Figure 6, Advanced display page with calculations, Bode diagram and time-domain waveforms

When the calculations, operating points and time-domain waveforms look acceptable, the software can then generate the necessary schematic, bill of materials and inductor specifications for the complete ballast. This output data can be directly used to build a ballast prototype on the bench.

Other features include a custom library for user-specific lamp types, website links to obtain more information about each control IC, and export or print diagrams, plots, data and tables.

### Dimming Ballast Prototype

An actual T5/35W dimming ballast prototype has been built and tested on the bench. The ballast was designed using the BDA V4.0 software and the bench results were summarized and compared against the software calculations. The schematics generated by the software include (Figure 7) an EMI filter at the mains input to block ballast noise, a power factor controller (PFC) boost converter to provide sinusoidal input current and regulate the DC bus voltage, the IR21592 dimming ballast control IC to drive the half-bridge MOSFETs and control the lamp dimming level, and final resonant output stage for preheating, igniting and dimming the fluorescent lamp.

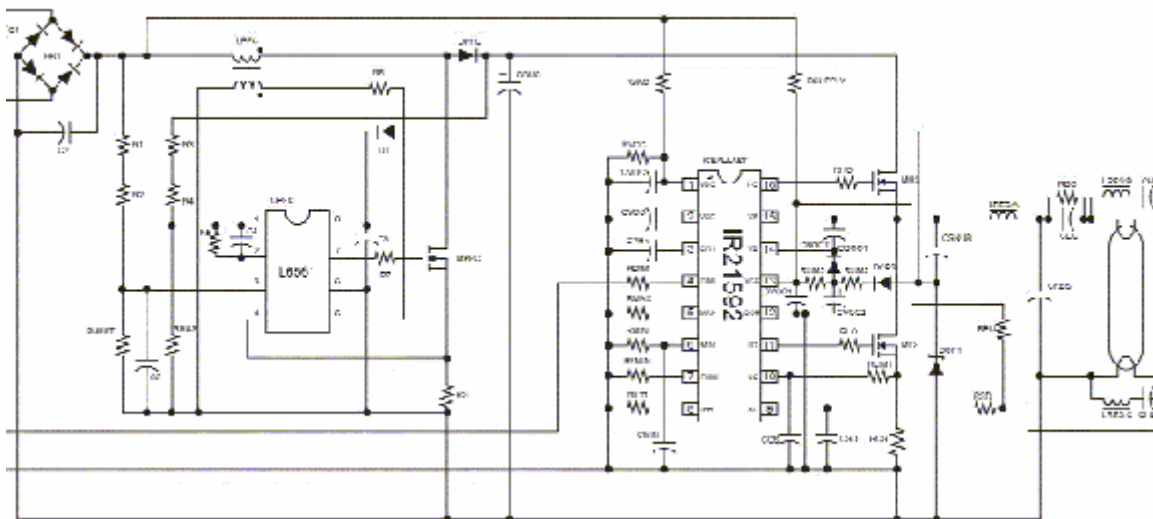


Figure 7, T5/35W dimming ballast schematics.

(Please note: EMI filter is not optimized and dimming input is non-isolated. More EMI filtering and an additional isolated dimming interface may be required.)

The ballast measurements include preheat, ignition and dimming lamp modes (Figure 8), dimming at 100% (Figure 9), and dimming at 5% (Figure 10).



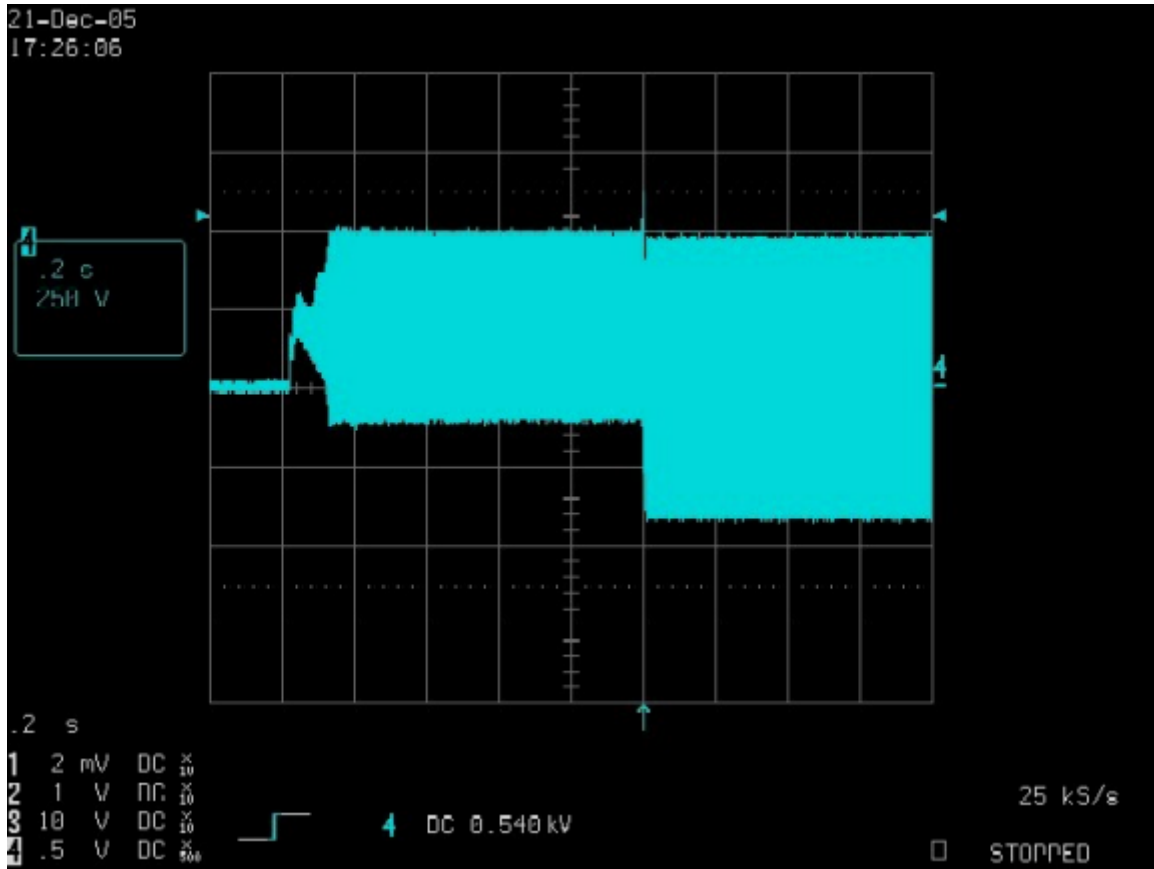


Figure 8, Lamp voltage during preheat, ignition and dimming operating modes

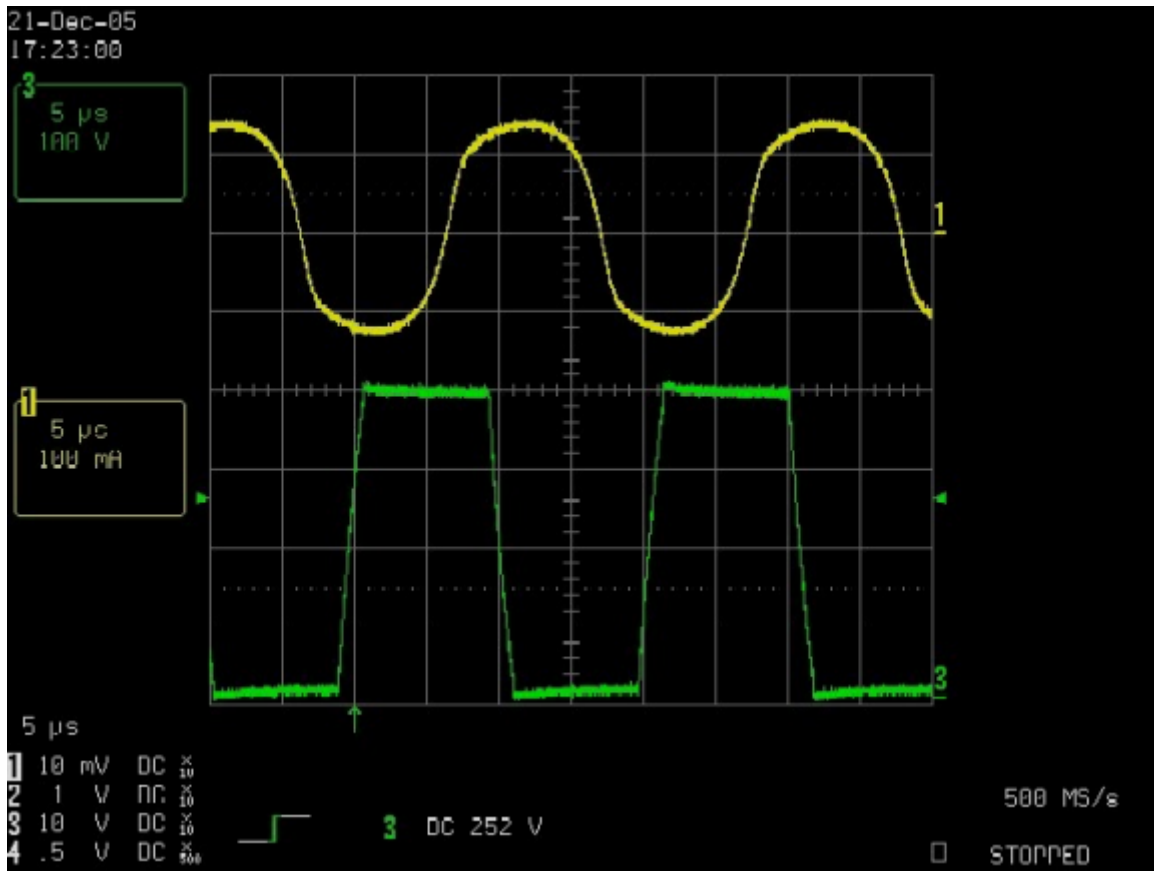


Figure 9, Half-bridge output (green) and lamp current (yellow) during 100% dimming level

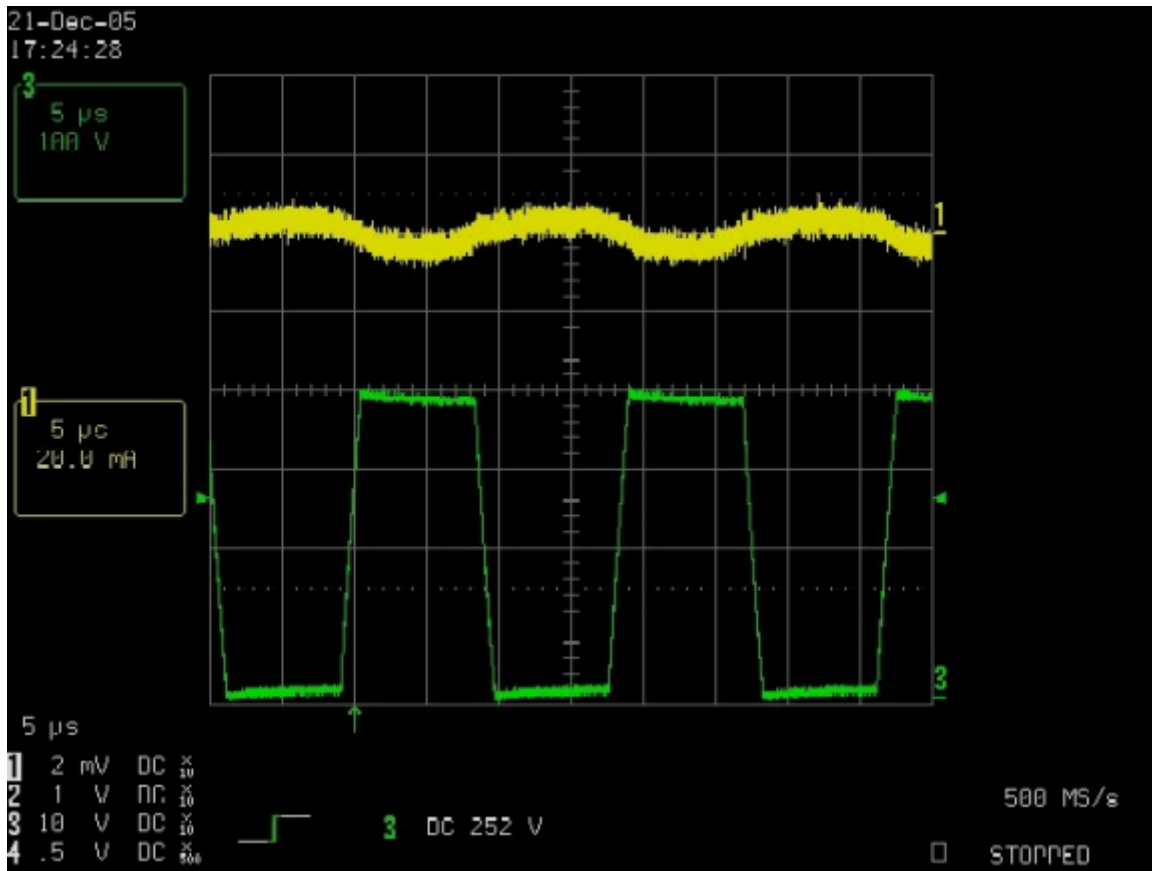


Figure 10, Half-bridge output (green) and lamp current (yellow) during 5% dimming level

The final ballast parameters have been summarized (Table II) and compared against the software calculations. Such deviations between calculated and measured values are normal and are due to component and lamp tolerances.

Parameter	Description	BDA Calculations	Measured
$L_{RES}$	Resonant inductor	4.0 mH	3.95 mH
$C_{RES}$	Resonant capacitor	3.3 nF	3.28 nF
$f_{PH}$	Preheat frequency	53.7 kHz	55.4 kHz
$f_{IGN}$	Ignition frequency	49.6 kHz	48.5 kHz
$f_{100\%}$	100% dimming frequency	44.8 kHz	45.5 kHz
$f_{5\%}$	5% dimming frequency	55.4 kHz	54.1 kHz

Table II, Calculated and measured ballast parameters

## **Conclusions**

An overview of a dimming electronic ballast has been presented. A simplified lamp model and requirements have been discussed for understanding fluorescent lamp electrical behavior. The resonant output stage has also been analyzed and a phase angle dimming control method has been described. The actual design of a complete dimming ballast has been facilitated using a new ballast design software program that gave good results compared to actual measurements. The prototype has been demonstrated to fulfill the lamp preheat, ignition and dimming lamp modes, with only minor tuning necessary to adjust the final dimming levels. Designing a dimming ballast is a difficult task that requires knowledge of fluorescent lamp electrical behavior, control theory experience and resonant converter design skills. The BDA software greatly simplifies this task and has proven to be an invaluable design aid allowing rapid analysis, design and construction of a fully-functional working prototype. This will result in simplified designs, shorter ballast design cycles, faster time to production, and faster time to market.

## **About the author**

*Tom Ribarich is Director of the Lighting Design Center at International Rectifier based in El Segundo, CA. Tom is responsible for defining and developing high-voltage control ICs for the global lighting market, including devices for fluorescent, halogen, HID and LED applications. Mr. Ribarich holds a BSEE from California State University (Northridge), a Masters in ASIC design from the University of Rapperswil (Switzerland), and has 16 years experience in IC design.*