Design A 25-W Mini-Ballast For Compact Fluorescent Lamps

Here’s a design procedure that covers output-stage design and programmable-IC component selection, as well as compares predicted and measured results.

By Tom Ribarich, International Rectifier Corp.

For decades, and continuing today, the fluorescent lamp has been the cheapest way to produce white light with the minimum amount of energy taken from the mains (lumens/watt). As such, hundreds of millions of compact fluorescent lamps (CFLs) are sold every year, with an ever-increasing demand for higher reliability. Today’s lighting systems need ballast control functions to drive compact fluorescent lamps, adding cost and requiring more design time. Also, these functions must often be readjusted for each different lamp type.

Consequently, designers now need solutions that integrate these control functions, so they can focus more on the lamp output-stage design and speed up time-to-market. This article describes the design of a 25-W compact fluorescent lamp ballast using an IC that integrates many necessary control functions. Also discussed is the output-stage design, selection of programmable IC components, the schematic, ballast-measurement waveforms, and a comparison between predicted and measured results.

Lamp Output Stage

A simplified model based on a standard resonant circuit topology is used to design the lamp output stage *(Fig. 1)*. The lamp requires a current for a specified time to preheat the filaments, a high voltage for ignition, and running power. Properly selecting L and C, along with changing the input-voltage frequency, satisfies these requirements. For preheat and ignition, the lamp isn’t conducting, and the circuit is a series L-C combination. While running, the lamp conducts, and the circuit is an L in series with a parallel R-C combination.

The circuit’s transfer function illustrates the output stage operating points as the lamp is taken through preheat, ignition, and run modes *(Fig. 2)*. The frequency is swept smoothly over a determined preheat time from a start frequency down to the final running frequency. During this frequency sweep, the lamp filaments are preheated, and the lamp voltage increases as the frequency approaches the resonance point of the high-Q, L-C circuit. When the lamp voltage reaches a high-enough level, the lamp ignites and the operating point moves to the low-Q, R-C-L curve. The frequency continues to decrease until the final run frequency is reached, at which point the lamp is driven at the correct power.

The transfer function for the high-Q, series L-C circuit is:

$$\frac{V_{ign}}{\frac{4V_{in}}{\pi}} = \frac{1}{\left|1-4LC\pi^{2} f_{ign}^{2}\right|} \qquad (1)$$

where V_{in} = input square-wave voltage amplitude in volts; V_{ign} = lamp ignition-voltage amplitude in volts; L = output-stage inductance in henries; C = output-stage capacitance in farads; and f_{ign} = lamp ignition frequency in hertz.

Solving Equation 1 for f_{ign} gives:

$$f_{ign} = \frac{1}{2\pi}\sqrt{\frac{1+\frac{\frac{4}{\pi}V_{in}}{V_{ign}}}{LC}} \qquad (2)$$

Equation 2 gives the location of the lamp-ignition operating point on the high-Q, L-C transfer curve. Note that the linear analysis uses the fundamental frequency of the input square wave, V_{in}. Once the lamp ignites, its resistance is no longer negligible, and the system becomes a low-Q, series-parallel R-C-L circuit with a transfer function:

$$\frac{V_{run}}{\frac{4V_{in}}{\pi}} = \frac{1}{\sqrt{(1 - 4LC\pi^2 f_{run}^2)^2 + \frac{L^2}{R^2} 4\pi^2 f_{run}^2}} \qquad (3)$$

Solving Equation 3 for the running-frequency (in hertz) operating point on the low-Q, R-C-L transfer curve gives:

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

where R is the lamp resistance determined from the running lamp power and voltage:

$$R = \frac{V_{run}^2}{2P_{run}} \qquad \text{(ohms)} \qquad (5)$$

where P_{run} = lamp running power in watts, and V_{run} = lamp running voltage amplitude in volts.

Finally, the start-frequency operating point on the high-Q, L-C transfer curve is given by the voltage-controlled oscillator (VCO) maximum frequency of the IC used:

$$f_{start} = 2.5 \times f_{run} \qquad \text{(Hertz)} \qquad (6)$$

Using these equations together with the lamp and ballast parameters, the lamp output stage can be designed. The lamp and ballast parameters for a 25-W CFL type and a 230-V ac line input are:

V_{in} = 280 V, V_{ign} = 380 V peak, P_{run} = 25 W, V_{run} = 175 V peak, and f_{run} = 45 kHz

Selecting C = 6.8 nF and using Equation 4, L is incrementally increased from 0.1 mH until the desired running frequency is achieved. Once L and C are obtained, Equations 2 and 6 will calculate the ignition and start frequencies.

The IC used is the IR2520. It sweeps the frequency from the start frequency down to the run frequency *(Fig. 3)*. The ignition frequency must be greater than the run frequency to ensure that the lamp will ignite successfully. Using the above design procedure gives an L value of 2.3 mH. The table summarizes the results.

Ballast Design

A 25-W mini-ballast demo board was designed, built, and tested for performance. The input stage was designed for 230 V ac. The ballast controller IC was used to program the frequencies and preheat time, perform the frequency sweep, and drive the high- and low-side half-bridge MOSFETs. The IC also includes brown-out reset, protection against failure to strike, non-zero voltage switching, open filaments, and lamp removal.

This procedure was used to calculate the L, C, and the frequencies of the lamp output stage. The results were used to select the programmable components of the IC *(Fig. 4)*.

With a chosen L and C of 2.3 mH and 6.8 nF, and the operating frequencies calculated, the programmable inputs of the IC are calculated with the following design equations:

$$R_{FMIN} = 3.27E9 \cdot \left(\frac{1 - (3.6E-6) \cdot f_{run}}{f_{run}}\right) \text{(ohms)} \qquad (7)$$

$$C_{VCO} = \frac{t_{ph}}{3.7E6} \qquad \text{(Farads)} \ (8)$$

where R_{FMIN} programs the desired running frequency (f_{run}) and C_{VCO} programs the desired preheat/ignition sweep time (t_{ph}).

Components R_{SUPPLY}, C_{VCC}, D_{CP1}, D_{CP2} and C_{SNUB} comprise the supply voltage for the IC. Initially, as the dc bus increases when the mains voltage is first applied, R_{SUPPLY} will charge the capacitor C_{VCC} up to the internal turn-on voltage of the IC. The IC only draws microamps of current before turn-on, so R_{SUPPLY} can be a very high value to minimize power losses.

When V_{CC} exceeds the IC's internal turn-on threshold, the gate drive outputs, LO and HO, begin to oscillate at the start frequency with a 50% duty-cycle, and a fixed non-overlapping dead-time between them. The charge-pump supply formed by C_{SNUB}, D_{CP1}, and D_{CP2} then takes over as the primary supply for the IC. It keeps V_{CC} maintained at its internal clamp voltage of 15.6 V. Capacitor C_{SNUB} also provides snubbing at the half-bridge output to limit the rise and fall time, thereby reducing EMI. Capacitor C_{DC} supplies dc blocking for the resonant circuit so that the ac lamp voltage and current are maintained during running. This prevents mercury migration of the fluorescent lamp, which can cause end blackening and reduce lamp life.

A breadboard was built, tested, and compared with the predicted model values. Figures 5, 6, 7, and 8 show the half-bridge output voltage, inductor current, and lamp voltage for start, ignition, and running conditions. During start and ignition modes, the voltage and current waveforms are sinusoidal. When running, nonlinear resistance effects of the lamp can be seen on the lamp voltage.

The measured and predicted frequencies match within 5%, while other lamp types and component selections can deviate as much as 10%. Such deviations are expected because the design procedure neglected harmonics, nonlinear lamp resistance, filament resistance, inductor losses, and component tolerances. Therefore, another iteration of the component selection process may be necessary.

A fully functional mini-ballast reference design was constructed using the above approach, and the output stage was dimensioned for single-lamp operation *(Fig. 9)*. Temperature, lifetime, performance margins, packaging, layout, manufacturability, and cost were all considered during the design process.

The design method described above 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 significantly reduces the time needed to dimension the ballast for different lamp types on the market, and is an effective and useful tool for optimizing ballast size and cost. It also helps reduce the number of ballast product families and increases manufacturability.

Tom Ribarich is responsible for defining and developing high-voltage control ICs for the global lighting market at International Rectifier Corp., El Segundo, Calif. (www.irf.com), including fluorescent, halogen, HID, and LED applications. He received a degree in ASIC design from Rapperswil Technical University, Switzerland. Ribarich can be reached Tribari1@irf.com.

Recommended Reading:

1. Elenbaas, W., ed., *Fluorescent Lamps*, Second Edition, Philips Technical Library, Eindhoven, The Netherlands, 1971.
2. *IR2520D Adaptive Ballast Control IC*, Data Sheet, International Rectifier Corp., 2002, *www.irf.com/product-info/lighting/*.
3. *IRPLMB1E 25W Small Sized Ballast*, Design Kit, International Rectifier Corp., 2002, *www.irf.com/technical-info/refdesigns/lightingkits.html*.
4. Ribarich, T., Ribarich,J., "A New High-Frequency Fluorescent Lamp Model," *IEEE-IAS Conf. Rec.*, 1998.