A New Control Method for Dimmable High-Frequency Electronic Ballasts

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Abstract - A new control technique has been developed for high-frequency dimming of fluorescent lamps using phase-sensing of ballast output stage current to regulate lamp power. This approach has the following ballast design implications:

P *Dimming to 1%*

P *Ignition at any dim setting*

P *End-of-life detection*

P *Multiple lamp management*

P *No heating or current transformers required*

P *No opamps required*

P *Immunity from lamp negative incremental impedance effects*

P *Reduction of PCB interconnects and IC pin requirements*

P *Minimum changes needed to adapt non-dimming ballast for dimming*

The result is a high-performance dimming solution with a significant cost reduction. A complete dimmable ballast has been built that incorporates a new integrated circuit verifying all of these features.

I. INTRODUCTION

The purpose of this paper is to present phase control for dimming fluorescent lamps. This paper includes an overview of phase control, dimming lamp requirements and dimming ballast design.

II. OVERVIEW

Dimming of fluorescent lamps at high-frequency includes additional functions to those performed by non-dimming electronic ballasts [3]. These include (Figure 1) a dim input for user-controllable brightness, sensing circuitry for monitoring lamp current, voltage or power, and feedback circuitry to regulate lamp brightness against the user input setting. The focus of this paper is on controlling

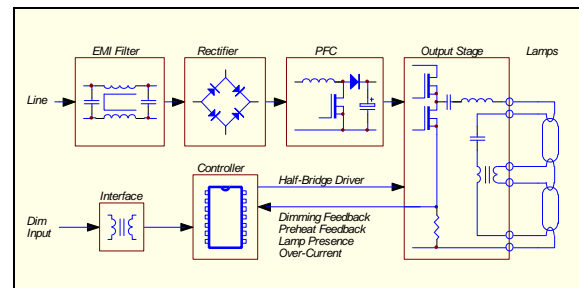lamp power using the phase of the output stage currrent.

Figure 1, Dimming ballast functional block diagram

To understand phase control, a simplified model for the ballast output stage is used (Figure 2). The lamp and filaments are replaced with resistors, with the lamp inserted between the filament resistors (R1, R2, R3 and R4). This traditional ballast output stage exhibits interesting phase relationships useful for closed-loop control.
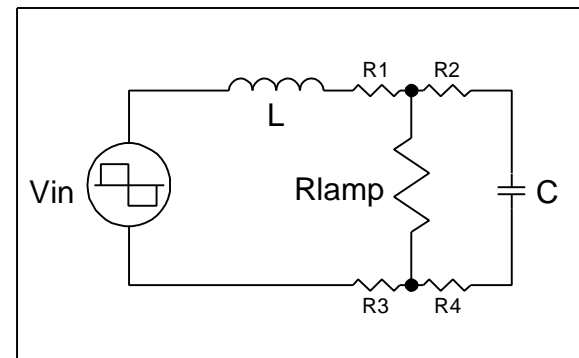

Figure 2, Dimming ballast output stage simplified model

During preheat and pre-ignition (Figure 3), the circuit is a high-Q series LC with a strong phase inversion from +90 to -90 degrees at the resonance frequency. For operating frequencies slightly above resonance and higher, the phase is fixed at -90 degrees for the duration of preheat and ignition. During dimming, the circuit is an L in series with a

parallel R and C, with a weak phase inversion at high lamp power and a strong phase inversion at low lamp power.
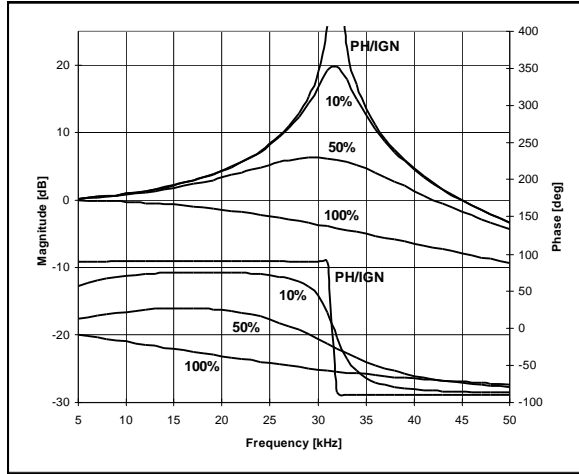

Figure 3, Typical output stage input current to input voltage transfer function for different lamp power levels.

In the time domain (Figure 4), the input current is shifted -90 degrees from the input half-bridge voltage during preheat and ignition, and somewhere between 0 and -90 degrees after ignition during running. Zero phase-shift corresponds to maximum power.
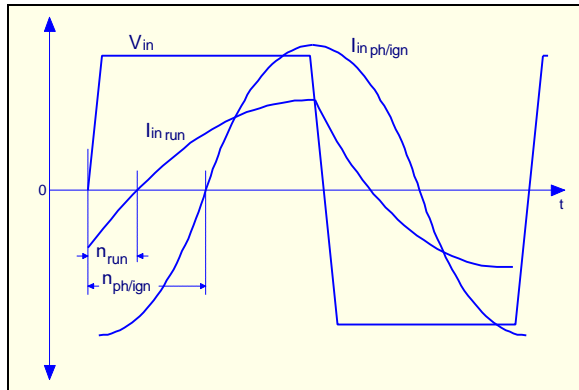

Figure 4, Typical output stage waveforms for ballast operating points.

Solving for the input current to input voltage transfer function of the simplified ballast output stage (Figure 2) yields,

$$\frac{I_{in}(s)}{V_{in}(s)} = \frac{1 + (R_{Lamp} + R_2 + R_4)Cs}{(sL + R_{Lamp} + R_1 + R_3)[1 + (R_{Lamp} + R_2 + R_4)Cs] - R_{Lamp}^2 Cs} \quad (1)$$

From **(1)** we see that the contribution of the filament resistances are negligible compared to the resistance of the lamp, and become even more negligible as the resistance of the lamp increases during dimming.

Solving for the phase angle [degrees] yields,

$$\boldsymbol{j} = \frac{360}{2\boldsymbol{p}} \tan^{-1}[(\frac{V_\%^2}{2P_\%}C - \frac{2P_\%}{V_\%^2}L)2\boldsymbol{p} f_\% - 4\frac{V_\%^2}{P_\%}LC^2 \boldsymbol{p}^3 f_\%^3]$$

(2)

where,

L	=	Output stage inductor [Henries]
C	=	Output stage capacitor [Farads]
$P_\%$	=	Lamp power [Watts]
$V_\%$	=	Lamp voltage amplitude at lamp power % [Volts]
$f_\%$	=	Frequency corresponding to lamp power % [Hertz]

The frequency at each lamp power is obtained from the output voltage to input voltage transfer function of the ballast output stage [3], and is given as,

$$f_\% = \frac{1}{2\boldsymbol{p}}\sqrt{\frac{1}{LC} - 2\left(\frac{P_\%}{CV_\%^2}\right)^2 + \sqrt{\left[\frac{1}{LC} - 2\left(\frac{P_\%}{CV_\%^2}\right)^2\right]^2 - \frac{1 - \left(\frac{4V_{in}}{V_\% \boldsymbol{p}}\right)^2}{L^2C^2}}} \quad (3)$$

When equation **(2)** is plotted versus lamp power (Figure 5), the result is a linear dimming curve, even down to ultra-low light levels where the resistance of the lamp can change by orders of magnitude. This relationship between the phase angle of the input current and running lamp power allows for closed-loop dimming control, and the change in phase when the lamp ignites allows for ignition to be detected and the loop to be closed.
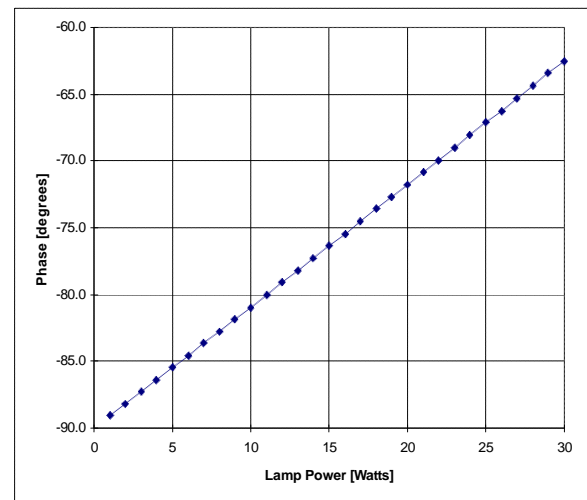

Figure 5, Lamp power vs. phase of output stage current

A phase-locked loop has been implemented to track the phase of the inductor current against an input reference phase. A major attraction of phase-locked loops are their ability to track a signal automatically while coping with large amounts of noise. In a traditional phase-locked loop, only the frequency is fedback to the mixer and the voltage-controlled oscillator (VCO) is adjusted until the error between the input reference frequency and the VCO output frequency is zero. To regulate a fluorescent lamp, the ballast resonant output stage is inserted into the loop between the VCO and the mixer (Figure 6). The error between the reference phase and the phase of the output stage current forces the VCO to steer the frequency in the proper direction, as determined by the transfer function of the output stage, such that the error is forced to zero. Once lock is achieved, the phase detector (PDET) outputs short pulses that "nudge" the integrator at the input of the VCO to keep the phase of the output stage current exactly locked in phase with the reference. The lamp power tracks the reference corresponding to the desired lamp brightness level.
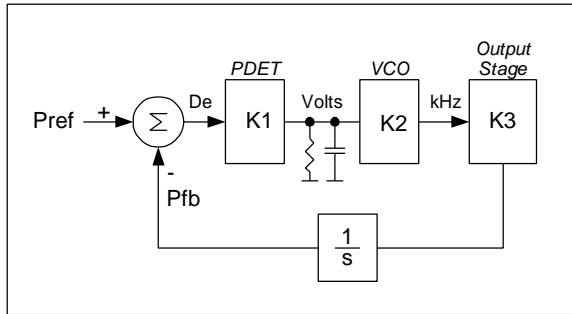

Figure 6, Phase control block diagram

The loop consists of two low-pass transfer characteristics. One is an inherent integration due to the phase being the time integral of frequency, and the second is the loop filter which integrates the error pulses. The open-loop frequency response (Figure 7) shows the gain decreasing by -20dB/decade throughout the frequency range due to the inherent integration, and by -40dB/decade due to the loop filter. The location of the loop filter is set above the transit frequency for good damping and to prevent ringing or a poor transient response. Because the gain of the output stage, K3, changes with lamp power, the system should be checked for good phase and gain margins over the entire dimming range. With this approach, neither lamp current nor lamp voltage are being controlled. The

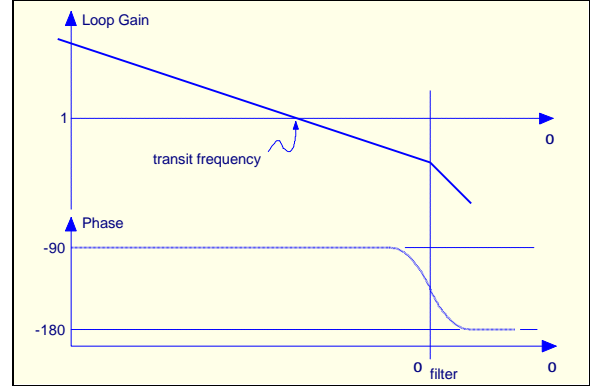system is therefore immune to lamp negative incremental impedance effects.

Figure 7, Typical open-loop frequency response for phase control system at a given lamp power.

III. DIMMING LAMP REQUIREMENTS

Non-dimming lamp requirements [3] include a preheat current, a maximum allowable lamp voltage during preheat, a minimum required ignition voltage, and, running power. The L and C (for a given Vin) of the ballast output stage should be selected such that all of these requirements are satisfied. For dimming, the filaments should be heated to their correct emission temperature to prevent the lamp from extinguishing. Excessive heating can cause premature end-blackening and degrade lamp life. The selection of L and C now includes checking the filament current at each dim setting for proper heating. Solving for the filament current, or current in capacitor C, at lamp power % yields,

$$I_{filament_\%} = \frac{V_\% 2 P f_\% C}{\sqrt{2}} \qquad \text{[Amperes]} \qquad \textbf{(4)}$$

During dimming, the lamp voltage increases with decreasing lamp power (Figure 8) due to lamp negative incremental impedance effects. A maximum is reached around 20% brightness, after which the lamp voltage decreases as the lamp is further dimmed. From equation **(4)** it is seen that the filament current increases with increasing frequency and lamp voltage. The filament current should be checked for over-heating at the dim setting corresponding to the maximum lamp voltage. Because lamp data for dimming is not available from lamp manufacturers, the author highly recommends that the designer choose the filament current

experimentally and verify it over all lamp manufacturers with lamp life tests.
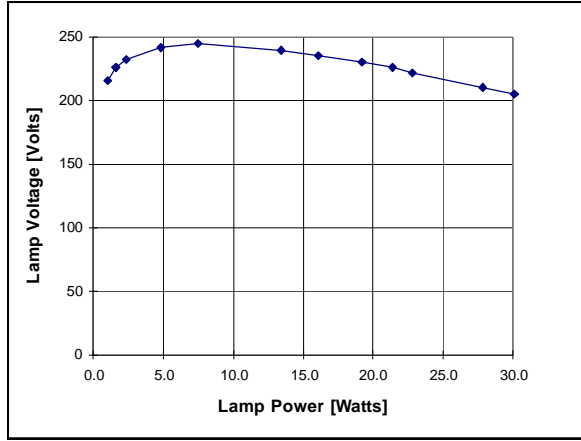

Figure 8, Lamp voltage amplitude vs. lamp power for T8/32W lamp type operating at high-frequency.

IV. BALLAST DESIGN

A fully functional dimmable ballast was built which uses a new phase-sensing ballast controller IC (Figure 9). Results from equation **(2)** are linked to the programmable inputs of the IC to track lamp power against an analog dim input. In addition to the phase control circuitry (Figure 10), the IR2159 also contains a high/low-side half-bridge driver, a 0 to 5VDC dimming interface with programmable minimum and maximum lamp power settings, programmable deadtime, closed-loop programmable preheat current control, programmable preheat time, over-current detection, over-temperature detection and a generic shutdown pin.
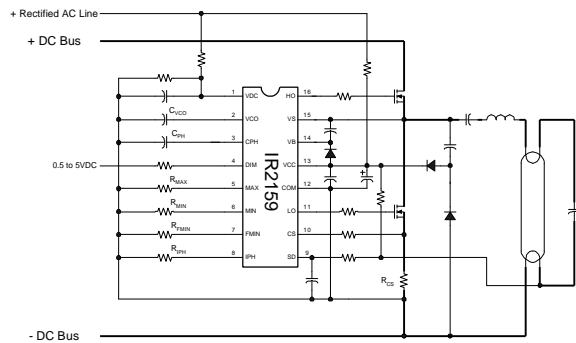

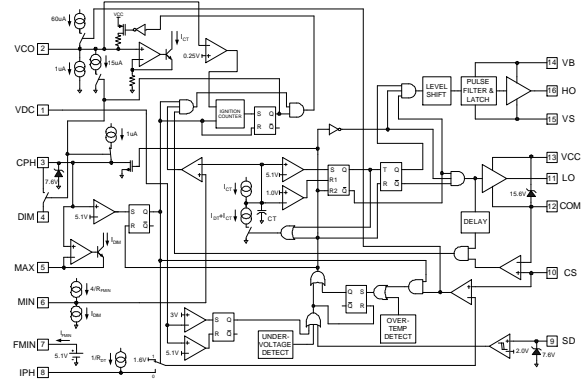Figure 9, IR2159 Dimmable ballast controller IC

Figure 10, IR2159 block diagram.
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The control sequence (Figure 11) is measured at the input to the voltage controlled oscillator (pin:VCO) which increases in frequency with increasing input voltage. Starting at the maximum operating frequency (100kHz), the voltage on pin:VCO ramps down to some level corresponding to a frequency where the peak preheat current (measured on pin:CS) is equal to the programmed voltage level on pin:IPH, and remains there for the duration of the preheat period. When the voltage on pin:TPH exceeds 4 Volts, the preheat period is over and the VCO input voltage ramps down further, forcing the output frequency of the half-bridge down towards the resonance frequency of the ballast output stage. The lamp voltage increases smoothly until the lamp ignites. Should the lamp fail to ignite (Figure 12), the voltage on pin:CS is regulated against an internal threshold voltage until the voltage on pin:TPH exceeds 5 Volts. The ignition time is over and the ballast is shutdown safely. If the lamp ignites successfully, the phase control loop is closed when the phase measured on pin:CS is equal to the reference phase. The reference phase is equal to a brightness level near the maximum setting due to the internal dim reference being connected internally to pin:TPH, which lies somewhere between 4 and 5V during ignition. When the loop is closed, pin:DIM is connected to pin:TPH and the voltage on the capacitor on pin:TPH discharges through the external resistor on pin:DIM. This causes the dim setting to ramp smoothly to the user setting. This external resistor on pin:DIM programs the "travel time" from maximum brightness to the user setting and therefore programs the amount of flash which can occur over the lamp just after ignition.
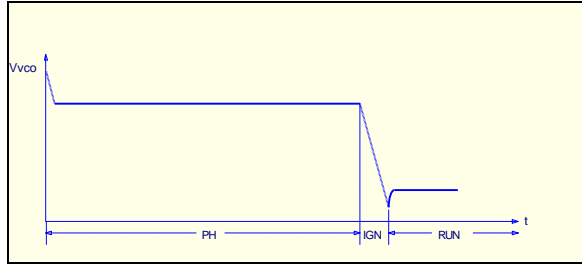
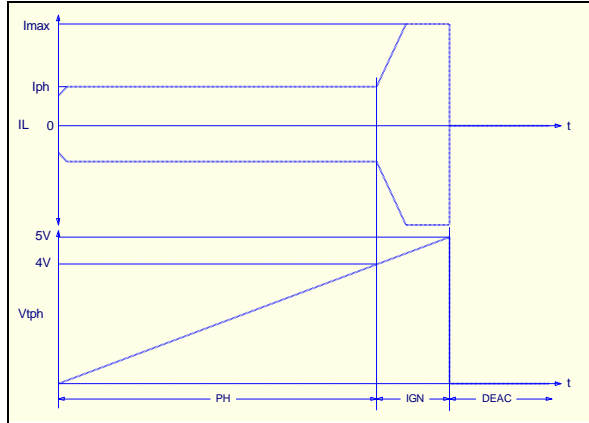Figure 11, Typical IR2159 VCO control sequence duing normal conditions.

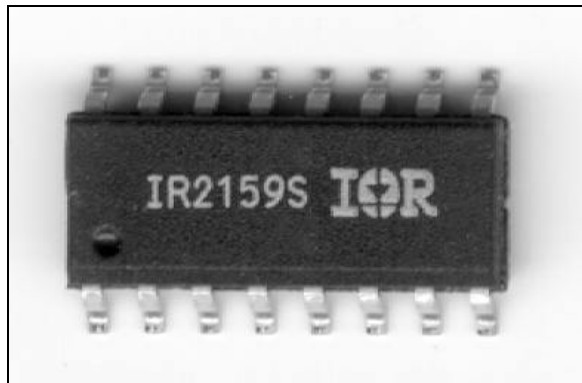Figure 12, Typical IR2159 control sequence during a non-strike lamp fault condtion.

Figure 13, IR2159 Dimming ballast IC.

V. RESULTS

Figures 14 and 16 show voltage waveforms on the VS, CS and FB pins of the IR2159 during 100% and 5% brightness settings. VFB is the error signal generated when the zero-crossing of VCS is equal to the reference phase. Figures 15 and 17 show the corresponding lamp voltage and lamp current for a T8/32W lamp type.
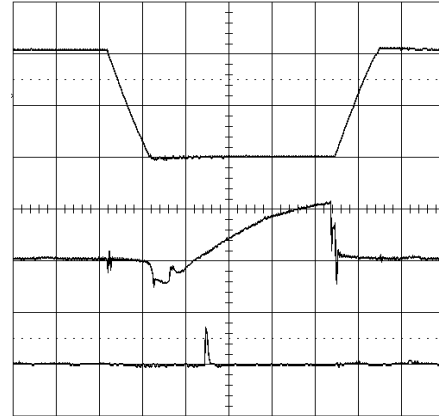

Figure 14, VS (upper trace, 200V/div), VCS (middle trace, 0.5V/div) and VFB (lower trace, 20V/div) at Plamp = 30W (100%) (t = 5us/div).
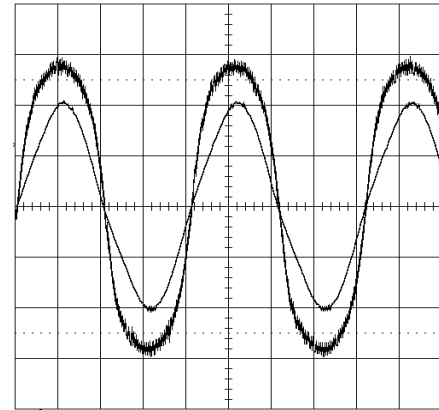

Figure 15, Lamp voltage (inner trace, 100V/div) and lamp current (outer trace, 100mA/div) at Plamp = 30W (100%) (t = 5us/div).
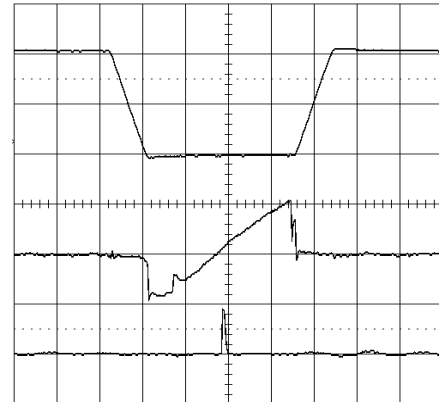

Figure 16, VS (upper trace, 200V/div), VCS (middle trace, 0.5V/div) and VFB (lower trace, 20V/div) at Plamp = 1.5W (5%) (t = 5us/div).
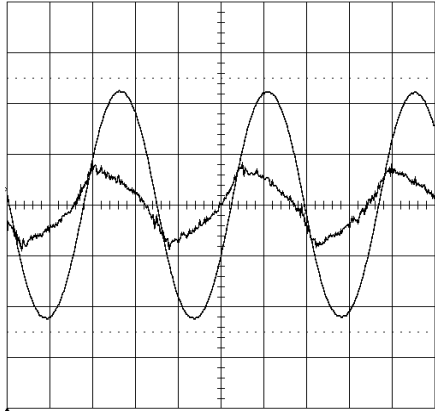
Figure 17, Lamp voltage (outer trace, 100V/div) and
lamp current (inner trace, 20mA/div) at
Plamp = 1.6W (5%) (t = 5us/div).

VI. CONCLUSIONS

Phase control is a simple approach which provides high-performance dimming of fluorescent lamps. The output stage is the same as for non-dimming, making it easy to adapt non-dimming ballasts for dimming.   The sensing method is also simple, making this approach ideal for implementation into an integrated circuit.

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[4]   T. Ribarich, J. Ribarich, *A New High-Frequency Fluorescent Lamp Model,* in IEEE-IAS *Conf. Rec.,* 1998.

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