ANALOG DIMMING: A Brighter Way to Design Lamp Ballasts

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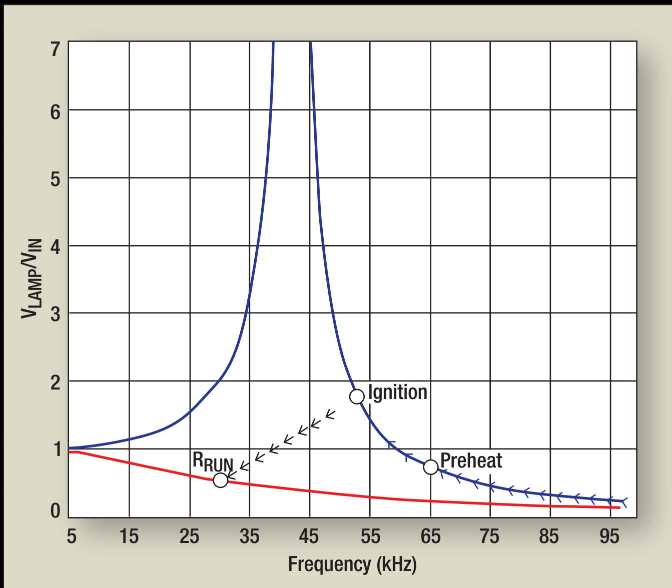
Arc-current and phase-control methods offer greater simplicity and accuracy than digital methods when dimming fluorescent lamps.

When considering alternative approaches to the design of dimmable electronic ballasts for fluorescent lamps, the lamp power regulation method employed is the critical factor. It determines the linearity (i.e., the linear response of the light output with the dimming control input), the smoothness of dimming and, most importantly, the stability of the light output. Both digital and analog approaches are possible.



The method most often used in dimming ballasts involves controlling the lamp power by modulating the frequency of the switched dc bus. This is done through a series inductor and a parallel resonant output capacitor network. Increasing the resonant circuit's frequency reduces the lamp current and vice versa (Fig. 1). Pulse-width modulation of the half-bridge voltage also is used in some dimming designs to widen the dimming range. However, this is not usually necessary.

Analog Versus Digital

Analog dimming control is generally simpler to implement than a digital approach in this application. This is mainly because microcontrollers are limited to adjustment of the ballast frequency in steps, as the output frequency is divided down from the clock frequency. Even with a clock frequency of 20 MHz, a single-step frequency change in the lamp is generally visible by the human eye. It then becomes a complicated problem to disguise these step changes in light output.

Fig. 1. *Dimming fluorescent-lamp ballasts is commonly done by controlling the lamp power by modulating the frequency of the switched dc bus. Results shown here are for single-lamp voltage-mode heating, 90-Vac to 265-Vac input, 500-Vdc output, TC -T 32 W lamp, L = 4.30 mH and C = 3.3 nF.*

Advanced microcontrollers are available that contain additional functionality specially designed to disguise frequency steps. However, such microcontrollers are relatively complex and expensive. Microcontroller designs also require additional high-side/low-side driver ICs to supply the half-bridge MOSFET switches, as well as circuitry to provide a 5-V supply capable of sourcing several milliamperes of current (Fig. 2).

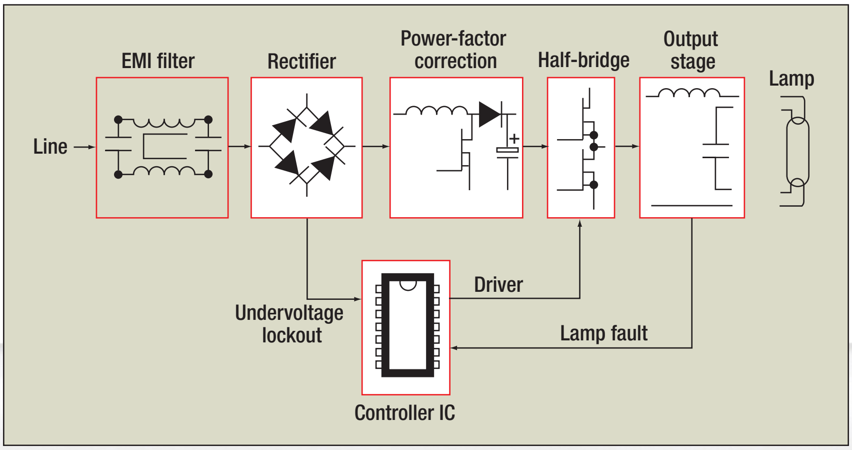


Fig. 2. *Overview of fluorescent-lamp ballast system.*

In analog designs, linear adjustment is possible at any frequency, which allows smooth dimming with no steps. Several different choices of analog ballast-control application-specific ICs (ASICs) are available for dimming control. They also include an integrated high-side and low-side driver, as well as a variety of fault-protection and ballast-management functions.

Two alternative approaches of analog dimming regulation will be considered here. Both employ frequency modulation as a means of power control, but use two different techniques for providing the feedback information from the lamp that the system uses to regulate. Frequency modulation enables effective dimming down to less than 5% of the Lumen output for fluorescent lamps. Below this level, and depending on the specific lamp characteristics, the frequency modulation method can run into difficulties maintaining very low arc currents, because the frequency is substantially above the resonant frequency of the output circuit.

Maintaining the arc discharge in the lamp is difficult at very low dimming levels, regardless of which control method is being used. This limitation is generally more problematic with an increasing lamp length and a smaller tube diameter.

The Arc-Current Method

The first feedback method considered here senses the arc current discharged through the lamp, which includes neither the cathode currents nor the current in the resonant output capacitor. This current is converted to a voltage through a shunt resistor and fed to one input of an integrating error amplifier. The other input of this error amplifier is connected to the dimming control reference input to provide the target dimming level, and the output is connected to a voltage-controlled oscillator (VCO), which drives the power switching stage. In this way, the loop is closed and the lamp arc current is directly controlled (Fig. 3).

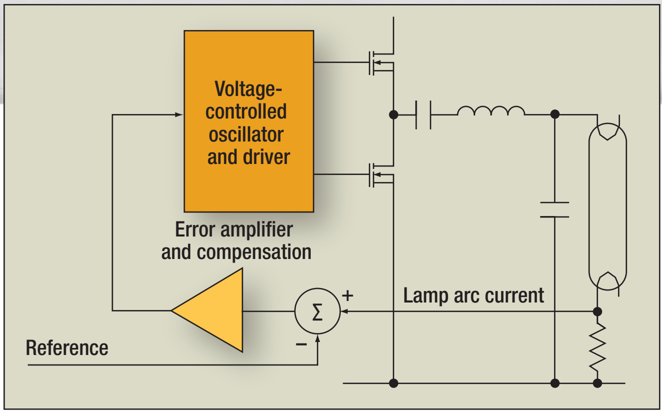


Fig. 3. *The analog arc-current control method of dimming a fluorescent lamp's ballast using frequency modulation is generally simpler than the digital approach.*

It is possible to obtain a very stable output response over the range of dimming by optimization of the integrating capacitor and resistor in the error amplifier circuit. The best results are achieved when the loop-frequency response is optimized for the particular lamp being driven, because the characteristics of different lamps vary. Lamps with smaller tube diameters, such as T5 types, are generally more susceptible to instability than those with larger diameters, such as T8 and T12 types.

The Phase-Control Method

The second dimming regulation method works by sensing the phase difference between the oscillator-driven power-switching signal and the current in the resonant output circuit. This operates on the principle that the lamp current is resistive, and therefore in phase with the power switching signal, but that the resonant output capacitor current is 90 degrees out of phase. As the frequency increases, the capacitor current increases and the lamp current falls, so that the combined current in the resonant output circuit has an increased phase difference with the power-switching oscillator.

This phase difference can be sensed, compared with a reference in a phase locked loop (PLL), where the error signal is used to adjust the VCO frequency until the phase difference matches the reference (Fig. 4). This method also produces excellent stability, smooth transition between dimming levels and good linear response. The relationship of phase difference to lamp power has been correlated and shows great linearity.

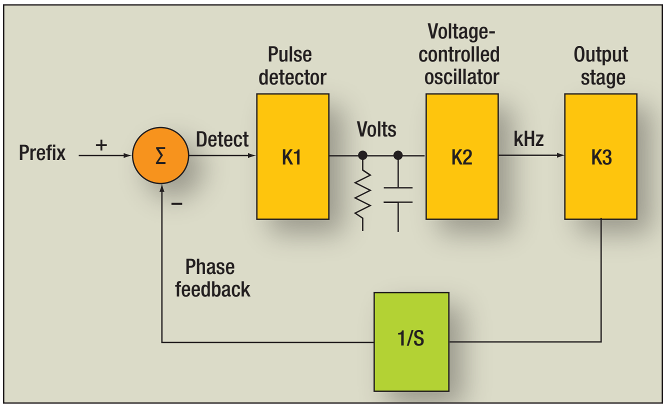


Fig. 4. *The analog phase-control method of dimming a fluorescent lamp's ballast produces excellent stability, smooth phase transitions between dimming levels and good linear response.*

How the Methods Differ

With both dimming approaches, it can be difficult to dim to very low levels, while maintaining performance uniformity between different lamps. Lamps of the same size and power rating vary between manufacturers or even between different lots from the same manufacturer. It is also necessary to allow for lamp operation at low temperatures, because fluorescent lamps are generally more difficult to control at lower temperatures.

In the phase-control approach, the lamp power feedback is sensed indirectly through the phase shift, whose relationship with the true lamp power is linear but changes to some extent with lamp temperature. The result of this is that if a lamp is adjusted to a certain dimming level while the lamp is cold, the power supplied to the lamp will gradually increase as the lamp heats up.

In the case of arc-current regulation, the lamp current is controlled directly, so the lamp power will always be maintained at a constant level regardless of temperature. In both cases, the light output increases with lamp temperature as a result of reduced impedance due to increased ionization of gases within the lamp. However, this effect is exacerbated in the case of phase control.

The phase-control method requires careful setting of the phase boundaries by selecting the correct resistor values in the circuit, which define the minimum and maximum dimming limits. These limits normally need to be trimmed on production to achieve acceptable uniformity between ballasts and compensate for tolerances within the control IC, as well as other components such as the output inductor. Trimming on production adds cost and complexity to the manufacturing process.

In the case of lamp arc-current regulation, it is only necessary to set the minimum dimming level, and trimming may be avoided by the use of high-precision external components in the feedback loop. The dimming limits are not affected by tolerances inside the control IC, other than the offset of the operational amplifier. This is generally not a problem if the operational amplifier has a low offset in the range of a few millivolts.

Figs. 5 and 6 show circuit implementations of dimming ballasts using the respective control methods discussed here. Each circuit is based around an ASIC that provides the ballast control functionality. The schematics do not show front-end power-factor correction circuitry for the sake of simplicity, though most practical designs do include this.

Achieving Good Linearity

Good linearity is necessary in a dimming ballast design. Such ballasts generally operate from a 0-V to 10-V isolated dc control input, where it is required that the Lumen output from the lamp be linearly proportional to the dimming control voltage.

Though it is possible to achieve good linearity with both control methods, the values of the output inductor and capacitor must be chosen carefully if phase control is being used. This is because, at a certain point, there is a large change in power that occurs over a very small change in phase shift, resulting in a noticeable step. This tends to happen when the dim level is close to maximum and where the load current is dominated by its resistive component. The reasons for this effect are explained by nonlinear changes of lamp impedance with arc current. If the load was a fixed resistance, then this problem would not occur.

This undesirable step function in the dimming response

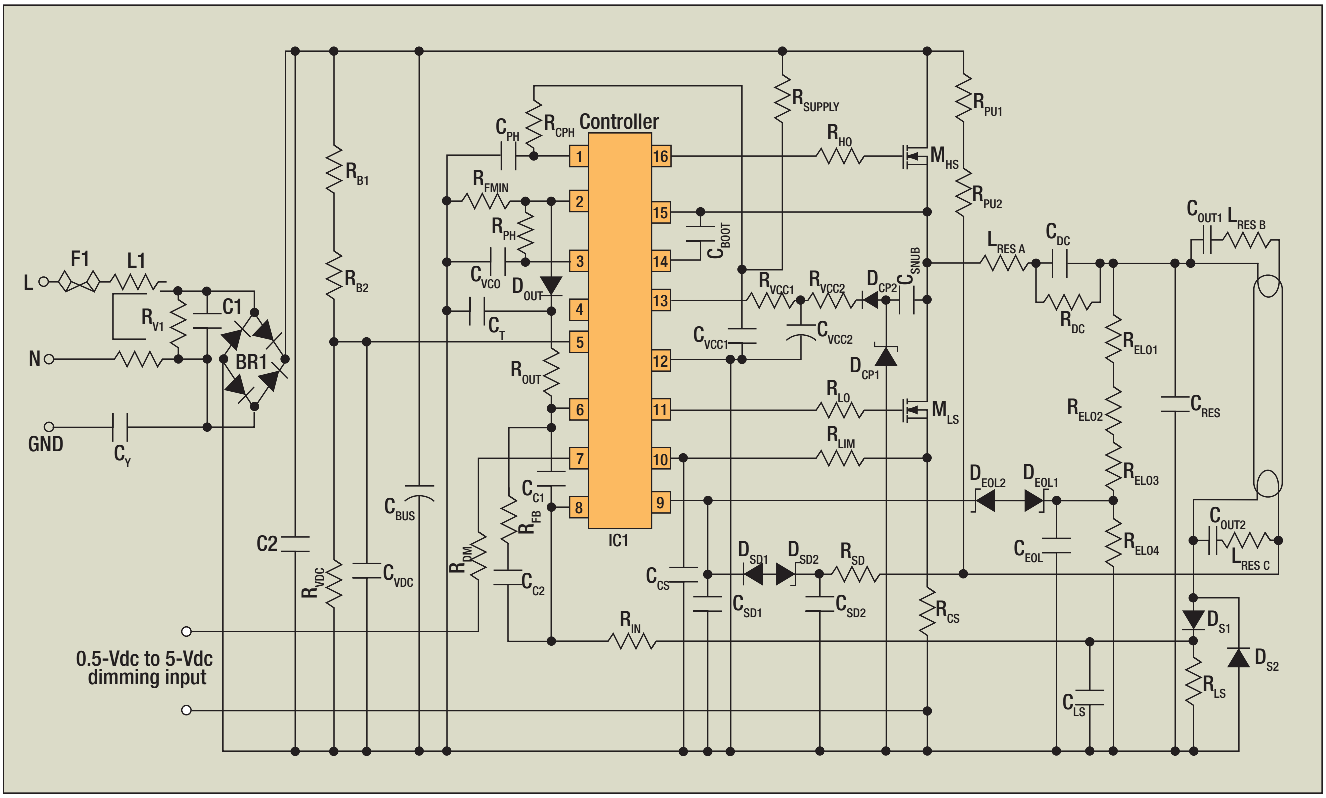


Fig. 5. *Actual implementation of dimming a fluorescent lamp's ballast with arc-current control.*

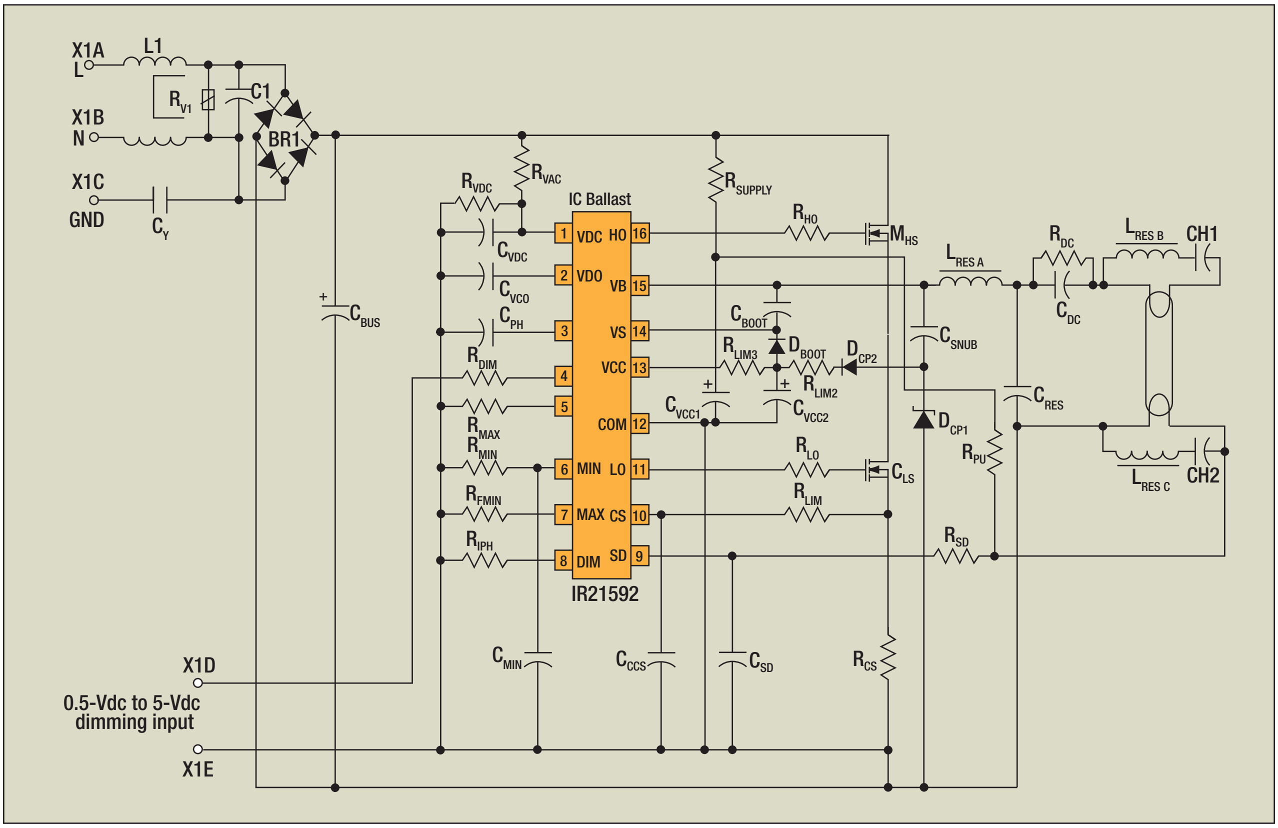


Fig. 6. *Actual implementation of dimming a fluorescent lamp's ballast with phase control.*

has been observed in dimming ballasts based on phase control becoming more severe with increasing lamp power, because this increases the resistive portion of the load current. It becomes a serious drawback with high-power fluorescent lamps and also high-intensity discharge (HID) lamps. Although it is not possible to dim HID lamps below about 50% of their nominal power, the option exists to adjust the power between 50% and 100% to save energy. Below 50%, the arc becomes unstable and the lamp flickers or extinguishes completely.

At first, it may seem that the obvious solution to remove the step would be to increase the resonant capacitor value. Unfortunately, this also increases the circulating current in the half-bridge, making the MOSFET switches run at a higher temperature with greater conduction losses. This can result in unacceptably high currents during ignition, which overstress the power switches and unacceptable loss of efficiency during operation.

Remember that one of the objectives of dimming is to save energy as well as control the light level.

The alternative method of regulation being discussed here avoids this problem by directly regulating the lamp arc current, which has a linear relationship with the light output. Though the amount of arc current is very small at low dimming levels, it is still sufficient for a good-quality op amp to be capable of regulating effectively.

Also note that if a ballast using phase control can be designed such that the dimming limits are set at phase points to avoid the step problem described previously, then the linearity is in fact a little better than in an arc-current regulated system. This is because the lamp voltage changes over the dimming range. The amount of voltage change varies from lamp to lamp, and the greater it is, the greater the resultant mismatch will be between the lamp arc current and the true lamp power. However, the phase shift is directly proportional to the true power. Normally, the error in linearity experienced with arc-current control is not considered to be a problem.

Loop Response and Stability

The question of loop response and stability also should be considered in both methods. With phase control, there is a capacitor at the input to the VCO, which is charged or discharged by the control IC by pulses of fixed current depending on the detected phase error. This method is effective when the ballast dc bus voltage is stable and regulated such as in systems that include a power-factor correction stage at the front end. In systems where the dc bus is not regulated and where there is more ripple, however, the loop is not able to compensate completely for this ripple, and some flicker can be seen at the lamp at a certain point in the dimming range. It is difficult to optimize the loop response such that it remains stable over the entire dimming range (Fig. 7).

In the case of arc-current control, the lamp current is regulated by an integrating error amplifier. This allows the

compensation components to be selected for optimum performance, providing fast response where necessary and making it possible to operate the ballast from a dc bus that contains ripple without noticeable flicker at the lamp.

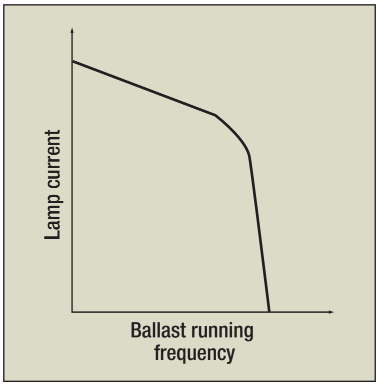


Fig. 7. *The increasing frequency of a fluorescent lamp's ballast sharply reduces the lamp's operating current.*

Another point that needs to be considered is the behavior of the ballast when the lamp is ignited at a low dim level. Generally, the end user prefers that the ballast is able to ignite the lamp at a reduced light level without showing any discernible initial flash. In order for this to be possible, the dimming control loop must be closed immediately after ignition and must transition to the dimmed level rapidly enough that the eye does not see any flash.

In a system based on arc-current regulation, the loop speed can be set by choosing the RC values of the integrating error amplifier appropriately. The tradeoff is making sure the loop does not react so quickly that the system loses stability. Ignition detection in this type of system is inherent, since before ignition, there is no arc current and no feedback, and after ignition, arc current is immediately detected. In the case of phase control, there is no inherent ignition detection, so it is necessary to add additional circuitry to detect when ignition has occurred. In the case of certain lamp types, such as the widely used 32-W T8, ignition generally occurs at a voltage not significantly higher than the lamp running voltage, making it difficult to reliably detect.

Niche Applications

The general conclusion is that an analog approach to designing a dimming fluorescent ballast is simpler and more cost effective than a digital alternative. Examining two different analog dimming methods, it appears that though both phase control and arc-current control can produce excellent results, the arc-current regulation method is simpler to implement, more flexible and less problematic than phase control in most ballast applications.

For this reason, as well as ease of design, arc-current control is more widespread in the lighting ballast industry. However, in certain niche applications where more accurate power control is required at low dimming levels, phase control may offer an advantage. **PETech**