LIGHTING CONTROL

Electronics in general and electronic power circuits in particular are becoming an increasingly important part of high-efficiency lighting systems. This article covers very broadly the areas of application of electronic ballasts in discharge lighting. First, the need for ballasts for discharge lamps is explained as are some of the specific requirements of starting and lamp current wave shapes. The next section describes electronic ballasts in a general manner, their advantages, and some of the benefits that can be obtained from using them in lighting systems. The current and future impact of electronic ballasts on lamp system efficacy in particular is discussed in more detail in the following section. Advances in component technology, circuit design, and construction are described as is the impact of these advances on lighting systems. Finally, a specific design example of an electrodeless lamp ballast is given, to illustrate the increasing need for close cooperation between the lamp and ballast designer.

DISCHARGE LAMP BALLASTS

Discharge lamps, be they high-pressure sodium, metal halide, or fluorescent, cannot be operated directly off the mains voltages. The impedance of these lamps exhibits a negative slope characteristic so that as the current increases the voltage across the discharge decreases. Figure 1 shows the impedance characteristics of a fluorescent lamp. Once the lamp is ignited and connected directly to the mains (which by design has a very low source impedance) the current in the lamp keeps increasing to catastrophic levels, until a fuse blows or the lamp fails. To prevent this from happening a *ballast,* which is a current-limiting device, is placed in series with the lamp and the source. The simplest ballast is a resistor of the appropriate value which raises the source impedance as seen by the lamp terminals. Thus, the lamp sees a source with a sharply sloping load line (Fig. 1). The lamp and ballast combination then operate at the stable intersection between the two load lines. Lamp physics dictate that the lower current, higher voltage intersection point is unstable. The lamp either extinguishes or the current increases until it reaches the stable point shown in Fig. 1.

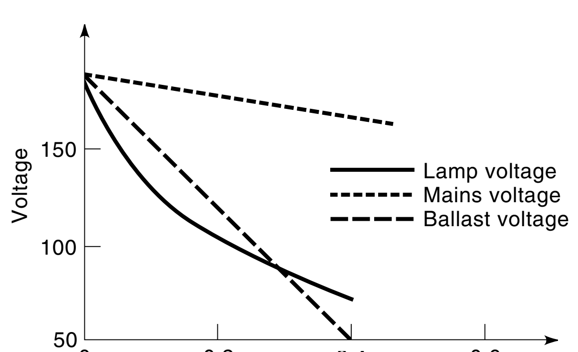


Figure 1. Graph illustrating the need for a ballast to operate a discharge lamp. The *V–I* curve of a compact fluorescent lamp (solid line) is overlaid with the load lines of the mains supply only (dotted line) and mains supply with resistive ballast (dashed line). The lamp operates at the stable intersection of its *V–I* characteristic and the ballasted mains load line. If operated off the mains with no ballast there is no intersection and the current would increase till either the lamp fails or the mains relays trip or fuses blow.

Electromagnetic Ballasts

A simple resistive ballast serves a useful purpose in explaining the principle of operation of a ballast; however, it is an energy-dissipating component. The overall system efficacy (a measure of the light-producing efficiency of a lighting system, expressed in lumens/watt) with a resistive ballast is less than half the efficacy of the lamp alone. Since the ballast's primary function is to limit the current in the lamp, a lossless impedance is desired. Inductors and capacitors that have a high impedance at the line frequency are used as low-loss ballasts. This impedance limits the current in the lamp to the required value for operation. There is always some loss associated with these components due to nonidealities in the materials used to make them. Traditionally most ballasts have been electromagnetic, i.e. inductors and transformers, but capacitors as the principal ballasting component are also available.

One of the reasons electromagnetic ballasts are more prevalent is that inductors limit the current crest factor. Current crest factor is defined as the ratio of the peak current to the rms current. Fluorescent lamps with electrodes require a crest factor of 1.7 or less in order to reach their rated life (1). A capacitor used as a ballasting component will have a large crest factor because high-frequency currents can flow in a capacitor. An inductor, properly sized to limit the current to its operating value, will also reduce the peak current in the lamp. In fact, a capacitive ballast often contains a small inductor to help reduce the current crest factor (2).

Lamp Starting

Electromagnetic ballasts also make lamp starting easier. A high ignition voltage (several times the operating voltage) is needed to start the lamp. The open circuit mains voltage is not always sufficient to start the lamp. Therefore, a ballast must also provide enough voltage to start the lamp. There are many different techniques to accomplish this, for example a properly sized capacitor can be placed across the lamp so that by resonance (with the inductive ballast) the voltage across the lamp builds up to the ignition level. Once discharge is established the lamp (arc) resistance loads the resonant circuit such that the voltage reaches the operating voltage of the lamp.

A ballast that starts a fluorescent lamp in this manner described is known as an instant-start circuit. The cathodes (filaments) are not heated and the voltage required to ignite the lamp is quite high because there is no thermionic emission from the cathode to help initiate the discharge. Such a starting circuit is detrimental to lamp life as the cathodes gradually lose the emission mix that lowers their work function at every start. Among the starting methods that apply cathode heat prior to raising the lamp voltage to starting levels the main ones are known as rapid start and switch start

(1,3). In a switch-start implementation, a switch closes a circuit consisting of the two cathodes in series with the ballasting inductor and the voltage supply. The current established in the circuit heats the cathodes. The switch is then opened which results in the voltage across the inductor building up until the lamp ignites. The starting voltage required is lower than in the instant-start case.

In a rapid-start implementation circuit the cathodes are preheated for about a second before ignition is initiated. The cathode heating current can be applied using additional windings that are placed either on the isolation transformer of the ballast or on the ballasting inductor itself. The ballast is designed so that the open circuit voltage (applied during the cathode heating period) is insufficient for starting with a cold cathode. However, once the cathode is heated the voltage is sufficient to ignite the lamp.

Another commonly used approach for preheating the cathodes for rapid-start lamps is placing a positive temperature coefficient resistor (PTC) in series with the cathodes. At start the impedance of the PTC is low, so a relatively large current flows through the cathodes and the PTC. This heats up the cathodes as well as the PTC, which becomes high resistance after about 1 s. During this time the cathodes are heated to the thermionic emission temperature thus allowing for a smooth discharge to be set up. Note, even though this is a simple start scheme the PTC does consume some power which affects the overall efficiency by 3% to 4%.

High-intensity discharge (HID) lamps go through several phases during starting: initial breakdown, glow discharge, glow-to-arc transition, and thermionic discharge (3–7). Each of these phases has its specific requirements that must be met by the ballast in order to successfully start the lamp. The ballast designer must understand the behavior of the lamp and its impact on the circuit during each of the phases. For example, a ballast that does not supply sufficient current during the glow discharge phase may cause the lamp to remain in that phase and not transition to the arc mode. Operation in this mode is detrimental to lamp life as it causes the cathode to sputter off material which blackens the lamp walls and eventually causes lamp failure. Starting can be enhanced by the application of starting pulses or the enhancement of UV radiation around the lamp by additional electrodes to promote the initial ionization for starting (7).

ELECTRONIC BALLASTS FOR DISCHARGE LAMPS

The same principles and requirements applied to electromagnetic ballasts are applied to electronic ballasts. In essence, an electronic ballast simply consists of a frequency converter that takes the mains (line) frequency (50 or 60 Hz) and converts it to a much higher frequency (tens of kHz to GHz). As the impedance of an inductor is proportional to the frequency, the inductance needed for ballasting is reduced accordingly. A line-frequency electromagnetic ballast is therefore much larger and heavier than a high-frequency electronic ballast.

In recent years electronic ballasts have begun penetrating the lighting field at an increasing rate. It was found early on that operation of linear fluorescent lamps at frequencies above 10 kHz resulted in an increase in lamp efficacy by 10% to 15% (8–10). Coupled with a higher electronic ballast efficiency, its smaller size and weight relative to the electromagnetic ballast, the efficacy increase provided an early impetus for electronic ballasts.

In spite of these advantages, the penetration of electronic ballasts had been slow principally because of increased costs relative to a conventional ballast. Recently however, lamp systems have been developed where electronic ballasts provide capabilities that cannot be matched by electromagnetic ballasts. Some examples of these capabilities are arc straightening in HID lamp (11–14), dimming in fluorescent and HID lamps (15–17), high-pressure sodium (HPS) lamp color improvement by pulsing (18–20) and lightweight, small sized fluorescent lamp replacements for incandescent lamps (21–23). In addition to the increased capability offered by electronics there are some systems that cannot be practically operated at the mains frequencies. Examples of these systems are the electrodeless fluorescent lamp (24–27), the electrodeless HID lamp (24,28), and the microwave sulfur lamp (29). The geometry of these systems and the efficiency of coupling the electric energy into the discharge dictates the frequency of operation.

Figure 2 shows the block diagram of an electronic ballast for a discharge lamp. The principal blocks will be found in one form or another in every electronic ballast. The first block consists of an ac-to-dc rectifier which converts the line frequency voltage to a dc voltage, and also always includes an electromagnetic interference (EMI) filter. The EMI filter prevents high-frequency noise generated in the ballast from being conducted back into the mains, in compliance with regulatory controls on emissions [e.g., Federal Communications Commission (FCC) in the United States and International Electrotechnical Commission (IEC) internationally]. In addition to the basic ac-to-dc conversion functions, this block could include a power factor correction circuit or a dc bus voltage control circuit. In the case of a microwave system this block would be the power supply for the magnetron.

The second block is a dc-to-ac high-frequency converter. In circuits operating at frequencies from the tens of kilohertz to the tens of megahertz this usually consists of one or more switching power devices [bipolar transistors, metal-oxide-semiconductor field effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs), etc.] that chop the dc voltage into high-frequency pulses. This block includes the ballasting element (inductor or capacitor) and auxiliary components for starting. Starting components can be as simple as a resonant capacitor, or as complicated as a separate high voltage supply. As in the rectifier block, control functions and feedback loops may also be included in this block. In a microwave system this block would represent the magnetron.

The third block is the coupling block that applies the high-frequency signal to the lamp. Typically with electroded lamps this is simply wires connecting the ballast to the lamp. However, in electrodeless lamps the coupling component is a very important one, worthy of being defined as a separate block. Some examples of these are the coils used in the electrodeless fluorescent lamps recently introduced by Phillips (26) and GE (27), the drive coil for the electrodeless HID lamp described by GE (28), and the microwave cavity used in the microwave sulfur lamp introduced by Fusion Systems (29).

The design of any ballast requires that the electrical engineer understand the principal characteristics of the lamp as a load as well as the requirements for properly starting and running a lamp. Traditionally, the lamp was treated as a black box where only the terminal characteristics were impor-

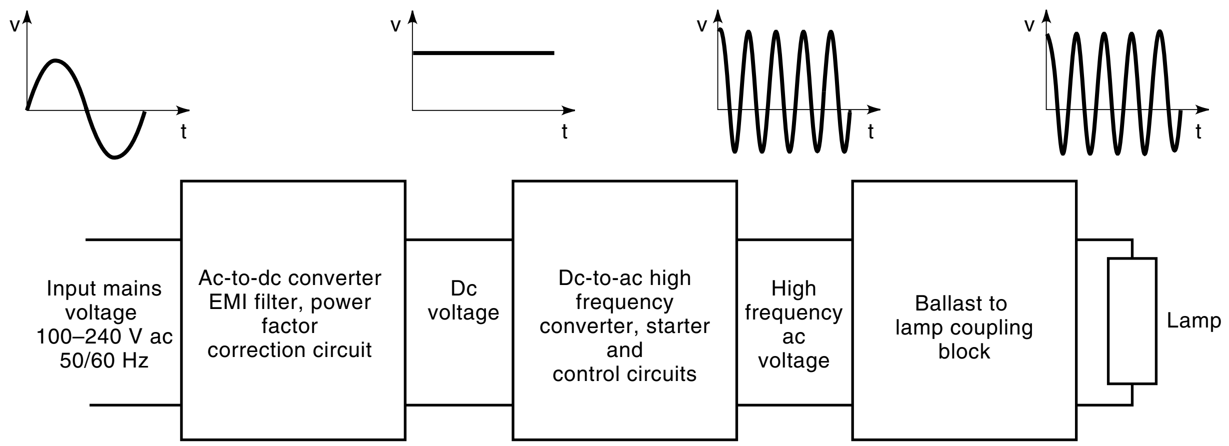


Figure 2. Block diagram of a generic electronic ballast, showing the different voltage waveforms at the inputs of the different blocks. All electronic ballasts contain these building blocks in one form or another.

tant. However, the design of the coupling blocks in the new electrodeless systems requires a more intimate cooperation between the lamp and ballast designers. The lamp/ballast combination becomes more of an integral system that needs to be designed as a single unit. In fact, decisions made by the lamp designer can have a significant impact on the ballast and vice versa. A process whereby lamp performance is optimized without any regard to system impact may result in a system that is far from optimum.

Component Technology for Electronic Ballasts

In general standard ballasts operate with efficiencies in the 85% to 93% range. Therefore, very little room exists for further improvements in system efficacy to be obtained from ballasts. However, insofar as the use of electronics enables types of lamps to exist that would normally be impractical or impossible to make and allows sophisticated light control schemes to be implemented, they can have an indirect positive impact on the overall power consumption for lighting application. For example, the electrodeless HID system (28) achieves lamp and coupling system efficacies of 140 lm/W (for the purpose of comparison, Table 1 lists efficacy of other standard lamp types). However, such a system is not feasible if the electronics needed to operate the lamp at 13.56 MHz is either unavailable or too inefficient.

Table 1. Typical Efficacy of Standard Lamp Types (30)

Lamp Type	Wattage (W)	Lumens	Efficacy (lm/W)
Incandescent	60 to 100	870 to 1750	14.5 to 17.5
Fluorescent			
Warm White	40	3200	80
Deluxe Warm White	40	2200	55
Warm White (Watt Miser)	32	2800	82.35
Deluxe Warm White (Watt Miser)	32	1925	56.60
HID-Mercury Vapour			
Deluxe White	400	22,500	56.25
HID-Metal Halide			
Clear, "any position"	400	36,000	90
HID-High Pressure Sodium (Lucalox)			
Clear, mogul base	150 to 250	15,000 to 27,500	100 to 110

The field of power electronics, of which ballast engineering is a specialty, has been advancing in the direction of increasing the efficiency of systems operated at ever higher frequencies. Whereas 10 years ago operation at 50 kHz was considered an upper limit for higher efficiency, now systems are being built that operate at 2.5 MHz and higher without compromising the efficiency.

These advances have come as a result of both improvements in the efficiency of components as well as advances in circuit techniques. The improvements in components have come in every area. In semiconductors, power MOSFETs have increasingly replaced bipolar transistors as MOSFET channel on-resistances have decreased and switching speeds increased. Similar improvements have occurred in power diodes with lower forward drops and reverse recovery times.

Magnetic materials used in ballasts such as ferrites have also improved over the years (31). Ferrites are now able to run at higher flux densities, higher temperatures, and higher frequencies. However, the improvements there have not been as impressive as with the semiconductor devices. In fact as the operating frequency gets up in the MHz range powdered iron cores are used, and finally as the frequency gets higher air core inductors gain the upper hand.

Ceramic capacitors have allowed operation at higher frequency with their low loss and extremely small size (32). However, one component that has seen very little improvement over the years has been the electrolytic capacitor. Electrolytic capacitors have, by far, the highest energy density per unit volume of all capacitors. They are used as the energy storage capacitor in the rectifier to allow the circuit to operate during the zero voltage crossings of the mains voltage.

However, electrolytic capacitors suffer from a very low temperature range of operation. Although rated for up to 105°C their life at this temperature is only 2000 h. The life of an electrolytic capacitor doubles for every 10°C temperature reduction. If we take into account that a metal halide lamp lasts 20,000 h, and that a ballast should last as long as two lamps, the electrolytic temperature must then not exceed 65°C. Given that electronic ballasts operate in ambient temperatures as high as 55°C, the thermal design problems caused by these components can easily be appreciated. The problems due to the size, cost, and thermals of electrolytic capacitors have a significant impact on the integral ballasts in compact fluorescent lamps in particular.

Integrated circuits are also beginning to appear in electronic ballasts. Unitrode (33), International Rectifiers (34), and other companies have begun producing, in large quantities, high-voltage ICs where the high and low side device drivers are integrated on the chip. This eliminates the need for a drive transformer and simplifies the design of the circuit. The introduction of ICs in ballasts means that we can foresee increasingly sophisticated control schemes that can be implemented at low cost. The addition of communications capabilities will also be possible, leading to the design of smart lighting systems, where, for example, the light level is kept constant throughout the day relative to changes in natural lighting. Alternately, the light in a large working area could be varied in intensity depending on the needs at different locations. These types of control would lead to reductions in overall energy consumption for lighting.

Electronic Ballast Design and Construction Techniques

In addition to component improvements, there have been tremendous advances in circuit design and construction techniques that have enabled the circuits to operate efficiently at very high frequency. A significant advance in this area has been the development of soft switching techniques to eliminate switching losses in power devices (35,36). Soft switching is accomplished by either zero-voltage switching or zero-current switching. Zero-voltage switching (ZVS), which is more widely used in electronic ballasts because of capacitor dominant losses, eliminates switching losses caused by the charging and discharging action of the parasitic capacitors at the output of power devices. When a power device is off the voltage across it is high. Since the device has an output capacitance there is some charge stored on that capacitor. When the device turns on, the charge gets dissipated in the device and this constitutes a loss. This loss is proportional to frequency. It is very large at high frequencies.

Capacitor discharge losses are eliminated by using resonant techniques to discharge the capacitor without loss before the device is turned on. There are many techniques for doing that, the most common in electronic ballasts, such as the one shown in Fig. 3, is one known as transition resonance (36), where the first device is turned off for a certain time interval

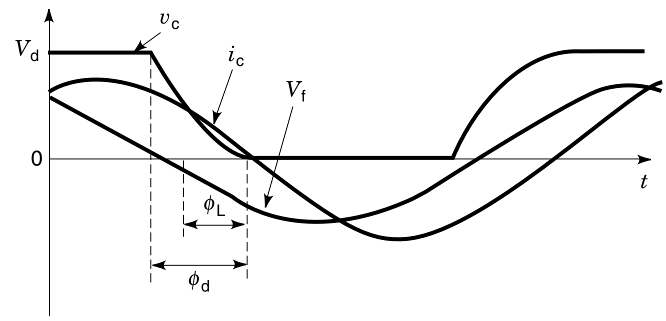


Figure 4. Graph showing waveforms used in deriving the zero voltage switching conditions that must be met to achieve high efficiency in high frequency electronic ballasts. The high frequency inverter midpoint voltage, v_C, its fundamental component, v_f, and the load (or ballast inductor) current, i_L, and their phasing relationships are shown. For zero voltage switching of the inverter devices, i_L must lag v_f by an appropriate phase angle ϕ_L. ϕ_d is the dead time angle and is selected so that the circuit can meet the ZVS requirements and deliver the required power to the lamp.

before the second device is turned on. During this time interval (known as the dead time) the load current flows through the parasitic capacitors discharging one and charging the other (the sum of the capacitor voltages has to be equal to V_d at all times). In order to maintain the ZVS condition the design must take into account the dead time, the frequency of operation, the load current, and its phase angle relative to the midpoint voltage. The relationship between these values and the requirements of the lamp must be well understood and characterized before the design can be finalized.

As a result of the switching action of the two devices a trapezoidal voltage appears at the midpoint, v_c. The load circuit acts as a low pass filter allowing a nearly sinusoidal current at the fundamental frequency of the midpoint voltage to flow. Figure 4 shows the midpoint voltage, v_c, the load current, I_L, and the fundamental component of the midpoint voltage, v_f. The timing relationships used in the design are also shown. In order to get ZVS, the current amplitude, its phase relative to the fundamental component of the voltage, ϕ_L, and the phase angle of the dead time, $\phi_d(\phi_d = t_d f_s \pi)$, are related to the frequency of operation, f_s, the dc bus voltage, V_d, and the output capacitance of the devices, C_o, as follows:

$$V_d = \frac{I_L}{\pi f_s C_o} \sin(\phi_d) \sin(\phi_L) \quad (1)$$

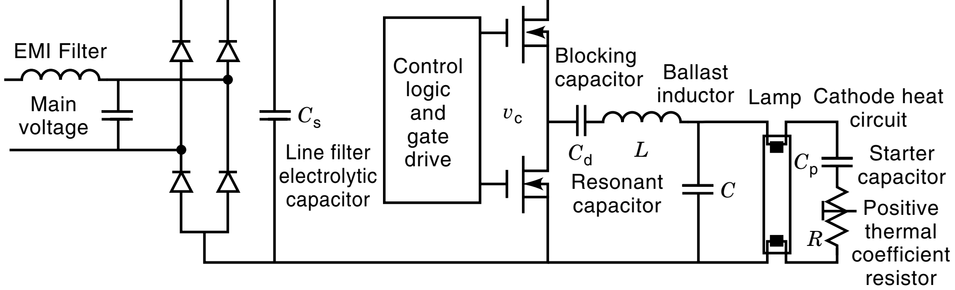


Figure 3. Circuit schematic of a conventional electronic ballast (low power factor) for fluorescent lamps. Each functional block of Fig. 2 is illustrated. The EMI filter, rectifier and line filter capacitor form the ac-to-dc block. The control logic, high frequency inverter, load network (C_d, L, and C) and cathode heat circuit form the dc-to-ac block. In this case, the ballast to lamp coupling block consists simply of the wires connecting the ballast to the lamp.

Circuit layout and device packaging are circuit areas in which we can expect rapid improvements in the near future. The use of finite element modeling to help with designing circuit boards and device packages for minimal parasitics is beginning to have an impact on the frequency of operation of power circuits. Whereas a few years ago high-efficiency operation at hundreds of kilohertz was the state of the art, converters operating at tens of megahertz are being reported in the literature.

It would then seem that for ballasts operating at frequencies from the tens of kilohertz to the tens of megahertz we can only expect small incremental improvements in efficiency. Most of the impact in years to come will be in the area of reduction in cost and size coupled with an increase in the ballast functionality as smart controllers using ICs become more prevalent. Dimming functions, light control functions, and energy saving functions will be more easily implemented. Improvements in circuits will be mostly directed toward raising the frequency at which circuits can operate with high efficiency. Ballasts operating at 100 MHz to 200 MHz will become as common as ones operating at 2.5 MHz.

Design Methodology

The primary focus of this section is the operation and design methodology of the dc to high frequency ac inverter and load network stage that interfaces with the discharge lamp, typical of most electronic ballasts available in the market today. Furthermore, there are two broad categories of electronic ballasts—low-power factor and high-power factor—the difference being in the front-end line frequency ac to dc conversion stage. In the low-power factor front-end, the electrolytic capacitor (required for energy storage and mains filtering) is directly connected to the dc side of the mains voltage diode bridge rectifier. The current drawn from the mains is zero except for the narrow spikes required near the crest of the mains voltage to refurbish the energy in the capacitor that is subsequently consumed by the ballast and the lamp. This process repeats once every half cycle of the mains frequency. This highly discontinuous and peaky mains current has a high harmonic content resulting in the low power factor, typically in the range of 0.6 to 0.7. Various high-power factor front-ends, discussed in detail in a later section, differ in their active mains current wave shaping schemes.

Figure 3 shows the circuit schematic of a typical high-frequency electronic ballast, shown with a low-power factor front-end for the sake of simplicity. The dc to high frequency ac stage consists of a pair of n-channel power MOSFETs connected in a totem-pole configuration across the dc bus, V_d. The electrolytic capacitor across the dc bus is assumed to be large enough such that V_d has a relatively small ripple at twice the line frequency. Hence, V_d is approximately constant and equal to the peak of the line voltage.

The MOSFET pair is gated on and off at a duty cycle slightly less than 50% in a complementary manner to generate a trapezoidal wave across the lower MOSFET that switches between zero and V_d. The less than 50% duty cycle allows a small dead time (approximately 1 μs to 2 μs) between the turn-off of one switch and the turn-on of the other which is necessary for zero voltage switching and prevention of short-circuit across the dc bus. C_b is a dc blocking capacitor that removes the dc bias on the trapezoidal wave to apply a symmetrical waveform switching between $-V_d/2$ and $+V_d/2$ to the series resonant circuit consisting of the ballast inductor, L, and resonant capacitor, C. The lamp, which is the load, is connected across the resonant capacitor. The gating or switching frequency of the MOSFETs is the control parameter for resonant ballasts to control starting or ignition of the lamp, to control lamp current crest factor against modulation caused by the dc bus voltage ripple and against component variations with temperature and life, and to maintain lamp power regulation against changes in the mains voltage. Typically, lamp current feedback is used as a control signal to a voltage controlled oscillator (VCO) to vary the switching frequency. All feedback, control, and drive electronics are represented as a functional block in Fig. 3.

Starting scenarios for rapid-start ballasts have been discussed earlier. Two typical implementations for preheating the filaments prior to ignition are as follows: (a) using a positive temperature coefficient (PTC) resistor in series with the filaments of the lamp (Fig. 3), and (b) using auxiliary windings on the ballast inductor to provide a preheating cathode voltage in the range of 3 V to 5 V as specified by ANSI.

With the circuit topology selected, design of the ballast involves the selection of the control circuit and power devices, the design of the resonant load network, and the ballast inductor. The key inputs to the design process are: the input voltage, the output power, the lamp impedance (or VI characteristics), the starting voltage, and the input current requirements. Electronic ballasts are always competing with the electromagnetic ballasts which places a severe cost constraint on the electronic ballast. Hence the cost of the ballast is also a significant input and it drives the selection process. Furthermore, selection of the PTC for filament heating and its influence on starting will also be incorporated in the design methodology.

To simplify the analysis of the ballast the following assumptions are made (37,38):

1. The MOSFET switches are ideal with zero on resistance, infinite off resistance, and negligible output capacitances.
2. The loaded quality factor of the resonant circuit is high enough so that the currents through inductance, L, capacitance, C, and load resistance, R, are sinusoidal.
3. Operating frequency is fixed at the undamped natural frequency of the resonant circuit.

The resonant circuit in Fig. 3 is a second-order low-pass filter and can be described by the following parameters:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad Z_0 = \sqrt{\frac{L}{C}} \qquad Q = \frac{R}{Z_0}$$

where, f_0 is the undamped natural frequency, Z_0 is the characteristic impedance, and Q is the loaded quality factor at f_0. Note that R represents the effective resistance seen by the resonant capacitor which is different under starting and running conditions. During starting, $R = R_P$, where, R_P is the resistance of the PTC which increases as the PTC gets hotter. Although the PTC is in series with the filaments, the filament resistance is small compared to the PTC hot resistance. Also, the lamp discharge resistance which appears in parallel with the PTC resistor is near infinite before ignition.

Under steady-state discharge conditions, $R = R_L$, where, R_L is the lamp resistance under nominal discharge conditions. This is a ratio of the nominal voltage and current specified for the lamp. It is assumed here that the hot PTC resistance is 3 to 4 times bigger than the lamp discharge resistance, thus having little influence on the effective load resistance, R.

The magnitude of the fundamental component of the trapezoidal voltage, v_c is:

$$V_f = V_d \frac{2\sin(\phi_d)}{\pi\phi_d} \tag{2}$$

The following relevant quantities can be derived for the design and selection of the resonant components. All these quantities are valid only at $f = f_0$, which is assumed to be the fixed operating frequency. By neglecting the impedance of the dc-blocking capacitor C_b and using the previously defined parameters, the magnitude and phase of the input impedance of the resonant circuit, respectively, are given as

$$|Z| = Z_0\sqrt{\frac{1}{1+Q^2}} \tag{3}$$

$$\phi_L = \arctan\left(\frac{1}{Q}\right) \tag{4}$$

As stated earlier, for high-efficiency operation requiring ZVS the circuit must operate in a lagging (inductive) mode. Operation at the undamped natural frequency ensures that the ballast will always run in the lagging mode.

The magnitude of the voltage across the load (or resonant capacitor, C) is

$$V_o = V_f Q \tag{5}$$

where, V_o is the peak voltage at either starting or discharge conditions depending on the value of R as defined. Hence, given the starting conditions, and using the definition for Q and the load voltage Eq. (5),

$$Z_0 = R_{P(hot)}\frac{V_f}{V_s} \tag{6}$$

where, V_s is the specified lamp starting voltage and $R_{P(hot)}$ is the PTC resistance after 1-s preheat. For the given lamp characteristics and a selected PTC resistor Z_0 can be calculated. Note, the selected PTC resistor must have a cold value low enough to allow sufficient filament current for proper preheating and prevent lamp ignition before thermionic emission sets in, for rapid-start lamps. Selecting f_0 and knowing Z_0, the resonant components L and C are calculated from the definitions given previously.

The magnitude of the ballast inductor current and load current, respectively, are given by

$$I_L = \frac{V_f}{|Z|} = \frac{2V_d\sin(\phi_d)}{\pi\phi_d|Z|} \tag{7}$$

$$I_R = \frac{2V_d\sin(\phi_d)}{\phi_d Z_0} \tag{8}$$

Note, that the peak inductor currents during starting and running conditions are given by using the respective values for $|Z|$.

Given the value of the ballast inductor, L (calculated from resonant circuit design methodology outlined previously), nominal operating frequency, f_0, starting and running peak inductor currents a simple iterative design process for the inductor can be formulated. First, a suitable core magnetic material (ferrites) and geometry (e.g. E-E, E-I) are selected. The following three equations are iterated to satisfy the peak flux density specified by core manufacturer while arriving at a reasonable number of turns, N_t, and the air gap, l_g where A_c is the core cross sectional area and I_L (start) and I_L (run) are the starting and running peak inductor currents, respectively.

The number of turns is:

$$N_t = \sqrt{\frac{Ll_g}{0.4\pi A_c}}\,10^4 \tag{9}$$

The starting and running peak flux density (in tesla) are:

$$B_m(\text{start}) = \frac{0.4\pi N_t I_L(\text{start})}{l_g}\,10^{-4} \tag{10}$$

$$B_m(\text{run}) = \frac{0.4\pi N_t I_L(\text{run})}{l_g}\,10^{-4} \tag{11}$$

High-Power Factor Ballasts

In the US market, fluorescent lamp ballasts have for years been marketed as high-power factor ballasts. This standard has not been enforced by any regulatory agency, but has become a de-facto standard. The power factor definition in this case is accepted to be greater than 0.9. In Europe and other countries, the IEC (International Electrotechnical Commission) has established a standard applicable to lamp ballasts known as IEC 61000-2-3 (39). This standard controls the power factor by specifying the maximum relative amplitude of harmonics of the mains current up to the fortieth harmonic (Table 2). The standard requires that any lamp ballast consuming more than 25 W has to be a high-power factor ballast.

Electronic ballast engineers have devised many circuits to meet power quality requirements. Some have been adapted from other power electronics disciplines while some others have been specifically devised for lighting applications. The need to balance the cost, input current, starting, running, and current crest factor requirements for the ballast has resulted in the development of some very innovative circuits.

Valley Fill Power Factor Correction Circuits. The first type of power factor correction circuit is used primarily in the US where the cost requirements are stringent and the power factor requirements are vague. These circuits are known as the valley fill circuits (40,41). The name refers to the dip that occurs around the zero crossings of the voltage at the output of an unfiltered mains rectifier. As described earlier, the narrow spiky nature of the mains current drawn by a low-power factor electronic ballast has a high harmonic content. The valley fill circuits attempt to increase the conduction angle of the input current as a way of improving the input power factor

Table 2. IEC 61000-2-3 specifications and the performance of three high-power factor circuits. The modified valley fill and multiresonant boost values are measured, while the integrated boost values are calculated.

Harmonic	IEC 61000-2-3 Specification	Modified Valley Fill	Integrated Boost	Multiresonant Boost
fund	100	100	100	100
3	28	17	13	0.83
5	10	6.7	0.13	0.14
7	7	16	0.21	0.39
9	5	15	0.14	0.45
11	3	8.9	0.056	0.48
13	3	3.1	0.36	0.49
15	3	5.2	0.03	0.44
17	3	7.7	0.065	0.37
19	3	6.7	0.42	0.4
21	3	3.6	0.033	0.34
23	3	2.2	0.0064	0.34
25	3	4.5	0.18	0.28
27	3	n/a	0.065	0.15
29	3	n/a	5.7	0.17
31	3	n/a	0.049	0.19
33	3	n/a	0.053	0.23
35	3	n/a	5.7	0.25
37	3	n/a	0.065	0.2
39	3	n/a	0.18	0.19

by charging the rectifier filter capacitor to some value smaller than the peak mains voltage.

The simplest of these circuit uses two capacitors and two diodes configured in such a way that the capacitors are charged in series but discharged in parallel [Fig. 5(a)]. Thus, the mains voltage supplies the current to the ballast for the duration when the mains voltage amplitude is greater than half the peak amplitude. During the rest of the period the capacitors provide the voltage to the ballast. This results in a power factor that is somewhat over 0.9. The variation in mains voltage causes the lamp current crest factor to be large.

Lamp current feedback is used in these circuits to minimize the crest factor. Self-oscillating circuits have a certain amount of lamp current feedback which serves to improve the current crest factor. As the lamp current decreases in amplitude the switching frequency also goes down which counteracts the reduction in current amplitude. However, the gain of these feedback circuits is typically very low. The self-oscillating circuit helps reduce the lamp current crest factor, but it does not eliminate the problem entirely.

The power factor of the valley fill circuits is marginal. In order to increase the power factor the conduction angle must be increased. The modified valley fill circuit [Fig. 5(b)] achieves this by charging the electrolytic capacitor to a value lower than half the line voltage amplitude. The circuit is a constant power circuit, thus the current is an inverse sine wave. The power factor of such a circuit reaches a maximum value of 0.961. This value occurs at a conduction angle of 135° (i.e. the conduction occurs between 22.5° and 157.5° relative to the line zero voltage crossing).

None of the valley fill circuits described meets the requirements of IEC 61000-2-3. Table 2 shows the harmonic components of the input current for the valley fill circuits compared to the IEC requirements.

Boost Power Factor Correction Circuits. One of the circuits that meets the IEC requirements has a discontinuous current boost power factor correction circuit as the input circuit [Fig. 6(a)]. The average value of the high-frequency discontinuous boost inductor current is proportional to the mains voltage. The circuit senses the mains voltage and the inductor current to ensure that the mains current mirrors the mains voltage. The storage capacitor, C_s, voltage is higher than the peak of the mains voltage. The circuit has been used in ballasts for conventional fluorescent lamps in the US market (Motorola) and may be used for high-intensity discharge lamp ballasts which typically cost more than fluorescent lamp ballasts. For compact fluorescent lamp (CFL) this ballast is not typically used for the cost reason but also because of size restriction. The circuit comprises two fully functional power electronic circuits that operate in series which makes it hard to fit in an CFL ballast housing.

Integrated Boost Circuit. The boost power factor correction circuit can be modified by merging the boost inductor, L_b, into

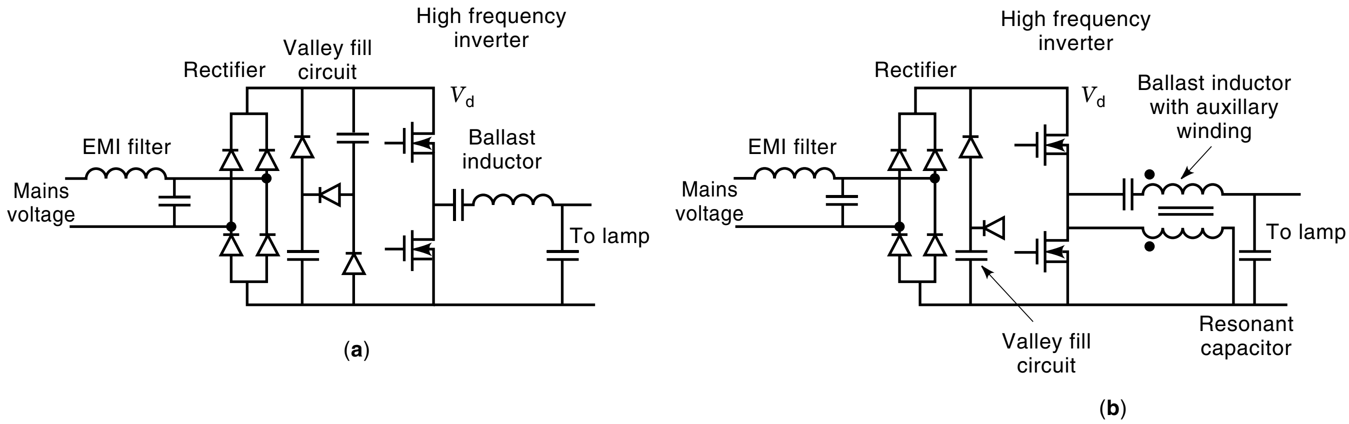


Figure 5. Schematics of two simple high-power factor electronic ballasts with (a) two capacitor valley fill power factor correction circuit, and (b) modified valley fill power factor correction circuit. These circuits are relatively easy to implement and are commonly used in the US, but do not meet IEC standards for high-power factor.

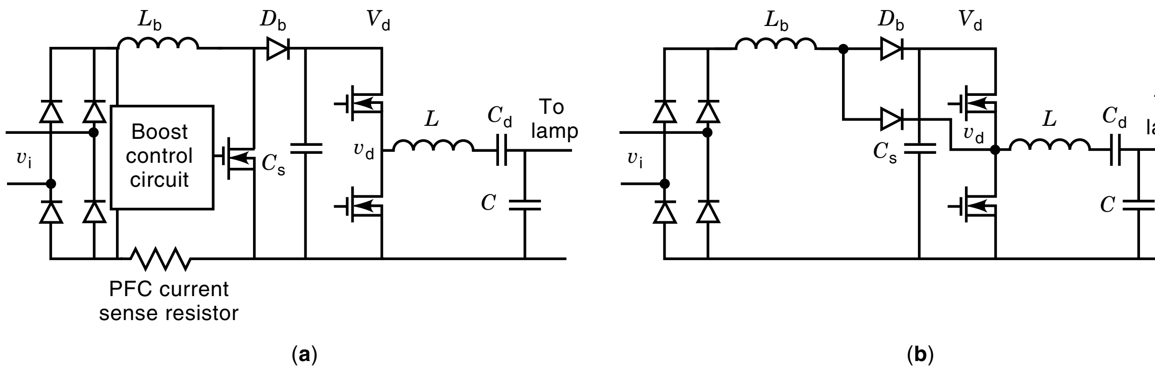


Figure 6. Schematics of electronics ballasts with (a) conventional boost power factor correction circuit and (b) integrated boost power factor correction circuit. The first circuit can meet all high-power factor requirements, but is considered too expensive and large for compact fluorescent lamps. The second is a simplified lower cost version which has very good power factor performance for the US market but fails to meet IEC standards for the European market.

the ballast circuit. In that circuit [Fig. 6(b)], the boost inductor is connected to the midpoint between the two devices via a diode. Thus, the boost circuit power device and control circuit are all eliminated. The boost inductor has a 50% duty cycle applied to it at the switching frequency of the ballast. The boost inductor current during one half cycle will flow through one of the power devices (in the case shown it flows in the top one). In the second half cycle the current flows through the diode, D_b, and into the capacitor, C_s. The current rises during this period with a slope equal to $v_i(t)/L_b$, where

$$v_i(t) = \sqrt{2}V_i \sin(\omega t) \tag{12}$$

and ω is the line angular frequency. The inductor is selected to be at the critical discontinuous conduction level at the peak mains voltage, which means that when the mains voltage is at its peak the inductor discharges exactly in the next half switching cycle. As the peak current reached in the inductor during the charging half of the switching cycle is proportional to the mains voltage during that time, this peak current will have a sinusoidal envelope. The volt-second balance on the inductor operated in this manner causes the voltage across the electrolytic capacitor to be equal to twice the peak line voltage. The discharge duration varies during mains cycle and is given by

$$t_d(t) = \frac{\sin(\omega t)}{2f_s[2 - \sin(\omega t)]} \tag{13}$$

The voltage across the electrolytic can be assumed for simplicity to be constant at the peak value. As the mains voltage varies, the peak current reached during each switching cycle will be equal to $v_i(t)/2L_bf_s$. Since the inductor is fixed and the switching frequency is fixed (to first order), the peak current is proportional to the input line voltage. The filter at the input to the ballast averages out that current so that the line current is equal to the average of the boost inductor current. This average value can be calculated as follows:

$$i_i(t) = \frac{V_i}{4f_sL_b}\frac{\sin(\omega t)}{2 - \sin(\omega t)} \tag{14}$$

The input power, P_i, to the ballast is equal to the lamp output power and the ballast losses. The equation for the input power to the ballast is combined with Eq. (14) to give the value of the boost inductor:

$$L_b = \frac{1}{4f_sP_i}\int v_i i_i \, dt \tag{15}$$

The design of the inductor follows a procedure similar to the one described for the ballasting inductor.

However, this circuit though attractive in terms of the cost and simplicity fails to meet the IEC requirements (Table 2). Another problem is that the dc link voltage is twice the line voltage. Since the rms line voltage in many countries that follow the IEC requirements is 230 V, the dc link is at 650 V which would require the use of power MOSFETs with a voltage rating of at least 800 V. These devices may be cost effective for stand-alone, multilamp ballasts, but they are too expensive for compact fluorescent ballasts. The integrated boost circuits are commonly used in the US because they have a significantly higher power factor and lower crest factor than the valley fill circuits.

Multiresonant Boost Circuit. In recent years, circuits addressing the particular needs of compact fluorescent lamp ballasts and the IEC specifications have been developed. One of these circuits is known as the multiresonant boost high-power factor circuit (42). The circuit consists of essentially a low power factor circuit to which a boost capacitor and two diodes are added (Fig. 7). The dead time between the switching devices is used to charge the boost capacitor from the mains and to discharge it into the electrolytic capacitor. The voltage to which the electrolytic capacitor is charged is determined by the amount of energy pumped in during each cycle of the switching frequency. If the voltage across the electrolytic capacitor is maintained at slightly above the mains voltage then all the input current is drawn by the power factor correction (boost) capacitor. The charge pumped into C_b during each switching cycle is proportional to the instantaneous mains voltage. Therefore, the filtered mains current is also proportional to the mains voltage. Thus, the power factor will be very high and the harmonic content will be very low. This circuit is capable of meeting IEC 61000-2-3 requirements.

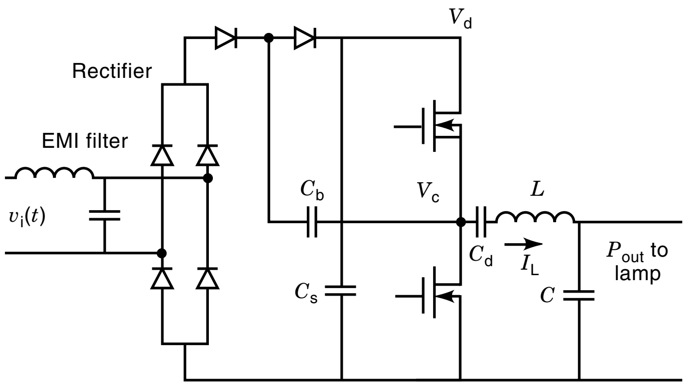


Figure 7. Multiresonant boost high-power factor electronic ballast. This circuit meets IEC standards for high-power factor circuits by adding two diodes and a capacitor. It is considered sufficiently compact and cost-effective for compact fluorescent lamps. However, the design of the circuit and its control is relatively more complex than some of the prior circuits.

However, the dead time between the two devices is now significantly longer than before, because the capacitor being charged and discharged is not the output capacitance of the power device but is the boost capacitor which is substantially larger.

The design equations used to calculate the component values are derived as follows. The condition that needs to be fulfilled in order to have a high-power factor is that the energy stored in C_b during a full mains voltage period has to be equal to the power being drawn by the circuit:

$$V_i^2 C_b f_s = P_i \tag{16}$$

where V_i is the rms mains voltage, f_s is the switching frequency, and P_i is the sum of the power delivered to the load and the losses in the circuit. In addition to this condition the voltage across the capacitor, C_s, V_d, must be greater than the peak mains voltage, $\sqrt{2}V_i$, to avoid drawing a capacitor charging current spike at the peak of the mains. The total power is then equal to:

$$P_i = \frac{I_L V_f}{2}\cos(\phi_L) \tag{17}$$

where I_L is the magnitude of the load current, V_f is the magnitude of the fundamental component of the voltage v_c, and ϕ_L is the load phase angle. The ZVS equation is derived by substituting the proper values for this circuit in Eq. (1):

$$\sqrt{2}V_i = \frac{I_L}{\pi f_s C_b}\sin(\phi_d)\sin(\phi_L) \tag{18}$$

The known quantities in these equations are the mains voltage, the switching frequency, the total power, and a selected dead time. The unknowns are the load phase angle, the load current, and the high-power factor capacitor, C_b. The three equations are solved simultaneously to give the following equation for ϕ_L:

$$\phi_L = \arctan\left(\frac{V_f \pi}{\sqrt{2}V_i \sin(\phi_d)}\right) \tag{19}$$

The fundamental component of the midpoint voltage is given in Eq. (2) and the equation for ϕ_L simplifies to:

$$\phi_L = \arctan\left(\frac{\sqrt{2}V_d}{V_i \phi_d}\right) \tag{20}$$

Because of zero-voltage switching the losses in the circuit are conduction losses in the power devices and in the components. Assuming an overall efficiency, η, the total power is given by:

$$P_i = \frac{P_o}{\eta} \tag{21}$$

Replacing P_i with this expression, we can now get the load current I_L as a function of ϕ_L from the following equation:

$$I_L = \frac{2P_o}{\eta V_f \cos(\phi_L)} \tag{22}$$

Finally the value of the high-power factor correction capacitor, C_b, can be obtained:

$$C_b = \frac{P_o}{\eta V_i^2 f_s} \tag{23}$$

The impedance of the load seen at point b can now be calculated from the power and the load current. The resistance of the lamp at the operating power is known and from that the values of the inductor L and the parallel capacitor C can be obtained. For a lamp with resistance equal to 410 Ω at a power of 26.5 W, with a switching frequency of 100 kHz and a dead time of 1.67 μs, the component values are: L = 497 μH, C_b = 5.6 nF, C_s = 10 μF, C = 11.8 nF, and C_d = 0.1 μF.

Dimming Controls

The emphasis on energy conservation and cost reduction has highlighted the importance of being able to reduce the lighting consumption in a gradual manner. Thus, an ambient light detector would control the lamp ballasts to maintain a constant light level as the external light changes during the day or throughout the year. A very large number of dimmers are sold in the residential market where the ability to control the lighting level is used primarily to set a certain mood. In these applications the lamps are incandescent lamps. The dimming action is achieved by simply modifying the input voltage to the lamp. A dimmer circuit known as a phase-control dimmer consisting of a simple triac or thyristor placed in series with the lamp and set to only turn on during a small portion of the mains voltage cycle is one of the most popular dimmers available. The firing phase angle of the semiconductor device is set via a control knob which allows essentially continuous control of the lighting level.

The phase control dimmer poses a severe problem for compact fluorescent lamps. The operating concept relies on the load being a simple resistor. CFL ballasts are electronic loads and, particularly in the low-power factor designs, can interact destructively with the phase controlled dimmers. The ballast only draws current from the mains during the peak of the mains voltage and that current amplitude is much higher than the amplitude of the currents the dimmer is typically designed for. The current spike may cause the dimmer to fail.

Alternately, the dimmer phase could be set so that the highest voltage applied to the ballast is much lower than the peak mains voltage. The ballast then operates at a dc bus voltage that is much lower than the design limits. The lamp may then flicker severely and the restarts may stress the ballast components to the point of catastrophic failure.

Because of their sinusoidal input current, the high-power factor circuits with high-quality input currents will not cause the dimmer to fail. A carefully designed high-power factor circuit with sophisticated control circuitry can operate on a phase control dimmer. However, no one has come up with a viable practical solution to this problem. All manufacturers of compact fluorescent lamps print warnings on their products against operating the lamps in sockets that are connected to phase control dimmers.

Commercial users are interested in the conservation of energy as a means of cutting their electrical bills. Most commercial locations already use high-efficiency lighting in the form of fluorescent lamps in offices, high-intensity discharge lamps in retail stores, warehouses, and factories, but they still need further reductions in their lighting bill. Dimming controls, motion sensors, and architectural modifications in the workplace are some of the ways of achieving these cost reductions. Laptop computer screens have backlit LCD screens. The backlighting is provided by cold-cathode fluorescent lamps. The ability to control the brightness of the screen by dimming the lamps is a standard feature. Therefore, demand exists for the ability to control the lighting level, especially in offices. For that purpose electronic dimming ballasts have been developed for controlling fluorescent lamps.

The problem with designing a ballast for operation over a wide range of output powers is mostly caused by the lamp's impedance characteristics. Electronic ballasts mostly use the switching frequency as a means of controlling the output power. The frequency is raised to dim the lamp. The ballast load curve must remain above the lamp impedance curve or the lamp will extinguish. Figure 8(a) shows the load curves for a standard ballast with an *LC* circuit. At some frequency the ballast load line falls below the lamp's, which means it is extinguished. The available dimming range for this load circuit is given in Fig. 8(a). The addition of a series capacitor to the lamp increases the dimming range significantly. Figure 8(b) shows the load curves and the dimming range for that circuit.

At very low dimming level, the discharge may begin to show some instability, striations show up, and the light level may flicker. The application of a very low level dc current to the lamp has been shown to reduce the instability of the plasma. Whereas, under normal operation the lamp current is sufficient to maintain the temperature of the cathode, at very low dimming ranges this is not true anymore. In these cases, additional cathode heat is applied to the lamp by an auxiliary circuit as the lamp is dimmed. Thus, dimming ranges as large as 1000 : 1 have been achieved in practical circuits (15).

FUTURE ADVANCES IN LIGHTING ELECTRONICS

The advances in electronics have enabled in recent years the introduction of new lamps which were not practical previously. The largest category of new lamps is known as electrodeless lamps. These lamps use inductive or capacitive coupling at radio frequencies (rf) and cavities at microwave frequencies to apply the power to the plasma. The lamps can then be built without electrodes which results in several features and advantages. First, new light-emitting materials can be used as one does not have to be limited to chemicals that are compatible with the electrodes. Second, as a general rule, the electrode life and hence the lamp life is limited by the number of ignition cycles. Electrodeless lamps have been demonstrated to sustain a very large number of starts without failure. Finally, lamp designers can design lamps with shapes that would not have been possible with electrodes. The basic limitation currently facing electrodeless lamps is the cost of the electronic ballasts.

Microwave Lamps

Fusion Systems recently introduced a microwave lamp that uses optical emissions from sulfur in the plasma to produce light. The microwave system uses a device known as a magnetron to generate the microwave frequencies (43). The efficiency of magnetrons in converting dc power to microwaves is in the range of 30% to 70%. Combining this with the conversion efficiency of the ac-to-dc supply of the magnetron (85% to 95%) results in at best a 67% efficiency from line cord to microwave. Even if we assume the microwave cavity coupling the energy into the lamp to be lossless, the relatively low efficiency of the electronics has a detrimental impact on the overall efficacy of a microwave system. Therefore, one would hope that improvements in the efficiency of these devices are forthcoming, although the technology is quite mature. One possible approach for obtaining the same performance from the microwave operated lamps while raising the system efficacy would be to operate the same lamps at frequencies in the tens of megahertz where high-efficiency ballasts have already been demonstrated.

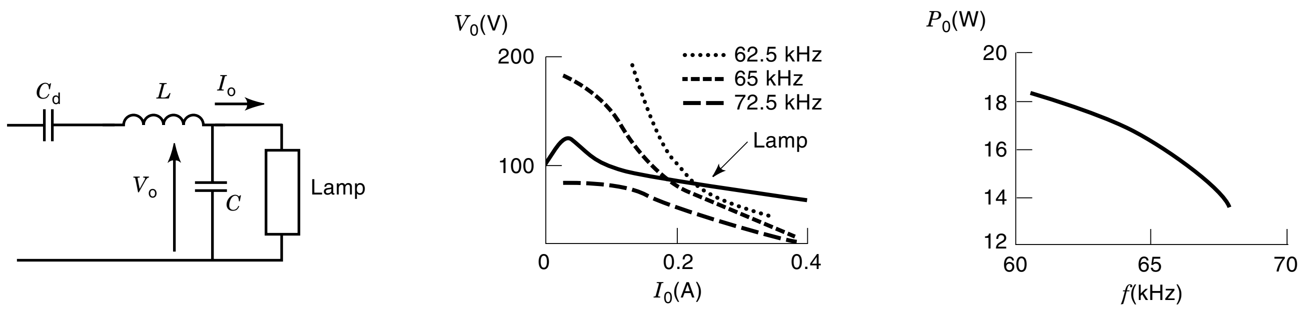
Electrodeless Lamp Ballasts

In recent years, several lamp companies have introduced or described electrodeless lamps operating at RF. In this section, the design of the ballast for an inductively coupled electrodeless lamp is described. In such a lamp the arc forms a single turn secondary in a very loosely coupled transformer (44–46). The arc has resistance and inductance, R_a and L_a, respectively, as well as a coupling coefficient to the primary, or drive coil. In order to simplify the notations we will use the arc Q defined as: $Q_a = \omega L_a / R_a$ (ω is the switching angular frequency here) to represent the arc impedance. The reflected resistance of the arc into the primary circuit is given by:

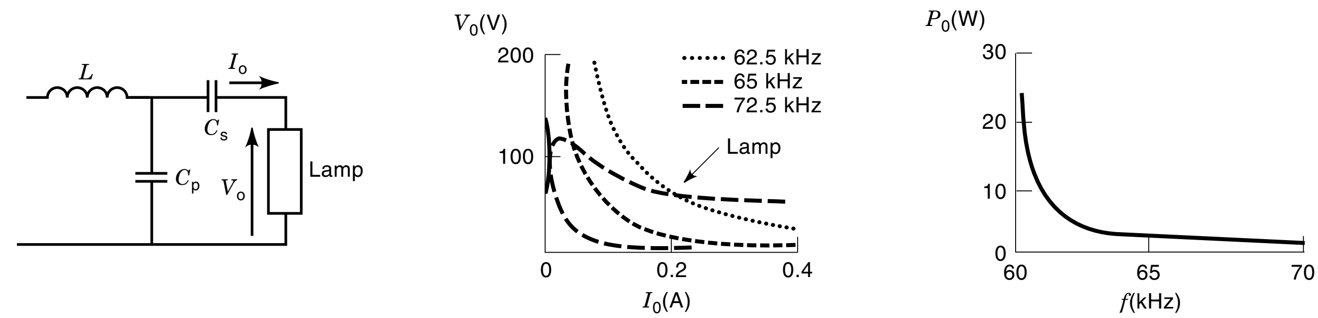
$$R_r = k^2 \omega L_c \frac{Q_a}{1 + Q_a^2} \tag{24}$$

where L_C is the drive coil inductance. The reflected reactance of the arc is given by:

$$X_r = -k^2 \omega L_c \frac{Q_a^2}{1 + Q_a^2} \tag{25}$$



(a)



(b)

Figure 8. The choice of load network can have a significant impact on the dimming range available for a given lamp. The dimming characteristics of two ballast load circuits showing the circuit, a chart of the lamp load line and the ballast load lines at 62.5 (solid), 65 (dashed), and 72.5 kHz (large dashes), and a chart of the dimming range. (a) A standard ballast circuit with a dimming range of 18 W to 14 W. The lamp extinguishes above 70 kHz (the 72.5 kHz load line is below the lamp load line). (b) A ballast circuit with the added series capacitor. The dimming range is from 30 W to 0.2 W.

The loaded impedance of the drive coil is:

$$Z_L = R_c + R_r + j(\omega L_c + X_r) \qquad (26)$$

where R_C is the series loss resistance of the drive coil.

As the reflected resistance of the arc appears in series with the loss resistance of the drive coil, the same current flows in the two resistors. The power dissipated in the reflected resistance represents the arc power, and that dissipated in the series coil resistance represents coil losses. Therefore, the coupling efficiency is a function of the ratio of the two resistances: the larger R_r is relative to R_C the higher the efficiency. The coil resistance, R_c, is minimized during the design of the drive coil as allowed by constraints on the coil (e.g., the maximum outer diameter) placed by the requirements of the lamp. Therefore, R_r must also be maximized. Examining the expression for R_r we see that it is a function of the coupling coefficient, the coil inductance, the frequency, and a factor dependent only on the arc impedance. The coupling coefficient and the coil inductance are primarily dependent on the geometry of the system. Therefore, decisions made by the lamp designer have a significant impact on the coil designer and vice versa. The lamp/coil system has to be optimized for maximum efficacy as a unit, and cannot be done separately.

The least-restricted parameter in the expression for coupling efficiency is the frequency of operation. This frequency is thus selected with a view to optimizing the coupling efficiency, while meeting regulatory requirements on electromagnetic interference (EMI).

An electrodeless fluorescent lamp using a ferrite core drive coil reaches acceptable efficiency levels at frequencies above 1 MHz. For these lamps, the frequency of operation is chosen to be in the middle of a relaxed emission level area in the CISPR 15 regulations between 2.2 MHz and 3 MHz. Therefore operating in the middle of that frequency window makes it possible for the system to meet the EMI regulations in a cost-effective manner. In the case of an air-core-driven electrodeless HID lamp the optimum frequency for efficiency and EMI consideration is 13.56 MHz which is an allowed frequency for industrial, scientific, and medical applications.

The circuit for an electrodeless lamp ballast is very similar to a standard ballast (Fig. 9). The higher frequency of operation makes lossless switching a key requirement. The shorter switching period requires the designer to consider ZVS from the very beginning. The current amplitude and phase must meet the power requirement of the lamp, P_o, and the losses in the ballast (including the coil losses), P_l, as follows:

$$I_L = \frac{2(P_o + P_l)}{V_f \cos(\phi_L)} \qquad (27)$$

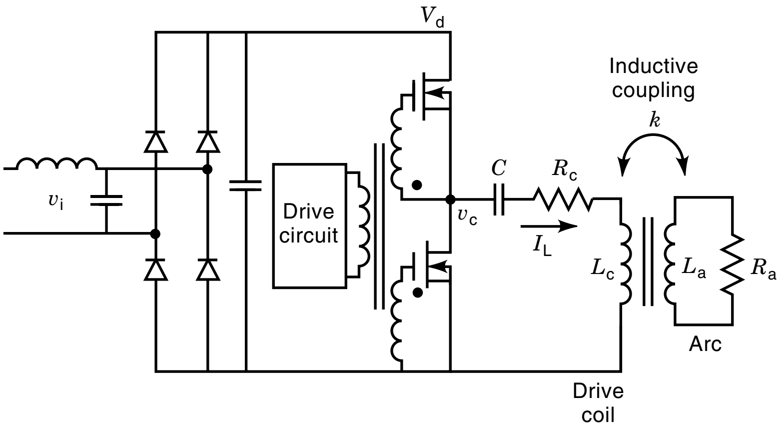


Figure 9. Electrodeless discharge lamps are among the exciting new developments in lighting technology. The ballast for an inductively coupled electrodeless fluorescent lamp is shown. The ac-to-dc and dc-to-ac blocks are similar to the generic ballast of Fig. 3. The load network consists of the resonant capacitor and the drive coil. The ballast to lamp coupling block also includes the drive coil (with an air core or ferrite core) which acts as the primary of a loosely coupled transformer and the discharge which is ring shaped and acts as a single turn secondary. The equivalent circuit of the arc is shown in the figure. The drive coil also acts as the starter for the lamp.

Simultaneous solution of Eq. 27 with the equations for V_f and for the ZVS condition [Eq. (1) and (2), respectively] gives the load impedance amplitude and its phase angle. The resistance in the circuit is equal to the loaded resistance of the coil in addition to the loss resistance of the circuit. Therefore, the coil inductance must be selected such that the reflected value of the arc resistance gives the correct resistance required by the ballast design. Given that the geometry has been optimized for maximum lamp/coil efficacy, the only way to change the coil inductance is to change the number of turns. Finally, a series capacitor, C_S, is added to correct the phase angle of the load to the required value.

The circuit operates at a frequency that is slightly above the series resonance of the load network. Therefore, the current lags the voltage slightly. When the lamp is off, the matching circuit is unloaded and since its components are low loss components the current in the coil increases by a factor of 5 to 6. This allows the voltage across the coil to rise to a level where it can breakdown the gas by capacitive coupling. The high magnetic field that also results from the large coil current causes the transition to a solenoidal discharge. Once the lamp ignites, the resistance of the discharge loads the resonant circuit. This causes the current in the matching circuit to be reduced down to operating levels.

CONCLUSIONS

Clearly, power electronic circuits are an integral part of many modern high-efficiency lighting systems. In fact, lamp concepts that were in the past relegated to the back-burner are becoming a reality with the advent of high-efficiency, high frequency power electronics. Similarly, in the next few years the introduction of sophisticated control electronics will help the introduction to the marketplace of lighting systems offering enhanced performance. In the search for new high-efficiency lighting sources the impact of the electronics on the system has to be taken into account. A lamp, no matter how inherently efficient, is not much practical good if it cannot be operated in a cost-effective manner from a high-efficiency circuit. Conversely, advances in electronics can and must be driven by lighting engineers to meet the requirements of advanced high-efficiency lighting systems. It is therefore necessary that the development of novel light sources goes hand in hand with the development of the ballast electronics for those sources.

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LIGHTING, INDUSTRIAL. See Industrial lighting.
LIGHTING TESTING. See Impulse testing.
LIGHT METERS. See Photometers.
LIGHTNING. See Lightning, lightning protection and test standards.
LIGHTNING GROUNDING. See Grounding.