APPLICATION NOTE 973

HEXFETs® Improve Efficiency, Expand Life of Electronic Lighting Ballasts

(HEXFET is a trademark of International Rectifier)

by Peter N. Wood

Summary

This application note illustrates how International Rectifier's new generation of HEXFET power MOSFETS are serving the lighting industry — an industry which for many years has relied on low frequency, inefficient magnetic ballasts for the control of fluorescent and other discharge lamps. Solid-state ballasts are not new; over the years there have been many attempts using bipolar transistors to manufacture viable ballasts but the biggest problems have been poor reliability and high cost. Now with HEXFET costs dipping to new lows because of International Rectifier's superior and revolutionary power MOSFET manufacturing process, solid-state ballasts are products whose time has arrived.

HID and Gas Discharge Lamps

Approximately 25 percent of the electricity generated worldwide is consumed by artificial lighting, making this essential function a good target for cost-saving design efforts. During the past 50 years, as generation costs have continued to escalate, the search for more efficient lighting sources to replace energy-hungry incandescent lamps has centered around gas discharge lamp technology.

The vast majority of these gas discharge lamps in use today are fluorescent, and the remainder are high-intensity discharge (HID) lamps such as mercury vapor, high pressure sodium, and metal halide types.

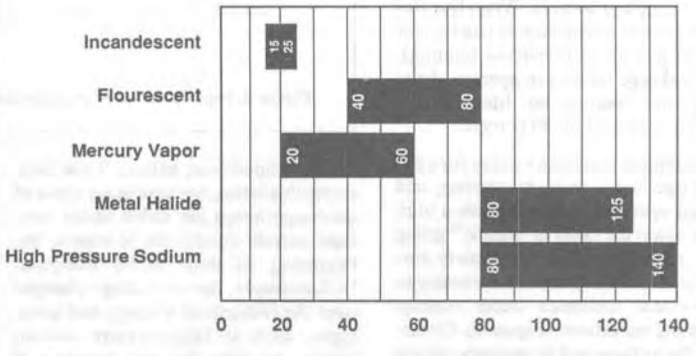
Fluorescent lamps are popular because they provide longer lifetimes than incandescents and because their low-intensity, even illumination is preferred in almost all indoor conditions such as offices, schools, shopping areas, etc. The HID types are used primarily in outdoor conditions to light large areas such as streets, parking lots, airports, freight yards, and so on.

When efficiencies in incandescent lamps are compared with gas discharge lamps, incandescents have efficiencies in lumens per watt in the low range of only 15 to 25, while gas discharge lamps have ranges as high as 140 lumens per Watt (Figure 1).

In physical dimensions, the low intensity lamps, such as fluorescents, have large arc tubes, while the HID lamps have much smaller arc tubes operating at higher vapor pressures and higher power densities. Generally, the higher the arc tube pressure, the higher the light intensity, and because the outer tube for fluorescents serves as the arc tube, vapor pressures must be low, and, therefore, light intensity is lower than the HID types.

Discharge Lamp Impedance Characteristics

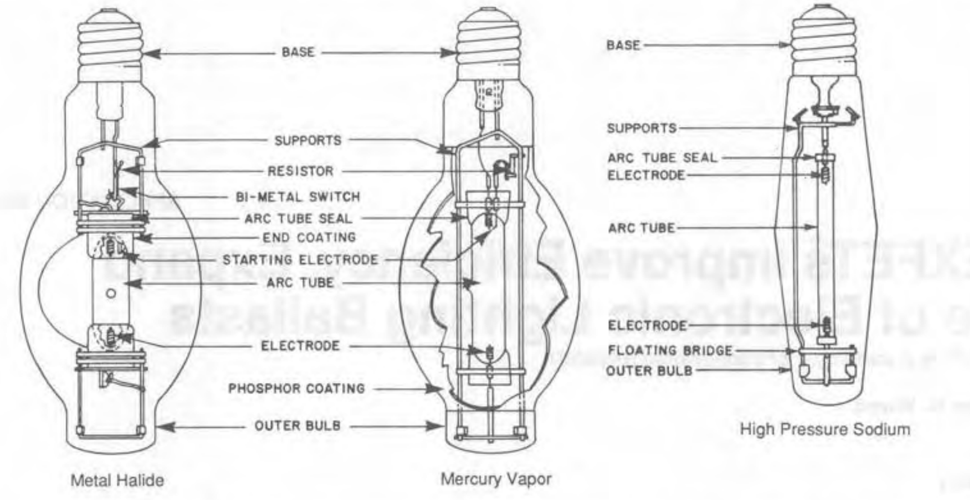
While incandescent lamps when hot are essentially constant resistance loads on the power lines, all gas discharge lamps have negative impedance characteristics that need some form of current limiting to prevent their destruction from excessive current. This, and sev-



NOTE: All discharge lamps show improvement over ordinary incandescent lamps.

Figure 1. Lamp efficiencies compared

(Courtesy of Westinghouse)



Metal Halide

Mercury Vapor

High Pressure Sodium

Figure 2. Lamp diagrams

(Courtesy of Westinghouse)

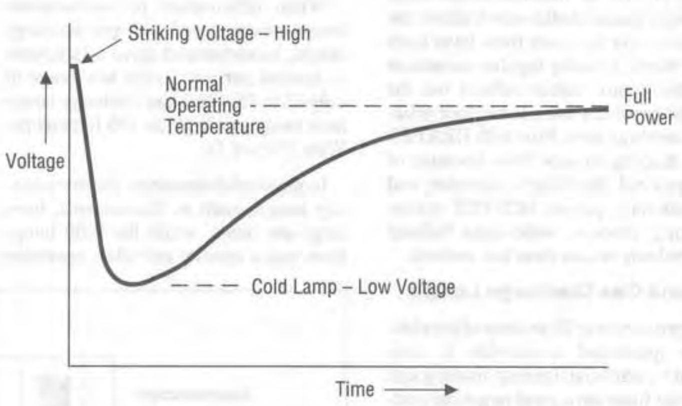


Figure 3. Impedance curve of typical discharge lamp

eral other necessary conditions such as resonant operation, shutdown protection, lamp failure/removal protection, high voltage striking, and data bus control are fulfilled by a circuit called an "electronic ballast."

What is needed ideally for gas discharge lamps is a constant current ballast with power limiting so that the rated power level is not exceeded over the lifespan of the lamp. It should be noted that gas discharge lamps normally are operated from AC voltages to equalize electrode wear, thereby achieving their maximum potential lifespans. Typical lifespans are 40,000 hours for both fluorescent and HID types when operated from AC power sources. When line frequency ripple is undesirable (such as for motion picture or television lighting), gas discharge lamps are operated from DC power sources, but lifespans are typically reduced by 50 percent.

The typical impedance curve for a gas discharge lamp over its starting and normal operating modes shows a high value when the lamp is "struck," going to its minimum value immediately during the cold lamp state, and increasing to its nominal resistance under average operating conditions (Figure 3). Generally, the voltage and impedance curves are congruent, and the current values are inverse.

It would appear that to accommodate the voltage vs. time curve, it is only necessary to provide a constant current, or infinite impedance, ballast. To a large extent this is true, because many types of discharge lamps are stable under constant current conditions, at least at the beginning of their useful lifespans. Unfortunately, the arc voltage changes over the lifespan of a lamp, and some types, such as high-pressure sodium lamps, go into thermal runaway if driven from constant current sources in heat-retaining reflector fixtures. In some reflector applications, the reflected heat causes a rapid rise in arc tube temperature, and if a constant current source is used, applied power increases radically and the HID lamp is destroyed.

Lifespan is generally limited as the emissivity of the active elements of the electrodes degrade, which causes an attendant and life-shortening increase in the arc voltage over the lamp lifespan.

Conventional Ballasts

When the lamp arc voltage requirement is less than the AC power line voltage, the simplest ballast is the series inductor type (Figure 4) because no voltage step-up is required.

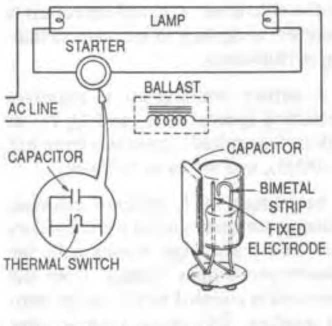


Figure 4. Simple magnetic ballast where lamp voltage is less than AC line voltage

(Courtesy of Westinghouse)

In this circuit, the high voltage kick needed to strike the lamp is obtained from the inductor and a bi-metallic switch that also supplies filament current when the contacts are closed. The heated filaments emit a space charge that lowers the ionization voltage of the mercury vapor within the lamp for easier starting. The operating voltages depend upon the type of lamp used, with longer lamps requiring higher voltages.

Moreover, as the length of the arc tube increases, ionization voltage also increases requiring ballasts to provide stepped-up operating voltages as well as higher striking voltages. As a consequence, conventional 4- and 8-feet fluorescent ballasts use bulky step-up, high reactance transformers with output windings to drive two or more lamps.

The problem associated with line frequency, magnetic ballasts are:

Flicker from 50 or 60 Hz power mains,

Significant size and weight penalties,

Low power factor, non-sinusoidal current waveforms, and

Non-compatibility with data bus control for ON/OFF and dimming.

These problems are eliminated by electronic ballasts. Furthermore, electronic ballast designs are now competitive in costs with conventional ballasts when initial cost is balanced against the lifetime savings in energy costs.

Fluorescent Lamp High Frequency Resonant Ballast

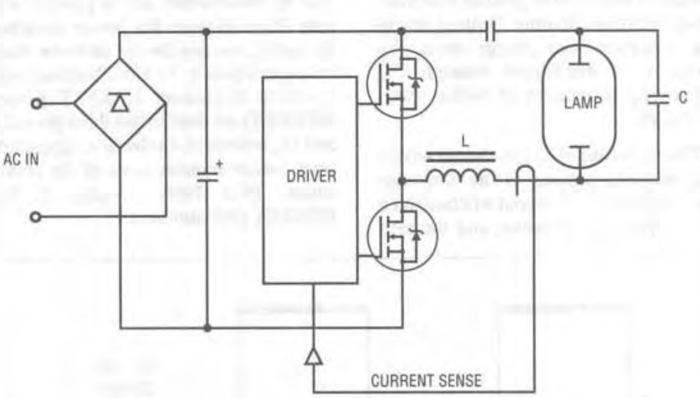


Figure 5. Basic series resonant ballast

Because fluorescent lamps operate at low temperatures resulting in only small vapor pressure changes within the arc tube compared with HID types, impedance changes within the lamp are small both during start-up and operation, making ballast designs less complicated than the HID types.

The self-resonant circuit design is well suited to this type of load, and can be used to drive a wide variety of fluorescent loads by merely changing the values of inductance and capacitance in the tuned circuit (Figure 5). Ruggedized HEXFET power MOSFETs from International Rectifier, with dramatically improved dv/dt and avalanche ratings, make these designs both low cost and highly reliable.

With the recent emphasis on providing sinusoidal, in-phase current on the AC line inputs to the ballast, an active power factor correction circuit also can be added to the front-end circuitry to perform this function. These circuits provide unity power factors, and result in considerable cost savings over long-term operation.

A detailed example of a half-bridge, self-resonant converter ballast using 2 medium voltage HEXFET power MOSFETs (Q_1 and Q_2) is shown in Figure 6A. Operation of this circuit is described as follows with the associated waveforms shown in Figure 6B.

R_1 and C_1 form a start-up charging circuit that reaches the 35V breakover of diac CR_2 in approximately one second after power is applied. With CR_2 conducting, a positive turn-on voltage pulse is applied to the gate of Q_1.

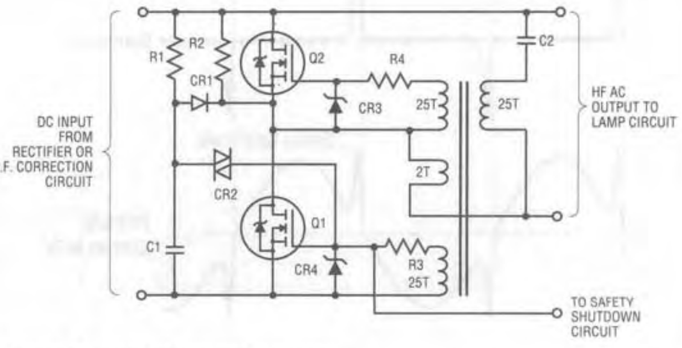


Figure 6A. HEXFET Half-Bridge Inverter

With Q_1 turned on by this pulse, the Q_1 drain voltage previously held high by R_2 is rapidly switched to ground thus initiating circuit oscillation. With Q_1 reaching saturation, any charge remaining across C_1 is discharged through CR_1 preventing generation of further start-up pulses.

The polarities of T_1 are chosen so that any AC load applied to the converter high frequency AC output will be driven by a voltage squarewave, and the load current flowing through the 2-turn (2T) primary of the current transformer T_1 will by transformer action produce the gate drive voltages for power switches Q_1 and Q_2, causing the circuit to oscillate at approximately 77 kHz. International Rectifier N-channel HEXFET power MOSFETs are used in this example as Q_1 and Q_2, with device selection dependent upon power requirements of the application. (See Table 1, page 8, for HEXFET part numbers.)

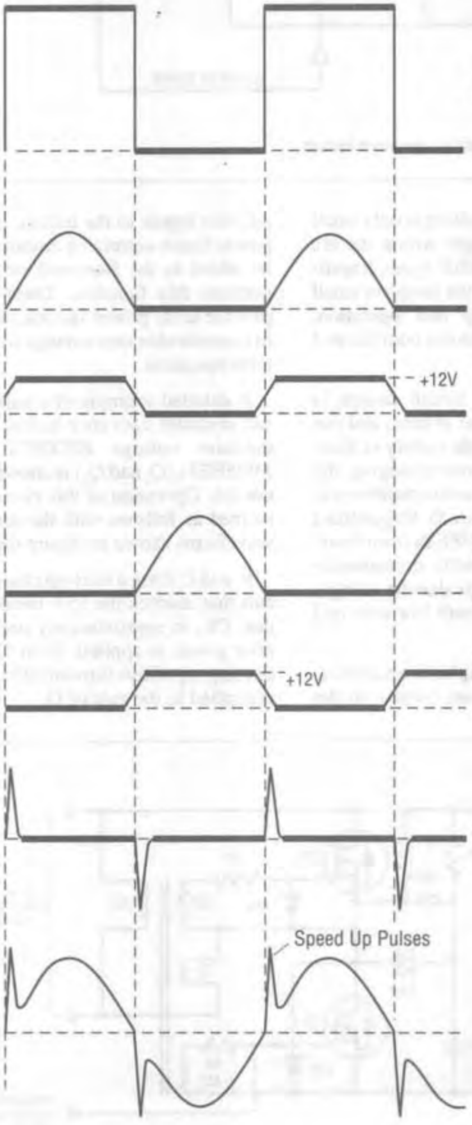


Figure 6B. Waveforms

While T_1 operates as a current transformer to produce the gate drive voltages, the resulting waveforms have poor rise and fall times because they are proportional to the sinusoidal load current on the converter. A speed-up circuit is therefore necessary to improve switching performance.

A tertiary winding on T_1 improves switching speeds of Q_1 and Q_2 by an order of magnitude (typically from 1µS to 100nS), and works as follows:

As current in T_1 primary changes, voltages are generated on the secondary and tertiary windings. Additionally the squarewave output voltage from the converter is coupled thru C_2 to the tertiary winding. This causes a regenerative switching action within T_1 which speeds up the charge and discharge of the HEXFET input capacitances.

Because T_1 is a current transformer, CR_3 and CR_4 are needed to protect the gates of Q_1 and Q_2 from overvoltages. Resistors R_3 and R_4 act as load resistors on T_1 to eliminate spurious high frequency oscillations and stabilize the output waveforms at the resonant frequency of the load circuit.

Note that by sensing current in the L-C load, the converter is forced to operate with the output voltage and current in-phase. This ensures optimum utilization of the HEXFET power MOSFETs, and minimizes switching losses.

If the AC load contains a series resonant circuit as shown in Figure 7A, the lamp voltage waveform will be a sinewave (See Figure 7B).

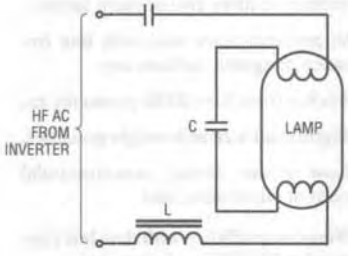


Figure 7A. Series resonant lamp circuit

After the lamp strikes, arc voltage determines the load tuning capacitor voltage. Because the "Q" of the tuned circuit is greatly reduced by the lamp loading, after the lamp strikes the resonant current decreases so that in normal operation the lamp approximates a constant voltage AC load driven by a series inductor, to provide current limiting.

The waveforms in Figure 7B illustrate this mode of operation. Note that the circuit is resonant as indicated by the lamp sinusoidal-voltage; while it is true that fluorescent lamps have better arc stability and less electrode wear when driven by sinewaves, the high frequency AC also yields another 10 to 15 percent luminous efficiency compared with 50 or 60 Hz line frequency operation.

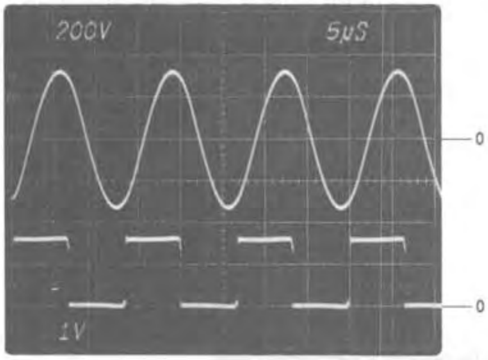
Fluorescent lamps wear out as their cathodes lose emissivity and lamp efficiency diminishes. However, the resonant ballast maintains luminous output longer by being able to supply additional lamp voltage to offset the normal wear-out process. Thus, re-lamping is required less often.

While this self-resonant circuit is elegantly simple, if the lamps are removed or do not strike, the circuit will drive sufficient current into the series resonant circuit to cause failure of the power switches after approximately 100mS if a protective circuit is not provided. These failures would occur from over-dissipation as the switches pull out of saturation at high drain currents.

This condition is easily prevented by monitoring the AC voltage in the inductor, and terminating oscillation if that voltage remains high for too long a period. A secondary winding of a few turns on the series inductor L is sufficient to generate this required AC shutdown signal (Figure 8).

Under normal lamp operating conditions, C_3 charges via R_6 and CR_7 to approximately 20Vdc, which is insufficient to cause CR_6 to avalanche and turn on Q_3. If the voltage across inductor L increases due to excessive current, C_3 charges to approximately 35V, CR_6 avalanches, and Q_3 saturates for a period controlled by the values of C_3 and R_5.

The AC drive signal at the gate of power switch Q_1 is now shunted by Q_3 and oscillation ceases. Starting capacitor C_1 (figure 6A) now recharges, and the circuit restarts after approximately 1 second. If the lamp fails to restrike after a period of 1 to 2mS of oscillation, the safety circuit once again terminates oscillation. At each restart attempt, the circuit is allowed to oscillate only until the R_6-C_3 combination reaches the breakover voltage of CR_6 (1 to 2mS).



Upper Trace: Lamp Voltage (200V/Div) Lower Trace: Inverter Output (100V/Div)

Figure 7B. Waveforms

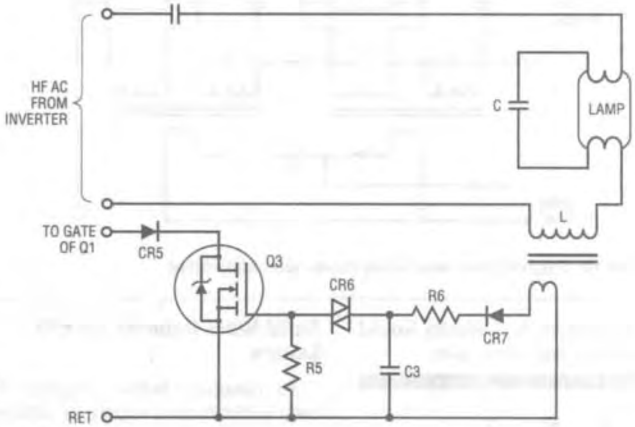


Figure 8. Safety circuit for protection of inverter circuits

A principal advantage of the series resonant ballast is that the AC output voltage is limited only by imperfections in the tuned load circuit, such as arc-over between turns of the inductor, dielectric failure of the capacitor, or resistance or dielectric losses that limit the "Q." In practical terms, this means that open circuit capacitor voltages up to 5kV peak-to-peak can be generated, which is more than adequate to start any of the 4–or 8-foot lamps whether or not the filaments (if present) are hot.

A twin lamp circuit shown in Figure 9 has cross-connected capacitors so that if one lamp fails or is removed, the fixture goes dark indicating lamp replacement is needed.

However, some safety codes now require that one side of the lamp circuit be grounded such as in the circuit of Figure 10.

In this circuit, the lamps are driven by secondary, isolated windings on the inductors, and it is important in the design of these inductors that inductive coupling from primary to secondary is "loose" to minimize lamp current variations. When using standard "E"-cores, loose coupling can be obtained by winding the primary winding on one "E," and the secondaries on the other half of the core as shown in Figure 11.

The current sensing secondary must be close-coupled to the tuned load cir-

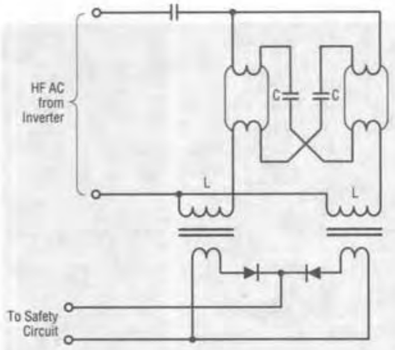


Figure 9. Double 40W non-grounded circuit

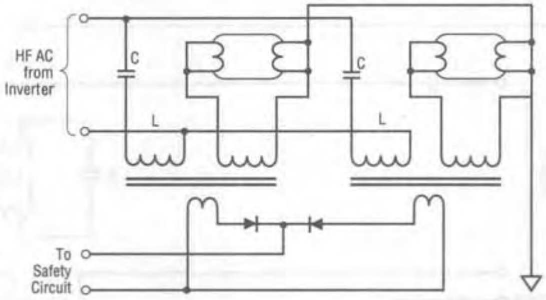


Figure 10. Grounded two-lamp fixture meets new safety codes

cuit, and therefore, it is usually wound on the primary half of the core.

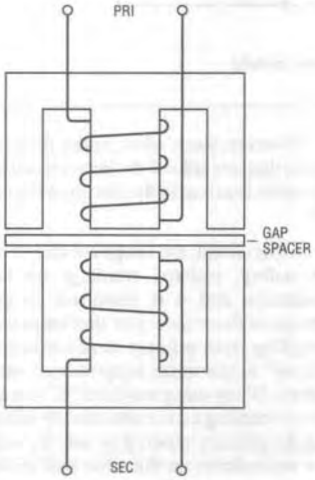


Figure 11. Loose coupling between choke windings limits lamp current

Solid-State Ballasts for HID Lamps

As mentioned before, magnetic ballasts suffer from a variety of deficiencies, but all of these are especially valid in the case of HID lamps where power levels are generally much higher than for fluorescents, with 1500W not uncommon.

For example, in the film industry, which uses high power discharge lamps extensively, mains frequency flicker is technically incompatible, and in environments such as machine shops these strobe effects are simply hazardous. In both of these applications, strobe-free light is mandatory.

The series resonant ballast can be used for these HID applications, even though the arc voltage changes by an order of magnitude or more due to arc tube pressure variations during warm-up.

Also, many HID installations require "on at dusk/off at dawn" operation, so the circuits shown in Figures 12 and 13 both use photocells to sense the ambient light conditions and control ballast operation.

In Figure 12, the 300V striking voltage for the 175W mercury vapor lamp is provided by the tuned load circuit. An M-39 lamp requires more than 300V to strike at -20 degrees F, which is generated easily across the series-tuned capacitor. Also, the high starting voltage reduces a typical hot restart period from six to four minutes.

Figure 13 shows the same basic resonant circuit, in this case used to drive a high pressure sodium lamp. Because sodium lamps do not have starting electrodes within the arc tubes, they require from 2.5 to 4 kV to strike the arc. In a magnetic ballast, this high voltage is provided by a separate ignitor circuit but in the series resonant ballast it can be supplied directly across the series tuning capacitor thus saving the ignitor cost. The resonant components are designed to withstand the voltage stress, resulting from the high Q of the series resonant circuit (Q>20). Using the resonant approach, the sodium lamp will hot restrike in approximately 30 seconds after a momentary power interruption. This is somewhat faster than a typical magnetic ballast with ignitor circuit.

Selecting the Right HEXFET

a) Voltage Ratings

The half-bridge ballast circuit is highly reliable because the switching HEXFET power MOSFETs see only DC line voltage and are not exposed to the high voltages of the resonant output AC. This DC line voltage has a maximum value approximately equal to the peak of the input AC sinewave. Thus, a 115VAC input has a peak value of $\sqrt{2}$ x 115 or about 160Vpk. Allowing for transient and steady state variations, HEXFETs with 250VDC BVDSS ratings are usually adequate.

b) Current Ratings

HEXFET power MOSFETs can be considered as "voltage modulated resistors." Thus, when a HEXFET is turned ON by the application of a 12-volt VGS signal its resistance is known as $R_{DS(on)}$. Obviously, if a large heatsink is available $I_D{}^2 \cdot R_{DS(on)}$ can be larger than if only a small heatsink is used. Consequently, there is always a tradeoff between device silicon area and heatsink area. Basically a small HEXFET needs a bigger heatsink than one with a larger die size, given that both designs supply equal output power. *Most* practical bal-

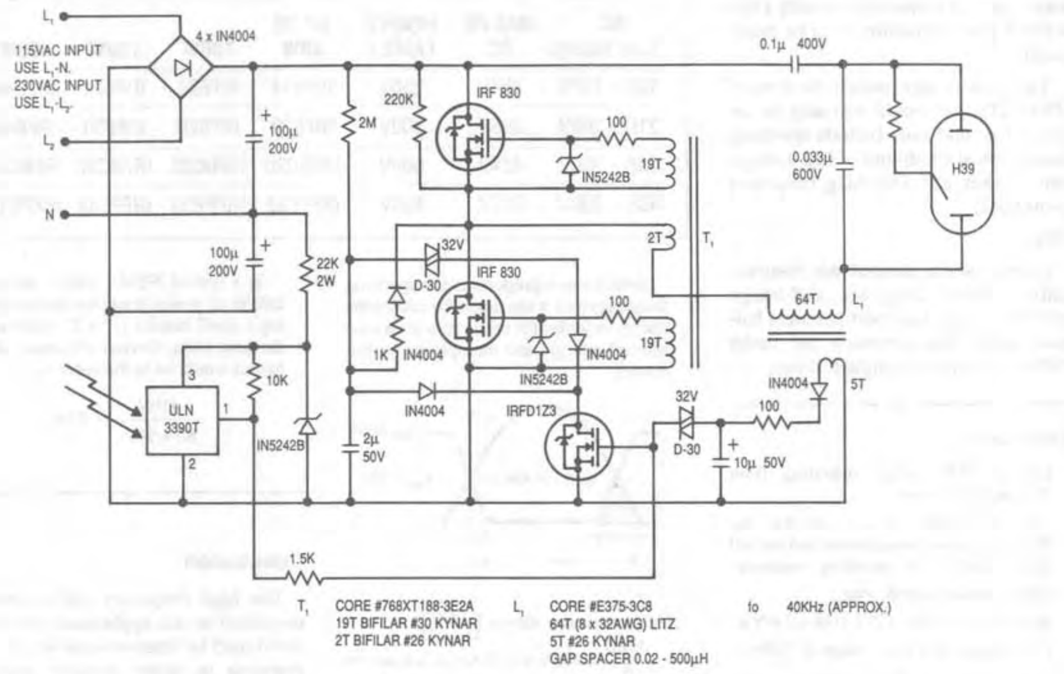


Figure 12. 175W mercury vapor ballast with "on at dusk – off at dawn" control

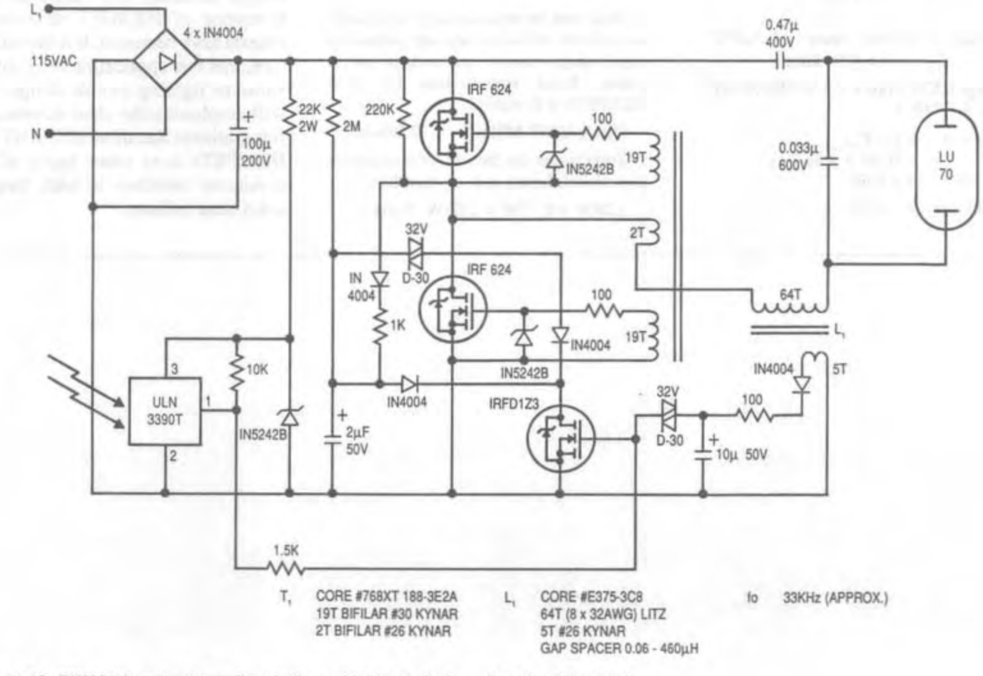


Figure 13. 70W high pressure sodium ballast with "on at dusk – off at dawn" control

lasts have marginal thermal designs (for cost reasons) and, therefore, on-state losses must be constrained to only a few watts if good reliability is to be maintained.

Table 1 is a rough guide to the types of HEXFETs that would normally be selected for solid state ballasts operating under typical conditions of line voltage, lamp power and switching frequency (f<100kHz).

Table I

AC Line Voltage	MAX PK DC	HEXFET FAMILY	UP TO 50W	100W	200W	500W
105 – 130V	184V	250V	IRF614	IRF624	IRF634	IRF644
210 – 260V	368V	500V	IRF820	IRF820	IRF830	IRF840
260 – 300V	424V	600V	IRFBC20	IRFBC32	IRFBC30	IRFBC40
400 – 500V	707V	800V	IRFPE22	IRFPE30	IRFPE42	IRFPE40

Note

Higher power designs are theoretically possible using the half-bridge resonant design but most practical ballasts using this approach are under 500W. A typical example follows.

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Requirement

Double 40W ballast operating from 277Vac 60Hz input

From the table we can see that the IRFBC32 is the chosen device and we will select 77kHz as the operating frequency.

Output power is 80W total.

AC input (low line) is 277-10% = 249Vac.

This yields a DC bus voltage of 350Vdc.

DC Bus current $= \frac{80}{350} = 0.23$A average.

Actual RMS drain current is

$$I_{RMS} = \frac{\pi\,(0.23)}{2} = 0.36\text{A}$$

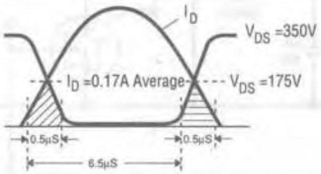
Assuming a device temp of 100°C $R_{DS}(\text{on}) = 2.7 \times 1.8 = 4.86$ Ohms

(See Page C395, Figure 9, 1987 HEXFET Databook HDB-4)

Conduction loss for one device: $= I_D^2\,R_{DS(on)}$
$= 0.36^2 \times 4.86$
$= 0.63$W

Both devices: $= 1.26$W

Switch loss is proportional to operating frequency and is calculated by adding the energy in joules for each cycle (turn on + turn off energy) and multiplying by frequency.



Turn-on energy shown ▨

$$= \frac{0.5\mu S}{6} \times 175V \times 0.17A = 2.5\mu J \text{ approx.}$$

Turn-off energy shown ▤

$$= \frac{0.5\mu S}{6} \times 175V \times 0.17A = 2.5\mu J \text{ approx.}$$

Note that in resonant operation turn-on and turn-off losses are approximately equal, since current and voltage are in phase. Total switch loss for both HEXFETs is therefore

$(5\mu J \times 0.077\ MHz)2 = 0.77$ Watts.

Total losses are the sum of conduction plus switch losses and are therefore

$1.26W + 0.77W = 2.03W$ Total

In a typical NEMA ballast enclosure 2.03W of power could be dissipated using a small bracket (1" x 2") mounted to the base plate. Overall efficiency of the ballast would be in the order of

$$\frac{80W}{80 + 7W} = 92\%.$$

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Conclusion

The high frequency ballast circuits described in this application note were developed by International Rectifier in response to many requests received from the lighting industry. They stressed from the very outset that reliability and costs were paramount. Because of the simple circuitry and outstanding performance of HEXFET devices these criteria have been met. It is hoped, therefore, that this application note will be of value to lighting circuit designers and will emphasize the clear advantages of International Rectifier HEXFET power MOSFETs over other types of semiconductor switches in high frequency solid state ballasts. □