APPLICATION NOTE U-162

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DRIVING A 35W AC METAL HALIDE HIGH INTENSITY DISCHARGE LAMP WITH THE UCC3305 HID LAMP CONTROLLER

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ABSTRACT

This application note expands upon Unitrode application note U-161 which describes the use of the UCC3305 HID lamp controller in a Metal Halide DC lamp application. This application note extends that topic to include a 35W Metal Halide AC lamp application.

When using these types of lamps it is beneficial to provide an improved means of driving the lamp in an efficient and cost effective manner. Electronic ballasts offer definite advantages in size, weight, efficiency and performance over their magnetic counterparts. Electronic ballasts can also provide additional protection features which would not easily be possible with a magnetic ballast.

Information is presented in a design example to help the user better understand the controller's many features.

INTRODUCTION

The UCC3305 controller integrates most of the features necessary to control one AC HID lamp. It is tailored to the demanding, instant start requirements of automotive headlamps, but is also applicable to other lighting applications such as emergency or theatrical lighting where HID lamps are being used.

The basic features of the UCC3305 HID controller are outlined below;

- OV input protection
- Output fault protection/timing
- Power regulation vs. lamp voltage
- Lamp startup/cool down simulation
- Current-mode control
- Fixed frequency operation
- DC or AC lamp drive capability
- High current drive capability
- Adjustable startup to steady-state lamp current ratio

A summation of the different functional blocks of the UCC3305 and their major electrical characteristics was included in U-161 and will not be repeated here.

The following section specifies typical design requirements necessary of an HID ballast that would be powering an AC lamp in a 12V automotive battery application. The lamp used in this application is a 35 AC metal halide lamp manufactured by Philips Lighting.

Input ballast voltage requirements - 9 to 16 Vdc

Protection/Fault Monitor/ I/O Controls - Protection against input overvoltage, output open circuit and output short circuit

Power regulation - Regulate power to the lamp within ±5% over a lamp voltage variation of 60 to 100 Vdc.

Lamp ignition voltage - Provide an open circuit voltage of 400 to 500 Vdc at startup in order to provide the necessary voltage to the ignition circuit to ignite the lamp.

Efficiency - Greater than 85%.

Hot restrike - The ballast must be able to properly light the lamp when hot without a cool down period.

Converter topology

The DC-DC converter topology chosen for this application, as in the DC lamp case is the SEPIC. This topology was chosen because it is a single ended topology and the power switch can be easily driven. Also, the output voltage can be higher or lower than that of the input. In this application the output is always higher than the input but varies widely from the time before the arc lamp is lit to when the arc has been established. This power stage converts the battery voltage to a level which is suitable for the lamp. This voltage is then converted to an AC voltage by an output H-bridge which feeds the lamp. All of the power regulation and protection is provided on the DC output. The H-bridge drivers are driven from the Q and $\overline{Q}$ outputs of the UC3305. The circuit is shown in the schematic at the end of this application note.

POWER REGULATION LOOP

An analysis of the power regulation loop, including the derivation of the power curve equation based on the 35W DC lamp was performed in [1] and will not be repeated here. This analysis holds for the AC lamp as well and should be reviewed for a complete understanding of the controller. A graph of the power curve is repeated below.

$Kv := 0.0032 \quad R2 := 16k \quad R1 := 4.7k$

$Ki := 0.83$

$Vo1 := 60,65..110$

$Vref := 2.4$

$Vo2 := 110,115..120$

$$P_{Vo1} := \frac{Vo1}{Ki} \bullet \left[\left(\frac{R1}{R2}\right) \bullet Vref - Kv \bullet Vo1 \bullet \left(\frac{R1}{R2} + 1\right)\right]$$

$$P_{Vo2} := \frac{Vo2}{Ki} \bullet \left[\left(\frac{R1}{R2}\right) \bullet Vref - 0.322 \bullet \left(\frac{R1}{R2} + 1\right)\right]$$

DC VS AC LAMP DRIVES

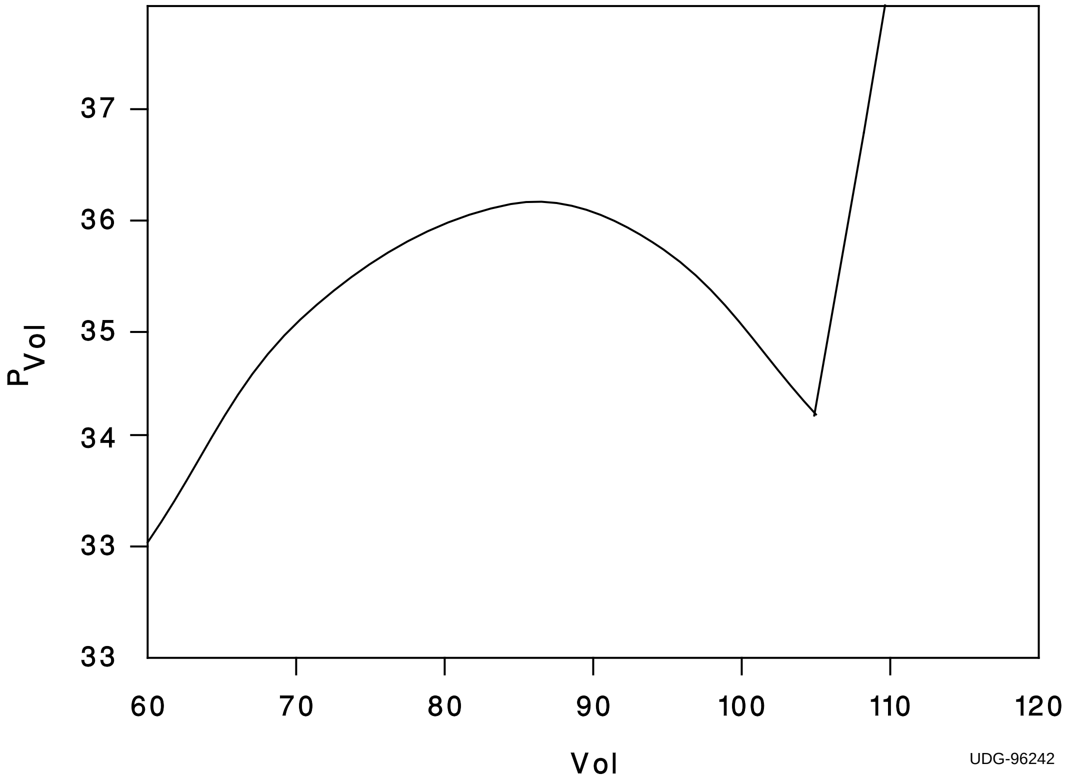
There has been much discussion regarding the benefits of DC vs. AC lamps over the years. The main advantage of a DC lamp is obvious to the ballast designer but not necessarily to the designer of the lamp. Driving the lamp with a DC source is easier and cheaper from a ballast standpoint for the following reasons:

1) An output H-bridge is not required.
2) The associated H-Bridge drivers are not needed.
3) The ignitor circuit design is simpler.

In addition to the reasons given above there is also an issue with acoustic arc resonance of the lamp. This problem arises because the arc tube can be thought of as an acoustic chamber which has certain unique properties. Given the right excitation frequency (or the wrong one in this case), a resonance occurs which causes the arc discharge to become unstable and move around within the arc tube. This unstable condition can result in the arc coming in contact with the arc tube wall, resulting in the destruction of the lamp. As a minimum, this condition results in problems with the optics of the lamp. Each lamp has its own resonant spectrum characteristics which will vary with manufacturing tolerances. A particular lamp may have several resonant frequencies of which the ballast designer must be aware and stay away from so that problems can be avoided. Information regarding the resonant frequencies of a particular lamp are typically not given as part of the design specification. The ballast designer must find this information on his own by trial and error or specifically asking the lamp manufacturer to characterize the lamp over frequency.

This discussion appears to provide a compelling reason to select a DC lamp. However DC lamps are not without drawbacks. In some cases the position in which the lamp can be operated is restricted i.e.; the electrodes must be vertical or horizontal depending on the lamp, limiting the applications. Also, in a DC lamp the cathode electrode must be designed larger then the anode due to a gradual migration of the cathode material over the operating life of the lamp. In the AC lamp, each electrode functions as both a cathode and anode so that material migration is of little concern. There are also issues relating to the symmetry of the arc discharge and optics which favor AC over a DC lamp.

As a result of these issues and others, the debate continues on the advantages of DC vs. AC lamp drives. In AC lamp applications, most ballast designers have settled on drive frequencies below 1kHz to avoid the problems associated with acoustic resonance but above 100Hz to avoid lamp flicker problems. Other designs use a frequency modulation technique to avoid acoustic resonance from occurring. This technique appears to have some merit but can still result in problems in some instances.



The expression for P_{O1} is valid for lamp voltages from 60 to 105V. The expression for P_{O2} is valid for lamp voltages above 105V (This is due to the limiter block inside the UCC3305). Above approximately 105V, the lamp will be driven in a constant current mode which results in the straight line for power vs. lamp voltage as shown. The output power can be regulated with a variation of less than ±5% from a nominal of 34.5W with a lamp voltage variation from 60V to 110V.

As the lamp ages, its terminal voltage will normally increase due to electrode material erosion. This erosion can occur for a variety of reasons which are described in [2]. Because of this, it is beneficial to operate the lamp with a constant current above a certain voltage. This will insure adequate current reducing the possibility of the arc being extinguished . Above a steady-state lamp voltage of 240 Vac, the ballast will terminate operation. This type of voltage increase is typical indication of an end of life condition and that the lamp is close to failure.

Figure 1. Calculated Power Curve vs. Lamp Voltage of UCC3305 Controlled 35W Ballast Powering AC Metal Halide Philips Lamp

The data suggests that a square wave drive current is required for long term lamp reliability. This results in constant power being delivered to the lamp and therefore a constant light output as well as a crest factor (ratio of peak to RMS current) close to 1. As mentioned above, this also eliminates the possibility of flicker since the lamp current transitions quickly through zero without the arc needing to be reignited at each zero crossing.

Current sense comparators/amplifiers

The INPUT ISENSE comparator/amplifier inside the UCC3305 provides cycle by cycle current control as in a typical peak current-mode converter. An added feature allows the user to program the ratio of startup to steady-state current. This feature provides increased power to the lamp at startup in order to get the light output up to its steady-state level as quick as possible. The simplified schematic of this section is shown in Figure 2.

The start to run current ratio is set by by an external resistor placed from the ADJ pin to ground. A detailed analysis of this feature as well as how the output current limit on startup operates is provided in [1].

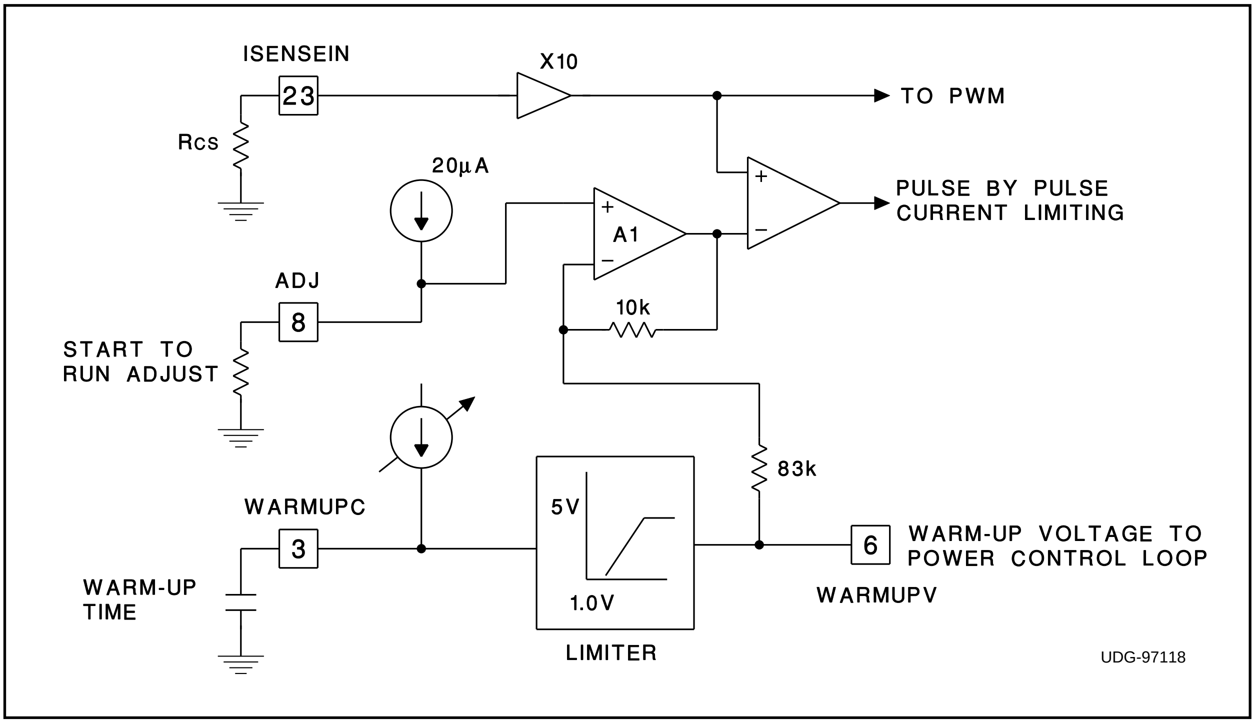


Figure 2. - ??????????

SLOPEC AND WARMUPC

The ADJ pin sets the maximum startup current which flows into the lamp at ignition. The current into the lamp will decay in an exponential fashion due to the voltage charging characteristic of the WARMUPC and SLOPEC capacitors. The current will decay to a steady-state value of approximately 450mA RMS after a period of time given by the time constant of an internal 50 Meg resistor and the capacitor placed from the SLOPEC pin to ground.

In this example, the time required to reach steady-state current is 150 seconds from:

$$t: = 50 \bullet \exp(6) \bullet C_{SLOPEC}$$

The WARMUPV capacitor has a shorter time constant and is used to tailor the first few seconds of the run-up characteristic for the lamp. As can be seen from the block diagram in the data sheet, this capacitor has no effect on the operation of the ballast controller after it has been charged beyond 5V due to the built in limit function.

Another function of both the WARMUPC and SLOPEC capacitors is to program the hot-restrike characteristics of the ballast. The voltage on these capacitors also provides information to the controller on the temperature state of the lamp. This allows the ballast to predict how the lamp should be started i.e.; whether or not the lamp needs to go through the warm-up phase or just proceed directly to steady-state operation. The ability of the controller to predict this optimum starting characteristic improves the reliability of the lamp and system performance. If the lamp has been started and is turned off for any reason, it is beneficial to restart the lamp in a manner that would prolong lamp life and reduce the cool down period between lamp starts. Typically, HID lamp ballasts in use today have no provision for hot restrike and instant start. To facilitate this, the UCC3305 has the capability to program the discharge of the SLOPEC and WARMUPC capacitors in a manner that simulates the cool down characteristics of the lamp.

A capacitor on the BYPASS pin provides the necessary energy to the internal current sources when the power to the IC has been disrupted. This will determine the discharge time of the SLOPEC and WARMUPC capacitors. The value of this capacitor should be chosen based on the current of 5µA and a discharge time (cool down time) desired based on the characteristics of the lamp used.

As an example, for a discharge time of 120 seconds and a maximum allowable droop of 5V;

$$C = \frac{I \bullet t}{V} = 5\mu A \ \frac{120S}{5V} = 120\mu F$$

If the lamp is operating for some period of time and is then turned off and instantly restarted, its power will instantly reach that level which occured before the lamp arc was extinguished. This occurs after the initial 10 to 20mS power burst which is required to get the arc to form properly on the tips of the electrodes. As a result, the lamp can be instantly started under any condition using a properly designed ignitor.

The capacitors used for the SLOPEC and WARMUPC functions must have low leakage characteristics since they are charged from nanoamp current sources internal to the IC. Any significant amount of leakage current caused by these components will have an effect on the output power regulation characteristics of the ballast.

Lamp ignition requirements

The ballast design is usually considered separately from that of the ignitor circuit although certain decisions must be made to help simplify the ignitor design. Below is a summary of some of the choices which must be made in designing the ignitor.

In designing the ballast, the open circuit output voltage is usually made as high as possible. This reduces the burden on the ignitor transformer design. Typical ignition voltages vary for different types of arc lamps but usually are in the range of 4kV to 30kV depending on the internal pressure of the lamp, temperatures and electrode spacing. HID lamps usually require a lower starting voltage to ignite a cold lamp and a much higher starting voltage for a hot lamp. This increase in ignition voltage for a hot lamp is due to an increase in pressure within the arc tube. Again, this depends on the lamp design. Some lamps are high pressure lamps and take approximately the same ignition voltage hot or cold (usually very high, 30kV) to start. The ignition pulse must be high enough in voltage to break down the lamp and ionize the gases and metals inside the arc tube. Then, within the first couple of milli-seconds, enough current must be available to properly establish the arc and maintain the discharge. During this period the electrodes are still cold and must be heated quickly to cause thermonic emission of electrons between cathode and anode. Once this process occurs, the arc is established and has to be maintained. In an AC lamp, the electrodes act as both anode and cathode due to the AC drive current. When the lamp is being ignited, it is sometimes recommended that the switching of the AC bridge be paused. This is so that the ignition process is not interrupted by an AC drive current which could result in the arc being extinguished. It hasn't yet been definitively proven that this facilitates ignition of the lamp.

The ignitor transformer design is not a trivial matter. The material chosen for the core must have good high frequency properties since the ignition pulse must have a very fast rise time, usually on the order of less than a micro-second. The interwinding capacitance of the transformer must be minimized since this element, in conjunction with the secondary inductance of the transformer, will act as a low pass filter. All of this, coupled with the fact that the secondary may need to generate tens of kilovolts for hot re-strike, puts enormous burden on the transformer design. The requirement to minimize the interwinding capacitance requires as low a number of turns as possible. This obviously conflicts with the high ignition voltage required. Because of this, the open circuit voltage of the ballast should be as high as possible so that the number of turns on the secondary can be reduced.

Typically a triggering device of some type is used in the ignitor. This triggering device must be able to handle a very large di/dt since hundreds of amps of current could be required to get the arc established within the first couple of microseconds. Currently, there aren't many semiconductor switches which meet this requirement. Because of this, most ignitors use spark-gaps as the transformer primary triggering element. These devices are capable of extremely fast breakdown times (typically < 50nS) and can switch hundreds of amps. Once the arc has been established, the lamp terminal voltage collapses and the ignitor firing circuit is no longer in the circuit. The only remaining element is the ignitor secondary inductance which, in a series ignitor, is in series with the lamp.

Slope compensation resistor

Slope compensation in the UCC3305 is provided by the addition of an external resistor in series with the INPUT Isense pin. This resistor adds a portion of the oscillator ramp into the current sense signal to provide the necessary slope compensation for duty cycles exceeding 50%. The amount of slope compensation that is needed is dependent on the topology used, as well as the inductor values chosen. In the SEPIC converter, both input and output inductors need to be considered when determining how much slope compensation is necessary. The analysis of this function was performed in [1] and will not be repeated here.

Frequency response of the power regulation loop

The frequency response of the ballast is determined by analysis of the power regulation loop in the same manner outlined in [1]. It is the output current that is being regulated since the lamp really regulates the output voltage. A simplified analysis can be performed by modeling the power stage as a voltage controlled current source with some transconductance gain, Gm.

The transconductance gain, Gm;

$$G_m = \frac{\Delta Io}{\Delta Ve}$$

The output current is converted to a voltage by the output current sense resistor. The gain of the power stage, Gp is;

$G_p = R_{ls}\, G_m$

where; R_{ls} = the load sense resistance (0.75 ohms)

$G_p = -22.5\text{dB}$

The loop response is now tailored for good power regulation by achieving as high a DC gain as possible. The gain of the LOAD SENSE amplifier is restricted since the gain of this stage effects the power curve characteristic as shown in [1].

The LOADSENSE amplifier is set up as an integrator to filter out switching frequency noise from the control loop. The pole frequency was chosen to be at 1Khz to give good rejection of the switching frequency noise. This results in a capacitor value of .01µF. The low frequency gain of this amplifier is set to 7.5dB. The combination of this gain and the power stage gain results in -15dB of low frequency gain with a pole at 1kHz.

The final loop response is tailored with the main error amplifier. A zero is added in the amplifier response at mid-band frequency so that the DC gain for the overall loop is as high as possible. The high frequency gain of this amplifier must be well below 0dB to ensure adequate gain and phase margin for the open loop gain. The 16Ω resistor has been determined based on the power curve characteristic desired leaving only the feedback resistor value to be chosen. If this resistor is chosen so that the high frequency gain is less than -20dB for good gain margin, feedback resistor value of 1Ω, the capacitor value can then be determined. A zero frequency of 3.4kHz is chosen to give adequate low frequency gain boost. The resulting value of series capacitor is 0.047µF. The gain and phase margin with these component values is greater than 20dB and 50 degrees respectively.

A PSPICE simulation of the control loop is shown in the figure below indicating more than adequate gain and phase margin.

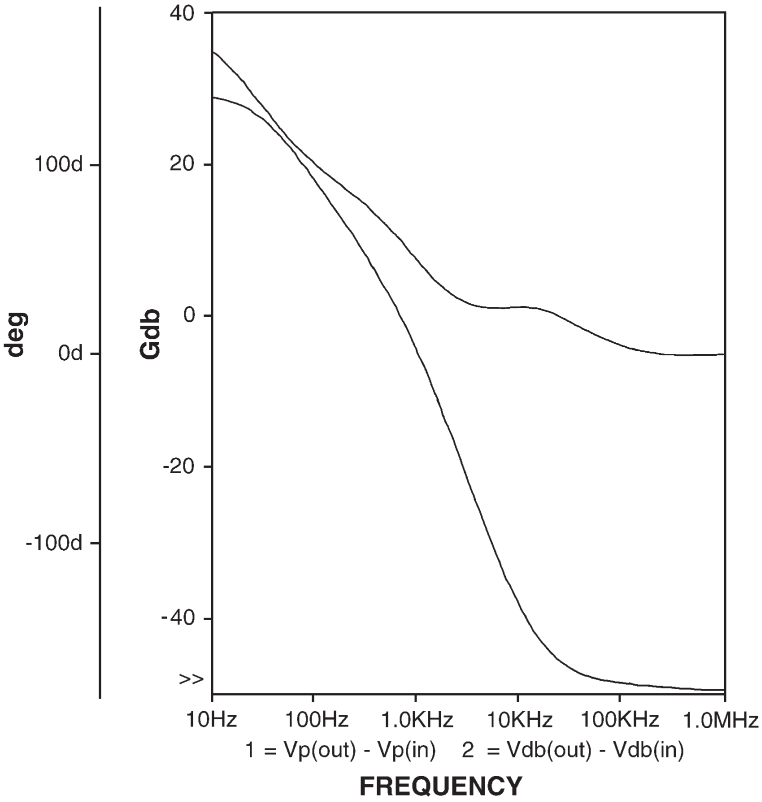


Figure 3. - ??????????

CIRCUIT EXAMPLE

A 9 to 16 Vdc input SEPIC converter powering a 35W PHILIPS AC lamp was built and tested. Data on power curve and various oscillagrams of current and voltages in the power/control circuit were taken and are discussed.

The magnetics design for this converter is exactly the same as in the DC lamp case outline in [1] and will not be repeated here.

The additional circuitry required for the AC lamp consist of the H-bridge and drivers. The H-bridge MOSFET must be able to withstand the open circuit voltage of the ballast which is set to approximately 450Vdc. MTP6N60 devices from Motorola were used which have a Vds rating of 600V at 6 Amps continuous. The MOSFET drivers used are 2-IRF2110 each of which are capable of driving the four H-Bridge MOSFETS.

An external boost converter is used to convert the 6.8 Vcc voltage to the 10V boost voltage required for the gate drive of Q1. This circuit is necessary since the internal charge pump circuit in the UCC3305 does not provide sufficient energy to drive the BOOST pin and driver. The voltage drop of the PUMPOUT pin, when used as a charge pump, is two to three volts which results in insufficient voltage to Vboost for driving the gate of Q1.

Performance data

Performance data on the ballast is presented in the following curves showing efficiency and the measured power curve. Oscillograms of Q1 voltage and current are also given as well as startup characteristics of the lamp voltage and current. The maximum efficiency achieved was 85.8% at a lamp voltage of 100V. The open circuit voltage of the lamp cannot be seen due to the aliasing of the oscilloscope, but the ballast output voltage is approximately 450Vac before lamp ignition. Once the lamp ignites, the voltage collapses and the lamp current increases to 2Aac. Eventually, the lamp voltage begins to increase and the current decreases. They will arrive to their steady-state values of 80 to 90Vac and 450mAac respectively after approximately 150 seconds.

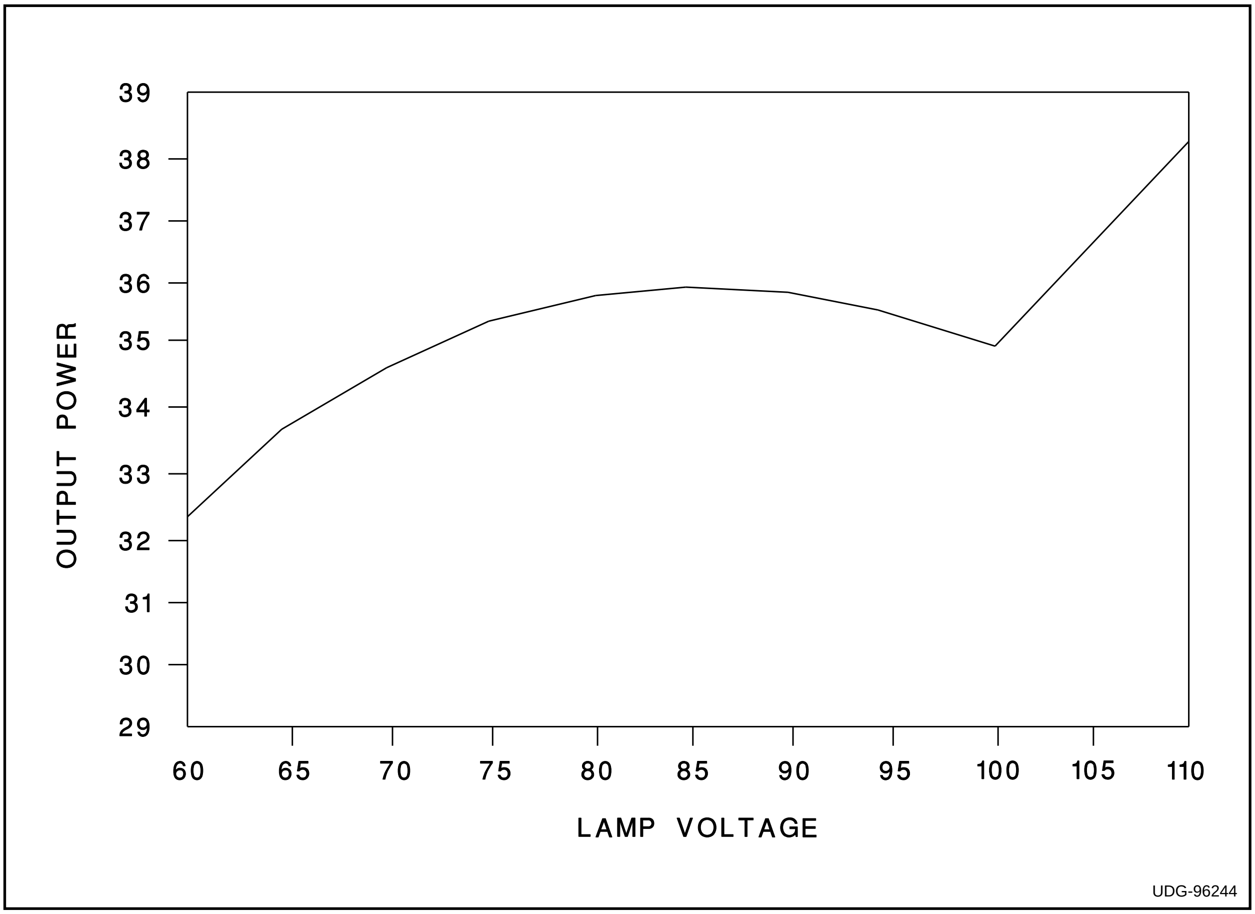


Figure 4. - ??????????

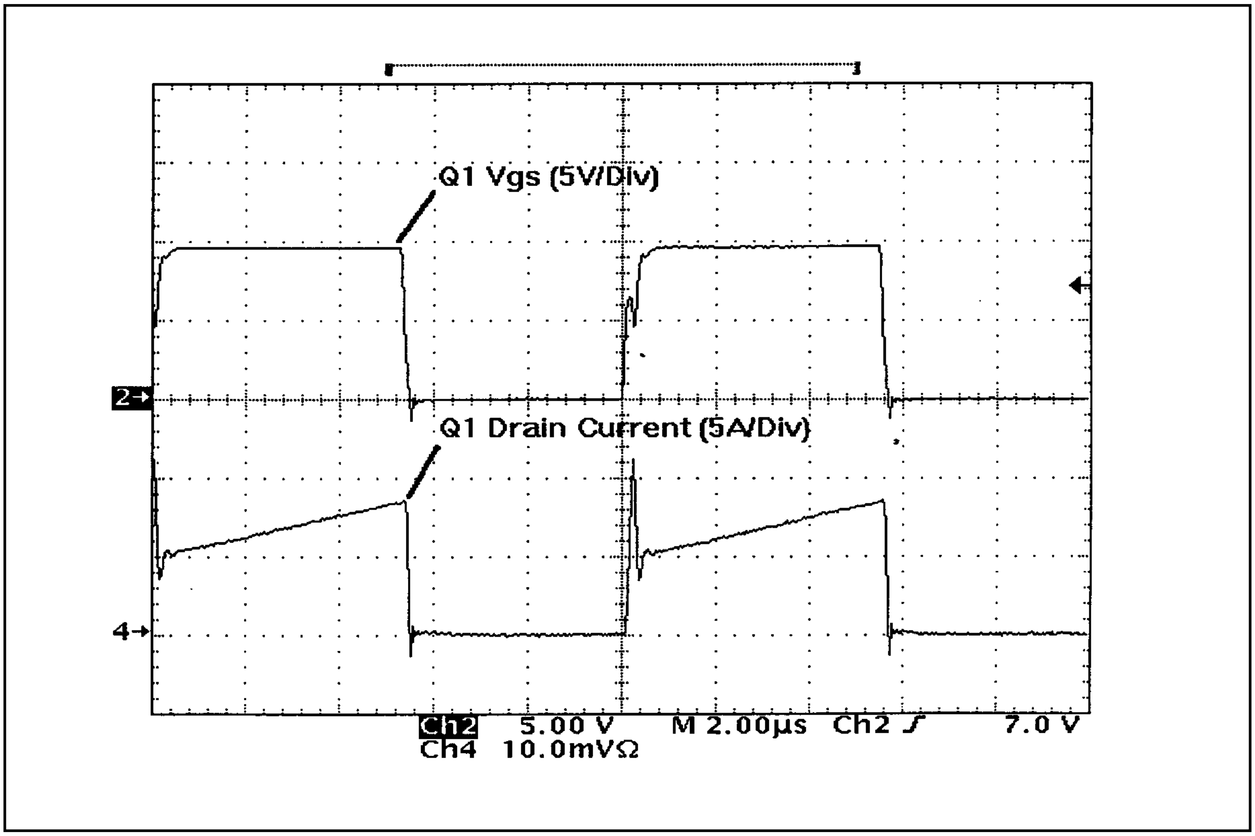


Figure 5. - ??????????

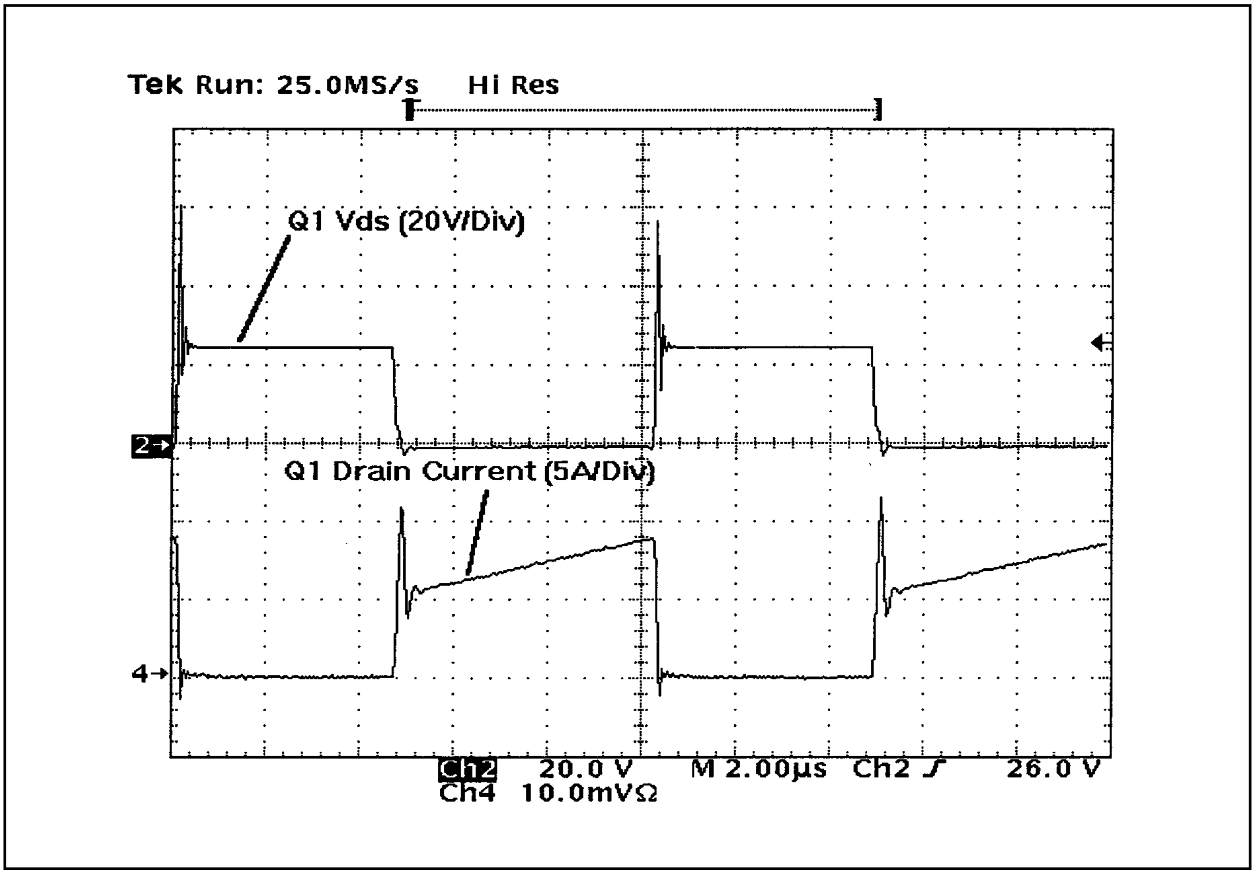


Figure 6. - ??????????

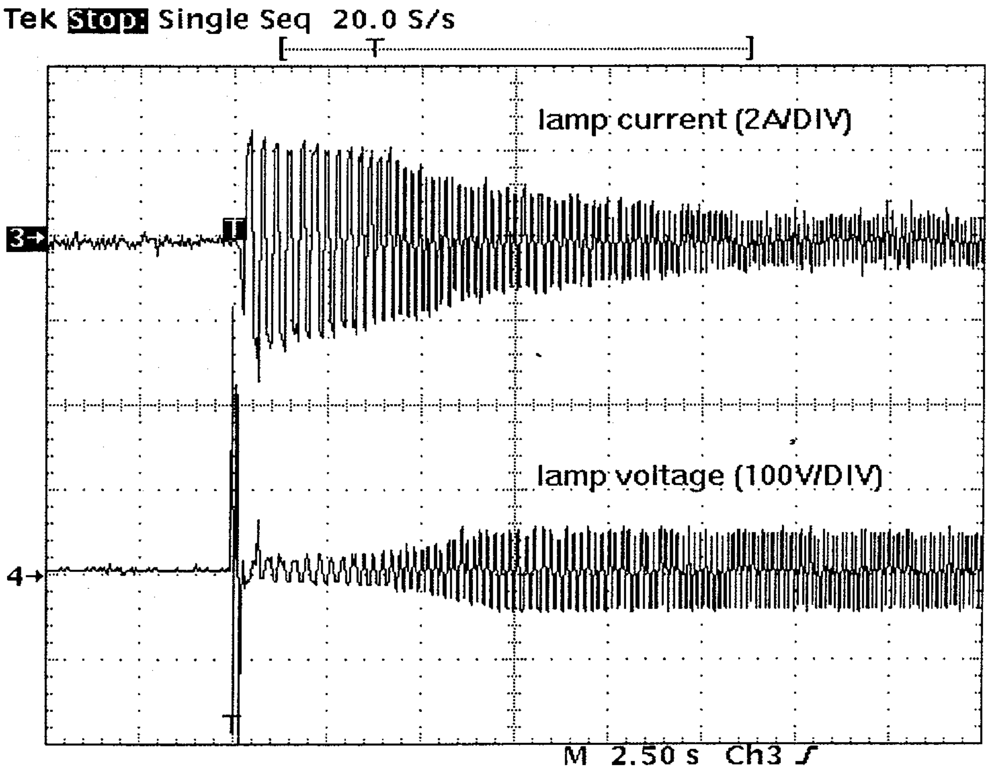


Figure 8. - ??????????

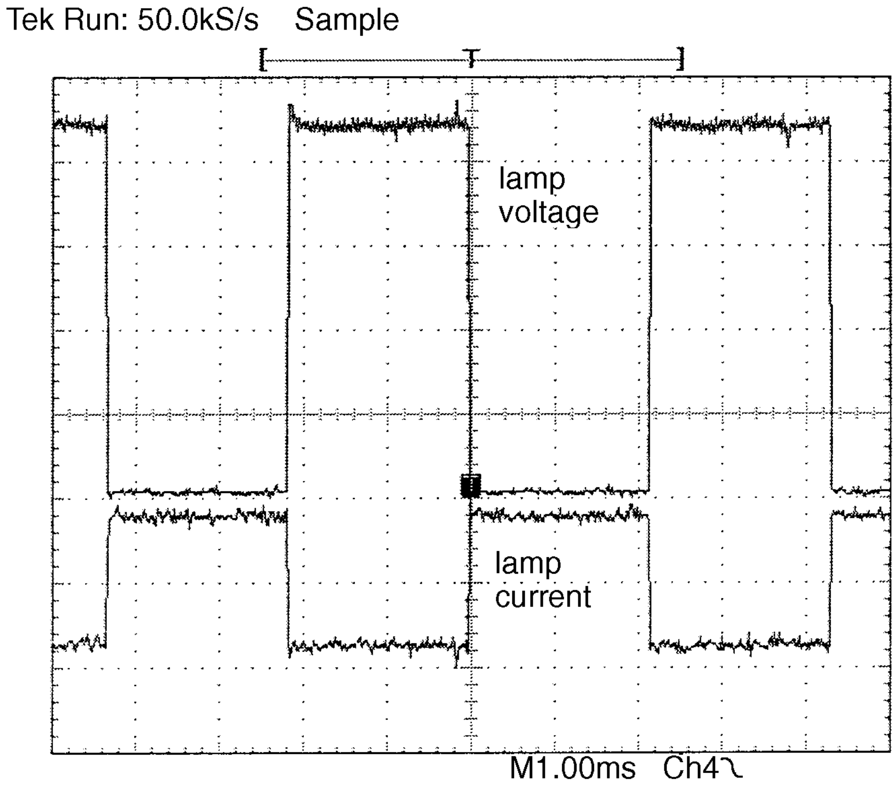


Figure 9. - ??????????

CONCLUSION

The performance data presented of a typical UCC3305 HID lamp controller application, demonstrated it to be a excellent means of controlling an AC metal halide HID lamp. The power regulation and efficiency achieved using the SEPIC converter topology proved it to be a good alternative to other conventional circuit topologies for this application. The many protection and control features of the UCC3305 simplify the task of the ballast designer considerably, making it an economically feasible choice for AC as well as DC HID lamp applications.

REFERENCES

[1] “Powering a 35W MH Lamp HID Lamp using the UCC3305 Unitrode Application Note U-161”

[2] Waymouth: :Electric Discharge Lamps M.I.T. Press” Cambridge MA.

[3] Loyd Dixon “High Power Factor Preregulator using Sepic Converter” Unitrode Power Supply Design Seminar SEM1100.

PARTS LIST

	35W HID BALLAST PARTS LIST		
REF DES	PART DESCRIPTION	DIGIKEY NUMBER	QTYPER
RI	10Ω 1/4 W CC	10QBK-ND	1
R3	1k 1/4W CC	1KQBK-ND	1
R4	4k 1/4W CC	4KQBK-ND	1
R5	240Ω 1/4W CC	240QBK-ND	1
R6	270k 1/4W CC	270KQBK-ND	1
R7	100k 1/4W CC	100KQBK-ND	1
R8	1.68k 1/4W CC	1.6KQBK-ND	1
R9	220Ω 1/2W CC	220HBK-ND	1
R10	120Ω 1/2W CC	120H-ND	1
R11	5.1k 1/4W CC	5.1KQBK-ND	1
R12	15k 1/4W CC	15KQBK-ND	1
R13	16.1k 1/4W CC	16KQBK-ND	1
R14	1k 1/4W CC	1KQBK-ND	1
R15	150k 1/4W CC	150KQBK-ND	1
R16	250k 1/4W CC	250KQBK-ND	1
R17,R18	27k 1/4W CC	27KQBK-ND	2
R19,R25,R32	10k 1/4W CC	10KQBK-ND	3
R20	0.75Ω 3W CC	VC3D.75-ND	1
R21	565k 1/4W CC	562KXBK-ND	1
R22,R23	282k 1/4W CC	280KXBK-ND	2
R24	560Ω 1/2W CC	560HBK-ND	1
R26,R27	100k 1/4W CC	100KQBK-ND	2
R28,R29	130k 1/4W CC	130KQBK-ND	2
R30	18Ω 3W CC	VC3D18-ND	1
R31	330Ω 3W CC	VC3D330-ND	1
R33	10Ω 1/4W CC	10QBK-ND	1
C33	10µF/100V POLY FILM	EF1106-ND	1
C1	1µF/50V METALLIZED FILM	P4675-ND	1
C2,C3,C26	470µF/50V ALUM ELEC	P1248-ND	3
C4	2.2µF/400V POLY FILM	EF4225-ND	1
C5,C8,C11, C27,C28,C29	0.47µF/50V CERAMIC	P4671-ND	6
C6,C7	4.7µF/250V ALUM ELEC	P6187-ND	2
C9	470pF/25V CERAMIC	P4808-ND	1
C10	10µF/35V ALUM ELEC	P1227-ND	1
C12,C13	1µF METALIZED FILM, ITWPAK #105K050RA4	NISSEI #R68105K63B	2
C14	220pF/50V CERAMIC	P4804-ND	1
C15	4.7µF/50V ALUM ELEC	P1240-ND	1
C16	47µF/25V ALUM ELEC	P1220-ND	1

PARTS LIST (con’t)

	35W HID BALLAST PARTS LIST		
REF DES	**PART DESCRIPTION**	**DIGIKEY NUMBER**	**QTYPER**
C17,C18,C19	0.01µF/50V CERAMIC	P4513-ND	3
C20,C22,C24	0.1µF/50V CERAMIC	P4525-ND	3
C21,C23	1µF/35V TANTALUM	P2059-ND	2
C25	1000pF/50V CERAMIC	P4812-ND	1
C30	100µF/25V ALUM ELEC	P1221-ND	1
C31	180pF/1kV CERAMIC DISK	P4119-ND	1
C32	1000pF/100V CERAMIC	P4036-ND	1
Z1	1N5235B, 6.8V ZENER	1N5235BCT-ND	1
Z2,Z3	1N4761A, 75V ZENER	1N4761ACT-ND	2
U2	LM317L, ADJ LINEAR REG, TO-220	9244B-ND	1
R2A,B	0.01Ω 3W CC		2
Q2,Q3	2N3904, 40V, 0.200mA TRANISTOR		2
Q1	IRF1310, 100V, 0.027Ω	NEWARK#IRF1310	1
Q2,Q3,Q4,Q5	MOTOROLA MTP8N50E,500V TO-220	NEWARK #MTP8N50E	4
D1	MOT MUR860, 600V, 8A FST REC	NEWARK#MUR860	1
D2,D3	MOT MUR160, 600V, 1A FST REC	NEWARK #MUR160	2
U3,U4	IRF2110, MOSFET DRIVER	NEWARK #IRF2110	2
HS2,3,4,5	THERMALLOY#7128D, HS FOR Q2,Q3,Q4	NEWARK#95F715	4
TB1,TB2	TERMINAL BLOCK	44F4435	
U1	UCC3305JP		1
HS1	THERMALLOY #6398-P2,HS FOR Q1		1
L1	E100-18 MICROMETALS		1
	CORE-30T #18AWG		
	30µH		
L2	RM10PA250-3F3 PHILIPS		
	10T PRIMARY LITZ (2X10X,1)		
	60T SECONDARY LITZ(1X15X,1)		
	WINDING SEQUENCE		
	(PRIM-10T, SEC-30T, PRIM-10T)		

APPLICATION DIAGRAM