International Rectifier

APPLICATION NOTE

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Low Voltage DC Supply Dimmable Ballast for 1 x 36W T8 Lamp

by

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I. INTRODUCTION

It is possible to design an effective dimmable ballast based around the IR21592, that is powered from a low voltage DC supply instead of the AC line. A non-dimmable version based around the IR2156 is also possible using the same basic configuration as described here. The following example shows a ballast for a single 36W T8 lamp driven from a 30V DC supply. Lower supply voltages are possible, however the IR21592 control IC requires up to 13V supplied to the VCC pin before it will operate, also as the current is high large conductors are needed to keep losses at an acceptable level (for a 36W ballast operating from a 30V supply the input current is around 1.25A).

II. FUNCTIONAL DESCRIPTION

The ballast control IC and associated circuitry is powered from the low voltage DC supply by means of a simple dropper resistor that provides the required 15.6V VCC supply from the 30V input, clamped by the internal zener diode of the IC. This can supply sufficient current for the ballast control circuitry, dissipating only a small amount of power and therefore no charge pump is needed to maintain the supply. The circuit topology consists of a push-pull power switching stage as opposed to the usual half-bridge employed in mains supplied ballasts. This simplifies the circuit since a high side driver is not needed so the VB pin of the IC can be connected directly to the VCC, the VS pin can be connected to COM (0V) therefore no bootstrap diode or capacitor are necessary. The output section has a step-up transformer with a split primary, which produces a high voltage switching voltage at the secondary that can be connected to a conventional series inductor and capacitor ballast output stage to the lamp.

In this system both power switching MOSFET sources are connected to COM. In order to obtain the required current level and phase information a sense resistor must be added from the source of the LO driven MOSFET to COM. The current will be much larger at this point than in a mains powered ballast circuit and consequently a appropriately lower resistor value is necessary, in this example 0.1R. Since the step up transformer introduces no significant phase shift, the waveform detected at the current sense CS input to the control IC IR21592 is almost identical to a current sense signal in a half bridge ballast circuit. This signal can be used in the same way to detect the output circuit phase shift for dimming control.

In this system as well as in non-dimming designs the CS pin is used to monitor the current and detect faults allowing the ballast to shutdown if the lamp fails to ignite correctly as in half bridge ballast circuits.

It is not necessary for the output section to be isolated from the input section and so one side of the secondary can be referenced back to COM. We can therefore connect one side of the lamp to COM allowing the SD pin of the control IC to detect lamp removal or an open circuit in the lower filament. During dimming the lamp is prone to produce *striations* (dark rings that appear to move along the tube). We can remove these by adding a small DC offset to the lamp voltage through

R16, which is connected back to the 30Vdc bus. A snubber network consisting of R15 and C10 is also added to reduce ringing overshoot voltages that occur when each MOSFET switches off. The snubber will also increase the commutation time at switch off so that soft switching can be achieved using the IR21592, which has a fixed dead time of typically 1.8uS. The MOSFETs used in this example are type IRF540, which have a Vdss rating of 100V and Rds(on) of 0.044? at 25ºC. The peak drain voltage is 60V plus the transient produced by the leakage inductance of the step up transformer when at switch off which is comfortably less than 100V limited by the snubber.

III. SELECTION OF THE OUTPUT L AND C VALUES

Using the lamp parameters supplied by International Rectifiers *Ballast Design Assistant* software we can calculate the preheat, ignition and running frequencies for a bus voltage of 300V (Revision 4 released this year is recommended and superceeds all older releases). The output from the step up transformer will be a square wave of 300Vp-p as would be obtained using a half bridge connected to a 300V DC bus. The output circuit will be the same as in a half bridge topology. A DC blocking capacitor must also be included so that the step up transformer does not drift into saturation in one direction if the primary volt-second products are not perfectly balanced in each flux direction.

In this example the step up transformer is designed to operate at 40kHz minimum frequency, where the ballast will be at maximum output. The core needs to be larger to cope with the same throughput power at a lower frequency so in this case in order to limit the size to EF25 we have chosen a 40kHz running frequency. By iterating the values of the output L and C in the software we are easily able find values that produce the desired running frequency. The values are L=1.6mH and C=6.8mH.

In advanced mode the BDA software generates a curve showing the ballast operating points:

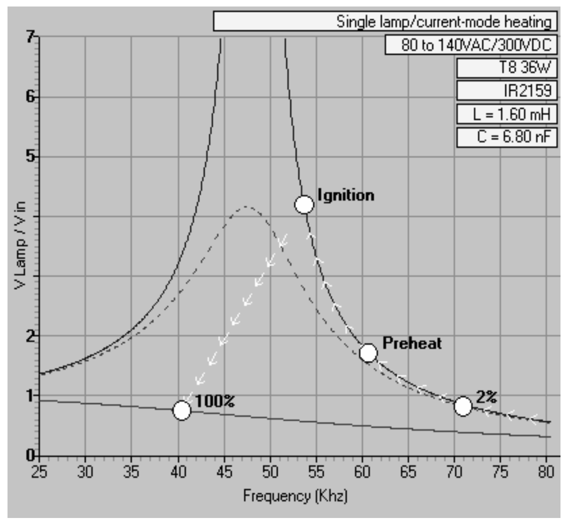


Fig. 1

These points are good because the preheat frequency is more than 5kHz higher than the ignition frequency, which will prevent the possibility of premature lamp ignition during preheat caused by the lamp voltage during preheat being too large. The run frequency is as required and is well below the ignition frequency, which will allow a smooth lamp startup sequence.

IV. PREHEATING AND CATHODE HEATING

Current mode pre-heating may be used in a dimming ballast designed for a 36W T8 lamp as it is able to produce the correct preheat current of 0.6A with this configuration. The required preheat frequency can be obtained from the formula

$$f_{ph} = \frac{i_{ph}}{2\pi C V_{ph}}$$

and

$$V_{ph} = \frac{-V_{in}}{\pi} + \sqrt{\left(\frac{V_{in}}{\pi}^2 + \frac{L \cdot I_{ph}}{C}^2\right)}$$

where Vin will be 300V.

In a dimming ballast it is also very important that the cathode current is sufficient when the lamp is dimmed. The Cathode current at minimum can be calculated with the formula

$$I_{cath} = V_{lamp(2\%)} \cdot 2\pi f_{2\%} C$$

The lamp voltage at 2% light output, is 165Vpk and the frequency is 71kHz therefore the cathode current is 0.5Apk, which is 0.35Arms.

A general rule is that the lamp filament (Cathode) resistance over the range of dimming levels should be between 3 and 5.5 times the resistance when cold. For a T8 36W lamp the cold resistance is around 3?. The resistance of the cathode at maximum brightness is not critical, as the arc current flowing in the lamp will serve to keep the temperature at a sufficient level. At minimum output the cathode voltage will be around 3Vrms so the resistance will be 9?, which is 3 times the cold resistance. This will not be the case for many other types of lamp and consequently voltage mode preheating is often needed.

V. CONTROL IC AUXILIARY COMPONENT SELECTION

The quickest and easiest method for doing this in each case is to use version 4 (or higher) of the International Rectifier Ballast Design Assistant software which can be downloaded from IR's website at www.irf.com. The BDA supports both the IR2156 and the IR21592 as well as the IR21571 which could also be used in a non dimming low voltage design. It can calculate approximate values of all external resistors and capacitors using the procedures described below. These values may be used to make an initial breadboard type ballast setup. The final refining and obtaining of the exact component values must be carried out in the lab by experimentation.

IR2156 based system (non-dimming):

For non-dimming design based around an IR2156, the selection of components is straightforward. CT should be selected to provide a dead time of approximately 1.8uS as close as possible to the fixed dead time of the IR21592. This can be calculated from the formula:

$$C_T = \frac{D_T}{1475} \quad \text{(Farads)}$$

The value obtained is 1.2nF, in practice 1nF would be acceptable. The next step is to determine the value of RT which can be calculated from the formula :

$$R_T = \frac{1}{1.02 \cdot C_T f_{run}} - 2892 \, (\Omega)$$

For Frun = 40kHz the value of RT is 22K. *

The value of RPH can be calculated from the formula :

$$R_{PH} = \frac{R_T \cdot \left(\frac{1}{1.02 \cdot C_T f_{PH}} - 2892\right)}{R_T - \left(\frac{1}{1.02 \cdot C_T f_{PH}} - 2892\right)} \quad (\Omega)$$

The preheat time is determined by the value of CPH calculated from the formula :

$$C_{PH} = T_{PH} \cdot 0.385 \times 10^{-6} \text{ (Farads)}$$

0.33uF is the value typically used to give a 1s preheat time.

In this circuit RCS is used to shut down the circuit in a fault condition. The shutdown threshold is 1.3V therefore the value can be calculated from the modified formula :

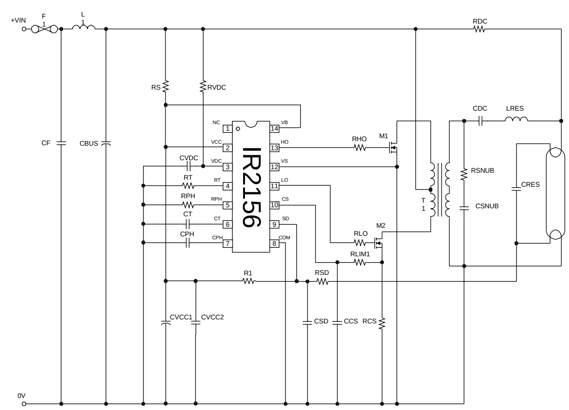
$$R_{CS} = \frac{1.3N_P}{I_{IGN}N_S} \quad (\Omega)$$

where Np is the transformer primary turns (center to one side) and Ns is the secondary turns. I_{IGN} in this case is defined as the maximum worst case ignition current that the ballast may produce before shutting down.

In this case, taking a value of 2A for the ignition current the value is 0.13Ω so we scale this down to the nearest preferred value 0.1Ω.

The VDC pin can be utilized by connecting it to the DC bus via a resistor so that if the supply voltage falls the output frequency will increase preventing the possibility of hard switching, which would cause overheating and possible failure of the MOSFETs. A value should be chosen that will start to take effect at around 25V in a system designed to run at 30V in this case 150K is recommended.

Schematic Diagram



IR21592 based system (dimming):

In a dimming system the selection of external components is more critical and the procedure more complicated.

The values of Fph, Fign, F(100%) and F(2%) can be calculated by hand using the procedure described in the Lighting Ballast Control IC Designer's Manual 2001* based on known values of lamp voltage and power. However the BDA software is able to do this far more quickly using lamp parameters from its own database.

* Please note that there is an error on p.213 of the Lighting Ballast Control IC Designer's Manual (2001) the formulae for f(100%) and f% should be as stated on p250 and p.251

The following procedure can be used to determine the values for the IR21592 external resistors. Firstly Fmin must be set, which limits the minimum frequency that the oscillator will run at. This must be lower than F(100%) or Fign, whichever is lower.

$$R_{FMIN} = \frac{25\times10^{-6} - (f_{MIN} - 10000)\cdot10^{-10}}{(f_{MIN} - 10000)\cdot 2\times10^{-14}} \ (\Omega)$$

In this case we can select Fmin to be 40kHz this will limit the maximum ballast power. This gives a value of 36K.

The next step is to determine RCS from the formula

$$R_{CS} = \frac{1.6N_P}{I_{IGN}N_S} \ (\Omega)$$

For an ignition current of 2A the value will be 0.16Ω, which can be scaled down to 0.15Ω or 0.1Ω. The over current shutdown will obviously be more sensitive for 0.15Ω so if no problems of false tripping are experienced this would give better protection.

If using the BDA software to calculate the resistor via the *Program IC* function, it should be noted that the step up function of the transformer is not be taken into account. Therefore the value given for RCS will need to be multiplied by Np/Ns to provide the correct value to use in a low voltage system. This is unlikely to result in a preferred E24 resistor value. The easiest way around this is to choose the nearest preferred value and multiply Ns/Np. Make a note of the result and then adjust the ignition current in the software and recalculate until the RCS is the same as the value required. Bear in mind that the values of Riph, Rmax and Rmin will change as RCS changes. In this example the value of 0.15Ω is multiplied by 125/25 giving 0.75Ω. The ignition current is changed from 1.8A to 2.2A and the resistor values recalculated to give RCS of 0.75Ω.

The next step is to calculate Riph from the following formula

$$R_{IPH} = \frac{\sqrt{2}R_{FMIN}R_{CS}I_{PH}N_S}{N_P} \ (\Omega)$$

Note 1

For a preheat current of 0.6Arms which is correct for this lamp the result is 22K.

It is a good idea at this point to verify this value on the bench by connecting pin CPH to COM, thus keeping the ballast in permanent preheat and ensuring that there is sufficient cathode heating taking place but that the lamp voltage is low enough to prevent the possibility of premature ignition, which in the case of the IR21592 does not allow the dimming control loop to close correctly and inhibits the dimming function.

Note that for the IR21592 to operate correctly the ignition detection function must be completed correctly, which requires that the current at ignition is more than 10% greater than the current during preheat and then falls when the system enters run mode.

In order to program the MIN and MAX settings of the dimmer interface, the phase of the output current stage at minimum and maximum lamp power must be calculated. This is a very complicated calculation requiring the lamp voltage and power to be known at minimum and maximum dim settings. The following method avoids the need for this by assuming that the phase will be very close to –90º at minimum brightness and using this value to calculate Rmin from the formula

$$R_{MIN} = \frac{R_{FMIN}}{4}\cdot\left(1 - \frac{\phi_{2\%}}{45}\right)(\Omega)$$

This gives the result 27K.

The BDA software can calculate the value of Rmax by first calculating the phase shift based on its database lamp data parameters, however to get a rough estimate of what Rmax should be we can use an approximation of the phase shift. We know from graph of *Fig 1* that the frequency at 100% power is below resonance and so the phase shift must be between 45º and zero. To obtain a starting point we can estimate a phase shift of 30º at maximum brightness and use the formula

$$R_{MAX} = \frac{0.86 R_{FMIN} R_{MIN}}{4R_{MIN} - R_{FMIN}\left(1 - \frac{\phi_{100\%}}{45}\right)} \quad (\Omega)$$

This gives the result 18K.

Having determined the values the circuit can then be assembled and tested. By measuring the input current to the ballast it is possible to know whether the maximum power is correct (i.e. the current is 1.25A) and if not to change the value of Rmax accordingly. It is possible to observe the lamp brightness at minimum and adjust the value of Rmin to obtain the desired result.

* If necessary values can be altered slightly to achieve fine adjustment of the frequencies to obtain the optimum preheat level and lamp running power.

Note 2

At this point it is also necessary to verify the values of Rmin and Rmax on the bench. In order to do this the ballast can be switched on and allowed to preheat and ignite the lamp, with the dimming control input to be set to 5Vdc.

The procedure is as follows:
Increase the voltage at the DIM input further if necessary until minimum frequency is reached. It will go no lower if the dimming level is raised further.

The minimum frequency limit set by Rfmin should be verified as being 40kHz as required. The calculations will not always give very accurate results for resistor values and these always need to be verified. Trim the Rfmin value to obtain the correct result.

Note 3

The next stage is to set the dimming control voltage to 0V and adjust the value of Rmin to give the required minimum dimming level.

The procedure is as follows:
The value of Rmin must ensure that the lamp does not extinguish when Vdim is set to 0V so gradually reduce the DIM input voltage to 0V, adjusting Rmin if necessary to prevent the lamp from extinguishing. When DIM is at 0V adjust to the desired minimum level. Finally adjust the dimming control input voltage to 5V and adjust Rmax to give the correct maximum light output and adjust between minimum and maximum levels tweaking the values of Rmin and Rmax until both limits are satisfactory.

(Notes 1,2, and 3 also apply to setting up an AC line supplied dimming that utilizes a IR21592)

Schematic Diagram

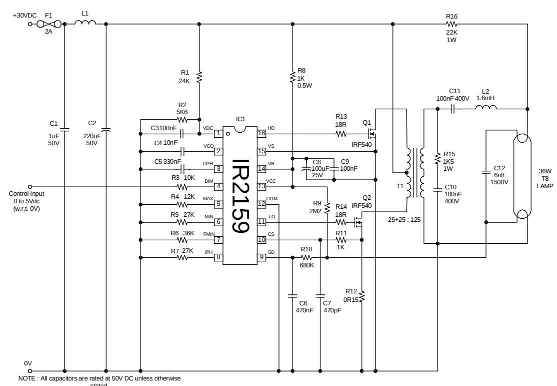


Fig. 2

VI. LAYOUT ISSUES

When laying out the PCB for this type of ballast it is important to allow the high current carrying traces to be as wide and as short as possible. The control IC COM should be a star point connected to the COM end of R12. The IC COM should be connected directly to this point via a very short track. The negative side of C2 should also be connected as close to this point as possible and the positive side should be connected as close to the center tap of T1 as possible. The C9 decoupling capacitor should be connected directly between VCC and COM and C3, C4, C5, R4, R5, R6, R7, C6, C7, C8 should all be connected back to the star point. Tracks around the IC should be kept short as far as possible except the gate drives and VS and VB, which can be a little longer if necessary. It is also important to keep traces that are carrying high switching currents away from sensitive components around the IC as much as possible.

VII. STEP-UP TRANSFORMER DESIGN

The oscilloscope traces in *fig. 3* show the voltage at the drain of each of the switching MOSFETS. The drain voltage rises to 60V when the MOSFET switches off. This is because the primary winding is center tapped and the center point is connected to the 30V DC bus. When one MOSFET is switched on the voltage between the center point and the drain is 30V therefore the voltage across the entire primary winding will swing from 60V in one direction to 60V in the other direction the result being 120Vp-p.

Voltage across the primary winding (from drain to drain)

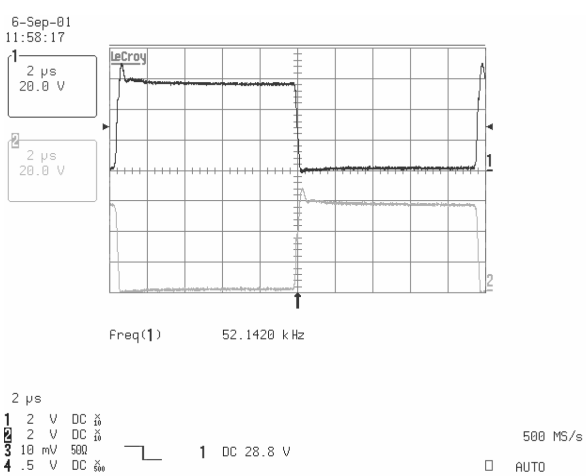


Fig. 3

In this design we have chosen the turns ratio of the transformer to give 300Vp-p at the secondary, which can be fed into the ballast resonant output circuit. The turns ratio required can be determined as follows :

300 / 120 = 2.5

2 x 2.5 = 5

Therefore the turns ratio will be 1 + 1 : 5.

The core size should be selected for a throughput power of 36W at 40kHz. We have used an EF25 (E25/13/7) core of 3C85 or N27 material, which ungapped has an Al value of 1900nH and an effective area Ae of 52mm².

Primary Volt-Seconds = 60V x 12.5uS = 750V-uS

We have chosen 25 + 25 : 125 turns.

This gives a primary inductance of 50² x 1900nH = 4.75mH.
Therefore the magnetizing current will be 750 x 10-6 / 4.75 x 10-3 = 0.16A (from V=L.dI/dT).

The peak flux will be

$$\frac{N_P A_L I_{PK}}{A_e}$$

= 50 x 1900 x 10-9 x 0.16 / 52 x 10-6 = 0.29T (2900 Gauss).

This calculation shows that the core is being pushed close to saturation in each direction but will not saturate at high temperature (see manufacturers B-H curve for the Ferrite material).
The winding wire sizes should be chosen such that they fill the winding area. The primary should have approximately twice the diameter of the secondary as the primary RMS current will be 1.25A and the secondary RMS current will be 0.25A.

Voltage across the secondary winding

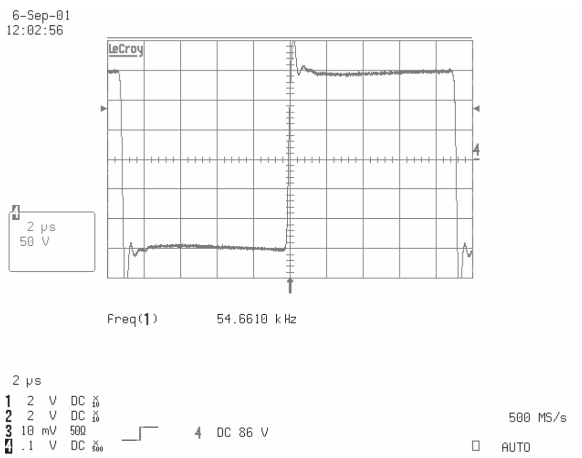


Fig. 4

VIII. OUTPUT INDUCTOR DESIGN

The BDA software will design the output inductor if required. It will suggest a wire diameter for a single strand, however a multi stranded wire that has an equivalent total cross sectional area will produce lower copper losses.

Alternatively the following procedure may be used :

1. Select the winding wire

In a dimming design because the frequency goes as high as 70kHz it is necessary to use multi stranded wire in order to keep losses due to the *skin effect* to a minimum. If single stranded wire is used the inductor will run at an increased temperature when the lamp output is low.

Consider the RMS running current of the lamp. This can be easily estimated by dividing the maximum lamp power by the RMS lamp voltage. The RMS lamp voltage can be approximated by dividing the peak lamp voltage by v2 in this case 100V giving 0.36A.

A *current density* 3A/mm² can be used to calculate to minimum cross sectional area of conductor that will be required. In this case the result is 0.12mm².

The *skin effect* must now be considered. For Copper conductors the penetration depth at a given frequency can be calculated by the formula

$$\Delta = \frac{65}{\sqrt{f}} \text{ (mm)}$$

Using the maximum frequency of 70kHz this gives the result 0.24mm therefore the strands should be less than 0.24mm diameter.

The conductor area for a wire of 0.24mm is

$$A = \frac{4D^2}{\pi}$$

This gives the result 0.073mm².

A practical solution would be to use 4 strands wire that has a diameter much smaller than 0.24mm. The area for each strand would have to be 0.03mm² this equates to AWG 32, which has an area of 0.046mm² including the insulation.

2. Select the core size

The BDA uses an iterative process that attempts the design procedure using a range of core and gap sizes finally selecting the smallest size that can contain the winding wire without saturating during lamp ignition. This is extremely important because if the core does saturate the resulting current pulse will be detected at the CS pin of the IC causing the ballast to shut down. A common design error is to fail to allow for a *hot re-strike* condition (i.e. when the ballast has been running and is switched off and back on again) where the Ferrite core is already at increased temperature and the saturation point of the material is reduced resulting in saturation at a lower current.

To follow the procedure of the BDA by hand is time consuming and therefore it is easier to pick an option based on experience. For a 36W ballast a reasonable starting point would be to design an inductor based on an EF25 (E25/13/7) core with a standard gap size of 1mm made of standard power grade Ferrite (type 3C85 or N27).

For this the Al value is 63nH and Ae is 52mm². The inductance required is 1.6mH therefore

$$N = \sqrt{\frac{L}{A_L}}$$

The number of turns required is 159.

The maximum ignition current is 2A so the peak flux density will be

$$B_{MAX} = \frac{N A_L I_{PK}}{A_e}$$

Which gives the result 0.39T (3900 Gauss). By looking at the manufacturers curve of B against H we can see that the material will saturate at around 0.42T at 25ºC and 0.35T at 100ºC. When the ballast is cold there is no possibility of saturation at ignition and during a *hot re-strike* situation the core is unlikely to be as hot as 100ºC. Therefore this solution is acceptable as in reality the ignition voltage of the lamp will be somewhat less than 2A if the lamp is correctly preheated. The inductor should be built and tested under *worst case* conditions to ensure that the lamp will strike. If there are problems then a larger gap or larger core will be required.

The available winding area in an EF25 bobbin is 56mm². The winding area required is

0.046 x 4 x 159 = 29.3mm²

Allowing for empty spaces there will be sufficient winding space. It is always an advantage to increase to wire size or better still add more strands as much as possible to minimize copper losses when the lamp is running. The BDA does this automatically.

IX. BILL OF MATERIALS

Description	Reference
Power MOSFET	Q1,2
Ballast Control I.C.	IC1
Fuse 2A	F1
Capacitor 1uF 50V 105ºC Radial Electrolytic	C1
Capacitor 220uF 50V 105ºC Radial Electrolytic	C2
Capacitor 100nF 50V	C3,8
Capacitor 10nF 50V	C4
Capacitor 330nF 50V	C5
Capacitor 470nF 50V	C6
Capacitor 470pF 50V	C7
Capacitor 100uF 25V 125ºC Radial Electrolytic	C9
Capacitor 100nF 400V Polyester	C10,11
Capacitor 6.8nF 1500V Polypropylene	C12
Resistor 24K 0.25W	R1
Resistor 5K6 0.25W	R2
Resistor 10K 0.25W	R3
Resistor 12K 0.25W	R4
Resistor 27K 0.25W	R5,7
Resistor 36K 0.25W	R6
Resistor 1K 0.5W	R8
Resistor 2M2 0.25W	R9
Resistor 680K 0.25W	R10
Resistor 1K 0.25W	R11
Resistor 0R15 0.25W	R12
Resistor 18R 0.25W	R13,14
Resistor 1K5 0.25W	R15
Resistor 22K 1W	R16
Filter Inductor	L1
Inductor 1.6mH EF25	L2
Transformer 1+1:5 EF25	T1

X. REFERENCES

Lighting Ballast Control IC Designer's Manual 2001 - International Rectifier