The design of an emergency lighting system for compact fluorescent lamps

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Synopsis:

Compact fluorescent emergency luminaires present unique challenges. Not only must the emergency gear and ballast be crammed into small confines of the luminaire but there is the additional problem of excessive temperature to deal with. This paper describes the design of an optimal electronic ballast/emergency control unit specifically aimed at the South African market where the traditional switch start solution usually prevails for cost reasons. A detailed design process is presented together with a proposed topology, solutions to hidden pitfalls and measured lamp (heater and arc discharge) characteristics.

1) General

Emergency lighting luminaires for compact fluorescent lamps, especially bulkhead types, have traditionally presented both installation and maintenance issues. The architect may well choose the most aesthetically pleasing slim bulkhead for the stairwells but it usually left to the lighting supplier to both shoe horn emergency lighting gear into the fitting at bargain basement prices and then provide support for the warranty duration. The cheapest system is usually designed around 2 x PL9W lamps driven via an electromagnetic choke. The temperature rise within the luminaire caused by a combination of lamp dissipation and ballast losses often results in severely reduced battery life [1]. An optimal solution would therefore be to reduce maintained circuit losses, simplify wiring and to reduce hardware cost.

2) Electronic ballast design

Circuit losses can be dramatically achieved by using high frequency electronic ballast topology instead of the traditional electromagnetic choke [2]. The benefits that can be realised are, *inter alia*:

- Lower ballast losses
- Reduced lamp power
- Reduced cathode fall voltage

These improvements translate directly into reduced dissipation and hence lower temperatures within the luminaire.

2.1) Series resonant lamp drive

An optimal electronic ballast topology typically uses a half bridge to drive the lamp via a series resonant circuit from a supply derived from full wave mains rectification. Full wave rectified mains from 230Vac produces roughly 300Vdc and so the bridge output cannot exceed 300V peak to peak. This voltage may be sufficient to cold strike small compact fluorescent lamps (CFL’s) but such a practise, although simpler and cheaper, results in reduced lamp life and unreliable starting and should therefore be avoided. Series resonance can be used to provide the dual role of providing high strike voltage and electrode heating current (see Figure 1). During ignition the lamp resistance is high and the heater resistances are relatively low therefore the circuit Q is high – approximately 50. The ignition conditions therefore provide a high voltage across the lamp (and capacitor) and high currents through the lamp heaters. This high value of Q would ultimately result in excessive circuit voltages and currents but as the lamp ignites the circuit becomes overdamped - the inductor now setting steady state lamp current. The circuit Q now falls to about 0.7 for small wattage lamps whose lamp voltage is typically less than the output of the half bridge. An added advantage of series resonance is that the steady state Q can exceed unity – necessary for larger wattage lamps. Capacitor C_2 is included to decouple the dc supply voltage from the load and its value is typically much greater than that of C_1.

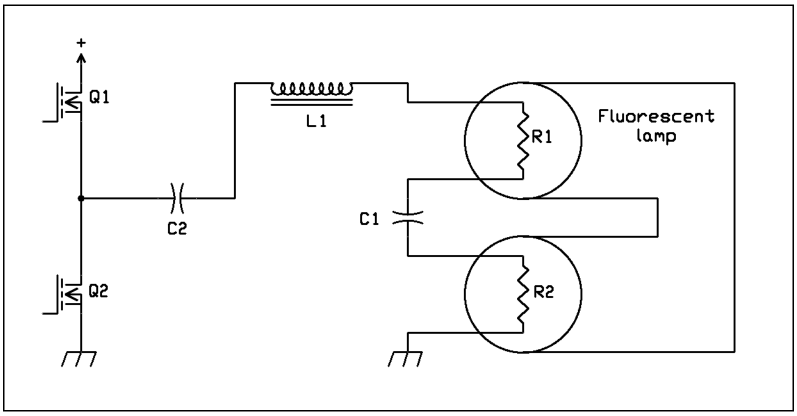

Figure 1: Series resonant circuit

During an arc discharge the lamp plasma can be modelled, at a given power, as a resistive load: R_L. The resistance of the heaters can now be disregarded as the circuit becomes heavily damped by the lamp plasma resistance across C_2. The expression determining the frequency for maximum voltage during an arc discharge (ω_m) is given by:

$$\omega_m = \sqrt{\frac{1}{L_1 C_2} - \frac{1}{2{C_2}^2 {R_L}^2}} \qquad (1)$$

where R_L is the lamp plasma resistance. It would be prudent to first select the operating frequency and then to determine the value of L_1 to drive the lamp at full power. The value of C_2 can then be determined from expression (1).

The voltage amplification at resonance is given by:

$$\left|\frac{V_O}{V_I}\right|_m = \frac{1}{\sqrt{\frac{L_1}{C_2 {R_L}^2}\left(1 - \frac{L_1}{4C_2 {R_L}^2}\right)}} \qquad (2)$$

It is evident from equation (2) that as R increases then so the absolute value of amplification also increases; this is intuitive because R is in parallel with C.

2.2) Lamp ignition

It should be borne in mind that there are a number of conditions which must be observed to ensure reliable ignition [3,4]. The two most important criteria are that the electrodes should achieve thermionic emission before lamp ignition otherwise electrode sputtering will reduce lamp life and that sufficient ignition voltage is provided to ensure reliable starting. Thermionic emission is manifested by a cherry red glow of the heaters, usually occurring at about 3R (where R is the cold heater resistance). In order to ascertain the preferred pre-heat current the electrodes of the lamps were characterised (see Figure 2). It is evident that, in general, heater resistance decreases with lamp power. This phenomenon is due to the requirement of maintaining sufficient joule heating to sustain thermionic emission, in combination with cathode phase ion bombardment, during an arc discharge. It follows that, in general, low wattage lamps with corresponding low discharge currents need higher heater resistance to provide the same electrode dissipation as lamps of higher wattage. The heater characteristics of a 120W CFL has been included to further illustrate this point. The tops of the curves represent thermionic emission – it is evident that 10V would ensure thermionic emission in the small lamps.

The heater resistance also varies with current; as the heater current increases so the heater gets hot and its resistance therefore increases too. This phenomenon must be accounted for when assessing steady state heater dissipation.

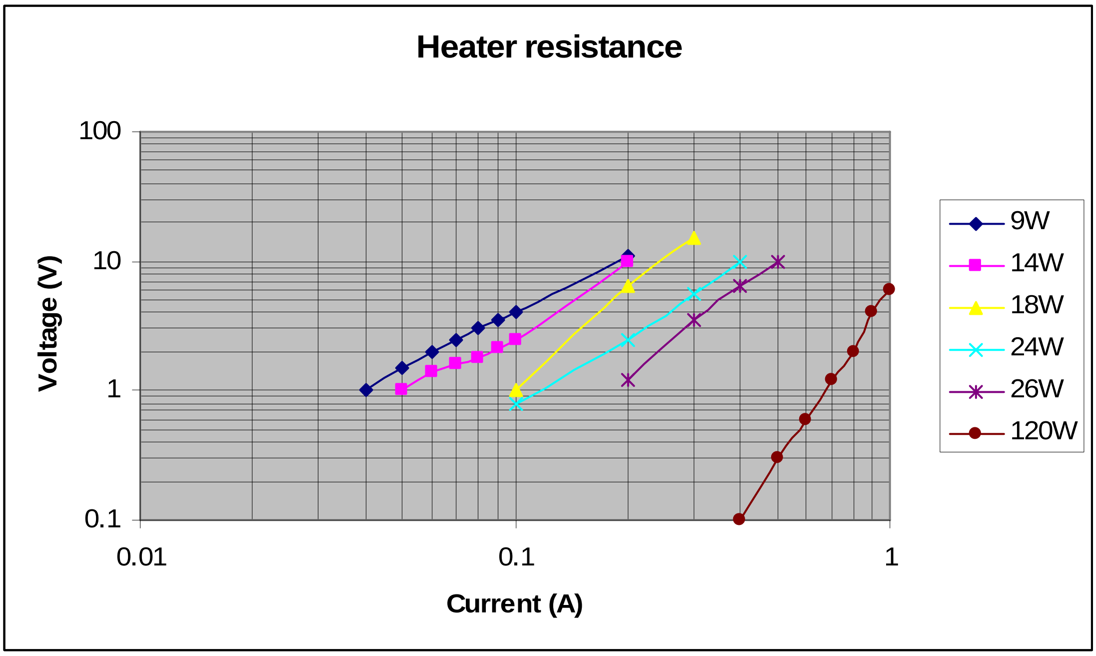

Figure 2 Measured heater characteristics

The measured lamp V-I characteristics are displayed in Figure 3. The Y axis represents ohms for resistance, peak-to-peak milliamps for current and peak-to-peak volts for voltage. In our experience there is very little value in trying to deduce trends from or interpolating the lamp data. It seems that, at least for low wattage CFL's, mercury pressure and other gas variables are selected to achieve the specific lamp power *i.e.*, increases in lamp power are not achieved solely by increasing tube length. The measurement of lamp electrical characteristics is very important to ensure that the lamps are driven at the correct power.

2.3) Arc discharge conditions

Steady state lamp power must also be kept within narrow limits. Too little lamp power and electrode damage will result from excessive ion bombardment, lower lumen efficacy and reduced luminous flux. Excessive lamp power will result in rapid electrode damage through excessive joule heating and will also result in lower luminous efficacy. Lamp power was measured both optically and electrically. Optical measurements were conducted by comparing the lamp light output with that of a reference circuit using an integrating chamber [5]. Electrical measurements were conducted by measuring lamp voltage and current. The steady state high frequency operating power is lower than the 50Hz rated power due to the higher lumen efficacy attained at high lamp current frequencies.

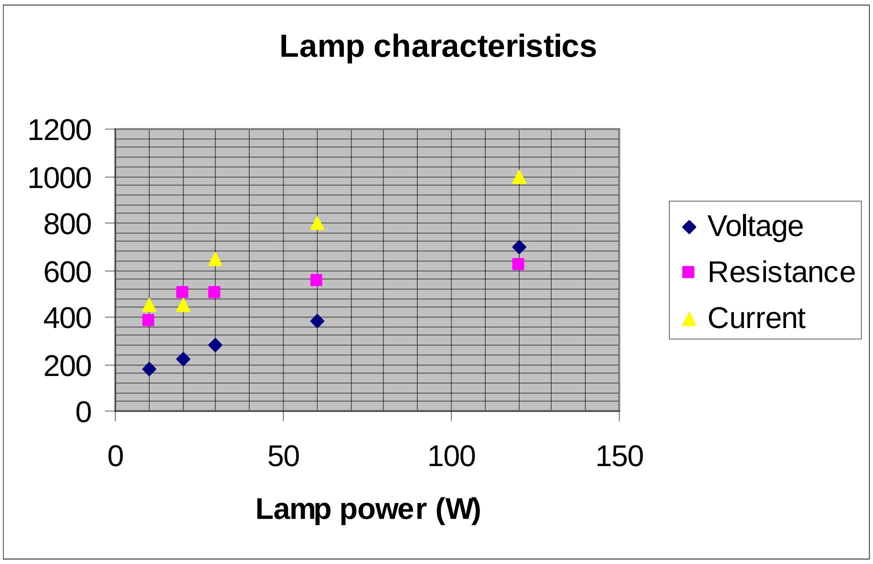

Figure 3 Measured V-I characteristics

The success of the chosen circuitry can only be reliably evaluated after exhaustive pre-production testing. This testing must include a significant sample of all desired lamps being subjected two tests: successive on-off cycles in and continuous burning. The on-off cycles are conducted to lamp destruction in order to ascertain a predicted cycle life and efficiency of the pre-heating.

Continuous burning tests can also uncover hidden problems. New lamps are used at the beginning of the test and the initial condition of their electrodes is note visually and photographed. The condition of the electrodes is thereafter noted for the characteristic sign of excessive oxide evaporation *viz*. end blackening. It is possible to cause excessive oxide evaporation without over driving the lamp using a series resonant circuit because during arc conduction the resonant capacitor commutates current past the lamp through the heaters. During the design stage this commutating current is tuned to approximately 50% of their cherry red temperature resistance which, in combination with a cooler and hence lower resistance heater, results in a continuous heater dissipation of less than 25% of the thermionic temperature.

2.4) FET half bridge shoot-through

The design of the electronic ballast was accomplished after conquering many electronic hurdles the one interesting and not often publicised gremlin is half bridge shoot-though. The use of FET's for the half bridge is usually promoted due to ease of drive and switching speed (and hence lower switching losses). This may hold true during normal operation but no-lamp operation may result in, surprisingly, excessive FET dissipation. This condition is caused by current shoot-through because of hard FET switching. The FET drain-source capacitance increases dramatically (see Figure 4) as the drain-source voltage approaches zero. This graph of an IRFR320 shows how the drain-source capacitance (Coss) changes with drain-source voltage. At a drain-source voltage of 20V or more the value of Coss is typically 50 pF – which is typical for such devices and of little consequence at 30kHz. However, when the drain-source voltage is 1 V or less then Coss rises above 600 pF. Note that the graph does not extend below 1 Volt where the measured capacitance increases to nano-Farads! The upshot is huge shoot-through currents during switching with no load (lamp) present. This can result in excessive FET dissipation and failure if heat sinking is inadequate. Even though most chip-sets provide dead time switching, the shoot through currents are still considerable with no load. The ideal remedy is to switch the drive circuitry off when no lamp(s) is present. This provides the twin advantages of zero device dissipation and low mains current with no lamp – a condition which will occur at the end of the lamp's service life.

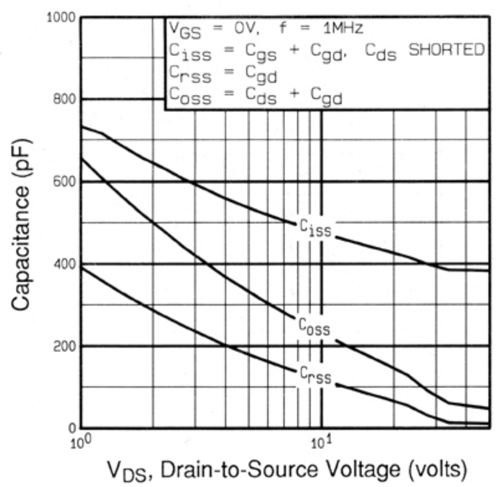

Figure 4 FET capacitance vs Vds (courtesy IR)

2.5) Reliability testing results

2.5.1) Starting reliability

Tests were conducted on various low cost locally available ballasts which, unsurprisingly, use a cold start scenario. Ballasts were switched on and off and lamps were visually inspected for blackening and time of failure. Each switching cycle consisted of 5 seconds on and 25 seconds off (to give the lamp a chance to cool down). Tests revealed that severe lamp blackening generally occurred after 140 cycles and that most lamps were destroyed at 1000 cycles.

To justify the use of warm start the same tests were conducted on the ballast architecture described above. Tests revealed that all lamps were capable of experiencing 20000 cycles before destruction. The results indicate cogent reasons for choosing a warm starting scenario.

2.5.2) Arc discharge reliability

In order to ascertain lamp life in continuous burning all ballast types are electrically measured for rated lamp current and electrode dissipation but there is no substitute for actual measurement of lamp life in a luminaire. For this test a sample of every lamp type was permanently powered in a bulkhead type luminaire alongside lamps powered by other reputable manufacturers. Photographs were taken at regular intervals of the electrodes to monitor electrode degradation with age. So far tests have revealed no excess electrode damage compared with other reference ballast designs.

3) The emergency control circuit

The emergency circuit consists of battery charging, mains fail detection, emergency lamp drive, battery low detect and lamp changeover circuits. The optimal circuitry for the emergency section is driven by cost: Luxuries such as warm start and long lamp life are compromised in the interests of reducing the number and size of the batteries; a fact not well publicised because usually the emergency lighting is seldom used or tested. The emergency section must drive the lamp (only one lamp is driven in multiple lamp ballasts) for the required duration (usually one or three hours) from the smallest battery pack. The emergency light output is therefore chosen to be the minimum necessary to initiate and sustain an arc discharge in the fluorescent lamp. The worst case starting scenario is a cold lamp strike or non-maintained mode. In this case the circuitry has to not only strike the lamp but must also provide sufficient power to achieve thermionic emission in the electrodes otherwise the lamp will remain in glow discharge mode where excessive cathode fall voltage will severely damage lamp electrodes and can, within minutes, result in lamp failure. A glow discharge is characterised by a bluish glow at either electrode, usually initially visible with ballasts using cold starting. This problem can also manifest itself towards the end of the emergency duration as the battery potential drops the lamp may revert to a glow discharge.

3.1) Emergency lamp driver

A current fed push-pull inverter topology (as shown in Figure 5) was used to drive the lamp in emergency mode [6]. The self-resonant circuit is switched on by pulling R2 high. Spurious oscillation is prevented by using the highest value of C1 and by prudent circuit layout. The collector oscillation is stepped up by means of a transformer and coupled to the lamp (R1) via the ballast capacitor (C2). Cold starting of the fluorescent lamp, even with near flat batteries, is ensured by a high (>1000V) secondary voltage. A remarkable feature of this circuit topology is its inherent current boost for lamp starting. The no-lamp resonant frequency, usually set to approximately 50kHz, is determined by C1 in parallel with the primary inductance of the transformer. During lamp starting (glow discharge) the ballast capacitor impedance is relatively low causing high current to flow through the lamp and heat the electrodes. As an arc discharge develops the lamp plasma resistance (R1) drops and the ballast capacitance is reflected back into the oscillator in parallel with C1 thereby lowering the frequency and reducing the lamp current.

A neat design trick is to drive the lamp with dc in emergency mode so it is only necessary to achieve thermionic emission in one electrode and so less starting power is required. Chromaticity shift due to mercury electrophoresis may occur but equilibrium will be restored when the lamp is next driven at full power.

3.2) Battery charge and supervisory circuitry

According the SANS Specifications the nickel-cadmium batteries require a C/20 rate constant current charge [7]. This is the minimum current required to charge the batteries within 24 hours assuming an 80% charging efficiency. As continuous charging rates above C/10 will reduce battery life and charging rates below C/30 may not bring flat batteries out of a deep discharge, a continuous C/20 rate makes good sense.

The SANS requirement for a low voltage cut-off of 0.8V/cell also has good merit. The cells in any given battery pack are not identical and so during discharge their potentials and capacities will differ slightly. If the battery pack is discharged completely at some point the lowest capacity cell will be depleted and begin to be reverse charged. This reverse charged cell may require a considerably higher charge rate than C/20 before it begins to accept normal charge. Also, it is evident from published discharge curves that there is little duration to be gained below 1V/cell [8].

The supervisory circuit must connect the lamp to the mains ballast during normal power conditions and connect the lamp to the emergency lamp drive circuit during a power failure. It is important that changeover is not initiated during brown-outs or mains fluctuations otherwise rapid ageing of the lamp will result. Also, emergency mode must not be activated when the batteries are connected for the first time as this will result in an unnecessary discharge and produce the corresponding dangerous voltages during luminaire manufacture.

3.3) Reliability testing results

SANS 1464:22 stipulates a test scenario of 500 mains fail cycles (with a freshly charged battery pack) of two seconds on and two seconds off in normal lighting mode *i.e.*, maintained operation. Positive results were achieved with all lamp types thereby justifying the emergency driver topology chosen.

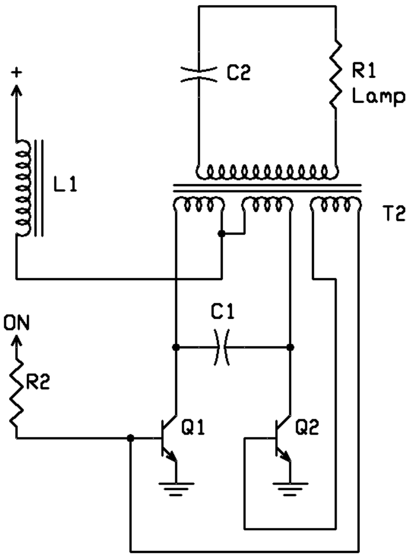

Figure 5 Current fed push-pull inverter

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