AN1731
APPLICATION NOTE

EMERGENCY LIGHTING APPLICATIONS

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1. ABSTRACT

This application note shows the topologies implemented in the Emergency Lighting Applications and the STMicroelectronics's power bipolar transistors used.
Today, the Emergency Lamps market has grown considerably due to the new improved safety rules. In fact, the Emergency Lamps are used in all public places and, also, in private homes replacing the traditional lighting applications.

2. STSA851 DESCRIPTION

The STMicroelectronics's power bipolar transistor STSA851 is housed in the TO-92 package. This device is manufactured in NPN planar technology using a 'Base Island' layout that involves a very high gain performance and a very low saturation voltage.
The main characteristics of the STSA851 device are:

1) $V_{ceo} \geq 60$ V;
2) $V_{ces} \geq 150$ V;
3) $V_{ebo} \geq 7$ V;
4) $I_c = 5$ A (continuous current);
5) $I_b = 1$ A (continuous current);
6) $V_{ce(sat)} = 140$ mV (typ) @ Ib = 50 mA @ Ic = 2 A (typical conditions);
7) $H_{fe} = 270$ (typ) @ Ic = 2 A @ $V_{ce} = 1$ V (typical conditions).

3. HIGH EFFICIENCY DC-AC CONVERTERS

The part of the circuit used to drive the emergency lamp is composed of DC-AC converters. The DC-AC converters transform the low DC input voltage in high AC output voltage required by the fluorescent tube. Fluorescent tubes are employed in these applications because they are much more efficient at converting electrical energy into light than conventional incandescent bulbs increasing the battery life. Usually, DC-AC converters used in these applications are the Push-Pull switching converter forced to run in synchronized mode by the inclusion of a supply inductor, and the Forward converter. Mainly, the DC-AC converters have suitable transformers that increase the output voltage and allow the electrical isolation between the secondary and primary of the transformer, and suitable switches. Usually, the switches are power bipolars driven by a third winding magnetically coupled to the transformer, like in the PUSH-PULL current FED converter.

The power bipolar transistor collector current I_c depends on the load, turns rapport

$$K = \frac{N_2}{N_1/2} \qquad \textbf{(3.1)}$$

where N_2 is the secondary turn number and N1 is the primary turn number of the transformer, and it also depends on the battery voltage.

Usually, in these applications the lamp power is in the range of 8-24W, and the turns rapport

$$\frac{N_2}{N_1/2} \qquad \textbf{(3.2)}$$

is about 30, the current I_c is in the range of 1.5-3.0A. Furthermore, usually, the emergency lighting boards are powered with an input voltage in the range of 3.6-6.0 V_{dc} so that the typical V_{ce_max} is around 10-20 V_{dc}. The voltage and current values ranges, V_{ce_max} and Ic, are inside the SOA of the STSA851 so that these devices can be used in all emergency lighting applications. The emergency lamp applications drive a lamp up to 58W. Usually, these emergency lighting applications do not supply such output powers but only 10-20 % of the nominal lamp power. Sometimes, such applications are used to power lamps that commonly light up rooms. When the net voltage disappears the emergency lamp switches on supplying around 10-20 % of the nominal lamp power just to light up the room.

4. FLUORESCENT TUBE CHARACTERISTICS

Fluorescent lamps are generally made with tubes filled with a gas mixture at a low pressure. The inner sides of the tubes are covered with fluorescent elements. When the net voltage disappears, before the tube lights on, the lamp has a higher resistance. In this moment, the electrodes voltage increases up to around 500V and the electrodes start to warm up and emit ions. Figures 1 and 2 show the V-time and I-time waveforms and the V-I waveform respectively before the start-up of a 24W tube.

Figure 1: V-time and I-time Waveforms Before the Striking

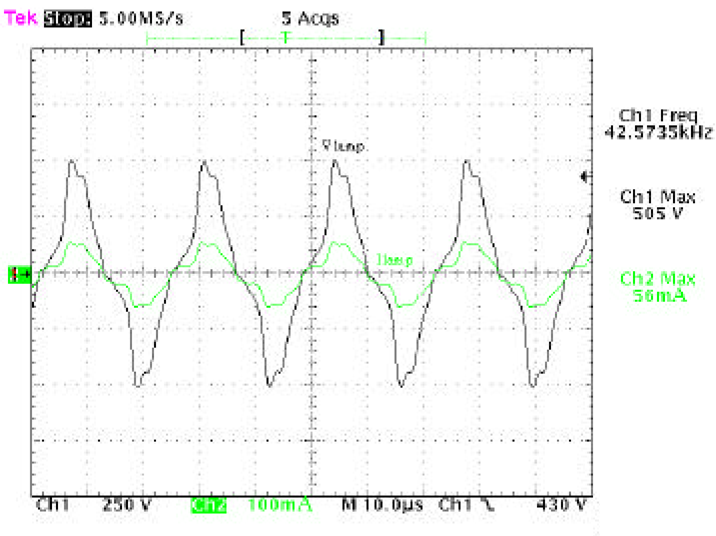
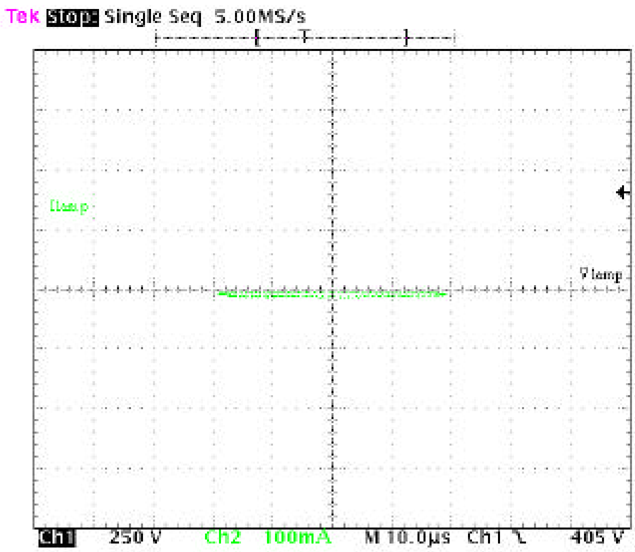


Figure 2: V-I waveform before the striking



As shown above, to strike the fluorescent tube the electrodes voltage reaches up to 505V of peak. Furthermore, the current that flows through the lamp is very low, 56 mA, because the resistance before the striking is high (around 10 KOhm).

When the fluorescent lamp lights on, the gas mixture inside is fully ionized, and an arc across the electrodes occurs. In this new condition, the lamp resistance drops to around 1 KOhm value (Figures 3 and 4 show the V-time and I-time waveforms and the V-I waveform after the striking.

Figure 3: V-time and I-time waveforms after the striking

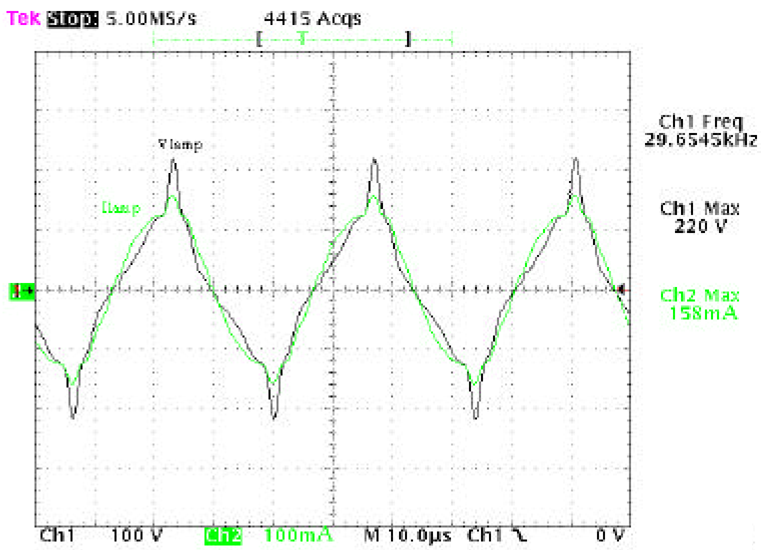
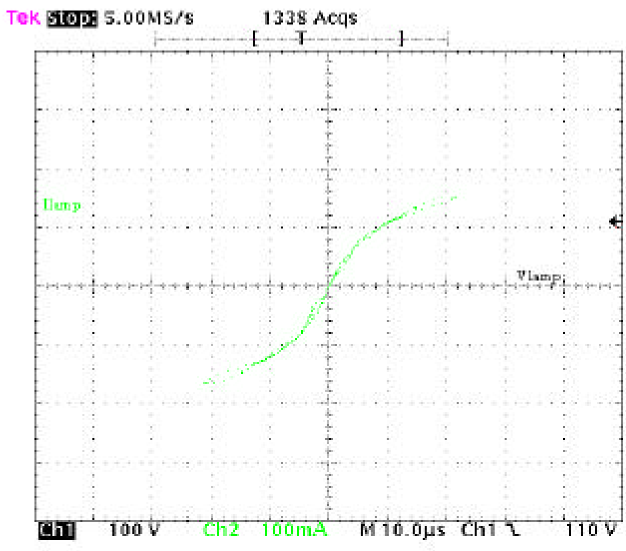


Figure 4: V-I waveform after the striking



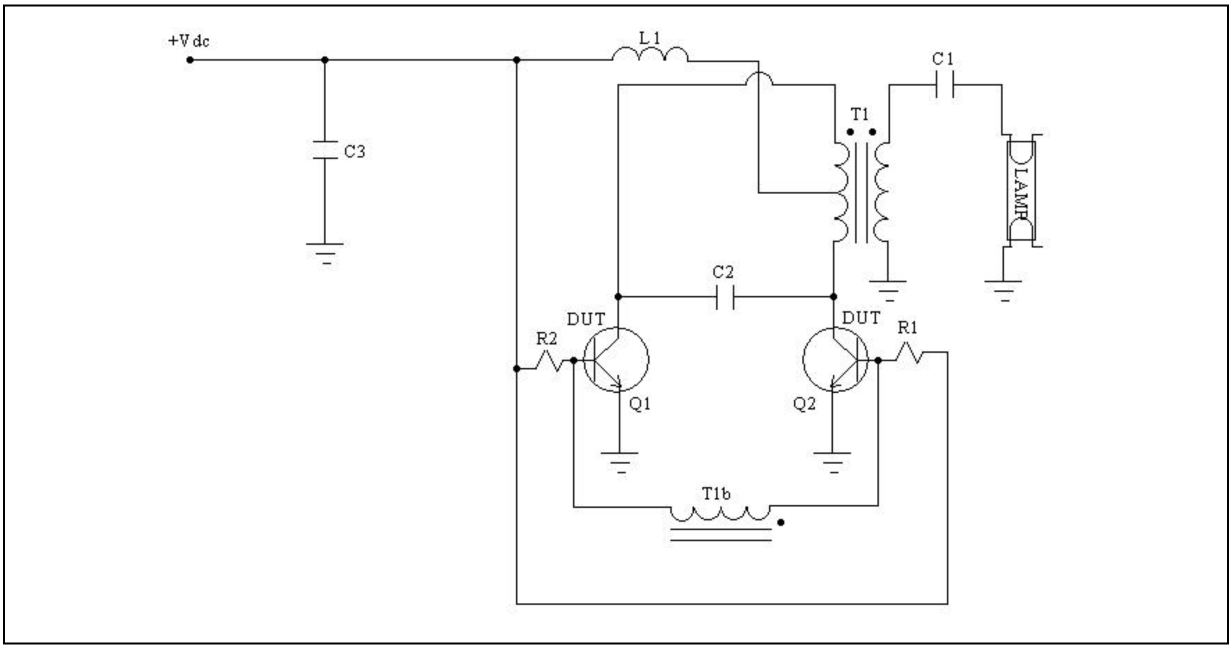
After the striking, the gas mixture emits radiations that excite the fluorescent elements inside the tube producing the light in the visible spectrum. In this example, after the striking, the voltage across the electrodes drops from 505V of peak to 220V of peak and the current increases from 56mA of peak to 158mA of peak.

Usually, after the striking, in order to increase the lamp efficiency up to 15%, the operation frequency is in the range of 25-30KHz. Furthermore, as shown in Fig. 4, the waveform I-V has a linear behavior until the established voltage value is kept. In fact, if the voltage across the electrodes overcomes this established voltage value, the characteristic becomes flat because no ion can emit other radiations.

5. PUSH-PULL CURRENT FED CONVERTER TOPOLOGY INTRODUCTION

As previously exposed, a topology solution for emergency lighting applications is the PUSH-PULL current FED converter topology. This topology solution has a Push-Pull switching converter forced to run in synchronized mode by the inclusion of a supply inductor.

Figure 5: PUSH-PULL current FED converter schematic circuit



The components values of capacitors, resistors, and inductors are selected operation on the input voltage, power lamp, and operation frequency.

6. TRANSFORMER DESCRIPTION OF PUSH-PULL TOPOLOGY

In figure 5 the transformer named T_1 has three windings. The primary winding vices are connected to the collectors of the NPN power bipolar transistors Q_1 and Q_2. The same primary winding has a central vice where the inductor L_1 is connected. The secondary winding vices are connected to the load.

The third winding vices are connected to the base of the transistors Q_1 and Q_2 so that when the first is on, the second is off and vice versa. During the Q_2 on state, the current flows through the same device and the respective half primary winding and vice versa. Usually the primary inductance LT of the transformer T_1 is much lower compared to the inductance L_1. The resonance frequency of the PUSH-PULL converter is also due to LT. N_2 (secondary winding turns) and $N_1/2$ (half primary winding turns) rapport is around 60, while $N_1/2$ and N_3 (third winding turns) rapport is around 5. Considering a 6 V_{dc} input voltage, the voltage v_{1max} (the max voltage across the vice of the primary winding central point and the reference) can be written as:

$$v_{1max} = \frac{\pi}{2} \cdot V_{dc} = \frac{3.14}{2} 6 \cong 9V \qquad \textbf{(6.1)}$$

v_{2max} (the max voltage across the secondary winding vices) can be written as:

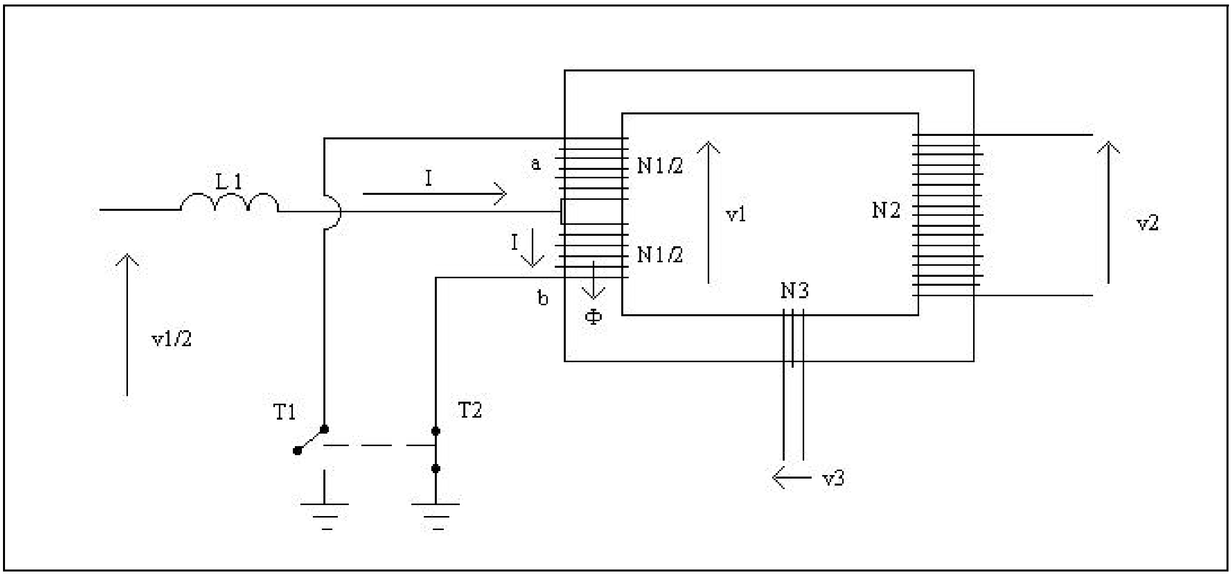
$$v_{2max} = \frac{\pi}{2} \cdot V_{dc} \frac{N_2}{(N_1/2)} = \frac{3.14}{2} 6 * 60 \cong 560V \qquad \textbf{(6.2)}$$

v_{3max} (the max voltage across the vices of the third winding) can be written as:

$$v_{3max} = \frac{\pi}{2} \cdot V_{dc} \frac{N_3}{N_1/2} = \frac{3.14}{2} 6 * \frac{1}{5} \cong 2V \qquad \textbf{(6.3)}$$

As exposed above, it is highlighted $N_1/2$ and not N1. In order to understand the reason of it, it is necessary to consider the graph below.

Figure 6: Particular of T_1



When Q_2 is on, Q_1 is off and vice versa. Now, considering fig. 6 where T_2 is on; the current 'I' flows through the half primary winding 'b' and it generates a magnetic force (Hopkinson law):

$$\frac{N_1}{2} \cdot I = \Re \cdot \Phi \qquad \textbf{(6.4)}$$

Φ is the magnetic flux and $\Re$ is the magnetic reluctance of the T1 core;Φ can be written as:

$$\Phi = \frac{\frac{N_1}{2} \cdot I}{\Re} \qquad \textbf{(6.5)}$$

$\Re$ can be written as:

$$\Re = \frac{l}{m \cdot A} \qquad \textbf{(6.6)}$$

µ is the core permeability, A is the core section and l is the core length. When T_2 switches off, T_1 switches on, the current flows through the other half primary winding 'a' and the flux Φ inverts its direction. Such flux flows into the transformer core creating a link with N_2, N_3 and also with the other turns $N_1/2$, generating the voltages v_2 and v_3 (magnetic law-Lenz law):

$$v_2 = -N_2 \frac{\Delta\Phi}{\Delta t}; \quad v_3 = -N_3 \frac{\Delta\Phi}{\Delta t}; \quad v_{1/2} = -\frac{N_1}{2}\frac{\Delta\Phi}{\Delta t} \qquad \textbf{(6.7)}$$

$$\frac{v_2}{v_1} = \frac{N_2}{N_1/2}, \frac{v_3}{v_1} = \frac{N_3}{N_1/2}, \frac{v_{c2}}{v_1} = 2 \qquad \textbf{(6.8)}$$

Furthermore, i_2 (the current that flows through the lamp) can be written as:

$$i2 = I\frac{N_1/2}{N_2} = I\frac{1}{K} \qquad \textbf{(6.9)}$$

In fact, the apparent input power can be written as:

$$A_{in} = v_1 I \qquad \textbf{(6.10)}$$

The output power can be written as:

$$A_{out} = v_2 i_2 \qquad \textbf{(6.11)}$$

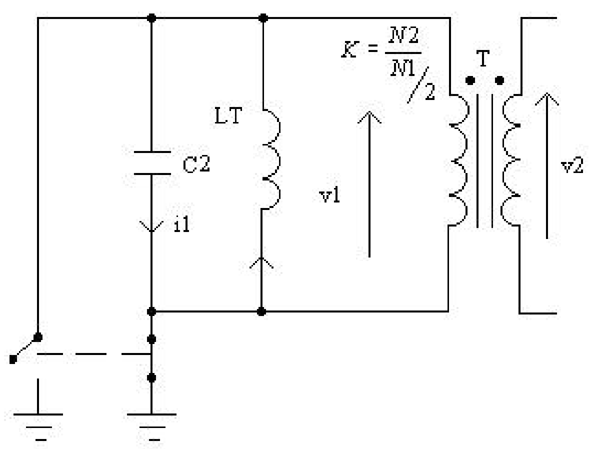
Considering an ideal transformer:

$$v_2 i_2 = v_1 I \qquad \textbf{(6.12)}$$

$$\frac{i_2}{I} = \frac{v_1}{v_2} = \frac{N_1/2}{N_2} = \frac{1}{k} \qquad \textbf{(6.13)}$$

Before the lamp strike, or when the lamp is disconnected, the operation frequency (about 60 KHz) is due to the resonance between C_2 and the primary transformer winding inductance LT (see fig. 7).

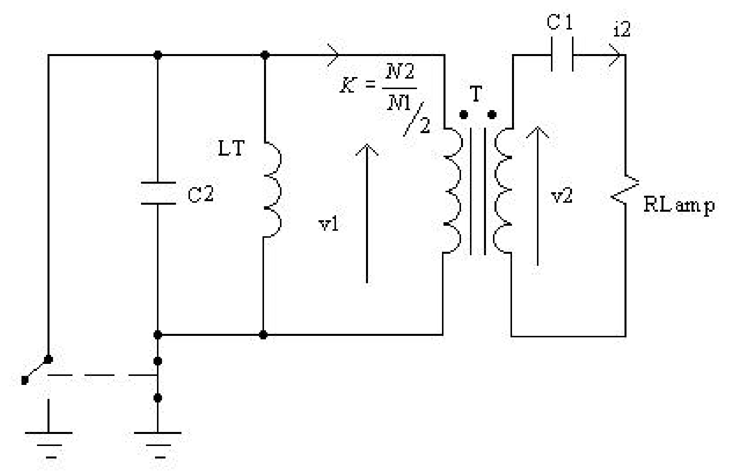
Figure 7: Resonant Schematic Circuit Before the Lamp Strike



$$f = \frac{1}{2 \cdot p \sqrt{LTC2}} \qquad \textbf{(6.14)}$$

When the lamp is connected, the transformer circuit can be showed as in the graph below.

Figure 8: Ideal Schematic Circuit of the Transformer After the Lamp Strike

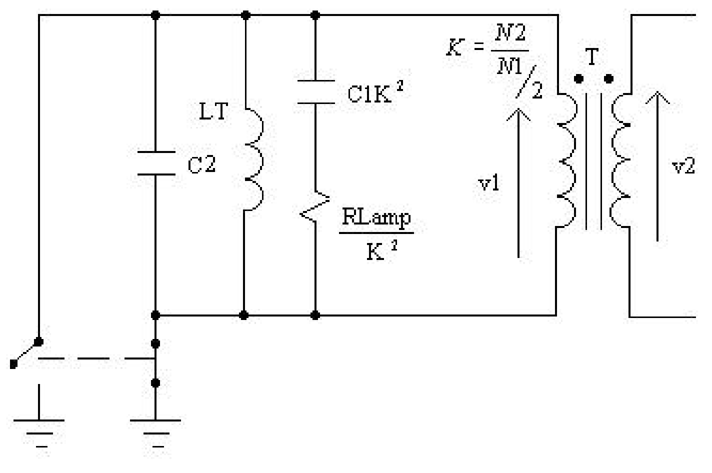


The input apparent power can be written as:

$$A_{in} = v_1 i_1 \qquad \textbf{(6.15)}$$

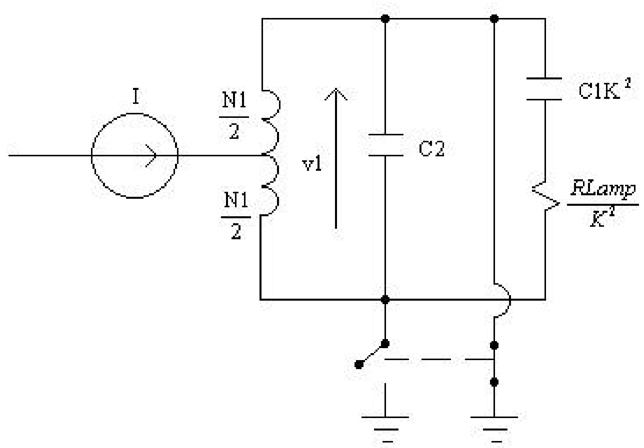
Now it is possible to consider an equivalent circuit to fig. 8, as in fig. 9, where the apparent input power is equal.

Figure 9: Equivalent Schematic Circuit of the Transformer After the Lamp Strike



Furthermore, after the lamp strike, the resonant schematic circuit can be represented as in figure 10 where, usually, the operation frequency is due to LT, C_2 and C_1K^2 (25-30 KHz).

Figure 10: Resonant Schematic Circuit of the Transformer After the Lamp Strike



In this transformer equivalent circuit the output impedance has been transferred from the secondary winding to the primary winding.

$$v_1 I = v_2 i_2 = i_2^{\,2}(R_{Lamp} - j\frac{1}{w \cdot C_1}) \qquad \textbf{(6.16)}$$

$$\frac{v_1 I}{i_2^{\,2}} = (R_{Lamp} - j\frac{1}{w \cdot C_1}) = \frac{V_1}{i_2}\frac{I}{i_2} = \frac{v_1}{I}\frac{N_2^{\,2}}{({N_1}/{2})^2} = \frac{v_1}{I}k^2 \qquad \textbf{(6.17)}$$

$$\frac{v_1}{I} = z_{eq1} = \frac{1}{k^2}(R_{Lamp} - j\frac{1}{w \cdot C_1}) \qquad \textbf{(6.18)}$$

Where:

$$\frac{R_{LAMP}}{k^2} \qquad \textbf{(6.19)}$$

is the primary equivalent resistance and where:

$$C_1 K^2 \qquad \textbf{(6.20)}$$

is the primary equivalent capacitance.

Now, the equivalent primary admittance (Y_{eq1}) can be written as:

$$Y_{eq1} = \frac{-j}{w \cdot LT} + jw \cdot C_2 + \frac{k^2 jwC_1}{(1 + jCR_{Lamp}w)} \qquad \textbf{(6.21)}$$

and where:

$$\frac{k^2 jw \cdot C_1}{(1 + jCR_{Lamp}w)} \qquad \textbf{(6.22)}$$

is the admittance of the series net

$$\frac{R_{Lamp}}{k^2} - C_1 k^2 \qquad \textbf{(6.23)}$$

Considering

$$\frac{R_{Lamp}}{k^2} \qquad (6.24)$$

negligible compared to

$$\frac{1}{w \cdot C_1 k^2} \qquad (6.25)$$

deriving Y_{eq1} compared to the pulsation and equal to zero, it is possible to achieve the frequency that maximizes, the Y_{eq1} (such frequency is the resonance frequency of the application during the lamps on state).

$$w^2 \cong \frac{1}{LT(C_2 + k^2 C_1)} \qquad (6.26)$$

$$f \cong \frac{1}{2 \cdot p \sqrt{LT(C_2 + k^2 C_1)}} \qquad (6.27)$$

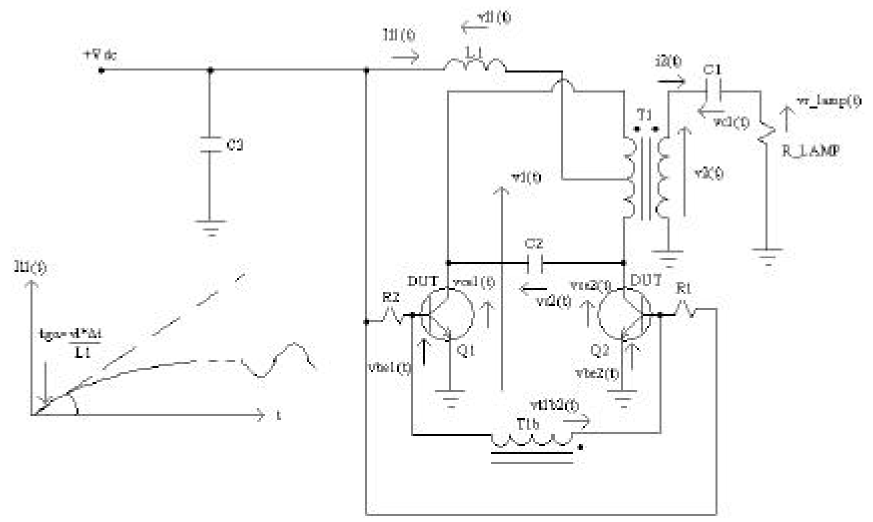
When the board is powered, R_1 and R_2 enable Q_1 and Q_2 and the lamp turns on. After the lamp start-up, during the Q_2 on state, the current flows through L_1, the half primary winding transformer T_1 and Q_2, and it increases as:

$$tga = \frac{v_{L1} * \Delta t}{L_1} \qquad (6.28)$$

angular coefficient but, after a while, the current curves and it becomes flat. However, in the permanent state, even if the current oscillates around its average value, there is a ripple of this same value. The current ripple decreases increasing the inductance value L_1.

Figure 11 shows the PUSH-PULL current FED converter schematic circuit with the theoretical waveform of 'I'.

Figure 11: PUSH-PULL Current FED Converter Schematic Circuit with the Theoretical Waveform

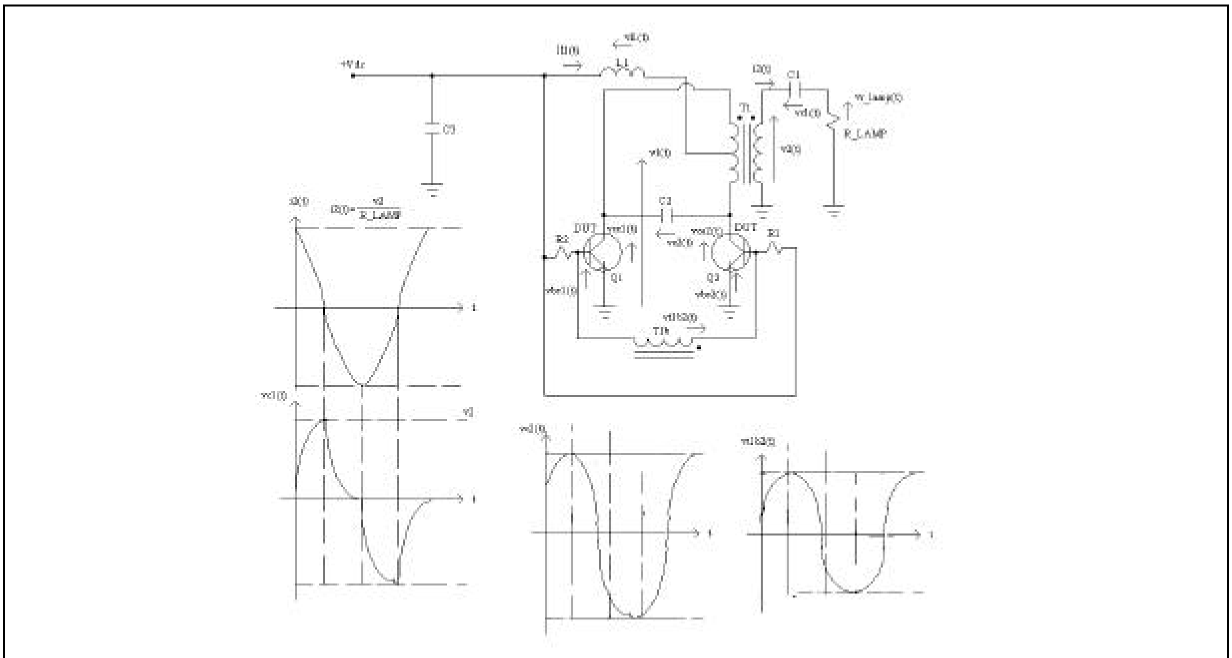


After the strike, 'I' generates the current i_2 and, at the beginning, the same i_2 can be written as:

$$i_2 = \frac{v_2}{R_{Lamp}} \qquad \textbf{(6.29)}$$

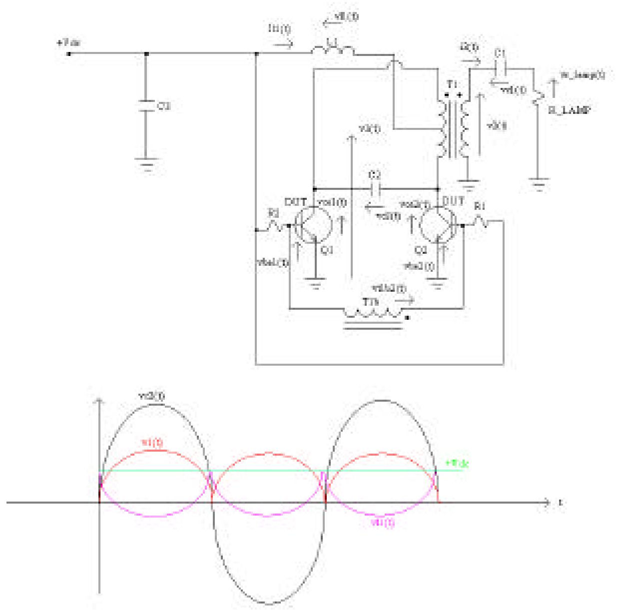
because the capacitor C_1 is discharged. Immediately after, C_1 gets charged and i_2 decreases to zero until the voltage across C_1 reaches the maximum value. A this time, the current i_2 inverts its direction and the capacitors C_1 start discharging until the charge inside it becomes zero and the current i_2 reaches its maximum negative value. Furthermore, when i_2 inverts itself, also the voltage across the third winding inverts its direction so that Q_2 switches off and Q_1 switches on and 'I' flows through the other half primary winding of the transformer T_1 (see fig. 11).

Figure 12: PUSH-PULL Current FED Converter Schematic Circuit with v_{c1}, v_{c2}, i_2, and v_{t1b2} Theoretical Waveforms



In the above graph, v_{c2} is the voltage between the vices of the Q_1 and Q_2 collectors. The maximum value of such voltage is twice v_1, where v_1 is the voltage between the vices of the central point of the primary winding of T_1 and the reference. The voltage v_1 is a half positive sine wave and this reaches the maximum value when Q_1 or Q_2 are on, while it drops to zero during the turn-off and the turn-on of the same transistors (see fig. 13).

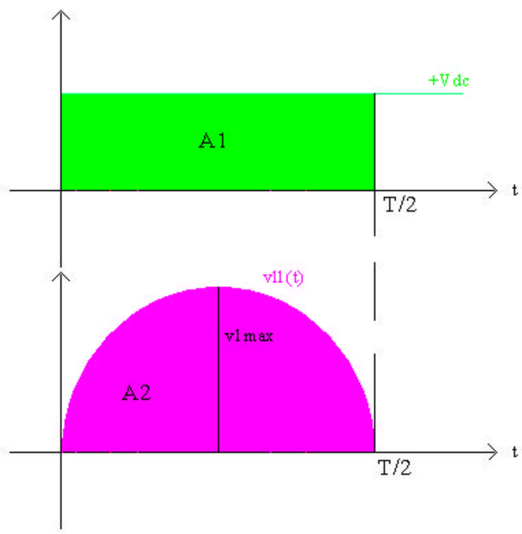
Figure 13: PUSH-PULL current FED converter schematic circuit with v_{c2}, v_1, and v_{L1} theoretical waveforms



The figure above also highlights the v_{L1} voltage. This is the voltage across L_1 and it is achieved considering the difference between V_{dc} and v_1.

Now focusing the attention on only one half-period of v_1 as showed in fig. 14, it is evident that the area A2 must be equal to the area A1 because v_1 and V_{dc} must have the same average value.

Figure 14: v_1 waveforms



A1 can be written as:

$$A1 = V_{dc}\frac{T}{2} \tag{6.30}$$

A2 can be written as:

$$A2 = \int_0^{\frac{T}{2}} V1\max sen(\frac{2p}{T})tdt =$$

$$= \frac{T}{2p} V1_{\max} [-\cos(\frac{2p}{T})t]_0^{\frac{T}{2}} = \frac{T}{p} V_{1\max} \qquad \textbf{(6.31)}$$

considering: A1=A2 **(6.32)**

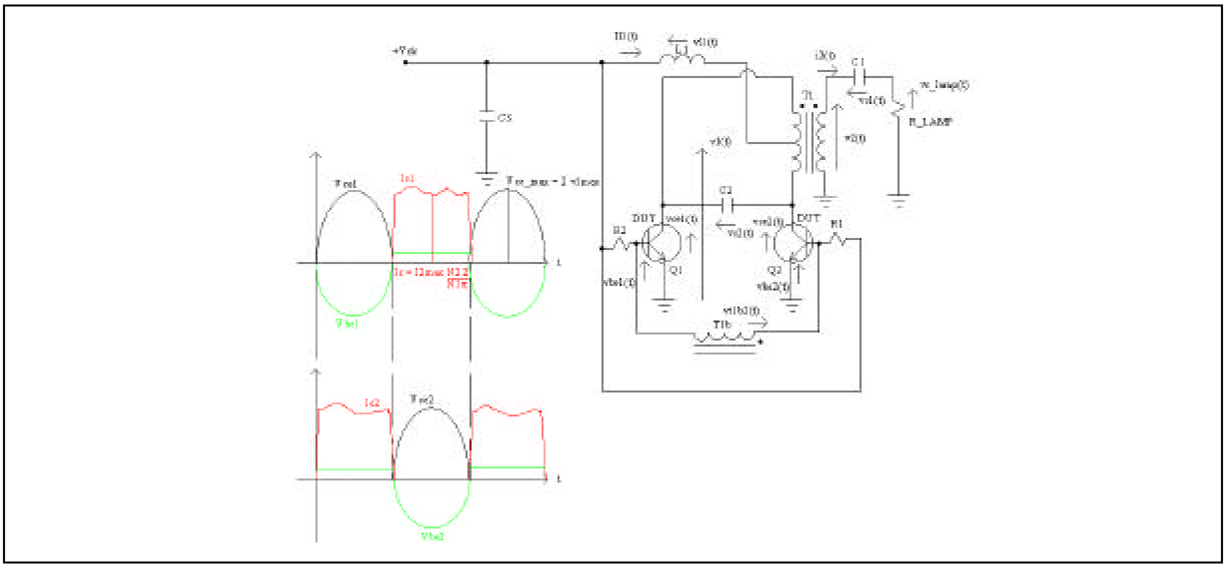
$$V\frac{T}{2} = \frac{T}{p} V_{1\max} \Rightarrow V_{1\max} = \frac{p}{2} V_{dc} \qquad \textbf{(6.33)}$$

v_{c2max} can be written as:

$$V_{2\max} = p \cdot V_{dc} \qquad \textbf{(6.34)}$$

v_{c2max} is also the maximum voltage value between the collector-emitter vices of Q_1 or Q_2.
The theoretical voltages and the currents waveforms of Q_1 or Q_2 are shown below.

Figure 15: Q_1 and Q_2 theoretical waveforms



Ic1 and Ic2 can be written as:

$$I_{c1\max} = I_{2\max} \frac{N_2}{N_1/2} \qquad \textbf{(6.35)}$$

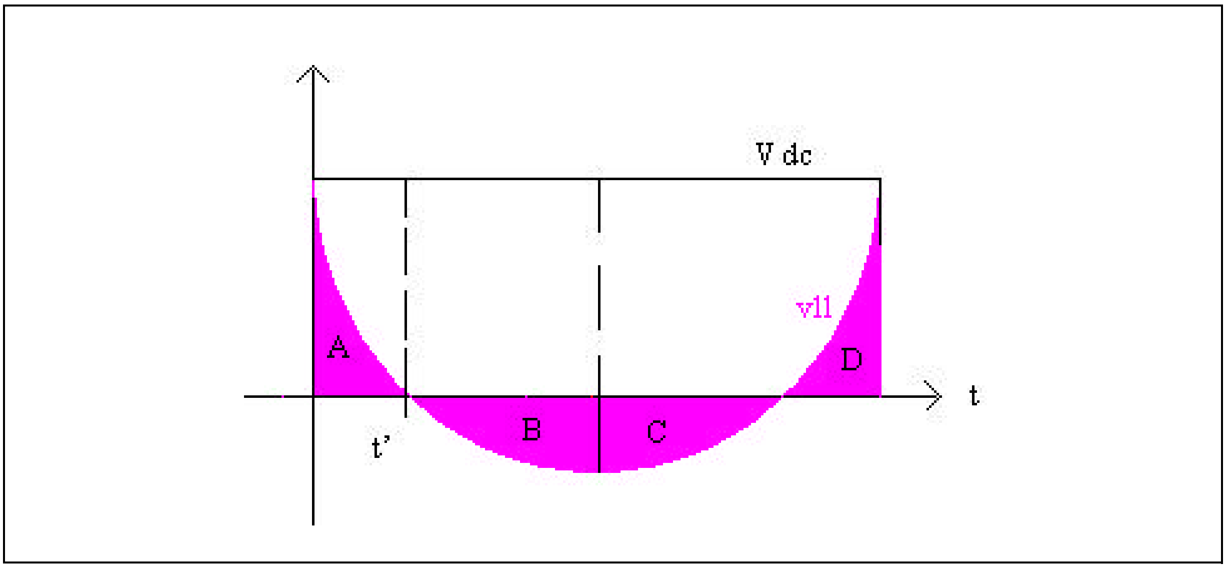
$$P_{out} = R_{Lamp} (\frac{I_{2\max}}{\sqrt{2}})^2 \qquad \textbf{(6.36)}$$

$$I_{2max} = \sqrt{2\frac{P_{out}}{R_{Lamp}}} \quad \textbf{(6.37)}$$

$$I_{c1max} = \frac{N_2}{N_1/2}\sqrt{2\frac{P_{out}}{R_{Lamp}}} \quad \textbf{(6.38)}$$

R_1 and R_2 can be also used to adjust the I_{b1on} and I_{b2on}.
Now focusing the attention on only one half-period of v_{L1}:

Figure 16: v_{L1} theoretical waveform detail



After the lamps strike 'I' fluctuates around its average value:

$$I_{max} - I = I - I_{min} = \Delta I \quad \textbf{(6.39)}$$

because:

$$v_{med} = 0 \quad \textbf{(6.40)}$$

where v_{med} is the average value of L_1.
v_{med} can be written as:

$$v_{med} = \frac{(A + D - B - C)}{T} \quad \textbf{(6.41)}$$

T is the period of v_{L1}.

$$A + D = B + C \quad \textbf{(6.42)}$$

$$A = B \quad \textbf{(6.43)}$$

$$C = B, D = A \quad \textbf{(6.44)}$$

v_{L1} can be written as:

$$v_{L1} = V_{dc} - \frac{p}{2} V_{dc} \cdot sen(\frac{2 \cdot p}{T} t) \quad \textbf{(6.45)}$$

t' is the time when v_{L1} is zero:

$$0 = V_{dc} - \frac{p}{2} V_{dc} \cdot sen(\frac{2 \cdot p}{T} t') \quad \textbf{(6.46)}$$

$$t' = \frac{T}{2 \cdot p} arcsen(\frac{2}{p}) \quad \textbf{(6.47)}$$

Considering that:

$$\Delta I_{\max\%} = \frac{\Delta I_{\max}}{I_{med}} \quad \textbf{(6.48)}$$

$$\Delta I_{\max\%} \cdot I_{med} = \Delta I_{\max} \quad \textbf{(6.49)}$$

Considering the Lenz law:

$$v_{med} = L_{1\min} \frac{\Delta I_{\max}}{\Delta t} \quad \textbf{(6.50)}$$

It is possible to achieve L_{min} (the minimum L_1 value that allows the established current ripple to be obtained) as:

$$L_{1\min} = \frac{\Delta t}{\Delta \mathrm{Im}\, ax} v_{med} \quad \textbf{(6.51)}$$

During the time interval 0-t' I increases by:

$$\frac{\Delta I_{\max}}{2} \quad \textbf{(6.52)}$$

v_{med} can be written as:

$$v_{med} = \frac{1}{t'} \int_0^{t'} v_{L1} \cdot dt = \frac{1}{t'} \int_0^{t'} [V_{dc} - \frac{p}{2} V_{dc} \cdot sen(\frac{2 \cdot p}{T} t)] dt \quad \textbf{(6.53)}$$

$$v_{med} = \frac{1}{t'} \{V_{dc} \cdot t' - \frac{T}{4} V_{dc} [1 - \cos(\frac{2 \cdot p}{T} t')]\} \quad \textbf{(6.54)}$$

L_{1min} can be written as:

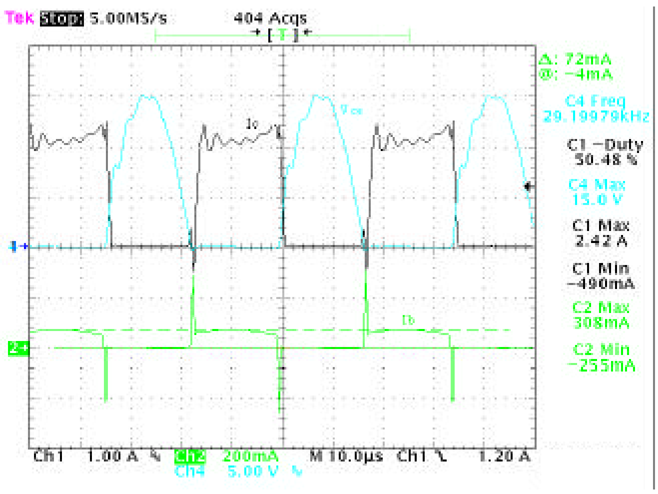
$$L_{1\min} = \frac{2}{\Delta I_{\max}} \{V_{dc} \cdot t' - \frac{T}{4} V_{dc} [1 - \cos(\frac{2 \cdot p}{T} t')]\} \quad \textbf{(6.55)}$$

7. EXAMPLE OF AN EMERGENCY LAMP APPLICATION

The following example takes into consideration a real emergency lamp application with a PUSH-PULL current FED converter topology using a 24W lamp and powered with 6 V_{dc} with STSA851.

The graph below shows I_c, I_b, and V_{ce} waveforms of the STN851 device when the lamp is connected.

Figure 17: Steady state of STSA851



The following graphs show the turn-off and turn-on switch modes respectively.

Figure 18: Turn-off of STSA851

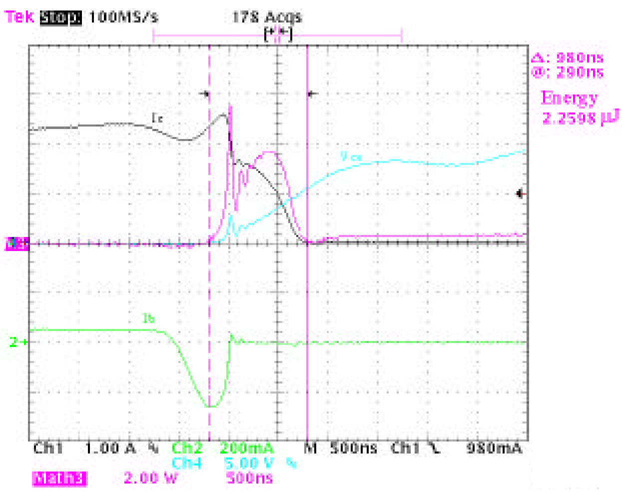
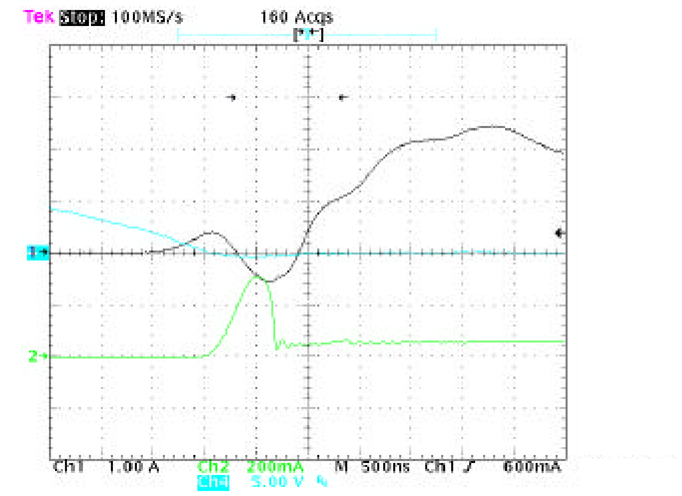


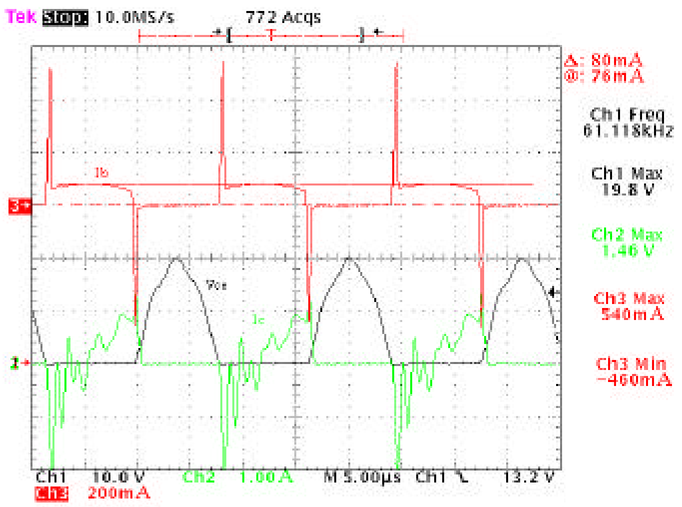
Figure 19: Turn-on of STSA851



In these graphs it is possible to see that the operation frequency is around 30KHz, I_c is around 2.4A and that I_{bon} is around 70mA. The I_b spike during the turn-on switch mode is due to the collector-base junction charge, while, the negative I_b spike during the turn-off switch mode is due to the storage charges extraction. Furthermore, in this example, during the turn-off switch mode, the dissipated energy is due to a $C_{2,}$ discharging on the power bipolar device, that decelerates I_c decreasing. Sometimes, in order to decrease the turn-off dissipated energy, two capacitors between the vices of the collector-emitter of both devices are connected.

The figure below shows the steady state of the STSA851 device without the lamp.

Figure 20: Steady state of STSA851 without the lamp



In this case the operation frequency is around 60 KHz.

The current and the voltage values measured on the power bipolar device are inside the STSA851 specifics.

The next graphs show the v_{L1}, ‘I’ and v_{c2} waveforms with and without lamp respectively.

Figure 21: v_{L1} and I Waveforms With Lamp Connected

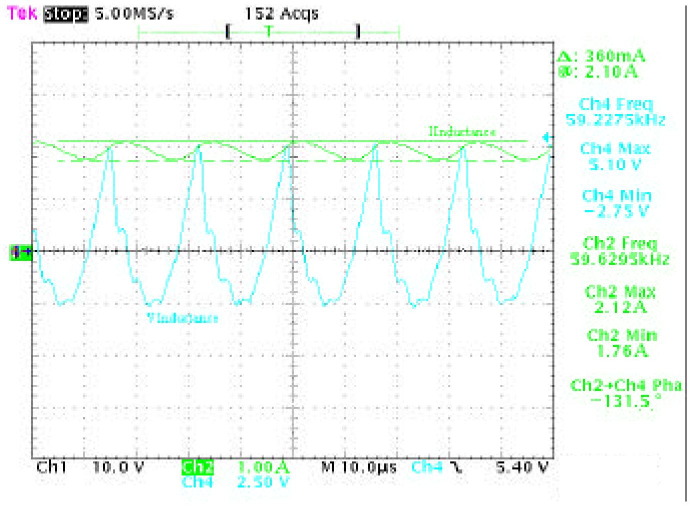


Figure 22: v_{c2} Waveform With Lamp Connected

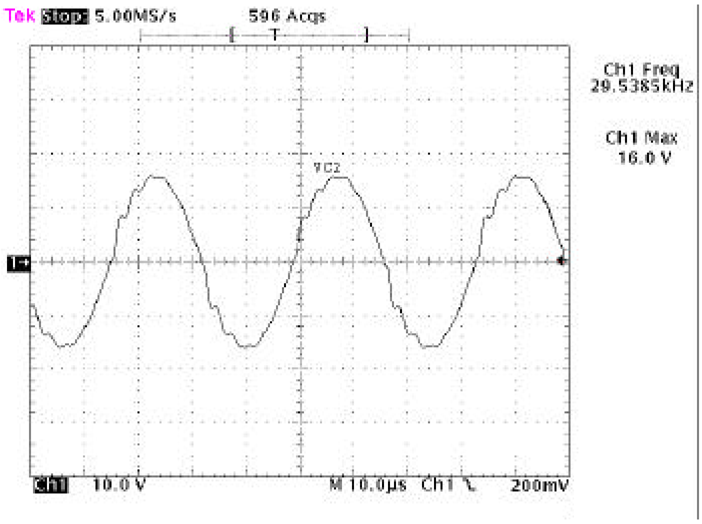


Figure 23: v_{L1} and I Waveforms Without Lamp Connected

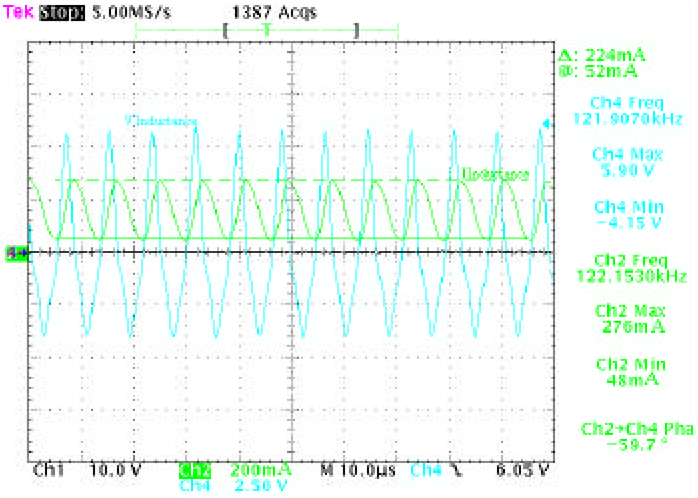
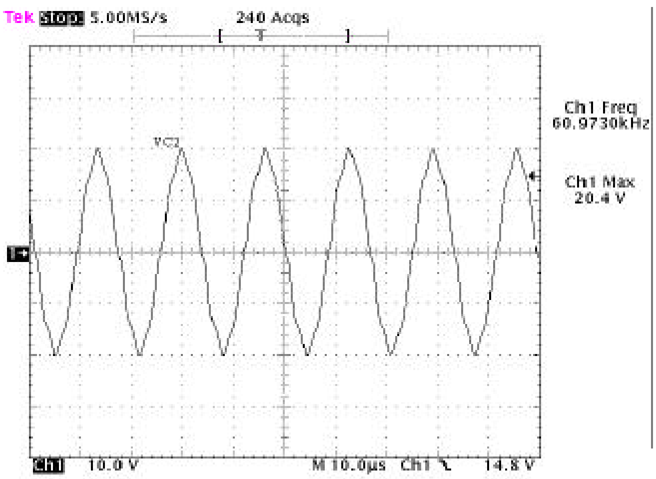


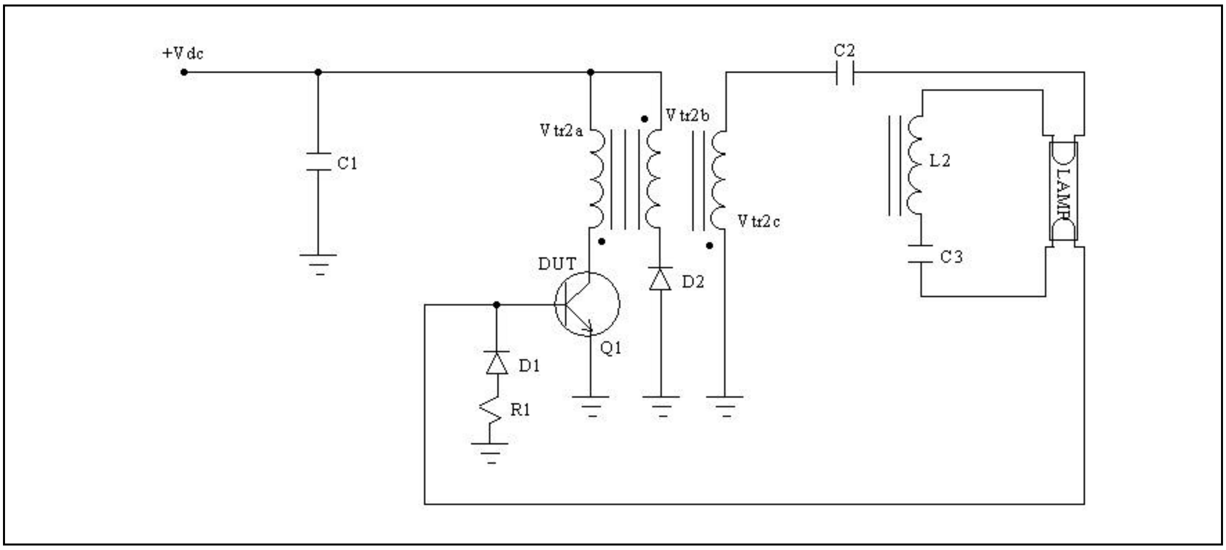
Figure 24: v_{c2} Waveform Without Lamp Connected



8. FORWARD VOLTAGE FED CONVERTER TOPOLOGY

As previously exposed, another topology solution for emergency lighting applications is the FORWARD voltage FED converter solution that uses a transformer with three windings.

Figure 25: FORWARD Voltage FED Converter Schematic Circuit



As shown in the PUSH-PULL current FED converter solution, the components values of capacitors, resistors, and inductors are designed in order to have an operation frequency of around 30 KHz, after the lamp strike and before too, in order to supply the right voltages to the load before and after the lamp strike considering the voltage value of the battery.

When the board is powered, a suitable trigger circuitry, usually consisting of a small signal bipolar transistor and a resistor, enables Q_1 and, immediately after, a current flows through the V_{tr2a} primary winding of the transformer T_{r2} and the same transistor. During the Q_1 on state, the input battery voltage V_{dc} is applied to the V_{tr2a} vices winding and the same voltage appears in the vice of the second winding T_{r2b}, in fact, the coils number of the both windings is the same, but no current flows through T_{r2b} because the diode D_2 is disabled. At the same time, a voltage appears in the winding V_{tr2c} and a current flows through the same winding depending on the output impedance. The V_{tr2c} voltage depends on the input voltage battery V_{dc} by means of the N_2/N_1 rapport.

In particular, V_{tr2} can be written as:

$$V_{tr2c} = V_{dc}\frac{N_2}{N_1} \qquad \textbf{(8.1)}$$

I_{1eff}, the RMS of the primary winding current, can be written as:

$$I_{1eff} = I_{2eff}\frac{N_2}{N_1} \qquad \textbf{(8.2)}$$

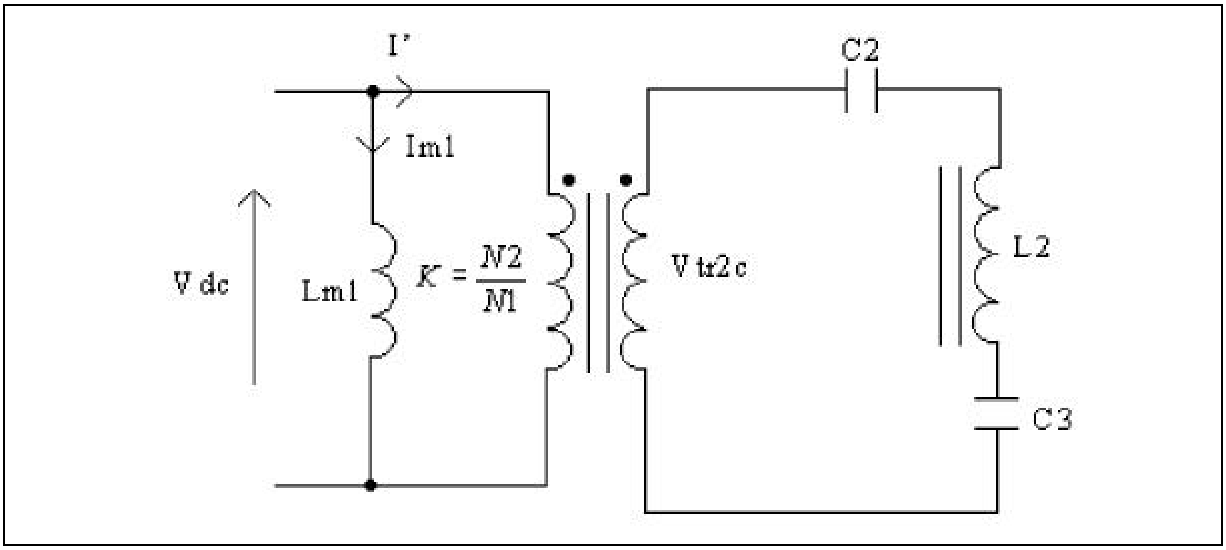
where N_1 and N_2 are the turn numbers of V_{tr2a} and V_{tr2c} respectively, I_{2eff} is the RMS of the lamp current and can be written as:

$$I_{2eff} = \frac{V_{tr2c}}{Z_{eq}} \qquad \textbf{(8.3)}$$

where Z_{eq} is the output impedance.

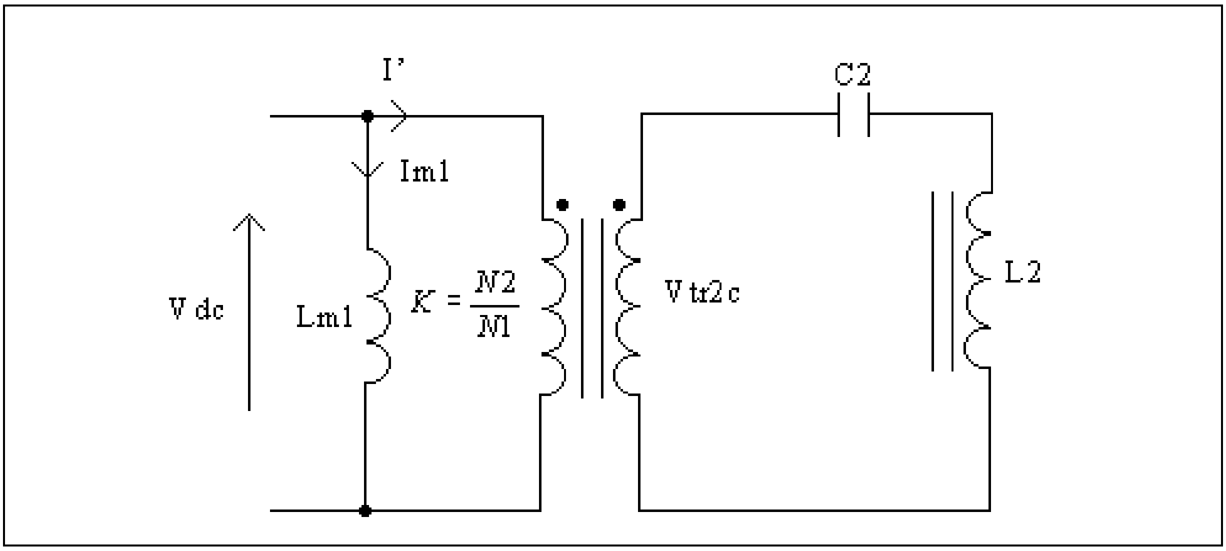
At the beginning, before the lamp strike, the lamp resistance is very high and the equivalent circuit can be showed as in the figure below.

Figure 26: Schematic Circuit Before the Lamp Strikes



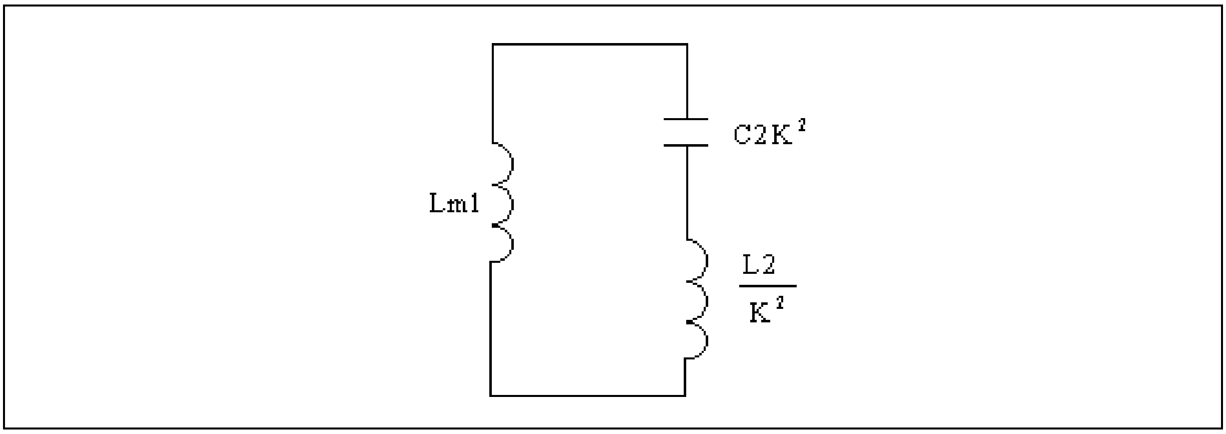
Usually, the capacitor value of C_3 is higher compared to the same of $C_{2,}$ so that the simplified schematic circuit can be showed as in fig. 27.

Figure 27: Simplified Schematic Circuit Before the Lamp Strikes



It is also possible to consider an equivalent circuit as in fig. 28 where the output impedance is transferred in the primary of the transformer.

Figure 28: Equivalent Schematic Circuit Before the Lamp Strikes



The series net K^2C_2-L_2/K^2 can be written as:

$$j\frac{\omega \cdot L_2}{K^2} - j\frac{1}{\omega \cdot K^2 C_2} = j\frac{\omega^2 L_2 C_2 - 1}{\omega \cdot K^2 C_2} \qquad \textbf{(8.4)}$$

The equivalent impedance can be written as:

$$Z_{eq} = j\frac{?^3 L_1 L_2 C_2 - ? \cdot L_1}{?^2 \cdot C_2 (L_1 K^2 + L_2) - 1} \qquad \textbf{(8.5)}$$

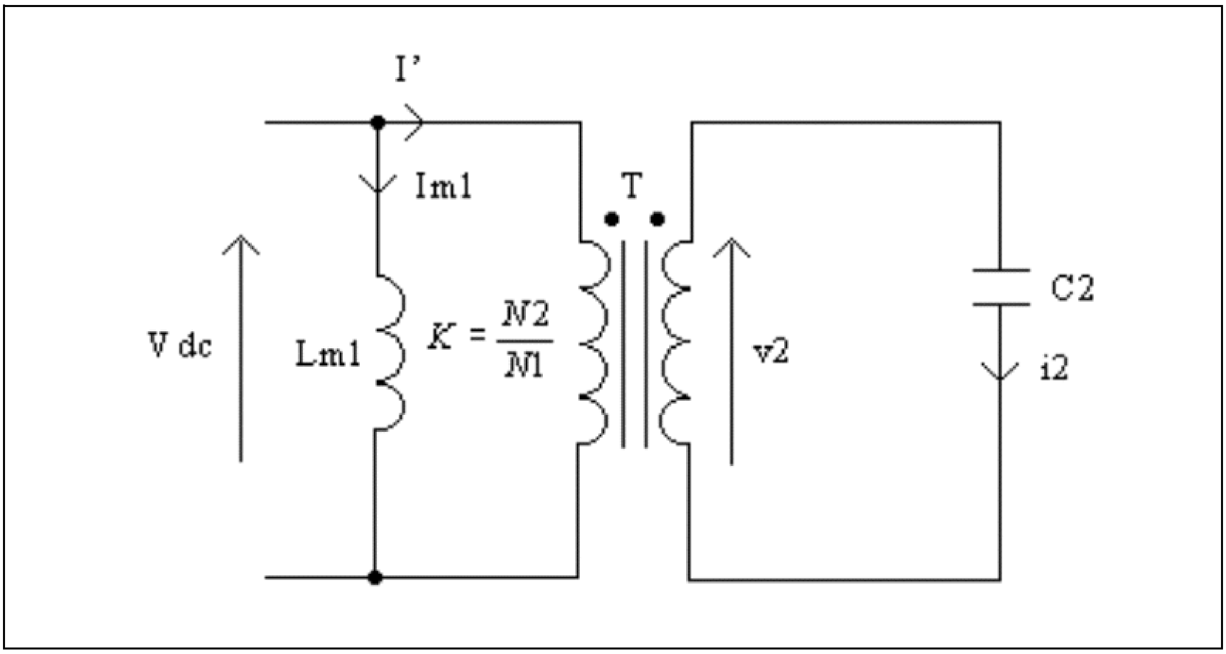
Deriving Z_{eq} from ω it is possible to obtain the resonance frequency.

$$\partial Zeq / \partial \omega = 0 \qquad \textbf{(8.6)}$$

$$\omega^2 = 1/L_2C_2 \Rightarrow f = 1/\ 2 \cdot \pi \sqrt{L_2C_2} \qquad \textbf{(8.7)}$$

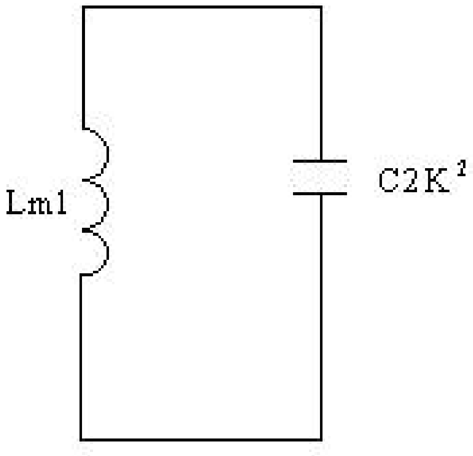
In order to know the resonance frequency after the lamp starts up, it is necessary to consider the schematic circuit with a short circuit condition.

Figure 29: Schematic circuit considering a short circuit condition



Furthermore, it is possible to consider the equivalent schematic circuit as in fig. 30 transferring the output impedance in the primary winding.

Figure 30: Equivalent Schematic Circuit Considering a Short Circuit Condition



The resonance frequency in this condition can be written as:

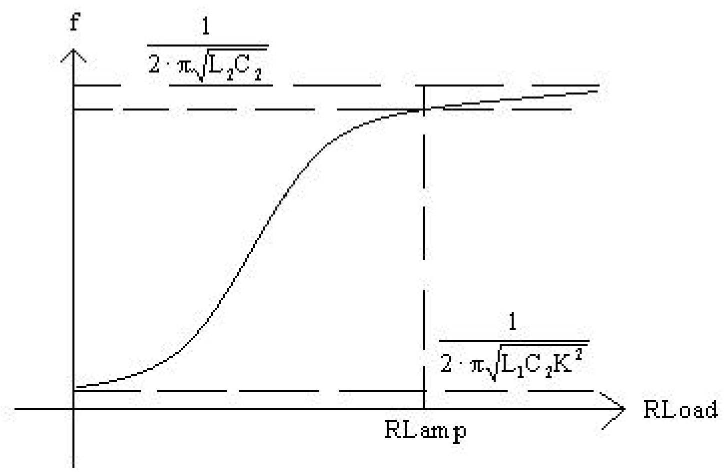
$$?^2 = \frac{1}{L_1C_2K^2} \Rightarrow f = \frac{1}{2 \cdot p\sqrt{L_1C_2K^2}} \qquad \textbf{(8.8)}$$

Usually, the resonance frequency considering the output short circuit condition is lower compared to the resonance frequency before the lamp start-up condition. The resonance frequency after the lamp start-up has got a value which is between the frequency before the lamp start-up and the output short circuit frequency.

$$\frac{1}{2 \cdot p\sqrt{L_1C_2K^2}} < f < \frac{1}{2 \cdot p\sqrt{L_2C_2}} \qquad \textbf{(8.9)}$$

However, after the start-up, the resonance frequency is almost equal to the resonance frequency before the lamp start-up. Fig. 31 shows the resonance frequency after the lamp start-up considering several loads.

Figure 31: Resonance Frequency After the Lamp Start-up vs. Resistance Load



During the positive half-wave, i_2 is the same as I_b because this flows through the base of the power bipolar transistor; instead, during the negative half-wave, when the current inverts its direction, i_2 flows through the net R_1- D_1. At the same time, the voltages across T_{r2a}, T_{r2b} and T_{r2c} windings invert their directions, Q_1 switches off, I_c drops to zero, and V_{ce} increases up to:

$$V_{ce} = 2V_{dc} \qquad \textbf{(8.10)}$$

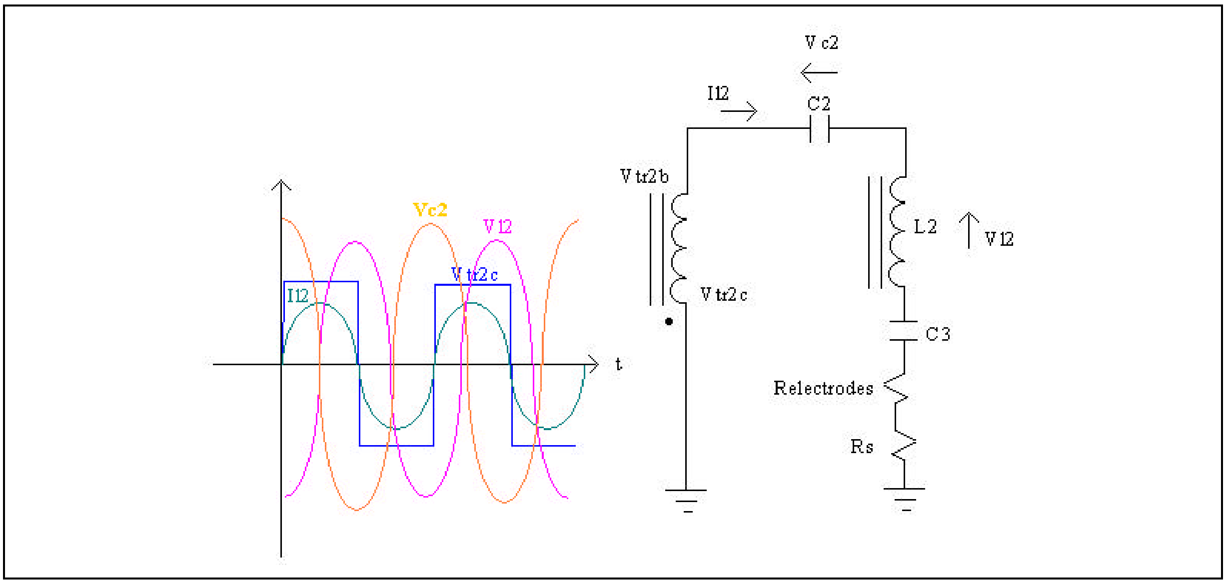
the sum of the input battery voltage V_{dc} and the third winding voltage:

$$V_{tr2a} = V_{dc} \qquad \textbf{(8.11)}$$

However, after Q_1 switches off, an extra-voltage can appear across collector-emitter vices due to a quick decrease in the I_c that flows through the V_{tr2a} winding. In order to avoid this effect, V_{tr2b} enables D_2 and the current passing through it creates a magnetic force N_3I_3 opposed to N_1I_c (N_3 and I_3 are the turn number and the current that flows through T_{r2b}).

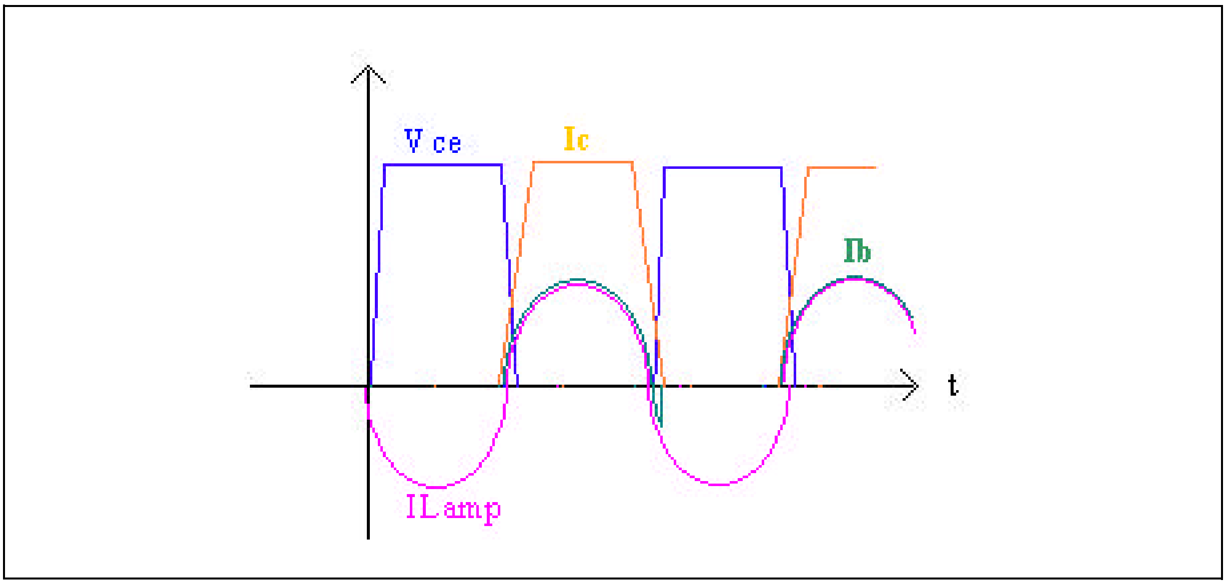
The graph below shows the output schematic circuit and the theoretical waveforms before the lamp strike.

Figure 32: Output Schematic Circuit Before the Lamp Strike and Theoretical Waveforms of the Main Output Electrical Parameter



The voltage across V_{tr2c} generates an i_2 having the same phase. v_{c2} (the voltage across C_2) is +90° out-phase compared to the i_2, while v_{L2} (the voltage across L_2) is -90° out-phase compared to i_2.
The graph below shows the I_b, V_{ce} and I_c theoretical waveforms of Q_1.

Figure 33: Q_1 Theoretical Waveformsr

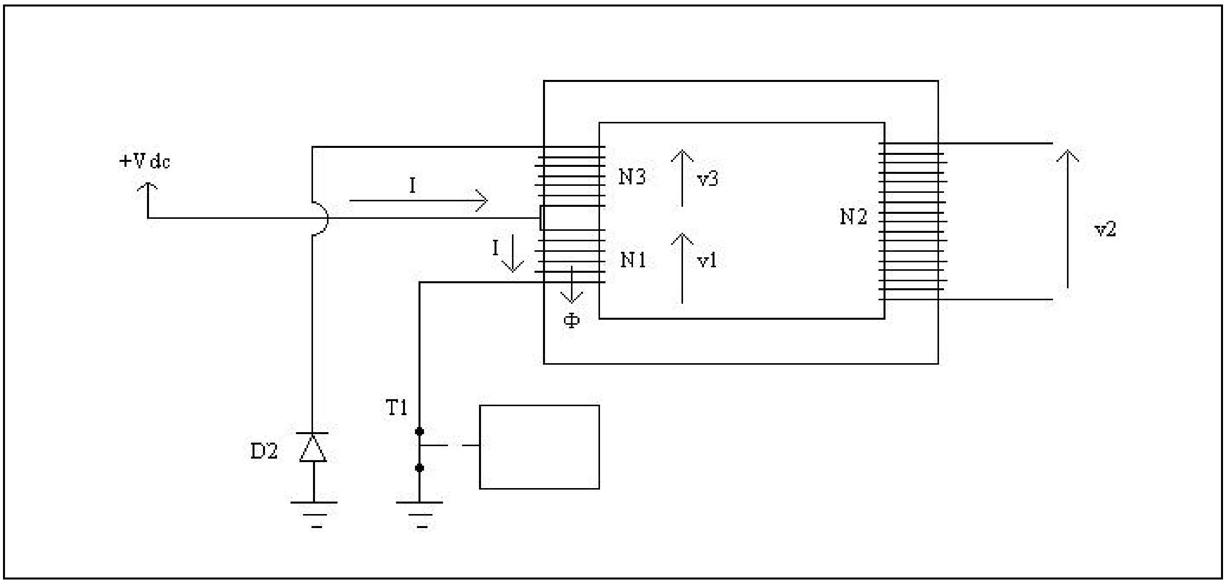


Note: a circuit similar to the Forward Voltage FED Converter shown in Fig. 25 is also described in the Italian Patent N.1285621 in the name of Beghelli S.p.A.

9. TRANSFORMER DESCRIPTION

The transformer has three windings. The primary winding vices are connected to the input voltage and the other vice to the collector of Q_1, while the secondary winding vices are connected to the load. The third winding vices are connected between the input voltage and the cathode of D_2. The schematic of the transformer can be shown as in fig. 34.

Figure 34: Transformer Detailr



The FORWARD converter works during the Q_1 on state (in this graph the switch T_1 is the equivalent component of Q_1). In such operation condition, current flows through the turn N_1 and a flux is generated.

$$\Phi = \frac{N_1 I}{\Re} \qquad \textbf{(9.1)}$$

This flux flows through the magnetic core of the transformer creating a link respectively with the turns N_2 and N_3 and it generates the voltages v_2 and v_3.

$$v_3 = -N_3 \frac{\Delta\Phi}{\Delta t} \qquad \textbf{(9.2)}$$

$$v_2 = -N_2 \frac{\Delta\Phi}{\Delta t} \qquad \textbf{(9.3)}$$

However, during the Q_1 on state, no current flows through the third winding because the diode D_2 is disabled, while output current flows through the secondary winding and the load. The voltage across the primary winding, equal to V_{dc}, can be written as:

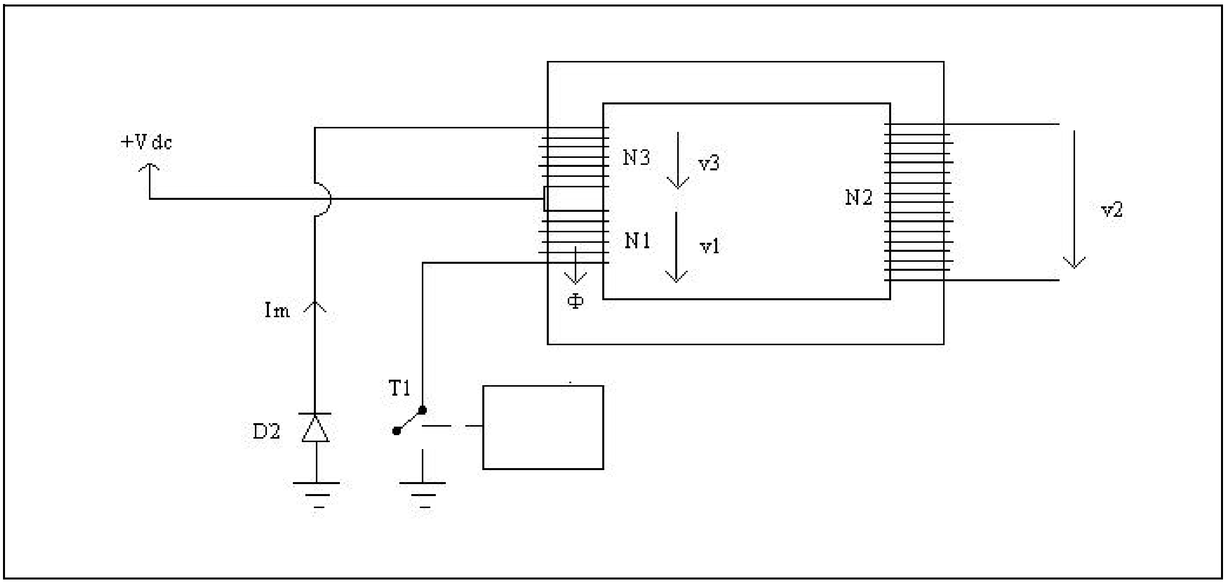
$$v_1 = V_{dc} = -L_{m1} \frac{\Delta I}{t_{on}} \qquad \textbf{(9.4)}$$

L_{m1} is the inductance of the primary winding and t_{on} is the time during the Q_1 on state.
When the secondary winding current inverts its direction, Q_1 switches off, the current 'I' suddenly

becomes zero and an overvoltage appears across the turn N_1. However, during the Q_1 switching off, a magnetic force appears across the third winding opposing the primary winding magnetic force and avoiding the extra voltage on Q1 (see fig. 35).

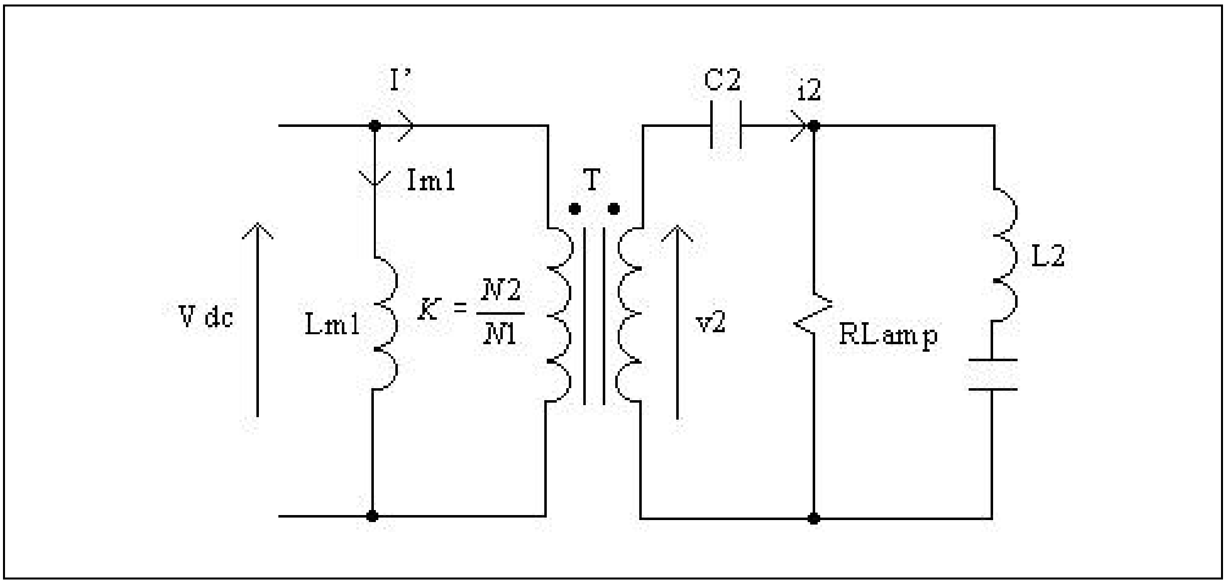
$$N_1 I = N_3 I_3 \quad \textbf{(9.5)}$$

Figure 35: Transformer Detail When T_1 Switches on



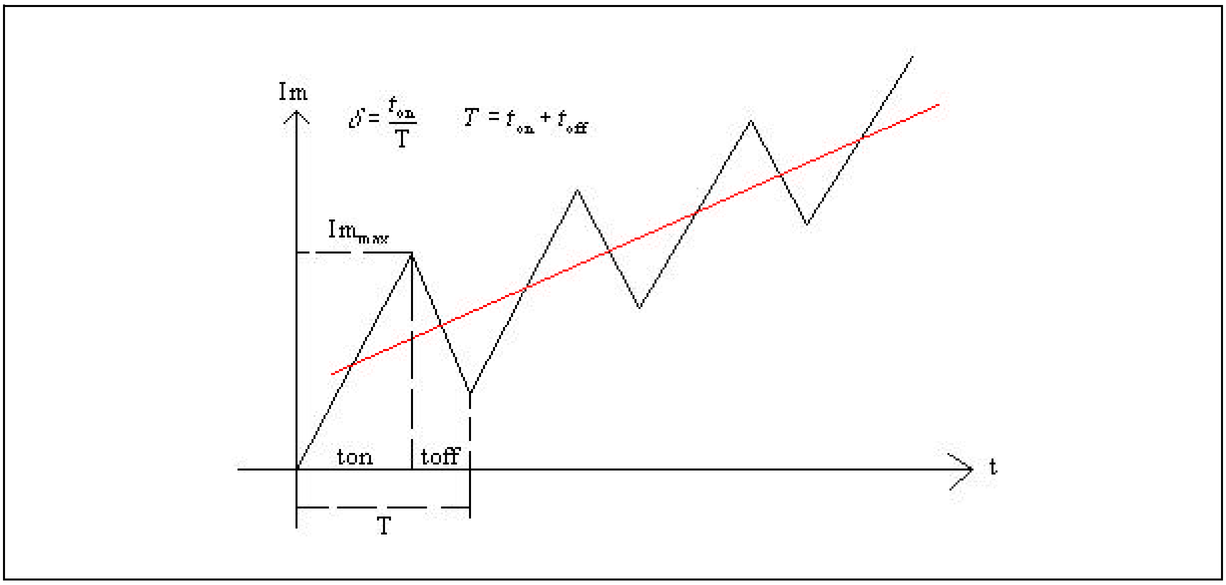
It is important to highlight that the current 'I' is the sum of the currents I_m and I' (see fig. 36). The extra voltage on Q_1 is due to I_m.

Figure 36: Detail of the Transformer Highlighting I_{m1} and I'



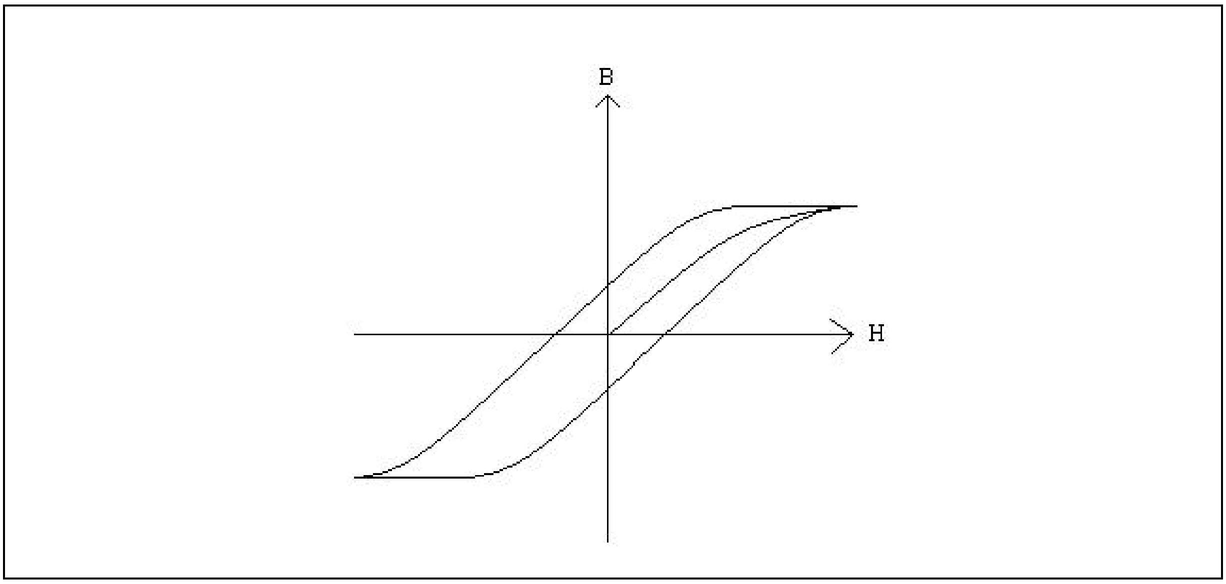
In the FORWARD converter it is important to consider the right turn N_3 and the right duty cycle, it is possible to have an increasing current I_m and a saturation of the transformer core might occur.

Figure 37: Theoretical Behavior of I_m Involving the Transformer Core Saturation



In fact, the B-H characteristic, where B is the induction vector and H is the magnetic vector, can be represented as in fig. 38.

Figure 38: Theoretical B-H characteristic



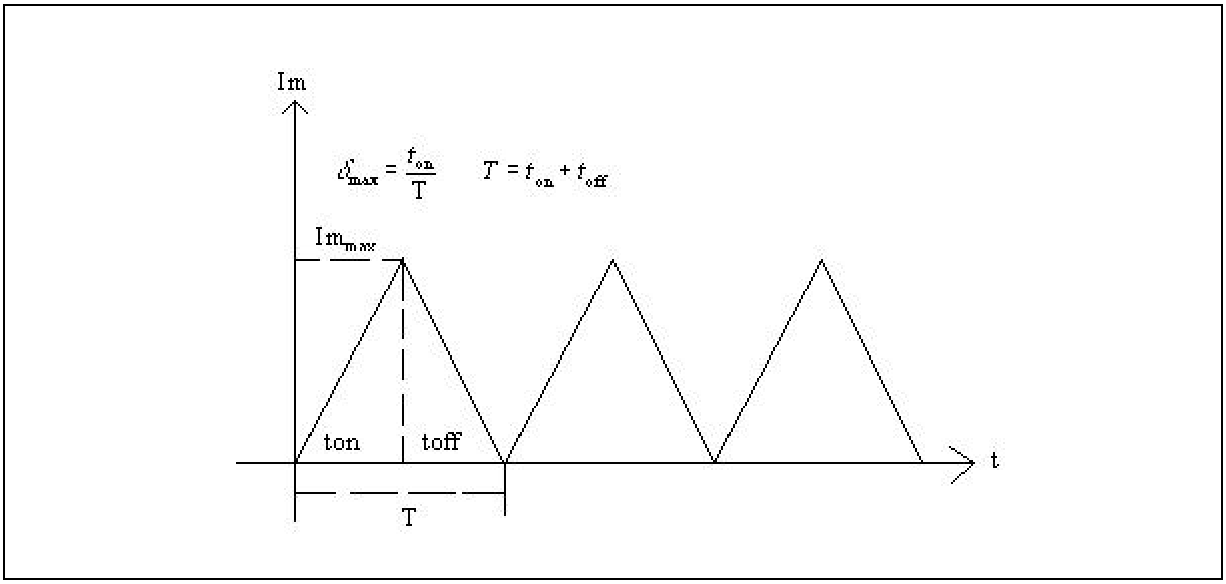
H can be written as:

$$H = \frac{N_1 I}{l} \qquad \textbf{(9.6)}$$

When 'I' increases then also H increases, and if H overcomes an established value even if H keeps increasing, B remains constant.

In order to avoid the core saturation, it is necessary to choose a right N_3 and duty cycle. The right limit case is shown in fig. 39.

Figure 39: Theoretical Behavior of I_m Considering the Right Limit Case



In this condition, v_1 and v_3 can be written as:

$$v_1 = v_3 = V_{dc} = -N_1 \frac{\Delta\Phi}{t_{on}} = -N_3 \frac{\Delta\Phi}{t_{off}} \qquad \textbf{(9.7)}$$

$$\frac{N_1}{t_{on}} = \frac{N_3}{t_{off}} \Rightarrow \frac{t_{on}}{N_1} = \frac{t_{off}}{N_3} = \frac{T}{N_3} - \frac{t_{on}}{N_3} \qquad \textbf{(9.8)}$$

$$\delta = \frac{t_{on}}{T} = \frac{1}{1 + \frac{N_3}{N_1}} \qquad \textbf{(9.9)}$$

Usually, N_1 and N_3 are equal so that the minimum duty cycle that avoids the saturation of the core is:

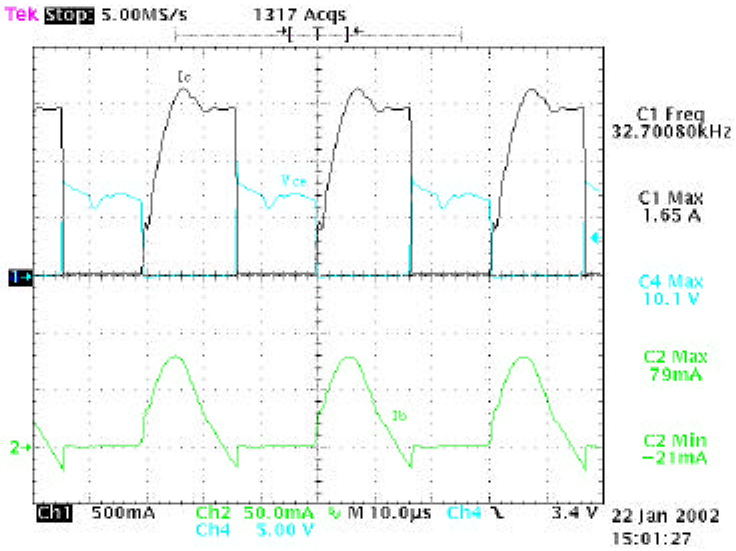
$$\delta = \frac{1}{2} \qquad \textbf{(9.10)}$$

The Emergency Lamp applications using the FORWARD topology work in resonance mode and their duty cycle is, obviously, 0.5.

10. EXAMPLE OF AN EMERGENCY LAMP APPLICATION WITH FORWARD TOPOLOGY

The following example analyzes a real emergency lamp application with FORWARD voltage FED converter topology using 8W lamp and powered with 3.6 V_{dc} and using also STSA851 (when the application is powered with the battery the output power on the lamp is around 30% of the nominal power lamp). In the graph below the steady state of Q_1, after the lamp strike, is showed.

Figure 40: Steady State of STSA851



The following graphs show the turn-off and the turn-on switch modes respectively.

Figure 41: Turn-off of STSA851

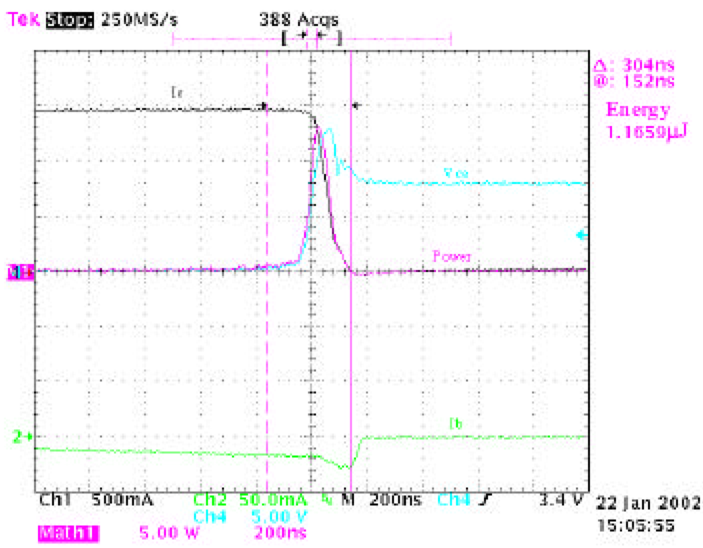
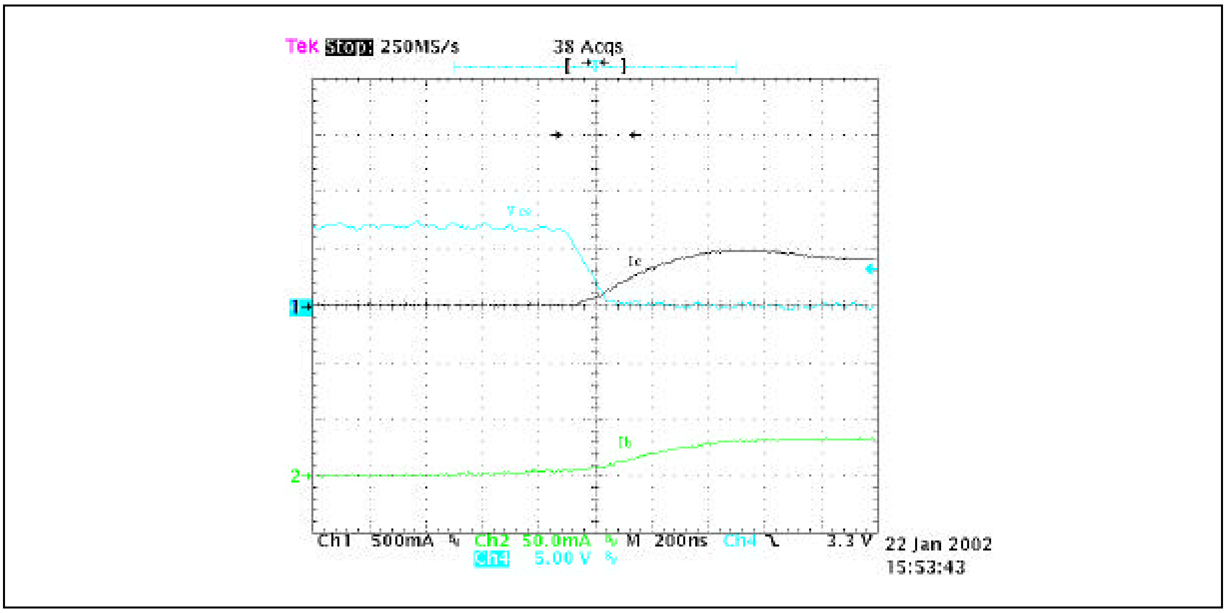
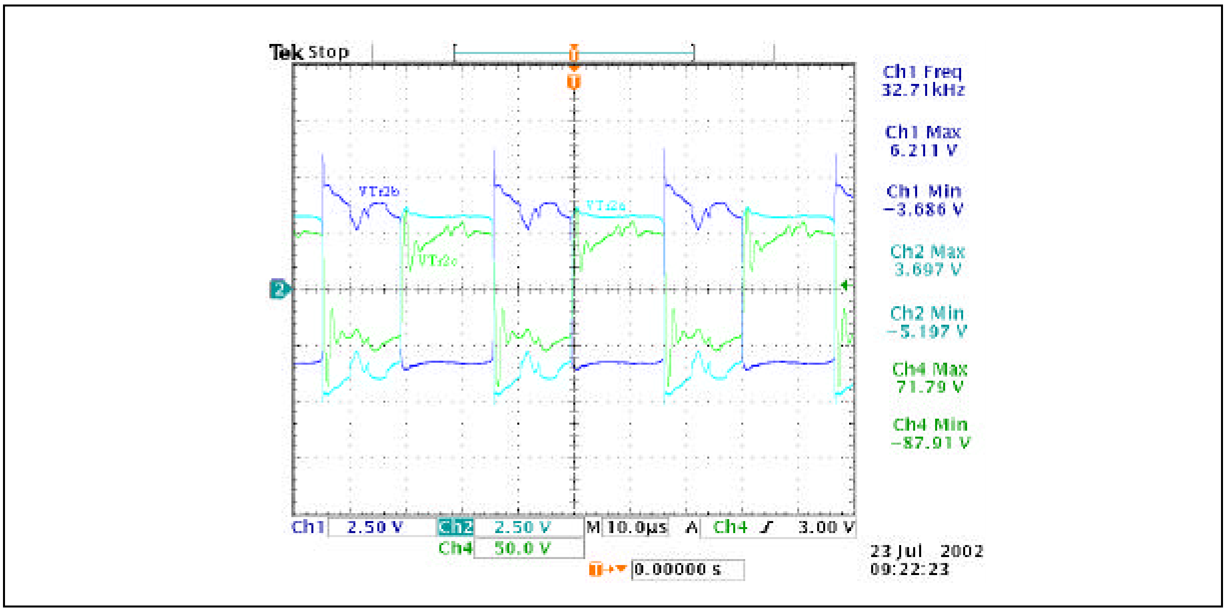


Figure 42: Turn-on of STSA8511



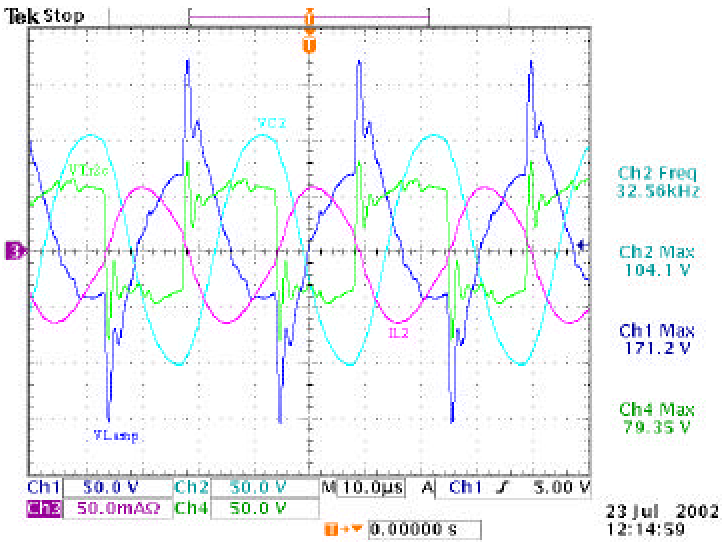
The graph below shows the waveforms of V_{tr2a}, V_{tr2b} and V_{tr2c} after the lamp strike.

Figure 43: Voltages on V_{tr2a}, V_{tr2b} and V_{tr2c} Windings1



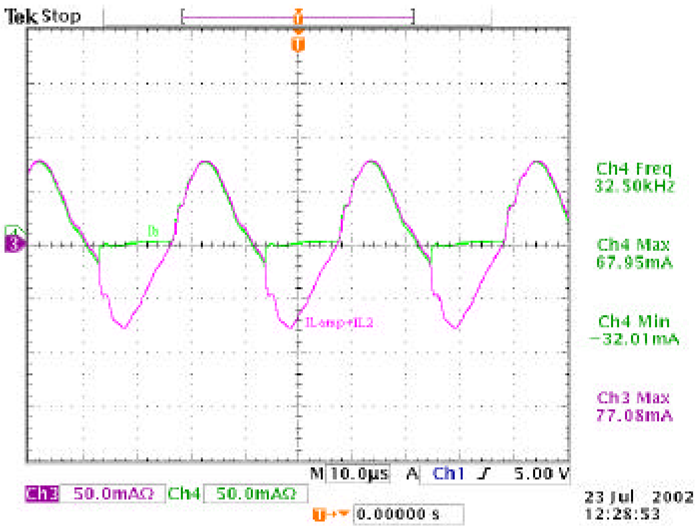
During Q_1 on state, the voltage on V_{tr2a} is imposed by the battery (Vdc=3.6 V) so that no noise is observed, instead, during Q_1 off state noise is highlighted on V_{tr2a} and V_{tr2b}. The next graph shows the waveforms of the electrical parameters considering the output impedance after the lamp strike.

Figure 44: V_{tr2c}, V_{c2}, V_{L2} and i_2 Waveforms1



The graph below shows the lamp current and the current I_b waveforms.

Figure 45: i_2 and I_b Waveforms



The graphs below show the steady state of Q_1 and the electrical parameters waveforms of the output stage before the lamp strike.

Figure 46: Steady State of STSA851 Before the Lamp Strike

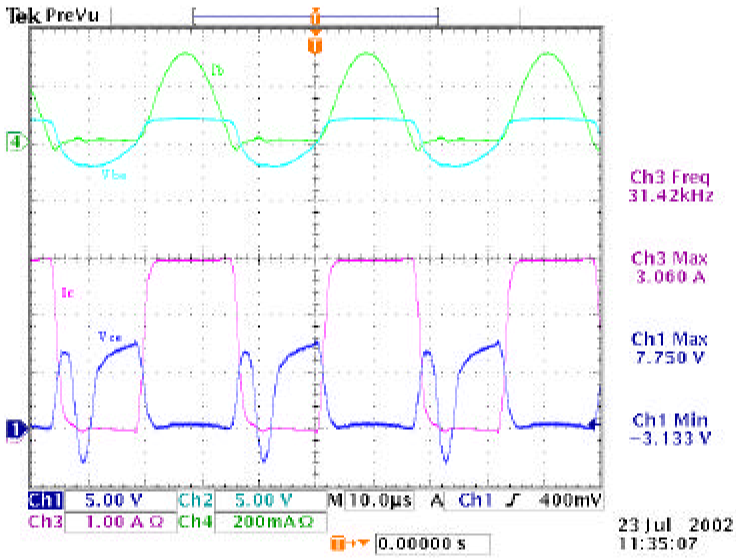
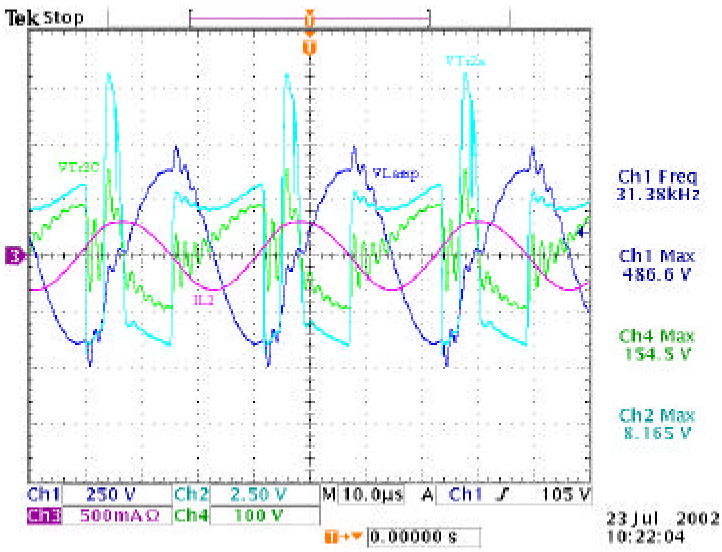


Figure 47: I_2, V_{tr2c}, V_{tr2a} and V_{Lamp} Waveforms Before the Lamp Strike



11. CONCLUSIONS

Today the Emergency Lighting applications are used in all public places and private homes due to new safety rules. Such applications use fluorescent tubes and are powered with 3.6 Vdc or 6 Vdc input voltages. Usually, the output power can be 8W or 24W but, sometimes, the Emergency Lamp applications can be used also to drive 58W fluorescent tubes. In this last case, however, the applications supply only around 10-15% to the nominal lamp power. The main topologies used are PUSH-PULL current FED and FORWARD. In the first solution, the frequency before the lamp strike is about 60 KHz, while after the lamp strike is about 30 KHz, the current Ic is about 2.5A, Ibon around 80mA and Vcemax around 15V considering an input voltage of 6Vdc. Using the second topology solution and a 3,6Vdc input voltage, the current Ic is about 1,7A, Vcemax 10V, Ibon around 70mA and the operation frequency, before and after the lamp strike, is around 30 Khz. However, considering both topology solutions, the power bipolar device STSA851 can be used because the voltages and currents values are inside the SOA area.