Self-oscillating inverter with bipolar transistors

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Abstract. The paper presents a self-oscillating inverter manufactured with bipolar transistors that supplies a high-amplitude alternating voltage to a fluorescent tube with a burned filament. The inverter is supplied from a low voltage accumulator that can be charged from a photovoltaic panel through a voltage regulator.

1. Introduction
In electric systems, converters are static equipment (electric plants), which through semiconductor devices, enable the conversion of electric energy between two or more systems by modifying the current, the frequency, the voltage, the number of phases, etc.

Hence, there are two types of converters, ones that convert the electric energy between AC and DC systems and others that convert between systems of the same kind only changing the electric parameters (amplitude, voltage, frequency, etc.).

Static converters use only two distinct states of conduction in the power-electronics elements that compose them: open (saturated) or cut-off. This mode of operation results in lower power dissipation on the devices in comparison to linear electronic circuits, which use intermediate states too. Converter efficiency is between 0.85 - 0.95%.

A fluorescent lamp operating at a frequency of 50 Hz goes out twice for every period of the supply voltage, this being when the supply voltage passes through zero, causing the flicker phenomenon (stroboscopic phenomenon) with a frequency of 100 Hz. This phenomenon has unpleasant effects, sometimes leading to work accidents.

If the lamp operates at high frequencies, a continuous light is produced since the response time of the discharge is too low to allow the lamp to extinguish [1].

Electronic ballast comprises of a full-wave rectifier, a self-oscillating inverter, with field effect transistors or bipolar transistors, and inductive ballast, for the high frequency determined by the inverter. In addition, the self-oscillating inverter may be provided with different correction and protection circuits [2].

The supply voltage is directly applied or, for higher power, through a power factor correction circuit.

Modern lamps include a filter to minimize the harmonic currents, in order to comply with EMC regulations [1].
2. Problem Formulation

2.1. Powering fluorescent tubes with DC powered electronic ballasts

The discharge lamp is characterized by a static characteristic $U_L=f(I_L)$ with a negative (falling) slope, having a negative dynamic resistance:

$$r_{dL} = \frac{dU_L}{dI_L} < 0$$  \hspace{1cm} (1)

Stable operating discharge lamps must be supplied from a source of alternating current with high impedance output.

The sum of the output impedance of the power source, which is positive, and the negative dynamic resistance must be positive in order to satisfy the condition of stability in operating when a constant current flows through the lamp.

The electronic inverters that work as class D (resonating) voltage switches have the resistive load of the lamp $r_{dl}$. They are a class of high-frequency circuits with high efficiency and are regarded as appropriate sources for these types of applications [2].

To ensure ignition and maintain the discharge of the lamp, DC energy needs to be transferred to the secondary winding of the transformer.

The power supply must have a high output reactance so that the sum of the positive source impedance and the negative reactance of the lamp (as the lamp voltage increases, the current flowing through the lamp drops) is positive, in order to ensure stable operation of the lamp [2].

A power supply installation for a fluorescent lamp through a “flyback” type self-oscillating inverter with isolation is shown in Figure 1.

The $Q_1$ transistor becomes conductive through a circuit consisting of a resistance $R_1$ and the 8-5 winding. The changes in the current amplitude through the 7-6 winding of the $T_1$ transformer induces voltage in the 2-1 secondary winding, which is connected to the lamp through the capacitor $C$ and the 8-5 feedback winding, causing a negative base voltage to the $Q_1$ transistor. The $Q_1$ transistor is blocked and the current through the 7-6 winding becomes void. This cycle resumes when there is a positive voltage in the base of the $Q_1$ transistor. The frequency of the oscillations is determined by the capacitor $C_1$ and the inductance of the 8-5 winding.

![Figure 1. A “flyback” type self-oscillating inverter with isolation](image)

The electric pulses, which control the $Q_1$ power transistor, are made with the integrated circuit $\beta E 555$ connected as an astable circuit. The frequency of the pulses is modifiable within the 5 to 15 kHz range with the help of the variable resistor $R_v$. By using transistor $Q_1$ in switch mode, variations will appear in the amplitude of the current flowing through the primary winding 1-2 of the $T_1$ step-up transformer. The voltage induced in the 3-5 winding is applied to the fluorescent lamp.
One of the connections commonly used as electronic ballast for discharge lamps is the push-pull connection (Figure 2) with a resonant circuit, which includes the resistance of the lamp, as a dynamic load [3]. The AC power is supplied to the dynamic resistor [4].

The Cc capacitor (of high capacity) is used to cut off the DC component of the current. The DC component of the current would cause the saturation of the magnetic core, destroying the T1 and T2 power transistors.

The voltage on the Cc capacitor is approximately equal to \( U_a / 2 \). The two static switches \((T_1, T_2)\) ensure that current flows through the parallel resonant circuit \( L-C_p-r_d \) [5].

![Figure 2. Electronic balast in a „push-pull” connection](image)

Antiparallel diodes enable the circulation of negative currents, but the collector-emitter voltage, in this case, will remain at \(-0.7\text{÷}1.5\text{V}\). The transistors are driven with base-emitter voltages \((U_{BE1}, U_{BE2})\), which are square waves (rectangular with a 50\% duty cycle). The attack voltage of the resonant circuit is rectangular \((U_{CE1}, U_{CE2})\) with values between \(0 \text{ ÷ } U_a\) (Figure 3) [6].

![Figure 3. The operation mode diagram of the push-pull circuit](image)
The analysis of the circuit in operation mode is simplified assuming a sinusoidal current flow through L-C\_p-r\_d. This approximation is indeed valid if the quality factor of the load circuit satisfies the following condition:

\[
Q_L = \omega_0 \cdot C_p \cdot r_d = \frac{r_d}{\omega_0 \cdot L} = \frac{r_d}{Z_0} > 2.5 \tag{2}
\]

where:

\[
\omega_0 = \frac{1}{\sqrt{L \cdot C_p}} \quad \text{- the angular frequency for natural resonance for the un-dampened circuit.}
\]

\[
Z_0 = \frac{L}{\omega_0 \cdot C_p} = \sqrt{\frac{L}{C_p}} \quad \text{- the impedance of the resonant circuit.}
\]

In this case, a non-linear load can be precisely modeled by linear impedance. Results show that, for a frequency higher than the resonance frequency, the output voltage and the output power of the inverter increase with load resistance (at \( f \geq f_{\text{resonant}} \), the parallel inverter can function very well during the open-circuit test output and cannot function at all during the short-circuit test). Therefore, the inverter can generate a high enough voltage to ignite the lamp and limit the current after the ignition of the discharge lamp.

The output power, voltage and current through the load can be controlled by changing the frequency of operation, which can be achieved by the continuous modification of the light output from 100% to 10%.

If the \( Q_L < 2.5 \) waveform of the current through the resonant circuit is not sinusoidal, it is more difficult to obtain an exact analytical solution.

Due to the delay in the entry into conduction and especially due to the delay of coming out of conduction, the duty cycle of the control signal (\( U_{\text{BE1}}, U_{\text{BE2}} \)) must be less than 50% (\( \Delta t \) - a few \( \mu s \)) to avoid short-circuiting the source.

Each transistor is turned on when the switching current is negative and it passes through the diode. The transistor can be turned off through its Base-Emitter voltage while it can only be turned on by turning off the opposing transistor. Hence only the cut-off is directly controllable through base biasing.

If \( T_1 \) is turned off by the \( U_{\text{BE1}} \) voltage, the \( U_{\text{CE1}} \) voltage increases, causing the \( U_{\text{CE2}} \) voltage to decrease. When the \( U_{\text{CE2}} \) voltage reaches -0.7V, diode D\_2 is turned on and the current is diverted through diode D\_2. Then \( T_3 \) is turned on, so the energy stored in the L coil causes the negative alternation of current i, etc. When \( f = f_0 \), the amplitude of the current and voltage on L-Cp become dangerously high, so high that it can destroy transistors and resonant components. Operating at this frequency is, therefore, to be avoided.

For \( f < f_0 \) the phase shift is negative \( \psi < 0 \), the resonant circuit represents a capacitive load (the current through the coil leads the fundamental of the voltage). This is not an advantageous operating mode (diodes are cut-off for large di/dt and cause current spikes through \( T_1 \) and \( T_2 \)).

For \( f > f_0 \), the phase shift is positive \( \psi > 0 \), the resonant circuit represents an inductive load (the current lags the fundamental voltage and thus the switching current is negative after entering into conduction and positive before cut-off).

The new generation of electronic ballasts is based on MOS-FET static power switches because they have the following advantages:

- the ability to switch high currents at frequencies of a few MHz;
- reduced switching losses;
- very low power consumption for control signals;
- the ability to withstand high reverse drain-source voltages.
The new requirements of the standards in this domain have encouraged the design of ballasts having a high power factor, diminished harmonic content, a high efficiency (electronic ballasts more efficient by 25% compared to the classic ones), increased reliability and lifetime.

An electronic ballast, with two MOS-FET static power switches in push-pull configuration (half bridge connection), and a self-oscillating type inverter having a control transformer are shown in Figure 4. Current flows through the primary winding of the Tr transformer from the lamp circuit and operates at the resonant frequency given by \( L-C_{2} \omega_{0} \).[3]

The disadvantages of this circuit are:
- the oscillations are not damped;
- transistor \( T_{2} \) must be pulsed by the DIAC D tied to the gate circuit.

The oscillations are maintained. A high frequency square wave (30 to 80 kHz) excites the resonant circuit \( L-C_{2} \). The sinusoidal voltage across \( C_{2} \) is amplified by \( Q_{L} \) or during resonance, it being able to produce a magnitude sufficient to ignite the lamp [3]. Then the fluorescent lamp functions at a higher frequency than the resonance frequency and provides illumination without pulsation (flicker) [7].

This circuit represented a "standard configuration" for electronic ballasts for several years, yet it has many disadvantages: no self-ignition, bad switching (control using signals with slowly increasing edges causing relatively high switching losses, the negative portion of the gate-drain voltage waveform is not usable), laborious construction, too expensive for large-scale manufacture, inappropriate for varying brightness output, etc. These disadvantages have been fully resolved using drivers - monolithic integrated circuits for controlling two MOS-FET/IGBT power transistors in half bridge configuration [8].

![Figure 4. Electronic ballast with 2 MOSFET switches](image)

![Figure 5. Conventional switching regulator](image)
Widely used as a replacement for incandescent lamps, discharge lamps have better efficacy and reduce electricity consumption. In spite of these advantages, discharge lamps have a low power factor, high total harmonic distortion, both with electronic and electromagnetic ballast. So the impact of these systems on the quality of power supply is of primary interest.

The diagram of a conventional switching regulator (Figure 5) contains a very small capacitor C\textsubscript{1}, the network frequency being filtered by a capacitor with high capacity C\textsubscript{3}. The output voltage is controlled by the duty cycle of the switching frequency Q\textsubscript{1} and presents a decent power factor correction and harmonic distortion correction. The circuit is of major complexity, small size and high cost.

2.2 Self-oscillating inverter with bipolar transistors used for powering fluorescent lamps with burned filaments

This inverter is also known as a Royer inverter.

2.2.1 The DC-AC function. The main component of this inverter model is the Royer oscillator. This is a very simple self-oscillating circuit, being made, in accordance with the diagram in Figure 6, out of NPN bipolar transistors, Q\textsubscript{1} and Q\textsubscript{2}, capacitor C\textsubscript{1} connected to the collectors of the transistors and step-up transformer T\textsubscript{1} [9].

The step-up transformer is composed of two identical sections (3-4, 4-5); a feedback coil (8-7) and a secondary coil (2-6), on which the fluorescent lamps with burned filaments are connected serially with capacitor C\textsubscript{2}.

Supply voltage +V\textsubscript{cc} is applied to its center tap from the voltage generator circuit PWM (PWM = Pulse Width Modulation, it is a pulse width modulated signal, modulated in duration). The transformer’s role is to ensure oscillation through the feedback coil and to increase the size of the impulses in the primary coil, ensuring a high voltage in the secondary winding required for the lamp to ignite [10].

When the supply voltage +V\textsubscript{cc} is connected through resistors R\textsubscript{1} and R\textsubscript{2}, the bases of Q\textsubscript{1} and Q\textsubscript{2} are polarized. They open and establish a current through the two primary windings of the transformer, current whose intensity varies rapidly from zero to maximum value. Due to these rapid variations in current, an induction voltage, with the positive potential in the base of transistor Q\textsubscript{1} and the negative potential in the base of transistor Q\textsubscript{2} will appear in the feedback coil. This voltage will cut off transistor Q\textsubscript{2}, will maintain transistor Q\textsubscript{1} on and will allow charging the capacitor C\textsubscript{1} through the following path: +V\textsubscript{cc}, winding center tap (4) - Q\textsubscript{2} collector, C\textsubscript{2}, Q\textsubcript{1} collector, Q\textsubscript{1} emitter, inductance, ground. Now, Q\textsubscript{2} is blocked.

The current pulse resulting from the rapid charging of the capacitor maintains the inductive voltage through the feedback coil, of the polarities specified above, in such a way as to keep Q\textsubscript{1} on and Q\textsubscript{2} off.

Figure 6. Self-oscillating inverter with bipolar transistors used to power fluorescent lamps with burned filaments
When capacitor $C_1$ is fully charged, the current will have the reverse change through the primary winding, decreasing rapidly from the maximum value to zero. This current pulse in the winding will induce a voltage of reverse polarity sided as described above: the plus in $Q_1$’s base and the minus in $Q_2$’s base.

As a result, $Q_1$ is cut-off and $Q_2$ turns on, allowing the loading and unloading of $C_1$ according to the following route: + $V_{cc}$, winding center tap (4)-collector $Q_1$, $C_1$, collector $Q_2$, emitter $Q_2$, inductance, ground. Now, $Q_1$ is blocked.

After unloading $C_1$ and loading $C_1$ with voltage of opposite polarity, $Q_2$ turns off and $Q_1$ turns on, unloading and loading $C_1$ again and the cycle repeats.

Thus, by turning off and on the two transistors, $Q_1$ and $Q_2$, capacitor $C_1$ is charged and discharged continuously through the two primary windings of the step-up transformer, generating a high voltage in the secondary winding, required to ignite the lights.

The voltage obtained in the secondary winding is a sinusoidal AC voltage, as is the supply voltage, thus chosen for the correct operation of fluorescent lamps [11].

This increases the life of the lamp. It is mandatory to use a sinusoidal voltage to control them; otherwise the resulting ions will accumulate at one end of the tube causing irreparable damage to it.

2.2.2 Adjusting the lamp lighting. The amount of light emitted by a fluorescent lamp depends on the voltage that is supplied to it and, if this voltage is low, the lamp can reach the extinction-ignition threshold, resulting in a flickering; a tremor of its brightness. This is the main disadvantage of adjusting lamp brightness by applying a varying voltage.

A variation of brightness of the lamp is adjustable through the application of a voltage of variable value; therefore, a low voltage would lead to a low light and a high one to maximum illumination [12].

Due to the characteristics of fluorescent lamps, they do not suddenly go out when power failure occurs. They have certain inertia, so they continue to produce light for short intervals of time, even without power.

This feature is used to control the brightness of the lamps through the intermittent supply method: multiple voltage pulses with constant amplitude. So, the second option of controlling the brightness of the lamps is the intermittent supply method.

A constant voltage is supplied to the lamp, and then the power is disconnected for a short time.

The supply and the break periods depend on the value of the brightness adjustment by the user, so that their average value would lead to a desired brightness [13]. Large break periods translate into lower brightness and large power periods result in maximum brightness.

2.3 PWM voltage generating circuit

PWM voltage generating circuits can be used to adjust the brightness of fluorescent lamps [14]. Such a signal can be seen in figure 7.

a) The PWM waveform for adjusting the brightness from maximum to minimum

b) The PWM waveform for adjusting the brightness from minimum to maximum

**Figure 7.** The PWM waveform for adjusting the brightness

The controller presented in Figure 8 supplies a signal as shown above (Figure 7), a signal whose duration (width) depends on the voltage control of the brightness [5].
The PWM signal supplied is positive and it is applied to the gate of the Q₁ transistor (IRF630 - n channel), which turns on putting the emitters of transistors Q₂ and Q₃ (2SC3039) to ground through an inductance:

$$L_1 = \frac{330 \mu H}{IA}$$  \hspace{1cm} (3)

The Royer oscillator is supplied, hence it starts to generate oscillations, the lamp being powered. The oscillator will be powered only during the positive pulse[15]. When the PWM signal becomes zero, the transistor Q₁ is cut-off, the oscillator and the lamp are no longer supplied through transistor Q₁[10].

A self-induced voltage appears in the inductance L₁, of opposite sign to the original voltage, and rectified by diode D₁. The assembly is further supplied by a lower voltage until the next positive pulse, when transistor Q₁ is opened again; the oscillator will again be powered etc. What follows is an intermittent supply of the lamp; the average voltage pulse sets the brightness level.

Figure 8. The flow diagram of the PWM circuit

Figure 9. PWM circuit diagram + self-oscillating inverter
The role of the potentiometer $R_3$ in Figures 8 and 9 is to adjust the brightness of the fluorescent lamp. When the cursor of the potentiometer $R_3$ moves to the right (towards diode $D_3$), the brightness of the fluorescent lamp is minimal, and when the cursor of the potentiometer is moved to the left (towards diode $D_4$), the brightness of the fluorescent lamp is at a maximum.

3. Problem Solutions

For autonomous sources of electric energy gas discharge lamps and LEDs are used.

In the case of the self-oscillating inverter with bipolar transistors used to power the fluorescent lamps with burned filaments, the current consumed by these varies depending on the duty cycle, i.e. the brightness.

Hence, for a duty cycle of:
- 10% of current consumption is approximately 100mA;
- 50% power consumption is about 820mA;
- 100% power consumption is about 1.76 A. This is illustrated in the following figure (Figure 10).
e) $\alpha = 1, i = 1760mA$

**Figure 10.** The relationship between the current and the duty cycle ($\alpha$) 

### 4. Conclusions

Using burned filament fluorescent lamps helps increase their life span as well as economizes on energy. This is shown through the brightness value and then relationship of the current and the duty cycle.

This application also presents the possibility that the duty cycle be controlled by a light sensor and so, automatically adjusts the level of brightness according to exterior requests.

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