HIGH-EFFICIENCY HIGH-FREQUENCY INVERTER FOR SILENT DISCHARGE LOAD

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***Abstract*—This paper presents a high-frequency voltage source-fed series resonant inverter with capacitive load for high-voltage application. The circuit takes profit of the transformer parasitic components to operate above the resonance, ensuring high efficiency. A supervisory strategy verifies if the converter operates in the inductive region. If not, a control procedure increases the frequency to get again soft-commutation and signalizes the fault. The converter was implemented to feed a silent-discharge ozone-generator tube. This application needs high voltage source to produce ozone. Results of a 6 kV, 300 VA single-phase inverter, and 800 VA three-phase inverter are presented.**

***Index Terms*—Soft-commutation, resonant converter, ozonizer.**

I. Introduction

Ozone gas is a powerful oxidizing substance, which leaves no residues harmful to the global environment. This characteristic allows using ozone for treatment of water, deodorization, disinfection, etc. In the case of water treatment, especially in swimming pools, chlorine – the traditional way – can be problematic in some circumstances. The reactions that naturally occur with chlorine in water can produce some dangerous organic compounds known as disinfection byproducts. The most common are trihalomethanes and haloacetic acids [1]. Due to the carcinogenic potential of these compounds, alternatives ways for water treatment are of interest.

A variety of applications of ozone are hindered primarily because of its low total efficient ozone gas generation and its relatively high cost. It is very important to improve the overall efficiency of the ozonizer and reduce the cost of the device.

An efficient way to produce ozone is the silent-discharge tube [2], [3]. Electrically this device behaves as a two series connected capacitors, as shown in Fig. 1.

This paper describes a resonant type inverter designed to feed the ozonizer using a high-voltage transformer. Soft-commutation ensures high-efficiency, while some protection strategies guarantee the inverter operation in the correct frequency range even in case of load parameters changes.

II. Silent-Discharge Ozonizer

A silent-discharge ozone-generation has a capacitive behavior. The Fig. 1 shows an electrical model of the device. For simulation purposes, simpler electrical models can be chosen according the necessity. For example, a fixed capacitance could be used to study the inverter commutation process. This considered model uses two capacitances in series. C_g is constant and represents the capacitance due to the glass insulation between the electrodes. C_a is the capacitance due to the air gap, in which the applied high-voltage produces the electrical discharge. When the silent discharge occurs, the terminal voltage of this capacitance is maintained constant voltage. This effect is represented by the voltage source V_z. This voltage depends on the air gap and, in our case, is about 5 kV.

The effective capacitances depend on the device geometry. For our applications, typical values are in the range on tens to hundreds of picofarads, depending on the expected ozone production.

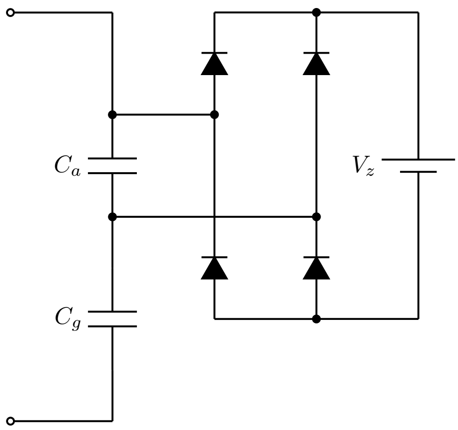


Fig. 1. Circuito equivalente da célula ozonizadora.

To achieve the necessary high voltage, a transformer is used. The equivalent lumped parameters circuit of the transformer is shown in Fig. 2, including a series resistance R_s, a series inductance L_{leak} – leakage inductance –, a parallel resistance R_p a parallel inductance L_{mag} – magnetizing inductance –, and capacitance $C_{p(winding)}$ – windings capacitance.

As typical of high-voltage transformers, the HV side has a large winding capacitance. Reflecting the secondary capacitance to the primary side, the value becomes n^2 larger, where $n \gg 1$ is the turns ratio. The result is a very large equivalent capacitance, as will be shown in the next sections.

Also the leakage inductance is large due to the necessary isolation between the windings.

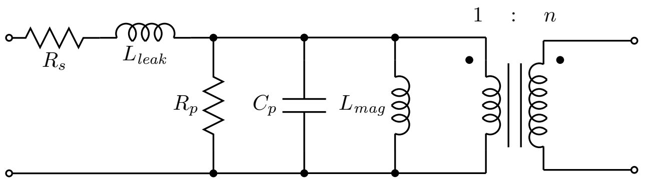


Fig. 2. Lumped parameters high-voltage transformer model.

The impedance module of the transformer, neglecting the resistances, can be evaluated by this equation:

$$|Z_{in}| = \frac{\omega(L_{leak} + L_{mag}) - \omega^3 L_{leak} L_{mag} C_p}{1 - \omega^2 L_{mag} C_p}. \qquad (1)$$

The Eq. 1 was used to calculate the parameters of the transformer as discussed later. The voltage gain module is:

$$|Gain| = \frac{1}{1 + \frac{L_{leak}}{L_{mag}} - \omega^2 L_{leak} C_p} \cdot n, \qquad (2)$$

where n is the turn ratio.

Fig. 3 shows the basic electrical schematics of the power circuit. For low power applications – up to few hundreds of Watts – it consists of a single-phase full-bridge diode rectifier with capacitive filter. A NTC limits the inrush current while a resistor discharges the capacitor when the converter is off.

The full-bridge inverter produces a squared-wave high-frequency output to feed the HV transformer primary. Typical frequency is the range of thousands of Hertz.

The high-frequency operation helps to increase the ozone production. The selected frequency depends on the load parameters and the desired output power. In spite of the inverter output be a square wave, due to the transformer behavior, the output voltage at the secondary is, in practice, sinusoidal, as will be shown [4], [5], [6].

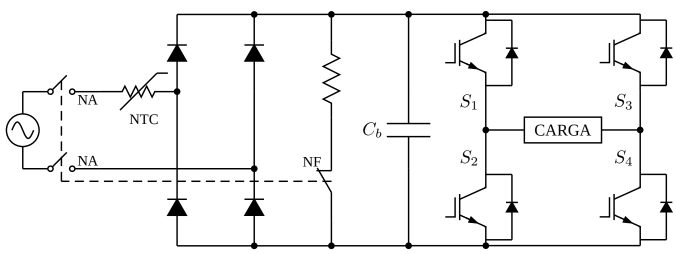


Fig. 3. Power circuit.

A higher power version of this circuit could be developed connecting several silent-discharge ozone-generator tubes in parallel. This method has the disadvantage of changing the resonance frequency every modification of the load. A three-phase version was developed in order to use all three branches of the device. Fig. 4 shows the topology used in the three-phase version. As the same capacitor was used in both versions, a three-phase rectifier was necessary in order to diminish the voltage ripple in the DC link as the output power becomes about three times higer.

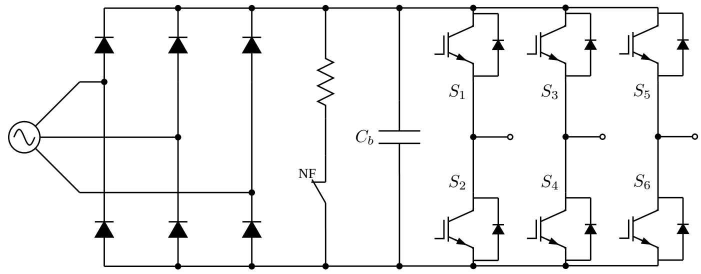


Fig. 4. Three-phase power circuit.

III. High-Voltage Parameters Evaluation

The Fig. 5 shows the transformer 1 impedance, as seen from the primary side. This response includes the load. The load effect is, essentially, to increase the parallel capacitance. This experiment was done with a low-voltage input signal, so no discharge occurs on the ozonizer.

The input voltage and input current were measured to obtain the module of the input impedance. To calculate the parameters value it was used the model of Fig. 2.

In the low-frequency range – around 100 Hz – the capacitor C_p can be neglected due to its high impedance. So, the equivalent impedance at this range is equal to L_{leak} plus L_{mag}.

Using similar analysis, at the high-frequency range – around 10 kHz –, as the capacitor presents very low impedance, que resulting equivalent impedance only depends on the leakage inductance.

The first resonance, around 0.9 kHz, is determined by C_p and L_{mag} and gives the maximum input impedance. Up to this frequency the impedance presents an inductive behavior. Above this frequency the circuit has a capacitive behavior, with the current leading the voltage. The second resonance – around 2 kHz – is between L_{leak} and C_p and determines the minimum input impedance. Above such frequency the circuit reassumes the inductive behavior.

The Table I shows the estimated parameters of three tested transformers. The magnetizing inductance of the transformer 1 is significantly different, probably because the device has been overloaded during some tests and the overheating has produced some damage on the epoxy insulation. $C_{p(total)}$ indicates the capacitance including the capacitance of the ozonizer, reflected to the primary side. $C_{p(winding)}$ indicates only the capacitance of the secondary windings, reflected to the primary side.

The Fig. 6 shows the transformer 1 voltage gain curve. For low frequency the ratio is given by the turns-ratio – about 20. Next to the frequency of the series resonance, there is a sudden voltage gain increase. This effect happens because the minimum impedance corresponds to the maximum current that gives the maximum voltage on the equivalent capacitance and, as a consequence, on the magnetizing inductance, which reflects such high voltage to the secondary side.

Since these measurements were made with low-voltage sinusoidal wave generator, one can expect some deviation when applying the nominal voltage.

Before the voltage on C_a reaches V_z the equivalent load

TABLE I
TRANSFORMERS PARAMETERS

	L_{leak} [mH]	L_{mag} [mH]	$C_{p(total)}$ [nF]	$C_{p(winding)}$ [nF]
Transformer 1	28.22	62.84	142.51	22
Transformer 2	25.64	285	129.55	16
Transformer 3	26.55	328	125.36	16

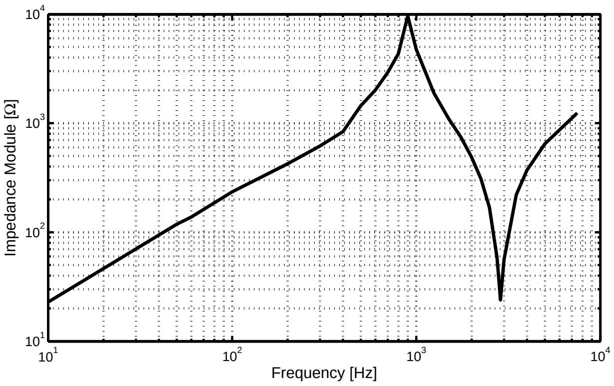


Fig. 5. Module of the transformer 1 input impedance, with load connected.

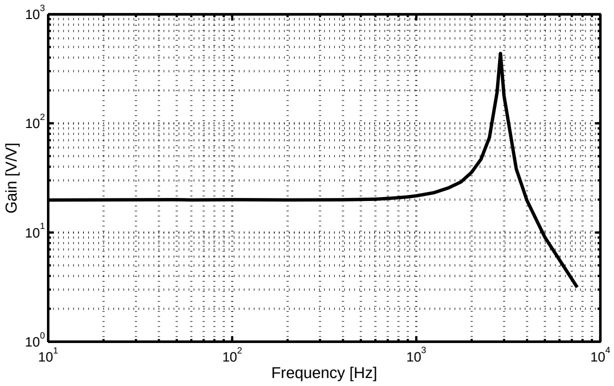


Fig. 6. Voltage gain x frequency.

capacitance is $C_a \cdot C_g/(C_a + C_g)$. As the voltage increases, and the discharge occurs, the voltage on the capacitor C_a becomes limited at V_z. Then the equivalent capacitance increases to C_g. This higher capacitance reduces the resonance frequencies.

This load variation occurs along each switching cycle – if the discharge takes place – and the analysis of the circuit operation must be done considering linear circuits whose parameters changes with the variables – the voltage on C_a.

From the operation point of view, the important result is that the frequency of the maximum voltage gain is lower than the one shown in Fig. 6, and that the inverter load presents an inductive behavior above this frequency.

IV. Implementation of the Power Supply

A. Frequency range identification

The first step for designing the electronic circuitry is to obtain the transformer and load parameters, what is done according to the previous description. Such results determine the frequency range operation.

B. Power converters

The power topology is shown in Fig. 3. For 220 V/60 Hz mains voltage, the average DC inverter voltage is about 300 V. The H-bridge produces a square-wave voltage to be applied to the transformer primary side. To avoid unbalanced operation of the transformer, a series capacitor is connected between the inverter output and the transformer, in order to block any DC voltage produced by the inverter.

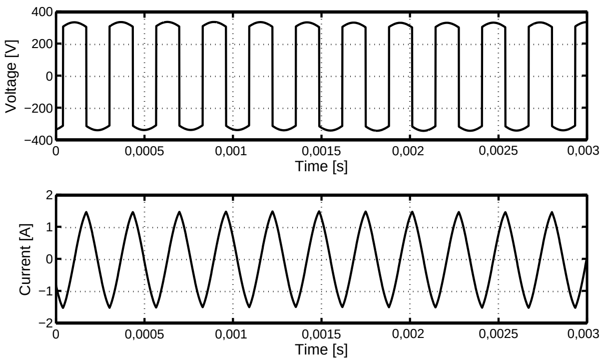
This capacitance selection must consider the following aspects: low impedance compared to the transformer impedance at the operation frequency range; low series resistance to limit power loss; low voltage drop to not excessively increase the voltage applied to the transformer.

C. Soft-commutation

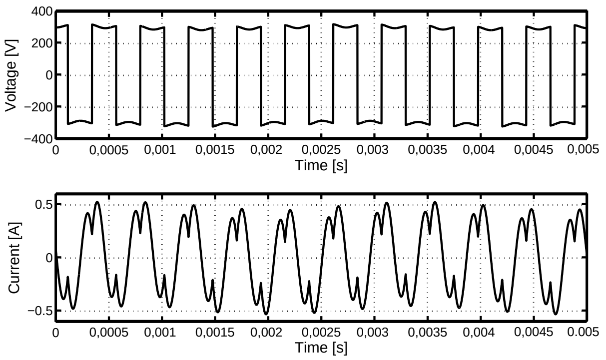
To obtain soft-commutation it is necessary that the circuit operates above the series resonance frequency. The soft-commutation occurs during the turning-on period. The parasitic capacitance and some additional external capacitor helps to decrease turn-off switching losses because the voltage increases slowly, allowing a pseudo-ZVS turn-off. In this range the current is lagging the voltage. Due to the inductive characteristic, when the transistors are turned-off, before the other transistor pair effectively conducts, the current flows through the anti-parallel diodes, discharging the transistor capacitance and zeroing the switching losses. Fig. 7 shows the simulated waveforms for three operation modes.

It would be possible to get the same voltage gain bellow the resonance, where the converter operates in the capacitive region. In this case, the transistor turns-off under zero current, since the current leads the voltage waveform. On the other hand, the turning-on process is dissipative and, differently of the inductive region, there is no a simple solution for reducing these losses.

If the converter operates bellow the parallel resonance, again the load response is inductive. However, in this range the transformer core should be bigger to support the higher magnetic flux. Additionally, the low-frequency square-wave would produce harmonic components that would excite the resonances, distorting the current and making difficult to control the output power. The low-frequency oscillation is due a resonance between the decoupling capacitor and the total transformer inductance.



(a)



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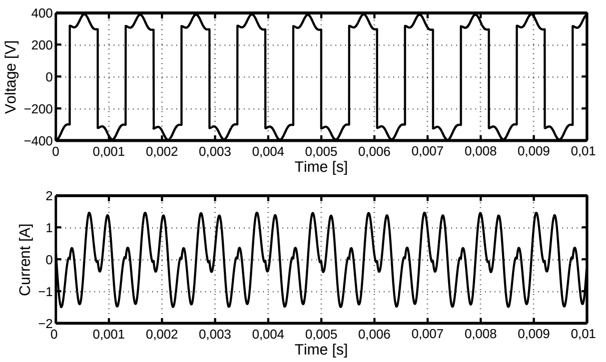


(c)

Fig. 7. Simulated inverter waveforms: (a) above series resonance frequency; (b) capacitive region – between parallel and series resonance; (c) bellow parallel resonance.

D. Digital controller

A microcontroller PIC 16F872 controls of the system. The microcontroller commands the switches in order to set the working frequency and also performs external interfaces and protection actions.

To get the maximum power, the converter operates close to the series resonance frequency. The allowed frequency range is previously set in the microcontroller program. In case of load parameters variations – including the transformer and the ozonizer –, it may occur the resonance frequency increases – due to capacitance reduction – and the circuit enters in the capacitive region.

To avoid such undesirable operation mode, the microcontroller verifies the state of the power transistor collector-to-emitter voltage before turn it on. In the inductive region, this voltage must be low due to the diode conduction. If the control detects a high voltage – what means the converter is in the capacitive region – it increases the switching frequency and signalizes this fact. Probably it will be necessary to replace the ozonizer.

Fig. 8 shows the circuit connected between the collector and the emitter of the transistor S_2 (see Fig. 3) used to detect the voltage.

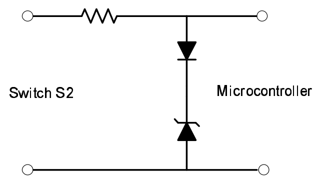


Fig. 8. Sensor circuit to identify soft-commutation.

The software was changed to use the same microcontroler PIC 16F872 to control the three-phase version. The deviation of the power among the transformers should be small, and if possible null in order to keep the power distribution equalized. Any small deviation in the transformer parameter can make a deviation in power.

E. Three-phase converter

The three-phase version should have a different strategy to control the output power. The power should be aproximately the same in the three transformers. The exact power measurement requires a current measurement. The current measurement analysis can show if the current is lagging or leading the voltage and the sensor circuit to identify soft-commutation is not needed. This current phase detection allows setting the switching frequency. If a small deviation occurs in the transformers parameters, there would be different powers in each one transformer. The frequency would be set in order to get one transformer with power above the nominal power, one transformer with nominal power and the last one with under the nominal power. The voltage could be adjusted in order to reduce the power in the transformer with power above the nominal power and raise the power in the other transformer. Within certain limits, the three transformers could work in the same power.

The primary winding is connected in delta in order to get a higher rms voltage in each winding. The secondary is connected in wye in order to get a common point to be grounded as shown in Fig. 9.

V. Experimental Results

A 200 W prototype was constructed. The single-phase inverter uses two branches of a three-phase inverter power module. The other branch can be used to realize an input rectifier with power factor correction if necessary.

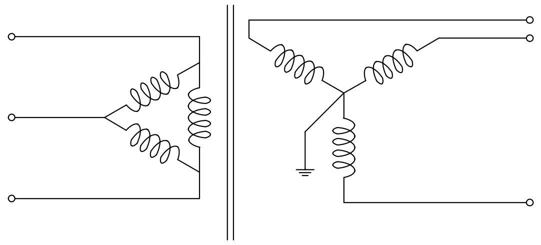


Fig. 9. Transformer connection – primary side connected in delta and secondary side connected in grounded wye.

The Fig. 10 shows the voltage, current and instantaneous power in the primary side of the transformer. The voltage applied to the transformer is approximately 350 V. This higher value is due to the effect of the decoupling series capacitor (2 μF) that adds an additional voltage to the DC side inverter voltage. The average power is 168 W and the working frequency is 2.73 kHz. The load has an inductive behavior characterized by the lagging current, that is the condition for obtaining soft-switching.

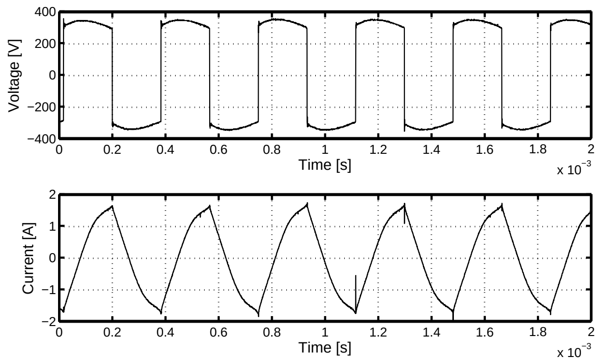


Fig. 10. Transformer input waveforms – voltage and current.

The Fig. 11 shows the output voltage – the voltage applied to the silent-discharge ozone-generator. The peak voltage is 8.5 kV. The waveform distortion indicates the region in which the discharges occur, beginning when the voltage reaches about 4 kV.

Fig. 12 shows the ratio between the switching frequency and the output power. The linear variation is very useful for controlling the ozone production with different loads.

The equipment can receive a remote reference (input 4-20 mA) or operate in the local mode, adjusting the power by changing the frequency.

A soft-start procedure is implemented. All the times the converter is turned-on, the microcontroller starts at the maximum frequency, decreasing up to the last value used before, or stopping this variation if a new reference is detected.

The Fig. 13 shows the output power vesus the voltage in the DC link. Also in this case there is a linear variation, what is convenient for controlling the output power.

The Fig. 14 shows the voltage, current and instantaneous power in the three-phase version. The transformers operate

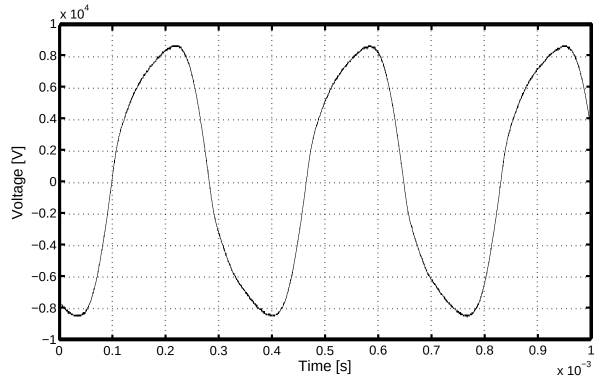


Fig. 11. Load voltage.

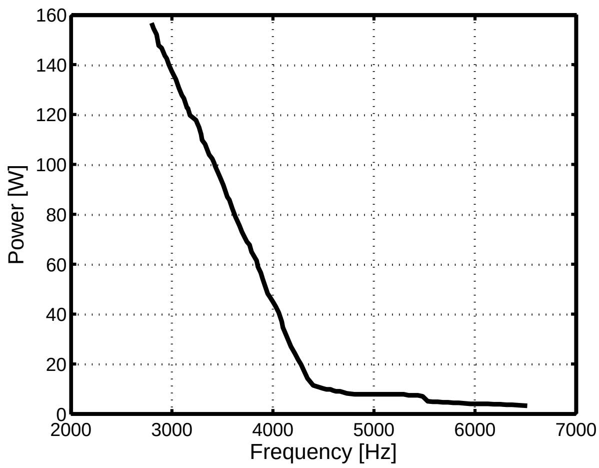


Fig. 12. Output power x frequency.

in the same frequency and the same rms voltage. The parameters deviations explains the different power. This power deviation can be – within limits – compensated. The voltage applied in the transformer 1 could be lowered, and at the same time, raised the transformer 3 voltage adjusting the respective voltage, what means unbalancing the three-phase voltage of the primary side but equalizing the output power. This implementation is under development.

VI. Conclusions

This paper has presented an H-bridge inverter feeding high-voltage loads. The converter operates as a series resonant inverter above the resonant frequency, what ensures soft-commutation for all switches. The parasitic parameters of the high-voltage transformer, the leakage inductance and winding capacitance, together with the load, determine the main resonance frequencies.

As the load parameters can vary along the time, a supervisory circuit, implemented with the microcontroller PIC 16F872, verifies the soft-commutation by measuring the collector-to-emitter voltage before turning-on the transistor. If the voltage is low, it means the anti-parallel diode conducts

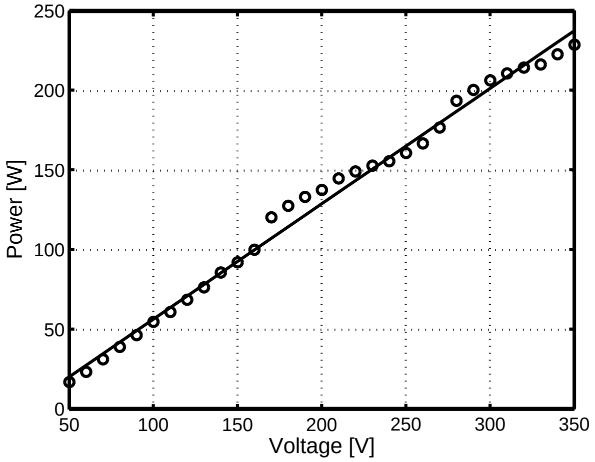
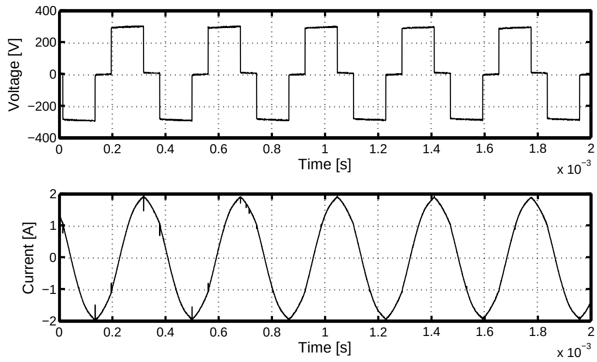
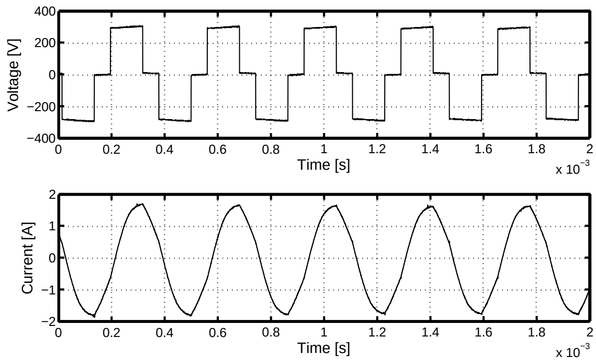


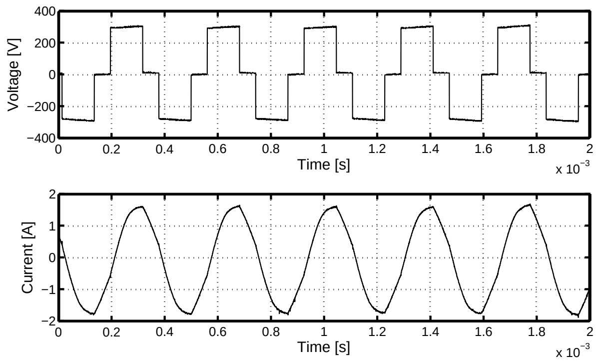
Fig. 13. Output power x voltage at 2.729 kHz.



(a) Transformer 1.



(b) Transformer 2.



(c) Transformer 3.

Fig. 14. Transformers input waveforms – voltage and current.

before the transistor, resulting soft-commutation. If the voltage is high, the control circuit increases the switching frequency and signalizes the occurrence.

The converter presents a linear ratio between the frequency and the output power, what makes easy to adjust the operation point.

This paper has presented a three-phase version inverter for feeding three high-voltage loads. The operation mode is similar to the single-phase version however the output power of each load can be adjusted unbalancing the output voltage since the switching frequency is the same.

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