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High-Voltage Resonant Converter with Extreme Load Variation: Design Criteria and Applications

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***Abstract*—**The power converter that feeds high-frequency, high-voltage transformers must be carefully designed due to parasitic components, mainly the secondary winding capacitance and the leakage inductance, that introduces resonances in relatively low-frequency range, next to the switching frequency. This paper considers applications in which the load (resistive) has an unpredictable behavior, changing from open to short-circuit condition faster than the output voltage control loop could react. In this context, to avoid overvoltage and over current situations, that could damage the converter, the transformer or the load, it is necessary to find an operation point that assure the desired output voltage in spite of the load condition. This can done adjusting the frequency response of the transformer adding an external inductance, together with selecting the switching frequency to get stable output voltage independently of the load.

***Keywords*—**High-voltage transformer, Resonant converter, Soft-commutation.

I. Introduction

RESONANT power converters [1] are a usual solution for high-voltage applications due to the possibility of exploiting the non-idealities of the magnetic devices, namely the winding capacitance and leakage inductance. Applications like sources for pulsed laser [2], ozone generation [3], [4], ballast for discharge lamps [5], [6], RF amplifiers [7] among others, have been developed using solutions based on such converters.

Each particular application has its specific characteristics. For example, for pulsed laser sources the converter always operates in transient condition, tuned at the resonance in order to get the maximum voltage gain while increasing the power factor and thus minimizing the conduction losses.

For ozone generation, the ozonizer device has a capacitive characteristic and the equivalent load behaves as a constant resistance. This steady-state operation allows the converter control and command be selected choosing the switching frequency and the modulation strategy for adjusting the output power and the ozone production rate.

For lighting devices, at the start-up, as the load has a higher resistance, the usual over-voltage is welcome to create the plasma. After the ignition, the lamp behaves as a constant resistive load.

However, there are other applications for which the load varies in the full range from open to short-circuit condition [8]-[10]. If such variation is slow, control strategies can be applied in order to compensate the perturbation. If the load variation is too fast and unpredictable, the solution to avoid dangerous operation (mainly related to over-voltage and over-current) has to be guaranteed by the converter operation, independently of the control loop action.

This work analyses the use of a controlled AC high-voltage high-frequency source, composed by a full-bridge converter that feeds a high-voltage transformer, as shown in Fig. 1. The transformer secondary side is connected to the output electrodes where a variable resistive load is connected. The objective of this paper is to define design criteria that enable the power source safe operation for load variation from short to open circuit condition, taking into account the high-voltage transformer behavior. Additionally, to improve the efficiency, the inverter must operate, ever possible, with soft-commutation.

As shown in Fig. 1, a DC blocking capacitor is introduced to avoid the transformer saturation due to possible DC voltage introduced by the inverter operation. The capacitance must be chosen in order to not affect the converter operation, as explained in the sequence.

Section II describes the high-voltage transformer modeling, analyzing its frequency response. Section III discusses the power converter operation and the necessary resonant parameters selection according to the application. Section IV presents experimental results in a 1.5 kVA prototype. Section V concludes the paper.

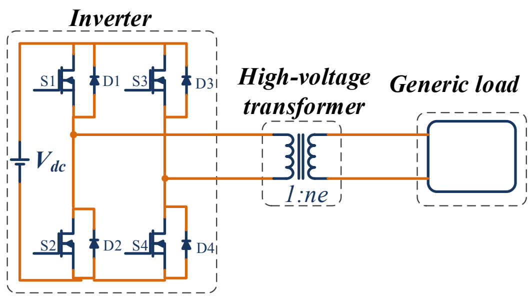

Fig. 1 Simplified full-bridge converter with high-voltage transformer and resistive load

II. High-Voltage Transformer

To achieve the necessary AC high voltage, a transformer is used. The equivalent lumped parameters circuit of the transformer is shown in Fig. 2.

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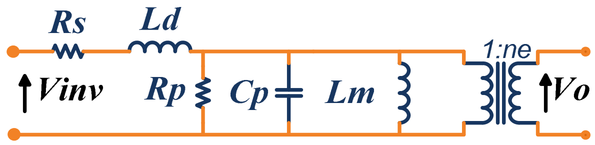

Fig. 2 Equivalent lumped parameters transformer model

The transformer parameters reflected the primary side are:
Rs - windings resistance;
Ld - equivalent leakage inductance;
Rp - equivalent parallel resistance;
Cp - equivalent windings capacitance;
Lm - magnetizing inductance;
ne – turns ratio.

The load resistance appears in parallel with the resistance that models the magnetic core losses. In case of secondary open circuit, the resulting parallel resistance is due to this effect.

A. HV-Transformer Parameters Estimation

Considering the transformer operates in the linear region, without saturation, its parameters can be estimated as follows.

A low voltage (10 V peak) sinusoidal signal is applied at the primary side. 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 the capacitor Cp can be neglected due to its high impedance. So, the equivalent impedance at this range is equal to Ld plus Lm. As the magnetizing inductance is dominant the leakage can be neglected.

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

The first resonance is determined by Cp and Lm and gives the maximum input impedance, what is identified by the minimum current and resistive characteristic, as shown in Fig. 3. Up to this frequency the impedance presents an inductive behavior. The turns-ratio can be verified also in Fig. 3 comparing the primary and secondary voltages.

Above this resonance the circuit has a capacitive behavior, with the current leading the voltage, as shown in Fig. 4. The second resonance is between Ld and Cp and determines the minimum input impedance. Above such frequency the circuit reassumes the inductive behavior, as shown in Fig. 5.

The input impedance and voltage gain respectively are given by:

$$Z_{in} = \frac{R_s + s\left[L_d + L_m\left(1+\frac{R_s}{R_p}\right)\right] + s^2 L_m\left[\frac{L_d}{R_p} + C_p R_s\right] + s^3 L_d L_m C_p}{1 + s\frac{L_m}{R_p} + s^2 L_m C_p} \quad (1)$$

$$\frac{V_o}{V_{inv}} = \frac{ne.sR_pL_m}{s^3 R_p L_d L_m C_p + s^2\left(R_s R_p L_m^2 C_p L_d\right) + s\left(R_s L_m + R_p L_d + R_p L_m\right) + R_s R_p} \quad (2)$$

As the load behaves like a resistance, it can be defined by a nominal value, in which the nominal voltage and power are applied. The minimum value is zero, due to a short-circuit condition at the transformer output. The maximum value corresponds to an open-circuit at the secondary side. In this case, the remaining parallel resistive effect is due to the core losses.

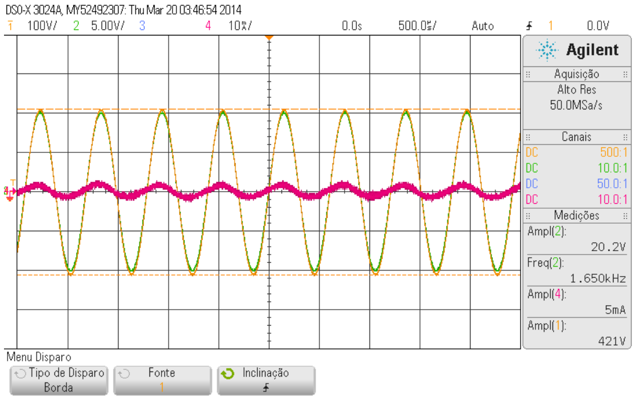

Fig. 3 Parallel resonance (without load).Primary voltage (5V/div), secondary voltage (100V/div) primary current (10mA/div)

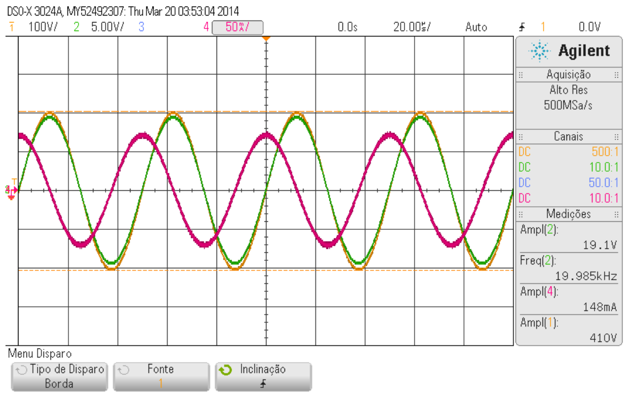

Fig. 4 Capacitive behavior at 20 kHz (without load).Primary voltage (5V/div), secondary voltage (100V/div) primary current (50mA/div)

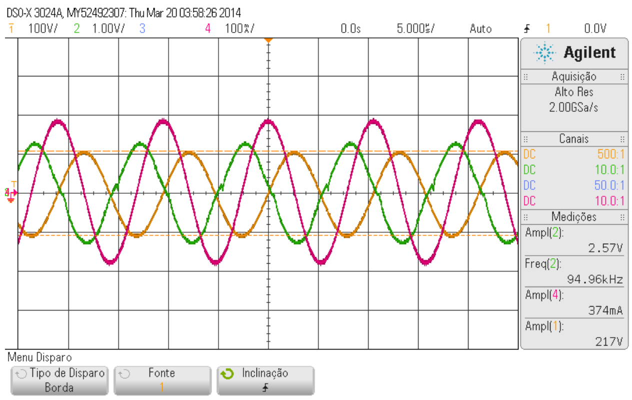

Fig. 5 Inductive behavior above the series resonance. Primary voltage (1V/div), secondary voltage (100V/div) primary current (100mA/div)

As shown in Fig. 6, for the parameters in Table I, the voltage gain increases next the series resonance that is determined by the leakage (series) inductance and winding (shunt)capacitance, resulting 86 kHz. Above this frequency, the load seem by the inverter (comprising the transformer plus the secondary load) has an inductive behavior, as Fig. 7 displays.

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{L_s C_p}} \quad (3)$$

TABLE I
TRANSFORMER PARAMETERS

Symbol	Values
Rs	1 Ω
Ld	57μH
Rp	4 kΩ (only core losses)
Cp	60 nF
Lm	153mH
ne	21.2
Primary nominal voltage	330 V
Nominal power	2 kVA

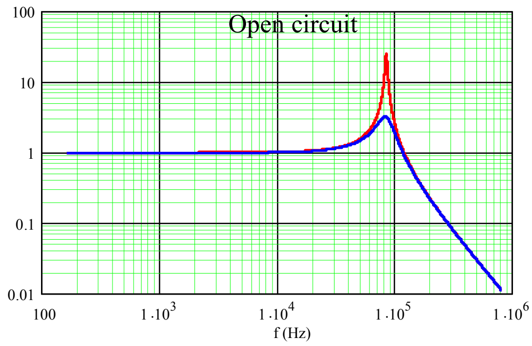

Fig. 6 Transformer voltage gain for nominal and open circuit load conditions (normalized to ne=21.2)

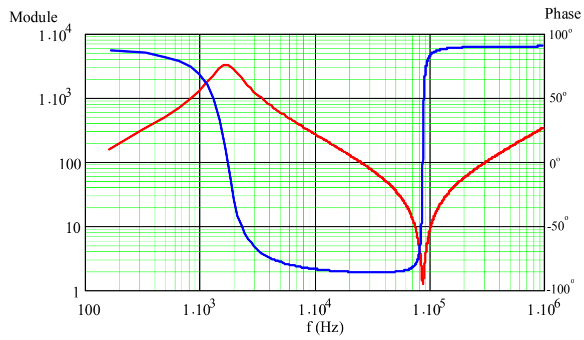

Fig. 7 Transformer input impedance (open load condition). Module [Ω] and phase [degree]

III. RESONANT CONVERTER

A. Direct Drive of HV-Transformer

The switching frequency is defined by a compromise between the semiconductors commutation losses and the transformer design. Obviously, the lower the frequency, lower the switching losses. In very low frequency (tens of Hz) FeSi cores are available, but the transformer will be large and heavy. In the range of tens of kHz, ferrite, some special metallic composite and iron powder are available, with acceptable losses, allowing reducing the transformer size. In this frequency range the switching losses are not so high, especially if soft-commutation [1] is implemented.

To get soft-commutation the load must have an inductive behavior. In this case the transistor conduction is preceded by the respective anti-parallel diode conduction. The transistor turn-on happens at zero voltage and zero current. At the turn-off, by using a simple snubber capacitor (as depicted in Fig. 1), results a zero-voltage commutation.

In the capacitive region, the power switches turn-off with zero current. The turn-on, instead, is dissipative and con not be solved by a simple snubber.

Let us consider that the power converter produces a square-wave in the range of tens of kHz. The respective spectrum contains components in the resonance band. Such components will be amplified, mainly in the open-circuit condition. Fig. 8 shows this situation. The switching frequency is 15 kHz, thus the 5th harmonic, at 75 kHz, is close to the resonance, being amplified. When the load is disconnected, the only resistive effect that remains is the core losses. As expected, according to Fig. 6, the harmonic amplification is very high and, in spite of the output power is zero, the input current increases. The input impedance is lower for open-circuit condition than for nominal power. The amplification is verified in both, current and voltage, stressing the transformer.

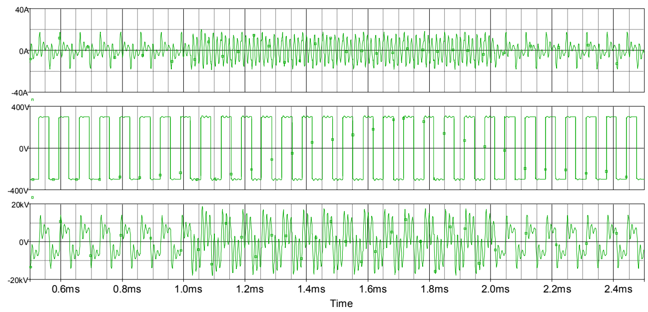

Fig. 8 From the top to bottom: primary current, inverter voltage and secondary voltage behavior under load variation

B. Modulation Strategy

The limitation of current and voltage amplification in no-load condition can be obtained by changing the input impedance, reducing the applied voltage or a combination of both.

Changing the commutation frequency if detected a voltage increase could reduce those stress, however this would be a slow control action, since it depends on a control loop response.

Voltage reduction by producing a three-level output voltage is an alternative control method. Phase-shift modulation [11] allows this kind of action. However it also depends on the control loop response and it is not possible to fully avoid over-current and over-voltage until the system control effectively reduces the applied voltage.

In order to avoid these stress conditions, while having a wide, fast and unpredictable load variation, it is necessary, at the switching frequency, to have a higher impedance and limited voltage gain for the open-circuit load condition, in comparison with the nominal load. This combination can be done by adjusting the resonance frequency, what changes the impedance, as follows.

C. Frequency Response Adjustment

The voltage gain varies due to the change of the load resistance (secondary side) between the nominal value, 50 kΩ (aprox. 1 kW @ 7.1 kV) and 1.8 MΩ (equivalent to the core losses)as shown in Fig. 6.

In order to increase the input impedance it is necessary to add an inductor in series with the transformer, what reduces the resonance frequency. Fig. 9 shows the module of the input impedance adding 500 µH. At 14 kHz the full load impedance is 84 Ω, and increases to 148 Ω for open-circuit condition. This means that the fundamental component is expected to reduce. Since the square-wave has no even order harmonics, the resonance at around 30 kHz is not relevant. For the third harmonic, the input impedance varies from 89 Ω to 69 Ω, thus a small current amplification is expected in such frequency.

In spite of the switching frequency is below the resonance, for nominal power, the equivalent load seen by the inverter is dominated by the series inductance, allowing soft commutation. For the open-circuit case, the converter is in the capacitive region, allowing soft-commutation at the turn-off but not at the turn-on. Fig. 10 shows simulated waveforms that, compared with Fig. 8, display the reduction of over-current and over-voltage. Initially the nominal load is connected. Between 1 and 2 ms the converter operates in open-circuit condition, then returning to nominal power.

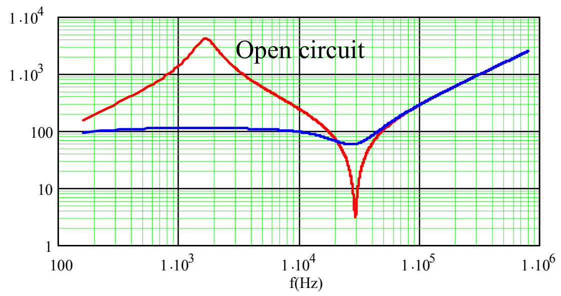

Fig. 9 Input impedance (module) for different loads with additional series inductor Open-circuit and nominal load

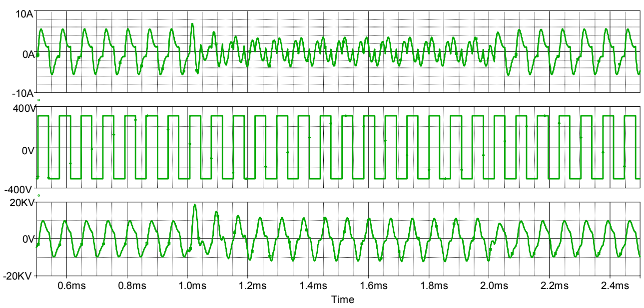

Fig. 10 From the top: primary current, inverter voltage and secondary voltage behavior under load variation with additional series inductor

Finally, as indicated previously, it is necessary to include a DC blocking capacitor to guarantee that the transformer will not saturate due to small DC voltage components produced by the inverter. Adding 1 µF capacitor in series with the transformer, results, in the frequency range of interest, the desirable behavior, indicating this is a good solution for the application.

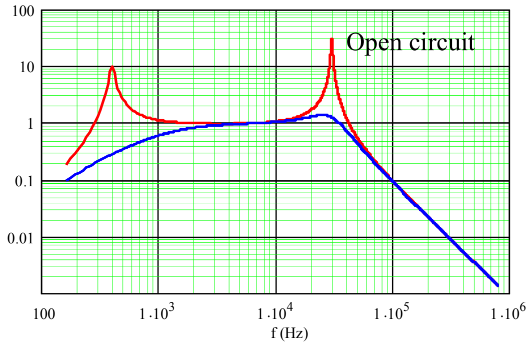

Fig. 11 Normalized voltage gain for different loads with additional series inductor and capacitor. Open-circuit and nominal load.

Next to 400 Hz, however, for the open circuit condition, appears a new amplification region, determined by the series resonance between the magnetizing inductance and the DC decoupling capacitor. The impact of such additional resonance in transients must be carefully evaluated.

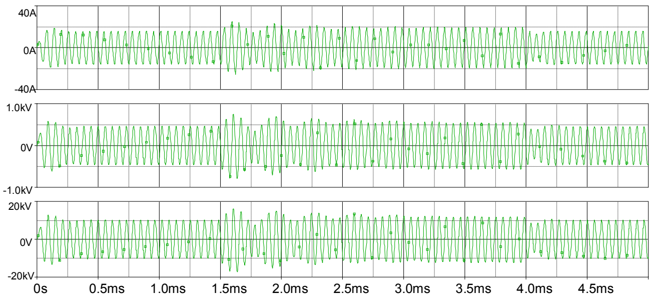

Fig. 12 Simulation results for variation from nominal load to open-circuit and vice-versa. Input current (top); primary side voltage (center) and output voltage (bottom)

IV. Experimental Results

The experimental setup uses a single-phase, square-wave inverter with adjustable DC voltage. A DC blocking capacitor of 1 µF and an external 500 µH inductance are add in series with the transformer (primary side). At the secondary, a resistive load of 50 kΩ represents the load at nominal power (1 kW @ 7.1 kV). The load is commuted to verify the circuit behavior also at open and short-circuit conditions.

Fig. 13 shows the inverter output voltage and the transformer primary side current. The filtering characteristic of the transformer plus the input inductor allows an almost sinusoidal current. The current is slightly delayed, indicating the equivalent load has an inductive behavior, allowing soft-commutation of the power switches.

Fig. 14 displays the almost sinusoidal voltage at the transformer terminals (primary side) for a lower input voltage. In this case the current leads the voltage, indicating the dominant effect is capacitive. A small ringing occurs at the commutations, due to other parasitic phenomena, not modeled in Fig. 2. Fig. 15 displays the secondary voltage corresponding to the condition of Fig. 14. For a 50 kΩ resistive load, the output power is 830 W.

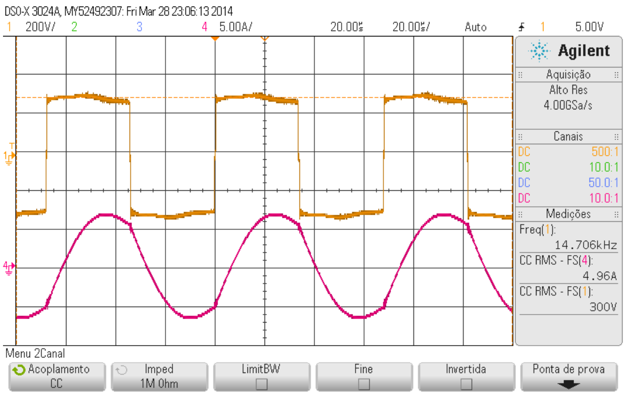

Fig. 13 Inverter voltage (top) and current (bottom) with nominal load @ Vdc = 300 V

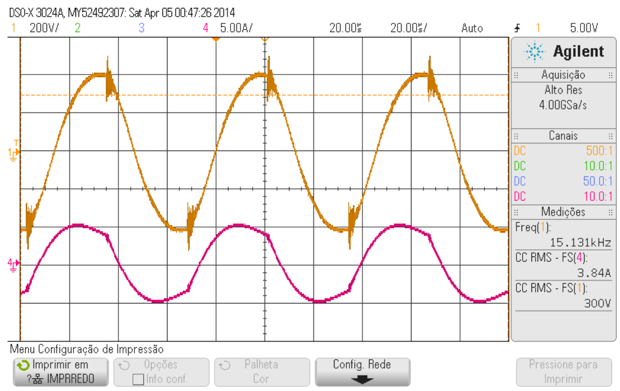

Fig. 14 Primary voltage (top) and current (bottom) with nominal load

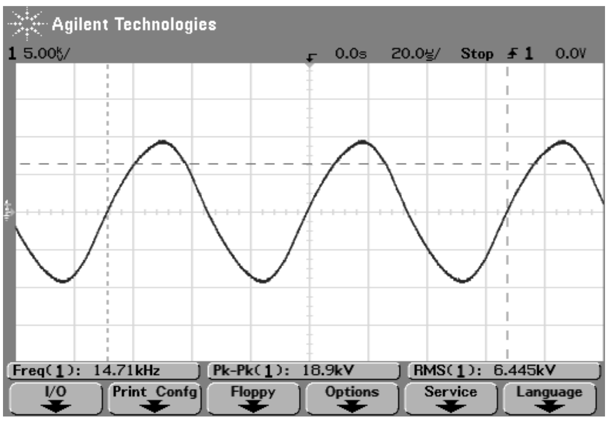

Fig. 15 Secondary voltage (830 W at load)

Fig. 16 shows the short-circuit situation. In this case the external series inductor limits the current, thus protecting the inverter and the transformer until this load condition changes.

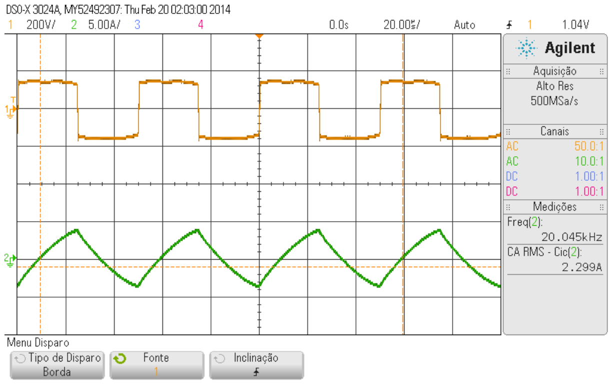

Fig. 16 Inverter voltage and current at short-circuit condition

Fig. 17 shows the overvoltage that can appear is an inappropriate switching frequency is adopted. In this case, initially the load is open and the resulting primary voltage is 60 % higher than with the nominal load, which is connected in the sequence. Such overvoltage probably exceeds the transformer specification and must be avoided by selecting a more suitable switching frequency.

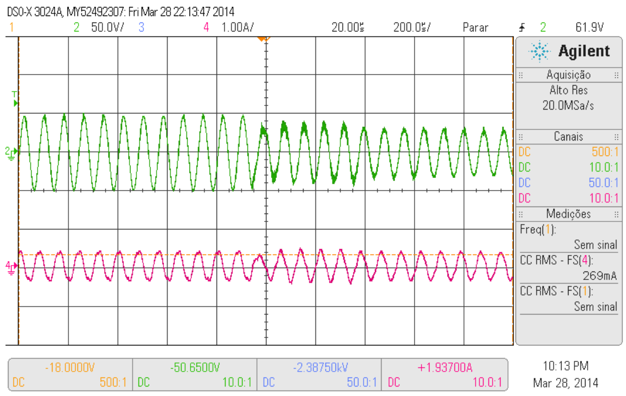

Fig. 17 Primary voltage and current transient from open-circuit to nominal load

V. Conclusion

This paper has considered applications of resonant converters in which the load (resistive) has an unpredictable behavior, changing from open to short-circuit condition faster than the output voltage control loop could react. As the power converter feeds a high-frequency, high-voltage transformer the parasitic components, mainly the secondary winding capacitance and the leakage inductance, introduce resonances in relatively low-frequency range, next to the switching frequency. In this context, to avoid overvoltage and over current situations, that can damage the transformer and the load, it is determined a secure operation point that assure the desired output voltage in spite of the load condition. The addition of an external inductance, together with the choice of the switching frequency, maintains constant the output voltage independently of the load. Simulation and Experimental results validate the proposition.

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