AN ELECTRIC FENCE ENERGIZER DESIGN METHOD

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Abstract—This paper introduces fundamental concepts of electric fence technology, presents a new design method for a livestock electric fence energizer circuit and impulse transformer as well a mathematic analyze of the circuit. A new expression for design single impulse transformers for this kind of application is presented who has different project criteria from conventional transformer applications. The Energizer equipment is rounded about many concepts, safety standards and data performance that are discussed. An electric circuit prototype of Electric Fence Energizer Equipment for livestock use was implemented and the results are showed. This work is based on a study developed in a Master Thesis.

I. INTRODUCTION

Nowadays the use of electric fence for control and content livestock are having a large application in almost all countries of the world. Electric Fence was starting to use in the thirties and nowadays is used in all world in little and big farms. Brazil, like the major exporter of beef cattle is a great consumer of this technology. Big farms with large areas of control need electric fences energizers of large capacity to keep high voltage in all its extension. But not much information about safety use and project is presented in papers and available for consumers and manufacturers as well electric fences characteristics. There are in Brazil many manufacturers of this kind of equipment, but these manufacturers use empiric rules to design this kind of equipments. This work intends to be a starting point to change this reality involving the academic researchers in the study of this problem. The different parts of the fence are shown in Fig. 1. The electric fence presents the following parts: Energizer, Wire, Isolation and Ground.

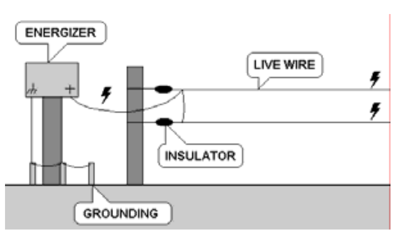

Fig. 1: Parts of the Electric Fence.

II. OPERATION

The current flow on the fence is showed in Fig. 2. When the cattle touch the wire the circuit is closed and the electric impulse current generated by the Energizer flows through the body. In practical experiences is evidenced that the cattle doesn't transpose the fence for a peak voltage higher than 2 kV measured where cattle touches the wire. For a fence with this peak voltage the livestock experiments a panic sensation and don't return to touch the wire. The simplified electric circuit for the fence circuit is showed on Fig. 2 too. This circuit was modeled from results obtained through measurements in a real fence [1]. The Z_0 is the characteristic impedance of the fence line and were in some cases the conductor capacitive and inductive reactance is more expressive than the conductor resistance. This impedance may be calculated in the same way that for a power line. In this study was observed that the reflection phenomenon is important to calculate the peak voltage in the fence because this effect can boost the peak voltage value in the system. The reduced voltage produced by faults in insulators produce reflections in the fence line that reduces the peak voltage on the fence.

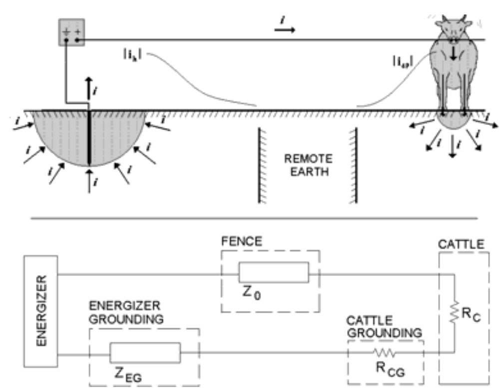

Fig. 2: Current flow (path) in a fence circuit at the cattle touch moment and the simplified equivalent electric circuit.

This electric circuit modeled is very useful to estimate the peak value of voltage and the dissipated energy in the cattle in the worst case – the end of the fence. It was evidenced that the energizer grounding and the fence line impedance need to be projected appropriated because they are the main design parameters and causes a reduction of the peak voltage in the cattle body who touches the fence at the end. It was observed too that the grounding of the hoofs of cattle is expressive comparing to the cattle body resistance. This voltage divider reduces the voltage and energy in the cattle body. The main grounding will depend in soil resistivity and in some cases a grounding wire in the fence will be necessary, even in small fences with few kilometers.

The resistance of the body of the cattle is assumed to be 175 Ω for impulse current and for a nose to the hoofs path [2]. This data is important to preview the voltage applied in the cattle that will depend of the wire impedance and the ground impedance. For human beings the resistance for impulse current is 500 Ω for the hand to the feet path. This data is important to the safety energy limits described in the standard IEC 60335-2-76 [3].

III. Safety Aspects

All safety information is important to develop an Electric Fence Energizer circuit. Is very relevant a correct understanding of electric characteristics of this circuit and the produced reaction of the electric shock derived from it. In the TABLE 1 is listed the mainly safety aspects provided by standard IEC 60335-2-76 [3]. The technical report IEC 60479-2 (chapter 6) [4] shows safety limits for single impulse waveform based on experiments presented in specialized bibliography. There are other two main standards for safety requirement for energizers: the UL-69 edited by Underwriters Laboratories (UL) and the DIN VDE 0131 and DIN VDE 0669 edited by the Deutsche Elektrotechnische Kommision (DKE).

TABLE I-Electric shock safety requirements.

Parameter:	Value:
Impulse repetition period	$T_r \geq 1$ s or $f \leq 1$ Hz
Impulse duration with a 500 Ω load	$t_i \leq 10$ ms
Energy of the discharged impulse in a 500 Ω load for energy limited energizer	$W \leq 5$ J
RMS current of the discharged impulse in a 500 Ω load for current limited energizer (RMS value for duration of the impulse t_i)	Depend of t_i (See Fig. 3). For $t_i < 0,1$ ms, $I_{RMS} = 15,7$ A

IEC 60335-2-76 – International Electrotechnical Commission – 2002

The energy discharged in the load is lower than the energy stored in the capacitor of the energizer circuit. The value of the discharged energy of an energizer will depend of the value of the load. So, it is possible that, an energizer with more the 5 J stored in the capacitor may accomplish the standard requirement for the energy impulse discharge.

The Fig. 3 presents a graphic that describes the safety limits and the panic limits of an exponential impulse discharged in the human body. This graphic presents a gray painted area where the values of peak voltage and duration of the impulse cause a panic sensation. This graphic was created using parametric limits values presented by IEC 60479-2 [4] and IEC 60335-2-76 [3] standard and can be used as reference for an energizer project.

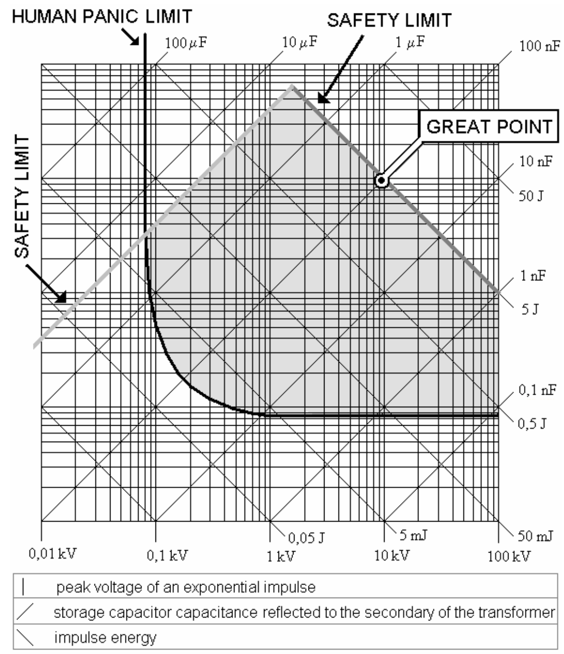

Fig. 3: Safety and panic limits.

An energizer designed to produce an electric impulse in a 500 Ω load with the peak voltage value and the energy value according to the "great point" of the graphic of the Fig. 3 will reach the maximum efficacy for this condition, within safety limits. An exponential impulse may be considered and circuit losses are ignored to obtain a correct relation between the values presented in this graphic.

IV. Energizer

The Electric Fence Energizer converts the electrical energy, which normally comes from the electrical utility, batteries or solar PVs in an electric impulse with limited energy associated according to safety limits. The electric circuit is divided in two parts as shown in Fig 4: Supply Circuit and Impulse Generator Circuit.

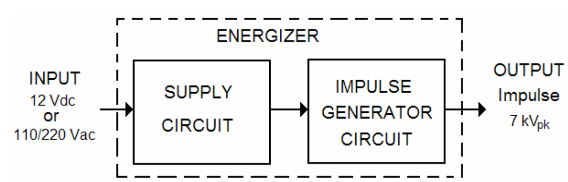

Fig. 4: Electric Fence Energizer Block Diagram.

A. *Supply Circuit*

The supply circuit provides a DC link to charge the storage capacitor C1. Two usual supply circuits are illustrated in Fig. 5 to exemplify. One is a conventional power supply, 127/220 Vac 50/60 Hz, grid connected (a) and the other one is a 12 V battery associated with a fly back converter (b). Both circuits are used in commercial equipments to raise the input voltage around 300 to 600 Vdc.

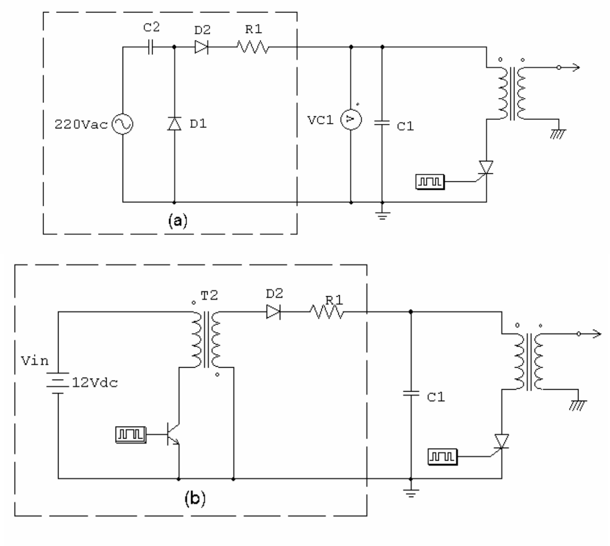

Fig. 5: (a) Means supply – voltage duplicator, (b) Battery supply – Fly Back CC-CC Converter.

For this study the supply circuit was implemented by a conventional rectifier circuit for use with 220 Vac (Fig. 6).

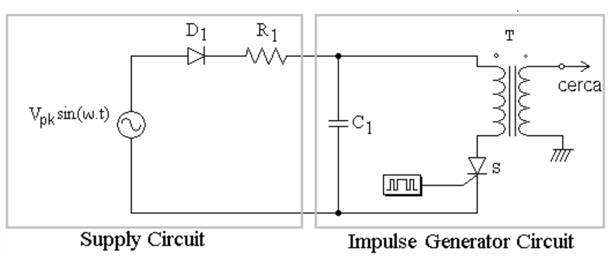

Fig. 6: Supply Circuit and Impulse Generator circuit.

B. *Impulse Generator Circuit - IGC*

The Impulse Generator Circuit - IGC (Fig. 6) consists in a Discharging Impulse Magnetizer circuit. This impulse generation circuit is present in almost all commercial energizers. The transformer T has two main functions to provide electrical isolation – according IEC60335-2-76 [3] requirement - and boosts the input voltage. This element is normally present in commercial circuits with turn ratio around 1:10. It will depend of the charge voltage of the capacitor and the desired peak voltage of the electrical impulse produced in the fence. The transformer secondary is connected to the wire of the fence and to the ground electrodes. The capacitor C_1 is the energy storage element, to charge this capacitor the circuit has about one second. The switch is usually implemented by a thyristor S that provide the discharge of the capacitor. The resistor R_1 limits the current of the supply in the charging of C_1 and in the discharging of C_1. The operation circuit is divided in two stages: Charge Capacitor Stage - stage 1 (Fig. 7) and Discharge Capacitor Stage - stage 2 (Fig. 8).

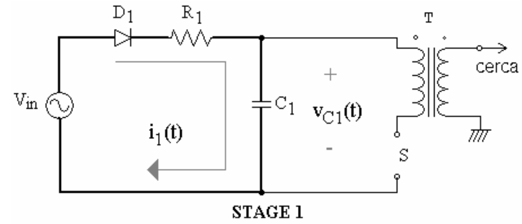

Fig. 7:Charge of the capacitor – stage 1.

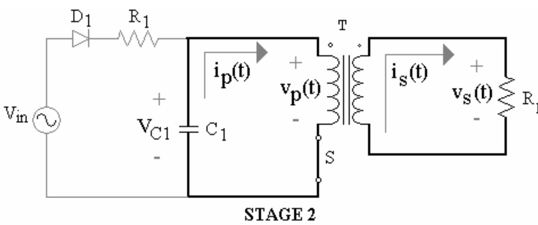

Fig. 8: Discharge of the capacitor – stage 2.

In the impulse magnetizer circuit, the transformer T needs to be modeled with the leakage and magnetizing parameters (Fig. 9) because the relative high frequency of the harmonics [5] of the impulse generated by the discharge of the capacitor C_1. Because of the low value of the load R_L reflected to the primary, the RSE value of the capacitor C_1 needs to be modeled too.

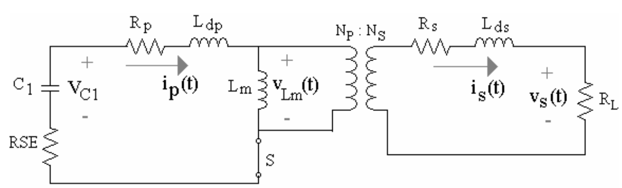

Fig. 9: Impulse Generator Circuit with a the transformer equivalent circuit.

V. ENERGIZER DESIGN PROCEDURE

To design the IGC is important to know the behavior of the $v_s(t)$ waveform and $i_p(t)$ waveform as well as they respective peak values. This information is useful to design the transformer, to define the thyristor parameters and know the energy dissipated in the 500 Ω load. Both curves can be obtained trough computer simulation or analytic analysis. However the development of the mathematic expressions of the IGC results in a complex work. With some conditions the circuit can be reduced to a series RLC circuit so the expressions for $v_s(t)$ and $i_p(t)$ can be easily obtained. To this simplification be correct, the reactance of the magnetizer inductance L_m for the di/dt applied by the capacitor C_1 discharge may be at least ten times higher than the resistance R_L according to the equation (1). The f_c is the characteristic frequency of the current impulse.

$$2.\pi.f_c.L_m \geq 10.R \qquad (1)$$

With the condition above the amount of the peak value of the current $i_p(t)$ flowing in L_m can be neglected (Fig. 10).

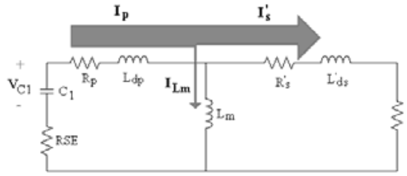

Fig. 10: Peak current distribution for simplification.

The Fig. 11 presents a simplified circuit without the magnetizer inductance L_m.

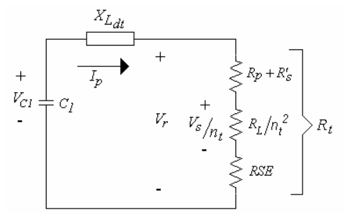

Fig. 11: Simplified impulse generator circuit.

In the Fig. 11, n_t is the turn ratio of the transformer, R_p is the primary winding resistance, R_s' is the secondary winding resistance reflected to the primary, V_{C1} is the initial voltage of the storage capacitor C_1, the leakage reactance X_{Ldt} is the total leakage reactance of the transformer and R_t is the total resistance of the circuit.

A. Input Data

The input data to design the energizer are:

- The stored energy - W_{C1};
- The RMS voltage of the mains - V_E;
- Initial voltage of the capacitor - V_{C1};
- The resistive lose of the transformer winding in percent of the energy - W_{C1};
- The load connected to the transformer secondary - R_L;
- The peak voltage applied in the load - V_{st}.

The value of V_{st} and W_{C1} is defined using the graphic presented in the Fig. 4 associated to a field experience criteria. It's important to remember that the dissipated energy in R_L is lower than the stored energy in C_1. So this observation needs to be on mind when specifying the V_{st} and W_{C1} values.

B. Determining the Capacitor - C_1

The value of the capacitor C_1 is determined by the amount of energy W_{C1} that needs to be stored in the capacitor and the charge voltage V_{C1}. The capacitance is obtained with the equation (2).

$$C_1 = \frac{2.W_{C1}}{V_{C1}^{\;2}} \tag{2}$$

C. Determining the resistance - R_1

To be sure that the capacitor's voltage reaches the determined V_{C1} in one second the resistance R_1 of the supply circuit is obtained with the equation (3).

$$R_1 \leq \frac{1}{100.C_1} \tag{3}$$

D. Specifying the diode - D_1

The rectifier diode D_1 of the supply circuit needs to support the initial current of the charge capacitor stage. The maximum value of the current $i_1(t)$ is determined by the equation (4).

$$I_{1\max} = \frac{V_E.\sqrt{2}}{R_1} \tag{4}$$

Where V_E is the RMS voltage value of the main utility.

E. Specifying the turn ratio of the transformer - n

This design method is preferred for transformers with EI laminated core with a turn ratio value between 10 and 30.

At first, a theoretical transformer turn ratio needs to be calculated with the equation (5) and the total resistance of the winding reflected to the primary needs to be calculated with the equation (6).

$$n_t = \frac{V_{st}}{V_{C1}} \tag{5}$$

$$R_{fp} = \frac{F_p.\left(\dfrac{R_L}{n_t^{\;2}}\right)}{100} \tag{6}$$

The total leakage inductance L_{dt} of the transformer needs to be determined with the equation (7) to provide to the series RLC circuit an overdamped response.

$$L_{dt} = \frac{C_1.\left(RSE + R_{fp} + \dfrac{R_L}{n_t^{\;2}}\right)^2}{8} \tag{7}$$

Now, with the values of the simplified circuit of the Fig. 11 it's possible to calculate the peak voltage on the load R_L through development the differential equation of the series RLC circuit with overdamped response [6] that results in the equation (8).

$$V_s = R_c \cdot \frac{\left(D_1.e^{(-\alpha+\beta).t_{\max}} + D_2.e^{(-\alpha-\beta).t_{\max}}\right)}{n_t} \tag{8}$$

The time t_{max} necessary to the voltage V_s reaches the peak value is obtained with the equation (9):

$$t_{\max} = \frac{\ln\left(\dfrac{-1}{-D_1.\alpha + D_2.\beta}.\left[D_1.(-\alpha+\beta).D_2.(\alpha+\beta)\right]^{\frac{1}{2}}\right)}{\beta} \tag{9}$$

Where:

$$\alpha = \frac{R_t}{2.L_{dt}} \tag{10}$$

$$\beta = \sqrt{\left(\frac{R_t}{2.L_{dt}}\right)^2 - \left(\frac{1}{\sqrt{L_{dt}.C_1}}\right)^2} \tag{11}$$

$$D_1 = \frac{V_{C1}.C_1}{2.\beta} \cdot \left(\alpha^2 - \beta^2\right) \quad (12)$$

$$D_2 = -D_1 \quad (13)$$

With the calculated peak value of voltage V_s and the turn ratio n_t and the specified peak voltage V_{st} a new turn ratio is determined with the equation (14) to assure that the peak voltage on R_L reaches a value around the specified V_{st}.

$$n = \frac{V_{st}.n_t}{V_s} \quad (14)$$

With the new turn ratio, is necessary to calculate again the resistance of the winding R_{fp} and the transformer leakage inductance L_{dt}. To verify the peak voltage reached in the R_L load with the new parameters the new series RLC series overdamped response can be calculated with the equation (8).

F. *Specifying the core size – A_e and A_w*

To design the core of the transformer a new equation was developed where is possible to calculate the effective area to avoid the saturation effect and the window area of the core to certify the availability space for windings. Is usual to design the core dimension of the transformer using the equation of the product area (A_p) [5] [7] [8] [9]. However this expression considers the power of the load and the elevation of the temperature for operation in steady state to avoid saturation effect. In this case the operation in steady state does not occurs and just a high current single impulse occurs in one-second period. This kind of operation does not induce heating, so the use of the equations found in bibliography results in a sub-designed core. The input data to calculate the core dimension parameter CDP in cm^3 trough equation (15) are:

- Maximum flux density for the material core - B_{max};
- Resistivity of the conductor material of the winding – ρ_c;
- Primary peak current - I_p – calculated with the equation (16) as commented above about the response of the simplified circuit;
- Utilization factor of the window area - K_{up};
- Magnetizing inductance of the transformer - L_m - from practical experience can be used a value around the value obtained using the equation (17);
- Turn ratio of the transformer – n;
- Coupling coefficient of transformer windings – k;
- Resistance desired for the primary winding – R_p – as the primary window is turned first, the value might use the equation (18).

$$CPD = \frac{4.\rho_c \left(\frac{L_m}{1+k.n}\right)^2 .I_p{}^2}{R_p.B_{max}{}^2.k_{up}} \quad (15)$$

Where:

$$I_p = D_1.e^{(-\alpha+\beta).t_{max}} + D_2.e^{(-\alpha-\beta).t_{max}} \quad (16)$$

$$L_m = 30.L_{dt} \quad (17)$$

$$R_p = 0{,}4.R_{fp} \quad (18)$$

So the relation between the CPD value and the effective area A_e and the window area A_w is given by the equation (19).

$$A_w.A_e^{1.5} \geq CPD \quad (19)$$

For the window utilization factor is important to take in consideration the insulation between primary and secondary required by the standard IEC60335-2-76 [3] and turns of secondary, necessary because of the high voltage produced by the circuit and by possible lightning discharges in the fence [10].

G. *Specifying the number of primary and secondary turns – N_p and N_s*

The primary winding turn N_p is calculated similar to an inductor using the equation (20) and secondary winding turn N_s is calculated with the equation (21) :

$$N_p = \frac{\frac{L_m}{(1+k.n)}.I_p}{A_e.B_{max}} \quad (20)$$

$$N_s = n.N_p \quad (21)$$

H. *Specifying the section area of primary and secondary conductors – A_{cp} and A_{cs}*

The above areas can be determined with the equations (22) and (23) that make use of the desired primary resistance R_p and secondary resistance R_s and also considering the number of turns N_p and N_s, effective area A_e, conductor resistivity ρ_c and the medium length of winding.

$$A_{cp} = \frac{4.10^4.N_p.\rho_c.\sqrt{A_e}}{R_p} \quad (22)$$

$$A_{cs} = \frac{N_s.\rho_c.l_m.10^2}{R_s} \quad (23)$$

The conductor resistance of secondary winding can be approached by the equation (24).

$$R_s = 0{,}6.R_{fp}.n^2 \quad (24)$$

I. *Specifying the thyristor S*

The thyristor S may be specified by the peak current I_p and the initial voltage of the capacitor C_1 as well the dv/dt ($V_s/n.t_{max}$) and di/dt (I_p/t_{max}) verified in the circuit. However is usual to take into consideration the voltage produced in the primary of the transformer by lightning discharges in the fence [10].

VI. ENERGIZER PROTOTYPE

An impulse generator circuit according to the input data of the table II was implemented as an energizer prototype, using the design procedure presented (Fig. 12). For the stage 1 the measured curve of $v_{C1}(t)$ is presented in the Fig. 13.

TABLE II-Input data for designed energizer.

Parameter	Value	Parameter	Value
W_{C1}	1 J	F_p	3 %
V_E	220 Vac	R_L	500 Ω
V_{C1}	311 Vdc	V_{st}	5 kV

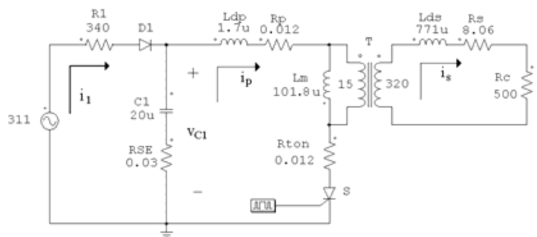

Fig. 12: Parameters of the implemented circuit.

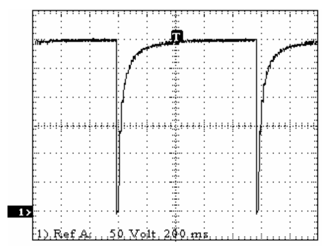

Fig 14: Measurement of the charging voltage $v_{C1}(t)$.

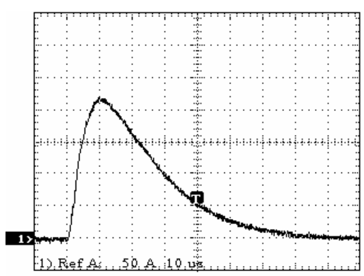

Fig. 21: Measurement current $i_p(t)$ in the primary of the transformer.

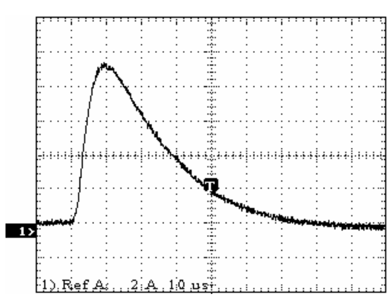

Fig. 22: Measurement current $i_s(t)$ in the R_L load.

The current $i_s(t)$ in the R_L load produces a peak voltage V_s with the value of 4,6 kV. This value compared with the 5 kV input data evidences that the parameters of the transformer are frequency dependent. Another cause for this difference may be due to 300 Vdc (not 311 Vdc) charge in the capacitor and the lower peak current (220 A versus 230 A) in the primary of the transformer as well differences between the calculated parameters and the real parameters of the components, mainly the transformer parameters.

Finally it's important to observe that the magnetic losses are neglected in the design method.

VII. CONCLUSION

The information presented in this paper shows important safety requirements for energizer circuit design. A presentation of the electric fence circuit model based on transmission line theory and propagation waves was showed. It was presented a panic standard graphic that is a useful tool for electric fence energizer design. The measured results of the prototype show clearly that this kind of circuit is appropriate to be used as Electric Fence Energizer because it complies with the standard safety requirements and shows that the circuit analysis and the circuit design of the circuit and of the transformer are appropriate. The measured results validate the design method however an improve of the this design procedure is necessary to obtain better results. With the continuation of this work and improvement of the design method and implementation materials a commercial version will be designed. So this study has a fundamental importance to increase the knowledge in this kind of circuit that is not approached by power electronics bibliography.

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