Coupling Transmission Lines for Wave Shape Adjust in High-Voltage Surge Tests

Sérgio H. L. Cabral Luiz H. Meyer Gabriel G. Madruga
FURB – Fundação Universidade Regional de Blumenau
Rua São Paulo, 3250 Blumenau, SC, CEP 89030-000, Brazil
scabral@furb.br meyer@furb.br ggmadruga@gmail.com

Abstract -- **High voltage tests are usually required for evaluating electrical withstand of equipments, like power transformers. These tests are based on standards that suggest values for the parameters of the voltage surge wave shape to be applied. However, for the personnel of HV Laboratory, the adjustment of the wave shape is not an easy task. Although standards usually have some flexibility for the parameters of the wave shape for some transformers, it may be even impossible to reach any wave shape that may be minimally acceptable. Based on this problem, the aim of this work is to present a special coaxial transmission line to be inserted between the equipment and the impulse generator. The proposed line has a special design in view of matching properties of the impulse generator and the equipment to be tested. Simulation results from the proposed configuration are presented with discussion of its performance.**

***Index Terms*-helical-coaxial cable, high-voltage test, power transformer.**

I. INTRODUCTION

The performance of any equipment in a power system under the incidence of a lightning stroke is checked by standard tests that are made in high voltage laboratories, in which an impulse generator simulates a lightning discharge. One of the main concerns about these tests is the wave shape of the impulse voltage in which some adjustment in the impulse generator is required, in accordance with the equipment to be tested. Although there is a tolerance for typical values of the wave shape, this adjustment is not an easy task and operation experience is usually the most important guide. While testing a power circuit breaker or an insulating string is not a hard task, to test a power transformer, the adjustment of the impulse generator in order to match an impulsive wave shape close to the 1.2/50 μs requirement, may be sometimes impossible[1]. The main reason for this critical situation lies in the fact that equipment under test-EUT does interact with the impulse generator, which is not an ideal one and thus presents internal voltage drop that drastically changes the wave shape of the output voltage after the connection to the EUT. The degree of interaction follows the same rules as for any basic circuit, that is, its intensity increases as long as the electric impedance of the EUT decreases. This is why circuit breakers and insulating strings, with high values of electric resistance to ground as well as low values of capacitances, present no significant difficulty for the adjustment of the impulse generator. On the other hand, a transformer has not only small series impedance, represented by a resistance and an inductance, but also significantly small shunt impedance, represented by its parasitic capacitance. Therefore, a strong interaction tends to happen in this case.

One of the ways to reduce this undesirable interaction consists in decoupling the circuits of the impulse generator from the EUT. Although it may be a simple idea, this is not an easy task. For example, whereas a circuit employing a coaxial cable, to play the rule of a transmission line, can provide the decoupling, its inherently long length makes this as an impossible option for most of high voltage laboratories, especially for the sake of required area for placing the cable. Nonetheless, by keeping in mind the use of a transmission line, this option may become interesting if a special kind of coaxial cable is applied as a transmission line. Thus, this is the aim of this work, in which a special design for a coaxial transmission line is proposed, decoupling the impulse generator and EUT, considering a practical length and having good compromise between cost and efficiency. Therefore, this circuit can be applied to minimize the cost and effort in the trial-and-error method to the adjustment of the wave shape in high voltage tests of transformers, which is interesting for technical team of high-voltage laboratories.

II. THEORETICAL BASIS

In a general way, an impulse generator consists in two stages. One stage is responsible for energy storage and voltage discharge by using charged capacitors, discharging resistors and triggering gaps. The other stage is a passive stage and it is responsible for adjusting output wave shape to a desired waveform, also by using capacitors and resistors. Usually, the desired output waveform is as double-exponential that can represent a standard 1.2/50 μs lightning impulse voltage [2-4], for example. Fig. 1 shows a schematic diagram of a typical impulse generator, in which the energy stage is represented by an equivalent capacitor, C_c, a resistor, R_c and a switch for representing the triggering system. The passive stage has typical elements like a series resistor, R_f, the resistance of the voltage divider, R_d and its parasitic capacitance, C_f. The output voltage is developed along the measuring resistor, R_d.

C_c and R_c are considered as having strong influence on the time to half value of the output voltage whereas R_f and C_f have stronger influence on its front time.

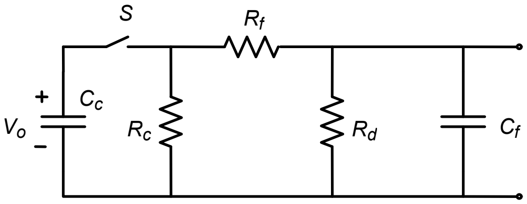

Fig. 1 Schematic diagram of the impulse generator.

This typical circuit is very well known in all of its features, and from its practical use for a long time, it is also quite well known that a double-exponential wave shape is only a good approximation for its output voltage. In fact, several factors intrinsically exist in the circuit that contributes for the output voltage to be quite different from that ideal double-exponential. For example, the unavoidable presence of all mutual and self inductances of the circuit of the generator can be taken into consideration through a series and effective inductance that makes this circuit to be of 3rd order, with the presence of another exponential term, which makes the wave shape of the output voltage to deviate from the standard required waveform [5]. Several authors have previously reported this problem and some other important details of this circuit and its features [1,5].

The case of a transformer test can be represented by adding to the circuit of Fig.1 an equivalent circuit of the transformer that is composed by a series resistance, R_t, and inductance, L_t and a shunt capacitor, C_t, as presented in Fig. 2. This is the simplest transformer representation although some more complex models can be used [6]. For the sake of comparison, the graphs of Fig. 3 present the wave shape of the output voltage for two conditions: with and without the equivalent circuit of the transformer. In Fig.3 it can be observed the drastic changes on the output voltages waveshapes when the transformer is connected. In this case, values of parameters of the impulse generator are $V_o = 118$ % , $C_c = 20$ nF, $R_c = 4300\ \Omega$, $R_f = 3500\ \Omega$, $C_f = 100$ pF, $R_d = 21340\ \Omega$ and correspond to the impulse generator available at FURB. On the other hand, values of transformer parameters are $R_t = 13.4\ \Omega$, $L_t = 46$ mH and $C_t = 2.5$ nF.

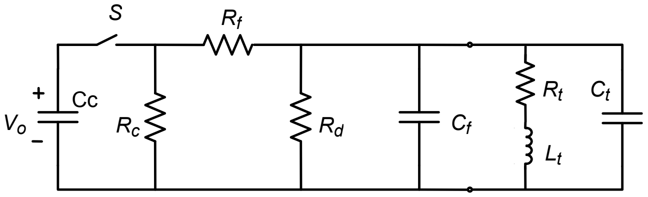

Fig. 2 Schematic diagram of the impulse generator with transformer connected.

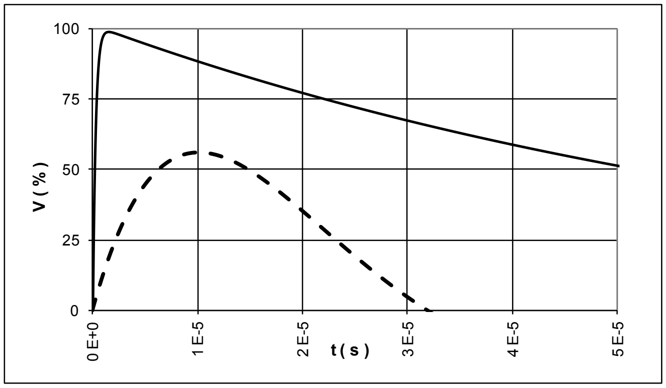

Fig. 3 Output voltage of the impulse generator – without transformer (full) and with (dashed).

III. PROPOSED CIRCUIT FOR SOLUTION

The significant change experienced by the output voltage after the transformer connection, presented in Fig. 3, can be compensated by changing values of R_f and/or R_d. But since the intensity of the change of the wave shape depends also on R_t, L_t and C_t, the choice for new values of R_f and R_d may become a very challenging task, because values of R_t and L_t may differ significantly from one transformer to another, and values of C_t may differ even more, since it is a parasitic parameter. Therefore, with the aim of reducing such a drastic change on the applied wave shape, a new device is proposed to be inserted between the impulse generator and the EUT, in order to cause the decoupling between these circuits.

Thus, consider the circuit presented on Fig. 4, in which the two stages of the impulse generator of Fig.1 have a long coaxial cable or a transmission line connected between them, in the place of the resistor R_f. Thus, the discharge of the same capacitor C_c is done through the same resistance R_c in parallel to a special coaxial cable with input surge impedance equal to Z_o and output impedance equal to Z'_o . The second stage of the circuit is connected to the end of the cable and it is composed by the same capacitance C_f, the same resistance R_d and the same transformer parameters, R_t, L_t and C_t. The only exception is with regard to V'_o that now presents 51 % instead of 188 %. The graph presented on Fig. 5 shows the behavior of the output voltage along R_d, for the conditions of with and without the transformer, as EUT for a 1.2/50 µs impulse test.

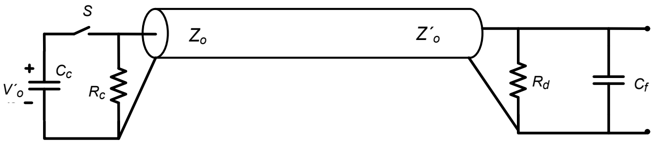

Fig. 4 Proposed circuit for the impulse generator. R_f is replaced by a coaxial transmission line.

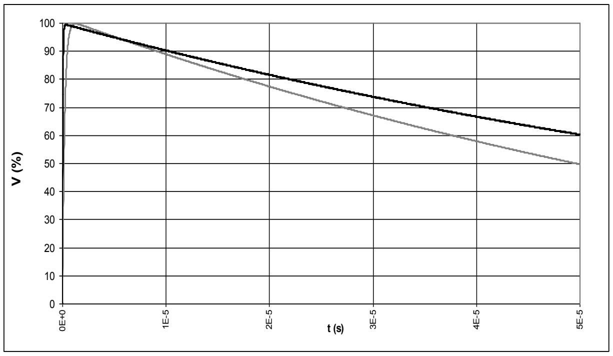

Fig. 5 Output voltage of the impulse generator – without transformer (black) and with (grey).

In this case the reason for a non drastic change of the output voltage lies in the fact that the coaxial cable between energy stage and the transformer decouples both circuits and it thus does not allow mutual interaction and consequent change of output voltage until any reflected wave may appear. Thus, the charged capacitor discharges its energy onto the resistor, R_c, and the cable surge impedance, Z_o , with no influence of any element of the other end. The consequent voltage that is developed on the sending (impulse generator) end of the cable, V_i, travels along it towards the receiving end (EUT) where the transformer, as well as the measurement elements, R_d and C_f, are connected. When getting there, the traveling voltage will interact to all of these elements connected to that end, but no interaction will now happen to those elements connected to the sending end before a reflection occurs. This condition can be represented by the circuits of Fig. 6, in which each of the two stages of the impulse generator are represented by an equivalent circuit.

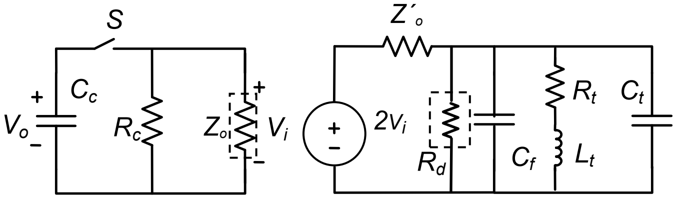

Fig. 6.a. Equivalent circuit during discharge 6.b. Equivalent circuit for the equipment under test

In Fig. 6.a the impedance of the cable, Z_o, can be considered as a resistance (dashed box) and the voltage developed along it is the voltage to propagate along the cable, V_i. In Fig. 6.b the equivalent circuit of the cable is the Thévénin´s circuit represented by the output impedance of the cable, Z'_o, in series with a voltage source that corresponds to the double of the incident voltage, in accordance with theory of travelling waves in transmission line [7].

Although this whole idea seems to be somehow simple, there are two crucial details to be considered for this proposed solution. The first detail is in regard to the fact that input and output impedances of the cable should be different. Thus, for the graph of Fig. 5, for the output voltage to have a time to half wave of 50 μs the input impedance of the cable was taken as 500 Ω. On the other hand, for the output voltage to have a time to front of 1.2 μs the output impedance was simulated with 150 Ω. In any case is important to consider that the value of impedance of 50 Ω is the most commercially available. The second detail is that the time interval of propagation of the traveling wave V_i along the cable must be high enough for not having any reflected wave on the output voltage. Again in regard to the graph of Fig. 5 time interval is higher than 17 μs (≈ 50/3 μs), since the presence of any reflected wave would require 50 μs to travel along the cable for three times, at least. This time interval may imply into a very long coaxial cable that can be not feasible for most of high-voltage laboratories. For example, a cable with speed of propagation about 80 % of the light speed should have a length not less than 4 km.

Thus, the combination of both crucial details represents a significant problem to be solved, for which the authors have an additional proposition to be presented in the following item, based on a special design of a coaxial cable to be used in the proposed circuit.

IV. SPECIAL DESIGN OF FOR A COAXIAL CABLE

Based on the two crucial details above described a coaxial cable with the aspect as shown in Fig. 7 is proposed. It consists in a coaxial cable in which the length for wave propagation along the inner conductor is increased by its helical winding around a dielectric rod. This helical winding not only contributes for decreasing the length of the cable as well as it increases the surge impedance of the cable, since it causes the increase of the inductance per unit of length of the cable through the enhancement of the magnetic field along the axis of the helix. With this aim, special attention must be paid to the distance between any two adjacent coils, Δ, so the capacitance between them does not become significant. If it will be so, a very fundamental characteristic of a transmission line may be lost, that is the time interval of wave propagation. On the other hand, this inductance can even be increased if a magnetic material is added to the dielectric material of the inner rod for increasing the relative magnetic permeability, as for example, by adding ferrite grains. In this case, the layer of insulating material along the helical conductor can play an important role for its voltage withstand against the rod. The degree of addition should not compromise the mechanical flexibility of the dielectric rod.

The capacitance per unit of length of the cable is also influenced by the geometry of the cable and the dielectric material between inner and outer conductors, represented by its relative dielectric permittivity. With regard to geometry, it depends on the ratio of outer, *De*, and inner, *Di*.

Therefore, considering the above, it is possible to design a cable with different input and output characteristic impedances. As in the example of Fig. 7, for having a high input impedance the cable must have a sending end with large inductance per unit of length and small capacitance per unit of length which can be done with the proposed helical winding of the inner conductor as well with a small ratio of *De* and *Di*. Thus, by keeping the inner diameter as constant and by increasing linearly the outer diameter, the inductance remains the same whereas the capacitance increase which causes the output impedance to decrease.

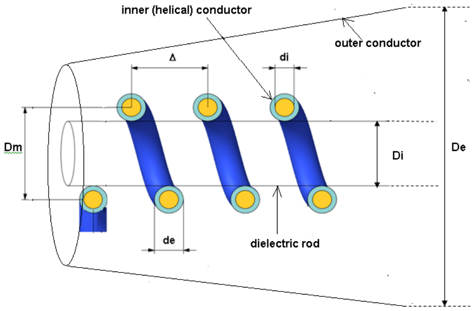

Fig. 7 Helical-coaxial cable – A Special design for increasing the cable impedance along its length.

Although the proposed cable can really present a significant time interval for a voltage wave to travel along it, it is almost unavoidable that still a long length of cable may be required for avoiding the successive incidence of reflecting voltage waves on the output voltage. Therefore, the proposed suggestion of the authors is that an additional resistor may be shunt to the input impedance of the cable as well as an additional gap, as presented in Fig. 9. Based on comparison to energy stage of Fig. 4, this new circuit has a resistance R_o with value equal to the input impedance of the cable, Z_o. Thus, the presence of a new spark gap, S' will cause disconnection between charged capacitor and cable and thus any reflected wave from the cable will face only the matching resistor R_o. In this way, no reflection wave will happen to travel towards the receiving end for influencing the output voltage.

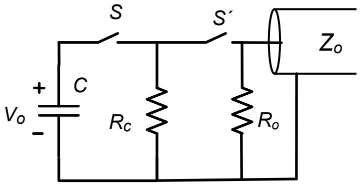

Fig. 8 Additional matching resistor and spark gap for avoiding the incidence of successive reflecting waves on the output voltage.

By taking the proposed solutions, the adjustment of any wave shape of a high-voltage impulse test may become an easier task. Nevertheless, it is necessary to check experimentally all the items of the proposed circuit. Only experimental tests will allow checking the degree of influence of some unavoidable items that were not discussed. As example, we can mention the effect of the edges for the electric and magnetic field within the cable that can cause significant changes in capacitances and inductances, respectively. Also, the degree of wave distortion and attenuation experienced for a traveling wave along any transmission line that depends on the electric characteristics of all the materials used for assembling the proposed cable.

However, if this proposed circuit becomes feasible, there will be some other achievements to accomplish about this proposition. One of them is that the charging voltage of the capacitor C_c of the energy stage can be significantly reduced with this proposed circuit. About a half of the previous voltage, if V'_o is compared to V_o that makes the efficiency of the impulse generator to increase as a whole. This is only possible due to the presence of the cable as a transmission line, which allows the incident wave to double its value when getting at the receiving end.

V. CONCLUSION

Since the adjustment of an impulse generator for matching its output voltage wave shape to standard requirement may represent a very troublesome task, based on trial-and-error, the authors have proposed a new conception of circuit to be used in this test. This circuit is based on principles of transmission line and wave propagation and a coaxial cable with a special design is suggested to be tested. This is a helical-coaxial cable with different input and output impedances. It itself does not solve the likely problems of successive reflecting waves, for which an additional spark gap and matching resistor are proposed. If proposition is as promising as it seems , a remarkable increase of efficiency of an impulse generator may be reached as well as the task of the wave adjustment of the impulse generator is no longer a so hard task. Experimental tests are required.

VI. REFERENCES

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