Application of computer simulation for the design of a new high voltage transducer, aiming to high voltage measurements at field, for DC measurements and power quality studies

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Abstract: - This paper shows the development of an improved high voltage transducer for field application, for DC measurements and for use in power quality studies. This paper shows the application of computer simulations using PSPICE program Student version [1], where many different approaches and solutions are analyzed, aiming to the damping of voltage oscillations in the capacitive divider output, caused by inductances present in field measurements, besides of the inherent undamped behavior of the capacitive divider, and for reducing the electromagnetic interferences during the measurements.

Key-Words: - capacitive divider, high voltage, PSPICE, switching transients, high voltage measurements, atmospheric impulse voltages

1 Introduction

High voltage measurements at field using capacitive dividers and others types of voltage transducers are becoming a common practice in distribution and transmission substations when information from instruments transformers are not available [2, 3, 4]. These measurements are useful, for instance, in power quality and system overvoltage studies [5, 6,7,8,9,10]. In this research, a novel type of capacitive divider was developed, which incorporates the capability of to measure also DC high voltages, useful for example when it is important to measure residual voltages in de-energized equipment of capacitive nature (high voltage cables, capacitors). The prototype developed in this research, for its very high impedance for DC voltages, almost don’t change the time constant of the circuit to be measured. This paper shows the computer simulations using PSPICE program Student 9.1 version, where many approaches and solutions were analyzed, aiming to damp the voltage oscillations caused by inductances present in the measurement setup.

2 Characteristics of the capacitive divider

Fig.1 shows a simplified circuit used in the computer simulations. In the real prototype, the secondary low voltage branch of the capacitive divider is composed by a more sophisticated electronic circuit, aiming to enhance the input impedance of the voltage recorder. All the capacitances of the high voltage branch (C1) are identical with nominal value of 500pF. The number of 500pF capacitances can be changed according to the expected voltage to be measured, in order to limit the voltage on the C2 capacitance (10uF) to its nominal value. The damping impedance has a very important role in the capacitive divider performance during transient voltages measurements, because of the inherent oscillatory behavior of the capacitive divider, caused mainly by the presence of parasitic inductances of the leads, represented by L1 inductance in Fig. 1.

The prototype of the transducer for high voltage measurements was conceived considering the characteristics:

- high input impedance, for not to discharge the C2 secondary branch capacitance during DC voltage measurements, in order to be possible the measurement of DC high voltages.
- compatibility of the discharging time of the secondary branch circuit with the time constant of the circuits to be measured.
- operation in DC, and frequencies from 60Hz up to 5 kHz.
- flat frequency response from DC up to 5 kHz.
- good performance at field, considering a typical environment with high temperature, moisture, dust and electromagnetic interference.

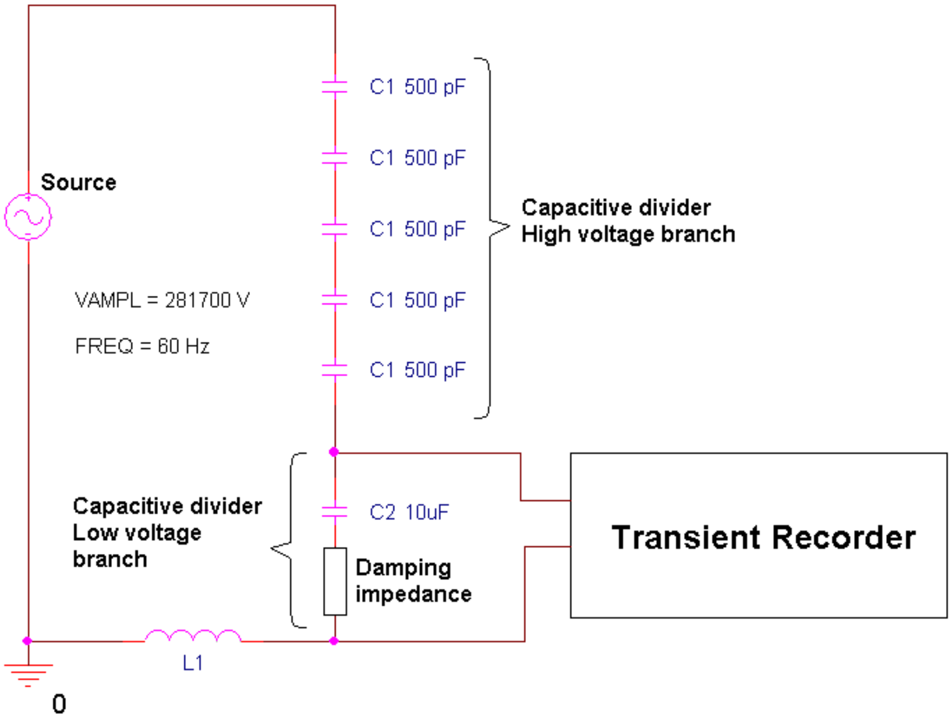

Fig. 1 Simplified circuit used in the computer simulations.

3 Factors influencing the performance of the capacitive divider

The performance of the capacitive divider is affected by many factors, including:

- Nature of the signal to be measured.
- Damping impedance.
- Inductances present in the measurement setup.

The inherent presence of the parasitic inductances of the leads between the capacitive divider and the voltage recorder causes an oscillatory behavior. The value of this parasitic inductance can change according to the particular setup used during the measurement.

The type of signal to be measured affects the performance of the divider. In this research, it was considered the measurement of voltages from DC up to 5 kHz, assumed to be sufficient for measurements of most switching transients in electrical power systems.

4 Influence of the inductance of the leads and connections and damping impedance – computer simulation

In this section, the influence of the leads and connections of the measuring setup, and also of damping impedance and filtering inductance were analyzed, by using computer simulation.

4.1 Performance of the voltage divider under switching and atmospheric impulse – influence of 100μH filter applied to the circuit's input - computer simulation.

In order to assess the expected performance of the voltage divider when measuring voltage switching transients, computer simulations using PSpice/Capture program were performed. The influence of a 100μH inductance applied to the circuit's input (for filtering purpose), between the voltage source and the high voltage branch C1 of the voltage divider, was analyzed. Fig. 2 shows the simulation result, considering a switching impulse voltage with front time of 250μs.

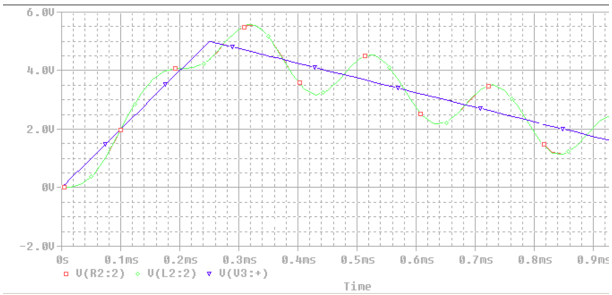

Fig. 2 Voltage divider output (in green) for switching impulse (in blue) with front time of 250µs, filter with inductance of 100µH.

In addition, computer simulations considering atmospheric impulse, with front time of 1us and 10 us were performed. Again non satisfactory results, shown in Figs 3 and 4, were obtained.

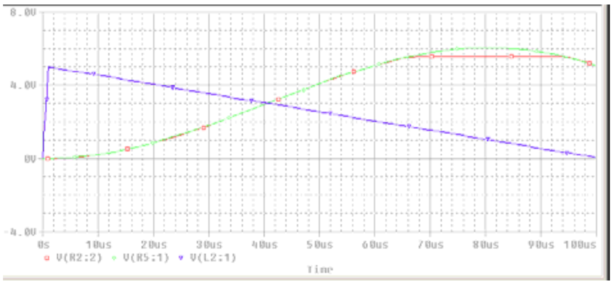

Fig. 3 Voltage divider output (in green) for atmospheric impulse (in blue) with front time of 1µs, filter with inductance of 100µH.

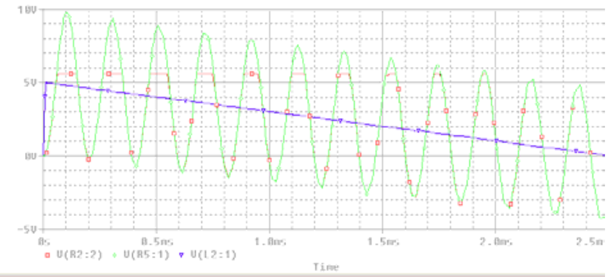

Fig. 4 Voltage divider output (in green) for atmospheric impulse (in blue) with front time of 1µs, filter with inductance of 100µH.

Simulation results in Figs. 2, 3 and 4 show that the use of inductive filter of 100µH value causes an oscillatory output voltage.

4.2 – Performance of the voltage divider under switching impulse – influence of damping impedance applied to the circuit's input (computer simulation).

In this section, the influence of a shunt damping impedance (see Fig. 1), applied in series with the capacitive column of the capacitive voltage divider was analyzed. Fig. 5 shows the output voltage when an atmospheric impulse in applied to the circuit's input. Damping impedance 1Ω and inductance of the grounding connection 100µH (L1 in Fig. 1).

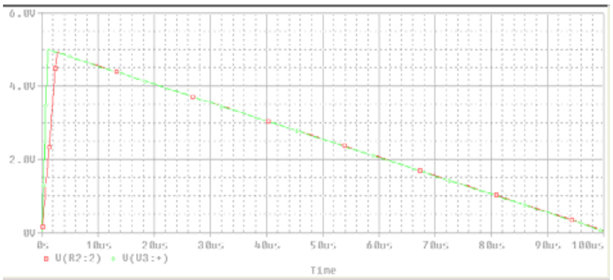

Fig. 5 Voltage divider output (in green) for atmospheric impulse voltage (in blue) with front time of 1µs, inductance of 100µH and damping impedance of 1Ω.

The influence of the inductance of leads and connections of the measurement setup was analyzed, considering different values of the damping impedance. Fig. 6 shows the output voltage, when an impulse voltage with a front time of 100µs is applied to the high voltage branch of the capacitive divider (inductance 100µH, damping impedance of 1Ω).

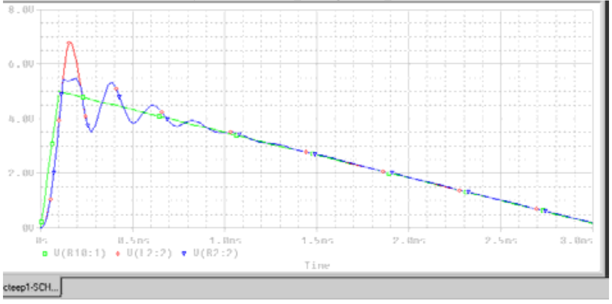

Fig. 6 Divider output (blue line) for impulse voltage (green line) with front time of 100µs, inductance of 100µH, damping impedance of 1Ω.

Fig. 7 shows divider output for impulse voltage with front time of 100us, inductance of 100µH, damping impedance of 10 Ω.

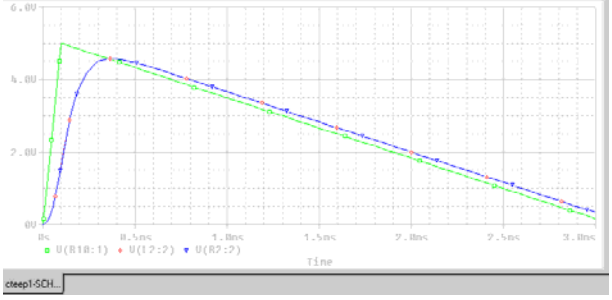

Fig. 7 Divider output (blue line) for impulse voltage (green line) with front time of 100µs, inductance of 100µH, damping impedance of 10Ω.

Fig. 8 shows divider output for impulse voltage with front time of 100µs, inductance of 100µH, damping impedance of 100 Ω.

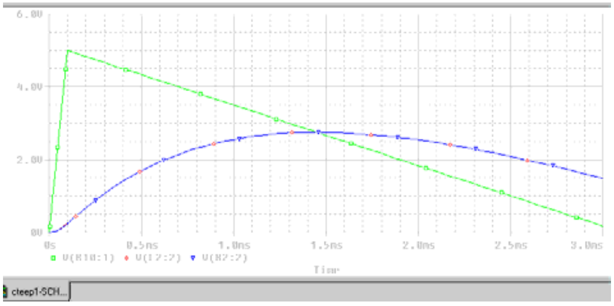

Fig. 8 Divider output (blue line) for impulse voltage (green line) with front time of 100µs, inductance of 100µH, damping impedance of 100Ω.

Additional computer simulations were made for input impulse voltage with front time of 250µs, considering that this is the typical front time value for power systems switching transients.

Fig. 9 shows divider output for impulse voltage with front time of 250µs, inductance of 100µH, damping impedance of 1 Ω.

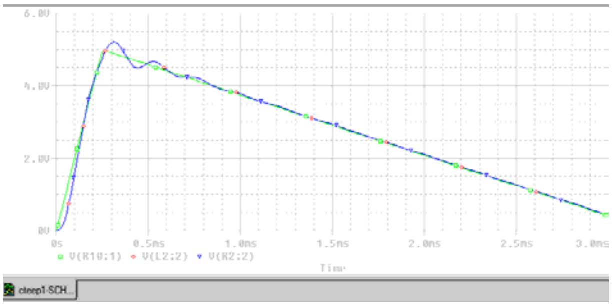

Fig. 9 Divider output (blue line) for impulse voltage (green line) with front time of 250µs, inductance of 100µH, damping impedance of 1Ω.

Fig. 10 shows divider output for impulse voltage with front time of 250µs, inductance of 100µH, damping impedance of 10 Ω.

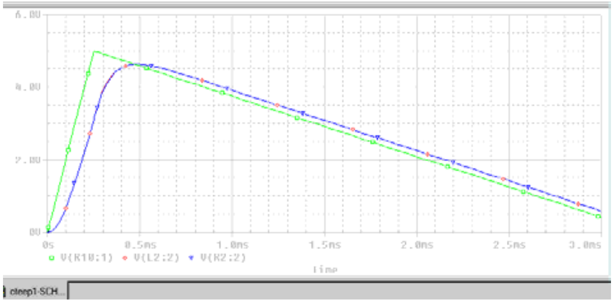

Fig. 10 Divider output (blue line) for impulse voltage (green line) with front time of 250µs, inductance of 100µH, damping impedance of 10Ω.

Fig. 11 shows divider output for impulse voltage with front time of 250µs, inductance of 100µH, damping impedance of 100 Ω.

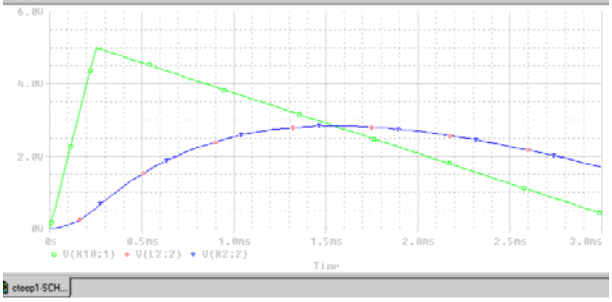

Fig. 11 Divider output (blue line) for impulse voltage (green line) with front time of 250µs, inductance of 100µH, damping impedance of 100Ω.

Considering the computer simulations, the best results were obtained with the damping impedance of 1 Ω.

According to the analyses, for switching impulses characterized by front time of 250µs and time to half-value of 2500µs [2], a good performance of the capacitive divider is expected.

5 Laboratory tests

Aiming to verify experimentally the results of the computer simulations, tests where performed in the high voltage laboratory, using an impulse generator (max. impulse voltage 4000kV). The lab tests can also simulate some field conditions, for the presence of high voltage sources and high electrical fields, and it is possible to verify the immunity of the cable used to transmit the divider signal.

Fig. 12 shows the laboratory setup for the switching transients tests.

Fig. 12 Laboratory setup for the switching transients tests, showing the capacitive divider (at left), impulse generator (center) and the reference divider (at right).

The switching transients tests were performed, by applying to the capacitive divider impulse voltages with peak amplitude of 220kV and front time of 200μs. Fig. 13 shows a record of the impulse voltage applied to the capacitive divider.

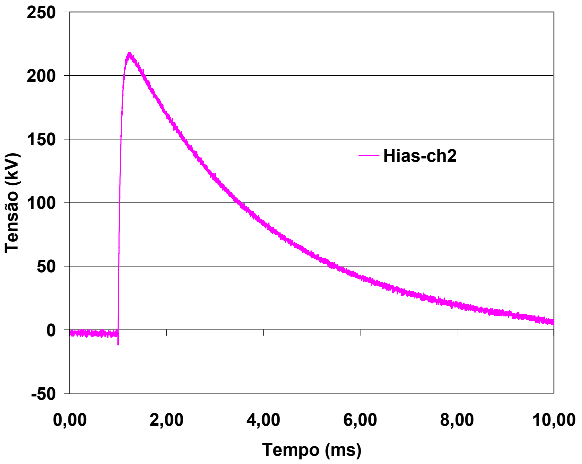

Fig. 13 Record of the impulse voltage applied to the capacitive divider, peak amplitude of 220kV, front time of 200μs.

Fig. 14 shows the effect of the damping impedance on the capacitive divider response to switching impulse, compared to the response of the divider without the damping impedance.

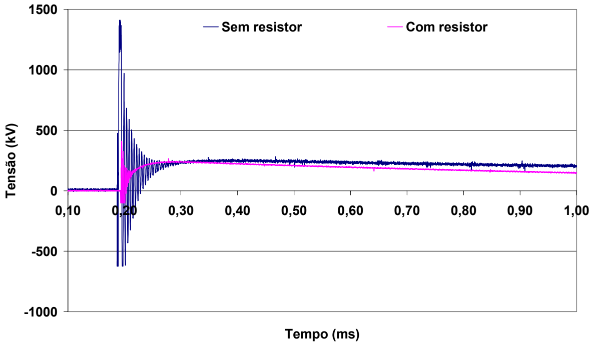

Fig. 14 Capacitive divider response, with a 1 Ω damping impedance (in blue), and without damping impedance.

The experimental results show the effectiveness of the damping impedance, by reducing the oscillatory behavior, as expected based on the computer simulation results.

By analyzing the experimental and simulation results, the oscillatory behavior seen in Fig. 14 is caused by the inductance of earth connecting leads. A rough estimate of those inductance is about 1 μH/m (10μH in 10 meters) [5].

5.1 – Performance of the voltage divider under switching impulse – laboratory tests

Considering the future use of the capacitive divider in the measurement of residual voltages in underground transmission lines, laboratory tests where performed in order to simulate this condition. Fig. 15 shows the experimental setup, using a 500pF capacitance as high voltage arm of the capacitive voltage divider

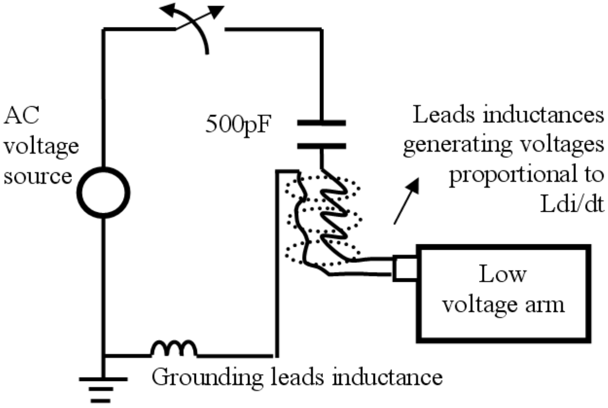

Fig. 15 Setup for switching transients tests.(experimental simulation of transmission line switching).

Fig. 16 shows an example of the measurements performed at the lab, using an oscilloscope. This Fig. shows the oscilloscope screen of discharging curve of a 7,5nF condenser, connected to a resistive divider acting as a load, and resulting in a discharging time of 2,5 seconds. Simultaneously, the signal was measured by the capacitive divider.

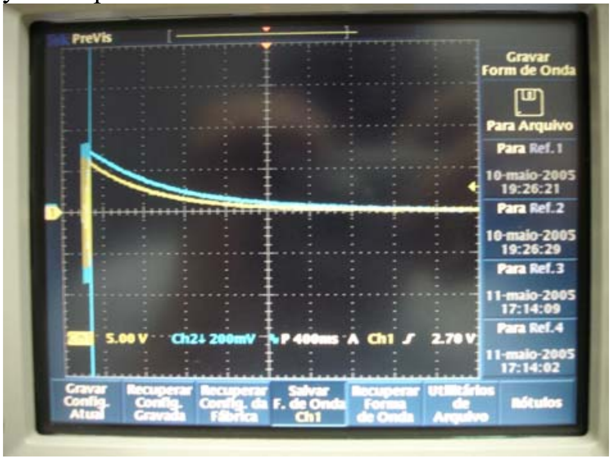

Fig. 16 Discharging curve of a 7,5nF capacitor, connected to a resistive divider acting as load. Comparison of the curves measured by the resistive divider (adopted as Reference) and the capacitive divider (upper line). Picture of oscilloscope screen.

Fig. 17 shows the same waveform obtained by using the digitalized points measured by the oscilloscope, and using Excel program [11].

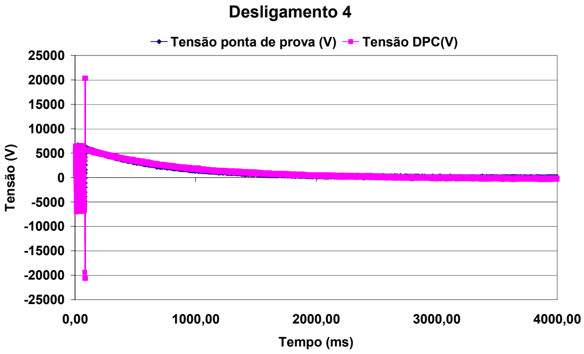

Fig. 17 Discharging curve of a 7,5nF capacitor, connected to a resistive divider acting as load. Comparison of the curves measured by the resistive divider (adopted as Reference) and the capacitive divider (upper line). Digitalized points measured by the oscilloscope, and using Excel program

In Fig. 17 an. overvoltage is observed near the voltage peak. This voltage peak is probably caused by the connecting leads between the Primary and Secondary arms of the voltage divider. During the

tests, it was observed that by using in this connection a twisted cable, the overvoltage can be reduced.
Fig. 18 shows the measurement of an AC switching transient using the capacitive divider and a resistive divider (adopted as reference), compared to computer simulation using PSpice/Capture. This Fig. shows the good agreement of these three results

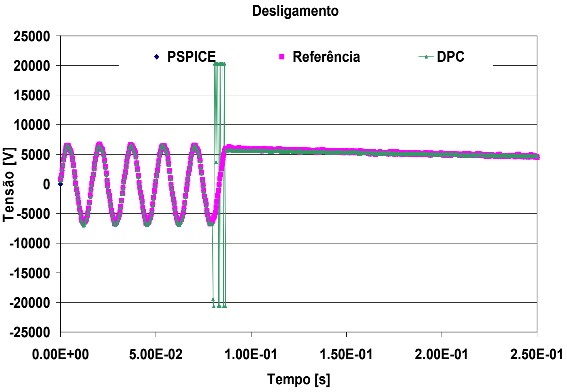

Fig. 18 AC switching transient - Comparison between measurements with a resistive divider, the capacitive divider (adopted as Reference) and computer simulation using PSpice/Capture program.

Fig. 18 shows good agreement between capacitive divider and reference divider (resistive divider). Additionally, Fig. 18 shows good agreement between capacitive divider and computer simulation results. The spurious overvoltage observed during the switching operation is probably caused by the inductances of the connecting leads capacitive and resistive dividers. This overvoltage is observed only in the secondary arm of the capacitive divider, and not in the primary arm, that is, the 500pF primary capacitance.
Additional tests showed that those spurious signals are caused also for radiated interference, generated during the switching process, and conducted interference from the oscilloscope mains.

5.2 Performance of the voltage divider under atmospheric impulse – laboratory tests

In order to verify the behavior of the capacitive divider under atmospheric impulse voltages, an impulse generator was used for to generate standardized atmospheric voltage impulses, with front time of 1,2μs and time to half-value of 50μs [5]. Fig. 19 shows the output voltage of the impulse generator.

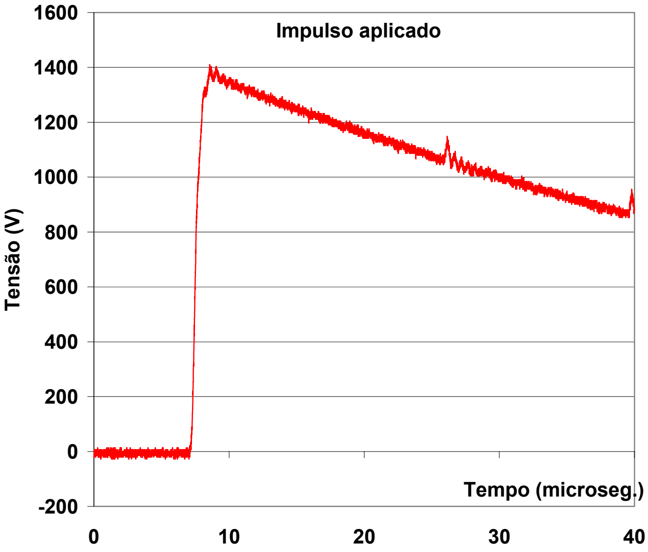

Fig. 19 Typical atmospheric impulse voltage applied to the high voltage arm f the capacitive divider.

Considering section 4.2, the grounding leads inductances' causes an oscillatory behavior in the capacitive divider output. The computer simulation showed that the divider performs poorly for an atmospheric impulse voltage of front time 1,2 μs and time to half-value 50 μs, considering and inductance of the connecting leads of 10μH.
Fig. 20 shows simulation results of the divider output, for an impulse voltage with front time of 1,2μs and time to half-value of 50μs, and inductance of leads of 10μH.

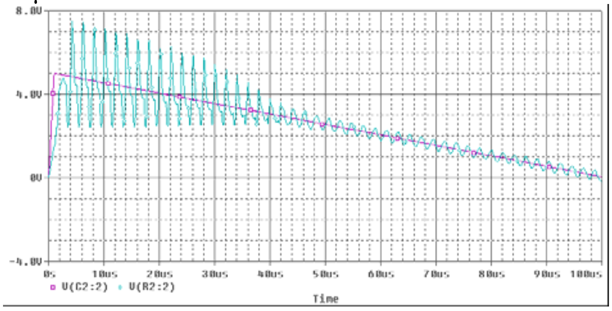

Fig. 20 Oscillatory behavior of the divider output for an atmospheric impulse voltage, caused by connecting leads inductances

During the laboratory tests, results resembling Fig. 20 were obtained. By using computer simulations, for different values of the impulse front time and considering a 10μH inductance for the connecting leads, the minimum value of front time was estimated, in order to obtain a good output voltage in the voltage divider, that is, the minimum value of impulse front time in which very few or negligible oscillation is observed was estimated.

Considering a 10µH inductance for the connecting leads, the minimum value for the front time of the input impulse voltage is 10µs, that is, good results of output voltages are expected for front time in excess of 10µs .

Fig. 21 shows the output voltage of the voltage divider, for an impulse with front time of 10µs. The oscillatory behavior is not present.

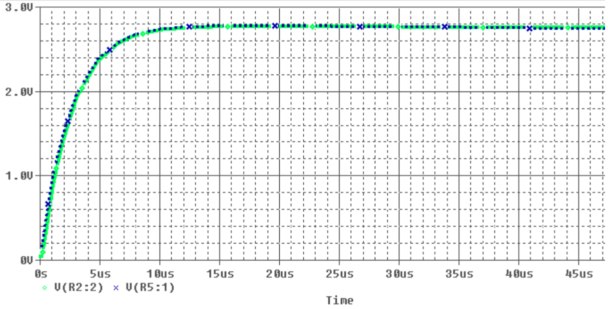

Fig. 21 Divider output (blue line) for impulse voltage (green line) with front time of 10µs, connecting leads inductance of 10µH.

6 Field tests

Additionally, field tests where performed. Fig. 22 shows the setup for the measurement of the residual voltage of an underground transmission line, after disconnection from power source. The tests where performed in a 9km long underground transmission line, voltage 230kV. After the transmission line de-energization, two phases of the line remained connected to inductive voltage transformers.

Fig. 23 shows results of the measurement of the residual voltage where, in this phase, an inductive voltage transformer remained connected to the line. In this way, the discharging of the underground cable can be observed, caused by the power losses in the inductive potential transformer.

Fig. 22 Setup for the measurement of the residual voltage of an underground transmission line (length 9km, voltage 230kV) after disconnection from power source. Capacitive dividers are shown at the right side.

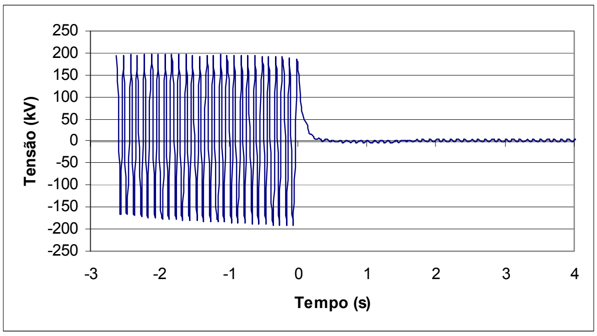

Fig. 23 Residual voltage of underground transmission line (length 9km, voltage 230kV) after disconnection from power source. After disconnection, this phase remained connected to inductive voltage transformer.

Figs 24 and 25 show results of the residual voltages for the other two phases, without inductive voltage transformers.

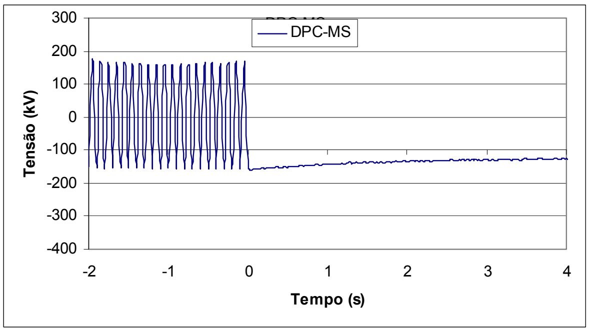

Fig. 24 Residual voltage of underground transmission line (length 9km, voltage 230kV) after disconnection from power source. Phase without inductive voltage transformers.

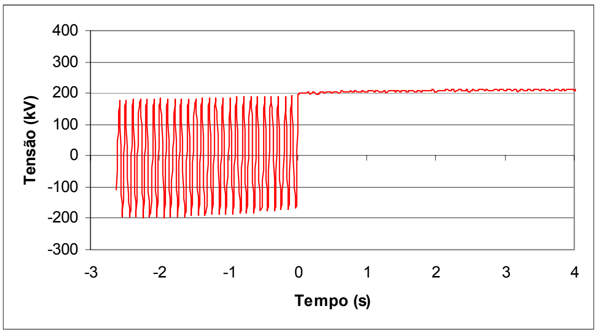

Fig. 25 Residual voltage of underground transmission line (length 9km, voltage 230kV) after disconnection from power source. Phase without inductive voltage transformers.

In Figs. 24 and 25, the discharging of the underground cable is slower, caused by little amount of power losses in these two phases. This measurement was accomplished successfully thanks to the very high input impedance of the secondary arm of the capacitive divider, for DC voltages.

The conventional measurement of DC like voltages, like the ones shown in Figs. 24 and 25 after the disconnection of the line from power source, is in general made by using resistive voltage dividers. This approach in this case wouldn't give good results, because the resistive voltage divider, acting as resistive load, could discharge by itself the cable electrical charge, leading to wrong results in the measurement of the residual voltages.

7 Conclusion

The capacitive divider developed in this research proved to be effective in the measurement of DC like high voltages. The very high impedance, for DC voltages, of the secondary arm of the capacitive divider make possible the measurement of the residual voltages, without changing the circuit's time constant and without becoming a resistive load for the circuit. The use of conventional resistive dividers would lead to wrong results in the measurement of residual voltages.

The laboratory tests and the analysis using computer simulation showed that the developed capacitive divider is effective in measurements of impulsive voltages with front time in excess of 10 µs. In this way this capacitive divider is suitable for the measurement of most of the switching transients in power systems.

The use of computer simulation optimized efforts, allowing reduction in the costs and in the time consumed during this development.

References:

[1] Cadence Design Systems, Pspice/Capture student 9.1 version program, (http://www.orcad.com/download/orcaddemo.aspx , accessed on May 1st, 2008).

[2] Mercure H.P., Nguyen D.H., et al., Effect of Stray Capacitance on the Accuracy of Capacitive Voltage Transformers, Proc. 10th International Symposium on High Voltage Engineering, Montréal, Canada, 1997.

[3] Seljeseth H, Saethre E.A., Ohnstad T., Voltage Transformer Frequency Response. Measuring Harmonics in Norwegian 300kV and 132kV Power Systems. Proceedings IEEE 8º International Conference on Harmonics and Quality of Power ICQHP '98, Athens, 1998.

[4] Bradley D.A., Bodger P.S., Hyland P.R., Harmonic Response Tests of Voltage Transducers for

the New Zealand Power System, IEEE T-PAS, vol PAS-104, nº 7, 1985.

[5] Zaengl W.S, Kuffel E.W., High Voltage Engineering, Newness, Oxford, 2000.

[6] Dugan R.C., McGranaghan M.F., Santoso S., Beaty H.W., Electrical Power Systems Quality, 2nd Edition, McGraw-Hill, 2004.

[7] Panoiu M., Panoiu C., Osaci M., Muscalagiu I., Simulation Result about Harmonics Filtering using Measurement of Some Electrical Items in Electrical Installation on UHP EAF, WSEAS Transactions On Circuits And Systems, Issue 1, Volume 7, January 2008.

[8] Tung .N.X, Fujita. G, Masoum. M.A.S, Islam .S.M, Impact of Harmonics on Tripping Time and Coordination of Overcurrent Relay, 7th WSEAS International Conference on Electric Power Systems, High Voltages, Electric Machines, Venice, Italy, November 21-23, 2007.

[9] Yang Han, Mansoor, Gang Yao, Li-Dan Zhou, Chen Chen, Harmonic Mitigation of Residential Distribution System using a Novel Hybrid Active Power Filter, WSEAS Transactions on Power Systems, Issue 12, Volume 2, December 2007, ISSN 1790-5060.

[10] Seifossadat S.G., Razzaz M., Moghaddasian M. Monadi M., Harmonic Estimation in Power Systems Using Adaptive Perceptrons Based on a Genetic Algorithm, WSEAS Transactions On Power Systems, Issue 11, Volume 2, November 2007, ISSN 1790-5060.

[11] Microsoft Corporation, Microsoft Office Excel 2003 SP3.