HIGH VOLTAGE IMPULSE GENERATOR TRANSIENT STUDIES -AN ALTERNATIVE TO THE STANDARD CALIBRATION PROCEDURE

Edilson E. de Castro, Marcelo Ricardo de Moraes and Manuel Luís Barreira Martinez

EFEI - Escola Federal de Engenharia de Itajubá
IEE - Instituto de Engenharia Elétrica
DET - Departamento de Eletrotécnica
LAT-EFEI - Laboratório de Alta Tensão da EFEI
Cx. Postal 50 - Itajubá - Minas Gerais - Brasil
CEP – 37.500-000
Phone: +55-35-629-1251 - Fax: +55-35-629-1187
E-mail: martinez@iee.efei.br
marcelomoraes60@hotmail.com

Abstract - **This paper shows results obtained in the High Voltage Laboratory of Escola Federal de Engenharia de Itajubá - LAT-EFEI regarding the necessity of determining the operational characteristic of a 1.2kJ - 450kV Impulse Generator. These data are normally supplied with the equipment. When considering the age of the present generator, from the beginning of the 60's, they were not originally supplied.**

All possible connections of the impulse generator, when testing lumped capacitances were modeled by EMTP-ATP - Electric - Magnetic Transient Program. The obtained results, i.e., impulse front and tail time and generator efficiency, were applied to determine the operational characteristics of the generator. Laboratory results on testing objects, capacitances and insulators, confirm the accuracy of this procedure.

A simplified method to validate the whole system, based on simulations and on low voltage measurements, was developed.

Keywords: Transient Analysis, Modeling, ATP-EMTP, Impulse Voltage Generators, Lightning Impulses Testing Procedures

I INTRODUCTION

High Voltage Impulse Generators aim at reproducing impulse voltages suitable to model lightning and switching discharges. These impulses are used for studying and checking the performance of the insulation of electrical equipment for power systems.

In *LAT-EFEI*, there is a *HAEFELY - High Voltage Impulse Generator - 1,2 kJ, 450 kV*. This generator has *4* standard connections, *6S-1P*, *3S-2P*, *2S-3P* and *1S-6P* *[Connection of the Charging Capacitors, S – Series, P – Parallel]* that present several possible combinations of resistors - series and parallel - and charging capacitors.

The modeling of the *1.2 kJ – 450 kV* impulse generator configurations were carried out considering all these possibilities. All studies were based on traditional studies of single stage impulse generators and considered the parameters related with the impulse shape; in the specific case of *LAT – EFEI, Lightning Impulses*. The models were developed in the *Electric Magnetic Transient Program – EMTP-ATP*.

The operational characteristics of *LAT-EFEI* impulse generator, as curves reporting the *Front Time*, *Tail Time* and *Efficiency* versus *Load Capacitance* were obtained from the results of the simulations.

The verification of the accuracy of the simulations were based on direct measurements, by oscillograms, on load-non load condition and fitted pretty well, in average, with the computed values.

These measurements were carried out in different days with different conditions of temperature, atmospheric pressure and content of water in the air. These results permitted to confirm the shape of the impulses. By the application of standard statistical procedures it was also possible for both polarities, positive and negative, to compute the average efficiency of the impulse generator that. Finally was checked against computed values.

For sure some deviations were found but in average the computed results are considered representatives. These deviations can be addressed, when of impulse with low and high amplitude to non-linearities in the *Trigatron Device*. When of impulses of high amplitude this can also be addressed to the presence of corona .

II DEVELOPMENT

II.1 THE VOLTAGE IMPULSE WAVE

The impulse voltages, reproduced by *the Impulse Generators*, must satisfy conditions issued in the standards.

Therefore, the voltage impulse shape used in impulse tests must be in accordance to the *Brazilian Standard – NBR 6936 – High Voltage Testing Techniques*. The impulse voltage must have a sharp front with a rise time - T_F close to $1,2\mu s$ - and a slow tail with a time to half value - T_C close to $50\mu s$. This impulse is known as *1.2/50 impulse*. The parameters, rise or front time - T_F and time to half value or tail time - T_C, are obtained directly from the oscilograms, according to the procedures stated in Fig. 1.

The following tolerances are acceptable:

- *Voltage Peak: 3%.*
- *Front Time – T_F: 30%.*
- *Tail Time – T_C: 20%.*

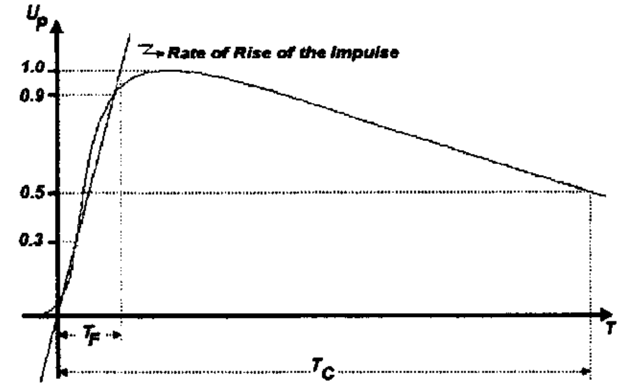

Fig.1. Standard Impulse Shape

Generally, the impulses presents high frequency oscillations due to trapped voltage and eddy current in the generator components. To consider the presence of oscillations, with a frequency at least *0,5 MHz*, it is possible to draw an average curve. This new curve is used to evaluate the impulse accuracy. In this case the amplitude of these oscillations can not exceed in *5%* the amplitude of the average.

II.2. STANDARD CONFIGURATIONS FOR THE IMPULSE GENERATOR

A- 6S-1P CONFIGURATION

Figure 2 shows the standard configuration *6S-1P*. This is the highest voltage configuration and also that one that has the lowest efficiency, because it presents the lowest ratio between the charging and surge capacitors.

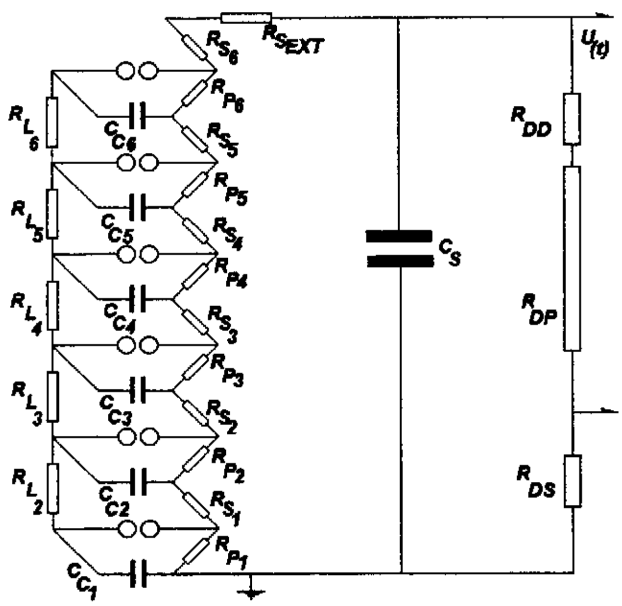

Figure 2. Electrical Diagram of the Configuration 6S-1P.

The system is formed by a group of capacitors – C_C *" Charging Capacitors"* that are charged in parallel by U_D *"Charging Voltage per Stage"* through resistors - R_L, *"Charging Resistors"*. When the generator sparks the charging capacitors are connected in series by the internal sphere gaps, then their voltages are added. *The Trigatron Device*, by means of a graded potentiometer controls the sparking voltage of the generator. After the generator spark the charging capacitors, now connected in series, discharge through a dümping circuit formed by the series resistors - R_S, *"Series Resistors - Internal and External"*, by the parallel resistors - R_P, *"Parallel Resistors - Internal and External (Voltage Divider Circuitry)"* and by the external capacitor – C_S, *"Surge Capacitor"*.

During the generator discharging time, the charging capacitors, in series, can be considered as a single capacitor with a capacitance equals to *1/6* C_C.

The parallel resistors R_{DD}, R_{DP} and R_{DS} are part of the voltage measurement system, the voltage divider, where the impulse oscilloscope and a peak voltmeter are connected. Through these systems the voltage impulse is measured and recorded. In the normal range of testing capacitances the impedance of the voltage divider system presents a small influence on the impulse peak and shape. The same comment can be addressed to the influence of the charging resistors - R_L.

B- 3S-2P CONFIGURATION

Figure 3 shows the standard configuration *3S-2P*. In this case *3* groups of charging capacitors are connected in series, with each group formed by *2* parallel capacitors.

The highest testing voltage level is lower, but a better efficiency is obtained. This can be addressed to an increase in the ratio between the charging and surge capacitors and also to a reduction on the voltage drop in the series resistors.

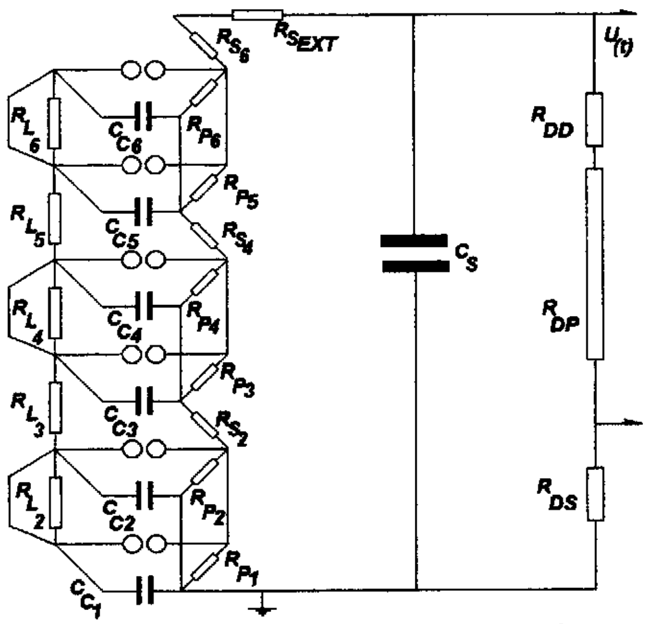

Figure 3. Electrical Diagram of the Configuration 3S-2P.

C- 2S-3P CONFIGURATION

Figure 4 shows the standard configuration *2S-3P*. In this case *2* groups of charging capacitors are connected in series, with each group formed by *3* parallel capacitors.

The highest testing voltage level is still lower, but again a better efficiency is obtained. This configuration is suitable for testing in equipment with *BIL - Basic Impulse Level* close to *100 kV*.

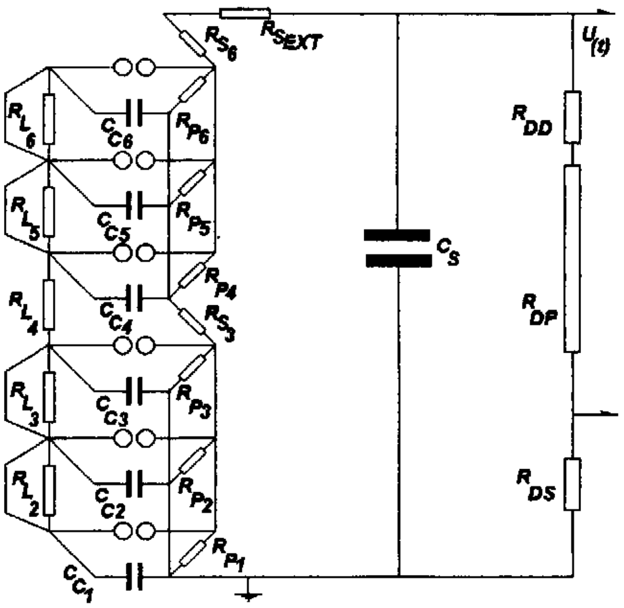

Figure 4. Electrical Diagram of the Configuration 2S-3P.

D- 1S-6P CONFIGURATION

Figure 5 shows the standard configuration *1S-6P*. In this case all the capacitors are connected in parallel. A final $6xC_C$ capacitance is obtained. This is responsible for the increase in the efficiency, the highest among all the configurations. This configuration is suitable for testing in equipment with *BIL - Basic Impulse Level* close to *50 kV*.

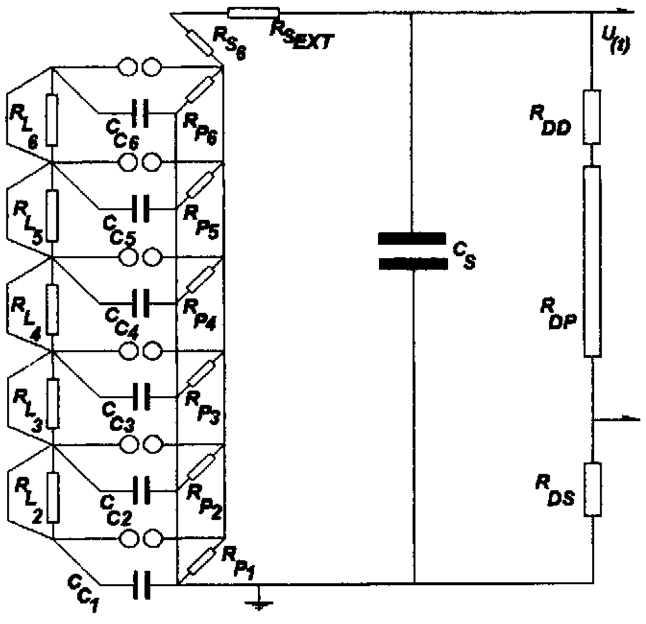

Figure 5. Electrical Diagram of the Configuration 1S-6P.

E- GENERAL COMMENTS

The *LAT-EFEI* impulse generator is very small with only *1.2 kJ*. This means that this generator presents a low charging capacitance – surge capacitance ratio. As a direct result of this the efficiency and the wave shape present a wide range of values. Once into reasonable range, normally stated in the standards this does not result in further claims. However, every time when testing new apparatus it is necessary to choose the right configuration.

The object of this paper is to show how to apply a common transient analysis tool to improve the solution of this problem. This paper deals with testing objects that can be modeled by lumped capacitors. Therefore, for cables or even transformers the presented data can be faced with some reservation due to the presence of oscillations.

III SIMULATIONS AND RESULTS

Simulations considering all the basic configurations were carried out by means of the *Electric Magnetic Transient Program – EMTP-ATP*. The operational data in form of characteristic curves reporting the prospective *Front Time - T_F*, *Tail Time - T_C*, and *Efficiency - η* of the generator versus the *Capacitance of the Testing Objective* were developed, as shown in *Fig 6*, *7* and *8*.

Considering the possibility of removing some fixed parts of the circuitry, normally, some series and parallel resistors, they were also developed characteristics that show the highest value for the energy in the resistive elements. In order to verify the adequacy of thesecircuitry modifications the obtained results were checked against the standard – i.e. the designed – limits, that were obtained when of the simulations of standard the configurations.

Taking into account the limits fixed in the standards these data are responsible for the definition of the operational data limits stated in *Table 2*.

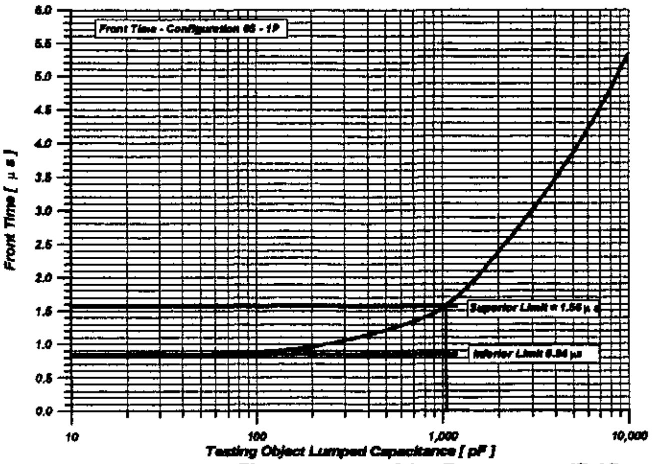

Figure 6. Front Time Characteristic of the Generator – 6S-1P

Specifically for *6S-1P* and*3S-2P* configurations, to consider the operational characteristic of all the possible testing set ups, complementary simulations taking into account modifications on the generator circuitry - by removing or short circuiting some series resistors - were carried out. This was aimed at obtaining a better *Front Time – T_F* when testing equipment designed to present high stray capacitances. The increase of the series resistance value results in an increase in the *Front Time – T_F*. An increase of the parallel resistance value results in an increase in the prospective *Tail Time - T_C*. Both parameters are responsible for the control of the impulse shape. It is also possible to deal with the charging capacitance value but, in this specific case, this is not an easy task, mainly due to the generator physical construction.

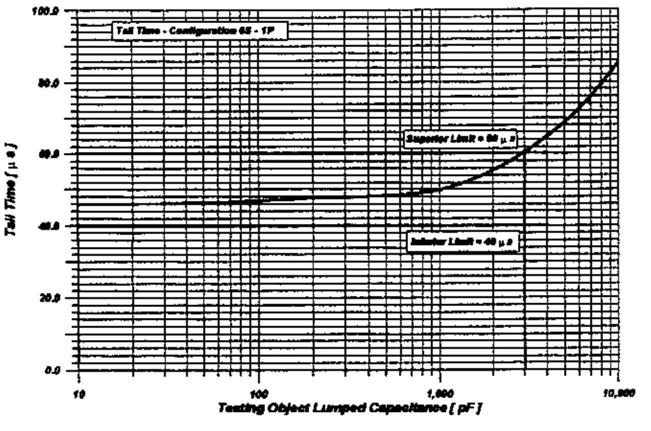

Figure 7. Tail Time Characteristic of the Generator – 6S-1P

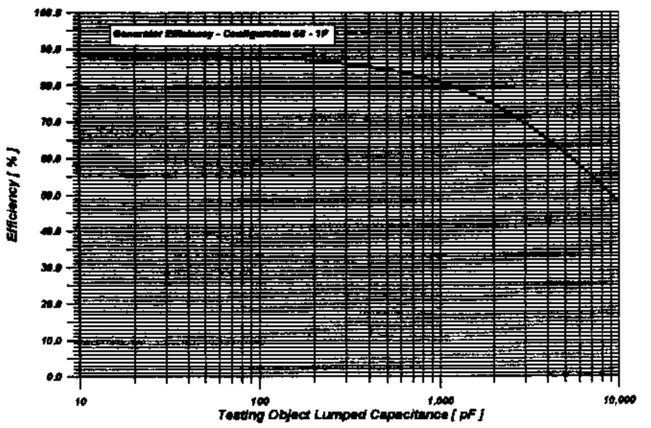

Figure 8. Efficiency of the Generator – 6S-1P

From the study of all the obtained operational characteristics - similar to *Fig. 6, 7* and *8* - it is possible to conclude that the range of the intrinsic capacitance of the testing is independent of the impulse generator configuration. This means that the choice of the generator configuration depends mainly on the *BIL - Basic Impulse Level* of the tested equipment, as shown by *Table 1*.

Configuration	Unload Peak Voltage [kV]	Unload Efficiency [%]	Testing Object Lumped Capacitance Range [pF]		
			Front Time	Tail Time	Operational Range
6S-1P	395	88.3	0-1150	3000	0-1150
3S-2P	210	94.5	0-1200	4000	0-1200
2S-3P	140	95.8	0-1100	3200	0-1100
1S-6P	70	96.7	0-1150	3000	0-1150
6S-1P less 1 R	395	88.5	0-1400	3500	0-1400
6S-1P less 2 R	395	88.7	30-1600	3500	30-1600
6S-1P less 3 R	400	88.9	150-1620	3700	150-1620
6S-1P less 4 R	400	89.1	200-1650	3800	200-1650
6S-1P less 5 R	400	89.4	250-1850	3900	250-1850
6S-1P less 6 R	405	89.8	350-2050	3500	350-2050
3S-2Pless 1 R	210	94.5	0-1300	5000	0-1300
3S-2Pless 2 R	210	94.6	0-1300	4500	0-1300
3S-2Pless 3 R	215	94.7	0-1400	4500	0-1400

Table 1 – Summary of the Operational Characteristic of the 1.2 kJ – 450 kV Impulse Generator of LAT – EFEI.

For all studied configurations, the key factor that limits the capacitance of test equipment is T_F - *Front Time* of the impulse voltage.

In all cases the generator efficiency, as in *Fig 8*, decreases with the increase of the capacitance of the testing object, since in this condition, there is an increase in the voltage drop in the series resistance, an intrinsic characteristic of each configuration.

When considering modified configurations, i.e., those where some of the series resistors were removed, it is possible to improve the requirements referring to the *Front Time* – T_F. This means to test equipment with larger capacitance ranges. In the studied case, these modifications are useful when testing equipment with stray capacitances up to *2 nano-Farads [nF]*.

Regarding the amount of energy dissipated by the resistors, it is possible to observe that the values are in accordance to the role of the resistor in the circuitry. In the case of series resistors, the energy of the resistors does not depend on the resistor position on the circuitry. The value increases with the stray capacitance of the testing equipment. For the parallel resistors, the critical energy value corresponds to the top resistor - R_{P1}, and this value decreases with the increase of the stray capacitance of the testing equipment.

As expected, the energy dissipated by the resistors of the voltage divider is similar to those obtained for the parallel resistors.

Characteristics similar to those shown by *Fig 6, 7* and *8* were developed and are part of the new operational manual of the *1.2kJ - 450 kV Impulse Generator* installed at *LAT-EFEI*.

IV SOME LABORATORY RESULTS

In order to verify the efficiency of the simulations, several lightning impulse tests were carried out and the obtained oscillograms confronted with the simulations and without observing deviations worth of note.

Based in the obtained data it was also verified, by applying standard statistical techniques, the *Medium Efficiency* of the impulse generator. The simulations carried out up to moment deals only with the generator power circuitry. Therefore, no attempt was aimed at the modeling of corona, a basic source of problems when of voltages higher than *250 kV* or even at the modeling of the *Trigatron* – in the present case a *Tube Device*, that is still working in a good shape.

The impulse voltmeter, bases for the comparison, has an internal impulse supply, used in calibration procedures, that was checked by an external oscilloscope.

The whole processes take into account humidity, temperature and other environmental influences because the final value is an average of several measurements carried out in different conditions.

When considering the obtained values it is possible to observe a reasonable difference regarding the generator efficiency. For the low voltage range this can be typically addressed to the *Trigatron Device* circuitry that loses part of its linearity. For the high voltage range this can be addressed to the presence of *Corona*. However the average value, for the complete *Trigatron – Generator* voltage range fits pretty well to the computed as can be seen in *Table 2*. This is a good indication that the generator model developed to the *ATP Program* is a suitable one.

When it is considered that the generator measuring system can be calibrated by easy simple procedures, this is specific for old systems, it is possible by means of simulation to define a calibration procedure. At *LAT-EFEI* this procedure claims for an individual calibration of the crest voltmeter and of the impulse oscilloscope, through a standard oscilloscope. An improved procedure makes use of an extra small surge generator. Considering that the impulse measured values attached pretty well to the computed, obtained from direct measurement of the generator components, i.e.; capacitances and resistances, this procedure can be used to postpone a very expensive in site calibration.

Figure 9 and *10* shows, for the configuration *6S-1P*, the values of *Front Time* – T_F and of *Tail Time* - T_C being the generator in a low load condition around *100 pF*. A *Polaroid Camera* obtained these pictures and the evaluation technique is the standard that claims for the use a ruler scale and a pair of set squares

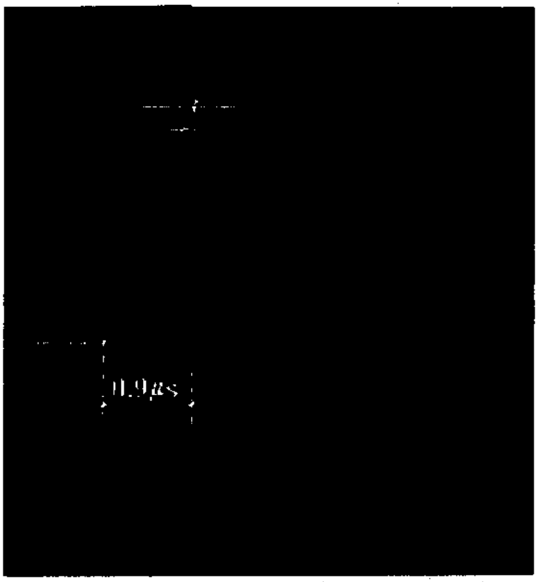

Figure 9 - Front Time – T_F for Configuration 6S-1P Testing a System with 100 pF Lumped Capacitance

V COMMENTS

The impulse generator system is a linear circuit, and in most cases can be simplified to a one stage configuration, as traditionally is done. However some insights on specific values, as for instance energy dissipated by the resistors are not obtained with this technique.

The use of a computer program to calculate these data can render some data for manufacturing and mainly repairing damage resistors. The use of the generator for testing, for instance, insulated cables requires another set of simulations due to the existence of oscillations in the voltage wave shape as can be seen in *Fig 11*. Therefore the present data can be focused as first guide and not a final solution for the operational problem of the generator.

However, it is interesting to remember that the use of the developed operational characteristics of the impulse generator and the measuring of testing object capacitance, by for instance a *Schering - Bridge*, allow the optimization of the calibration of the impulse shape when testing lumped capacitance objects. This also makes easy to define the impulse generator charging voltage and operational range.

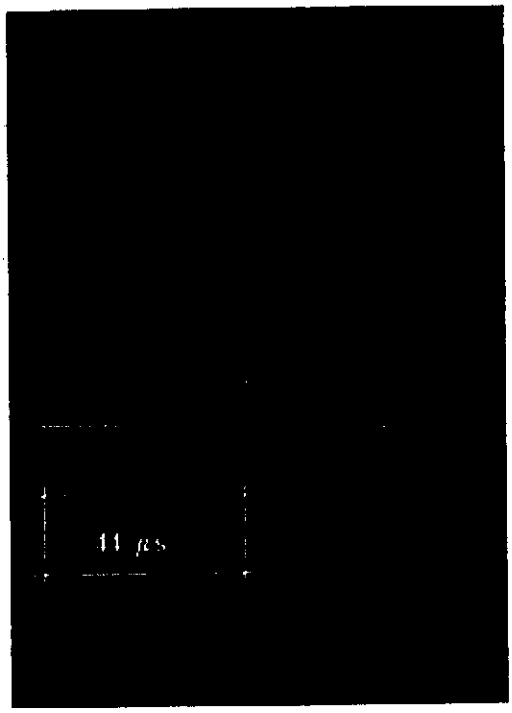

Figure 10 - Tail Time - T_C for Configuration 6S-1P Testing a System with 100 pF Lumped Capacitance

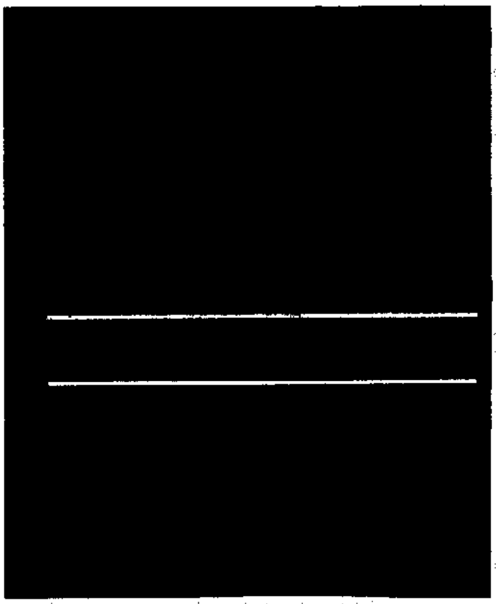

Figure 11 - Front Time – T_F for Configuration 3S-2P Testing 12 meters of 10/8 kV Insulated Power Cable – 35 mm²

In spite of not being a final solution the presented data is a powerful tool when operating the system because can supply in advance a reasonable idea regarding the possibility of using the impulse generator for testing a specific insulating system. Normally it is possible to find a *Front Time* – T_F higher than the issued value, mainly due to

	Efficiency – Positive Polarity (+)				
	Minimum Efficiency	***Minimum Average Efficiency***	***Average Efficiency***	***Maximum Average Efficiency***	***Maximum Efficiency***
	85.103 %	*89.634 %*	*90.384 %*	*91.134 %*	*92.083 %*
	Efficiency – Negative Polarity (-)				
6S1P	***Minimum Efficiency***	***Minimum Average Efficiency***	***Average Efficiency***	***Maximum Average Efficiency***	***Maximum Efficiency***
	83.672 %	*86.287 %*	*87.113 %*	*87.939 %*	*87.787 %*
	Mean Average Efficiency - η = 88.749 %				
	Efficiency – Positive Polarity (+)				
	Minimum Efficiency	***Minimum Average Efficiency***	***Average Efficiency***	***Maximum Average Efficiency***	***Maximum Efficiency***
	89.959 %	*94.692 %*	*95.306 %*	*95.920 %*	*97.160 %*
	Efficiency – Negative Polarity (-)				
3S2P	***Minimum Efficiency***	***Minimum Average Efficiency***	***Average Efficiency***	***Maximum Average Efficiency***	***Maximum Efficiency***
	88.476 %	*91.919 %*	*93.040 %*	*94.61 %*	*94.155 %*
	Mean Average Efficiency - η = 94.173 %				
	Efficiency – Positive Polarity (+)				
	Minimum Efficiency	***Minimum Average Efficiency***	***Average Efficiency***	***Maximum Average Efficiency***	***Maximum Efficiency***
	92.876 %	*94.985 %*	*95.796 %*	*96.544 %*	*96.964 %*
	Efficiency – Negative Polarity (-)				
2S3P	***Minimum Efficiency***	***Minimum Average Efficiency***	***Average Efficiency***	***Maximum Average Efficiency***	***Maximum Efficiency***
	94.244 %	*95.186 %*	*95.837 %*	*96.487 %*	*96.417 %*
	Mean Average Efficiency - η = 95.816 %				
	Efficiency – Positive Polarity (+)				
	Minimum Efficiency	***Minimum Average Efficiency***	***Average Efficiency***	***Maximum Average Efficiency***	***Maximum Efficiency***
	83.158 %	*95.331 %*	*96.178 %*	*97.026 %*	*98.123 %*
	Efficiency – Negative Polarity (-)				
1S6P	***Minimum Efficiency***	***Minimum Average Efficiency***	***Average Efficiency***	***Maximum Average Efficiency***	***Maximum Efficiency***
	85.366 %	*95.533 %*	*96.002 %*	*96.471 %*	*96.902 %*
	Mean Average Efficiency - η = 96.090 %				

Table 2 – Summary of the Impulse Generator Efficiency

oscillations, as can be seen in *Fig. 11*. However, by the other hand the peak value and the *Tail Time* - T_C attaches pretty well with the data as can be seen in *Fig.12*.

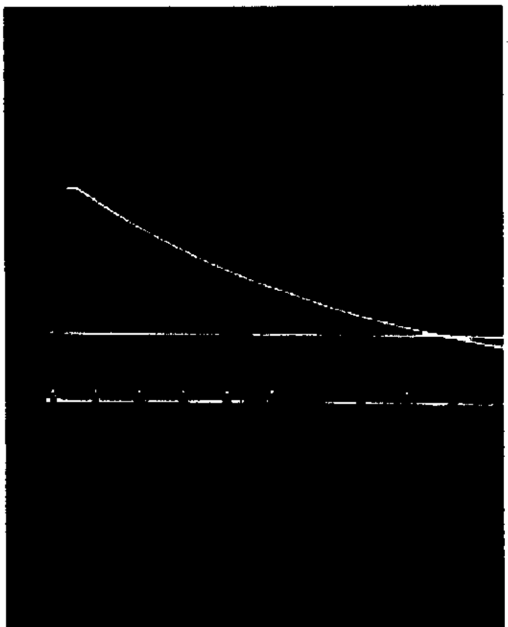

Figure 12 - Tail Time – T_C for Configuration 3S-2P Testing 12 meters of 10/8 kV Insulated Power Cable – 35 mm^2

A complete model of the system, including *Corona* and the *Trigatron Device*, can further explain some differences found in laboratory. However this probably will not improve the day by day laboratory procedures and if it is considered the main application of the generator, for testing distribution class equipment – medium voltage system - this probably will not be so effective for the common practice.

The model can be extended to deal with transformers. The main question in this case is related to the transformer model for impulse voltages. However, according to the present experience the use of the present operational data present a good result.

This paper presented a typical application of simulation techniques to solve a standard problem in a high voltage laboratory. There are a lot of similar problems like this in any *HV-LAB* and the application of these techniques will be a common place in a near future.

REFERENCES

[1] – ATP. User's Manual.

[2] – NBR – 6936, "Técnicas de Ensaios de Alta Tensão". High Voltage Standard

[3] – HAEFELY High Voltage Generator Technical Manual 450 kV - 1.2 KJ.

[4] – ANSI – IEE Standard – 4; "Standard Techniques for High Voltage Testing".

[5] – J.D.Craggs and J.M.Meek; "High Voltage Laboratory Technique; Butterworths Scientific Publications London 1951.