Portable High Voltage Impulse Generator

Generador Portátil de Impulsos de Tensión.

S. Gómez[1], M.P. Buitrago[2], F.A. Roldán[3]

***Abstract*— This paper presents a portable high voltage impulse generator which was designed and built with insulation up to 20 kV. This design was based on previous work in which simulation software for standard waves was developed. Commercial components and low-cost components were used in this work; however, these particular elements are not generally used for high voltage applications. The impulse generators used in industry and laboratories are usually expensive; they are built to withstand extra high voltage and they are big, making them impossible to transport. The proposed generator is portable, thereby allowing tests to be made on devices that cannot be moved from their location. The results obtained with the proposed impulse generator were satisfactory in terms of time and waveforms compared to other commercial impulse generators and the standard impulse wave simulator.**

***Keywords*— Electrical insulation, voltage impulse generator, insulation coordination, power disruption, standardised waves, standardised wave simulator.**

***Resumen*—En este trabajo se presenta un generador portátil de impulsos de tensión, diseñado y construido con un aislamiento hasta para 20 kV. El diseño fue basado en un trabajo previo en el cual se desarrolla un software de simulación implementado exclusivamente para ondas de impulso normalizadas. Los componentes empleados fueron en su totalidad de bajo presupuesto, comerciales y algunos generalmente no son usados en alta tensión. Con el generador de impulsos se obtuvieron resultados satisfactorios en cuanto a tiempos y formas de onda, comparados con otros generadores de impulsos comerciales y el simulador de ondas de impulso normalizadas. Los generadores de impulso utilizados en la industria y laboratorios eléctricos son normalmente de gran tamaño, costosos y fabricados para soportar trabajos en extra alta tensión, ocupando demasiado espacio e imposibilitando su transporte. De ahí la importancia de este proyecto, pues siendo portátil facilita realizar pruebas en elementos que no se puedan desplazar de su ubicación.**

***Palabras Claves:* Aislamiento eléctrico, Coordinación de aislamiento, Disrupción eléctrica, Generador de impulsos de tensión, Ondas Normalizadas, Simulador de Ondas de Impulso.**

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1. INTRODUCTION

Dielectricstrength testsof materialsused aselectrical insulatorsare part of widely used andinternationally accepted qualitytests or trials and they are subject to rulesor standardsestablished bycorresponding institutions,such asthe AmericanSociety forTestingof Materials(ASTM) and the InternationalElectrotechnicalCommission(IEC).

An insulationcoordination study must be done toensurethat high voltagematerialstolerateddifferent overvoltage throughout their life. These techniquesare used to selectthe dielectric strengthor insulationlevel for high voltage materials which mustbe able to support normalised voltages havingdifferent waveforms (the most common types are lightning and switching).

Some authors, (ASTM,2004;IEC, 2001), have stated that impulse voltage generatorscapable ofproviding impulsewaveslarge enough tocause apowerdisruptionin the proof element are neededfordielectric strengthtesting.The tested material's electrical parameters,such ascapacitance,can affectmagnitude and the waveformappliedby the generator. Such capacitance should thus be taken into account when measuring,adjusting andmonitoring thevoltagewaveform.

An impulse generator was designed in (Lora,2008)where most ofthe projectcomponentswere imported,expensive, not verycommercial and built for very specific applications, thisbeingthe greatest disadvantage(high implementation costs).

A simulation and numerical optimisation tool was developedin (Carmano et al) which used a minimum squares variant to compare mathematical model output against the output system. This tool calculated electrical circuit values during impulse trials for elements which could be handled. It was stated that the optimisation model would be better as soon as the amount of difficult to obtain experimental data became expanded.

Another article (Electrical Testing Group) has shown how a voltage impulse generatoris typically used in techniques forfindingfaults inelectricaltransmission and distribution systemsin high and mediumvoltage,calledhigh power reflectometry. It was concluded thatan impulse generatorallows testing transformerstoobtaindatarepresentation, associated capacitance and fault detection regarding transformer insulation.

To complement the aforementionedwork, a voltage impulse wave simulator wasdeveloped,based on wave normalisation using agraph technique ornomogramstudied in (Aguet and Ianoz, 1990) and previously usedinthe proposedsimulation by

(Idarraga and Roldán, 2005),where it was onlynecessary to set thecomponents to be simulatedwithout obtainingpreliminaryexperimental datatoconduct an impulsewave analysis. A portable generatorwas thus designedfrom simulation results,considering the field applicationnoted above; a portable impulse generator was then constructed giving normalised voltage waves for lightning and switching types, using low-cost implementation components. Because of the small scale design, there were limitations on the voltage generator supply as the generator only delivered up to 20kV impulse voltage waves.

2. THEORETICAL BACKGROUND

Voltage impulse generatorsproducewaves which can be classified asimpulselightning and impulseswitching,with 1.2-250 µsstandard front time and 50-2,500 µs for tail time (IEC Standard 60060-1, 1989).

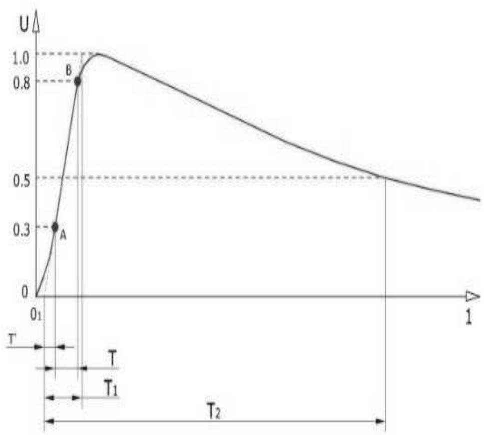

Fig. 1. Lightning Impulse

A. Time measurements for a lightning wave

FronttimeT_1 for a lightning impulse is 1.67 times time interval T (Figure 1, (IEEE Standard 4, 1995)) between the instants when an impulse is 30% and 90% of peak value.Tail time$T_2$for a lightning impulse is the time interval between virtual origin T_o and the instant on the tail when the voltage has decreased to half (50%) peak value.Standardtolerances forfront and tail timeare 30% and 20%, respectively (IEEE Standard 4, 1995; Kuffel andZaengl, 1970).

B. Time measurement for a switching wave

Front time T_{cr},ismeasuredby reaching peak voltage, while tail time$T_h$is measuredwhenmaximum voltagedrops to50%.Standardfront and tail timetolerances are 20% and 60%, respectively (IEEE Standard 4, 1995;Kuffel and Zaengl, 1970)

C. Impulse generator

The generalised schemes for a single stage withcapacitive, resistiveand inductive components are used to generatea standard impulse wave, as shown in Figure 2.

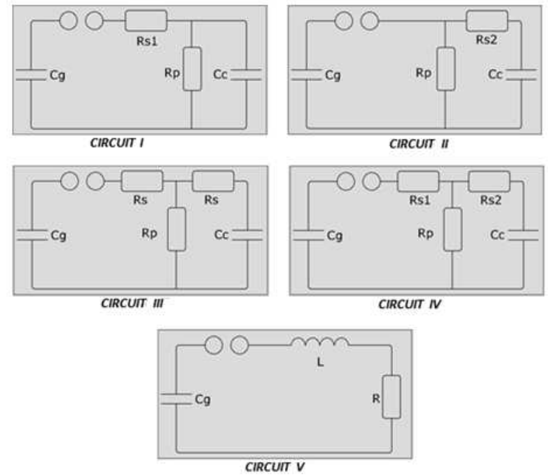

Fig. 2.RLC Circuits. Rs1,Rs2,Rs: Front resistor, Rp: Tail Resistor, Cg: Discharge capacitor, Cc: Charge capacitor, L: Inductor

These kinds of circuit give an impulse wave as output (such as that in Figure3) resulting fromsubtracting twoexponential functions (Aguet and Ianoz, 1990).

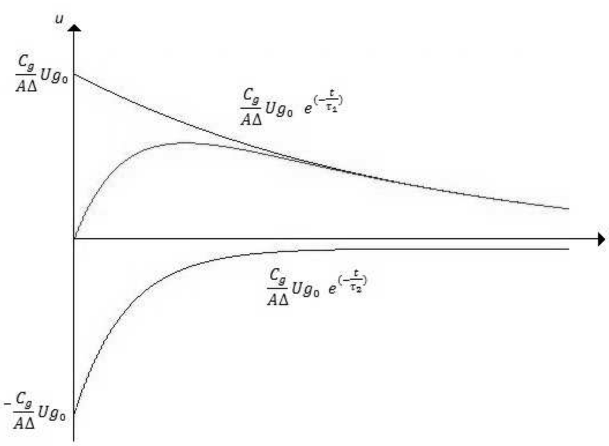

Fig. 3.Characteristic Impulse Voltage

Equation (1) describes this kind of impulse:

$$u_c(t) = \frac{C_g}{A\Delta}Ug_0\left[e^{(p_1 t)} - e^{(p_2 t)}\right], \qquad (1)$$

where, p_1 andp_2 are time constants depending on circuit components (Aguet and Ianoz, 1990).

D. Normalising the wave equation

According to (Aguet and Ianoz, 1990), impulse wave(2) is used fornormalisation:

$$\eta U_c(t) = \frac{\alpha U_{g0}}{\sqrt{\alpha^2-1}}\left[e^{-(\alpha-\sqrt{\alpha^2-1})\frac{t}{\theta}} - e^{-(\alpha+\sqrt{\alpha^2-1})\frac{t}{\theta}}\right]. \qquad (2)$$

Such simplificationis associated with a graph callednomogram orabacus (shownin Figure4) (Aguet and Ianoz, 1990).This graph relatesthe determinant factor ofvoltage impulse shapeα,and the determinant coefficient of time θ.

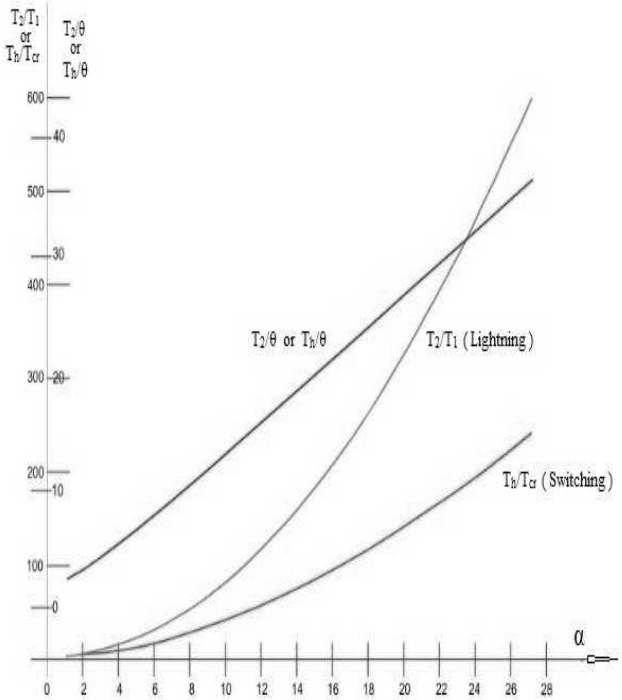

Fig. 4.Nomogram orAbacus

Expressions forT_2/T_1, T_2/θor$T_h/\theta$and$T_h/T_{cr}$are derivedfromthe nomogram curvesusedfor component andtime calculations.

Theseequations simplify the characteristic component calculation for an impulse generatorfrom thetype of knownvoltagewave or voltage impulse waveregardingthe components being used.

E. Characteristic coefficients

Characteristic coefficients α, θ and η are determined for each type of circuit according tothe equations shownin Table1, which were obtained from (Aguet and Ianoz, 1990).

Table 1. Formulas for the characteristic coefficients

Circuit	$\Theta_{(s)}$	$\eta_{(1)}$	$\alpha_{(1)}$
1	$\sqrt{C_g C_c R_{s1} R_p}$	$1+\frac{C_c}{C_g}+\frac{R_{s1}}{R_p}$	$\frac{1}{2}R_p C_g \frac{\eta}{\theta}$
2	$\sqrt{C_g C_c R_{s2} R_p}$	$1+\frac{C_c}{C_g}\left(1+\frac{R_{s2}}{R_p}\right)$	$\frac{1}{2}R_p C_g \frac{\eta}{\theta}$
3	$\sqrt{C_g C_c R_s (R_s+2R_p)}$	$\left(1+\frac{C_c}{C_g}\right)\left(1+\frac{R_s}{R_p}\right)$	$\frac{1}{2}R_p C_g \frac{\eta}{\theta}$
4	$\sqrt{C_g C_c (R_{s1}R_p+R_pR_{s2}+R_{s2}R_{s1})}$	$1+\frac{R_{s1}}{R_p}+\frac{C_c}{C_g}\left(1+\frac{R_{s2}}{R_p}\right)$	$\frac{1}{2}R_p C_g \frac{\eta}{\theta}$
5	$\sqrt{LC_g}$	---	$\frac{1}{2}R_p C_g \frac{\eta}{\theta}$

The equations presented inTable2, which were obtained from (Aguet and Ianoz, 1990), can be used for calculatingthe componentsbased onthe selection of thekind of scheme.

Table 2. Formulas for the components

Circuit	X(1)	Rsi(Ω)	Rp(Ω)
1	$\frac{1}{\alpha^2}\left(1+\frac{C_g}{C_c}\right)$	$R_{s1}=\frac{\alpha\theta}{C_g}(1-\sqrt{1-X})$	$\frac{\alpha\theta}{C_g+C_c}(1+\sqrt{1-X})$
2	$\frac{1}{\alpha^2}\left(1+\frac{C_g}{C_c}\right)$	$R_{s2}=\frac{\alpha\theta}{C_c}(1-\sqrt{1-X})$	$\frac{\alpha\theta}{C_g+C_c}(1+\sqrt{1-X})$
3	$\frac{1}{4\alpha^2}\left(1+\frac{C_g}{C_c}\right)\left(1+\frac{C_c}{C_g}\right)$	$R_s=\frac{2\alpha\theta}{C_g+C_c}(1-\sqrt{1-X})$	$2\frac{\alpha\theta}{C_g+C_c}\sqrt{1-X}$
4	---	---	---
5	---	$L_{(H)}=\frac{\theta^2}{C_g}$	$R_{(\Omega)}=\frac{2\alpha\theta}{C_g}$

3. EXPERIMENTAL FRAMEWORK

A. Simulator

The standardisedvoltage impulsesimulator shownin Figure5was designed using the Matlab platformguide. This softwareallows theuser to obtain thewaveform forthe type of selected circuitfromfive possible optionsby determiningfront andtail times forlightningorswitching. The component values can also be obtained the typeof impulse,theselected circuitand capacitor values.

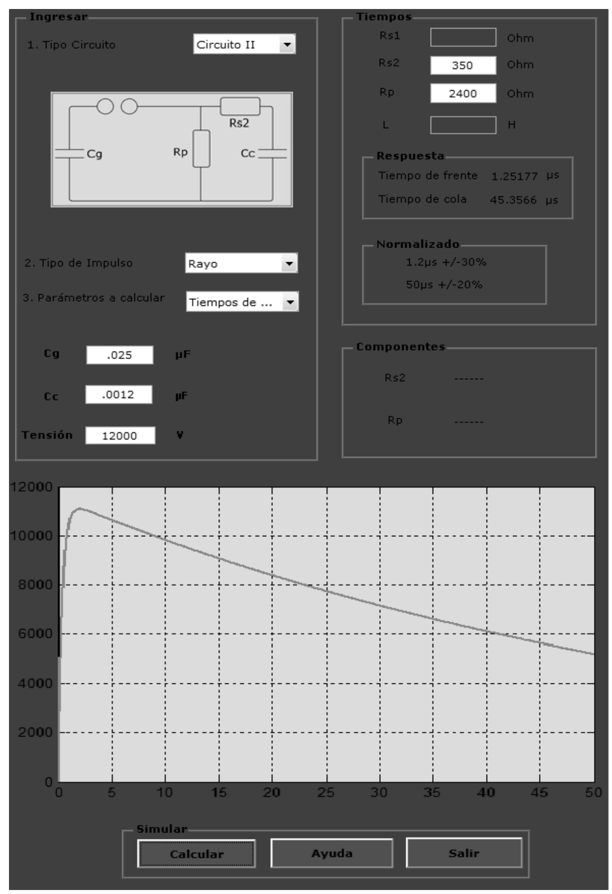

Fig.5.Graphical interface of thesimulator

The procedurecan be summarised bythe scheme presented inFigure 6.

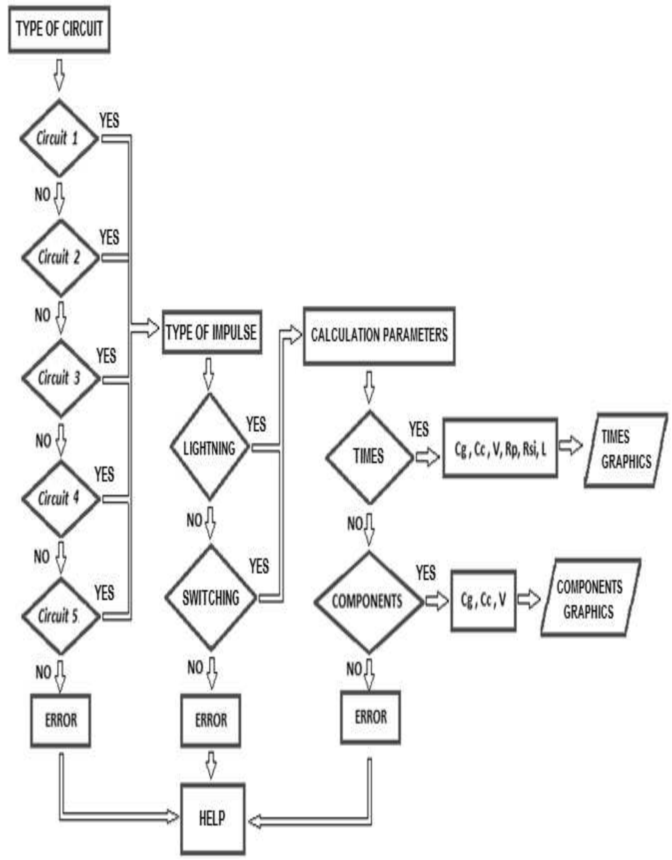

Fig.6.Flowchartof the simulator

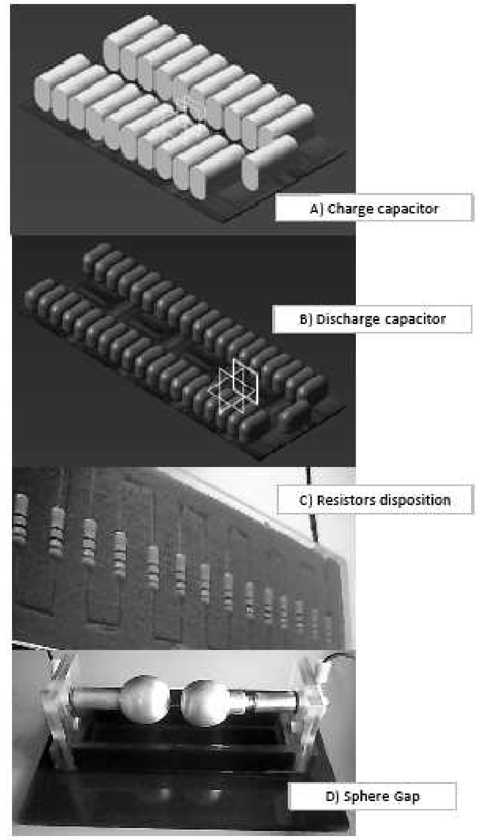

Fig. 7.Elements of the Portable Voltage Impulse Generator

The simulator wasused to testcommercial generatordatabases and selectappropriate valuesfor space requirements,constructioncosts and electrical insulation. It was then decided to buildthe elements using the values describedin Table3.

Table 3. Nominal Values of Generator Components

Impulse type	Circuit Type	Capacitors		Resistors		
		C_g(µF)	C_c(µF)	R_{s1}(Ω)	R_{s2}(Ω)	R_p(Ω)
Lightning	2	0.025	0.0012	----	350	2,400
Switching	2	0.025	0.0012	----	46000	120,000

B. Capacitors

Theproposedcapacitorshad to withstand 20kVvoltage and theirsmallcapacitanceswere notcommercially available.For eachcondenserit was necessary toassemble aseries ofcapacitors, insulated from each otherbyrigid polyurethane foamand encapsulatedin acrylic, thereby obtaininggreaterdielectric strength.Thebuildingmodelsare shownin Figure 7 (a)and 7 (b).

Table4summarisesthe technical characteristics andrequired amounts of elements usedto build thecapacitors for the portable voltage impulse generator.

Table 4. Capacitors design and construction

Impulse Type	Charge Capacitor C_g(µF)		Discharge Capacitor C_c(µF)	
	Individual Value (µF)	Amount of Capacitors	Individual Value (µF)	Amount of Capacitors
Lightning & Switching	0.56	21	0.047	39
	0.025 µF		0.0012 µF	

C. Resistors

The resistors weremade fromtraditionalelectronic carbon resistors connected in seriesto withstand the required stress. The resistors were isolated from each other by using rigid polyurethane foamand encapsulating themin acrylic, thereby obtaininggreaterdielectric strength. Table5 showsthe values forthe resistors used;the resistance configuration for lightning is presented in Figure7 (c).

Table 5. Resistors design and construction

Impulse Type	Front Resistor R_{s2}(Ω)		Tail Resistor R_p(Ω)	
	Individual Value (Ω)	Amount of Resistors	Individual Value (Ω)	Amount of Resistors
Lightning	20	18	200	12
	360 Ω		2400Ω	
Switching	4.7k	10	10k	12
	47kΩ		120kΩ	

D. Sphere Gap

The sphere gap is used as voltage switch in voltage impulse generators, asin IEEE Standard 4, 1995; Bedoya, 2004). Due to the impulse generator's designed voltage, the spheregapwas proposedforuniform fielddistribution, using horizontalarrangementand supportedon an acrylic structure. The switch could thus be calibratedto the generator's maximum possible voltage.

The spheres had 30mm diameterand maximum 8 mm distance; they were made ofaluminiumand designed to withstand a maximum 20kV voltage. The sphere gap is shown in Figure 7d.

E. Powersupply

The power supply was formed by a 120/7,000Velevatortransformer followed by a Schenkel voltage doubler circuit, as proposedin (Aguet and Ianoz, 1990), to achieve maximum 15kV voltage. The circuit was built using two 0.07µF/8000Vcapacitorsand tworectifier diodeshaving 7,000Vpeak inversevoltage.

4. RESULTS AND DISCUSSION

The portable voltage impulse generator was tested in the laboratory to confirm thatthe results conformed toestablished standards andwere withinthe tolerances setby them. Simulations were made to test the generator's performance.

Table6 (a) shows the data obtained from laboratory testing foralightning impulse usingthe portable voltage impulse generator. The data obtained for acommercial impulse generator(having the same resistor andcapacitor values) and thevalues calculated by the impulse wave simulator are also presented.

Table 6. a). impulse lightning results

Time [Front/Tail] (µs)			Peak Voltage (kV)
Portable Generador	Commercial Generator	Wave Simulator	
1,184/43.2	1.172/43.1	1.25/45.36	10-20

b). impulse typeswitching results

Time [Front/Tail] (µs)			Peak Voltage (kV)
Portable Generador	Commercial Generator	Wave Simulator	
224/2140	----	256.4/2,360	10-20

The lightning impulse registered by the oscilloscope as described by (IEC Standard 60060-1, 1989; IEEE Standard 4, 1995) is presented in Figure 8 (a).

Table 6 (b) presents the measured switching impulse values from a portable voltage impulse generator compared to those supplied by the impulse wave simulator. The switching impulserecorded by theoscilloscopeas describedby (IEC Standard 60060-1, 1989;IEEE Standard 4, 1995)is presentedin Figure 8 (b).

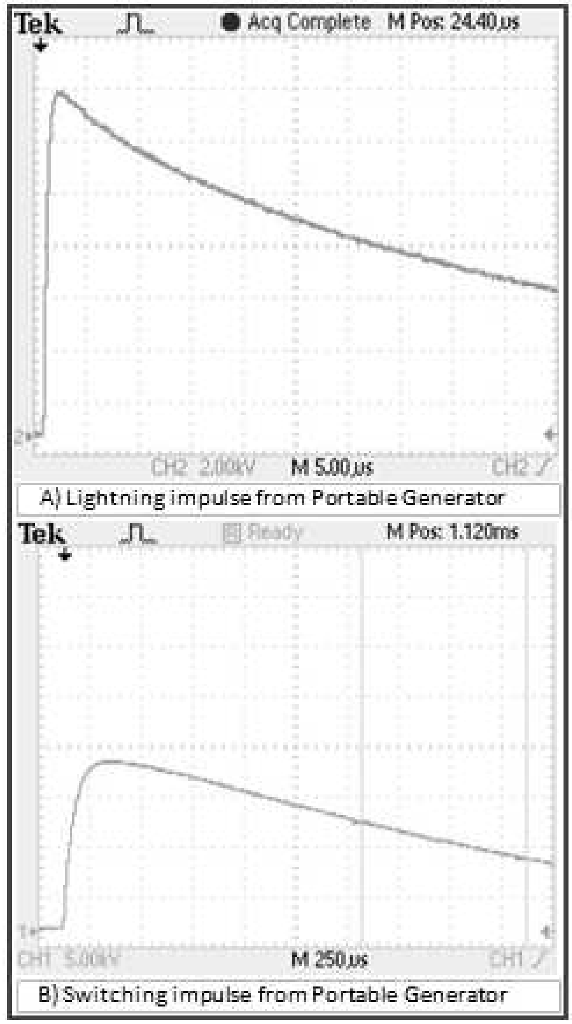

Fig.8. Waves from Portable Generator

Lightning and switching impulses were within established standards when error rate associated with the portable voltage impulse generator was within such range (Table 7).

Table7. Tolerances

Impulse Type	Admisible Error [Front/ Tail] (%)	Portable Generator [Front/ Tail] (%)
Lightning	30/20	1.33/13.6
Switching	20/60	10.4/14.4

The resultsshowed thatthe errorscalculated for lightning andswitching impulses came withinthe percentage limits set bythe aforementioned regulations.

The final version of the portable voltage impulse generator components is presented in Figure 9. Tuning tests were performed with a bell-type insulator and the results showed that the generator outputs came within the range of tolerances mentioned above.

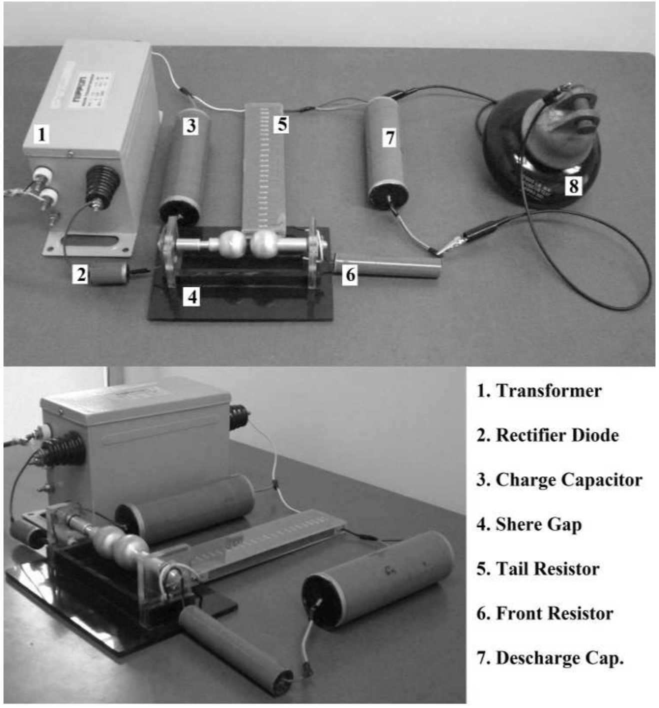

Fig.9. Portable High Voltage Impulse Generator

5. CONCLUSIONS

This paper has presented the design and construction of a portable voltage impulse generator. The proposed generator's performance was compared to that of commercial generators and the established standards for such instruments. The results came within the ranges established by the standards and the generator could thus be regarded as being valid.

The generator satisfied the main objective and needs proposed in this work due to the low cost of its implementation and its comfortable size for use and transport.

Future work will be aimed at expanding insulation components and power supply level to encompass jobs inhighervoltage rangesand diversify thenumber of componentsto be tested.

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