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http://revistas.udistrital.edu.co/ojs/index.php/Tecnura/issue/view/687
DOI: http://doi.org/10.14483/udistrital.jour.tecnura.2014.DSE1.a03

INVESTIGACIÓN

Transient surges analysis in low voltage networks

Análisis de transitorios de sobretensión en redes de baja tensión

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Fecha de recepción: June 10th, 2014 **Fecha de aceptación:** November 4th, 2014

Citation / Para citar este artículo: Rodríguez, A. A., Perdomo Orjuela, L. E., Santamaría Piedrahíta, F., & Gómez Vargas, C. A. (2014). Transient surges analysis in low voltage networks. *Revista Tecnura, 18* (Edición especial doctorado), 41–50. doi: 10.14483/udistrital.jour.tecnura.2014.DSE1.a03

ABSTRACT

Sensitivity analysis of a power system against overvoltage was performed. The analysis took into account the origin of the overvoltage, the grounding resistance magnitude and overvoltage injection point. The IEEE 13 bus test feeder system was implemented in EMTP-ATP and lightning and switching overvoltages were applied. Three cases were evaluated: the first one, applying lightning overvoltage and varying the grounding resistance magnitude; the second, applying lightning overvoltage in different points of the system with a fixed grounding resistance magnitude; and finally, applying switching overvoltage and varying the grounding resistance magnitude.

Keywords: EMTP-ATP, Ground Resistance, Power Quality, Transformer Model, Transient Overvoltage.

RESUMEN

Se realizó un análisis de sensibilidad en un sistema de potencia frente a sobretensiones. El análisis tuvo en cuenta el origen de la sobretensión, la magnitud de resistencia de puesta a tierra y el punto de inyección de sobretensión. El sistema IEEE 13 nodos se implementó en EMTP ATP y se introdujeron sobretensiones tipo rayo y maniobra. Se evaluaron tres casos, el primero, aplicando una sobretensión tipo rayo y variando la magnitud de resistencia de puesta a tierra; el segundo, aplicando sobretensiones tipo rayo en diferentes puntos del sistema con una magnitud de resistencia de puesta tierra fija y, por último, aplicando sobretensiones tipo maniobra variando la magnitud de resistencia de puesta a tierra.

Palabras clave: EMTP-ATP, resistencia de tierra, calidad de potencia, modelo del transformador, sobretensiones transitorias.

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INTRODUCTION

Low voltage feeders may be affected by surges, giving rise to phenomena such as short interruptions and voltage sags (Cooray, 2003). These surges are generated by direct lightning strikes in low voltage feeders, induction by indirect discharges (intra-cloud, cloud-to-cloud, cloud-to-air or cloud-to-ground) (Pham, Pham & Tran, 2010), and surges of slow, fast and very fast front, transferred from medium voltage networks to low voltage networks (Piantini, 2010; Varju & Ladanty, 2007; Borghetti et al., 2006; Watson & Arrillaga, 2007).

The probability of direct lightning strikes in low voltage networks is very low due to the shielding action of medium voltage networks, trees and nearby structures. However, the length of rural and semi-urban low voltage feeders may exceed 1000 m, increasing the lightning strike probability (Piantini, 2010). Surges in low voltage networks transferred from medium voltage feeders through distribution transformers are mainly caused by direct and indirect lightning strikes (Piantini, 2010; Bachega & Martínez, 2004). Therefore, in the system modeling it is necessary to consider the transformer behavior to these transient signals; however, the transformer steady state model is not useful for a lightning overvoltage frequency range (Das, 2010), (Papadias, Hatziargyriou, & Prousalidis, 1993). In this sense, implemented models of surge transfer from medium voltage feeders to low voltage feeders include a capacitive network of the transformer (Scott & Liu, 1992; Costa & López, 2007; Justo de Araújo, Cleber da Silva & Kurokawa, 2013).

This work is part of the first phase of the project called "prototype for recording transient surges in less than 1 kV feeders". The project main goals are: development of a surge recorder prototype applying electromagnetic compatibility standards, remote information transmission from prototype to desktop software, and development of a mobile application for downloading the recorded information on site and display the database information.

This paper shows typical surge parameters of low voltage systems, as peak voltage and rise time, in order to identify the behavior of surges in systems lower than 1 kV. This information is also used for designing the prototype signal conditioning stage. Simulations for IEEE 13 node test feeder (IEEE PES Distribution System Analysis Subcommittee's Distribution Test Feeder Working Group, 2000-2010), were done using the Alternative Transient Program (ATP) (Scott & Liu, 1992) for two conditions. In the first case, normalized waveform voltages 1,2/50 ms were applied in many system points. In the second case, surges caused by disconnection of an industrial load were evaluated. Furthermore, the grounding system effect on surge value was evaluated in all cases.

SYSTEM DESCRIPTION

IEEE 13 node system (IEEE PES Distribution System Analysis Subcommittee's Distribution Test Feeder Working Group, 2000-2010) was used as reference for characterizing low voltage feeder surges. The topology of the test system is shown in Figure 1.

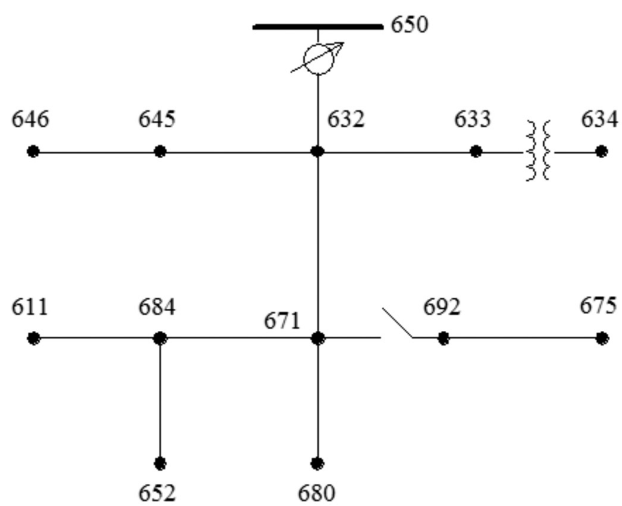


Figure 1. IEEE 13 node feeder

Source: IEEE PES (2010).

The ATP implemented system is shown in figure 2. Nodes 650 and 633 were used for simulating the lightning impact, and the distributed loads were located in nodes 632 and 671. Additionally, a Heidler source of 4 kV peek voltage was implemented to represent a standard lightning surge 1,2/50 μs. (Martínez, 2008; Morched, Matí & Ottevangers, 1993; Costa & López, 2007). Opening of one phase of an industrial load has a highly inductive characteristic and causes system high power consumption. Therefore, the opening was used for slow front surge characterization. The system was implemented in order to evaluate the sensitivity to direct impact and switching surges. IEEE 13 node feeder was modified to analyze overvoltages in low voltage for ground resistance variation.

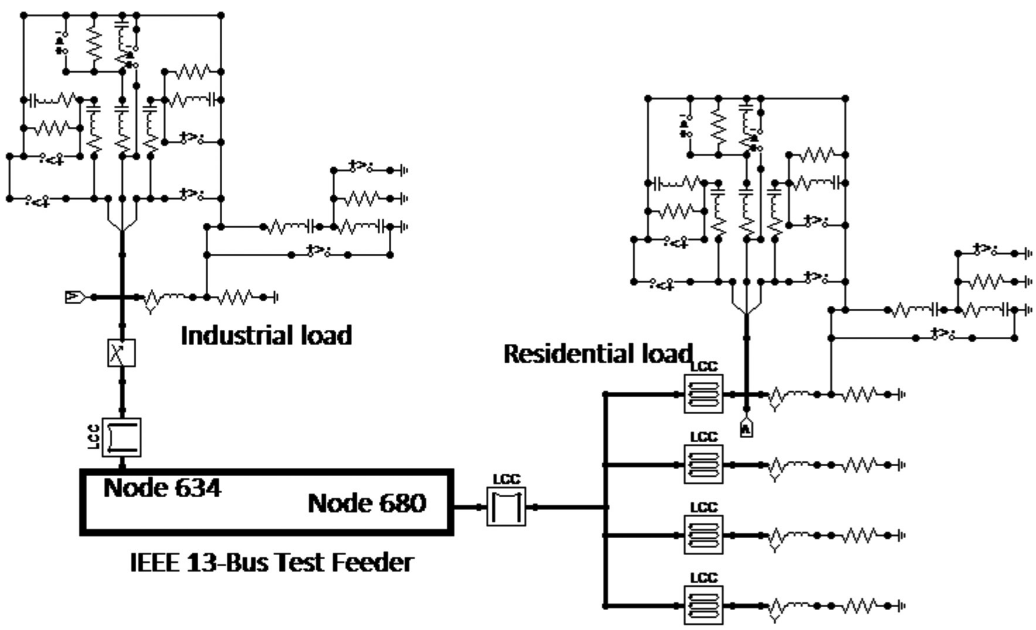


Figure 2. IEEE 13 node feeder and charges implemented in ATP

Source: Own work.

Industrial load

An inductive load of high power consumption (0,25 MVA and power factor of 0,85) was included in the distribution system. This load is connected to node 634 through a distribution line whose characteristics are given in Table 1.

Table 1. Distribution line characteristics

Node	Length (m)	Resistance (mW)	Reactance (mW)	Frequency (Hz)
633	324	119,9	144,5	60

Source: Own work.

Residential load

Four residential loads, each one of 7 kVA and power factor 0,85 lagging were added. Connection of IEEE 13 node system to residential loads was performed through a distribution transformer located on node 680. Distribution overhead and underground cables were implemented to represent the supply connection of loads (Martínez, 2010), (CIGRE Working group 33.02, 1990). Table 2 and Table 3 show the transformer and cables characteristics.

Table 2. Distribution transformer characteristics

Node	Power (MVA)	Primary Voltage (kV)	Secondary Voltage (V)	Windings connection
680	0,5	4,16	208	Yn – Yn

Source: Own work.

Table 3. Underground cables characteristics

Node	Length (m)	Resistance (mW)	Reactance (mW)	Frequency (Hz)
680	100	9,68	107,2	60

Source: Own work.

Transformer model

Right modeling of low voltage feeder components influences the analysis of surges (Bachega & Martínez, 2004). The transformer deserves particular attention because it transfers surges present in medium voltage networks to low voltage feeders (Antunes Tavares & Melo e Silva, 2014), (Martínez, 2010). Searching a suitable high frequency model transformer is considered a complex task because of the physical phenomena occurring in this device. Physical Phenomena such as (CIGRE Working group 33.02, 1990), (IEEE standars association, 2011):

- When the transformer is turned on, winding capacitances charging process starts and current flow begins in the dielectric structure.
- Losses in the transformer core are negligible because it has a linear behavior. Magnetic flux penetration into the core is not presented until 1 μs elapsed.
- After 1 μs, the flux begins to penetrate into the core, the main current path are the capacitances.
- From 1 μs to 10 μs, the transformer core saturates.
- Completed 10 μs, the inductance coil has a non-linear behavior and magnetic flux will be fully penetrated into the core. In this stage, capacitive couplings remain its importance.
- After 10 μs, the behavior of transformer is considered stable. Losses come from cables, core, dielectric and housing. Skin effect is considered in this section.

Transformer parameters importance depends on the analyzed process. Table 4 shows the transformer parameters influence in a power system transient analysis. The classification proposed in Martínez (2008) is: I unimportant, II important, and III very important.

Table 4. Transformer parameters importance based on fast transient

Parameter/ Effect	Low Frequency	Slow front	Fast front	Very fast front
Short circuit impedance	III	III	II	I
Saturation	III	II	I	I
Iron losses	II	I	I	I
Eddy currents	III	II	I	I
Capacitive coupling	I	II	III	III

Source: (Martínez, 2008).

CIGRE Working Group 33-02 has elaborated a document (CIGRE Working group 33.02, 1990) for specifying the power system elements representation according to the frequency ranges in which the system behavior will be evaluated. Table 5 shows this information.

Table 5. System representation according to working frequency

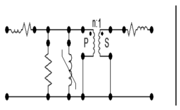
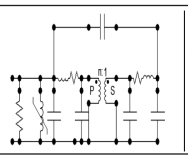
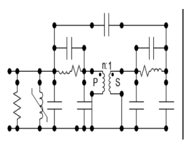
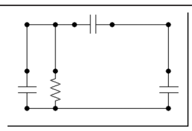
Group	Frequency Range	Designation	Representation
I	0,1 Hz – 3 kHz	Low frequency oscillations	Permanent surges
II	50 Hz – 20 kHz	Slow wave front	Switching surges
III	10 kHz – 3 MHz	Fast wave front	Lightning surges

IV	100 kHz – 50 MHz	Very fast wave front	Switching surges in Gas Insulated Substations

Source: (CIGRE Working Group 33.02, 1990).

Table 5 shows the transformer modeling information respect to frequency range (Martínez, 2008).

Table 6. Transformer model according to working frequency

Model	Description
	Group I: 0,1 Hz – 3 kHz Takes into account saturation effects and iron and copper losses. Single-phase and three-phase cores can be identified.
	Group II: 50 Hz – 20 kHz Takes into account saturation effects and iron and copper losses. Single-phase and three-phase cores can be identified.
	Group III: 10 kHz – 3 MHz Capacitive coupling between windings. Short circuit impedance must be included.
	Group IV: 100 kHz – 50 MHz Capacitive coupling between windings. It is necessary to know the windings impedances.

Source: (Martínez, 2008).

Grounding resistance

Grounding impedance has been included in order to evaluate its impact on surge in the low voltage system; it allows also to record surges in the neutral line. For simulation, a resistive model of grounding impedance was implemented, following electromagnetic compatibility design criteria, which allow neglect inductive coupling. High and medium voltage grounding resistance values are 1 and 10 Ω respectively (Ministerio de Minas y Energía, República de Colombia, 2008). Low voltage resistances are in the range of 1 to 100 Ω.

METHODOLOGY

This section describes the scenarios proposed to evaluate the system sensitivity against surges caused by direct lightning strike impacts and system switching. Direct lightning strike has a 1,2/50 μs standard waveform with an amplitude of 4 kV, and 90% of occurrence probability (Borghetti, Napolitano, Nucci, Paolone, & Morched, 2006).

Case 1: direct lightning strike and low voltage grounding resistance variation: A lightning surge wave was injected in phase A of node 650. Grounding resistance was varied between 1 and 100 Ω, with 10 Ω steps. For residential and industrial loads, surges were measured in phases and neutral of the system.

Case 2: fixed low voltage grounding resistance and variable lightning strike point: A 25 Ω ground resistance was fixed (Ministerio de Minas y Energía, República de Colombia, 2008). A lightning surge wave was injected in phase A of nodes 650, 633 and in the distributed line in nodes 632 and

671. Surges were measured in phases and neutral of the system for residential and industrial loads.

Case 3: Switching phase A of industrial load. Low voltage grounding resistance kept constant and simultaneous measurement at different points of the system: The magnitude of low voltage ground resistance is 25 Ω. Phase A of industrial load was opened, which caused a switching surge. Surges were measured in phases and neutral of the system for residential and industrial loads.

RESULTS

Results of ATP simulations for the described study cases are presented below. The results are in p.u., line voltages base values are 480 V and 208 V for industrial and residential loads, respectively.

Case 1: direct lightning strike and low voltage grounding resistance variation

Figure 3 and figure 4 show the magnitude of the surge registered respectively in residential and industrial load, in all phases and neutral. Phase voltage is measured with respect to neutral and neutral with respect to ground. Phase A results in Figure 3 suggest the need of a protection device for connected electronics and electric machines to avoid the progressive damage of components (Chowdhuri, 1996; Indulkar, Thomas & Bijwe, 1992). Figure 4 shows that for a grounding resistance larger than 15 Ω, an electronic device or an electric machine would be subject to voltages higher than 4 kV. These levels cause electromagnetic susceptibility problems (IEEE Std 1159 Recommended practice for monitoring electric and power quality, 2009), (IEEE Std 446 Recommended practice for emergency and standby power systems for industrial and commercial applications, 1995), (Herrera, Perez, & Torres, 2003), (Escamilla, Gomez, & Tejada, 2009), (Gómez, 2013).

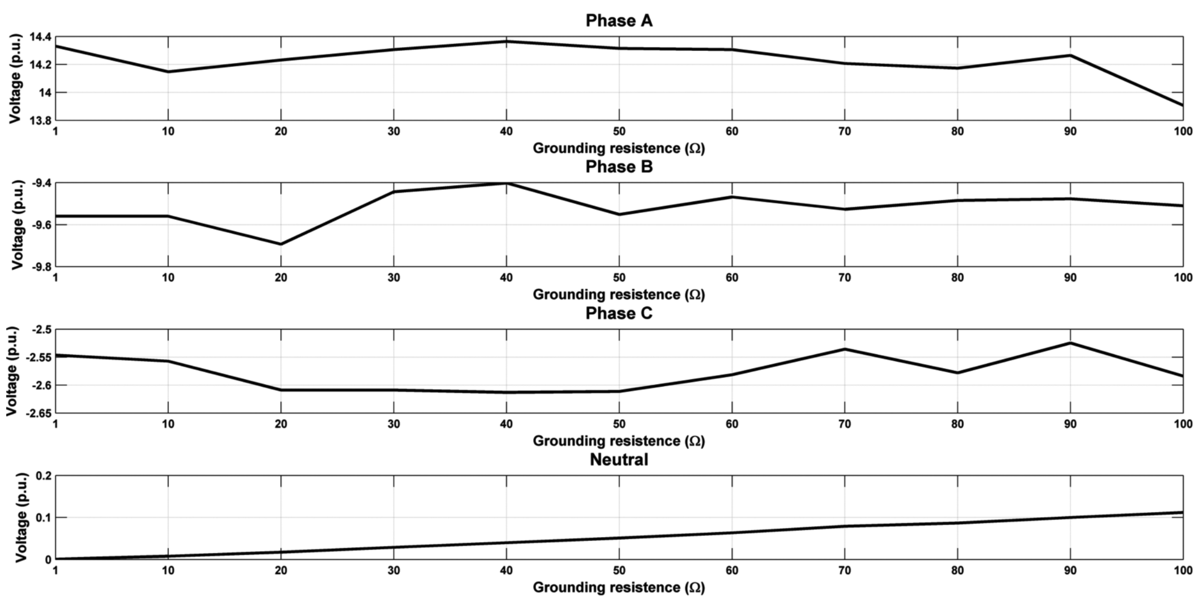


Figure 3. Phase surges relative to ground resistance for residential loads

Source: Own work.

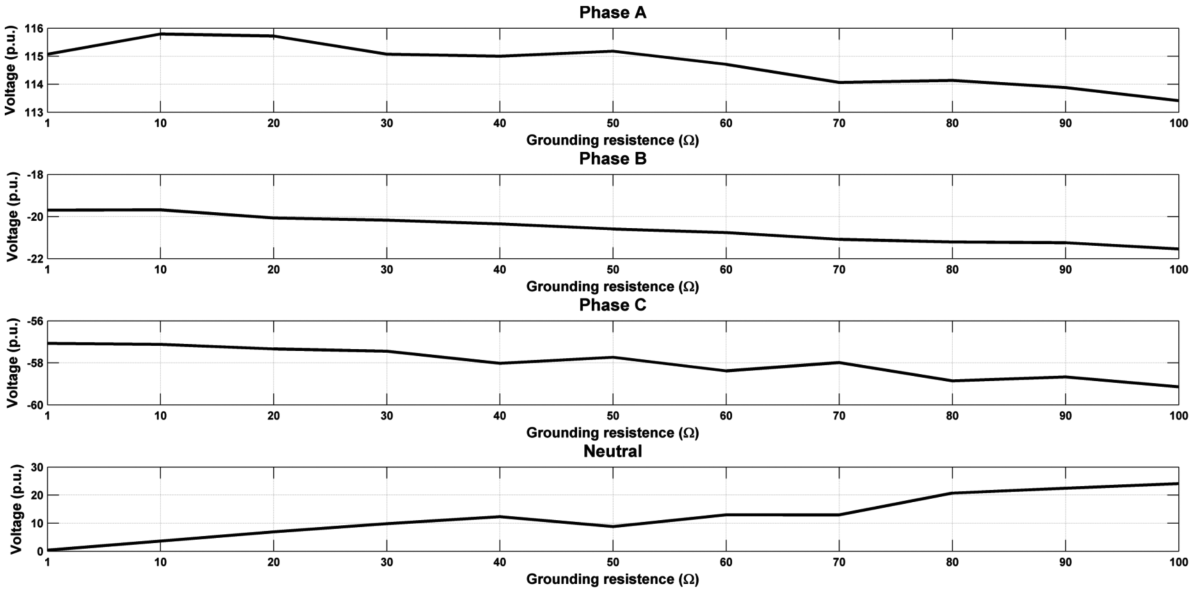


Figure 4. Phase surges relative to ground resistance for industrial loads

Source: Own work.

Case 2: fixed low voltage grounding resistance and variable lightning strike point

Figure 5 and Figure 6 show the surges at 90% of the peak value, recorded in residential load phases and industrial load phases, respectively, with respect to neutral and neutral with respect to ground, for different lightning strike injection points.

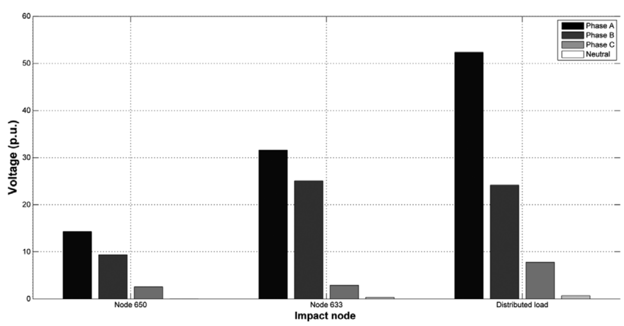


Figure 5. Surges in each residential load phase, with respect to neutral and neutral with respect to ground

Source: Own work.

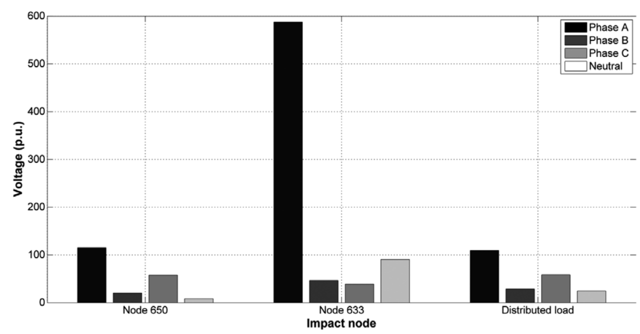


Figure 6. Surges in each industrial load phase, with respect to neutral and neutral with respect to ground

Source: Own work.

Surges produced by disturbances in several points of the system, and recorded in the residential load, confirm that for grounding resistance lower than 25 Ω, the grounding potential level can be tolerated by electronic devices (Ministerio de Minas y Energía, República de Colombia, 2008).

Surge recorded in phase A when a lightning transient occurs in node 633 reaches levels up to four times the ones recorded in other nodes of industrial load. This is due to the low impedance between the impact point and the register point, together with the non-transposed lines, as shown in figure 6.

Case 3: Opening phase A of industrial load. Low voltage grounding resistance kept constant and simultaneous measurement at different points of the system

Table 7 and Table 8 show the magnitudes at 90% of peak value and rise time of surge between each phase and neutral measured in the residential and industrial load, when a surge is generated by phase A opening of industrial load.

Table 7. Switching surges in industrial load

Surge Register	Magnitude at 90% (p.u)	Rise-time (μs)
Phase A – Neutral	3243,22	0,98
Phase B – Neutral	371,30	2,99
Phase C – Neutral	373,80	2,86
Neutral – Ground	25,90	0,90

Source: Own work.

Table 8. Switching surges in residential load

Surge Register	Magnitude at 90% (p.u)	Rise-time (μs)
Phase A – Neutral	1,53	29,18
Phase B – Neutral	1,30	29,22
Phase C – Neutral	0,023	19,14
Neutral – Ground	0,027	41,33

Source: Own work.

Slow front surges produced by switching the phase A, depends on time when the switch opens and the arc dynamic behavior at the same time (Indulkar, Thomas, & Bijwe, 1992). According to table 7, in the industrial load the surge magnitude in phase A is ten times higher than the recorded in phases B and C. This is due to the inductive load rises the voltage level in response to abrupt current changes. Furthermore, induced surges in the other circuit phases are exponentially attenuated with respect to the network characteristic impedance. Table 7 and table 8 show the surge values in phase B (371,3 p.u. and 1,3 p.u., respectively).

Colombian standard for internal surge protection systems (NTC 4552 Protección contra rayos, 2004), shows the impulse voltage values that devices must withstand according to their operation levels. For Colombian power system at residential low voltage, the impulse values would be equal to or less than 2,5 kV. This value was exceeded in the first two simulation cases; therefore, surge protection devices are required. Proper design of protection devices as diodes, thyristors, surge protectors, etc., must follow appropriate selection criteria. For protection of electronic devices at residential load, three diodes with different characteristics were selected. Type I is an avalanche diode, type IIA and IIB are non-avalanche diodes, as shown in table 9 (Chowdhuri, 1996).

Table 9. Susceptibility data for transient voltages in three types of high power diodes

Diode type	I	IIA	IIIB
Peak Reverse Voltage PRV (V)	1200	800	1200
Transient PRV (V)	-	1250	1500
Direct current (A)	250	250	250
Reverse Breakdown voltage (V)	2350/2500	1620/1200	1950/1650

Source: (Chowdhuri, 1996).

CONCLUSIONS

Surge magnitude depends on distance to impact point, regardless if load is industrial or residential, at shorter distances, greater magnitudes.

Design values of grounding resistance for residential loads must be less than 25 Ω, in agreement with Colombian regulation standards. Surge registered in neutral line presents a linear behavior with respect to grounding resistance value. This linear behavior enables a proportionality constant to predict the surge level at neutral. However, in the phases the behavior is not predictable, making impossible to use a proportionality constant.

Signals recorded from ATP simulations show the importance of measuring and characterizing the overvoltages in low voltage systems, in order to determine the origin of these surges and possible strategies to reduce their negative effects. According to the registered magnitudes, it is necessary to calculate and implement protective devices designed to protect the life of sensitive equipment installed in the low voltage system.

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FUNDING

This work was supported by Universidad Distrital Francisco José de Caldas.