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Transient Overvoltage in Distribution Networks in Rural Areas

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***Abstract*— A surge sensitivity study of distribution transformers in rural areas of Cundinamarca - Colombia was performed. The analysis took into account the grounding resistance magnitude and the transient overvoltage injection point. Lightning overvoltages are introduced in the IEEE 13 bus system test feeder by using the EMTP-ATP program, results show that delta surge arrester configuration used to protect delta winding of distribution transformers before some microseconds, limits overvoltage transients over zero time axes., contrary to phase – neutral configuration which limit overvoltage to residual voltage in both sides of time axes.**

Keywords-component; EMTP – ATP; grounding Resistance; high frequency transformer model; surge arrester model; Transient Overvoltage.

I. Introduction

Distribution transformer may be exposed to lightning in two ways: by direct lightning stroke and waves traveling leading to the windings. That transients may be caused permanent and costly damages [1], [2].

Probability of direct lightning strikes on low voltage networks are very low due to the natural shielding of medium voltage networks, trees and nearby structures. However, rural distribution systems at Cundinamarca can exceed 1 km and have no shielding, which increases the probability of being impacted by lightning[3].

Therefore, it is necessary to consider the behaviour of the transformer in high frequency [4], [5], by taking in consideration the capacitance between weddings [6]–[8].

Surge arresters are connected across an apparatus to provide a low – resistance path and to limit the various types of transient voltages below the corresponding insulation level of the apparatus [9]. Rural areas in Cundinamarca are protected by a traditional surge arrester configuration. This paper shows a comparison between the traditional winding transformer protection and an alternative configuration.

Grounding resistance model are represented by a PI model in order to have a real transient response [10]. Model implemented in this study, includes distributed parameters and electromagnetic coupling between electrodes [1], [11].

This article presents surges parameters, as peak voltage and rise time, evaluated in a test network. This information is useful to design an electronic device to register the effects of the lightning phenomena in distribution networks in Cundinamarca.

Simulations are performed in the EMTP – ATP software [12], implementing IEEE 13 nodes bus test feeder [13] and applying current pulses at an specific point. Section II presents the system description. The methodology carried out in this study is described in section III. Results and analysis are presented in section IV, and conclusions are drawn in section V.

II. System Description

IEEE 13 nodes bus test feeder has been taken as a reference to characterize direct lightning surge in medium and low voltage (MV/LV) networks. Fig. 1 shows the test system.

In order to evaluate the surge sensitivity of distribution transformers in rural areas of Cundinamarca – Colombia, it was necessary to add high frequency models of transformer, surge arrester, and ground resistance. An industrial load at node 634 and a residential load at node 680 were included.

In this section, the modifications included in the network described in [13], are presented. Most of the lines at IEEE 13

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nodes bus test feeder are overhead; and then, in this study transpositions of conductors in the segments between the nodes 650 – 632 and 632 – 633 were included.

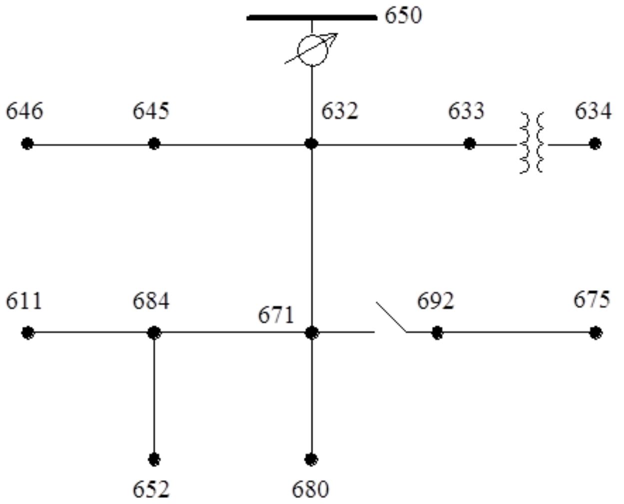

Figure 1. IEEE 13 nodes bus test feeder [13]

A. *Current pulse generator*

EMTP - ATP program has a font library of surge generator, which is difficult to assign parameters. Front and tail times do not match the standard and a negative polarity cannot be assigned [14].

EMC – UNAL group proposed a non-conventional generator coupled to a control element called MODEL. The control element includes a model (Amp-i), which allows varying the amplitude and polarity of the conventional current generator. A type device TACS (TACSOURCE) permits coupling waveform with the circuit to which the surge is applied [14].

B. *Industrial load*

An inductive load is connected to the 634-node system through a distribution line with high power consumption. Characteristics are presented in Table I. This load has a power consume of 0.25 MVA with a power factor of 0.55 lag.

TABLE I. TABLE TYPE STYLES

Node	**Characteristics**			
	Length [m]	***Resistance [mΩ]***	***Reactance [mΩ]***	***Frequency [Hz]***
633	324	119.9	144.5	60

C. *Residential load*

This modification consists in adding four residential loads. Each one has a consumption of 7 kVA and power factor of 0.85 lag; this load has an access through a distribution transformer located in the node 680. An underground cable is used through the distribution network and the loads. Table II and Table III present features of these elements.

TABLE II. RESIDENTIAL LOAD TRANSFORMER

Node	**Characteristics**			
	Power [MVA]	***Primary Voltage [kV]***	***Secondary Voltage [kV]***	***Frequency [Hz]***
680	0.5	13.2	0.208	60

TABLE III. UNDERGROUND CABLE

Node	**Characteristics**			
	Length [m]	***Resistance [mΩ]***	***Reactance [mΩ]***	***Frequency [Hz]***
680	100	9.676	107.2	60

D. *Model Transformer*

Right modelling of low voltage components influences the analysis of surges [6], [15]–[17]. The transformer deserves particular attention because it transfers surges present in medium voltage networks to low voltage feeders [6]. A detailed description of this phenomena is presented in [1].

Transformer parameters depend on the process being analysed. Table IV summarizes the influence of each parameter respect to transients that may occur in a power system. Where: I unimportant, II important and III very important, according to the classification proposed in [1].

The CIGRE working group 33-02 has established a document [18] which specifies a representation according to frequency ranges of power system elements.

TABLE IV. TRANSFORMER BASED ON THE FRONT TRANSITION

Parameter/ Effect	**Characteristics**			
	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

E. *Surge arrester*

Overhead power distribution lines have a high probability to be impacted by direct lighting strikes due these are not shielded by grounded wire. As the BIL of an overhead power distribution in Colombia is low (95 kV – 170 kV), a direct stroke usually results in a permanent damage and deterioration power quality indices. Some results show the benefits of include lightning arresters on all phases [1], [2].

The IEEE working group 3.4.11 has modelled the dynamic characteristic of metal – oxide surge arresters [19]. This model is presented in Fig. 2.

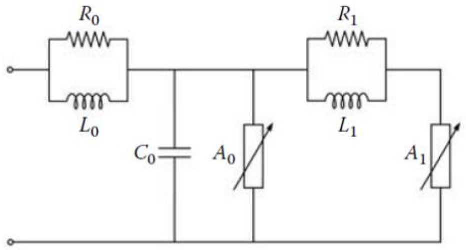

Figure 2. IEEE MO arrester model for fast front surges [20].

The model incorporates two nonlinear resistors (A_0 and A_1). "The characteristic of A_1 is slightly less than the 8/20 µs waveform while A_0 is 20 – 30 % higher" [9]. Fig. 3 presents the A0 and A1 behaviour for the LV surge arrester implemented. L_0 and R_0 are implemented to stabilize the numerical iterations. A filter (R1 - L1) separates both nonlinear elements. For slow front surges, this filter has a little impedance and then the two nonlinear sections are in parallel. Fast – front surges implies a significant impedance of the RL filter [19]–[27]. C_0 represents the capacitance between the arrester terminals [19]–[27].

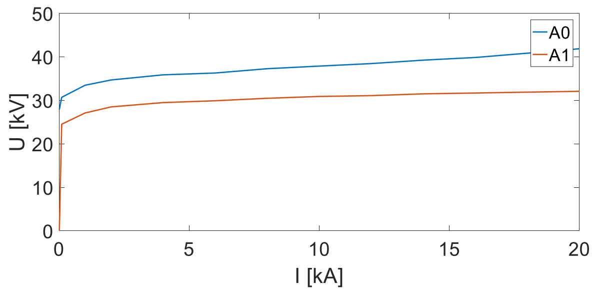

Figure 3. A0 and A1 response for the LV surge arrester implemented.

Fig. 4 shows the alternative protection scheme of windings in delta configuration. To protect wye windings configuration a traditional phase – neutral configuration surge arrester was implemented [28].

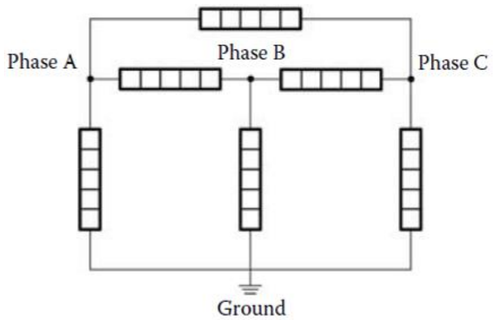

Figure 4. Phase to phase protection delta winding [9].

The traditional selection process is used to select the phase to ground surge arresters; while the "phase to phase surge arrester MCOV rating is equal to or slightly greater than the maximum phase to phase system voltage" [28], [9]. Table V shows the parameters of the LV and MV surge arrester models.

TABLE V. SURGE ARRESTER CHARACTERISTICS

Surge Arrester	Characteristics				
	L0 [µH]	***R0 [Ω]***	***L1 [µH]***	***R1 [Ω]***	***C0 [pF]***
Phase – Neutral in MV	0.082	41	6.15	26.65	243.9
Phase – Neutral in LV	0.058	29	4.35	18.85	344.82
Phase – Phase in MV	0.108	54	8.1	35.1	185.18

F. *Grounding Resistance*

The response of a grounding system to both, peak current and frequency range is important when lightning current is flowing through its terminals [10], [11], [29], [30]. "If a grounding system is considered like a resistor (Re), large errors occurs due to the difference between the responses at low frequencies (DC - 50/60 Hz) and at high frequencies, like a current impulse (1 - 10 MHz), with a short rise time (0.7 - 3.8 µs) and high front steepness (7.2 - 24 kA/µs)" [1].

It was necessary to include the high frequency model at this element. This considers "the characteristic impedance of the electrodes (Zc), the propagation coefficients (γ), electromagnetic couplings, the nonlinear distribution of voltages and currents, and the ionization potential. Based on the transmission line model, characteristics per unit length of the electrode, both longitudinal (resistance R, inductance L), and transversal (conductance G, capacitance C) and soil characteristics (resistivity ρ, ε permittivity, permeability µ) are taken into account" [1], [31]. Fig. 5 shows the frequency responds of vertical grounding rod that was used in the simulations in distributed, residential and industrial charges. The characteristic impedance - Zc presents a constant response until 100 MHz.

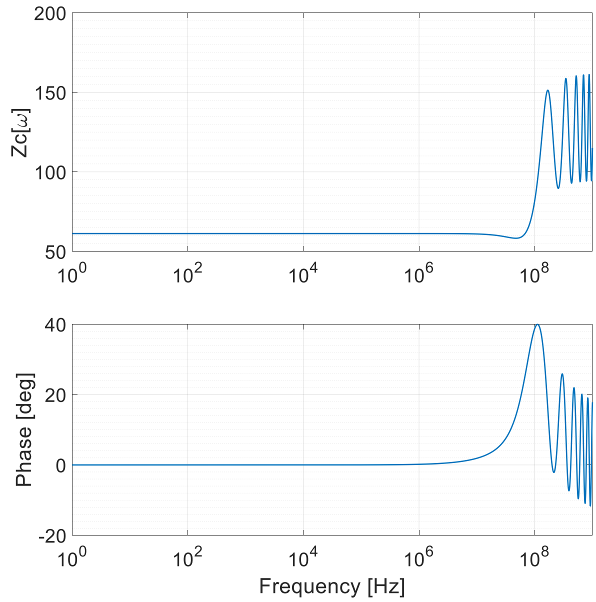

Figure 5. Magnitude (upper trace) and phase (lower tracer) vs Frequency.

The grounding resistance parameters implemented in the simulation process at this charge were 41.27 Ω, 1.24 µH and 89.29 pF. To distributions transformers were 17.9 Ω, 3.04 µH and 0.0847 µF.

Fig. 6 presents a simplification of the model implemented in the EMTP – ATP program, including the elements described before.

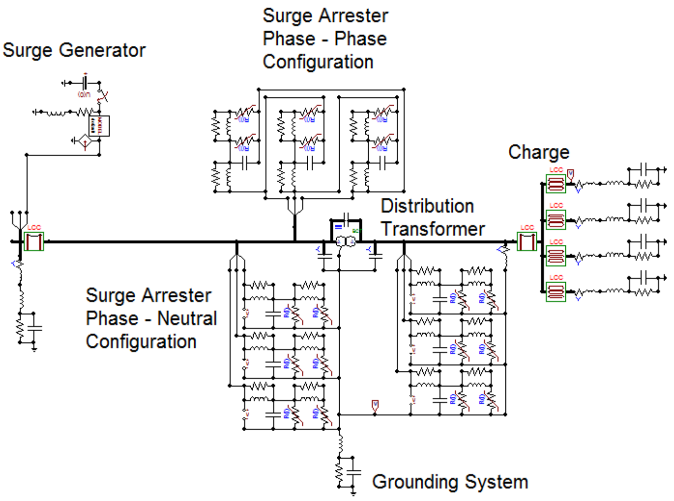

Figure 6. Simplification of IEEE 13 bus test feeder model implemented in EMTP - ATP.

III. Methodology

In this section, a case study is described, in order to analyse the effect of transient overvoltage in distribution transformers due to direct lightning strikes in distribution networks with similar features to those of the rural networks of Cundinamarca - Colombia. The lightning surge generator has an 8/20 µs waveform with an amplitude of 20 kA.

In other to emulate a direct impact into the network, surges are injected in phase A between nodes 632 – 671 where a distributed load is located. Currently, delta windings transformers for rural distribution networks in Cundinamarca are not protected by phase-to-phase surge arresters. In this simulation study three cases are developed: i) surge arresters are not included in the system; ii) only phase – neutral surge arresters are included; iii) phase-to-phase surge arresters are included. Based on these simulations, the surge arresters configuration effect is analysed. It should be noted that the inclusion of surge arresters in each of the analyzed cases was performed for all MV transformers.

Data are collected in the substation located at node 650, in the transformer located at node 634 and in the transformer added at node 638, which was described in previous section. In both nodes, the response of surge arresters located at 13.2 kV and the voltage in grounding system are analysed.

IV. Results

When an overhead distribution line is directly or indirectly stroken, a transient voltage can reach a distribution transformer, which can be transferred to the low voltage windings. This transferred voltage from MV to LV is due to the capacitive coupling between windings. The description about the four components of the phenomena (electrostatic voltage, space harmonics, free oscillation and exponentially rises) is presented in [2].

Fig. 7 shows the surges at the 13.2 kV windings of a residential distribution transformer located at node 680 without any surge arrester. The peak value of the transient phenomena is 7 times higher than the BIL. In many cases, these transient phenomena cause permanent damage to the windings, which represents high cost for utilities.

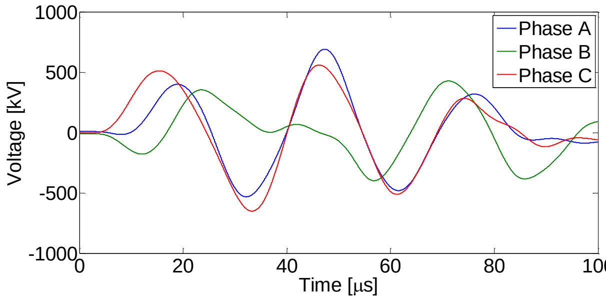

Figure 7. Voltage in phases to neutral wire substation at the node 680. Without any surge arrester to protect the windings.

A network operator in Colombia invests 327.800 USD per year in corrective maintenance and replacing transformers [32]–[34]. In [35] is reported that approximately 700 distribution transformers were damaged by transient phenomenon during 10 years in Colombia.

On the other hand, the capability to withstand the stress of an electrical insulation system depends of the applied voltage waveshape. Therefore, from the waveshave in Fig. 7, surge arresters must be used to limit the transient overvoltages to safe levels. [2].

Fig. 8 present the wave shave of voltage at the residential transformer located at node 680 with a phase – neutral surge arrester.

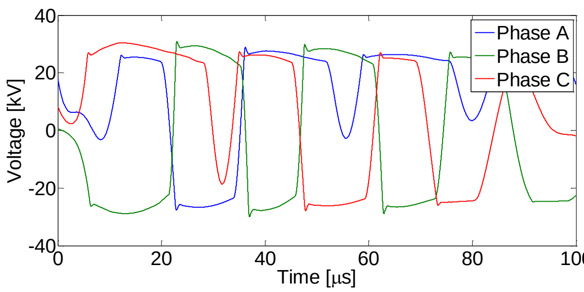

Figure 8. Voltage in phases to neutral wire substation at 680 node. A phase – phase surge arrester to protect delta windings is not included.

The implementation of the surge arrester in the system has improved the wave shave at the terminals of the transformer distribution, and the maximum voltage is less than the BIL. It is a cheaper solution to the winding deterioration by transient overvoltage; however, it is possible to reduce the stress in the distribution transformer by using another surge arrester package. Fig. 9 presents the results when a delta surge arrester configuration is included to protect delta windings.

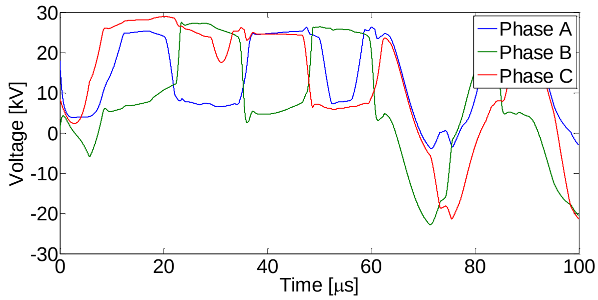

Figure 9. Voltage in phases to neutral wire substation at 680 node. None include phase – phase surge arrester to protect delta windings.

Some differences are observed between the signals in Figs. 8 and 9. Before 60 µs, delta winding configuration limits overvoltage transients over the zero time axes; however, the maximum voltage over the windings is almost the same (30 kV). Beyond 60 µs, both configurations has a similar behaviour.

When current flows through a phase – neutral surge arrester configuration, the electric potential at the grounding system increases. Fig. 10 presents the electric potential of the grounding grid at node 680 when is included a phase – phase surge arrester to protect the delta windings.

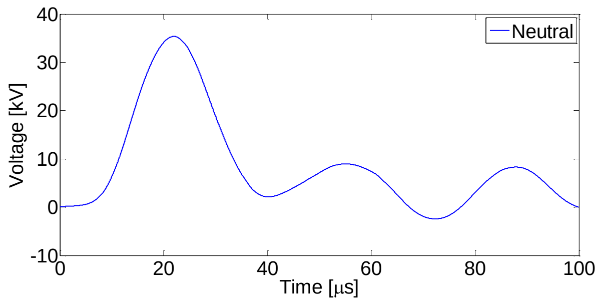

Figure 10. Voltage grounding grid in transformer at 680 node. Include phase – phase surge arrester to protect delta windings.

The peak value in Fig. 10 is closer to 40 kV, and therefore it is exceeding the BIL, which is 30 kV for a nominal voltage system of 1.2 kV.

Depending on the type of electrical installation required, there are different types of neutral - ground connections. In Colombia, TN configurations are used. If the peak value in neutral wire is taken into account, it is possible to include a protection (surge arresters, diodes, etc.) to mitigate the transfer voltage to end user. This configuration always looking for the equipotential grounding installation [10].

Table VI presents the maximum voltages in a substation and the transformers located at nodes 650, 634 and 638.

TABLE VI. MAXIMUM VOLTAGE AT TERMINALS WINDINGS 13.2 [KV]

Node	Surge arrester configuration			
	Phase	***Maximum Voltage without any surge arrester [P.U]***	***Maximum Voltage without delta surge arrester [P.U]***	***Maximum Voltage with delta surge arrester [P.U]***
650	A	3.93	2.12	2.12
	B	5.45	1.89	1.90
	C	7.50	2.12	2.12
634	A	15.15	1.89	2.27
	B	12.80	1.13	2.19
	C	18.10	2.57	2.57
680	A	30.30	1.60	1.96
	B	13.20	2.00	1.96
	C	37.80	1.89	2.04

Table VI shows a comparison between the maximum phase – neutral voltages at the substation at node 650 and the transformers at nodes 634 and 680. In the case that there are no surge arrester to protect the transformer windings in nodes 634 and 680, it can be observed that the voltage level in the substation is between 2.5 and 5 times lower. The first reason is the surge attenuation caused by the length of the transmission lines. With reference to the lightning injection point, the distribution line which interconnect the substation is 4 times longer than distribution line which interconnect the transformer at 634 node and 1.01 times longer than transformer at 680. The second reason is the transposition of the lines. The transient phenomena which flows toward the substation and the distribution transformer at the node 634 travel across a transposed distribution line, but this is not the case for the transient overvoltage that flows to transformer at node 680.

According to Table VI, when any surge arrester configuration was implemented, the maximum overvoltage at windings transformer was not greater than 2.57 p.u.

V. CONCLUSIONS

Delta surge arrester configuration improves the signal voltage at windings transformer during transient phenomena. The maximum voltage level in a negative reflection is 3.5 times less than the phase - neutral surge arrester configuration.

Transposition and length of the distribution lines are the mainly reason to attenuate overvoltage transients. In this particular case, when a transient overvoltage in a substation was analysed with respect to the two other transformer, it was possible to determine that the maximum voltage at the substation was 2.5 – 5 times less than the maximum voltage in distribution transformers.

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