LIGHTNING OVERVOLTAGES ON LV NETWORKS FED BY MV LINES WITH A MULTIGROUNDED NEUTRAL

Y. Rajotte, J. Fortin, B. Cyr

Hydro-Québec (Canada)

ABSTRACT

Hydro-Québec conducted a research program aimed at characterizing lightning overvoltages on LV (low-voltage) networks. Field measurements were made at five sites and the results were used to validate an EMTP-based computer model. Finally, the main conclusions of a sensitivity analysis identifying the key system parameters that influence overvoltages on LV networks are presented.

Keywords: lightning, multigrounded neutral, LV networks, transformer model, field tests

1. INTRODUCTION

In recent studies [1, 2], the mechanisms which lead to lightning overvoltages on LV networks have been classified in three groups:

- Direct strokes on the LV network.
- Induced overvoltages on the LV network by a nearby stroke to ground.
- Overvoltages on the MV (medium-voltage) line (due to a direct stroke or induced from a nearby stroke to ground) transferred to the LV line. Two mechanisms are identified in this case. The first relates to the overvoltages transferred capacitively through the MV/LV transformer. The second comes from the fact that in the systems considered in these studies, the LV neutral is isolated from the transformer tank and ground; if the LV terminal flashes over, the lightning current is injected in the LV grounding network.

The relative importance of these three causes depends on the characteristics of the system. A brief description of Hydro-Québec's system is given below.

As elsewhere in North America, residential loads are fed by single-phase MV/LV transformers (see Fig. 1). MV lines carry a neutral conductor to ensure the return path of the load current. Grounds on MV, LV and telephone systems are connected[1]. The grounds along the line, including those of customers, are thus tied to the MV neutral and constitute an extended grounding system called **"multigrounded neutral."**

MV/LV transformer power ratings typically range from 25 to 100 kVA. They feed one or two customers only in rural areas and up to ten in urban areas. LV networks are short: their length rarely exceeds 100 m. There are almost no LV structures. For lengths up to 30 m, the LV cable connects the transformer directly to the customer installation. Otherwise, the LV cable is usually installed on the MV line where the LV and the MV neutrals share the same conductor (see Fig. 1).

1 The TN-S system is applied in customer installations: the customer ground is connected to the neutral of the LV line and a separate protection conductor (PE) is used (see Fig. 1).

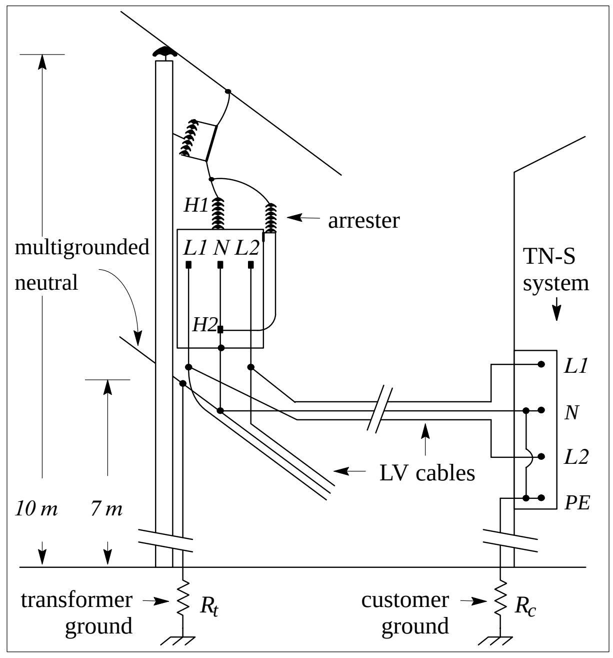

Figure 1 Distribution system including a single-phase MV line, MV/LV transformer and LV cables (three-phase MV lines are similar)

Because of the short length of the LV circuits, the probability of a direct stroke on the LV network is reduced.

The probability that the induced voltage on a line exceeds a given value is proportional to the square of the distance between grounds [1]. With typical distances of 20 to 50 m, the probability of reaching harmful voltages from induction on LV lines is very low.

If the topology of North American distribution systems contributes to reducing overvoltages originating from the LV network, the probability of transferred overvoltages from the MV line is increased (see Fig. 2).

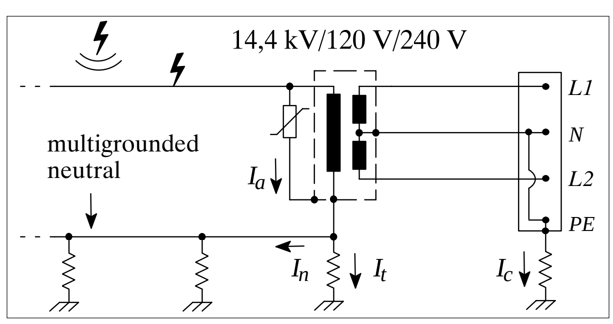

Figure 2 Distribution of the arrester current in the grounding system ($I_a = I_t + I_c + I_n$)

The arrester protecting the transformer limits the overvoltages on the MV line (induced or due to a direct stroke) by diverting the lightning current in the grounding system. This current (I_a) splits between the transformer ground (I_t), the customer ground(s) (I_c) and the other grounds connected to the multigrounded neutral (I_n) (see Fig. 3). These currents produce both neutral-to-ground and phase-to-neutral voltages in the LV network.

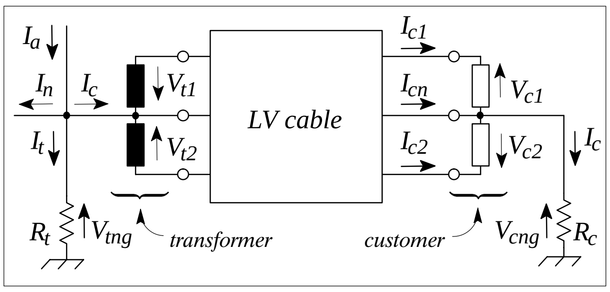

Figure 3 Overvoltages on the LV network caused by the arrester current I_a

Neutral-to-ground voltages at both ends of the LV cable result from currents I_t and I_c in the transformer and customer grounds, respectively. The current in the customer ground (I_c) splits between the neutral and phase conductors of the LV cable. The respective impedances of the transformer, the LV cable and the customer load determine the current division between the phase and neutral conductors.

As the overvoltages reach a few kilovolts on the LV network, surge protection devices operate and/or flashovers occur at the customer installation (the transformer BIL on the LV side is 30 kV) and the current in the transformer LV windings increases. Laboratory tests [3] have shown that surge currents entering the secondary windings can produce local overvoltages in the MV winding and cause an insulation failure. However, the influence of the multigrounded neutral on surge currents and associated voltages in the LV network is poorly documented. Hydro-Québec has conducted a project to study this phenomenon.

Section 2 describes the model implemented in EMTP and Section 3 presents the field test results including a comparison with the model. Section 4 summarizes the results of the sensitivity study.

2. COMPUTER MODEL

The model includes an MV/LV transformer located in the middle of a 2-km MV line (see Fig. 4). The LV network representation includes each customer fed by the transformer and the LV cables connecting them (Fig. 4 shows one customer).

To model adequately the multigrounded neutral, the MV line is divided in 100-m sections. The ground resistance at each node results from paralleling all the grounds located within a 50-m distance. At each end of the line, R_{pf} is equal to the multigrounded neutral impedance at the power frequency (in the order of 1 Ω for rural lines). The transformer and the customer grounds (R_t and R_c) are represented individually.

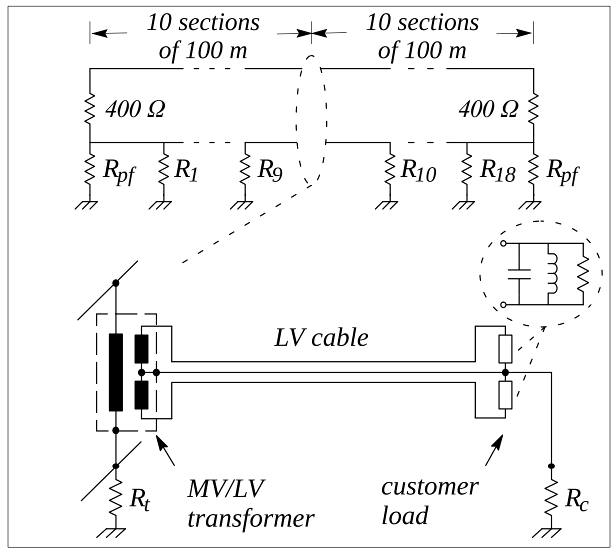

Figure 4 Topology of the computer model including the MV line, the MV/LV transformer and the LV network

Due to the inductance reduction and high attenuation which characterize lines in the ground return mode at high frequencies, a frequency-dependent model is used for both the MV line and LV cables.

The MV line topology is shown in Figure 1. For this study, phase and neutral conductors were modeled using 85 mm^2 Al and 68 mm^2 ACSR conductors, respectively. Twisted conductor cables are used on the LV network. A polyethylene insulation is used on the two phase conductors. A cable with 34 mm^2 Al conductors was modeled.

During the tests, the customer load is constantly changing and its exact nature is unknown. It is therefore approximated by a simple parallel RLC circuit with the inductance representing the subtransient reactance of motors and C, the total capacitance of the installation.

Figure 5 presents the transformer model. The frequency dependence of the leakage inductances and winding resistances are taken into account. The inter-winding capacitances are not included because they are very small and they play no significant role in the phenomenon studied.

Typical short-circuit impedances of MV/LV transformers vary between 1.5 and 2%. Table 1 gives the model parameters for a 25-kVA transformer.

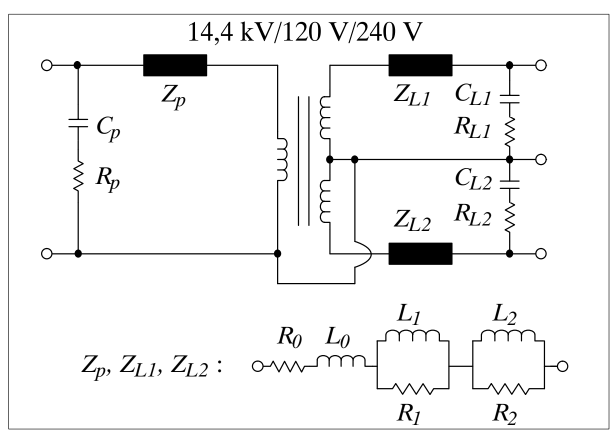

Figure 5 Model of a single phase MV/LV transformer

Table 1 Computer model parameters of a 25-kVA MV/LV transformer (shell-type, non-interlaced LV windings)

	R_0 (Ω)	R_1 (Ω)	R_2 (Ω)	L_0 (μH)	L_1 (μH)	L_2 (μH)
Z_p	17	100	1	0	20 000	2 000
Z_{L1}	0.0024	2	18	12	35	4
Z_{L2}	0.0037	3	24	17	51	5
	R_p	C_p	R_{L1}	C_{L1}	R_{L2}	C_{L2}
	100 Ω	1.3 nF	20 Ω	1 nF	20 Ω	1 nF

The parameters are obtained from impedance measurements in the frequency domain. The resistance of winding L1 for example, increases from 2.4 mΩ to 20 Ω between DC and 1 MHz while the inductance drops from 51 to 15 μH over this frequency range. Figure 6 shows the driving impedance of winding L1 with L2 short-circuited.

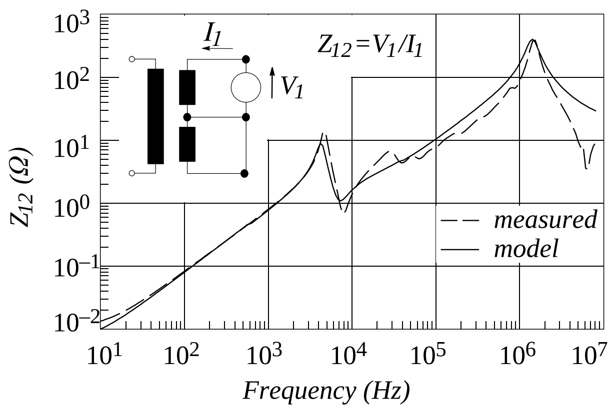

Figure 6 Driving impedance of winding L1 with L2 short-circuited (25-kVA transformer)

The first resonance at 5 kHz relates to the resonance of the MV winding. The main resonance frequency of LV windings exceeds 1 MHz.

3. FIELD TESTS

Field tests were performed to study the overvoltages on the LV network caused by the arrester current injected in the multigrounded neutral. A current pulse (I_i) is injected in the neutral from a ground electrode located 100 m from the line (see Fig. 7). This current dissipates into the ground similarly to the arrester current (I_a) in Figure 3 in the case of a direct stroke to the transformer.

A portable pulse generator (called "GOFM") was designed and used for the tests. It produces 10-A current pulses with a time to crest (t_c) of 1 μs and a time to half value ($t_{50\%}$) of 25 μs. Both the MV line and the LV network remained energized during the tests. The transient currents and voltages had to be extracted from the power frequency component. Pulses were generated at a rate of approximately 5 pulses/sec.; noise cancellation was achieved by averaging measurements over a 10 to 30-second period.

The measurements include currents I_i, I_n, I_t and I_c, the neutral-to-ground voltage (V_{tng}) and phase-to-neutral voltages on the LV network (see Fig. 3).

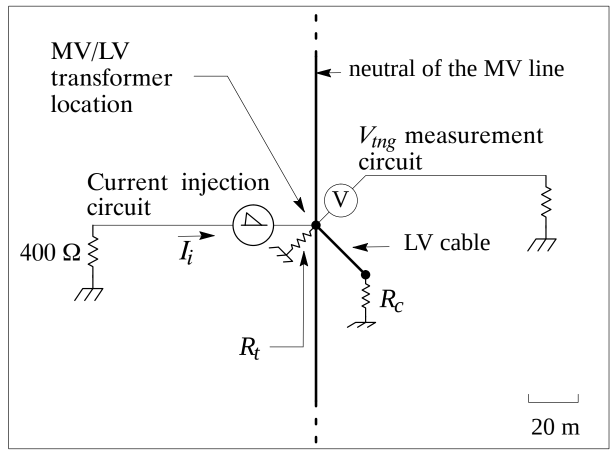

Figure 7 Current pulse injection in the neutral of the MV line

Five rural sites were chosen. Sites 1 and 2 are located 20 km east of Montréal, site 3, 80 km at the north-east and sites 4 and 5, 50 km north of Québec City. Soil resistivity is low at sites 1 and 2 ($\varrho<100$ Ω·m), medium at site 3 ($100<\varrho<500$ Ω·m) and high at sites 4 and 5 ($\varrho>1\,000$ Ω·m). Sites 4 and 5 are located on the same line only a hundred meters apart.

Table 2 gives the values of the main parameters for the five sites. All transformers feed only one customer except for the 100-kVA at site 5 which feeds two customers via two 100-m LV cables. In all cases except one, the customer ground resistance is lower than that of the transformer. An extensive measurement campaign on rural lines [4] has shown that the average resistance of grounds at the foot of poles on MV lines is 2.5 times higher than that of customer grounds.

Results are grouped in three sections: the ground current distribution, the impedance of the grounding system and the phase-to-neutral voltages on the LV network. Results from the measurements at site 1 are compared with those of the model.

<u>All current and voltage measurements are normalized and refer to the crest value of the injected current ($\hat{I}_i$).</u>

Table 2 Transf. kVA rating, number of cust., ground resist. and length of LV cable for the 5 sites

site	kVA	# cust.	R_t (Ω)	R_c (Ω)	l_{LV} (m)
1	25	1	20	10	30
2	50	1	30	30	40
3	25	1	100	20	50
4	25	1	>1000/50[2]	50	20
5	100	2	1000/50[2]	50, 200	100

[2] Problems related to lightning were experienced by customers at sites 4 and 5. Since the ground resistances (R_t) exceeds 1 kΩ, a 200-m-long counterpoise was installed under the MV line on an experimental basis. The DC ground resistance of the counterpoise is 15 Ω and its transient impedance is 50 Ω. Tests were performed with and without it.

3.1 Ground currents

Figure 8 gives the measured and calculated values at site 1 of the distribution of the injected current (I_i) between the transformer ground (I_t), the customer ground (I_c) and the neutral (I_n).

Despite the fact that the transformer ground resistance is twice that of the customer, it initially dissipates almost 80% of the current; this is the lowest inductance path. Only 40% of the total current reaches the customer ground and it has a longer time to crest. The closest grounds on the multigrounded neutral are located more than 200 m from the transformer. Consequently, the neutral dissipates only a small fraction of the current during the first microseconds. The calculated currents are in agreement with the measured values.

Measurements were made with three different values of the transformer ground resistance (R_t) to evaluate its influence on the current in the customer ground. Figure 9 presents the results at site 1.

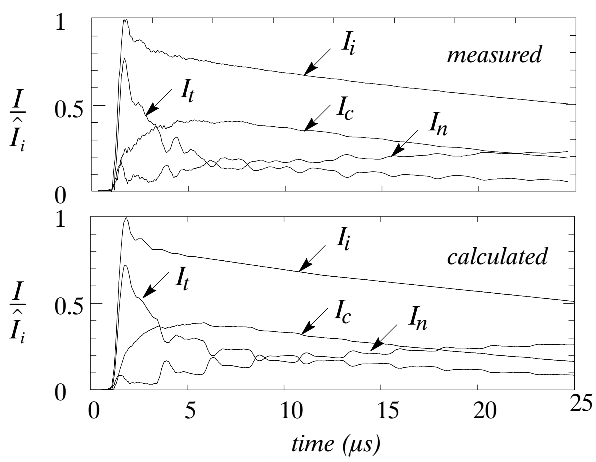

Figure 8 Distribution of the current in the grounding system at site 1

By disconnecting the transformer ground ($R_t=\infty\ \Omega$), the fraction of the current in the customer ground is increased to 90% of the total current and the time to crest drops below 2 µs. By reducing the resistance of the transformer ground to 10 Ω, the customer ground current is reduced to 30% of the total current.

Table 3 summarizes the results for the 5 sites. The time to crest of the current in the customer ground is increased by the LV cable inductance. Although the arrester may inject currents with very fast rise times in the ground

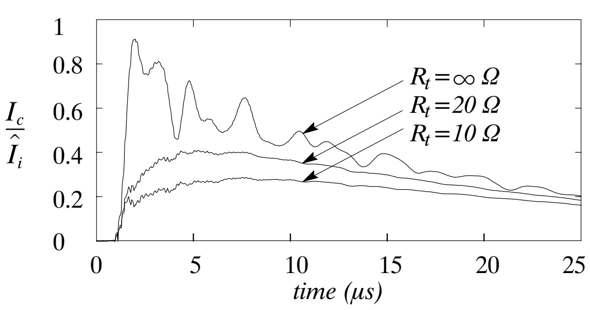

Figure 9 Current in the customer ground (I_c) for different values of R_t at site 1

Table 3 Peak value and time to crest of I_c for the five sites

site	1	2	3	4	5[3]
$I_c/\hat{I}_i$	0.4	0.35	0.6	0.5/0.2[4]	0.23/0.16[4]
t_c (µs)	5	5	3	1.5/1.5[4]	1/3[4]

[3] current in the 50 Ω customer ground [4] with counterpoise

system, the time to crest of currents in the LV cable typically reaches a few microseconds. At site 4, the LV cable is short (20 m) and the time to crest is similar to the injected current. The counterpoise contributes to reducing the current in the customer ground by more than half at site 4.

3.2 Impedance of the grounding system

Figure 10 presents both the measured and calculated neutral-to-ground (V_{tng}) voltages at site 1. The voltage exceeds 20 V/A and drops significantly during the first microseconds.

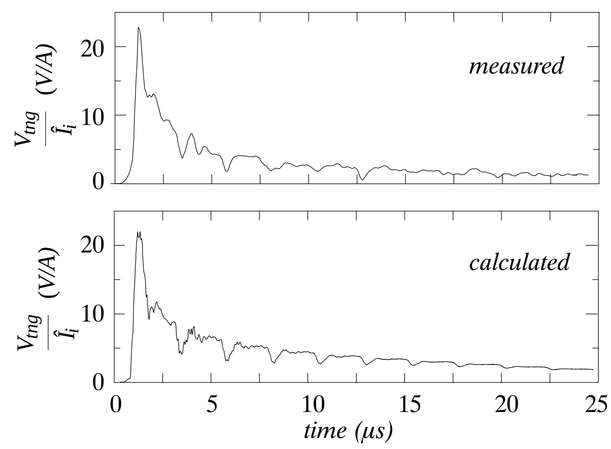

Figure 10 Neutral-to-ground voltage at site 1

Figure 11 gives transient ground impedance of the neutral. The impedance reaches 40 Ω during the first microsecond. This impedance results mainly from the sum of the local transformer ground resistance (20 Ω) and the inductive impedance of the 7-m-long conductor connecting it to the neutral. As the *dI/dt* decreases, the customer ground and other grounds on the MV line contributes to the impedance reduction. The impedance drops below 5 Ω within 5 µs.

Oscillations on the voltage and impedance curves result from reflections on grounding points along the multigrounded neutral.

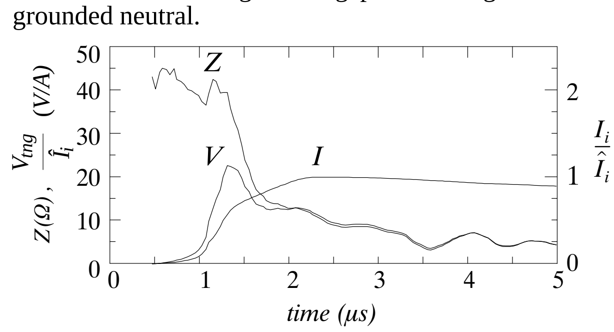

Figure 11 Measured transient impedance of the multigrounded neutral at site 1

The impedance of the multigrounded neutral at site 1 was also measured at 50, 500 and 5 000 Hz using the series injection method described in [4]. Figure 12 presents measured and calculated values. Between 50 Hz and 5 kHz, the impedance increases by a factor of twenty. The impedance of the multigrounded neutral, particularly in rural areas, increases significantly with the frequency.

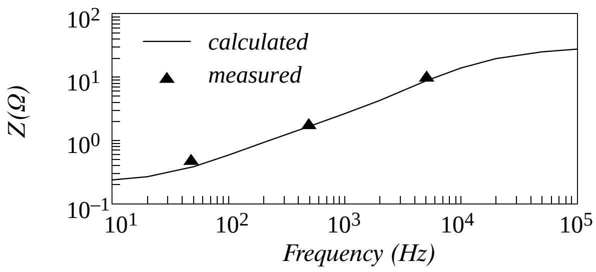

Figure 12 Impedance of the multigrounded neutral as a function of frequency at site 1

From customer ground resistances (Table 2) and measured currents (Table 3), neutral-to-ground voltages at customer installations (V_{cng}, see Fig. 3) vary from 4 to 25 V/A (the customer ground inductance is neglected). In TN systems, all grounded conductors at the customer installation are at the same potential since the customer ground is tied to the LV line neutral. Consequently, neutral-to-ground voltages do not pose significant problems in these systems.

3.3 Phase-to-neutral voltages on the LV network

Phase-to-neutral voltages were measured at both the transformer and customer ends of the LV cable (see Fig. 3). Figure 13 compares the measured and calculated phase-to-neutral voltage on winding L2 of the transformer at site 1. The customer load is disconnected in order to obtain a circuit with known parameters. The main resonance frequency is close to 1 MHz. High frequencies are to be expected since both the transformer and the LV cable resonates at such frequencies.

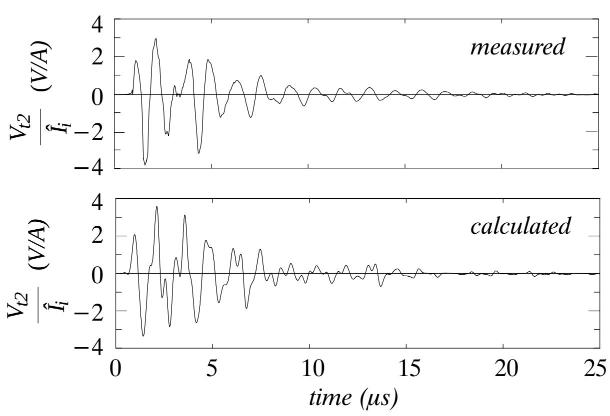

Figure 13 Phase-to-neutral voltage at site 1 on winding L2 of the transformer ($R_t = \infty\ \Omega$), no load

Table 4 presents the results for the five sites. The value of V_{t2} is given since the voltage is systematically higher on winding L2 of the transformer due to its higher impedance.

The high frequencies in Figure 13 are found at each of the five sites. In some cases, lower frequencies (tens of kHz) are also present. By improving the transformer ground at sites 4 and 5, voltages are reduced by half at the customer end and by one third at the transformer.

Table 4 Peak value of phase-to-neutral voltages (in V/A) measured at the transformer and customer ends of the LV cable

site	1	2	3	4	5
$V_{t2}/\hat{I}_i$	3.8	2.3	1.8	3.7/2.1[6]	0.9/0.6[6]
$V_c/\hat{I}_i$ [5]	−−	0.8	1	2.3/1.2[6]	0.8/0.4[6]

[5] the maximum of V_{c1} and V_{c2} is given [6] with counterpoise

Voltages at the customer end tend to be lower due to the overall capacitance of the installation. With voltages in the order of 1 V/A, a current of a few kA in the arrester will cause the surge protection devices to operate and/or multiple flashovers to occur at the customer installation. The LV cable being short-circuited at the customer end, the current in the LV windings of the transformer increases. The sensitivity study assumes this condition.

4. SENSITIVITY STUDY

The comparison of the field test results with the model in the preceding section shows that the latter is adequate to calculate the overvoltages on the LV network. The sensitivity study uses the circuit in Figure 4 to illustrate the influence of five parameters on the phase-to-neutral voltages across the transformer LV windings: the transformer kVA rating, the transformer ground resistance (R_t), the ratio of the transformer to the customer ground (R_t/R_c), the length of the MV cable and the time to crest of the injected current. Table 5 lists the values of these parameters. Ground resistances on the MV line (R_1–R_{18} and R_{pf}) depend on R_t and are defined to obtain typical values for the ground impedance of rural lines. The transformer feeds one customer and the load is short-circuited.

Table 5 System parameters for the sensitivity study

parameter	values
transformer capacity (kVA)	25, 50, 100
R_t (Ω)	10, 100, 1000
R_t/R_c	1, 3, 10
R_1–R_{18} (Ω)	$R_t/3$
R_{pf} (Ω)	$\sqrt{R_t/30}$
length of LV cable (m)	15, 30, 100
time to crest of injected current (μs)	1, 2, 10

Figure 14 gives the range of values obtained for the 25, 50 and 100-kVA transformers, respectively; the current injected has a 1 μs time to crest.

Smaller transformers tend to produce higher overvoltages due to their higher impedance. Laboratory tests [3] have shown that they are more vulnerable to LV current surges.

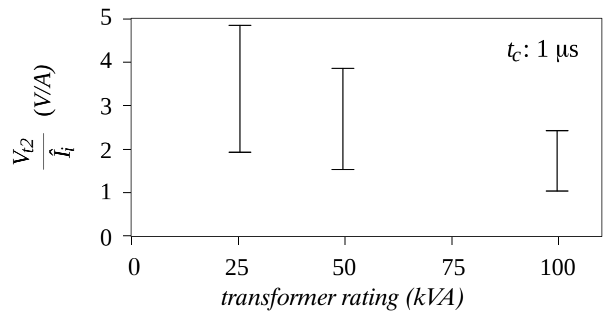

Figure 14 Range of phase-to-neutral voltage values on the LV side of the transformer

Figure 15 shows the influence of the ratio of the transformer to the customer ground resistance. For low ground resistance values (R_t=10 Ω), R_t/R_c has little influence on overvoltages. However, with higher ground resistance values, overvoltages can be reduced by improving the transformer ground. For example, voltages were reduced by half at sites 4 and 5 with a reduced transformer ground resistance.

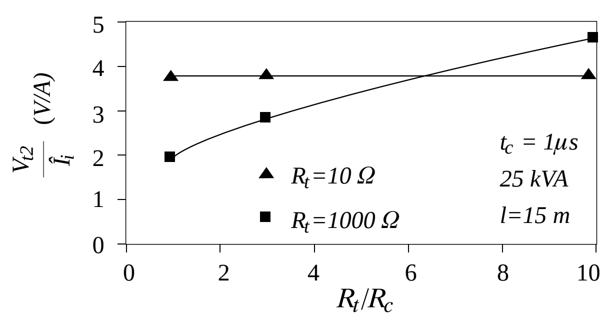

Figure 15 Influence of the R_t/R_c ratio on phase-to-neutral voltages on the LV side of the transformer

The time to crest of the current injected in the neutral influences the LV overvoltages (see Fig. 16). Resonance frequencies in the MHz range are hardly excited by currents with lower *dI/dt*. These currents consequently produce lower overvoltages.

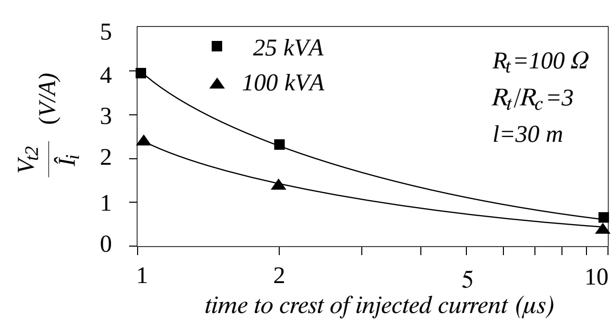

Figure 16 Influence of the time to crest of the injected current on phase-to-neutral voltages on the LV side of the transformer

5. CONCLUSIONS

LV networks on Hydro-Québec's system are short, typically under 50 m. The probability of a direct stroke or reaching harmful induced overvoltages from a nearby stroke are consequently reduced compared to extended LV networks.

The multigrounded neutral of the MV line connects the transformer ground, the LV line neutral and customer grounds. Overvoltages on the MV line (induced or due to a direct stroke) cause the arrester protecting the transformer to inject high-energy current pulses in the LV network. Consequently, the probability of overvoltages originating from the MV line are increased compared to systems with the transformer ground isolated from the LV neutral.

A portable pulse generator (called "GOFM") was designed and used to perform tests at five sites. Results show that 20-60% of the current in the arrester dissipates into the ground via the LV network. This current pulse causes voltages to appear both in common and differential modes. In rural areas where the transformer feeds only one or two customers, values in the order of 10 kV/kA and 1 kV/kA for neutral-to-ground and phase-to-neutral voltages, respectively, are typical at the customer installation (voltages are referred to the current in the arrester). In TN systems, problems are mostly related to phase-to-neutral voltages.

As the overvoltages reach a few kilovolts at the customer installation, flashovers occur and the current in the transformer LV windings increases. The sensitivity study shows that voltages across the transformer LV windings range between 1 to 5 kV/kA, with higher values related to small kVA ratings.

When problems caused by lightning overvoltages in the LV network require mitigation measures, different solutions are available. In high soil resistivity areas particularly, improving the transformer ground helps reduce the current and associated overvoltages in the LV network. Changes in the design of transformers and/or the installation of arresters on the LV side can help reduce their failure rate when economically justified.

6. REFERENCES

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