Risk of voltage escalation due to a single-phase fault on the ungrounded MV network of an industrial plant

A. Xemard, B. Deneuville, P. Girard, I. Uglesic, B. Filipovic-Grcic, V. Milardic, N. Stipetic.

***Abstract*— In an ungrounded electrical system, successive reignitions and extinctions of a single-phase to ground fault is known to potentially generate a voltage escalation phenomenon. This is the so-called arcing ground fault whose theory has been thoroughly described in literature, even though very few practical occurrences have been experienced in existing electrical systems due to the specific and rare conditions that cause its appearance.**

This paper studies the risk of appearance of voltage escalation in the 10 kV auxiliary system of an industrial plant. It describes the physical principles at the origin of voltage escalation and presents a study conducted using an EMT-like program. The results show that, thanks to the presence of a permanent insulation monitor (PIM) connected to the system through voltage transformers, the successive reignitions and extinctions of single-phase faults cannot cause severe overvoltages or voltage escalation. The paper ends with some general conclusions.

***Keywords*: ungrounded MV network, voltage escalation, EMT-like program, insulated neutral, permanent insulation monitor.**

I. INTRODUCTION

This paper studies a specific issue related to ungrounded three phase AC systems. The use of ungrounded systems is justified by their high reliability: as neither the neutral nor any live conductor of the system is directly earthed, the ground fault current is of such low value that in the event of a single fault to an exposed-conductive-part or to earth, automatic disconnection is not imperative. In contrast, when a ground fault occurs at two or more points, it results in high current and faults needs to be cleared. Therefore, to support the system reliability and avoid the relay protection operation upon the second fault, prevention measures that would potentialy avoid or postpone the switching should be considered [1].

In ungrounded electrical systems, successive reignitions and extinctions of single-phase to ground faults can lead to a voltage escalation phenomenon. This phenomenon, commonly known as arcing ground fault, leads to a progressive and sustained increase of the phase voltage and occurs when some specific conditions are met. Its theory has been thoroughly described in literature [2], [9], [3]. However, a very few practical occurrences have been experienced in existing electrical systems because of the specific conditions to be fulfilled for it to appear.

This paper studies the risk of appearance of voltage escalation in a 10 kV ungrounded auxiliary system of an industrial plant. The first part of the paper is devoted to theoretical considerations regarding voltage escalation. Then the configuration under consideration and the modelling approach in an EMT-like program [5] are described. The presented simulations results show how the existence of voltage transformers used for PIM connection prevents the occurrence of voltage escalation.

II. THEORETICAL BACKGROUND

This paragraph, which is largely based on [1], is devoted to a presentation of the general theoretical background required for understanding the results of the electromagnetic transient calculations presented in this paper.

An arcing ground fault occurs in an ungrounded electrical system. It is a single-line-to-ground fault which extinguishes and reignites successively. Under some very specific circumstances, these reignitions can cause a voltage escalation.

It can be explained the following way. Fig. 1 shows an example of simplified representation of an ungrounded electrical system. In normal operating condition, the three-phase system is balanced and its neutral is at zero potential.

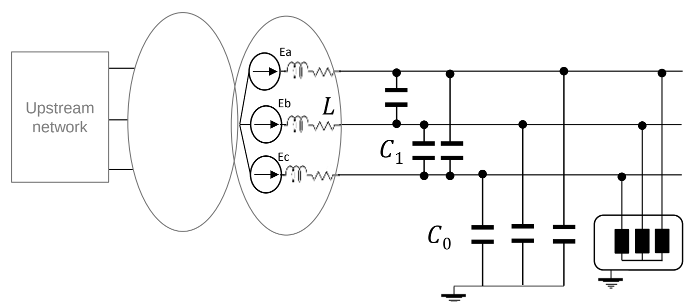

Fig. 1. Representation of the ungrounded system with the phase to ground (C_0) and the phase-to-phase capacitances (C_1).

If a ground fault occurs in phase A when its voltage reaches the negative peak of - 1 p.u., the whole system translates for 1 p.u., keeping the vector balance between the phases. (the sum is geometric for the phases). The capacitance C_0 of phase A rapidly discharges through the fault and the capacitances of phases B and C. The discharged current is distributed between phases, phase B and C reach a new potential V, as defined by (1);

$$V(C_0 + C_1) = \tfrac{1}{2}C_0E_p + \tfrac{3}{2}C_1E_p, \qquad (1)$$

where E_p is the absolute value of the maximum phase to neutral

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voltage. The transient discharge progressively brings voltages of phases B and C to their final voltage of 1.5 E_p. The electrical circuit involved in the transient is depicted in Fig. 2., where capacitance C_1 between phases B and C is neglected. This circuit has an oscillation frequency whose value is determined by the expression:

$$f = \frac{1}{2\pi}\frac{1}{\sqrt{3L(C_0+C_1)}} \quad . \tag{2}$$

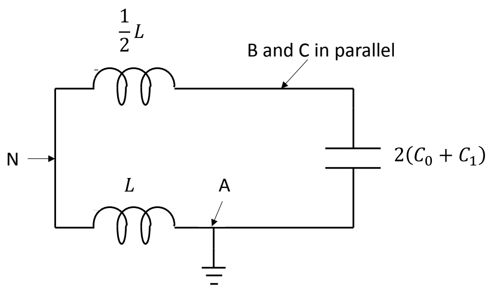

Fig. 2. Circuit involved in the transient leading to the modification of potential at phases B and C following a phase to ground fault in phase A.

These oscillations can be seen in Fig. 3, where phase to ground voltages in phases A, B and C calculated using an EMT-like program are depicted. The results in Fig. 3 are obtained in case of a phase-to-ground fault in phase A in the industrial plant, without (PIM). The dominant oscillation frequency of the transient following the fault is around 2.9 kHz.

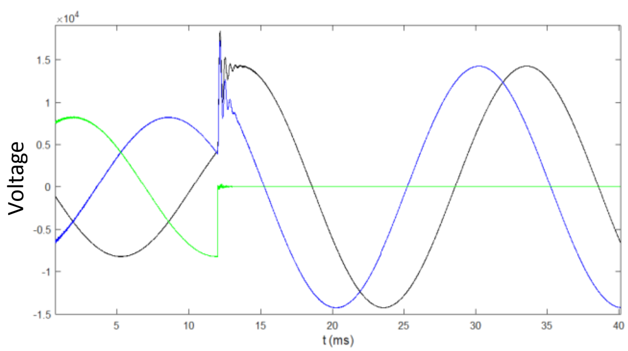

Fig. 3. Phase to ground voltage (V) on phase A (_), B (_) and C (_) with a phase to ground fault on phase A at 12 ms.

Two different cases of current interruption can occur, depending on fault type and time instant:

- the current extinguishes at the next 50/60 Hz current zero-crossing.
- the current is interrupted at a high-frequency zero current crossing.

The results of fault extinction are explored in following paragraphs.

A. Extinction at the next 50/60 Hz current zero-crossing

If the arc that is causing the fault extinguishes at the following natural zero-crossing, the voltage phasors will find the balance as depicted in Fig. 4.

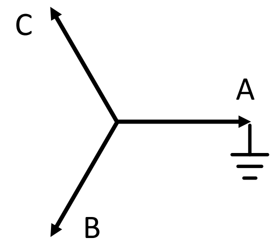

Fig. 4. Position of the phasors if the fault extinguishes at the first 50/60 Hz natural zero-crossing, following the beginning of the fault.

The potential of the whole electrical system has an offset of 1 p.u. or 8.16 kV phase-to-ground in the studied case. The phase voltages are shown in Fig 5.

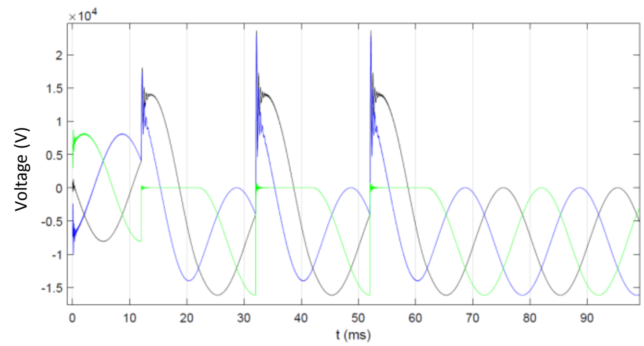

Fig. 5. Voltage on phase A (_), B (_) and C (_) with a succession of faults on phase A occurring at the crest of a negative half-cycle of the voltage followed by extinctions of the fault current at the next 50/60 Hz zero-crossing.

After the fault, the voltage in phase B reaches 1.5 p.u. After the first transient, whose crest value is 2.2 p.u., if the fault reignites again at the next voltage peak in phase A, the neutral point voltage increases to 2 p.u. (from -1 p.u. to 1 p.u.), making the second transient more severe. The crest value of the voltage in phase B reaches 2.9 p.u. A further cycle of reignition/extinction occurring in the same conditions leads to the same overvoltages as in Fig. 5 and there is no further voltage escalation.

B. Arc extinction at high-frequency current zero-crossings

If the arc is extinguished at the first high-frequency current zero-crossing, the capacitances C_0 and C_1 have, just before arc extinction, a voltage to ground $V_{C0/C1}$ constituted of 2 components:

- The voltage due to the system = 1.5 E_p;
- The voltage due to the oscillatory current = 1.5 $E_p - V$.

Therefore:

$$V_{C0/C1} = 1.5\, E_p + 1.5\, E_p - V = 3\, E_p - V \tag{3}$$

Consequently, after the arc extinction, the voltage difference between $V_{C0/C1}$ and 1.5 E_p will appear between phase A and the ground: $1.5 \cdot E_p - V$. The neutral is subject to the same displacement. Successive reignitions at maximum voltage followed by an extinction at one of the next high-frequency zero currents leads to a transient quite similar to the one considered previously, but this time the overvoltages are more severe because of the increasing trapped charges in the zero-sequence capacitance. Hence, there is a risk of further voltage escalation. An example of such overvoltages in the same configuration is given in Fig. 6.

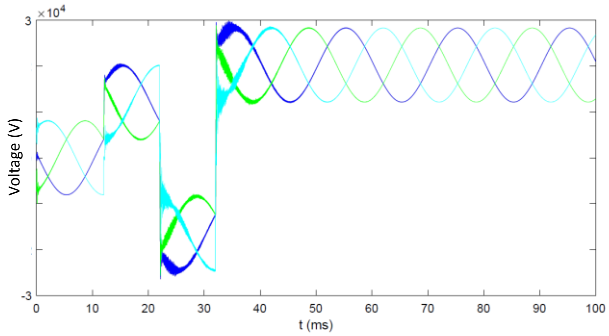

Fig. 6. Phase to ground voltage A (_), B (_) and C (_) when a succession of reignitions, and extinctions at high-frequency zero current crossing occur.

III. Considered Configuration

In this study, the 10 kV auxiliary system of an industrial plant is considered. It is energized by 400 kV/10 kV YΔ transformer. The system has a radial structure, it is ungrounded and mainly supplies electricity to 10 kV motors through cables and MV/LV transformers which are connected to LV motors (Fig. 7). Different characteristics are used for cables depending on the loads they supply energy to. The length of cables ranges from of a few 10 m to a few 100 m.

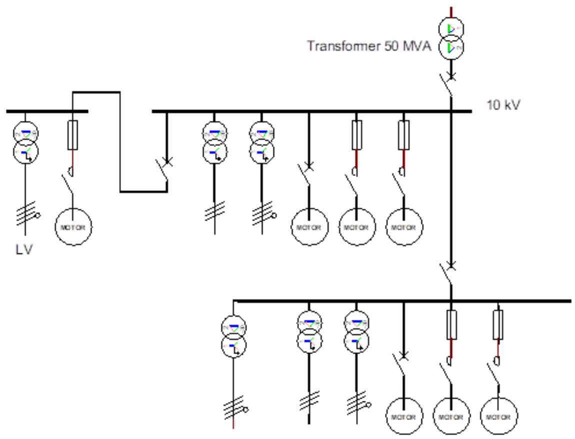

Fig. 7. Scheme of the 10 kV auxiliary system of an industrial power plant

A PIM [4] is used in this system for insulation monitoring. Its principle is to inject a low DC current which closes its path via fault location, as depicted in Fig. 8. The phase to ground resistance of the insulated system is permanently measured and an alert is given when the resistance between an active phase conductor and ground becomes lower than a preset value, which indicates a fault occurrence. This technic is very robust and largely used nowadays but it does not allow to localize the fault [7].

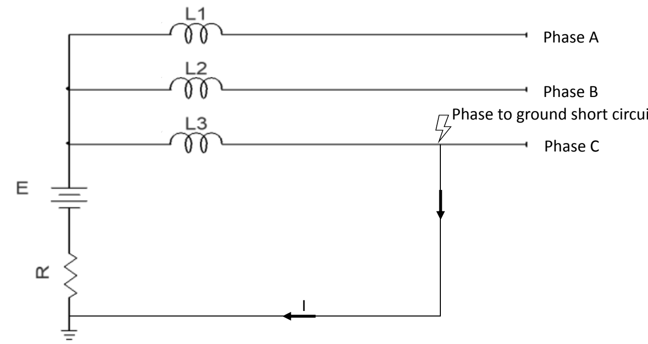

Fig. 8. Principle of a PIM based on the injection of a DC current.

The PIM is connected to the MV system with voltage transformers [8] as indicated in Fig. 9. The PIM is protected by a surge arrester whose continuous operating voltage U_c is 280 V and its residual voltage U_P 1.2 kV at nominal discharge current 10 kA (when 15 cm leads are considered). A 10 µF capacitor is installed in parallel with the PIM for potential stability. The secondary of the voltage transformers are delta connected to a resistance of 47 Ω, whose function is to suppress ferroresonance during transient phenomena [3], [7].

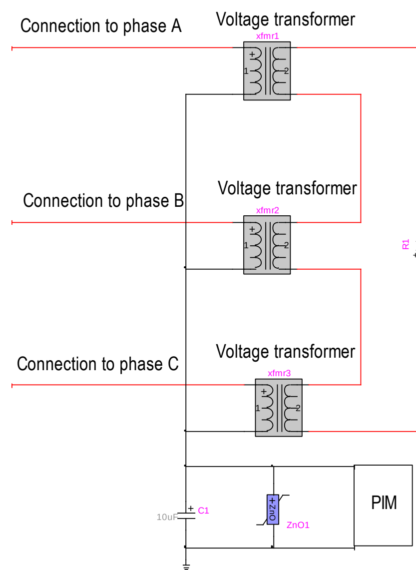

Fig. 9. Connection of the PIM to the phases of the MV system.

IV. Modelling of the System

The modeling follows the recommendations of the IEC 60071-4 [9][9] for low-frequency (up to a few kHz) overvoltages. The most noticeable elements are indicated below:

- Medium voltage motors (asynchronous) are individually represented based on the Park's equations. The external mechanical torque applied to their shaft is proportional to the angular speed of the shaft.
- Voltage transformers are represented with their saturation curve.
- Low voltage motors connected to a MV / LV transformer are represented by an equivalent motor whose power is equal to the sum of the power of the individual motors. This technic allows to limit the

number of motors in the representation to 20.

- Cables are quite short compared to the minimum wavelength of the significant electromagnetic phenomena involved, therefore they are represented by π models.
- Power transformers are represented by low frequency models (up to a few kHz).
- The arrester protecting the PIM, is modeled by its nonlinear *U-I* characteristic.
- The PIM itself has not been represented because it does not have a major influence on the considered phenomenon.
- Faults are represented by an ideal switch which close (ignition) and open (extinction) in one power-frequency time period.

The arc model was not considered since the voltage escalation phenomena was initiated intentionally by ideal switch, with predefined ignition and extinction time instants, in order to analyze the influence of PIM/voltage transformers on the voltage escalation. However, the dynamic arc resistance would influence the voltage phenomena, since it would lead to less severe voltage escalation. The ignition and reignition times depend on arc behavior and would differ from the ones used in this paper, which provoked the worse voltage escalation.

Cable insulation disintegrates because of the heat produced by the arc and the cable arcing fault differs from the arcing fault in air insulation, i.e. overhead lines. There is not much experimental investigation of overvoltages caused by intermittent arcs in MV cable networks [10] According to literature, the constants of intermittent electric arc model determined from laboratory or field measurements [11], [12], [13], [14], Applicability of such constants on different networks is questionable and appropriate measurements were not available in the considered case.

EMTP software is used to conduct simulations [5] [6].

V. Calculation Results and Interpretation

Four cases are considered for the arcing fault simulation. In first one, a fault is simulated in the system without PIM and without MV surge arresters. In the second case, a PIM was included, but connected through ideal voltage transformers without saturation curve included, and again without MV arresters. The third case considers PIM connected using a real voltage transformer model, without MV surge arresters and fourth case finally includes a real PIM connection and MV arresters.

A. Case 1: configuration without PIM and without MV surge arresters

In this configuration the system is simulated without the PIM connection to the MV system and without MV phase arresters. A case in which a fault appears on phase A and reignites several times when the 50 Hz voltage is maximum is simulated, as indicated in Table I. By hypothesis, the extinctions take place at a high frequency current zero-crossing after the fault.

TABLE I

Fault (re)ignition and extinction times in a configuration without PIM and without phase arresters

Fault (re)ignition time (ms)	12	22	32
Fault extinction time (ms)	12.159	22.173	32.159

These very unlikely conditions lead to voltage escalation in phase A as shown in Fig. 10.

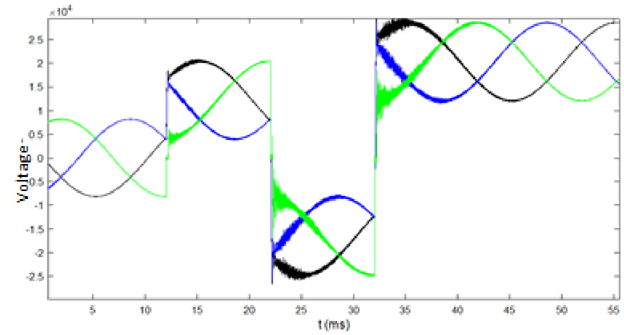

Fig. 10. Voltage escalation due to a succession of faults on phase A (green curve) when the phase/ground voltage is maximum, followed by interruptions at HF zero-crossing currents in a configuration without PIM and phase arresters.

Fig. 11 shows the increase of the voltage in all phases which takes place after the first sequence of fault and extinction.

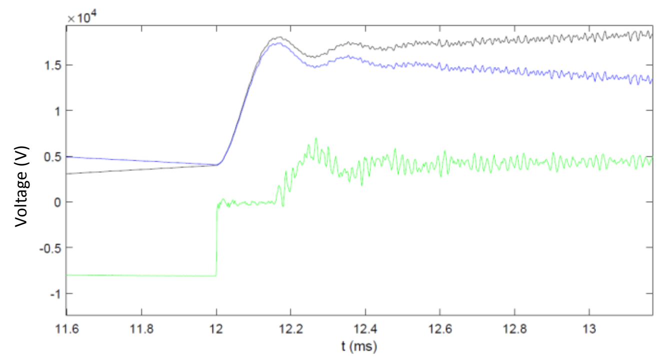

Fig. 11. Zoom on a part of Fig. 9. corresponding to the first fault on phase A at 12 ms (green curve) followed by an extinction at a high frequency zero current (12.159 ms).

B. Case 2: Configuration with PIM connected through ideal voltage transformers, without MV surge arresters

The PIM represented in Fig. 9 is included in the network model. The voltage transformers used to connect the PIM to the phases are considered as ideal: their magnetizing resistances and inductances are considered infinite (no saturation). There are no phase arresters. It was chosen that the fault on phase A starts and reignites at 50 Hz crests of the phase voltage and extinguishes at a high frequency current zero-crossing following the fault. Table II provides fault's (re)ignition and extinction times.

TABLE II

Fault (re)ignition and extinction times in a configuration with the PIM and without phase arresters (the voltage transformers are ideal)

Fault (re)ignition time (ms)	12	22	32
Fault extinction time (ms)	12.159	22.173	32.159

Fig. 12 shows that the phenomenon of voltage escalation still exists but there is a slight dissipation of the DC component of the overvoltage, due to the resistance on the secondary side of the voltage transformers.

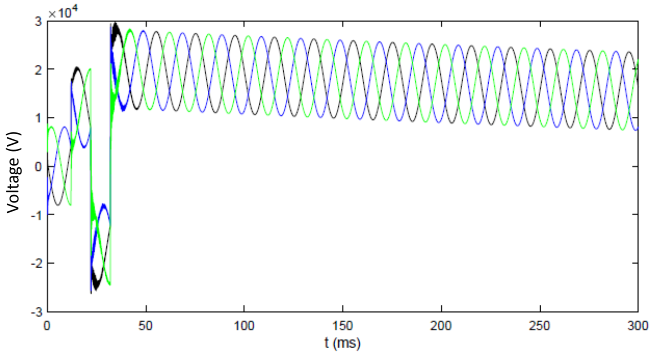

Fig. 12. Voltage escalation due to a succession of faults on phase A (green curve) when the phase/ground voltage is maximum, followed by interruptions at HF zero currents in a configuration with a PIM connected to the system with ideal voltage transformers.

C. Case 3: Configuration with a PIM connected using real voltage transformers, without MV surge arrester

In this case, the PIM is again included in the model, but the magnetizing curve of the voltage transformers is taken into account. The curve is based on the voltage transformer data sheet and it is given in the Appendix I. Again, no surge arresters are included in the model.

As previously, the fault starts and reignites at 50 Hz crests of phase A voltage and extinguishes at high frequency current zeros. Table III gives fault (re)ignition and extinction times. Fault (re)ignition and extinction times differ from the case 2 in order to obtain the most critical overvoltages.

TABLE III

FAULT (RE)IGNITION AND EXTINCTION TIMES IN A CONFIGURATION WITH THE PIM AND WITHOUT PHASE ARRESTERS (THE VOLTAGE TRANSFORMERS ARE NON-IDEAL)

Fault (re)ignition time (ms)	12	31.6	51.6
Fault extinction time (ms)	12.159	31.77	51.76

Fig. 13. shows the phase to ground voltages. In this configuration there is no voltage escalation. The presence of voltage transformers introduces a limitation of the overvoltages since a part of the transient currents circulates to the ground via the input inductance and resistance of the voltage transformers, and through the capacitor and arrester. This is a similar phenomenon which eliminates trapped charges on a transmission overhead line after the opening of the breakers at both ends.

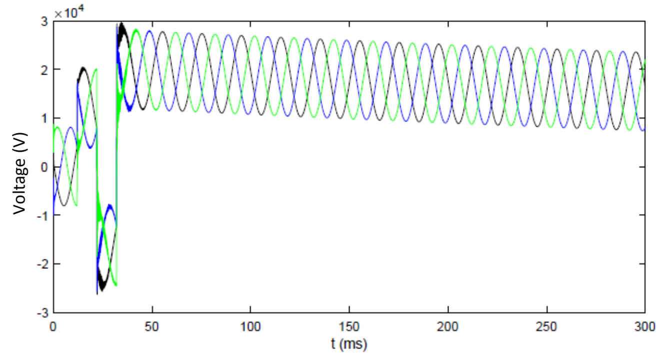

Fig. 13. Overvoltage due to a succession of faults on phase A (green curve) when the phase/ground voltage is max, followed by interruptions at HF zero currents in a configuration with a PIM connected to the system with non-ideal voltage transformers.

In addition, after the series of fault reignition/extinction, the phase to ground voltages settle back to their nominal values. This is an important result because it shows that after a series of reignition / extinction no significant, long duration overvoltage stresses the insulation.

D. Case 4: Configuration with a permanent insulation monitor connected with real voltage transformers and with MV surge arresters included

This case aims to determine the influence of the surge arresters on the overvoltages due to multiple reignitions.

Fig. 14. shows that the MV surge arresters do not have any significant impact on the overvoltages. Their peak value is around 19 kV while the residual voltage of the MV surge arresters is 37.5 kV (for 5 kA).

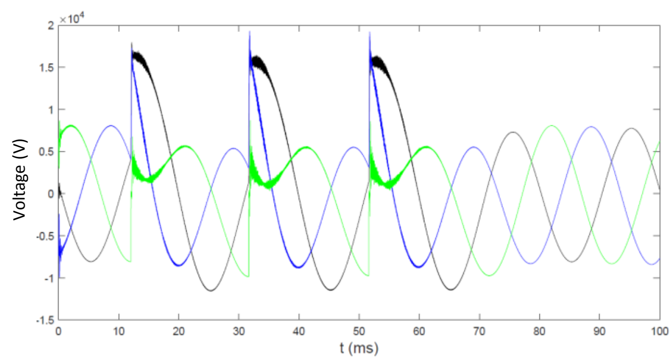

Fig. 14. Overvoltage due to a succession of faults on phase A (green curve) when the phase/ground voltage is max, followed by interruptions at HF zero currents in a configuration with a PIM connected to the system with non-ideal voltage transformers and where phase arresters are present.

Regarding the arresters, an important issue is the energy stress of the LV arrester which protects the PIM. Fig. 15. shows the energy absorbed by this LV surge arrester. After 4 fault (re)ignitions/extinctions, this energy is in the order 200 J. If a class 2 arrester is used, its energy is 1.15 kJ (4.1 kJ / kV U_c with U_c = 280 V). It can be concluded that the LV arrester can withstand a series of fault (re)ignition / extinction without damage due to thermal stress.

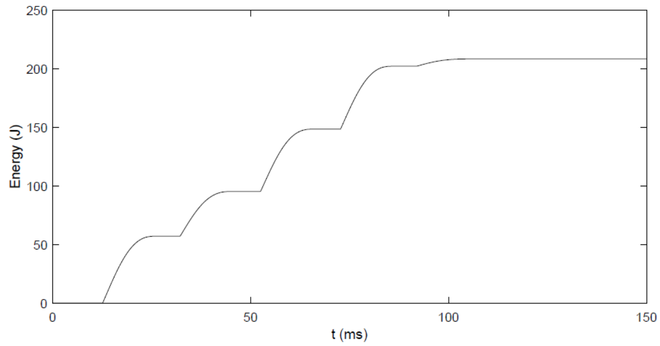

Fig. 15. Thermal energy stored in the LV arrester in parallel with the PIM during the sequence of 4 (re) ignitions / extinctions.

VI. CONCLUSIONS

The simulations performed in this paper show that in pure theory, voltage escalation can occur in configurations without inductive voltage transformers and PIM connection circuit, but the risk is quite low because it involves fulfilling very rare conditions: voltage escalation requires successive arc (re)ignitions and extinctions at a high frequency current zero-crossing in a phase-to-ground fault. It was shown that the presence of a PIM connected to the system through voltage transformer eliminates the risk of voltage escalation. The inductive character of voltage transformers can be considered as short circuit for the trapped charges of the phase to ground capacitances. These trapped charges circulate through the voltage transformers and PIM connection circuit. The residual voltage of this arrester is low (0.76 kV at 1 kA with a 15 cm lead) and in case it conducts, it contributes to voltage reduction. MV surge arresters have no real influence on the overvoltages because their protection level (this is 33.5 kV) is higher than the amplitude of the considered overvoltages.

The calculations in the paper were conducted on an industrial system but the same reasoning might also probably explain the scarcity of voltage escalation due to faults in public electricity distribution networks.

VII. APPENDIX I

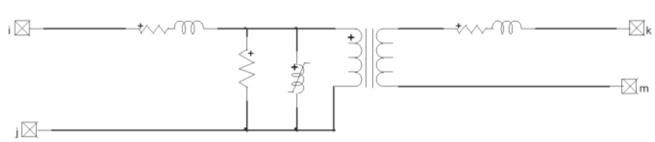

Fig. 16. Modelling of the voltage transformer.

TABLE IV
CHARACTERISTIC OF THE PHASE ARRESTERS

Current (A)	Voltage (kV)
10^{-3}	22
1	28
5 000	37.2
10 000	40
20 000	44.4

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