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B2 OVERHEAD LINES
PS3 - Environmental and Safety Aspects from OHL (joint PS with C3)

Design and protection criteria for passive loops on a 400 kV double circuit line

Piero BERARDI, Luca BUONO, Gianluigi GEMELLI, Francesco PALONE, Lorenzo PAPI*, Alberto PICCININ, Roberto SPEZIE, Marco VALENTE
Terna S.p.A.
Italy

piero.berardi@terna.it, luca.buono@terna.it, gianluigi.gemelli@terna.it, francesco.palone@terna.it, (*)lorenzo.papi@terna.it, alberto.piccinin@terna.it, roberto.spezie@terna.it, marco.valente@terna.it

SUMMARY

Passive Compensated Loops (PCLs) are an effective solution for reducing public exposure to magnetic fields due to Overhead Lines (OHLs); Terna is currently building a new 400 kV OHL between Colunga and Calenzano substations, using a 3-conductors passive loop to guarantee a magnetic field lower than 3 µT, near any public or urban areas. Whereas the allowable ICNIRP magnetic field limit for public exposure is 100 µT, the Italian law adopts a more challenging threshold of 3 µT for new HV/EHV OHLs. Two 40.5 mm loop conductors will be installed below phase conductors and a third loop conductor will be installed above phase conductors in lieu of a shield wire. In order to maximize the shielding effect, while not exceeding the loop conductors ampacity, PS will be equipped with a Series Capacitance Compensation System (SCCS), with 4 mF capacitors.
Given the relatively small voltage expected in normal operation, the loop conductor insulation is, in principle, not an issue. However, as the loop conductor voltage can attain some thousands of Volt, safety and design issues shall be carefully addressed.
The first issue is related to the design and sizing of the capacitor banks: as in EHV series capacitors installation, a fault on phase conductors causes significant overcurrents and overvoltages on the capacitor units. A proper choice of the capacitors rated voltage, protective surge arresters, and by-pass switch is thus of paramount importance for a safe and reliable installation. To mitigate the visual impact and footprint of the SCCS and the switching equipment, a containerized solution has been detected. Series capacitances, surge arresters, by-pass switch and firing protection system are going to be installed inside a 40’ standard container with an innovative camouflage pattern, inspired to the local landscape.
A fault on a phase conductor is, typically, cleared in few power-frequency cycles (usually less than 100 ms), thanks to line distance protections. However, a fault on a loop conductor is unnoticeable from conventional line protection, as well as by any protection relying on HV current and voltage transformers measurements. Terna thus investigated the possible fault scenarios, involving both permanent (e.g. contact between a loop) and transient faults (e.g. due to a direct lightning strike or due to back-flashover).
The paper deals with design and protection criteria of the PCLs; Section I describes the design of the main components, including both technical and environmental issues. ATP-EMTP studies are reported in Section II both at steady state and upon fault condition. The design of line fittings is reported in

Section III. Section IV includes arc extinction analysis for the proposed arching horns, using a detailed ATP-EMTP model based on the Kizilcay arc model. Protection relay choice and simulations are reported in section V. Conclusions are eventually reported in section VI.
The paper introduces risk and safety issues related to PCLs, as well as possible mitigating solutions, applied to an actual 400 kV double circuit line project; results evidence that using a proper design, PCLs can be an effective, safe and environmentally friendly solution for OHLs.

KEYWORDS
Magnetic Field, Environmental Impact, Passive Loops, Overhead Lines.

I. INTRODUCTION

The Italian Transmission System Operator (TSO) Terna is currently building a new 400 kV Overhead Lines between Colunga and Calenzano substations, in order to increase the expected power flow between North and Centre-North of Italy. As reported in Figure 1, the 400 kV OHL is in double circuit between Calenzano substation and tower number 218, and in single circuit between tower number 218 and Colunga substation. Different tower structures (both steel tubular and guyed towers), number of shielding wires (1 or 2) and phase conductors will be installed along the OHL route.

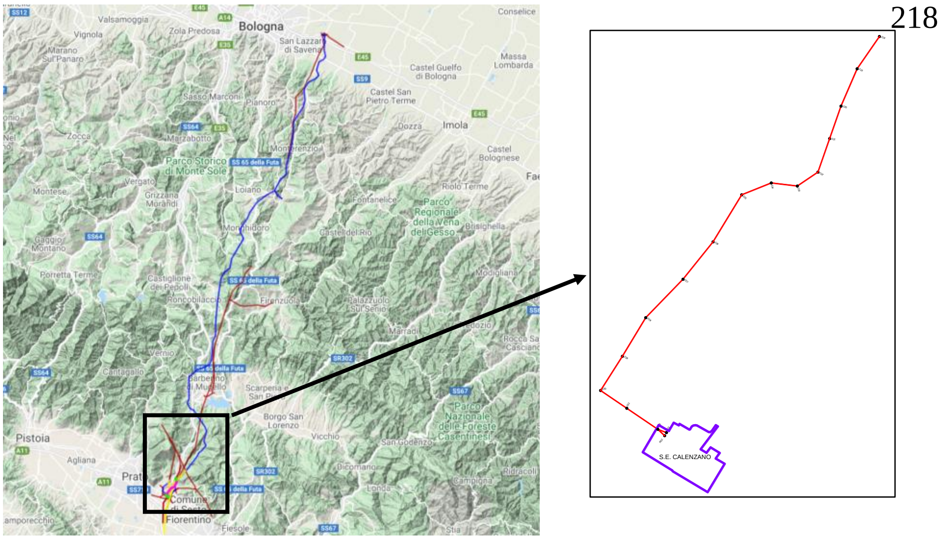

Figure 1 - 400 kV overhead line route between Colunga and Calenzano substations.

In order to satisfy the Italian Law constrains [1][2] related to magnetic field public exposure (3 μT), a portion of OHL between Calenzano substation and tower number 218 will be equipped with a passive compensated loop. A dedicated steel tubular double circuit tower was developed by Terna allowing the installation of loop conductors. As reported in Figure 2, three passive loop conductors with a diameter equal to 40.5 mm will be installed to mitigate magnetic field induction: two loop conductors will be installed below phase conductors, whereas the third loop conductor above phase conductors, in lieu of a shield wire. Tower cost increases by +20-25%, if compared to a standard solution without the compensation loop, instead, in term of time, there are not significant increase. Regarding the public acceptance, a tubular structure has been adopted in order to obtain a lower visual impact.

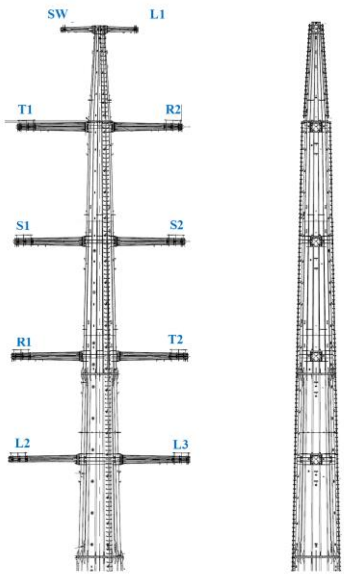

Figure 2 - Steel tubular tower with double circuit (R,S,T), shielding wire (SW) and loop conductors (L).

To increase the induced current on passive loop and, therefore, to reduce magnetic field induction, series capacitances will be installed on passive loop; an optimization algorithm was developed by Terna in order to find the value of capacitance able to mitigate magnetic induction near OHL [7]. Thus, a 4 mF capacitance value was detected. As reported in Figure 3, the Series Capacitance Compensation System (SCCS) identified by Terna is composed by:

- a circuit loop bay (M1) for the connection of SCCS to 400 kV OHL and protection from overvoltage and overcurrent related to internal and external faults;
- a capacitive compensation bay (M2) for the connection of 4 mF capacitors banks in series with passive loop;
- a bypass bay (M3) for the connection of a resistive-inductive load to mitigate inrush current and specific energy of surge arresters, installed in parallel to the capacitors banks.

A dedicated protection logic system is going to be developed by Terna in order to guarantee a safe operation of surge arresters and capacitors banks: in case of overvoltage, circuit breaker of passive loop (M1) will be switched off, whereas circuit breaker of the resistive-inductive load (M3) is going to be switched on, avoiding the increasing of surge arrester specific energy.
The main characteristics of SCCS equipment are reported in Table I.

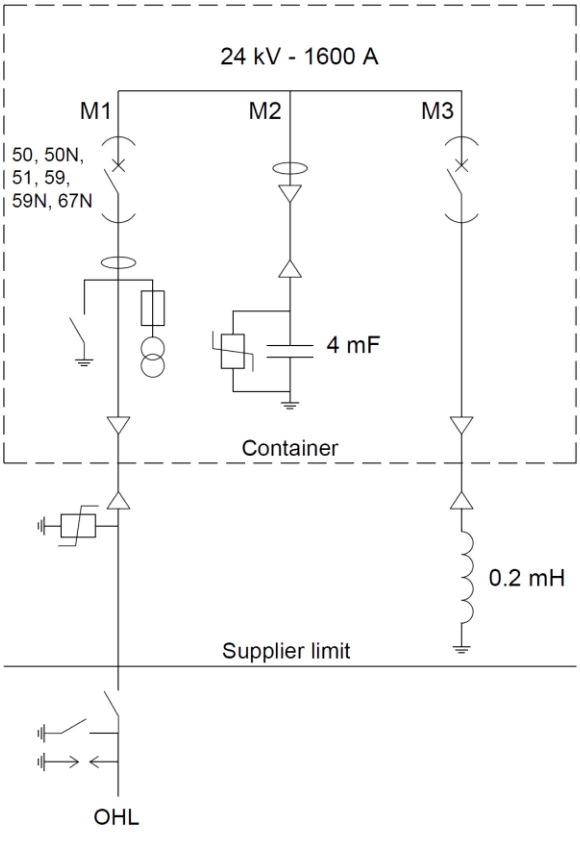

Figure 3 – Single line diagram of series capacitance compensation system for the 400 kV OHL between Colunga and Calenzano substations.

Capacitor banks	
Rated capacitance	4 mF
Rated voltage	1732 V_{rms}
Rated current	1256 A_{rms}.
Surge Arresters	
Continuous operating voltage	≥ 1.5 kV
Temporary overvoltages (TOV)	2750 V_{rms} / 1 s
Nominal discharge current	≥ 10 kA
Residual voltage/Discharge voltage	5.4 kA_{peak} – U_{res} ≤ 3.75 kV_{peak}
Bypass load	
Rated inductance at power frequency	0.2 mH
Rated current	800 A
Short circuit current (I_{kn})	20 kA
Specific energy	≥ 400 kJ

Table I – Main characteristics of SCCS equipment.

Overhead line magnetic fields have been evaluated both with and without compensated loop conductors according to Italian Standard CEI 211-6 [4]; simulation results referred to the optimized and not optimized double circuit arrangement, with and without compensated loop conductors, are reported in Figure 4 and Figure 5 respectively. Results evidence that compensated loop conductors ensure a significant reduction of induction field near to 400 kV OHL.

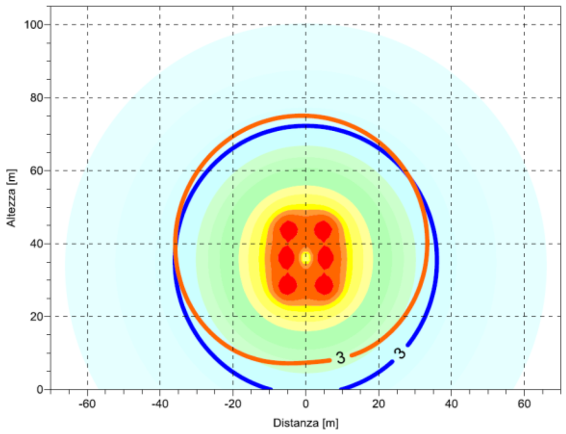

Figure 4 – Magnetic induction distribution when double circuit operates at 2310 A rated current: optimized double circuit with (orange) and without (blue) compensated loop conductors.

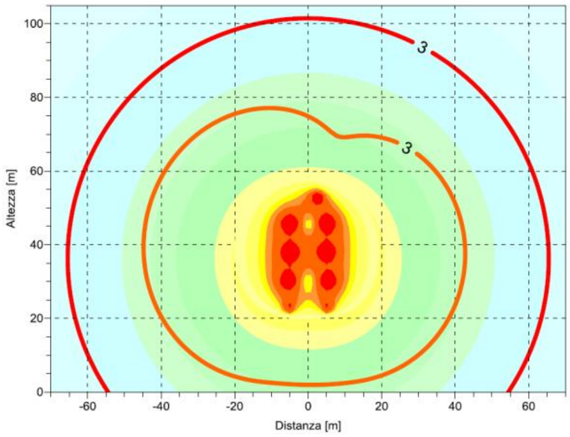

Figure 5 – Magnetic induction distribution when double circuit operates at 2310 A rated current: not optimized double circuit with (orange) and without (red) compensated loop conductors.

II. STEADY STATE AND TRANSIENT ANALYSIS

The induced currents and voltages on compensated loop conductors are manly functions of line currents of the double circuit; as reported in Section I, the two three-phase circuits are connected at the same 400 kV busbars only on one terminal (Calenzano substation), whereas, on the other terminal, the two three-phase circuits are connected to different 400 kV busbars. Therefore, line currents of double circuit could be different, according to line impedance and terminal voltages. A sensitivity analysis has been carried out to evaluate the maximum induced currents and voltages on passive loop conductors, both in normal and transient operations.

In normal operation the maximum induced currents and voltages on passive loop conductors arise when the double circuit carries the rated current (2370 A) and the three-phase currents of double circuit are 180° shifted; simulation results evidence that, the maximum expected currents and voltages on passive loop conductors are about 1200 A and 950 V respectively. For the consideration above, rated voltage and current of capacitors banks have been detected as reported in Table I. According to IEC 60871-1 [5], capacitors units shall be suitable for continuous operation at an r.m.s. current of 1,30 times; therefore, a safety margin of about 36% is guaranteed.

In case of external faults (i.e. on the double circuit), transient overvoltages and overcurrents will arise on passive loop conductors due to the higher magnetic induction generated by the fault currents. Surge arresters installed in parallel to the capacitors banks will mitigate transient overvoltages. In order to mitigate the specific energy of surge arresters during transient overvoltages, bypass switches are installed in parallel to capacitors banks.

According to the consideration above, a short circuit analysis has been carried out by Terna with software ATP-EMTP; the maximum short circuit impedance has been considered, corresponding to a short circuit current equal to 31.5 kA. Simulation results evidence that the worst condition is phase-phase to ground fault on the line terminal, as reported in Figure 6.

As reported in Figure 7, specific energy of surge arresters installed in parallel to capacitors banks attains 900 kJ. Rated specific energy of surge arresters as a function of discharge current is between 4 and 10 kJ/kV as reported in IEC 60099-4 [6].

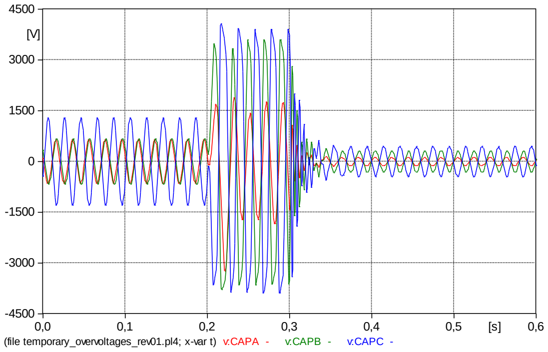

Figure 6 – Expected overvoltages on passive loop conductors due to external faults (t = 0.2 s fault time, t = 0.3 s bypass switching-on).

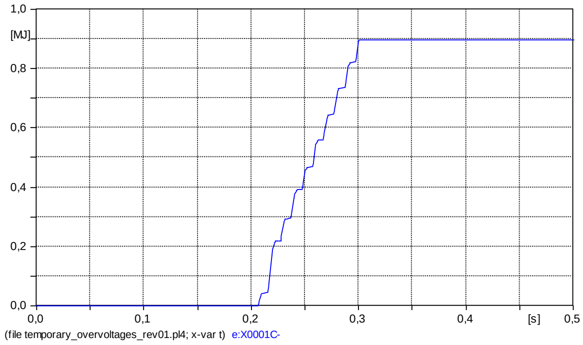

Figure 7 – Maximum specific energy of surge arrester due to transient overvoltages on passive loop conductors.

III. DESIGN OF LINE FITTINGS

Compensated loop conductors must be ground insulated and short circuited at the loop terminal (i.e., tower number 218). Assuming a maximum continuous operating voltage equal to 24 kV_{rms}, the minimum clearance distance must be equal or higher than 27 cm, considering a standard rated lightning impulse withstand voltages of 145 kV (IEC 60071-1).
Phase conductors and lower loop conductors are going to have the same number of string insulators; therefore, a higher clarence distances than 27 cm is guaranteed to the lower loop conductors. Instead, due to mechanical constrains the number of string insulators of higher loop conductor cannot be the same of lower ones.
Although simulation results reported in previous Sections evidence that induced voltages in normal operation and external short circuits are not an issue, discharge risk of higher loop conductor cannot be neglected in case of lightning strokes on the higher loop conductor itself or shielding wires (i.e., back-flashover). In these cases, the clearance distance must be higher enough to ensure self-extinction of secondary arc current.
A first insulation design can be carried out considering that the primary average arc voltage gradient is equal to15 V/cm [8][9]; therefore, the minimum clearance distance can be evaluated as follow:

$$L = K_s \cdot \frac{V_{MAX}}{V_P} \qquad (1)$$

being

- K_s: safety margin, [pu];
- V_{MAX}: maximum induced voltage on the higher conductor, [V];
- V_P: primary average arc voltage gradient, [V];
- L: minimum clearance distance, [m].

Simulation results evidence that the maximum induced voltage on higher loop conductor is equal to 350 V; according to equation (1) the minimum clearance distance is about 35 cm, with a safety margin equal to 1.5. To mitigate potential superficial burning and/or ablations, string insulators must be equipped with arc corns.

IV. ARC EXTINCTION ANALYSIS

According to Section III, higher loop conductors must have a clearance distance equal or higher than 35 cm in order to guarantee the self-extinction of secondary arc. In case of lightning strokes on the higher loop conductor itself or on shielding wires (i.e., back-flashover), a discharge current could arise. As known, from a modelling point of view, the arc can be classified into the primary arc, after fault inception, and secondary arc, after faulted phase is isolated. In this last case, arc current is sustained by mutual coupling between the healthy and faulted phases. However, in case of loop conductor discharge, primary and secondary arc currents are sustained by the same source voltages, i.e. the induced voltage by line currents. Primary arc resistance is expected to be high according to Kizilcay's model [8][9] as visible in Figure 8. Similar results are found using the arc resistance for low voltage AC faults [10][11].

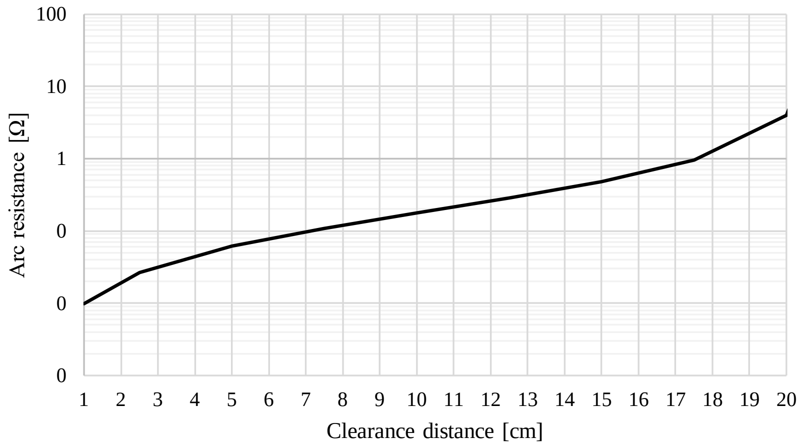

Figure 8 – Primary arc resistance as a function of clearance distance of higher loop conductor.

For clearance distance higher than 20 cm, primary arc current is on the same order of secondary currents (tens of ampere); therefore, secondary arc model is directly simulated in ATP-EMTP software, not taking into account the primary arc model.
Kizilcay's model of secondary arc has been implemented in software ATP-EMTP using type 94 component. Simulation results reported in Figure 9 evidence that, increasing clarence distance from 27 cm (according to IEC 60071-1) to 35 cm, the duration time of secondary arc current is reduced from about 250 ms to 30 ms.

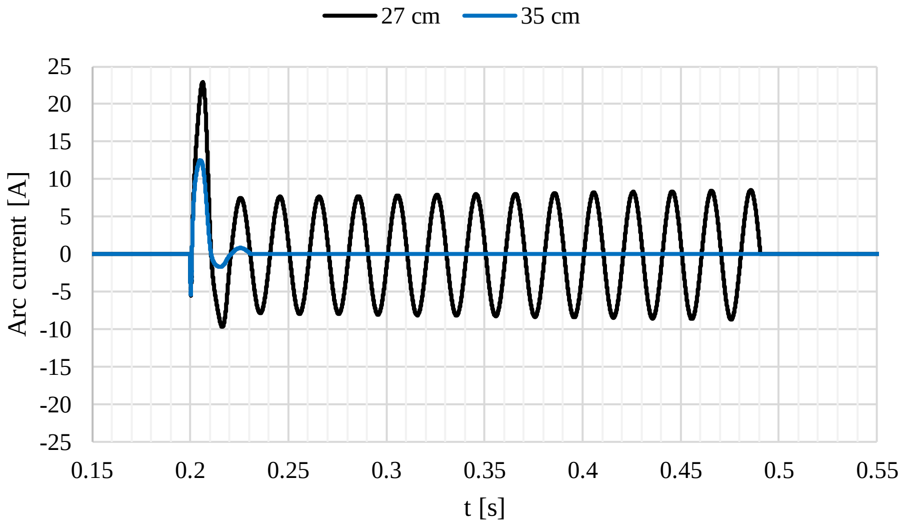

Figure 9 – Secondary arc current as a function of time in case of discharge on the higher loop conductor.

V. PROTECTION RELAY

As reported in Section II, transient overvoltages arise on passive loop conductors in case of external faults; in case of internal faults (i.e. phase to ground fault on a passive loop conductor), overvoltages and overcurrents on passive loop conductors are functions of fault resistance, line currents and fault location. Fault on passive loop conductors cannot be detected by OHL protection relay and, therefore, fault conditions could persist for a long time, increasing the risk of personnel damages due to conductive transfer potential and touch voltages near to OHL towers [12].
In order to identify if the fault is internal or external, Terna found a possible protection relay based on zero-sequence current measurement; thus, in case of external and internal faults, the instantaneous zero-sequence impedance is higher or below the expected value and, therefore, zero-sequence current will be different according to the fault location. Zero-sequence current will be practically near to zero in case of external faults, whereas it will be on the order of thousands of amperes for internal faults, as reported in Figure 10.
Therefore, neutral instantaneous overcurrent protection (50N) is needed in addition to the switches provided against faults on the overhead line (50, 51, 59, 67N). In case of a fault on the capacitor banks, only zero-sequence voltage arises and, therefore, a neutral overvoltage protection (59N) is necessary; as the OHL protection relay sees the same component, a time delay will be applied on neutral overvoltage protection of SCCS.

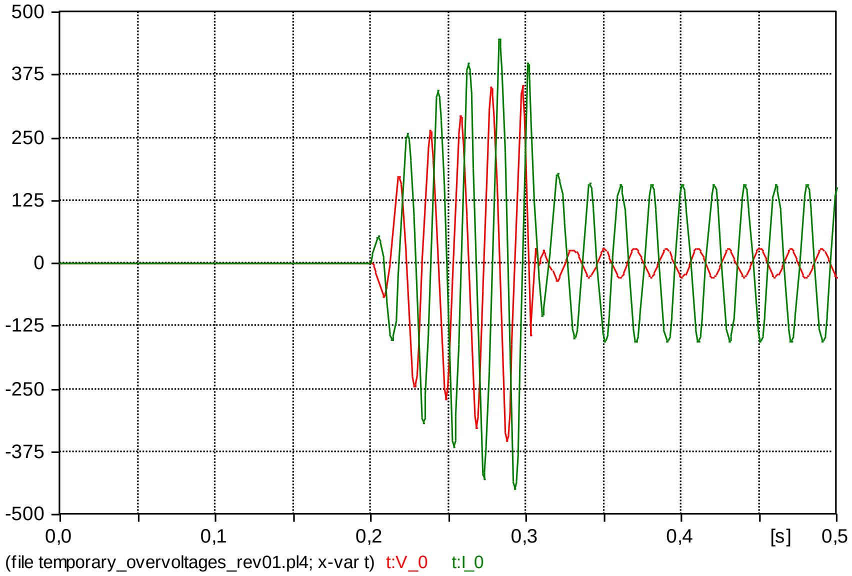

Figure 10 - Zero sequence voltage (red), and current (green).

As reported below, in case of internal faults on passive loop conductors the SCCS control and protection system are going to be able to detect and protect the SCCS itself. Regarding personnel safety, phase-to-ground faults are not an issue as the loop circuit is isolated by the loop circuit breakers; however, in case of polyphase to ground faults on the same location or cross-country faults [12], although circuit breakers are switched off, loop continuity is not interrupted. Simulation results evidence that:

- in case of polyphase to ground faults on the same location, fault current is below to 1 A, as visible in Figure 11;
- in case of or cross-country faults, fault current can attain hundreds of amperes, as visible in Figure 12.

Cross-country faults are, therefore, more dangerous, due to fault currents will continue to circulate until OHL double circuit is in operation. As secondary arc extinction is guarantee by insulation clearances, permanent cross-country faults could arise mainly for string insulation faults; therefore, cross country faults can be mitigated by string insulators maintenance.

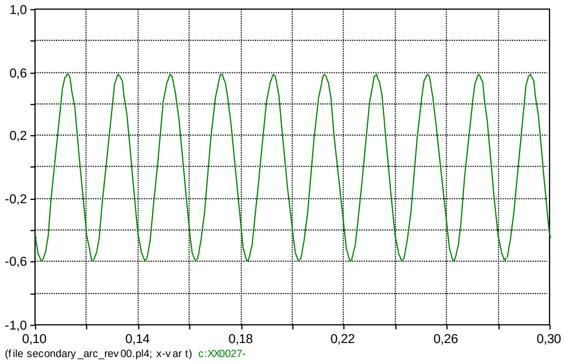

Figure 11 – Ground currents in case of polyphase faults on passive loop conductors (without SCCS).

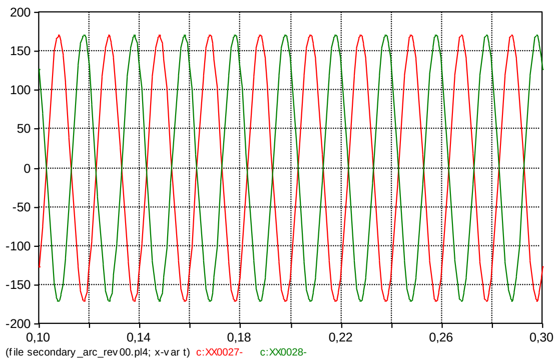

Figure 12 – Ground currents in case of cross-country faults on passive loop conductors (without SCCS).

V. CONCLUSIONS

Compensated passive loops can be an efficient and effective solution for mitigating the magnetic field nearby HV and EHV lines; compensated passive loops do not significantly affect the management of HV/EHV OHLs, although higher pylons are required if compared to the standard OHL design.

An optimization algorithm was developed by Terna in order to identify the optimal series capacitance of the passive loop, able to mitigate magnetic induction near the EHV OHL. Therefore, the Series Capacitance Compensation System (SCCS) identified by Terna has been introduced with a detailed focus on main equipment such as capacitors banks, surge arresters and load bypass.

Although compensated passive loops have a simple working principle, insulation coordination design and protection system criteria are more complex.

The induced currents and voltages on compensated loop conductors are not an issue in normal operation; in case of external fault transient overvoltages arise on capacitor banks; therefore, surge arresters are able to guarantee a safe operation of capacitors bank until their rated specific energy is not overcame. Load bypass is therefore switched on in order to mitigate specific energy on surge arresters.

In order to guarantee self-extinction of secondary arc, a preliminary design of insulation clearance of higher loop conductor has been carried out. Kizilcay's arc model has been implemented in software ATP-EMTP, evidencing that, in case if discharge of higher loop conductor due to direct lightning strokes or back-flashover, 35 cm clearance distance ensures self-extinction of secondary arc current.

Finally, a possible protection relay, based on zero-sequence current measurement, has been introduced in order to discriminate internal and external faults; indeed, zero-sequence current is near to zero in case and hundreds of amperes for external and internal faults respectively.

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