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Electromagnetic Transients on Power Plant Connection Caused by Lightning Event

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Abstract - **Lightning events can seriously damage the power systems and they represent one of the most dangerous causes of faults in the transmission lines. Usually, when one want to analyze such effects it is necessary to rely on approximate models or to simplify in some ways the power system. As a consequence, an overall analysis taking into account the complexity of the power system is difficult to find. This paper presents the study of the electromagnetic transients caused by lightning events in a point of connection between a real power plant and a large power grid. The analysis is achieved with a high level of details of the power system and the simulations are obtained through an EMT-type software (PSCAD-EMTDC). Different simulations are analyzed, showing how the cables and the transformers are affected by the electromagnetic transients.**

***Keywords*: Lightning, Protection, EMC, Power system**

I. INTRODUCTION

Lightning events represent one of the most common issue that can affect the reliability of transmission and distribution lines. Between them, the most common are related to the overvoltages that can be induced in the lines due to circuit breakers switching operation and lightning events. With respect to switching operation the lightning events can be very dangerous for line and cable safety [1][2]–[4].

In the literature, usually, lightning events are separated in two main categories: direct and indirect. This distinction is made for two reasons: indirect ones are characterized by a lower energy content but their frequency of occurrence is much more higher. This category, typically causes damages to the overhead distribution networks [4]–[6]. In order to compute the lighting-induced voltages, many finite-difference time-domain (FDTD) codes have been developed (such as [7]–[11]). Starting from the channel-base current [12]–[14], they are based on two different steps: the electromagnetic field computation [15], [16] and the field-to-line coupling through the Agrawal's model [17]. On the other hand direct events are more rare but represent a typical source of damage for power system characterized by an high Critical Flashover value (CFO) [2].

In this framework, we will focus our attention of understanding the effects of direct strikes.

The lightning effects on power cables, telecommunication wires and buried structures have been deeply analyzed in [18]–[23] but all the presented papers focus their attention only on the effects caused on the transmission lines and what it miss is an overall analysis on all the components of the power system network, including near generators or transformers.

Moreover, it is necessary to provide a complete discussion on: 1) how the values of the power system parameters affect the possible damage of the power system due to the lightning strike and 2) which portion of the main grid should be considered when we discuss this topic.

This work treats on the evaluation of the effects of direct lightning events on the interconnection between a real power plant (located in Italy) and a large power grid. The analysis focuses mainly on transformers and buried cables since they may represent the most critical elements. Moreover a deep discussion on the dependence of the lightning voltage and damage from the transformer capacitance value and the equivalent power system definition is proposed. The study takes into account a deep analysis of each grid component, lingering on their high frequency modelling. The analysis will be performed with the software PSCAD-EMTDC. The paper will be structured as follow: section II provides the details of the power system and of the components modeling. Section III and IV show the test cases of the analysis and the results. Section V and VI are devoted to the conclusions.

II. POWER SYSTEM CONFIGURATION AND MODELING

The analysis focuses on three cables (A,B,C) which connect a power plant (two generating groups) with an high voltage grid thanks to two transformers (T1 and T2). The details of the electrical system are available in Figure *1*. Cable A, B and C are characterized by a length of 211, 212 and 1951 m respectively.

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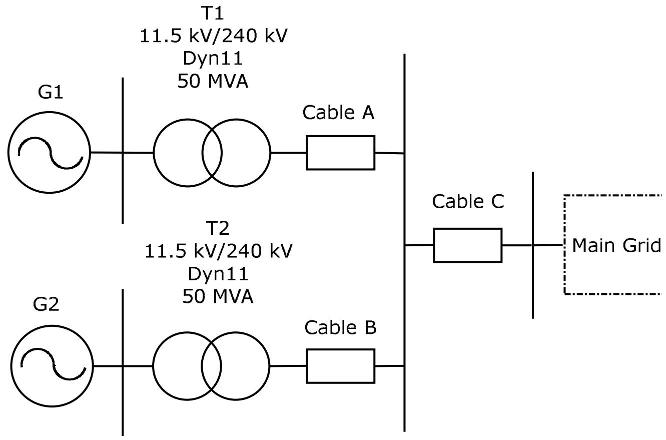

Figure 1 Electrical configuration of cable A,B and C

Each transformer (50 MVA, 11.5 kV/240 kV) is a Dy_n11group with a 10 % short circuit voltage, while the no load current and the copper losses are 0.16% and 0.50% respectively.

It is important to define the portion of the main grid which will be analyzed. In this framework, it is important to design the portion such that: i) the computational effort is limited and ii) its definition does not influence the final results.

Consequently, the portion proposed in Figure 2 is considered. The nodes N4,N5,N6,N7 and N10 are characterized by voltage = 1 p.u. while their phases have been chosen in order to obtain the rated current in the connection between the power plant and N2.

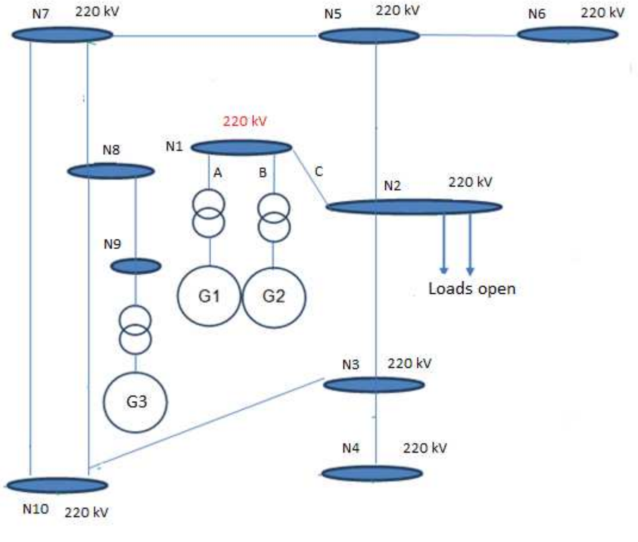

Figure 2 Portion of the transmission grid considered

For what concern the grid component, it is fundamental to define them in a correct way in order to replicate all the dynamics related to the lightning event.

A. Transformers

Since no high frequency transformer model is available in PSCAD, in the following, the classic model are adapted to the high frequency dynamics. This is achieved considering the capacitive couplings that may occur between the windings and the between the windings and the ground. According to [24], two empirical formulations are used.

The first resonance frequency is a function of the rated voltage V_N (kV) and the rated power A_N (MVA) and can be computed according to one of the following formulas:

$$f_R = 325\frac{A_N^{0.275}}{V_N^{0.95}} \tag{1}$$

$$f_R = 220\frac{A_N^{0.36}}{V_N^{0.95}} \tag{2}$$

Let us consider the complete transformer model as shown in Figure 3. Powering the primary winding with rated voltage and variable frequency we can obtain the equivalent circuit of Figure 4, where r_{cc} and x_{cc} are the short circuit resistance and reactance, while r_m and x_m are the resistance and the reactance of the magnetic branch. The circuit of Figure 4 can be simplified to the circuit of Figure 5, taking into account that C_{20} is in parallel with a short-circuit. As a consequence, one can easily calculate the equivalent impedance:

$$Z_{T1}(\omega) = \frac{\dfrac{1}{j\omega(C_{10}+C_{12})}\left[Z_1(\omega)+Z_p(\omega)\right]}{\dfrac{1}{j\omega(C_{10}+C_{12})}+\left[Z_1(\omega)+Z_p(\omega)\right]} \tag{3}$$

$$Z_p(\omega) = \frac{Z_2(\omega)Z_m(\omega)}{Z_2(\omega)+Z_m(\omega)}$$

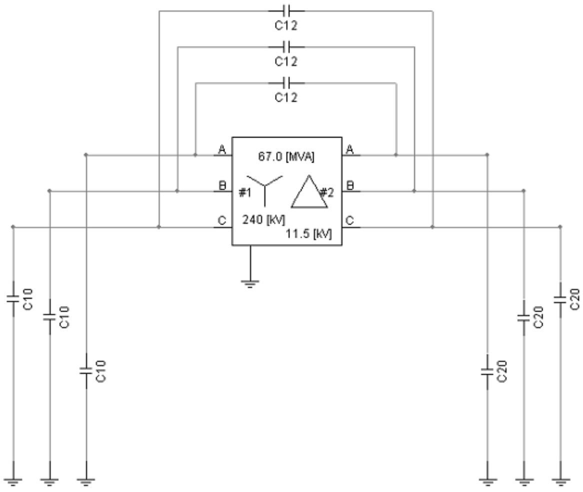

Figure 3 Complete transformer model

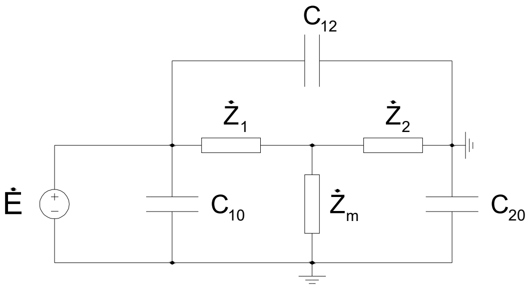

Figure 4 Transformer single phase equivalent circuit

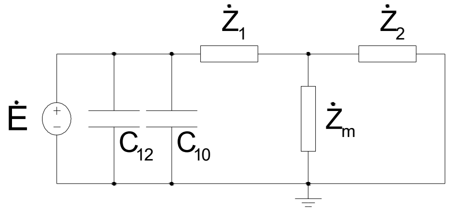

Figure 5 Transformer single phase equivalent circuit simplified

If one set equation (3) equal to zero, it is possible obtain the resonance frequency as a function of the unknown capacitances. Consequently, such result can be compared with the empirical formulas of (1) or (2). The result is shown in Figure 6a and Figure 6b for the primary and secondary winding, leading to an optimal capacitance of 3 nF and 2.5 nF respectively. It is important to consider that this is the total capacitance, while a separated identification of C_{10} and C_{12} is not possible.

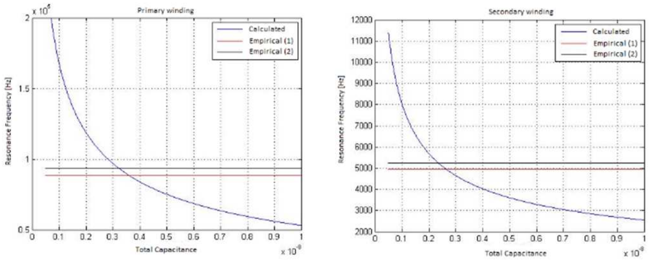

Figure 6 Resonance Frequency as a function of the total capacitance :a) primary winding b) secondary winding

B. *Transmission lines*

The transmission lines are modelled according to the one provided by PSCAD, based on telegraph equations. The overhead conductors are considered to be made of aluminium and steal. The resistance , inductance and capacitance per unit length are 2.96 10^{-5} Ω/m, 9.63 10^{-7} H/m and 1.18 10^{-11} F/m respectively.

C. *Cables*

The cables are modelled according to the model provided in PSCAD. The electromagnetic and geometrical details are presented in Figure 7 and Table 1. Please note that a depth of 1.2 m characterizes cable A and B while cable C is buried in a wire strand configuration.

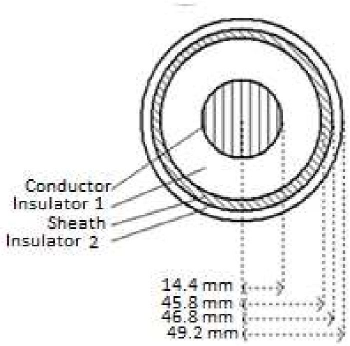

Figure 7 Cable section details

Central aluminium core resistivity	2.95 10^{-8} Ωm
Central aluminium core diameter	28.8 mm
First insulating layer ε_r	2.1
First insulating layer external diameter	91.6 mm
Rod screen resistivity	1.6 10^{-8} Ωm
Rod screen external diameter	93.6 mm
Second insulating layer ε_r	2.1
Second insulating external diameter	98.4 mm

Table 1 Electromagnetic and geometrical cables details

D. *Surge arrester*

The voltage-current characteristic provided in Figure 8, is implemented in PSCAD. The rated voltage is 198 kV.

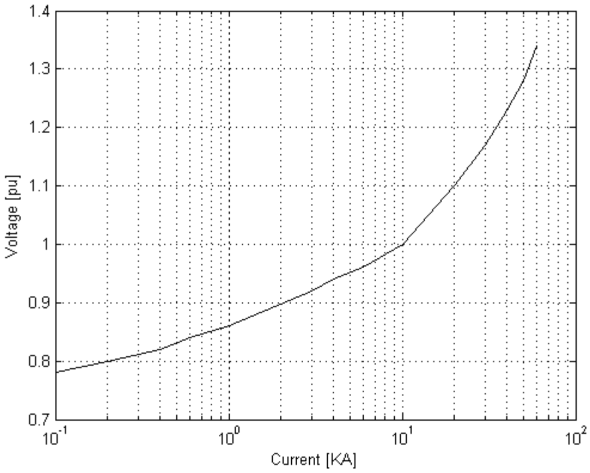

Figure 8 V-I characteristic of surge arrester

III. TEST CASES

In this section, the authors will present the test cases related to lightning events striking the power system presented in Figure 1.

It is important to remind that, a direct event striking the line can be represented by its equivalent circuit (Figure 9) formed by a current source in parallel with a resistance equal to the characteristic impedance of the lightning channel (in this framework 1 kΩ will be used). As current source, the well-known Heidler-function will be adopted [12]. The peak current is 12 kA (subsequent stroke).

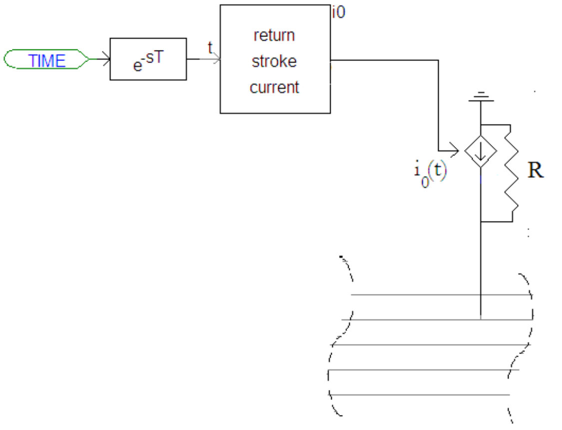

Figure 9 Direct Lightning event model

In the following, the lightning strikes the line N2-N5 but each event is characterized by a different configuration of the breakers at each side. In particular, the following events are defined:

1. Test T1: line N2-N3 closed.
2. Test T2: line N2-N3 open.
3. Test T3: the lightning strikes the line before the breaker at N2 side (open). The line N2-N3 is closed
4. Test T4: the lightning strikes the line before the breaker at N2 side (open). The line N2-N3 is open.

Concerning the initial conditions, they are set as follows:

- G1 is supplying 47 MW
- G1 breaker at N2 side (open). The line N2-N3 is closed is characterized by a leading power factor = 0.95
- G2 is supplying 47 MW
- G2 is characterized by a leading power factor = 0.95

IV. RESULTS

This sections shows the results related to the cases presented in the previous section focusing on the voltages on Cable C at the beginning and at the end. Moreover, also the voltages on transformers T1 and T2 are proposed .

A. Test T1

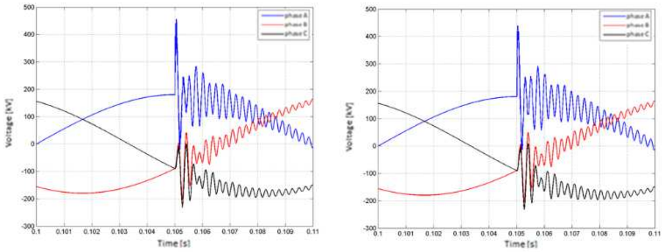

Figure 10 Lightning event – Test T1, voltages on cable C, N1 side (left) and N2 side (right)

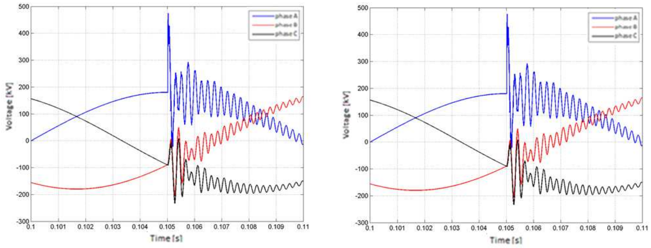

Figure 11 Lightning event – Test T1, voltages on T1(left) and T2(right)

As shown in Figure *10* and Figure *11*, both transformers and the cable present a peak near to 500 kV. In principle, this results could be influenced by the choice of the transformer capacitance, thus in Figure *12*-Figure *13*, test T1 is proposed again with a capacitance of C_1= 30 nF.

The comparison between Figure *10*-Figure *11* and Figure *12*-Figure 13 show the independence of the results from the capacitance value, so in the following C_1= 3 nF will be adopted.

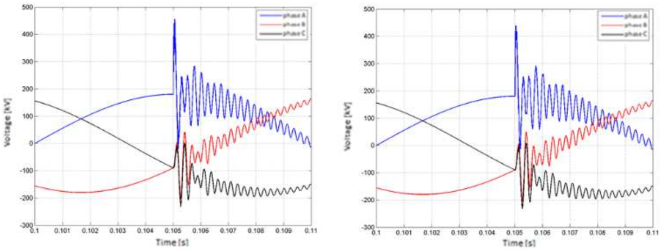

Figure 12 Lightning event – Test T1, Voltages on cable C, N1 side (left) and N2 side (right) – Capacitance value modified

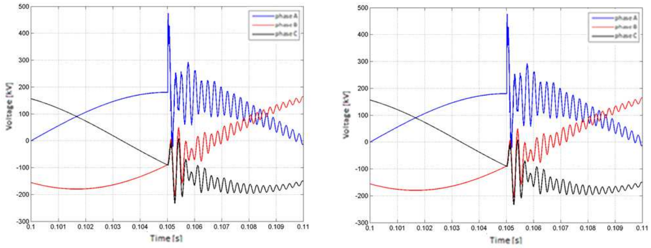

Figure 13 Lightning event – Test T1, Voltages on T1(left) and T2(right) - Capacitance value modified

B. Test T2

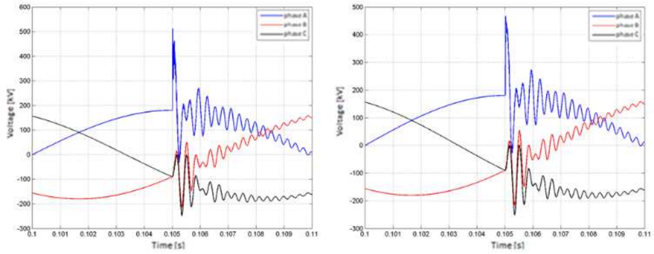

Figure 14 Lightning event – Test T2, Voltages on cable C, N1 side (left) and N2 side (right)

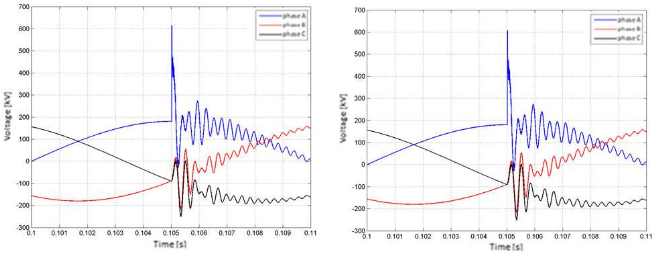

Figure 15 Lightning event – Test T2, Voltages on T1(left) and T2(right)

Since the lightning current cannot flow in the line N2-N3 due to the breaker open, the only way is represented by the cable C. As a consequence, the voltage is higher with respect to the previous case.

C. *Test T3*

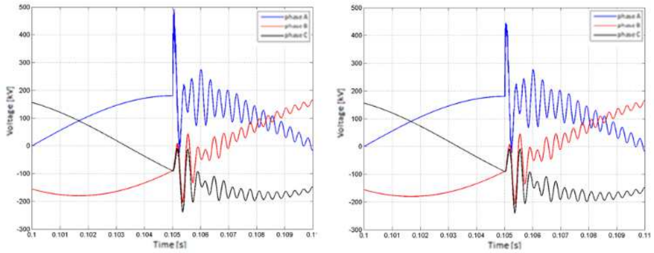

Figure 16 Lightning event – Test T3, Voltages on cable C, N1 side (left) and N2 side (right)

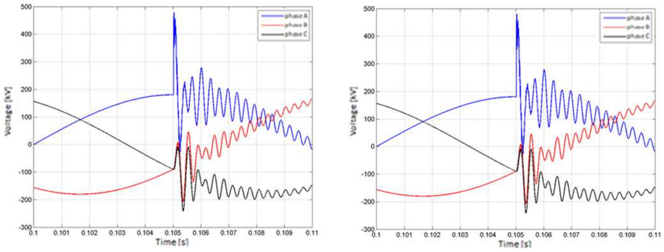

Figure 17 Lightning event – Test T3, Voltages on T1(left) and T2(right)

This case does not show meaningful differences with test T1 because the only variation is the stroke location which is before the circuit breaker at node N2.

D. *Test T4*

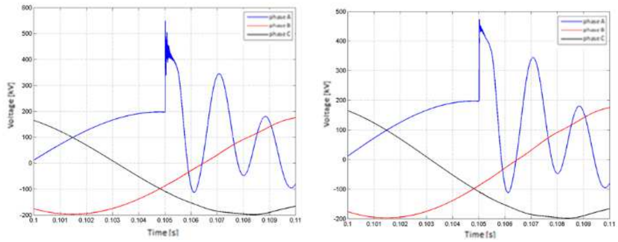

Figure 18 Lightning event – Test T4, Voltages on cable C, N1 side (left) and N2 side (right)

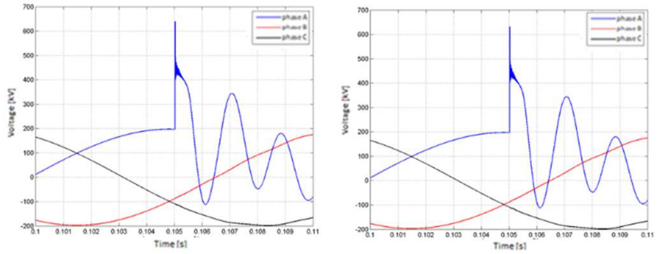

Figure 19 Lightning event – Test T4, Voltages on T1(left) and T2(right)

In this case, the voltages reach values similar to Test T2. With respect to T2, in this case, a slower transient can be observed. This is mainly ascribed to the circuit breaker at N2 node, which is open in this configuration.

V. DISCUSSION

The analysis of the previous cases shows that, with respect to the switching operations which has been deeply analyzed in literature, it has 1) a faster transient and 2) a higher peak.

Although the voltages are not negligible, it is important to remind that for such cable and transformers they are not going to be damaged since their basic insulation level (BIL) is 1050 kV and 950 kV respectively.

Ref. [25] states that in order to ensure a correct behavior of the power system, the maximum overvoltage should be kept below BIL/1.15, which is 913 and 826 kV for cables and transformers respectively.

This value is never observed in the proposed cases, since the maximum overvoltage is lower than 700 kV.

However, if the BIL of the components was lower, the lightning could damage them.

VI. CONCLUSIONS

This work focuses on the overvoltage that can occur when a lightning strikes a typical connection between a power plant and a transmission grid. Firstly, we modeled each element of the power system in order to consider the high-frequency phenomena. In particular, the transformers have been modeled with an identification procedure which requires only datasheet values. Transmission lines, cables and surge arresters have been modelled with the well-known telegraph equations (transmission lines) and with the PSCAD-EMTDC model respectively. The analysis has neglected the indirect-lightning events because they are usually considered not-dangerous for transmission line.

On the other hand, it has been shown that direct events can cause overvoltages comparable to the BIL values of the proposed components. In particular, the case with a line out-of-service represents the most critical one . However, it is concluded that, for the considered power system, the components are not damaged by the considered lightning events.

It is important to notice that this preliminary analysis has involved a 240 kV transmission line, but in many cases the voltage level and the BIL of the components are lower and can be damaged by lightning events as the one described in the paper. Consequently, a deep analysis on the possible damages of the lightning in a complex power system as the one presented should be included when the design of a power system is needed.

Future developments will regard the study of lightning performance of the proposed power system.

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