Temporary Overvoltages due to Harmonic Resonance in Long EHV Cables

L. Colla, S. Lauria, F. M. Gatta

Abstract-- With the increasing recourse to cables in EHV networks the likelihood of low-order harmonic resonance is becoming of even more concern.

The scope of this paper is to analyze the overvoltages due to harmonic resonance at the no-load energization of a prospective 400kV-50Hz double circuit submarine cable line. ATP-EMTP analyses are carried out to predict the possibility of occurrence of low-order harmonic resonance; a phenomenon more liable to happen in case of EHV cables connected to low short circuit power networks.

The occurrence of resonances is sought for in the frequency domain and overvoltages are calculated in the time domain for the no-load energization of the EHV double circuit cable line. A sensitivity analysis is carried out varying the switching instants of line circuit breakers and the network short circuit power, while load and operating configurations are taken as a parameter. The effect of shunt reactor saturation voltage on the harmonic overvoltages is also investigated.

Operational and design countermeasure are proposed.

Keywords: EHV AC cables, resonance, overvoltages, harmonics, ATP, EMTP.

I. Introduction

THE liberalization of the electricity market leads, in general, to the request of strengthening existing transmission lines to warrant a competitive market. Moreover, in many countries worldwide the ever growing territory anthropization and the strong demand of conservation of the environment by the population and by the local and central public administrations, make very difficult the construction of new overhead lines. Use of long stretches of EHV underground cables is therefore considered also in non-urban areas. Besides, in case of marine crossings of several kilometers the submarine cable is the only applicable solution for electricity transmission.

Long EHV AC cable lines must be provided with line-connected shunt compensation, in order to keep the cable's reactive power surplus from entering the network, as well as for limiting power frequency overvoltages and no-load charging currents in the circuit breakers (CBs).

L. Colla is with Terna Rete Elettrica Nazionale S.p.A., Planning and Grid Development Department, Via Ostiense 92, 00154 Rome, Italy (e-mail of corresponding author: luigi.colla@terna.it).

S. Lauria and F. M. Gatta are with the Department of Electrical Engineering, University of Rome "La Sapienza", 00184 Rome, Italy (e-mail: stefano.lauria@uniroma1.it fabiomassimo.gatta@uniroma1.it).

Presented at the International Conference on Power Systems Transients (IPST'07) in Lyon, France on June 4-7, 2007

EHV shunt reactors are usually designed to retain a linear behavior well above their rated voltage. However, iron-cored shunt reactors draw significant low order harmonic currents during inrush transients, when they are often driven into saturation.

The cable-network system, owing to the large cable capacitance, can be resonant at, or near to, one the magnetizing current harmonic frequencies. The ensuing low order harmonic resonance can give rise to temporary overvoltages, dangerous to line apparatuses due to their sustained nature. Notably, the energy absorption withstand capability of commonly adopted surge arresters can be exceeded [2].

With the increasing recourse to cables in the EHV network the likelihood of low-order harmonic resonance is therefore becoming of even more concern.

The scope of this paper is to analyze the overvoltages due to harmonic resonance at the no-load energization of a prospective 400kV-50Hz double circuit submarine cable line. The ATP-EMTP analyses are carried out to predict the possibility of occurrence of low-order harmonic resonance; a phenomenon more liable to happen in case of EHV cables connected to low short circuit power networks.

II. The Simulated System

A simplified one-line diagram of the simulated system is shown in Fig. 1. the double-circuit 400 kV-50 Hz submarine cable line is 43 km long; each cable circuit being shunt compensated with two 250 Mvar-420 kV shunt reactor banks solidly connected at its terminals (shunt compensation degree is 88%).

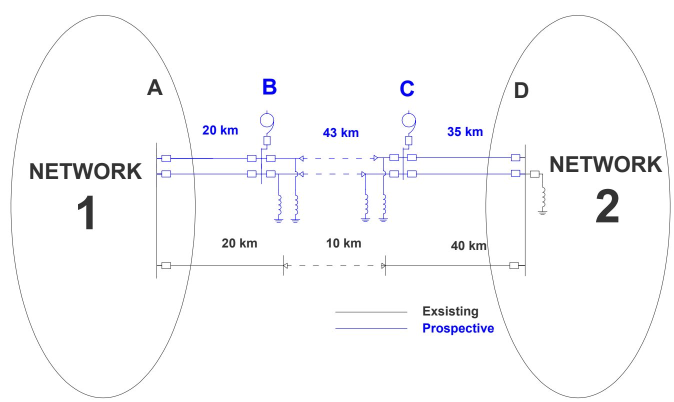


Fig. 1. Simplified scheme of the simulated system

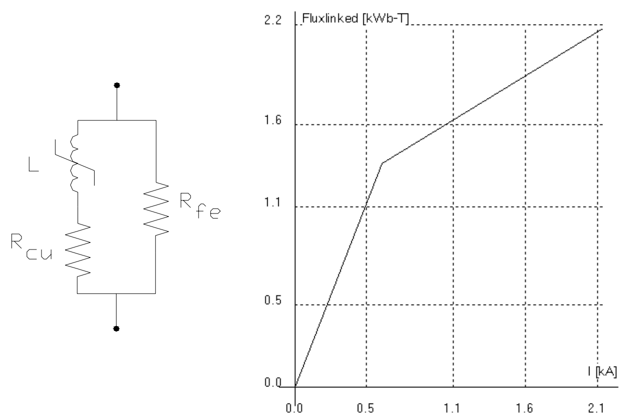
Detailed three phase simulation of the Fig.1 system, consisting of 185 three-phase buses, has been performed at the 400 kV and 220 kV levels, while 150 kV primary distribution lines have been simulated as lumped loads on the LV side of autotransformers. In the following the models adopted for the frequency domain and the time domain studies are described.

A. Shunt Reactors

Either a bank of single-phase reactors or a three-phase unit with five limbs core have been envisaged, so that the zero sequence impedance is equal to the positive sequence impedance. Each shunt reactor bank is therefore modeled by three single-phase uncoupled circuits, as shown in Fig. 2a. The assumed two-slope relation between flux and current peak values is schematically shown in Fig 2b. The knee point has been assumed to be either at 1.25 or 1.50 times the flux amplitude at rated voltage, with the slope of the saturated part being 30 percent of the slope in the unsaturated range in all cases. The saturation curve has been taken into account only in the time domain simulations.

The modeled shunt reactors have 0.4% of losses assumed to be distributed as follows:

- 70% winding losses (R_{cu})
- 30% core steel losses (R_{fe})



(a) (b)

Fig. 2. 420 kV 250/3 Mvar shunt reactor model of one phase (a) and saturation curve with saturation voltage at 125% of rated voltage (b)

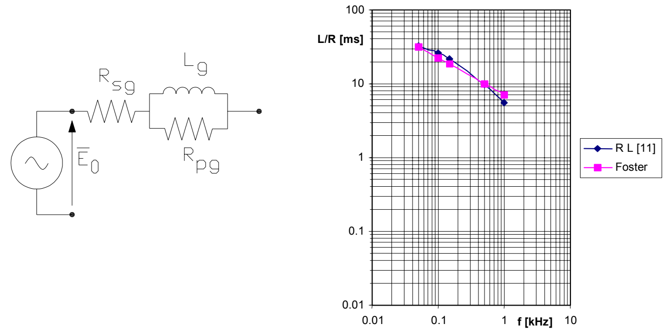
B. Synchronous generators

In the frequency domain, synchronous generators have been represented at the fundamental frequency with the constant emf E_0 behind their 50 Hz negative-sequence reactance X_i in series with the 50 Hz generator resistance R_{50}, taken as R_{50}=0.1 X_d" (X_d" subtransient reactance).

According to [11], the frequency behaviour for a given harmonic order h=f/50 can be described by the R-L bipole:

$$R_h = \sqrt{h} \cdot R_{50}, \qquad X_h = h \cdot X_i \qquad (1)$$

In practice, the above frequency dependency has been simulated with the simple Foster circuit of Fig. 3a, where $L_g=X_i/(2\pi\ 50\text{Hz})$. R_{sg} and R_{pg} have been chosen to fit (1) in the range (50÷1000) Hz, with the actual fitting shown in Fig. 3b.



(a) (b)

Fig. 3. Frequency domain synchronous generator equivalent circuit of one phase (a) and time constant L/R of the equivalent R-L series circuit (b)

In the time domain, generators have been simulated with the widely accepted ATP type 59 synchronous machine model.

C. Transformers

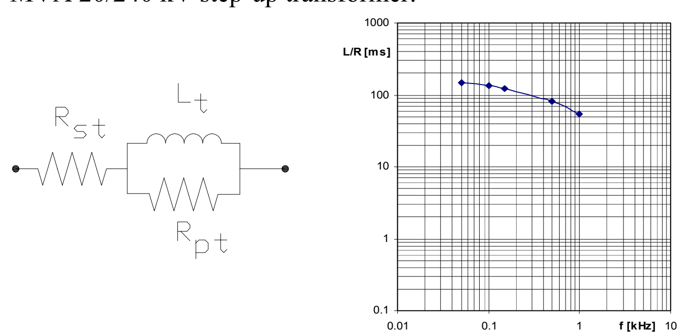
The short circuit impedance Z(f) of transformers and autotransformers has been represented, both in the frequency and in the time domain, with the Foster circuit of Fig. 4b. The inductance L_t is given by $L_t=X_1/(2\pi\ 50\text{Hz})$, where X_1 is the short circuit reactance of the transformer at 50 Hz. Resistances R_{st} and R_{pt} are estimated according to [11] as :

$$R_{st} = \frac{X_1}{\tan \psi_1} \qquad\qquad R_{pt} = 10 X_1 \tan \psi_1$$

with:

$$\tan \psi_1 = e^{\left[0.693+0.796 \ln S_n - 0.0421 (\ln S_n)^2\right]}$$

where S_n is the rated power of the transformer. The corresponding time constant is shown in Fig. 4 for a 370 MVA 20/240 kV step-up transformer.



(a) (b)

Fig. 4. Equivalent circuit of the transformer series impedance (a) and assumed time constant for the leakage inductance of a 370 MVA 20/240 kV step-up transformer (b)

The magnetizing branch has been simulated with a constant resistance in parallel with a two slope nonlinear inductance connected to the LV side, with a saturation voltage equal to either 1.05 and 1.15 times the transformer rated voltage.

D. Loads

The impact of load modeling on the resulting harmonic currents and voltages is particularly relevant at the parallel resonance frequencies. Differences in the calculated impedance at the resonance frequency can vary significantly depending on the load model. In studies concerning mainly the transmission network the loads are usually equivalents part of the distribution network, normally known by the consumption of active and reactive power.

In order to verify the damping influence of the load condition to the harmonic resonance, loads have been considered as a parameter in a sensitivity analysis. Therefore, although different models have been proposed in the literature, a simplified purely constant resistance load has been adopted varying the resistance as a parameter in between the minimum and the maximum resistive load.

E. Overhead lines and submarine cables

The high voltage transmission lines are often untransposed and this causes the electrical parameters to be different for each phase. Under these conditions the sequence networks are mutually coupled, that is, a current flow of one sequence induces voltages and currents to flow in the other sequences. For the purpose of taking into account the phenomenon described above all the transmission lines have been simulated with multi-phase JMarti frequency dependent models.

Single-core submarine cables are generally spaced at a distance about equal to sea depth, for maintenance and cable mechanical safety. The sheath is regularly bonded to the armor, with the latter solid-bonded at land terminals and often in electrical contact with sea water since the outer jacket is not always insulating. As a consequence nearly 100 percent of the phase current returns on a combination of the armor and concentric sheath. The three single-core submarine cables can thus be individually represented by single-phase uncoupled models. The above conditions have allowed an effective cable modeling by means of JMarti fitting in the frequency range of interest, in spite of the well known limits of multiphase JMarti cable modeling. Fig. 5 compares the short circuit positive and zero sequence impedance of the JMarti model with those of the exact Pi equivalent circuit.

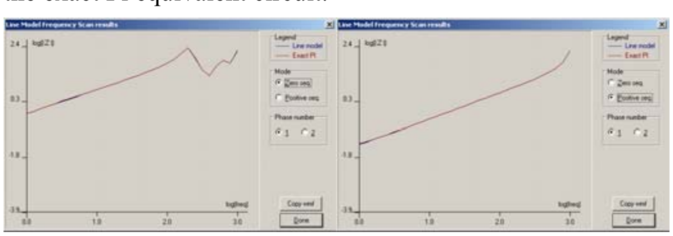


Fig. 5. Short circuit impedance obtained as Line Model Frequency Scan output for the cable model, compared to "exact" values. Left column, "differential mode", right column "common mode".

III. Preliminary Resonance Estimation

A preliminary estimate of the first parallel resonance frequency, f_r is given by:

$$f_r = f_1 \sqrt{\frac{S_{sc}}{Q_{cap}}} \qquad (2)$$

where

S_{sc}: network short circuit power (subtransient) at the cable supply busbar (shunt reactors may be factored in at weak nodes)

Q_{cap}: charging reactive power, at fundamental frequency, associated to total capacitance seen at cable supply busbars, (without considering inductive compensation: shunt reactors are instead paralleled "into" short circuit impedance).

f_r: the frequency of the first parallel resonance

f_1: the system fundamental frequency

This simple expression only provides a quick estimate of f_r without any indication about severity. For the studied system without the prospective link, (1) yields f_r in the range of 230÷350 Hz, depending on the short circuit power, while with the prospective link included the range for f_r moves down to 95÷150 Hz. As low-order harmonic resonance is of particular concern in power systems, a more detailed analysis has been carried out both in the frequency and in the time domain.

IV. Frequency Analysis

In the frequency analysis the system, assumed to be linear, is represented and driven by a variable frequency source. The source voltage displacement angles can be set to excite the different sequence modes of the system (i.e. 120-degree displacement for positive sequence, 0-degree displacement for a zero-sequence source). Through this method the network resonant frequencies are determined.

Fig.6 shows the phase A driving point impedance, in modulus and phase, calculated at bus A of Fig.1, for the system at no-load, without the prospective link in case of positive and zero sequence current excitation.

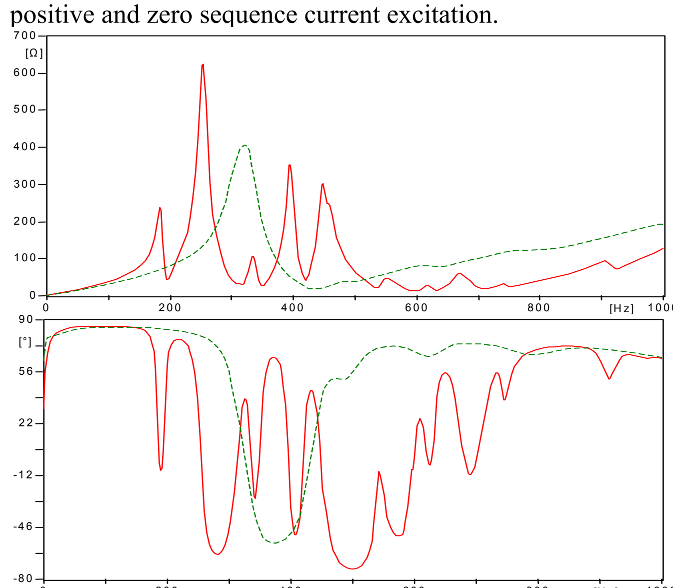


Fig. 6. Phase A driving point impedance, in modulus and phase, calculated at bus A of the Fig.1 system at no-load, without the prospective link in case of positive (solid) and zero (dashed) sequence current excitation

Fig. 7. shows the phase A driving point impedance, in modulus and phase, calculated at bus A of the Fig.1 system at no-load, with the prospective link in case of positive and zero sequence current excitation. A comparison of Figs. 6 and 7 clearly shows the large downward shift of the first resonance frequency when the prospective cable link is included.

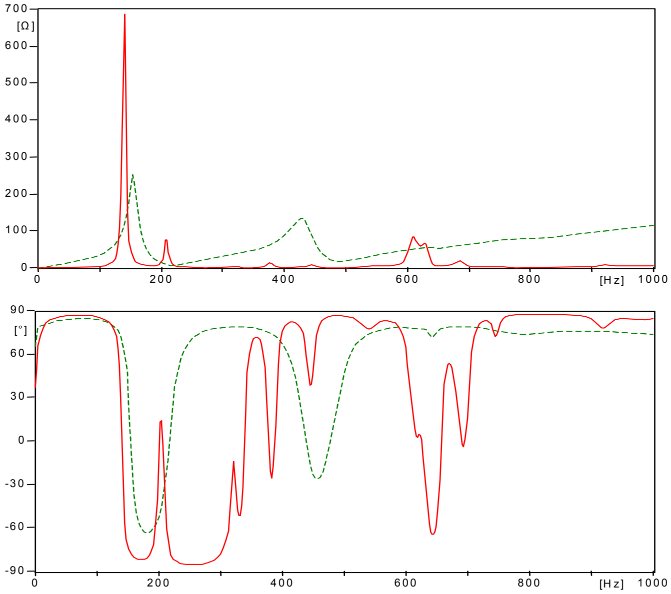


Fig. 7. Phase A driving point impedance, in modulus and phase, calculated at bus A of the Fig.1 system at no-load, with the prospective link in case of positive (solid) and zero (dashed) sequence current excitation

The knowledge about network parameters for harmonic studies, especially for loads, transformers and generators is limited, moreover the network can have many operating conditions, resulting from combination of load, generation and lines, and there is always some uncertainties about the future evolution of the system. In order to cover the majority of operating conditions a sensitivity analysis has been carried out on system parameters as load, number of generators connected to the grid, and line outages.

Fig. 8 shows the diagram of phase A complex driving point impedance calculated at bus A (see Fig. 1) with prospective link in place, for some different load and network conditions. The numbers near to the points marked are frequency in Hertz.

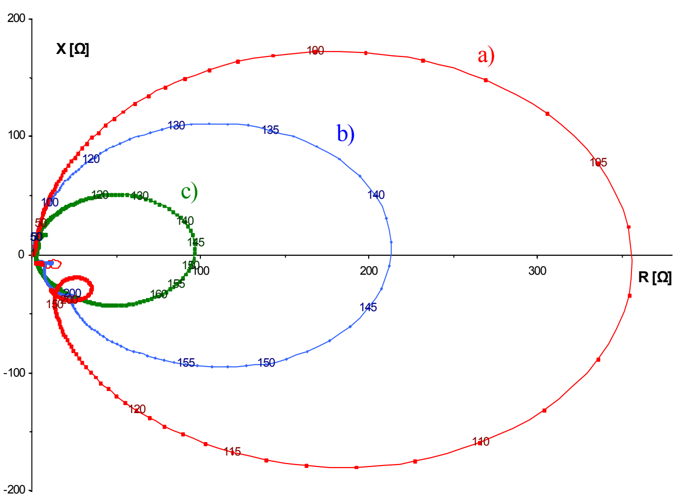


Fig. 8. Phase A diagram of the complex impedance of the network calculated at bus A with the prospective link (see Fig. 1). The numbers near to the points marked are frequencies in Hertz. a) Minimum load with "weak" network; b) minimum load; c) maximum load

V. Time Domain Analysis

After having identified in the frequency domain the possible most critical network conditions for harmonic resonance, a time domain analysis has been carried out in order to evaluate the system behavior, with all its relevant non-linearities taken into account. In particular, the analysis has been focused on the no-load energization in case of a system configuration close to 3rd harmonic resonance, with normal dispatch.

The energization transient of the 2nd circuit of the prospective link from bus B of Fig. 1 has been simulated taking the closing time of CBs as a parameter, assuming simultaneous pole closure. Shunt reactors with 1.25 p.u. kneepoint voltage have been initially considered. The worst case for the harmonic resonance occurrence has been found when the closure is made at zero voltage in one phase. However, as shown in Fig. 9, for the minimum load configuration (Fig 8b), the maximum reached temporary overvoltage is about 1.13 p.u., and 4% higher than the MCOV of surge arresters (265 kV_{rms} for the studied system), with 3rd harmonic content in phase voltage up to 16% of the fundamental frequency component. CB currents, shown in Fig. 10, exhibit a pronounced zero-crossing delay.

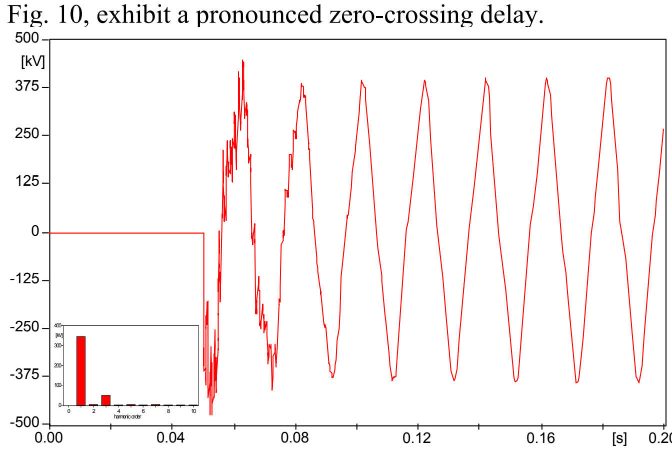


Fig.9. Phase-to-Gr overvoltage and FFT analysis (initial time 0.18 s, final time 0.20 s), in A phase for the no-load energization of the prospective link from bus A (see Fig. 1) with the system at minimum load (case b of Fig. 8). Saturation voltage of the shunt reactors equal to 125% of their rated voltage

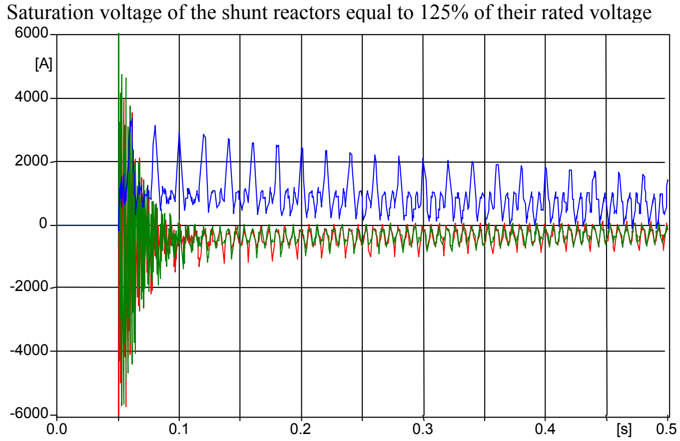


Fig.10. Phase currents, in case of no-load energization of the 2nd circuit of the new prospective link from bus A (see Fig. 1) with the system at minimum load (case b of Fig. 8). Saturation voltage of the shunt reactors equal to 125% of their rated voltage

Third harmonic voltages in Fig.9 waveform are mostly positive sequence, and not zero sequence, due to the unbalance in the saturation of the three phases of the shunt reactors.

Simulations have been repeated, considering 1.50 p.u. shunt reactors kneepoint voltage: results are shown in Figs. 11 and 12 due to the reduction in 3rd harmonic inrush currents, the maximum temporary overvoltages in Fig. 11 reduces to 1.07 p.u., while link currents in Fig. 12, although less distorted, still do not cross zero for several tens of cycles following energization: fundamental components of reactor and cable charging current nearly cancel each other, while reactor DC offset decays very slowly.

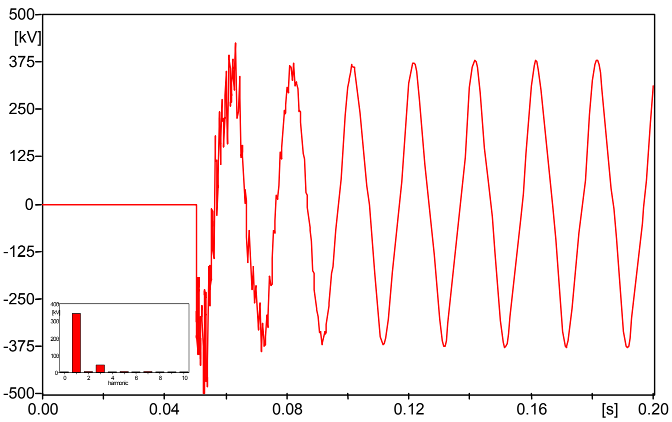


Fig.11. Phase-to-Gr overvoltage and FFT analysis (initial time 0.18 s, final time 0.20 s), in A phase for the no-load energization of the prospective link from bus A (see Fig. 1) with the system at minimum load (case b of Fig. 8). Saturation voltage of the shunt reactors equal to 150% of their rated voltage

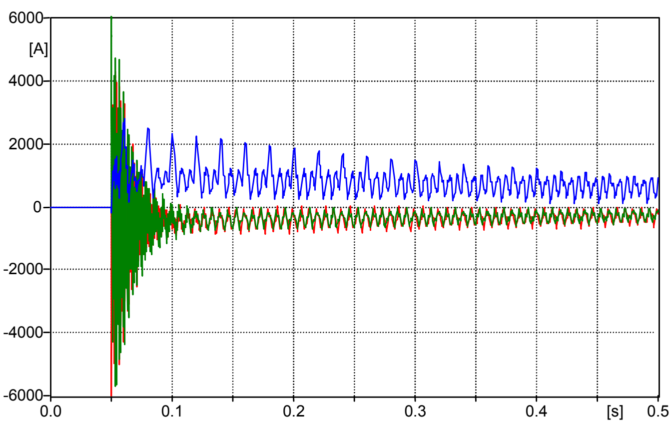


Fig. 12. Phase currents, in case of no-load energization of the 2nd circuit of the new prospective link from bus A (see Fig. 1) with the system at minimum load (case b of Fig. 8). Saturation voltage of the shunt reactors equal to 150% of their rated voltage

An effective countermeasure to prevent both the build-up of harmonic resonance and the current zero delays in the energization transients has been obtained with the simulation of synchronizing relays on the cable line CBs, closing separately each phase when the relevant voltage is near to peak value. Fig. 13 shows that with this provision no relevant harmonic distortion occur, while Fig. 14 shows that DC offset in currents is limited by means of synchronized switching. The assessment of actual benefits to be accrued requires consideration of CB behaviour (pole spread and pre-arcing).

For the planned link, more severe harmonic resonance can be expected in case of energization during system restoration, with very low short-circuit power and practically zero system load. A wider analysis including such contingencies will be part of further research.

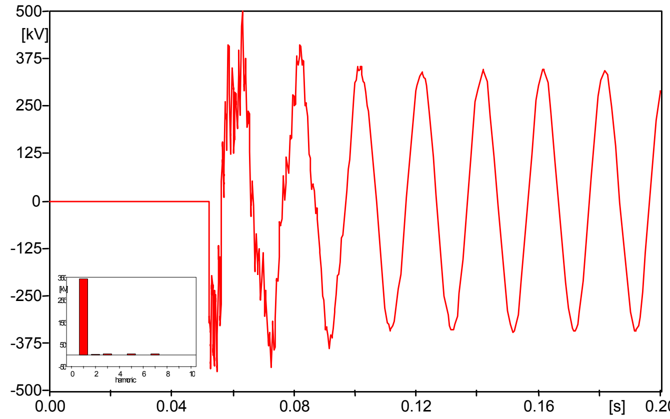


Fig.13. Phase-to-Gr overvoltage and FFT analysis (initial time 0.18 s, final time 0.20 s), in A phase at bus A for the no-load energization of the system with the prospective link. Synchronized switching simulated. Saturation voltage of the shunt reactors equal to 125% of their rated voltage

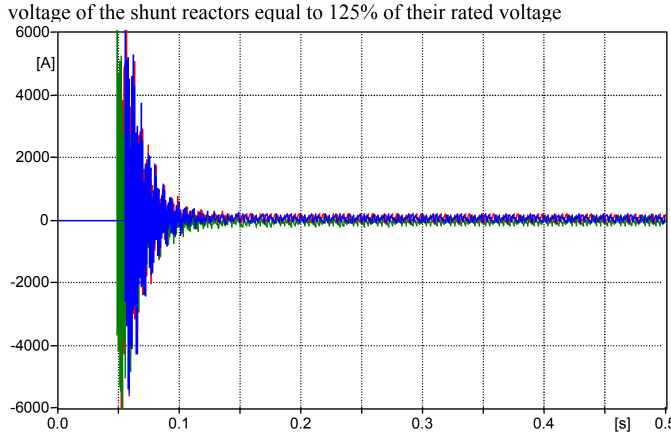


Fig.14. Phase currents, in case of no-load energization of the 2nd circuit of the new prospective link from bus A (see Fig. 1) with the system at minimum load (case b of Fig. 8). Synchronized switching simulated. Saturation voltage of the shunt reactors equal to 125% of their rated voltage

VI. Conclusions

Low order harmonic resonance can occur in EHV networks including cables of relevant length. The harmonic resonance can be excited by the inrush current harmonics generated by shunt reactors solidly connected to the line at no-load energization.

At the design stage studies have to be carried out, possibly in both the frequency and time domain, to predict possible dangerous sustained overvoltages. Studies should cover the majority of possible system operating conditions resulting from combination of load, generation and line configuration and they should cover also the uncertainties about the future configurations by means of sensitivity analysis.

For the prospective double circuit EHV cable under study, 3rd harmonic resonance is liable to occur in some network conditions. Nevertheless the overvoltage values, calculated at no-load energization, for the minimum load scenario with ATP-EMTP simulations, are deemed not dangerous for the equipment. Other scenarios, especially the ones with extremely low network short circuit power, such as system restoring after black-out, load shedding due to lack of generation or islanding must be examined to assess possible overvoltages due to low-order harmonic resonance.

Prolonged current zero delays can occur at no-load energization of long highly shunt compensated EHV cables. An effective solution to both the low-order harmonic resonance and current zero delays at no-load energization is represented by synchronized switching of the cable line CBs.

VII. References

[1] CIGRE WG 36-05 "Harmonics, Characteristic Parameters, Methods of Study, Estimates of Existing Values in the Network*" Electra N° 77*, pp. 35-54, 1981

[2] CIGRE WG 06 of SC No. 33 "Metal oxide surge arresters in AC systems. Part 3: Temporary overvoltages and their stresses on metal oxide surge arresters" *Electra N° 128*

[3] CIGRE WG 33.10 "Temporary Overvoltages - System Aspects" *Electra N° 185,* August 1999

[4] CIGRE WG 33.10 "Temporary Overvoltages Test Case Results" *Electra N° 188,* February 2000

[5] Task Force on Harmonics Modeling and Simulation "Modeling and simulation of the propagation of harmonics in electric power networks—Part I: Concepts, models and simulation techniques*," IEEE Trans. Power Del*., vol. 11, no. 1, pp. 452–465, Jan. 1996.

[6] Task Force on Harmonics Modeling and Simulation "Modeling and simulation of the propagation of harmonics in electric power networks—Part II: Sample systems and examples," *IEEE Trans. Power Del*., vol. 11, no. 1, pp. 466–474, Jan. 1996.

[7] CIGRE JTF 36.05.02/14.03.03 "AC system modeling for AC filter design, An overview of impedance modeling" *Electra N° 164*, pp. 132-151, June 1993

[8] H.W. Dommel, EMTP Theory Book, 1986.

[9] CIGRE WG 33.10 and IEEE Task Force on TOV "Temporary Overvoltages: Causes, Effects and Evaluation" *Cigré 1990 Session*

[10] L. Colla, F. M. Gatta, F. Iliceto, and S. Lauria, "Design and operation of EHV transmission lines including long insulated cable and overhead sections," in *Proc. 2005 IEEE International Power Engineering Conference*, paper TM-3.6J.

[11] *Guide for Assessing the Network Harmonic Impedance*, CIGRE WG CC02, 1996

VIII. Biographies

Luigi Colla was born in Marino, Italy, in 1980. He received the master degree in electrical engineering from the University of Rome "La Sapienza" in 2004. In 2005 he joined the Planning and Grid Development Department of Terna, Italian TSO. His main research interests are in power systems analysis, HVAC and HVDC transmission, electromagnetic transients and long distance transmission.

Stefano Lauria was born in Rome, Italy, in 1969. He received the master degree and the Ph.D. in electrical engineering from the University of Rome "La Sapienza" in 1996 and in 2001, respectively. In 2000 he joined the Department of Electrical Engineering of University of Rome "La Sapienza" as a Researcher. His main research interests are in power systems analysis, HVAC and HVDC transmission, distributed generation, power quality and electromagnetic transients.

Fabio Massimo Gatta was born in Alatri, Italy, in 1956. In 1981 he received a doctor degree in Electrical Engineering from Rome University (Hons). He then joined the Rome University's Department of Electrical Engineering

where he was appointed Researcher and in 1998 appointed Associate Professor in Applied Electrical Engineering.
His main research interests are in the field of power system analysis, long distance transmission, transient stability, temporary and transient overvoltages, series and shunt compensation, SSR, distributed generation.