Electrical Power and Energy Systems 105 (2019) 1–16

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Dynamic simulation of induced voltages in high voltage cable sheaths: Steady state approach

Matilde Santos[a,*], Miguel Angel Calafat[b]

[a] *Computer Science Faculty, Universidad Complutense de Madrid, Spain*
[b] *Red Eléctrica de España, Spain*

ARTICLE INFO

Keywords:
Modeling
Simulation
Underground cables
Cable sheath
High voltage
Induced voltages
Steady state

ABSTRACT

This paper presents a novel approach to the modeling of high voltage underground cables. Its main contribution is that it considers induced effects. Indeed, it incorporates the estimate of induced voltages and currents in cable sheaths in steady state due to the nearby cables and sheaths, for different types of sheaths connections and for various single-phase short-circuit configurations and three-phase short-circuits. Furthermore, it allows multiple circuits to be coupled automatically in a simple way. An intuitive and friendly simulation tool has been implemented that allows the automatic generation of multiple coupling circuits and to calculate all these induced effects caused by the connection of the sheaths and the distance between cables. It has been validated by comparing it with the expected theoretical data and to other simulators with satisfactory results.

1. Introduction

Objections to the construction of overhead power lines (OHL) are becoming increasingly common. This is influenced by several factors, such as their visual impact, strong social opposition, the difficulty of carrying out the relevant expropriation of land within the time and cost constraints imposed by the project, etc. This is happening not only in urban environments where space restrictions make clear that overhead technology is impossible, but also occurs increasingly in rural areas. Besides, high voltage cables have an insulation layer, so electroshock and short circuit risks of high voltage underground cable lines are lower than overhead lines. For all these reasons, in recent years we have seen an improvement in the technology of the manufacture and installation of underground insulated high voltage cables [1].

However, this solution has also drawbacks; the cost of an underground cable of the same length and power transmission capacity than an overhead one can be up to 5.6 times higher for the level of 400 kV, although for 150 kV is comparable in price. In addition, underground cables can cause environmental problems by obstructing runoff and the effect on the underground animal habitats.

Moreover, from a technical point of view, electrical calculations for high-voltage (HV) underground cables are very complex and have a number of electrical characteristics that make them very different from those for overhead transmission lines [2–4]. Although a great deal of research work on PD based cable insulation monitoring, diagnostics and localization has been published in recent years on medium voltage (MV) cables, few of them are found on cross-bonded HV cable systems [5,6].

Besides, the sheaths of these insulated cables are bad conductors and generate magnetic fields that originate induced voltages. Then, depending on the type of connection to ground of the sheaths, currents are generated which in turn also induce voltages in nearby sheaths. Indeed, the sheath current generated on metallic sheath can cause electroshock for human, cable fault and reducing of cable performance. These effects must be considered as they influence both line transport capacity and the design of the protections.

Therefore, if the sheath current of high voltage underground cable line is determined before this underground cable is installed in the project phase, the required precautions can be determined according to this estimated value. That is why modeling and simulation are so useful tools. But the modeling of these circuits is not easy, indeed many factors influence the voltages and currents and thus, formulation of the sheath current is difficult and complex [7].

The first objective of this work is to mathematically model and then simulate the voltages induced in insulated cable sheaths of every kind and configuration, in order to visualize their magnitudes and phase angles. It is worthy to remark that the dynamic simulation must have into account how each element influences the other. That is, it is not just to replicate different circuits, but to estimate how the electrical magnitudes of the entire system are affected since a power line behaves

---

[*] Corresponding author at: Computer Science Faculty, University Complutense of Madrid, C/ Profesor García Santesmases 9, 28040 Madrid, Spain.
E-mail addresses: msantos@ucm.es (M. Santos), mcalafat@ree.es (M.A. Calafat).

https://doi.org/10.1016/j.ijepes.2018.08.003
Received 19 January 2018; Received in revised form 24 July 2018; Accepted 9 August 2018

differently if another cable or even two or more cables are near enough.

This dynamic modeling is required as the coupling effects influence energy transportation and the design of the electrical facilities. Even more, the induced voltages and currents have an influence on sheath circulating loss, which increases the thermal resistance of cable and then reduces the permissible current. These effects may also cause damage to the cable and to the maintenance personnel [8].

To achieve this goal a simulation tool has been developed. It breaks down the various components of these voltages and enables, in design time, the visualization of different parameters (section cables, grounding resistors, connection settings, line lengths, etc.) that affect the voltages. These effects depend on the connection of the sheaths and the distance between wires. This is important because many of the papers that discuss cable modeling for long high-voltage ac underground cables do not focus on these induced effects. In addition, we are interested in developing an easy and friendly simulator which allows to obtain results in a quick way, in order to roughly check if the measures are right and to properly plan a project with further details.

Many papers are focused on some spurious effects at high frequencies, specifically, skin and proximity effects. They mainly affect the transport capacity of the cables. Although they may not play a major role for lower frequencies (below around 10 kHz), there are significant deviations between the simulation and the measured results at high frequencies. Some works use EMTP (ElectroMagnetic Transients Program), such as in [9,10], to calculate them. In [11] authors also use EMTP to investigate some basic and qualitative characteristics of the proximity effect depending on the current directions on the conductors. In [7], authors try to forecast the sheath current using statistical methods and simulate high voltage underground cable lines. In a recent paper by Brito et al. [12], the influence on the resistance and inductance per unit length matrix elements of the proximity and skin effects are considered. An analytical methodology based on the magnetic vector potential formulation where appropriate boundary conditions allow the magnetic field solution to be obtained is applied to three-phase underground cable with conductive sheaths. From the point of view of distribution networks reliability, the work reported in [13] characterizes the fault process in underground cables using a time-domain system model and a statistical parameter estimation strategy.

Other papers that also include the proximity effect in the cable models are, for instance [14], where a systematic approach for calculating electrical per-unit-length parameters of signal cables by the finite-element method is presented. Techniques based on FEM are used. Paper [15] takes into account the proximity effect arising from currents mutually induced by nearby conductors which, in turn, modify their internal current density distribution and, hence, their impedance. They apply a semi-analytical method base on conductor partitioning. MoM-SO (Method of Moments-Surface Operator) can also capture accurately the skin and proximity effects by solving Maxwell's equation in 2D [16,17]. They propose a surface current approach for systems of round solid and tubular conductors, allowing to model realistic cables with tubular sheaths, armors, and pipes. These techniques compute proximity-aware impedance parameters which can be used to compute voltages/currents. In [18], after numerical simulations, authors conclude that proximity effect will lead to uneven current distribution in cables.

Our work is not focused on the proximity effects, so important for line transport capacity, but on the induced currents and voltages caused by the fact that cables and sheaths are nearby. Besides, we work on the steady state, where the proximity effects are not relevant. Indeed, we have calculated the proximity effects to see how they affect the induced voltages on screens. This has been useful to verify that these effects on a hollow conductor such a sheath are negligible. For a 220 kV trench with standard conductors, the skin effect would cause an increase around 0.0006% and the proximity effect an increase of approximately 0.8% in the sheath ohmic resistance. In a more restrictive case (for example, if the three cables are closed together), the proximity effect would increase the resistance of the sheath by 6% (modeling it as an impedance, just to estimate it). Thus, in the most unfavorable case (cables attached), the variation on the effective output voltage of the sheaths is about tenths of a volt. Therefore, the important part of the sheath voltage is induced and it is not caused by the current flow.

The paper [19] presents a review on analytical techniques used to calculate induced sheath voltage in metallic sheaths of underground cables and overhead lines. The findings indicate that when two parallel cables are fairly close together then the electromagnetic coupling effect between the adjacent cables is difficult to calculate.

Another contribution of our work is that it allows multiple circuits to be coupled automatically, without the need to manually define each individual coupling. Other papers found in the literature do not allow this dynamic modeling or are focused on other aspects, such as the transient characteristics of grounding systems used in under-ground distribution power cables [20,21]. In [20,22] a simulation tool developed with Matlab/Simulink is proposed to prelocate insulation faults affecting electrical single-phase cables by using measurements of voltage and current. In fact, simulation has been typically used for fault location on cross-bonded cable systems, using sheath currents [23]. In [24] authors only deal with single-core cable line and an additional conductor that are reduced to a simple equivalent π-circuit and modeled by an analytical approach. The same configuration is presented in [25], where the effect of configuration of high voltage power cables on induced voltages in their metallic sheaths is computed. In other papers, such as in [26], or in [27], several cables are generated, including mutual coupling between them. In the first case, this is based on a general formulation of impedances and admittances of single-core coaxial and pipe-type cables, allowing to handle a coaxial cable consisting of a core, sheath and armor, a pipe-type cable of which the pipe thickness is finite and an overhead cable. In the paper by Patel and Triverio [27], MoM-SO technique automatically include mutual coupling via ground return impedance between cables.

Back to our proposal, the developed model emulates the performance of the different configurations on the basis of the power line data introduced by the user. The simulation tool is designed and implemented with SPICE [28]. Unlike other approaches, this way of modeling allows greater speed of development because it is dynamic and the model itself does not appear in SPICE language until the end. If an element by element modeling is performed using a graphical environment (like Simulink or graphics-based environments such as Schematics SPICE), it is not possible to connect a line with another efficiently if you do not have a module for a dual circuit. Obviously, this applies to a triple circuit, quad circuit, etc. Although some newer versions of certain simulators allow the ability to couple multiple circuits, it is at the expense of laboriously defining each connection manually, a task performed automatically by our software. For this reason, it is common in professional environments to see a single circuit line being modeled instead of two lines (when applicable), with the assumption that having a double circuit will not change the induced voltages in the first circuit in the event of a short circuit [29].

The modeling carried out in this work is quite consistent with reality in terms of modeling the underground line with all the parameters that play an important role in calculating the induced voltages. It has been validated by comparing it with the expected theoretical data and to other well-known simulators with satisfactory results. The program works well and it is simpler and more intuitive than other commercial ones. Even for steady state, it improves the usability of other general simulators, as far as we know, taking into account aspects not included by other programs, such as the simulation of induced currents and voltages.

The structure of the paper is as follows. Section 2 briefly describes the components of an insulated high voltage power cable and the possible connections between sheaths. Section 3 presents the calculation and modeling of the induced voltages. Section 4 shows the software tool developed and simulation results are then discussed to test and validate the proposal. Conclusions end the paper.