Electric Power Systems Research 138 (2016) 113–119

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Propagation of intersheath modes on underground cables

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ARTICLE INFO

Article history:
Received 9 December 2015
Received in revised form 5 February 2016
Accepted 6 February 2016
Available online 26 February 2016

Keywords:
Underground cable
Cross-bonded cable
Wave propagation
Electromagnetic transients
Intersheath modes
Homogeneous model

ABSTRACT

Wave propagation and transients associated to intersheath modes on normal-bonded and cross-bonded cables are the main topic of this paper. Intersheath mode characteristics are not easily identified in practice using the standard circuits for field testing of normal-bonded cables because the source grounding introduces several overlapping modal components. The differences between cross-bonded and normal-bonded cables are highlighted based on the propagation characteristics of the two systems. In particular, inter-core mode propagation is substantially affected by the cross-bonding of sheaths. Discrete and homogeneous models of a cross-bonded cable are compared in a time-domain simulation. The accuracy of the homogeneous model improves when the number of sheath grounding points is high. It is clearly shown that even though intersheath modes cannot be excited in a cross-bonded cable they can still be induced by the currents in the core conductors and have an impact on the cable's transient response.

1. Introduction

Over the last few years, underground cable systems have risen in popularity compared to overhead line systems due among other factors to the increasing cost of rights-of-way and the growing popularity of renewable energies. For example, a 400 kV AC submarine cable connecting Italian mainland and Sicily Island is under construction [1]. The Boutre-Trans project of the French Transmission System Operator (Réseau de Transport d'Électricité) involves the installation of a 64 km long 225 kV AC cable in the south east of France. In Denmark, all the 132–150 kV overhead transmission lines are planned to be undergrounded by the year of 2040 [2].

There are many papers investigating wave propagation and transient characteristics of cables [3–19]. Most of these papers are concerned with coaxial mode wave propagation and transients. Only few papers investigated wave propagation and transient characteristics of earth-return and intersheath modes, i.e. propagation between metallic sheaths including earth [3,12,18].

Refs. [3,18] discussed the significance of a transient due to an intersheath mode based on a field measurement. In the field test, both ends of the metallic sheaths were open-circuited. Thus it is not clear how the measured results apply to the case in which the sheaths are grounded, as in most underground cable systems.

This paper investigates wave propagation characteristics of intersheath modes and resultant transient voltages and currents on underground cables with normal-bonded and cross-bonded sheaths. In Section 2 the circuits recommended by CIGRE's working group C4.502 for intersheath mode excitation in field tests [3] are first analyzed and explained based on simulations and on the propagation characteristics of an XLPE trefoil cable system. The effect of grounding the source in a field test is also explained. In Section 3 the analysis of the circuits is verified in transient simulations carried out in EMTP-RV [20]. Section 4 is dedicated to the case of cables with cross-bonded sheaths. In Section 4.1 the homogeneous model for cross-bonded cables [11,21] is briefly explained and it is used in Section 4.2 to calculate the propagation characteristics of a cross-bonded cable system. Differences between normal-bonded and cross-bonded cables are highlighted. In Sections 4.3 and 4.4 transients in one and two major sections of a cross-bonded cable are simulated to compare discrete and homogeneous cable models. The conclusions are given in Section 5.

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http://dx.doi.org/10.1016/j.epsr.2016.02.015
0378-7796/

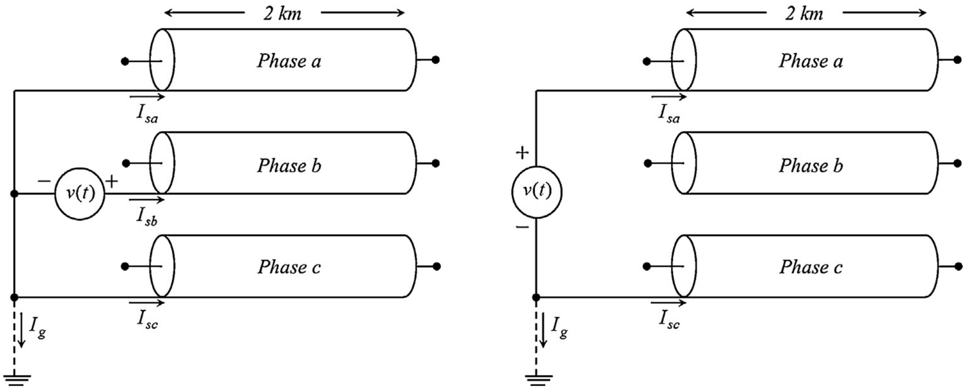

Fig. 1. Circuits for energization of intersheath modes [3]. If the source is grounded, an earth-return mode is excited.

2. Theoretical analysis of intersheath modes

2.1. Basic equations

Wave propagation on a multi-phase conductor is characterized by the modal propagation constant γ and the voltage and current transformation matrices **A** and **B**. In the case of a three-phase single core coaxial (SC) cable composed of a core conductor and a metallic sheath, the transformation matrices are given approximately in the following form in the high frequency region, i.e. for a transient analysis [14]. Bold characters are used to denote vectors and matrices hereinafter.

$$\mathbf{V_m} = \mathbf{A}^{-1}\mathbf{V_{ph}}, \quad \mathbf{A}^{-1} = \begin{bmatrix} 0 & \mathbf{a} \\ \mathbf{U}' & -\mathbf{U}' \end{bmatrix} \tag{1}$$

$$\mathbf{a} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ -1 & 2 & -1 \\ -3/2 & 0 & 3/2 \end{bmatrix}, \quad \mathbf{U}' = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \tag{2}$$

$$\begin{aligned} \mathbf{V_m} &= \begin{bmatrix} V_0 & V_1 & V_2 & V_3 & V_4 & V_5 \end{bmatrix}^T \\ \mathbf{V_{ph}} &= \begin{bmatrix} V_{ca} & V_{cb} & V_{cc} & V_{sa} & V_{sb} & V_{sc} \end{bmatrix}^T \end{aligned} \tag{3}$$

In (3), subscript '*c*' is used for core-to-ground voltage and subscript '*s*' is used for sheath-to-ground voltage. Subscripts '*a*', '*b*', and '*c*' identify each phase and numbers 0–5 identify the modes. It is observed in (1)–(3) that modes 0–2 depend only on sheath voltages V_{sa}, V_{sb}, and V_{sc}. It is also observed that $V_0 = (V_{sa} + V_{sb} + V_{sc})/3$ is a 0-sequence (or earth-return) voltage, whereas modes 1 and 2 are intersheath modes. From these observations and because this paper is focused on intersheath mode propagation, we can simplify Eq. (1) by eliminating core voltages:

$$\mathbf{V_e} = (\mathbf{A}')^{-1}\mathbf{V_s}, \quad (\mathbf{A}')^{-1} = \mathbf{a} \tag{4}$$

where $\mathbf{V_e} = [\,V_0 \quad V_1 \quad V_2\,]^T$ and $\mathbf{V_s} = [\,V_{sa} \quad V_{sb} \quad V_{sc}\,]^T$ are subvectors of $\mathbf{V_m}$ and $\mathbf{V_{ph}}$, respectively. In a similar way for currents

$$\mathbf{I_e} = (\mathbf{B}')^{-1}\mathbf{I_s}, \quad (\mathbf{B}')^{-1} = (\mathbf{A}')^T = \begin{bmatrix} 1 & 1 & 1 \\ -1/2 & 1 & -1/2 \\ -1 & 0 & 1 \end{bmatrix} \tag{5}$$

where $\mathbf{I_e} = [\,I_0 \quad I_1 \quad I_2\,]^T$ and $\mathbf{I_s} = [\,I_{sa} \quad I_{sb} \quad I_{sc}\,]^T$.

Table 1
Cable constants at f = 50 kHz–modal components.

Mode no.	0	1	2	3–5
Attenuation (dB/km)	12.42	0.10	0.10	0.16
Velocity (m/μs)	15.94	66.89	72.48	181.2

2.2. Circuits for intersheath mode excitation

Fig. 1 illustrates the circuits proposed by CIGRE's working group C4.502 for intersheath mode excitation in field tests [3]. Considering the circuit in Fig. 1(a), if we assume that the three phases are absolutely symmetrical (approximation validated in Section 3.1), then the source will inject a current that will return half in each of the adjacent phases, that is

$$I_{sa} = -I/2, \quad I_{sb} = I, \quad I_{sc} = -I/2 \tag{6}$$

By combining (5) and (6), the modal currents become

$$I_0 = 0, \quad I_1 = 3I/2, \quad I_2 = 0 \tag{7}$$

This result shows that only mode 1 (first intersheath mode), as defined in Eqs. (1)–(3), exists in the circuit of Fig. 1(a).

In the circuit of Fig. 1(b) the currents at the sending end are given by

$$I_{sa} = I, \quad I_{sb} = 0, \quad I_{sc} = -I \tag{8}$$

By combining (5) and (8), the modal currents become

$$I_0 = 0, \quad I_1 = 0, \quad I_2 = -2I \tag{9}$$

The above equation clearly shows that only mode 2 (second intersheath mode) current exists in the circuit in Fig. 1(b).

It is common in a field test to ground the source to avoid dangerous voltages in accessible terminals. When the voltage source in the circuits of Fig. 1 is grounded, the sum of the three-phase sheath currents is not zero and from (5) it results that $I_0 = I_{sa} + I_{sb} + I_{sc} = I_g \neq 0$. In such a case, an earth-return mode will be superposed to the intersheath modes observed in the circuits of Fig. 1.

2.3. Propagation characteristics of a normal-bonded cable

Fig. 2 illustrates the cross-section and the arrangement of a three-phase XLPE cable. Figs. 3 and 4 show the modal attenuation and velocity of the system in Fig. 2. The earth-return mode (mode 0) is substantially different from the other modes for any frequency above 100 Hz. Attenuation of intersheath modes 1 and 2 and coaxial modes 3–5 is not very different. However, intersheath modes have propagation velocities substantially lower than coaxial modes, and thus it is possible to identify the intersheath modes on transient voltages and currents from the traveling time of the modal components [14]. Table 1 gives values of modal attenuation and velocity at 50 kHz which are used for analyzing simulation results in Section 3.