Effects of Conductor Counter-Transposition on the Positive-Sequence Impedance and Losses of Cross-Bonded Cables

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***Abstract*—In this letter, we show that contrary to common belief, counter-transposing the conductors when power cables are cross-bonded can increase the positive-sequence resistance by close to 20%. This is very important because the losses of a power cable are determined (for balanced operation) from the Joule loasses caused by the positive-sequence resistance $(3R_1I_1^2)$.**

***Index Terms*—Ampacity, cable parameters, cables, cross-bonding, losses, positive-sequence impedance, resistance.**

I. Introduction

CROSS bonding is often used in power cables to increase ampacity (by reducing circulating currents) and prevent high induced voltages in sheaths (and/or concentric wires). Two types of cross-bonding arrangements will be analyzed below: 1) when the sheaths (or concentric wires) are transposed and the conductors are not transposed and 2) when the sheaths are transposed and the conductors are counter-transposed. Fig. 1 shows the arrangements under consideration. It is common belief that the latter, transposing conductors, is better [1].

A typical 220-kV installation used in Red Eléctrica de España (Spanish TSO) is selected for the analysis; see Fig. 2 for the installation details and Fig. 3 for the cable construction data. Our conclusion that counter-transposing conductors increase the losses by close to 20% is based on this example. However, similar results have been observed in several other flat formation installations. The impedance of trefoils does not seem to be affected by conductor transposition.

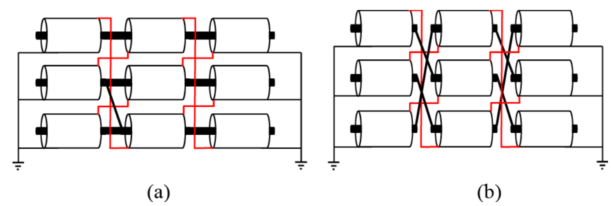

Fig. 1. Cross-bonding alternatives. (a) Conductors not transposed. (b) Conductors counter-transposed.

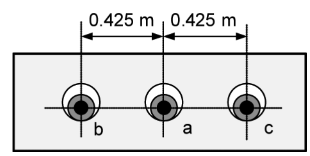

Fig. 2. Installation configuration.

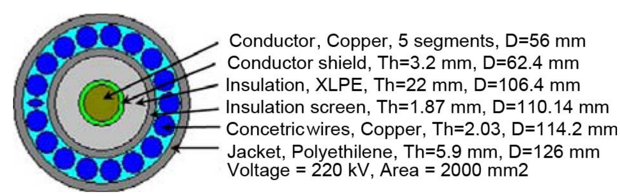

Fig. 3. Cable construction details.

II. Positive-Sequence Impedance

In this letter, Z_1 (the positive-sequence impedance) is computed from basic principles starting with the calculation of the primitive impedance matrix including the self and mutual impedances between all metallic components in the installation. Then, the elements of the primitive matrix are permuted (and counter-permuted when required) to account for the transpositions (and counter transpositions). Next, Kron reduction is used to eliminate the grounded wires from the matrix. Finally, the symmetrical components transformation is applied to compute the sequence impedances.

The elements of the primitive matrix are computed by using Carson's equations as in [2], but the conductor resistance is computed as per IEC Standard 60287-1-1 (to account for skin and proximity effects) [3]. The geometrical mean radius (GMR) is computed by using the IEC Standard 60287-1-3 to consider the construction details of the conductor [4]. Thus, the self and mutual impedances are computed from

$$Z_{ii} = (r_i + k_1 f) + jk_2 f \ln\left(\frac{k_3}{\alpha_i R_i}\sqrt{\frac{\rho}{f}}\right) \tag{1}$$

$$Z_{ij} = k_1 f + jk_2 f \ln\left(\frac{k_3}{d_{ij}}\sqrt{\frac{\rho}{f}}\right) \tag{2}$$

where

- Z_{ii} self impedance of conductor (Ω/km);
- Z_{ij} mutual impedance between conductors (Ω/km);
- r_i resistance of the conductor at operating temp (Ω/km);

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R_i radius of conductor (in meters);

d_{ij} distance between conductors I and j (in meters);

f frequency (in Hertz);

ρ electrical resistivity of earth = 100 [Ω-m]

k_1 $\pi^2 \times 10^{-4} = 9.8696044 \times 10^{-4}$

k_2 $4\pi \times 10^{-4} = 1.2566371 \times 10^{-3}$

k_3 658.87165;

α_i conversion to GMR (from 0.678 to 0.779); see [4].

Concentric wires are treated as in [2]. The copper conductor resistances at the operation temperatures are $r_a(90°\mathrm{C}) = 0.015842\ \Omega/\mathrm{km}$, $r_b(86.9°\mathrm{C}) = r_c(86.9°\mathrm{C}) = 0.015749\ \Omega/\mathrm{km}$. The resistance of the concentric wires is $rw_a(76.4°\mathrm{C}) = 0.08759\ \Omega/\mathrm{km}$, $rw_b(73.3°\mathrm{C}) = rw_c(73.3°\mathrm{C}) = 0.0867\ \Omega/\mathrm{km}$. For a frequency of 60 Hz, the product $k_1\ f = 0.059218$; therefore, the primitive matrix of resistances in Ω /km becomes the first equation shown at the bottom of the page.

The value of individual reactances very much depends on the separation distances between conductors ($d_{ab} = d_{ac} = 0.425$ m; $d_{bc} = 0.95$ m). The primitive reactance matrix in Ω/km is shown in the second equation at the bottom of the page.

A. *Conductors Nontransposed*

For illustration purposes, we assume that the transpositions take place exactly at one-third and two-thirds of the run; producing three equal section lengths. When the concentric wires are transposed, but the conductors are not [see Fig. 1(a)], the resistance matrix (after bonding) only deviates from the primitive resistance matrix in the self-resistances, corresponding to concentric wires. They are now equal for all three phases and obtained as the average $= (rw_a + rw_b + rw_c)/3$. Thus, we have (note that only the highlighted elements change value), shown in the first equation at the bottom of the next page.

With the exception of the elements in the submatrix corresponding to the self conductor-conductor (highlighted below), all other elements of the reactance matrix are averaged. Thus,

$R_{\mathrm{primitive}} =$

		conductor			concentric wires		
	phase	a	b	c	a	b	c
cond.	a	0.07506	0.05922	0.05922	0.05922	0.05922	0.05922
	b	0.05922	0.07497	0.05922	0.05922	0.05922	0.05922
	c	0.05922	0.05922	0.07497	0.05922	0.05922	0.05922
c. wires	a	0.05922	0.05922	0.05922	0.14681	0.05922	0.05922
	b	0.05922	0.05922	0.05922	0.05922	0.14592	0.05922
	c	0.05922	0.05922	0.05922	0.05922	0.05922	0.14592

$X_{\mathrm{primitve}} =$

		conductor			concentric wires		
	phase	a	b	c	a	b	c
cond.	a	0.79705	0.57315	0.57315	0.72585	0.57315	0.57315
	b	0.57315	0.79705	0.52089	0.57315	0.72585	0.52089
	c	0.57315	0.52089	0.79705	0.57315	0.52089	0.72585
c. wires	a	0.72585	0.57315	0.57315	0.72576	0.57315	0.57315
	b	0.57315	0.72585	0.52089	0.57315	0.72576	0.52089
	c	0.57315	0.52089	0.72585	0.57315	0.52089	0.72576

after bonding, we have the reactance matrix as shown in the second equation at the bottom of the page.

Applying Kron reduction ($Z_{abc} = Z_{cc} - Z_{cw}(Z_{ww})^{-1}Z_{wc}$), we obtain

$$Z_{abc\_NT} = \begin{bmatrix} 0.04576 & 0.02906 & 0.02906 \\ 0.02906 & 0.04403 & 0.02828 \\ 0.02906 & 0.02828 & 0.04403 \end{bmatrix} + j \begin{bmatrix} 0.16265 & -0.04363 & -0.04363 \\ -0.04363 & 0.19742 & -0.07875 \\ -0.04363 & -0.07875 & 0.19742 \end{bmatrix}.$$

After the application of the symmetrical components transformation ($Z_{012} = T^{-1}Z_{abc}T$), we have

$$Z_{012\_NT} = \begin{bmatrix} 0.10220 & 0.00084 & 0.00084 \\ 0.00084 & \boxed{0.01580} & 0.00005 \\ 0.00084 & 0.00005 & 0.01580 \end{bmatrix} + j \begin{bmatrix} 0.07515 & 0.00012 & 0.00012 \\ 0.00012 & 0.24116 & -0.03500 \\ 0.00012 & -0.03500 & 0.24116 \end{bmatrix}.$$

As expected from an imperfect electromagnetic balancing process, the decoupling of the sequences is not complete. The positive-sequence resistance (highlighted) is $R_1 = 0.0158\ \Omega/\text{km}$.

B. Conductors Counter-Transposed

When the concentric wires are transposed and the conductors are counter-transposed [see Fig. 1(b)], all of the elements of the primitive matrices are averaged. This now includes the (highlighted) self resistances and reactances for conductors as shown in the equation at the bottom of the next page.

Using the Kron reduction, we obtain

$$Z_{abc} = \begin{bmatrix} 0.04652 & 0.02784 & 0.02784 \\ 0.02784 & 0.04652 & 0.02784 \\ 0.02784 & 0.02784 & 0.04652 \end{bmatrix}$$

$R_{\text{bond\_}NT} =$

		conductor			concentric wires		
	phase	a	b	c	a	b	c
cond.	a	0.07506	0.05922	0.05922	0.05922	0.05922	0.05922
	b	0.05922	0.07497	0.05922	0.05922	0.05922	0.05922
	c	0.05922	0.05922	0.07497	0.05922	0.05922	0.05922
c. wires	a	0.05922	0.05922	0.05922	$\boxed{0.14621}$	0.05922	0.05922
	b	0.05922	0.05922	0.05922	0.05922	$\boxed{0.14621}$	0.05922
	c	0.05922	0.05922	0.05922	0.05922	0.05922	$\boxed{0.14621}$

$X_{\text{bond\_}NT} =$

		conductor			concentric wires		
	phase	a	b	c	a	b	c
cond.	a	0.79705	0.57315	0.57315	0.62405	0.62405	0.62405
	b	0.57315	0.79705	0.52089	0.60663	0.60663	0.60663
	c	0.57315	0.52089	0.79705	0.60663	0.60663	0.60663
c. wires	a	0.62405	0.60663	0.60663	0.72576	0.55573	0.55573
	b	0.62405	0.60663	0.60663	0.55573	0.72576	0.55573
	c	0.62405	0.60663	0.60663	0.55573	0.55573	0.72576

$$+j\begin{bmatrix} 0.18216 & -0.05351 & -0.05351 \\ -0.05351 & 0.18216 & -0.05351 \\ -0.05351 & -0.05351 & 0.18216 \end{bmatrix}.$$

The sequence impedance matrix becomes

$$Z_{012\_CT} = \begin{bmatrix} 0.10220 & 0 & 0 \\ 0 & \boxed{0.01868} & 0 \\ 0 & 0 & 0.01868 \end{bmatrix}$$

$$+j\begin{bmatrix} 0.07515 & 0 & 0 \\ 0 & 0.23567 & 0 \\ 0 & 0 & 0.23567 \end{bmatrix}.$$

One can note that the decoupling when the conductors are counter-transposed is perfect; however, the positive-sequence resistance is larger by almost 20% from the case where conductors are not transposed to a value of $R_1 = 0.01868\ \Omega/\text{km}$.

III. Losses

We have computed the losses when a balanced current of 1000 A circulates in the conductors. As expected, we found that $P_{\text{loss}} = R_{abc}(I_{abc})^2 = 3R_{012}(I_{012})^2 = 3R_1 I_1^2$. For the case when the conductors are not transposed, we have $P_{\text{loss}_{NT}} = 47.42\ \text{W/m}$; for the case when the conductors are counter-transposed, we have $P_{\text{loss}_{CT}} = 56.04\ \text{W/m}$ (i.e., 18.2% more loss).

References

[1] *IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths*, ANSI/IEEE Std. 575-1988, 1988.

[2] W. H. Kersting, *Distribution System Modeling and Analysis*. Boca Raton, FL: CRC, 2002.

[3] *Electric Cables—Calculation of the Current Rating—Part 1-1: Current Rating Equations (100% Load Factor) and Calculation of Losses. General, Edition 1.2*, IEC Std. 60287-1-1, 2001–11.

[4] *Electric Cables—Calculation of the Current Rating—Part 1-3: Current Rating Equations (100% Load Factor) and Calculation of Losses. Current Sharing Between Parallel Single-Core Cables and Calculation of Circulating Current Losses, First Edition*, IEC Std. 60287-1-3, 2002–05.

$R_{\text{bond}\_CT} =$

		conductor			concentric wires		
	phase	a	b	c	a	b	c
cond.	a	$\boxed{0.07500}$	0.05922	0.05922	0.05922	0.05922	0.05922
	b	0.05922	$\boxed{0.07500}$	0.05922	0.05922	0.05922	0.05922
	c	0.05922	0.05922	$\boxed{0.07500}$	0.05922	0.05922	0.05922
c. wires	a	0.05922	0.05922	0.05922	0.14621	0.05922	0.05922
	b	0.05922	0.05922	0.05922	0.05922	0.14621	0.05922
	c	0.05922	0.05922	0.05922	0.05922	0.05922	0.14621

$X_{\text{bond}\_CT} =$

		conductor			concentric wires		
	phase	a	b	c	a	b	c
cond.	a	0.79705	0.55573	0.55573	0.58921	0.62405	0.62405
	b	0.55573	0.79705	0.55573	0.62405	0.62405	0.58921
	c	0.55573	0.55573	0.79705	0.62405	0.58921	0.62405
c. wires	a	0.58921	0.62405	0.62405	0.72576	0.55573	0.55573
	b	0.62405	0.62405	0.58921	0.55573	0.72576	0.55573
	c	0.62405	0.58921	0.62405	0.55573	0.55573	0.72576