Superconductivity Centennial Conference

Electrical model of balanced AC HTS power cable

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Abstract

The future electricity grid will be more sustainable and it will have more power transmission and distribution capability with more electrical power added from decentralized sources on distribution level and from wind parks and other large sources on transmission level. More interconnections and more underground transmission and distribution will be put up. Use of high temperature superconducting (HTS) power cables provides solutions to many of the future grid problems caused by these trends. In this paper we present an electrical model of a balanced 6 km-long three phase triaxial HTS power cable for the Dutch project being developed by a consortium of Alliander, Ultera™ and TUD. The cable currents in all three phases are balanced by selecting proper twist pitches and insulation thickness. The paper focuses on determining inductances, capacitances and AC losses of the balanced cable. Using the developed model, we also determine the voltage drop as function of the cable length, the neutral current and the effect of the imbalanced capacitances on the current distribution of the Dutch distribution cable. The model is validated and it can be used for accurate simulation of the electrical behaviour of triaxial HTS cables in electrical grids.

1. Introduction

Declining conductor price makes it possible to integrate HTS power cables and fault current limiters in electricity grids. Expected is that the critical current of HTS tapes will further increase in the future, enabling even higher power capacity of HTS cables. Today, HTS conductor technology allows to combine high power capability, low ac loss and fault current limiting property in one cable. Additional advantages are: less permits, less EMF exposure, cold electrical insulation, etc. Currently, in the national project "Supernet" we study possibilities to integrate HTS cables into the future Dutch grid of year 2030.

One can distinguish between transmission cables and distribution cables. A HTS transmission cable has often one phase in a cryostat whereas for distribution cables triaxial arrangement is a natural choice (with three phases in one cryostat). In this paper we discuss the Dutch distribution cable design which is a triaxial type designed for retrofitting purpose (a transmission cable is discussed for instance in [4]). It is expected that future energy demands will increase; and connections into inner cities need to be strengthened. Inner cities are highly populated areas that form an obstacle for strengthening electrical connections. HTS retrofitting can be the solution. The high power capacity of the HTS cable gives the opportunity to move substations outside city areas which saves on land. Assumed in this paper is a mature cable cooling technology.

2. HTS distribution cable design of the Dutch project

To integrate HTS distribution cable in the grid, the cable parameters need to be determined for grid simulations studies such as: voltage drop, reactive power flow, fault current, etc. Since the triaxial cable configuration consists of three concentric phases around cylindrical former, phase currents are not balanced and a current through neutral causes losses. A straightforward solution is to balance the phase currents by transposition of the phases. Alternatively, in [2] a cable design is proposed where the phase inductances are balanced by dividing the cable into sections with different twist pitch. For Dutch cable project the parameters in case of inductively balanced cable are indicated in Table 1. In this case only the most outer phase needs a joint, as it has two sections with opposite twist pitch, see Tables 1, 2. To balance the inductances properly, we developed in Matlab Simulink a cable model that agrees well with the model of [2]. Resulting cable parameters for an inductively balanced cable are listed in Table 1, and for a totally balanced cable the parameters are in Table 2.

Table 1. Electrical parameters for inductively balanced Dutch triaxial HTS cable: 50 kV, 250 MVA, 3 kA and 6 km

Twist pitch section 1[m]	Twist pitch section 2 [m]	Self inductance [mH/km]	Mutual inductance [mH/km]	Capacitance [µF/km]
$TP_a = 0.236$	$TP_a = 0.236$	$L_a = 0,1557$	$M_{ab} = 0.0312$	$C_{ab} = 0,725$
$TP_b = -0.191$	$TP_b = -0.191$	$L_b = 0,1557$	$M_{bc} = 0.0312$	$C_{bc} = 0,910$
$TP_c = -0.192$	$TP_c = 0.192$	$L_c = 0,1557$	$M_{ca} = 0.0312$	$C_c = 1,09$

Table 2. Electrical parameters for inductively and capacitively balanced Dutch triaxial HTS cable: 50kV, 250MVA, 3kA and 6km

Twist pitch section 1[m]	Twist pitch section 2 [m]	Self inductance [mH/km]	Mutual inductance [mH/km]	Capacitance [µF/km]
$TP_a = 0.226$	$TP_a = 0,226$	$L_a = 0,1564$	$M_{ab} = 0.0410$	$C_{ab} = 0,725$
$TP_b = -0.188$	$TP_b = -0,188$	$L_b = 0,1564$	$M_{bc} = 0.0410$	$C_{bc} = 0,725$
$TP_c = -0.185$	$TP_c = 0,158$	$L_c = 0,1564$	$M_{ca} = 0.0410$	$C_c = 0,725$

2.1. Balanced configuration

For a balanced triaxial cable configuration, twist pitches have to be calculated. In [2] an analytical method is proposed based on the calculated cable inductances and capacitances, however an error was spotted in the article. After communication with the author [3], the corresponding equations are corrected as shown below, see Eq. (1-4), where $L_{a,1}$ is the twist pitch length of the first phase section, $M_{a,b,2}$ refers to the mutual inductance between phases the most inner and the middle phase, of the second cable section. Herewith the balanced cable parameters for the Dutch project are selected based on a one layer per phase configuration.

$$(L_{a,1}-L_{b,1}) + (M_{b,c,1}-M_{a,c,1}) / 2 + (L_{a,2}-L_{b,2}) + (M_{b,c,2}-M_{a,c,2}) / 2 = 0 \tag{1}$$

$$-2M_{a,b,1} + (M_{b,c,1}+M_{a,c,1}) - 2M_{a,b,2} + (M_{b,c,2} + M_{a,c,2}) = 0 \tag{2}$$

$$(L_{b,1} - L_{c,1}) + (M_{a,c,1} - M_{a,b,1}) / 2 + (L_{b,2}-L_{c,2}) + (M_{a,c,2} - M_{a,b,2}) / 2 = 0 \tag{3}$$

$$-2M_{b,c,1} + (M_{a,c,1} + M_{a,b,1}) - 2M_{b,c,2} + (M_{a,c,2} + M_{a,b,2}) = 0 \tag{4}$$

The calculated winding pitch lengths for the inductively balanced Dutch cable are shown in Table 1.

2.2. Simulated pi-model results

Since the inductances of the 6 km cable are balanced, no neutral current is expected. For the original case of an unbalanced triaxial cable, the neutral current is also calculated using the pi-model and parameters shown in Table 1. The cable neutral currents for unbalanced cables (a) and balanced (b) are shown in Figure 1.
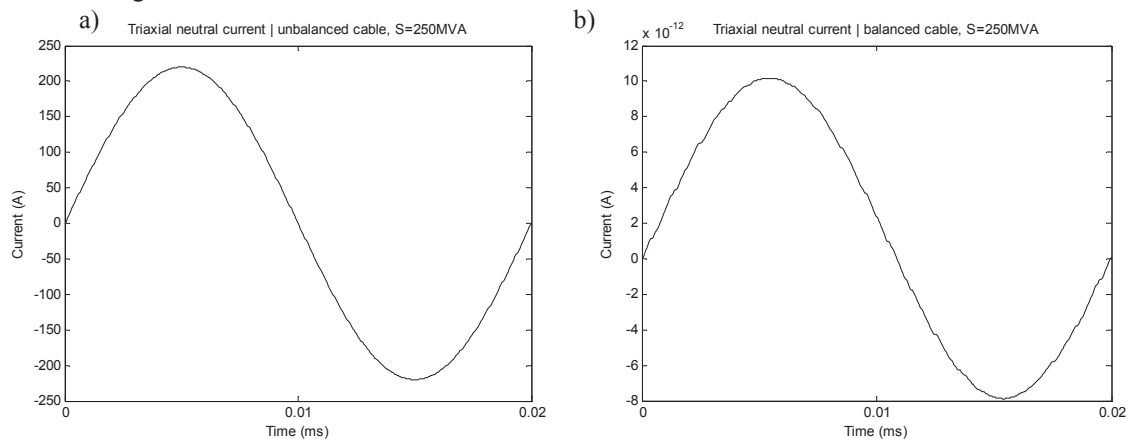

Fig. 1. (a) Neutral current for a balanced cable; (b) Neutral current for unbalanced cable.

Since the cable phases are inductively balanced, in the 10 km-long cable, capacitance imbalance affects the steady state phase currents (I_a, I_b and I_c) by respectively: 1.87%, 0.13%, 2.55% and the cable voltage drops ($U_a=U_b=U_c$) by 2.8%. As a result, the neutral current amplitude in the cable is almost 10 A. In order to reduce the effect, the cable capacitances can be further balanced by adding an external capacitance and/or by changing the electrical insulating thicknesses in the cable. For fully balanced cable (phase inductances and capacitances are balanced) of the Dutch project, the insulation thicknesses are increased for the middle and most outer phases is respectively, 28% and 56%, as compared to the inductively balanced cable. Table 2 indicates in the most right column, the capacitance based on the variation in insulation thickness, whereas the change in inductance in balanced situation is indicated in the two columns next to the capacitance. The twist pitches that belong to the inductances are indicated in the first column of Table 2. Moreover, HTS cable insulation has no significant temperature gradient and therefore the increase of insulation thickness has lower risk as compared to the conventional cable.

3. Conclusion

In the framework of the national project Supernet, we studied a possibility to balance HTS distribution cable for the Dutch cable project. Inductive balancing of the cable is possible by proper selecting twist

pitches in the phases. However, in this case capacitances of the cable remain unbalanced. To fully balance the cable, one can change the insulation thicknesses. Therefore it is possible to eliminate the neutral current without transposition of the phases in a triaxial HTS cable.

References

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