

Grid impact analysis of a HTSC cable by using an enhanced conventional simulator

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Abstract. Conventional simulators for power system studies do not include the new superconducting (SC) elements in order to perform analysis of their behaviour on the grid, however these simulators allow users to include external functions specifically designed. In this case, a specific library with the corresponding physical model of Very Low Impedance SC cables has been designed and included. This article reports on the developed algorithm and the results obtained by applying it to standard grids including SC cable.

1. Introduction

High temperature superconducting cables have been arisen as a solution for saturated underground urban areas and for retrofits, wherever space is a constraint and power rating must be significantly increased to satisfy demand. Several pilot projects have been executed worldwide since 1997, with some of them including operation of SC cables on the grid [1]. In that sense, grid operators must include this new type of power transmission cable in their regular grid studies, such as the load flow study. In this type of study, modeling of SC cables under steady state conditions is required. Standard power system simulation programs include the equivalent pi model of transmission line to represent cable parameter like resistive, inductive and capacitive losses [2]. However, AC losses associated with current transmission through SC cables have different behaviour than resistive losses in conventional cables, as reported by [3] or [4]. Despite this, in load flow studies, representation of AC losses is usually simplified at a constant equivalent resistance value in the pi model [5]. This paper proposes a new algorithm to simulate AC losses in SC cables pi model to be used in load flow studies using conventional power system simulation programs. This work includes algorithm design and its implementation with Python programming language, and an example of SC cable integration on the grid using PSS/E program.

2. Cable Modeling

The electric parameter model that is established for the cable superconductor corresponds to the equivalent pi model of transmission line depicted in 1, usually used in studies of power systems. In conventional lines, line resistance R_t represents Joule losses and the reactance

X_t and susceptance B_t , that represent magnetic and electric field, respectively. In Very Low Impedance SC cables, R_t will represent AC losses instead of joule effect losses, due to the different behaviour of this type of cables compared to conventional power lines. However, X_t and B_t have the same physical origin in SC cables as in conventional cables.

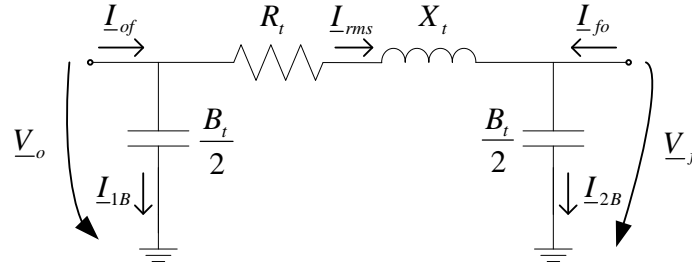


Figure 1. Equivalent pi model of a transmission line. R_t , X_t and B_t correspond to equivalent resistance, reactance and susceptance of the transmission line, respectively.

X_t and B_t of Very Low Impedance SC cables are calculated as

$$X_t = (\omega \cdot L) \cdot l \quad (1)$$

$$B_t = (\omega \cdot C) \cdot l \quad (2)$$

where ω is the base angular frequency of the grid, L is the equivalent inductance per unit length, l is the cable length, and C is the equivalent capacitance per unit length. Both L and C have known expressions reported in literature [5] by

$$L = \frac{\mu_0}{2\pi} \ln\left(\frac{r_s}{r_2}\right) \quad (3)$$

$$C = \frac{2\pi \varepsilon_0 \varepsilon_r}{\ln\left(\frac{r_s}{r_2}\right)} \quad (4)$$

where μ_0 is the magnetic constant, r_s is the radius of the SC shield, r_2 is the outer radius of one SC phase, ε_0 is the electric constant and ε_r is the relative permittivity of the dielectric.

On the other hand, cable AC losses, P_{AC} , are expressed as a function of RMS current, I_{rms} , for both states, i.e. hysteresis losses and hysteresis losses combined with flux-flow regime losses

$$P_{AC} = K_1 I_{rms}^{q_1} \quad (I_{rms} < I_{nom}) \quad (5)$$

$$P_{AC} = K_2 I_{rms}^{q_2} \quad (I_{rms} > I_{nom}) \quad (6)$$

where K_1 , K_2 , q_1 and q_2 are empirical parameters, I_{rms} is RMS current through the cable branch between original bus and end bus and I_{nom} is the SC cable nominal current.

In this work, the expressions for AC losses are used for the development of the expression to calculate the value of the resistance R_t . The conversion of the AC losses value to the resistance value is carried out with an analogous expression of Joule's First Law for conventional conductors

$$R_t = \frac{P_{AC}}{I_{rms}^2} \quad (7)$$

leading to

$$R_t = \begin{cases} K_1 I_{rms}^{q_1-2} & (I_{rms} < I_{nom}) \\ K_2 I_{rms}^{q_2-2} & (I_{rms} > I_{nom}) \end{cases} \quad (8)$$

3. AC losses calculation algorithm

As shown in (5), (6) and (8), it is necessary to know I_{rms} value to calculate AC losses or its equivalent R_t . On the other hand, pi model is a suitable model for load flow calculations, which allow to know relevant information about power systems operation, for instance, AC current injected from one bus to another bus. In this work, an iterative algorithm based on utilization of expression (8) and load flow resolutions to approach R_t real value is proposed. This algorithm is depicted in Fig. 2.

First of all, an initial R_t value is estimated and it is introduced in the SC cable pi model. R_t value may be estimated to a reasonable value. Afterwards, a load flow calculation is executed, and an initial I_{rms} value is obtained for the SC cable. Next, an alternative value for R_t is calculated by applying the I_{rms} value in (8). Finally, the absolute value of the discrepancy between both R_t values is compared with an acceptable absolute error, named epsilon. From this point, a bifurcation point occurs. If the discrepancy between both R_t values does not exceed epsilon's value, the initial R_t estimation is considered to be good enough and the algorithm finishes. On the contrary, if this discrepancy does exceed epsilon's value, then the initial R_t estimation is considered not to be good enough, and an iteration loop starts. Each iteration is executed as follows. Every R_t value that is calculated in the previous iteration is introduced in the SC cable pi model in order to execute a new load flow calculation. Then the I_{rms} value obtained from load flow calculation is introduced in (8) in order to obtain a new value for R_t . Finally, discrepancy between both R_t values is evaluated again.

4. Integration of the Cable in the Power System Simulation Program

The proposed methodology for the integration of the SC cable in the power system simulation program is structured in two parts. First, a selected grid is modeled, and second, AC losses calculation algorithm is executed.

The grid modeling is a process that can be divided in three main steps. First of all, introduction of model parameters of all grid elements is performed. SC cable pi model is also included in the grid modeling, except the resistance value, representing AC losses, which is an unknown parameter. Secondly, the bus classification and variable initialization is executed. In the last step, a load flow resolution algorithm is executed, such as Newton-Raphson or decoupled Newton-Raphson methods.

At the end of the methodology's first part, the grid is completely modeled in steady state operation except for SC cable AC losses. In the second part, AC losses calculation algorithm is executed, as explained in section 3.

PSS/E program, version 31.0.0, is used for the power system simulation Program that has been used is . Phyton programming language has been used for the algorithm implementation.

This methodology has been verified with a particular example in PSS/E. The verification consists in the comparison between AC losses measured in a real cable and AC losses obtained with the algorithm under different I_{rms} values.

The test grid is composed by one generator, one load and one SC cable, depicted in Fig. 3. Bus number 1 is slack type bus at 13,8 kV, 0 degrees, and bus number 2 is PQ type bus. The generator consumes zero apparent power and the load generates zero apparent power and consumes inductive power with power factor equal to 0,8. The grid base frequency is set to 60 Hz.

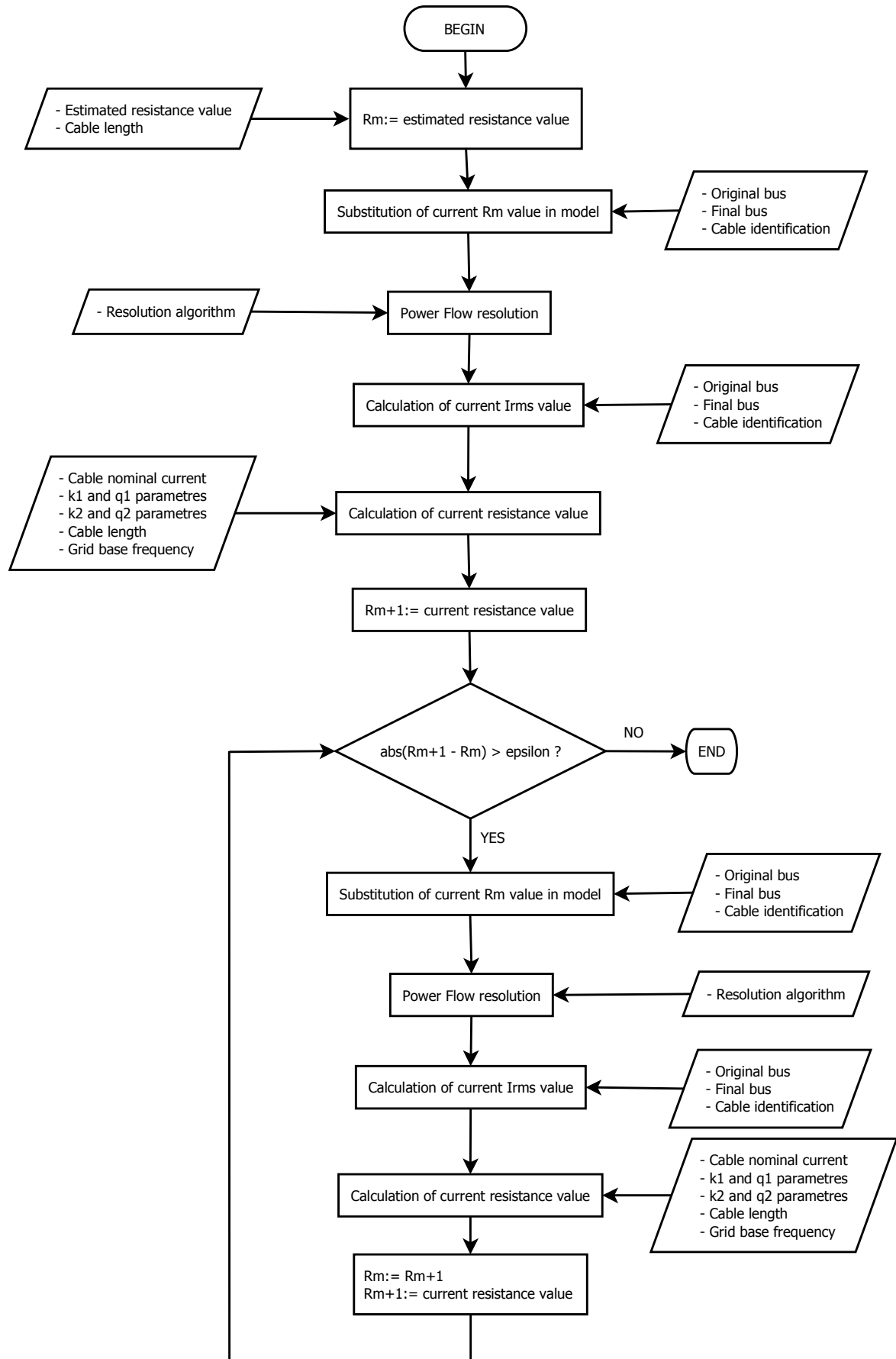


Figure 2. AC losses calculation algorithm flux diagram



Figure 3. Grid diagram for methodology's verification.

Table 1. Cable specifications. Data from [3], voltage modified to 13,8 kV.

Description	Value
Nominal current	1250 A
Nominal tension	13,8 kV
Cable configuration	Three phases in one cryostat.
Dielectric type	Cold dielectric.
Dielectric material	PPLP (4,5 mm).

On the other hand, SC power line between buses 1 and 2 consists of a one km length three-phase cable and the majority of its specifications are obtained from [3], except for the nominal voltage, that is set to 13,8 kV instead of 22,9 kV. SC cable parameters are shown in Table 1.

The initial resistance value is estimated at $1e-6$ pu ($1,904e-6 \Omega$) and the epsilon value is set to $1e-6 \Omega$. Newton-Raphson is the Power Flow resolution method selected for the methodology's validation.

The results are shown in Table 2 and Fig. 4. In all cases, algorithm convergence was reached after three iterations.

5. Application Example

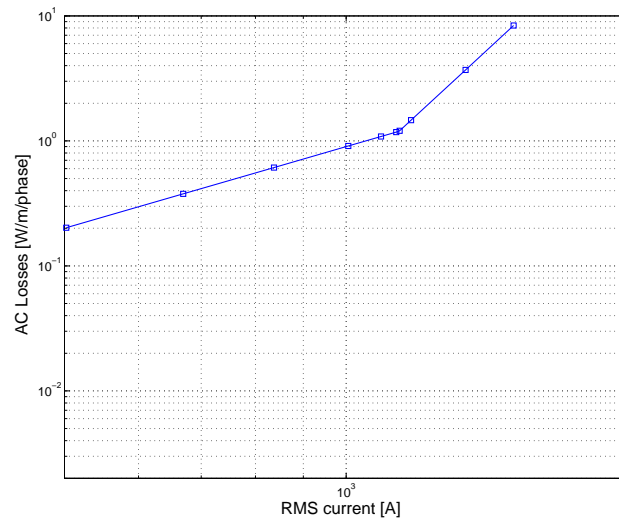
The algorithm presented in this article is intended to be a tool suitable in studies involving integration of SC power cables in real power systems, which are more complex than the grid presented in the methodology's validation. An example of application of this algorithm in a realistic grid model will be explained in this section.

The test grid system is provided by PSS/E [6], depicted in Fig. 5. In this test system, the generator called Urbgen- bus number 206, is moved to another location and is re-connected to the grid through a new SC power line. The initial and the later cases are shown in Fig. 6. The initial case is drawn in dotted line. A new bus is created in the grid in order to represent the new connection point between one SC line end and the substation. The new SC line is composed of five three-phase cables that have the parameters shown in Table 3.

The objective of this example is to calculate the line length corresponding with a maximum voltage drop set at 5%. Results for different voltage drops are shown in Table 4. The line with 5% voltage drop is 27 km.

Table 2. Results for the methodology's validation.

S load (MVA)	P load (MW)	Q load (Mvar)	R (Ω/km)	I rms (A)	AC losses (W/m/phase)
36	28,8	21,6	0,00367	1510,2	8,373
34	27,2	20,4	0,00277	1426,0	5,631
32	25,6	19,2	0,00205	1341,6	3,697
30	24	18	0,00149	1257,5	2,364
28	22,4	16,8	0,00106	1173,4	1,464
27,22	21,78	16,33	0,00093	1140,9	1,205
27	21,6	16,2	0,00092	1131,4	1,176
26	20,8	15,6	0,00091	1089,5	1,084
24	19,2	14,4	0,00090	1005,4	0,910
20	16	12	0,00087	837,5	0,612
16	12,8	9,6	0,00084	669,7	0,377
12	9,6	7,2	0,00080	502,0	0,202

**Figure 4.** AC losses obtained with the algorithm.**Table 3.** SC cable parametres.

Parametre	Value		Units
R	$10^{-3,5555} (I_{rms})^{0,1699}$	$500A < I_{rms} < 1138,9A$	Ω/km
	$10^{-18,041} (I_{rms})^{4,9090}$	$1138,9A < I_{rms} < 1500A$	
L	0,056		mH/km
C	441		nF/km

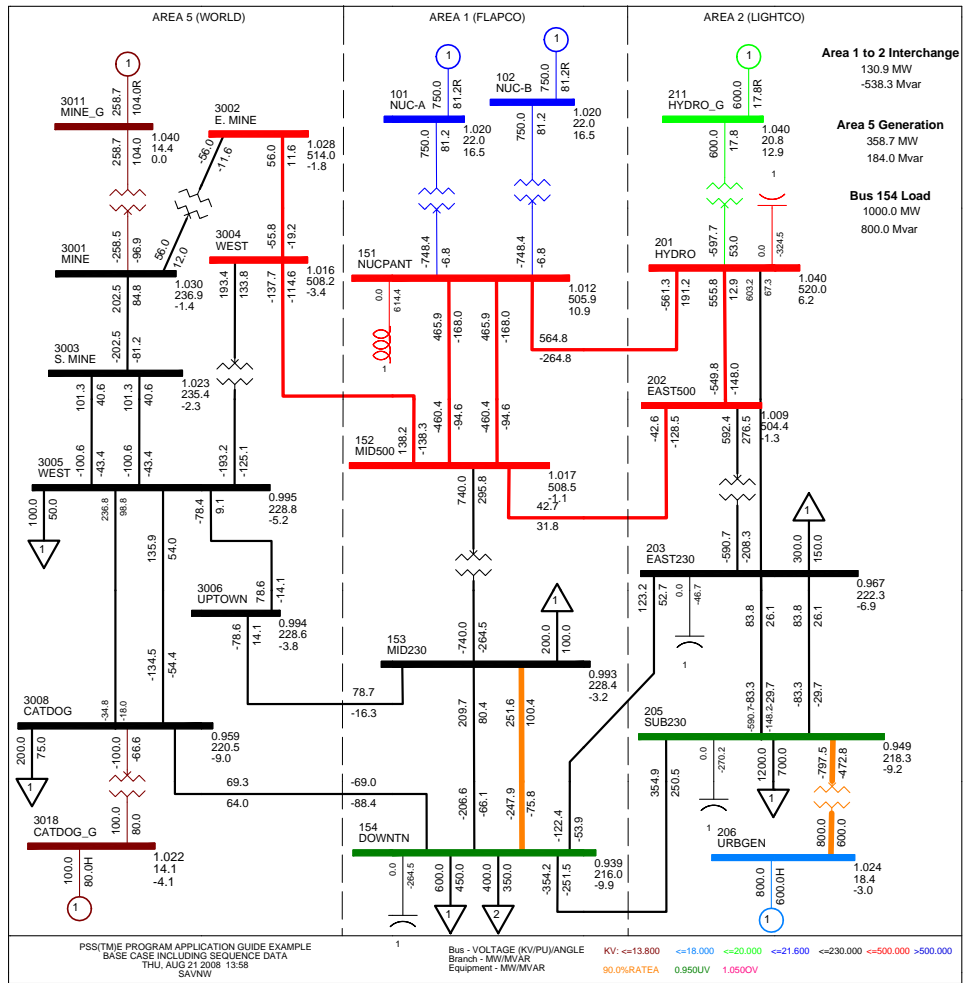


Figure 5. PSS/E SAVNW grid test system.

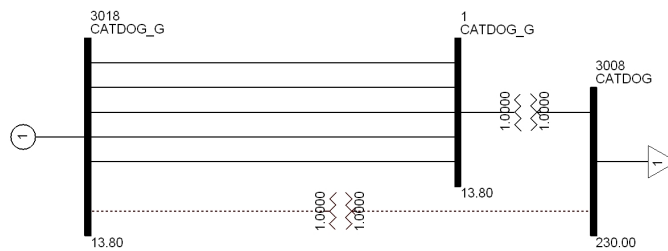


Figure 6. Introduction of a SC power line in SAVNW grid (PSS/E image).

Table 4. Voltage drops between buses 3018 and 1.

length (km)	voltage bus # 3018 (p.u.)	voltage bus # 1 (p.u.)	drop (%)
5	1,0299	1,0208	0,91
10	1,0379	1,0199	1,80
15	1,0459	1,0191	2,68
20	1,0537	1,0183	3,54
25	1,0615	1,0176	4,39
30	1,0692	1,0169	5,23
30,5	1,0700	1,0168	5,32

6. Conclusions

In this work, development of an new algorithm to calculate AC losses of SC cables has been successfully executed. A suitable electrical equivalence between AC losses and a resistive parameter has been proposed in order to enable the utilization of the SC cable model in conventional power system simulation programs. The algorithm has been implemented with Python programming language and the SC cable model has been used in PSS/E. Both algorithm and model have been validated in a particular case with real data obtaining successful results. An application example of the connection of a generation unit to a standard PSS/E grid through a SC power line has also been executed. The algorithm and its corresponding physical model here proposed are restricted to AC steady state operation conditions. Dynamic characterization of SC cables could be considered in future works.

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