A Transient Model of High-Temperature Superconducting Cables in Electric Power Supply

Kim Høj Jensen and Vladislav Akhmatov

Abstract--**A transient model of high-temperature superconducting (HTS) cables is implemented in the simulation tool PSS/E as an user-written model. Dependence of the resistance of HTS material on the electric current and the temperature of the HTS tapes is taken into account. This is necessary in simulations of transient events occurring in the power network and influencing on the current, the power losses and the temperature of the HTS tapes. Implementation in the tool PSS/E makes it possible to apply the transient model of HTS cables in power stability investigations of large, meshed power networks containing such superconducting cables.**

Index Terms--**High-temperature superconductor, cables, transient models, simulations, simulation tool PSS/E.**

I. Nomenclature

A. Symbols

a	Cross-area of a HTS tape.
A	Surface area of HTS tapes in contact with coolant (fluent nitrogen).
C_P	Heat capacity of HTS tapes.
h	Heat transfer coefficient.
I	Current in a single phase.
l	Length of HTS tapes.
L	Inductance.
n	Power-factor.
N	Number of HTS tapes in a single-phased cable.
P	Power losses in HTS tapes in a single phase.
r	Matrix/HTS ratio of a tape cross-area.
R	Resistance of HTS tapes in a single phase.
t	Time.
T	Temperature in a single phase.
T_0	Initial operational temperature.
ΔT	Temperature difference between HTS tape surface and coolant (fluent nitrogen).
ΔU	Single-phased voltage drop.
α	Temperature coefficient.
β	Temperature coefficient.
ρ	Resistivity.
d/dt	Time derivative.

B. Subscripts

C	Critical value of HTS material.
HTS	High-temperature superconductor.
M	Matrix material of HTS tapes.
T	Total of HTS material and matrix material.

II. Introduction

HIGH-TEMPERATURE superconducting (HTS) cable systems are nearing technical feasibility. May the 28th 2001, a three-phased HTS cable was taken in operation at the Amager power-utility substation, Copenhagen, Denmark [1]. The cable length is 30 m, the operating voltage and current are 36 kV and 2 kA RMS, respectively, [1]. This demonstration project is the first case of practical application of HTS cables in electric power supply in the world. Also in U.S.A., Japan and many European countries, there are a large number of R&D projects to reach practical application of HTS cables in electric power supply. The main target is use of HTS cables for transport of huge amount of electric energy through the HTS cables [2], [3].

The fabrication technology of HTS components is improving rapidly [2]-[4]. This makes the HTS components and cables to be attractive for practical applications in electric power supply. In the years to come, it can be expected that HTS cables will found more application in electric power supply in situations where the HTS cables are technically and economically more favorable than the conventional cables [4], [5]. This implies that it shall be possible to represent the HTS cables by sufficiently detailed simulating models. These models shall be implemented in simulation tools for investigations of power system stability.

In this article, a transient model of HTS cables to be applied in investigations of transient voltage stability of large power networks is presented. The model is implemented in the simulation tool Power System Simulator for Engineers (PSS/E) from the supplier Power Technologies, Inc., (PTI), New York,

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U.S.A., as an user-written model. This work has taken place at the Danish power company NESA, where the tool PSS/E is applied in investigations of power system stability.

III. MODELING CONSIDERATIONS

Presently, detailed models of HTS cables are developed with static representation of the tapes of HTS cables [4], [5]. In such static representations, the HTS tape resistance, its current and temperature are described in equilibrium at different operating conditions. The magnitude of the current going through the HTS tapes is often given by *a consideration*, e.g. independently from the factual operational conditions in the power grid.

The current is defined by the operational conditions of the HTS tapes as well as the voltage at the cable terminals, according to the Ohms law. The voltage may depend on the operational conditions of the meshed power network and also fluctuate at disturbances. Consequently, this may lead to other operational conditions than been *considered*.

In load-flow investigations, e.g. at steady-state operational conditions, of electric power networks, the HTS cables are simply represented as lines without electric resistance [5]. In investigations of transient voltage stability, the HTS components are often given as switches with two levels of the resistance [5]-[7]. At normal operation of the power grid, the cable resistance is set to zero. At a transient event, the cable resistance is switched to a finite (high-resistant) value, which the device *considerably* will reach. It is noticed that this switching algorithm is mostly used for modeling of short-circuit current fault limiters (SCFL) [6], [7].

At such considerations, the accurate values of current and temperature of the HTS tapes are not taken into account. This over-simplified representation may introduce inaccuracy in the simulating results. It may also lead to misleading conclusion about the state of the HTS material of the tapes – superconducting or normal (high-resistant). It is because the resistance of HTS materials is very sensitive with respect to its current and temperature [4], [8], [9].

The process of the resistance change at transient events is strongly dependent on the factual values of the current, the power losses and the temperature of the HTS tapes. Furthermore, the current, the power losses and the temperature of the HTS tapes in the cable depend on the factual value of the resistance [8], [10]. This introduces the coupling, which is often missed in over-simplified representations of HTS components.

A. Resistance of HTS Cables

Generally, the superconducting material can be in one of the three states [4], [11].

- The superconducting state with zero dc-resistance.
- The flux-flow state.
- The normal state (high resistance).

The flux-flow is the transition state between the superconducting and the normal states [4]. When in the superconducting state, the resistance in dc-mode is zero, but the ac-resistance of the HTS component shall be modeled at the flux-flow state. In the flux-flow state, the resistivity of the HTS material is given by the power-law [8].

$$\rho_{HTS}=\rho_C\left(\frac{I(t)}{I_C}\right)^{n-1}\left(\frac{T_C-T_0}{T_C-T(t)}\right)^n. \tag{1}$$

In the normal state, the resistivity of the HTS material is temperature-dependent according to [8], [11].

$$\rho_{HTS}=\alpha T(t)+\beta. \tag{2}$$

Equations (1)-(2) are written for bulk-HTS devices. In case of HTS tapes applied in the cables, the HTS material is formed as filaments and surrounded by a matrix material [4], [10], [12]. Often the HTS filaments are within a ductile matrix of silver or silver-alloys. In that case, the total resistivity of the tapes will be [11].

$$\rho_T=\left(\frac{1}{1+r}\rho_{HTS}^{-1}+\frac{r}{1+r}\rho_M^{-1}\right)^{-1}. \tag{3}$$

The resistance of the HTS component (consisting of a number of tapes) becomes

$$R(t)=\frac{l}{aN}\rho_T(t). \tag{4}$$

This corresponds to the resistance of one-phased HTS cable of length l.

B. Transient Model of Line Current

The current of the one-phased HTS cable is given by the following expression.

$$L\frac{dI(t)}{dt}=-R(t)I(t)-\Delta U(t). \tag{5}$$

This is a well-known relation where $R(t)$ is the resistance of the single-phased HTS cable given by Eqs. (1)-(4).

C. Temperature and Cooling Models

Typically, the critical temperatures of HTS ceramic materials are around 90 K [4], [10]. Therefore, the HTS devices operate under cooling of fluent nitrogen (at 77 K) [1], [4], [5]. The temperature of the HTS component (in a single phase) is described by the following equation.

$$C_P\frac{dT(t)}{dt}=P(t)-h(\Delta T)A\Delta T(t). \tag{6}$$

It is noticed that $h(\Delta T)$ describes an irreversible process of the heat exchange between the HTS tape surface and fluent nitrogen [4], [11], [13]. When cooling is effective, the temperature of the HTS tapes is slightly above the temperature of the coolant. It can be considered that T_0=80 K and ΔT=3 K through the whole cable length at steady-state operation.

It is noticed that the cooling process is much more complex. The coolant is pumped through the cable cryostat, which is why the temperature of the flowing coolant increases through the length of the cable [14]. The temperature at the two ends of the cable is different [4], [14]. In this work, such factors are neglected. It is because a long HTS cable may consist of a number of shorter cable sections in series with their cooling and pumping stations. This arrangement will lead to that the effect of the temperature increasing through the cable length is reduced.

D. Three-phased HTS Cables

The above-presented expressions are all for representation single-phased HTS cables. The three-phased HTS cable will be given by three models of single-phased HTS cables. This implies that the resistance, the current, the power losses and the temperature of HTS tapes shall be computed independently in the three phases.

Coupling of the transient model of the HTS cable to the power network equivalent is according to the dynamic interface of the simulation tool. The simulation tool PSS/E works with positive-sequence equivalents, which is why the coupling between the transient model of three-phased HTS cable and the tool PSS/E is through the positive-sequence resistance of the cable.

Changes of the current going through the HTS cable can occur at grid faults. Those changes are computed with relation to the current changes in the (conventional) lines connected to the terminals of the HTS cable, according to the Kirchhoffs current law. The current changes in the HTS cable lead to the changes of its positive-sequence resistance. Interfacing to the simulation tool corresponds to representation of these changes in the network solution. This produces the feed-back between the transient model of the HTS cable and the network model.

IV. SIMULATING EXAMPLE

Use of the transient model of HTS cables in investigations of transient voltage stability is illustrated by a simulating example. Here a 5 km, three-phased HTS cable is incorporated into a transmission power network, represented by a simplified, but sufficiently detailed, model of the eastern Danish power system, and transmits 150 MW. The rated voltage level is 132 kV. It is kept in mind that it is only an example chosen for illustration of the model with coupling between the three-phased HTS cable and the power network. Incorporation of HTS cables into transmission power networks will be for transport of significantly more electric power.

The HTS tapes of the cable are superconducting bismuth ceramic filaments (BSCCO) within the ductile silver matrix [1], [10], [12]. The cross-section of one tape is 0.2 mm × 3.0 mm and there are 66 tapes in the one-phased HTS cable. The tapes are cooled with fluent nitrogen.

The current through the cable is 650 A RMS per phase at rated operation. The HTSC is dimensioned to the critical current of 1200 A peak per phase. The power-factor n =5.

The simulation results are shown in Fig. 1. When the transmission power network is subjected to a short-circuit fault, the voltage drop occurs.

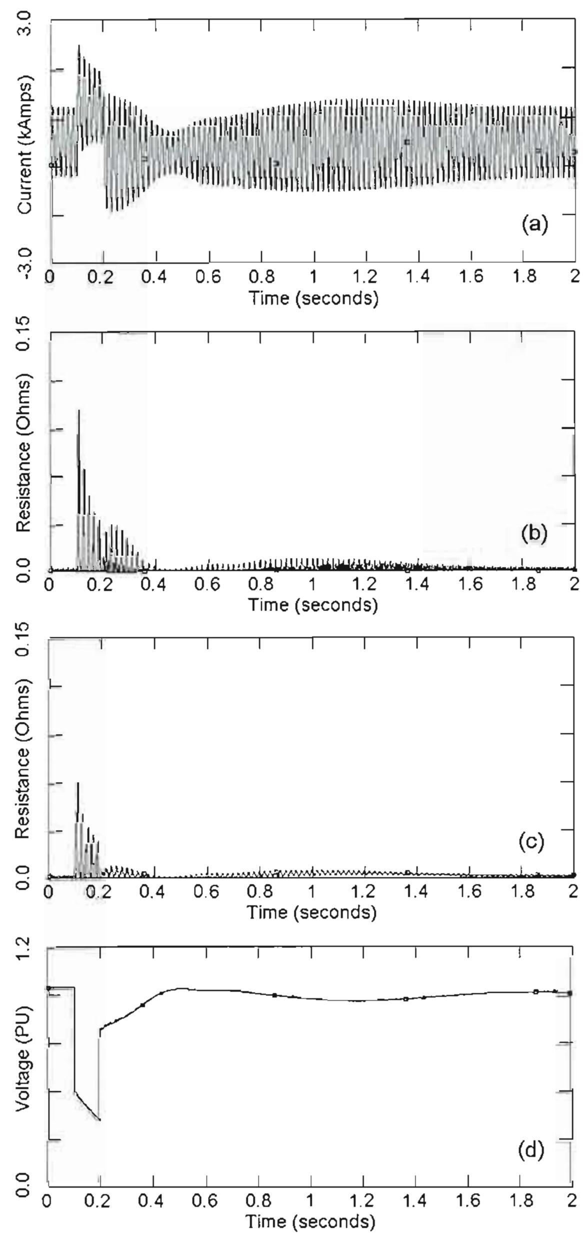

Fig. 1. Simulation results of the HTS cable model: (a) – current in a single-phased HTS cable, (b) – resistance of a single-phased HTS cable, (c) – positive-sequence resistance of three-phased cable, (d) – voltage at the terminals of the three-phased HTS cable, 1 PU =132 kV.

The resistance of the HTS cable increases as the result of the current transients. The HTS material is in the flux-flow state. The behaviors of the resistance of the HTS cable in a single phase and of the positive-sequence resistance of the three-phased HTS cable contain both the fundamental frequency (50 Hz in Europe) and its higher harmonics. It is because the resistance in each phase increases when the current transients in this phase approach or exceed the critical current of the HTS material. At the short-circuit fault, the dc-offset in the current is sufficiently high in at least one of the three phases. It explains why the positive-sequence resistance of the three-phased HTS cable contains a strong representation of the fundamental frequency (50 Hz). Such transient behavior has been confirmed by the experiments of [11].

As expected, the short-circuit fault causes neither significant increase of the cable resistance nor fatal overheating of the cable. It is because the current of the HTS cable at the fault is not significantly high compared to the critical current. The temperature increases only with 1 K and such an increase cannot cause quenching of the HTS cable. When the short-circuit fault is cleared, the resistance decays and the HTS material returns to the superconducting state.

V. CONCLUSION

The transient model of HTS cables to be applied in investigations of power system stability is presented. The model acknowledges the dependence of the resistance of the HTS tapes on the current and the temperature. The model is implemented in the simulation tool PSS/E as an user-written model, which makes it possible to make investigations on large, meshed power networks with a number of HTS cables. Implementation is made so that there is a coupling between the results of the transient model of HTS cables and the network solution produced by the simulation tool PSS/E.

It is demonstrated that the resistance of the HTS cable contains the fundamental frequency and its higher harmonics. It is because it follows the current transients of the respective three phases.

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VII. REFERENCES

[1] M. Daumling, C.N. Rasmussen, F. Hansen, D.W.A. Willen, O.E. Schuppach, B.S. Hansen, C. Traeholt, K.H. Jensen, S.K. Olesen, C. Rasmussen, E. Veje, O. Toennesen, J. Oestergaard, "Test results of full-scale high temperature superconductors cable models destined for a 36 kV, 2 kA RMS utility demonstration", *Physica C*, 2001, vol. 357-360, part. 2, pp. 1241-4.

[2] S. Spreafico, P. Carasino, N. Kelley, M. Nassi, "Progress in manufacturing of HTS power transmission cable", *IEEE Trans. on Applied Superconductivity*, 2001, vol.11, no.1, pp. 2359-62.

[3] K. Miyoshi, S. Mukoyama, H. Tsubouchi, A. Takagi, S. Meguro, K. Matsuo, S. Hojo, T. Mimura, Y. Takahashi, "Design and production of High-Tc superconducting power transmission cable", IEEE Trans. on Applied Superconductivity, 2001, vol.11, no.1, p.2363-6.

[4] T. P. Sheahen, *Introduction to High- Temperature Superconductivity*, New York, Plenum, 1994, 580 p.

[5] O. Toennesen, S. Hansen, P. Jorgensen, K. Lomholt, S.D. Mikkelsen, J. Okholm, S. Salvin, J. Oestergaard, "Power applications for super-conducting cables", *Supercond. Sci. Technol.*, 2000, vol. 13, no. 5, pp. 506-9.

[6] M. Tsuda, Y. Mitani, K. Tsuji, K. Kakihana, "Application of resistor based superconducting fault current limiter to enhancement of power system transient stability", *IEEE Trans. on Applied Superconductivity*, 2001, vol. 11, no.1, p.2122-5.

[7] Y. Goto, K. Yukita, H. Yamada, K. Ichiyanagi, Y. Yokomizu, T. Matsumura, "A study on power system transient stability due to introduction of superconducting fault current limiters", *Electrical Engineering in Japan*, 2000, vol. 133, no. 4, pp. 41-52.

[8] J. N. Nielsen, "Superconducting fault current limiter", Ph.D. dissertation, Dept. of Electric Power Engineering, Technical University of Denmark, Feb. 2000.

[9] K. H. Jensen, C. Traeholt, E. Veje, M. Daumling, C. N. Rasmussen, D.W.A. Willen, O. Toennesen, "Short circuit experiments on a high-Tc superconducting cable conductor", *Physica C*, 2002, vol. 372-376, part. 3, pp. 1585-7.

[10] P. Vase, R. Flükiger, M. Leghissa, B. Glowacki, "Topical review. Current status of high-Tc wire", *Supercond. Sci. Technol.*, 2000, vol. 13, no. 7, pp. R71-R83.

[11] K. H. Jensen, "Transient analysis of superconducting cables", Ph.D. dissertation, Dept. of Electric Power Engineering, Technical University of Denmark, Sept. 2002.

[12] K. Sato, N. Shibuta, H. Mukai, T. Hikata, M. Ueyama, T. Kato, J. Fujikami, "Bismuth superconducting wires and their applications", *Cryogenics*, 1993, vol. 33, no. 3, pp. 243-6.

[13] F. P. Incropera, D. P. Dewitt, *Introduction to Heat Transfer*, 3rd Edit., New York, Wiley, 1996, 801 p.

[14] R. F. Barron, *Cryogenic Systems*, 2nd Edit., New York, Oxford University Press, 1985, 507 p.

VIII. BIOGRAPHIES

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