

Application Guide for AC High Temperature Superconducting (HTS) Cables

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Document Revision History

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Introduction

Purpose

This Application Guide is intended for use by power system planning engineers, consultants and those in related fields, to gain a high level understanding of the applications and modeling of AC High Temperature Superconducting (HTS) Cables for applications on utility scale power systems. This guide should be helpful for studies using power system simulation software such as PSS/e, PSLF, DigSILENT, PowerWorld, PSCAD and similar packages.

Any user of this Application Guide should feel free to contact AMSC at any time for additional guidance and support on aspect of studying applications of HTS cable. Contact information is provided at the end of this document.

This Application Guide is NOT intended for applications of DC HTS Cables, industrial/commercial applications, or transportation/military applications. The level of detail provide is sufficient for simulation accuracy on the order of cycles (i.e. 10's of mS) in phase-domain type simulations. In time-domain simulations, the approaches presented are reasonable for RMS type results, but are not sufficient for sub-cycle, "waveform" type simulations such as EMTP or PSCAD.

Please contact AMSC regarding applications and levels of accuracy outside that discussed above.

Technology Overview

The key characteristics of HTS cables, from the perspective of power system modelling, that differentiate the cables for traditional copper or aluminum cables are:

- 1) *High Ampacity*
- 2) *Zero Resistance*
- 3) *Low Inductance*
- 4) *Fault Current Limiting*

The primary characteristic of superconductor cables is the ability to carry very high levels of current at zero resistance. In general, the ampacity of the cables is limited more by ancillary equipment (breakers, bus bars, etc.) than the cables themselves. Many utilities assume the cables at 3000A maximum current, as that is the maximum breaker rating they typical procure, but cable designs up to 5000A are available.

The cables have zero resistance, relatively low inductance and comparable capacitance to conventional cables. This document provides guidance on R, X and B values for modeling.

HTS Cables have "Fault Current Limiting" characteristics in the resistance of the cable, which changes from near zero, to a relatively high value in the event that the cable is exposed to

current levels above the cable's rating, such as during fault events. This change in resistance is utilized to manage fault current levels through the cable. While the mechanics/physics of this characteristic is outside the scope of this document, this document does provide guidance on how to correctly model the cable during fault conditions to capture this characteristic. Please contact AMSC if more information is desired regarding this feature of the cables.

Other advantages of HTS cables that are important to the siting and installation of the cables, but are not necessarily important to the software simulation and modeling of the cables are:

- A) *High power density (i.e. small cross-sectional area)*
- B) *Thermal Isolation (no heat emitted from cables)*
- C) *Nearly undetectable Electro-Magnetic Fields (near zero EMF)*
- D) *Simplified Permitting*

The small size and lack of heat or EMF signatures are extremely helpful in the siting, permitting, civil works, and installation of the cables. From an application / planning perspective this is important in that the cables can be installed in places where conventional cables are not typically allowed (i.e. thermally limited duct banks, deep directional bores, across bridges, etc.), however these characteristics do not directly impact the modeling of the cables and therefore are not heavily discussed in this document.

Application Overview

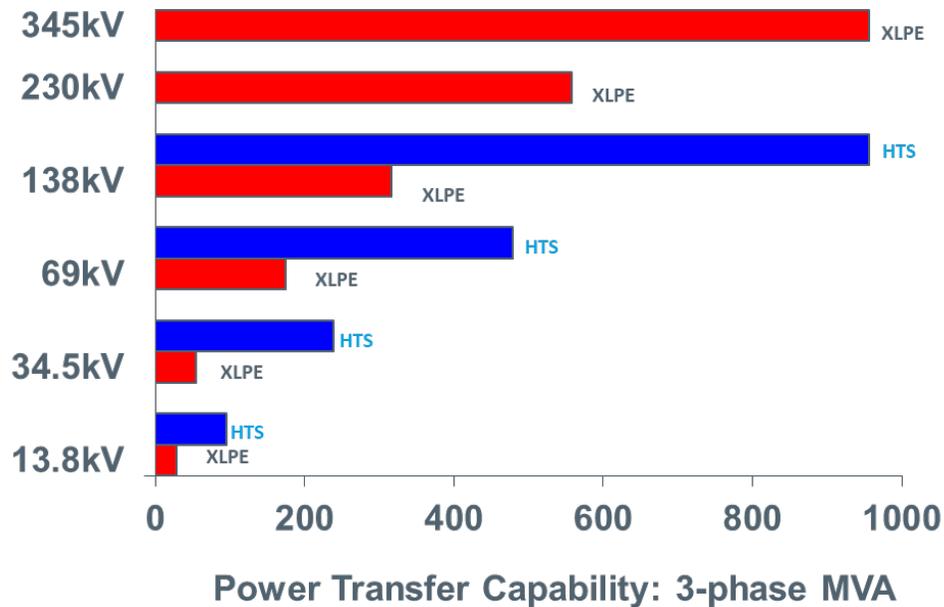
Due to the high ampacity and compactness of HTS cables, the primary utility application of the cables is as a distribution voltage alternative to transmission cables in urban (or otherwise space constrained) areas. This is because a distribution voltage HTS Cable can, in many cases, carry as much power as a transmission voltage cable. The characteristic creates several sub-application options discussed in detail in this document.

Other applications include the replacement of many conventional cables with a much smaller number of HTS cables (allowing for smaller Rights-of-Way), overcoming thermal and geographical limitations (i.e. substation get-a-ways, thermally limited duct banks, directional drilling under rivers/highways), and undergrounding of overhead circuits.

Primary Applications

Transmission Power at Distribution Voltages

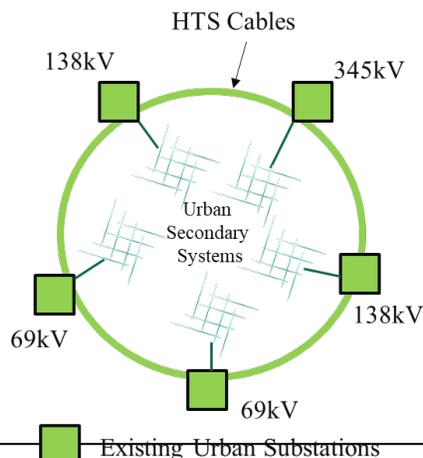
The primary applications of HTS cables take advantage of the ability of the technology to move bulk, transmission level power at distribution voltages because of their ability to carry high levels of current. The figure below assumes a maximum XLPE cable ampacity of 1000A (high end of typical range) and an HTS cable ampacity of 4000A (maximum commercially available non-gas insulated switchgear rating).



From a planning perspective, this capability allows for three major applications of HTS cables:

1) Loop Applications for Reliability/Resiliency Improvement

HTS cables have applications that increase the reliability and resiliency of service to one or more substations in urban power systems. This is generally achieved by “looping” the substations together with HTS cables **at the distribution voltage level** such that the HTS cables behave as a “back-up” to the transmission system.



This approach is effective because in the event of an N-1 to N-4 type loss of transmission or transformation serving the load at one or more of the substations, power can be transported from substation to substation via the HTS cable system; effectively creating redundancy.

This is possible in part because most urban substations already have redundancy in transformation (typically N-1 to N-2). This application of HTS cable effectively makes the spare transformation at the various stations “fungible” in that the spare transformation at one station can be utilized to serve load at another, in the event of outage conditions.

In another variation on this application, additional spare transformation could be installed at one substation, but utilized (via the HTS cables) at one or more other substations, helping to overcome space constraints and creating strategic and operational flexibility.

The fault current limiting aspects of the HTS cables are important to this application as without that feature modelled properly, the fault current levels at the interconnected substations may rise to unacceptable levels.

It should be noted that as this approach utilizes the HTS cables for “back-up” or redundant purposes, meaning that the HTS cables can be placed out of service during “system normal” conditions. This may be recommended even in scenarios without fault current concerns as the cables may cause undesirable “loop flows” if closed in during normal conditions. In such cases, the cables are often placed into service following N-1 outage events to increase resiliency in the event of a second and subsequent outages.

If simulations show elevated fault current levels for desired applications and conditions even when the Fault Current Limiting aspects of the cable are modelled properly, this situation can typically be resolved with the addition of conventional reactors installed in series with the cables.

That this application is generally attractive as an alternative to improving reliability and resiliency in urban areas via conventional means, such as additional transmission circuits and/or new or expanded substations, which are extremely costly, difficult to permit and disruptive and time consuming to construct.

2) Branch Applications for Capacity Increases

HTS cables can also be applied to increase capacity at existing substations or serve as the primary source to new substations. Common configurations in this scenario involve distribution voltage HTS cables effectively replacing transmission voltage conventional cables as the means to move bulk power to the new or expanded substation, which eliminates the need for new transformation (and any transmission voltage equipment) at that substation.

This approach requires sufficient transformation at the substation(s) that serves as the source to the new or expanded substation and may require the installation of additional transformers. This application is generally considered if 1) the new/expanded substation is space constrained, and/or 2) the cable route (ROW) between the source substation and the new/expanded substation is space constrained or otherwise is not well suited for transmission voltage cables (for permitting, safety, or constructability, or other reasons). It is helpful to think of this application as creating “flexibility” in the location of new transformation (i.e. new transformers can be located where there is sufficient space) with the HTS cables serving the function of an extend “bus” to the load substation. Consider the application in the figure below:

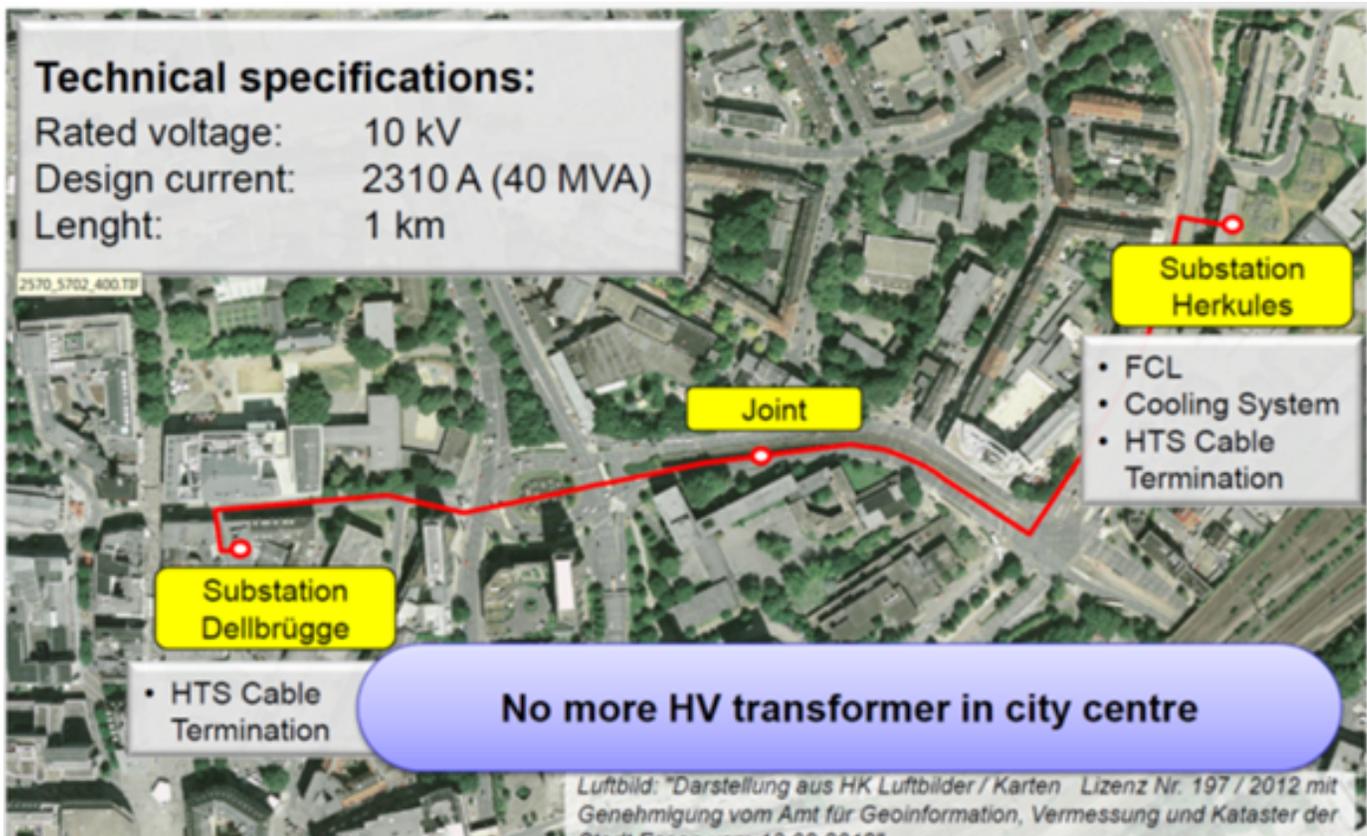


Image credit: Nexans S.A.

The application of an HTS cable described in the figure above (Ampacity project, Essen, Germany, commissioned in 2014) shows a scenario where increased capacity is desired at the urban Substation Dellbrugge, with that capacity to be served from the suburban Substation Herkules. The conventional solution would have been to run a 110kV transmission cable from Herkules to Dellbrugge and install a new transformer at Dellbrugge. However, Dellbrugge is severely space constrained and the addition of a new transformer would be prohibitively costly.

The HTS cable (10kV, 2310A, 40MVA) instead allows the new transformer to be installed at Herkules (which is not space constrained) and brings the new power to Dellbrugge at the local

distribution voltage (10kV), removing the need to install large equipment at Dellbrugge and simplifying the permitting and cost of the new cable ROW.

3) HPFF Cable Backup/Replacement for System Modernization

HTS cables can be applied to assist in the transition away from High Pressure Fluid Filled (HPFF or “Pipe-Type” cables). HPFF cables technology is rapidly becoming obsolete in the utility industry primarily due to the potential environmental hazards they create (oil spills) and a single manufacturer of such cables remains active. Many utilities that currently have HPFF cables deployed on their systems are in the process of developing strategies to eventually decommission and remove these cables from service.

This effort presents challenges because HPFF cables are relatively current dense and replacing the cables with conventional XPLE cables without either 1) reducing ampacity or 2) substantial civil works can be challenging. Furthermore, HPFF cables represent a critical and substantial part of many urban transmission networks, and the time required to replace the cables create extended duration contingency scenarios that can threaten the reliability of the system.

HTS cables can be applied in these projects in two possible ways. One application is to directly replace the HPFF cables with HTS cables using the existing HPFF pipes. Because HTS cables have an even higher current density than HPFF cables, this approach may increase the ampacity of the circuit. However, this approach does not eliminate the risk to the system during the time it takes to replace the HPFF cables with the HTS cables, as well as the risk of the HTS cables to physically fit within the existing pipes.

Another application is to install distribution voltage HTS cables in parallel with the existing transmission voltage HPFF cables. This approach allows the HTS cables to act as a distribution voltage (but equivalent power level) “back-up” to the existing cable, similar to the “Loop Application” discussed earlier. This approach does require the civil construction of new cable ducts and possibly new Right-of-Way (RoW) for the HTS cables. However, this approach allows for construction and installation to occur without taking the HPFF cables out of service, allows for the continued utilization of the HPFF cables, allows for a deliberate transition from HPFF cables to the HTS cables, and preserves the HPFF cable pipes for alternative uses such as XLPE cable replacement without significant civil works (albeit with a lower ampacity than the original HPFF cables). Furthermore, it is very likely that such an HTS cable approach would be lower cost and less disruptive than full scale replacement of the HPFF cables with larger cable ducts to allow for similar or higher ampacity XLPE cables.

Modeling HTS Cables in Power System Simulation Software

As discussed earlier, the key consideration with the modeling of HTS cables is capturing the change in impedance of the cable during fault conditions (i.e. the Fault Current Limiting feature). This characteristic is a fundamental difference between HTS cables and conventional copper or aluminum cables. The mechanics/physics that are the cause of change of impedance of HTS cables are outside the scope of this document, but the following items should be noted:

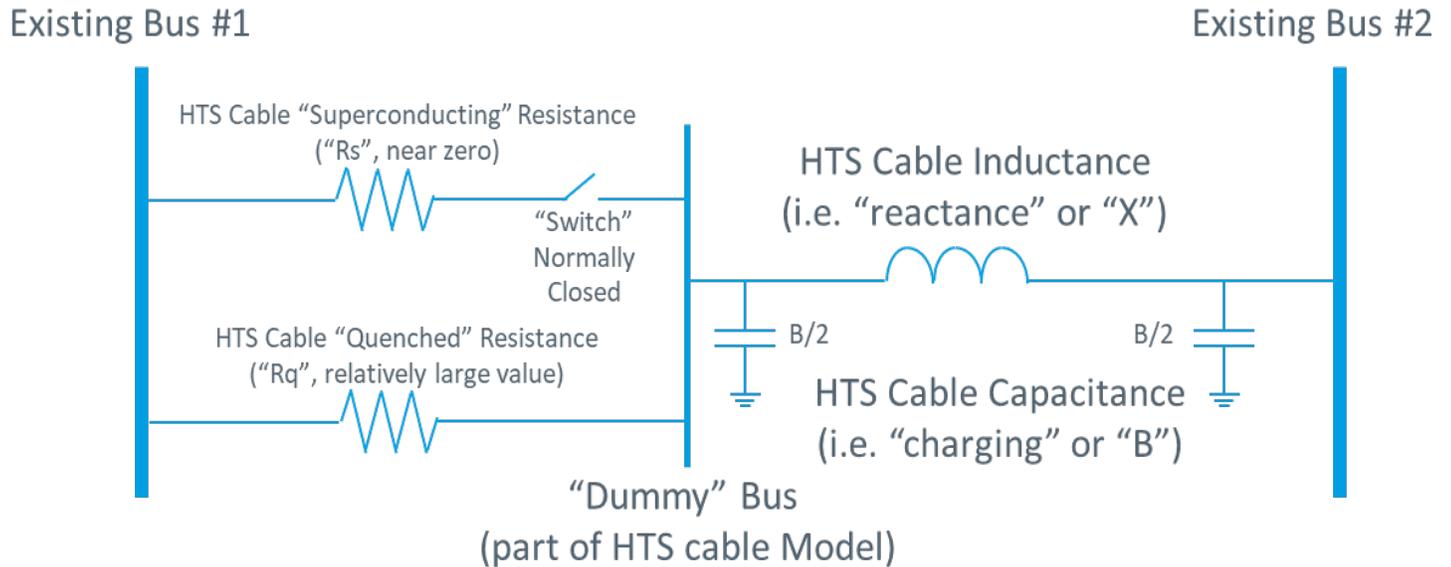
- 1) The impedance of the HTS cables is unchanging as long as the current through the cable is below the rated current of the cable (e.g. 3000A).**
 - a. For load-flow simulation work that does not consider fault conditions, the impedance changing characteristic of the cable can be ignored, which significantly simplifies the cable model.**

- 2) For the purposes of phase-domain simulations (i.e. PSS/e, PSLF, PowerWorld, Cyme, etc.) the change of impedance of the HTS cables is effectively instantaneous upon the current in the cable exceeding the rating of the cable (i.e. upon fault initiation), and returns to the original value instantaneously upon fault clearing, assuming normal primary or backup fault clearing.**
 - a. There is no time delay between fault initialization/clearing and the impedance change; both events should occur in the same time step.**

- 3) In the event that a system fault is causing fault current to flow through the HTS cable for longer than normal backup clearing durations (i.e. simulation of events more severe than typical breaker failure events), the cable will trip offline.**

- 4) The modelling techniques discussed below are NOT appropriate for detailed, time-domain simulations, such as PSCAD or time-domain DigSILENT simulations, if accuracy in RMS current flow and wave forms through the cables are critical to the simulation results during and shortly (1 cycle) after fault events.**

The figure below describes the model of an HTS cable, subject to the comments above:



The model described above shows that the cable is modelled with single, unchanging values for Inductance (reactance) and Capacitance (charging), but with two parallel branches for resistance. The resistance branches are 1) the near zero "superconducting resistance" (R_s) and 2) the relatively large "Quenched Resistance" (R_q).

The model is operated by having all components "in-service" during the normal case. During this scenario, the value of R_s is much lower than R_q causing near zero current flowing through R_q , resulting in a near zero-resistance circuit (but still featuring Inductance and Capacitance).

When a fault is placed on the system, the switch in the R_s branch is opened (i.e. taken out of service or changing the resistance to an extremely high value), forcing all current through R_q , effectively representing the cable resistance when "quenched" or non-superconducting.

When the fault is cleared from the system, the switch in the R_s branch is re-closed (i.e. placed in-service or changing the resistance to the original near-zero value), returning the circuit to the original, pre-fault resistance.

The Inductance and Capacitance of the cable should be modelled using the typical circuit modelling approach available in the modelling package being used, except with zero resistance. For most packages, the capacitance is split into two halves, with each half located on either end of the circuit as shown above (" $B/2$ "). Other generally accepted approaches to modeling capacitance are acceptable.

To determine the actual value of the parameters (R_s , R_q , X & B), it should be noted that there are two primary configurations of HTS cables: Cables that are 36kV and below use a “tri-axial” configuration, whereas cables of 69kV and above use a more conventional “one cable per phase” configuration. The configuration impacts the inductance and capacitance values, but does not impact the resistance values (R_s or R_q).

The table below provides typical values for the cable parameters in ohms, mH, and uF per kilometer:

HTS Cable Parameter	Value	Unit
X (\leq 36kV)	0.049	mH/km
X (\geq 69kV)	0.06	mH/km
R superconducting	0.0001	ohm / km
R quenched	0.724	ohm / km
C (\leq 36kV)	1.1	uF/km
C (\geq 69kV)	0.2	uF/km

Multiply values above by 1.609 for values per mile

For reference, the table below converts the parameters to units commonly used in PSS/e (p.u. on 100 MVA base), for various base voltage levels.

Voltage (kV L-L)	PSS/e Inputs, <i>per km</i>					
	p.u. X on 100 MVA Base	p.u. R on 100 MVA Base		Charging Current (A)	kVAR of Charging	p.u. B on 100 MVA base
		R superconducting	R quenched			
12.47	0.01188	6.43E-05	0.466	2.99	21.5	0.000215
13.8	0.00970	5.25E-05	0.380	3.30	26.3	0.000263
26	0.00273	1.48E-05	0.107	6.22	93.4	0.000934
34.5	0.00155	8.40E-06	0.0608	8.26	165	0.00165
69	0.000475	2.10E-06	0.0152	3.00	120	0.00120
115	0.000171	7.56E-07	0.00547	5.01	332	0.00332
138	0.000119	5.25E-07	0.00380	6.01	479	0.00479
161	0.0000873	3.86E-07	0.00279	7.01	651	0.00651
230	0.0000428	1.89E-07	0.00137	10.0	1330	0.0133
345	0.0000190	8.40E-08	0.000608	15.0	2991	0.0299

Multiply values above by 1.609 for values per mile

The values above are typical and representative for 3000A cables. The R_q value, in particular, may vary significantly and can be specified to a point.

Please contact AMSC for details and any further questions.

QUESTIONS?

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