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Multiplex Superconducting Transmission Line for green power consolidation on a Smart Grid

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Abstract. A multiplex superconducting transmission line (MSTL) is being developed for applications requiring interconnection of multi-MW electric power generation among a number of locations. MSTL consists of a cluster of many 2- or 3-conductor transmission lines within a coaxial cryostat envelope. Each line operates autonomously, so that the interconnection of multiple power loads can be done in a failure-tolerant network. Specifics of the electrical, mechanical, and cryogenic design are presented. The consolidation of transformation and conditioning and the failure-tolerant interconnects have the potential to offer important benefit for the green energy components of a Smart Grid.

1. Introduction

Superconducting transmission lines for utility-scale power transmission were first proposed 50 years ago, and a number of short-length operating units have been installed and operated successfully (Figure 1) [1]. Most firms who developed prototypes in the first several generations of effort have since left the field, but a number of new designs have emerged recently in response to growing interest in >GW capacity DC or AC interconnects among transmission grids [2]. All such designs seek to optimize a configuration to carry >GW electric power in a single 2- or 3-phase circuit.

We propose a very different transmission line which would contain many discrete superconducting transmission lines, each with ~10 MW capacity, with total >GW capacity. Green power generation configure most effectively in 10 MW – 100 MW units. For solar power, a typical concentrated solar power unit has capacity ~20-100 MW. For wind power, present wind turbines have capacity 5-10 MW.

The geographic regions where each green energy resource is most abundant are being developed for large-capacity wind farms and concentrated solar power (CSP) systems in many countries. A significant challenge is to match the unit size of generation to the most cost-effective equipment for matching the electrical characteristics of the generated power (typically low-impedance) to the high-impedance required to deliver the power onto long-distance transmission lines. The interconnection within a wind farm or a network of CSP units is potentially a significant part of the cost and reliability [3]. The Multiplexed Superconducting Transmission Line (MSTL) offers a novel method to efficiently transmit the power from many generating units to a common location where the power is conditioned and connected to the grid. That is the motivation of the present work.

An example embodiment of the MSTL is shown in Figure 2. It contains 48 individual transmission lines, bundled within a common coaxial cryostat. The bundle is structured so that each individual
transmission line can be extracted at one location along the >km length of the bundle and interfaced through a high-temperature-superconductor (HTS) lead assembly so that it can be connected to the output of one green power generating unit. In this way, the multiplex superconducting transmission line (MSTL) offers a cost-effective means to efficiently collect the power generation from a network of many green power units spread over a large geographical area so that it can be cost-effectively conditioned and delivered to a transmission line at one favorable location.

2. Multiplex Superconducting Transmission Line

The Multiplex Superconducting Transmission Line (MSTL) is an ordered cluster of 2- or 3-conductor transmission lines (TLs), cabled with a twist pitch around a central insulated return-flow line as shown in Figure 3b. Each TL is designed to operate with 10 kV and 2 kA. The TL could operate with either AC or DC; an AC choice would carry additional implications about filament size and optimizing the wire matrix for AC losses.

Figure 2 shows the cross section of an example MSTL design containing 48 3-phase transmission lines housed within a coaxial cryostat. Table 1 summarizes its main parameters. Each TL contains three insulated, heavily stabilized NbTi/Cu wires, pulled into a perforated sheath tube in a die-guide process that feeds a flow of spherical ceramic beads which fill the spaces among the wires, as shown in Figure 3a. The die-guide is rotated as the wire pattern is drawn into the sheath to produce a twist-pitch pattern of wires with a constant symmetric pattern within the sheath cross section.

The purpose of the twist-pitch is to accommodate large-radius bending of the fabricated TL. It is essential that it be possible to bend each TL, and the complete MSTL, so that it can be spooled on a <6 m spool for transport and installed along a non-straight alignment if necessary in an application site. So long as the bend radius of the TL is a multiple of the twist pitch of the spiralling of the conductors within the TL, each wire will spend as much length on the inside of the twist axis as it does on the outside, so that the total length of all wires remains the same when the TL is straight and when it is bent.
Likewise, so long as the bend radius of the MSTL is a multiple of the twist pitch of the spiralling of the TLs within the MSTL (shown in Figure 3c), each TL will spend as much length on the inside of the MSTL axis as it does on the outside, so that the total length of all TLs remains the same when the MSTL is straight and when it is bent. Figure 3b shows a cross-section of one TL, containing three Cu-stabilized NbTi/Cu wires. Each wire has two round ~1 mm diameter NbTi/Cu wires, bonded into grooves on opposite sides of a 4 mm diameter OFHC Cu round wire. The wire is fabricated with a twist pitch so that induced emfs transpose locally within each wire, and within the TL cable. Each wire is coated with Formvar insulation.

The MSTL is designed to operate with supercritical helium (SCHe) so that, under the range of operating conditions for the cable, the helium is always single-phase and there can be no bubbles formed within the interior of the TLs. This is important because the high-voltage isolation among the wires inside the TL relies upon the dielectric strength of liquid helium. The ceramic beads in the TL interior serve two purposes: they stabilize the positions of the three wires within the transmission line so that it can be bent without changing the internal geometry; and they enhance the high-breakdown electrical insulation within the cable. The dielectric spheres suppress the electric field in the liquid helium surrounding them by a factor two, as shown in the simulation of Figure 3d, as discussed below.

2.1. Cryogenic design

The MSTL is structured as a low-loss pipeline cryostat, shown in Figure 2. Within it the assembly of 48 transmission lines is contained in the MSTL sheath tube, a ~50 K intermediate heat shield is cooled by return vapor flow, and a room-temperature outer tube provides the vacuum enclosure. The sheaths of all 48 transmission lines are perforated with 0.5 mm diameter holes to provide free flow of...
SCHe between the interstice space of the MSTL cryostat (green in Figure 2) and the interior of each transmission line.

ATC has developed a cost-effective method for manufacture of the perforated tubes: the holes are die-punched into SS foil strip in a reel-reel process, then the perforated strip is formed into tube and laser-welded at the seam.

The MSTL is designed to accommodate connection points along its length where one transmission line is extracted from the bundle and connected through HTS leads to a power source. The connection access is provided during fabrication of the MSTL as a tee junction, shown in Figure 4. The tee junction is an important design element of the MSTL: it contains the 3 HTS leads, a Joule-Thompson (J-T) expansion valve, and instrumentation to monitor conditions within the MSTL in that region. A fraction of the SCHe is passed through the J-T valve where it is expanded to 2-phase liquid. The expanded liquid is injected to the 2-phase return line in the center of the MSTL cryostat (blue in Figure 2). A flow of liquid nitrogen (LN2) runs along a tube that is bonded to the 50 K heat shield. It also provides a 50 K heat intercept on each HTS lead. The J-T expansion at each HTS lead location removes that heat where it is produced, so that the overall MSTL should sustain ~constant cryogenic conditions along its entire length.

The thermodynamics of this distributed line is remarkably similar to the design analyzed by Morgan and Jensen [4] for a superconducting transmission line. A similar operating point was optimized for SCHe flow in a ~1.1 km-long cable-in-conduit (CIC) conductor for the superconducting magnet in the GEM experiment that was proposed for construction at the SSC [5]. In Ref. 4 the dependences of temperature increase vs. pressure drop, available enthalpy vs. pressure, mass flow rate vs. pressure, and heat load vs. pressure are calculated. From those dependencies it is shown that, in the 1.1 km long CIC for the GEM magnet, a mass flow of 1.3 g/s with inlet pressure 5.4 bar is sufficient to maintain a temperature of 6 K in the CIC with a total distributed cooling capacity 23 W.

The heat load of the MSTL for refrigeration at 5 K arises from two sources: the heat load $Q_{\text{load}}$ associated with the 3 HTS current leads through which a TL is connected at a succession of 48 locations along the overall length; and the heat load $Q_{\text{line}}$ in the MSTL cryostat from the sheath of 48 Tls to the LN2 shield and to ambient temperature.

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**Table 1. Major parameters of the MSTL**

| NbTi/Cu wire:               |       |
|----------------------------|-------|
| Diameter                   | 2 mm  |
| Insulation                 | 25 mm Formvar |
| # Filaments                | 500   |
| Cu:SC                      | 25    |

| Transmission line:         |       |
|----------------------------|-------|
| Sheath OD                  | 21 mm |
| # Wires                    | 3     |
| Gap between wires          | 5 mm  |
| Gap from wire to sheath    | 5 mm  |
| Insulation filling         | 0.6 mm Al2O3 balls |

| Multiplex Transmission Line|       |
|----------------------------|-------|
| Overall diameter           | 25 cm |
| Cold mass diameter         | 17 cm |
| # Transmission lines       | 48    |

**Figure 4. Tee junction at which one transmission line is extracted from the MSTL and coupled through HTS leads to an external power source.**
Ballarino [6] reported the development and characterization of optimized HTS leads for the power buses at LHC. For D.C. current conditions the minimum required mass flow of 2-phase liquid helium is .045 g/s per kA of lead capacity. The transmission lines in the example MSTL are designed for 10 kV, 2 kA operation. Thus, the minimum mass flow required to cool the 3 leads at each tee is (.045 g/s/kA/lead)(2 kA)(3 leads/TL) = .27 g/s. The flow provisions in the MSTL should therefore be sufficient to provide cooling for the 48 tees distributed along a multi-km line, connected to one refrigerator at one end location. The total required SCHe flow to refrigerate $Q_{lead}$ over the 2 km length of the MSCL is then $M_{lead} = (48$ tees$)(0.27$ g/s/tee$) = 13$ g/s.

The heat load $Q_{line}$ per surface area from the 50K thermal shield to the cold mass can be estimated using measurements from LHC commissioning [6]. The heat load per unit area is $Q_{line}/A = 0.084$ W/m². The diameter of the 48-cable, 2 km MSTL cold mass is 17 cm, so $Q_{line} = 90$ W. The J-T expansion removes the heat of vaporization, $H_v = 10$ J/g as SCHe is expanded to 2-phase liquid at 5 K [7]. The mass flow required to refrigerate the line heat is $M_{line} = Q_{line}/H_v = 9$ g/s.

The total cryogenic heat load for the 2 km MSTL is 22 g/s ~16,000 liters/day. This is about twice the capacity of one L280 commercial liquefier manufactured by Linde [8].

2.2. Electrical design

The example MSTL is designed to operate with 2 kA current in each wire and 10 kV maximum voltage between wires and from wire to sheath. The critical current density $J_c$ in superconducting NbTi filaments is 6.2 kA/mm² at 4.2 K, and 1.2 kA/mm² at 8 K [9]. Each wire thus requires a minimum cross-sectional area of superconductor $A_{SC} = 1.7$ mm² in each wire.

2.2.1 Quench protection

Referring to Fig. 10 of Ref. 7, the sustainable heat transfer with $\Delta T = 2$ K is $q_{trans} = 0.1$ W/cm². In order to protect the cable during quench, we will require sufficient heat transfer at the wire surface to limit to $\Delta T < 2$ K. There must be sufficient stabilizing Cu in the composite wire that the heat dissipated at the rated current in a normal region respects that condition. The resistive loss in a length $L$ of normal-state wire of radius $r$ is $Q_n = \rho_{Cu} L J^2$, where $\rho_{Cu} = 0.132$ nΩm is the Cu matrix electrical resistivity at 5 K and $k_{Cu} = 1$ JK⁻¹m⁻¹ is the thermal conductivity at 4.2-15 K.

Ref. 5 reports that a SCHe flow of 1.3 g/s can sustain 23 W of distributed load with peak temperature $< 6$ K. We use this requirement to choose the ratio $r^2/L > 7.3\mu$m.

We must now account for where the heat from the normal region goes. One part is transferred to the SCHe at the surface of the wire: $Q_{surf} = q_{trans} 2\pi r L$. Another part conducts from the two ends of the normal segment of wire to the neighboring superconducting regions: $Q_{cond} = 2\kappa_{Cu} \frac{T_g - T_s}{r}$. Solving for the choice of $L$ and $r$ that limit the temperature rise to $T_g - T_s = 0.6$ K: $L = 80$ cm, $r = 2.5$ mm, $A_{Cu}/A_{SC} = 30$. We have simulated quench propagation in the TL wire; the quench velocity is $v_q \sim 40$ m/s. Thus, a quench remains essentially quiescent, producing a voltage spike but very little temperature increase for a time $t = L/2v_q \sim 10$ ms. In event that a quench is detected contactors can be used to open the circuit for a given TL for a brief time with a response time of a few AC cycles. The quench would then recover in a short time and service could be restored on that line, all without disturbing the service of the other 47 TLs.

The conductor is designed as a channel conductor (Figure 3b) with two NbTi/Cu wires bonded into symmetric channels on opposite sides of a 4 mm diameter solid OFHC wire, then drawn smooth on its surface. The composite conductor is insulated either with a Formvar coating or by epoxy-bonded polyester.

2.2.2 Dielectric breakdown stability

The breakdown electric field in helium is 55 MV/m [10] in SCHe. The threshold for corona onset in He vapor at 4 K is $\sim 10$ kV [11]. This important difference motivates the choice of (single-phase) supercritical He for the MSTL cryogenics. A potential difference $\Delta V = 20$ kV across the spacing $g = 5$ mm of round wires would produce an electric field $E_g =$
$\Delta V_{\text{rms}}$ = 8 MV/m at the wire surface. The ceramic bead filling further reduces the electric field in the SCHe by a factor of 2, as shown in the surface electric field distribution shown in Figure 3d. Thus, the TL should be stable against dielectric breakdown within its operating parameters.

3. Applications of the MSTL to green power distribution

Figure 5 shows two example configurations for interconnecting a network of green power generators using a MSTL. In Figure 5a, wind turbines are connected within a wind farm. In Figure 5b, a regional cluster of CSP arrays is interconnected. One or more TLs can be brought out at each tee, so that any distribution of generating units can be accommodated.

The SCHe refrigerator and power conditioning systems are shown at a common location at one point along the MSTL. The overall line length and spacings between tees can be placed according to the requirements of a given application. The MSTL could be fabricated in lengths up to ~1 km, and two segments could be spliced to make an overall 2 km line.

The centralization makes it possible to optimize the performance/cost for combining, conditioning and transforming ~GW power and connecting it to a grid transmission line. In effect, the MSTL consolidates distributed green power generation so that it can be treated much like a GW power plant for conditioning and injection to the Smart Grid.

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