Fault Management of a Cold Dielectric HTS Power Transmission Cable

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Abstract. High temperature superconductor (HTS) power transmission cables offer significant advantages in power density over conventional copper-based cables. As with conventional cables, HTS cables must be safe and reliable when abnormal conditions, such as local and through faults, occur in the power grid. Due to the unique characteristics of HTS power cables, the fault management of an HTS cable is different from that of a conventional cable. Issues, such as nitrogen bubble formation within lapped dielectric material, need to be addressed. This paper reviews the efforts that have been performed to study the fault conditions of a cold dielectric HTS power cable. As a result of the efforts, a fault management scheme has been developed, which provides both local and through faults system protection. Details of the fault management scheme with examples are presented.

1. Introduction
HTS cable has long been considered an enabling technology for power transmission. Power cables using HTS wires have been developed to increase the power capacity in utility power networks while maintaining a relatively small footprint. However, not only must the cable be reliable during normal operating, it must also be safe when extreme conditions occur, such as fault conditions, which can affect how power is distributed throughout the network. Due to the unique characteristics of HTS power cables, the fault management of an HTS cable is different from that of a conventional cable. First, cold dielectric HTS power cable requires that the cooling fluid, which participates in the electrical insulation by impregnating the lapped dielectric material, remain in a sub-cooled state during a major fault or multiple through faults. This is necessary to maintain the dielectric strength between the high voltage cable core and the shield, which is at ground potential. Any bubble formation inside dielectric will threaten the dielectric properties of the insulation system. Second, the cable must be taken off line following major faults in order to allow enough time for the HTS conductors to be cooled back down to the operating temperature range. Therefore, it is important to study the cable thermal and electrical behaviors under fault conditions in order to provide the proper system protection.

This paper reviews the efforts that have been made to study the fault condition of a cold dielectric HTS power cable, which is approximately 620 meter long and is designed for permanent installation in the Long Island Power Authority (LIPA) grid [1]. Descriptions of the fault management scheme are provided. A few fault examples are also included.
2. Cable Configuration
The cable used in the LIPA project is a cold dielectric design. The cable system contains three individual HTS cables and six terminations. The cable configuration consists of a copper former, two HTS conductor layers, an insulation layer, an HTS screen layer, a copper screen stabilizer and a cryogenic envelope. The LIPA cable has an operating voltage/current of 138 kV/2400A, respectively. Fig.1 shows a schematic of cable cross section. During the normal operation, the cable core is maintained at operating temperature by circulating sub-cooled liquid nitrogen.

3. Fault Management
As with conventional cables, HTS cables must be safe and reliable when abnormal conditions, such as local and through faults, occur in the power grid. Typically, the through faults are those that are generated at other locations but affect the power flow on the superconductor cable, while the local faults are those which happen directly on superconductor cable or related peripherals and in general require repairs, maintenance or replacement of equipment by utility operating personnel [2]. During a local fault, a large current many times greater than the rated current of the cable is created for a brief period of time until the breakers can be opened. As a result, a tremendous amount of energy is dissipated into the cable core in a relatively short time. This dissipated energy drives not only cable system design but also cooling system design. In the following paragraphs, first a general fault management scheme is presented and follows by two fault examples in greater details. Finally, the cable and refrigeration system reactions to a major fault (69kA, 200ms) are examined.

3.1. Fault Protection Scheme
To provide proper system protection, it is necessary to have a general fault protection scheme that can be used to handle both local faults and through faults. For an HTS power cable, the key of the protection scheme is the determination as to whether to disconnect the HTS cable from the utility power grid and for how long. For a major fault (69kA for current cable project), it is straightforward decision. However, for a low level through fault or a series of low level through faults, the determination becomes complicated. For example, a low level through fault or a series of low level through faults, which itself is not enough to damage the cable, but it may have raised the HTS cable core temperature to a certain level at which the cable can not withstand a major fault. A determination must be made in this case to disconnect the HTS cable from the power grid since if there is a major fault right after the low level through faults, the HTS cable could face permanent damage. However, it is also possible that the low level through faults occur over a long enough period of time such that there is no accumulative effects of each fault due to recooling effect. The HTS cable in this case can remain on line as long as the HTS cable core temperature is below the predetermined level. The methodology used in the current protection scheme is to observe the accumulative effect of each fault and to check if the cable still has the capability to withstand a major fault. Once the HTS cable core
temperature reaches a certain level due to accumulative effects, the HTS cable must be taken off line for a certain time period to be allowed to recool back to a predetermined temperature.

The protection scheme for the current cable project is illustrated in Fig.2, where \( E \) is the energy stored in HTS cable core due to faults; \( I_j \) is the fault current of fault \( j \); \( t_{d,j} \) is the time duration of fault \( j \); \( f(I_j, t_{d,j}) \) is the function to calculate energy dissipated into HTS cable core due to fault \( j \); \( I_{\text{off line}} \) is the single off-line current at which the cable must be taken off line; \( t_{\text{critical}} \) is the time period during which the effect of the previous fault is entirely diminished and \( E_{\text{margin}} \) is the pre-determined threshold at which the cable must be taken off line. The Cable Off Line table shows how long the cable must be taken off line for a specific fault current \( I_j \) when the fault current is larger than single off-line current \( I_{\text{off line}} \). The off-line time is a function of refrigeration power and coolant flow rate. Even though, the scheme is designed for the current cable project, it could be used for the other cold dielectric cable design. To best demonstrate the protection scheme, two examples are provided as follows.

3.2. Fault Management Examples

To better understand the fault management scheme, two fault examples are examined utilizing flow diagram shown in Fig.2. The first fault protection example, Fig.3a shows the fault current levels of three successive fault current events as a function of time and the corresponding temperature of superconductor layer within HTS cable as a function of time. In this first example, the particular combination of fault current events was not sufficient to cause the fault management system to remove HTS cable from the transmission line. This means even if there is a major 69kA fault just after a 4kA fault, the cable will not be damaged.

In a second fault protection example, unlike the example shown in Fig.3a, the fault management system sends control signals to circuit breakers to disconnect HTS cable from transmission line. If the cable remains on line, a major fault of 69 kA just after 3 kA fault could possibly cause damage to the cable.

![Figure 3. Examples of fault management](image)

4. Major Fault

The cable reaction to a major fault is the rapid temperature rise of the HTS layer. Since faults usually occur in a very short time frame (~200 ms), an adiabatic model is utilized to predict the temperature rise of each layer during a fault. Fig.4 illustrates the temperature rise of the two HTS layers during a 69kA fault. The transient thermal modeling indicates that the highest conductor temperature is lower than the saturated temperature of pressurized liquid nitrogen, which means that bubbles can not be formed inside the cable core during a fault duration of 200 ms.

During the major fault condition, a large amount of energy is deposited into the cable core creating an instant temperature increase of the cable core and the coolant. With this increase in temperature, the liquid nitrogen will expand because the density of the nitrogen is dependent upon the temperature. A buffer system must be installed in the cooling system to provide a mechanism by which the volume change of the liquid nitrogen in the cable can be either relieved or compensated. To determine the size of the buffer volume, a simulation has been carried out to investigate the mass flow.
into the buffer volume and the buffer pressure change as function of time. The pressure change inside
the buffer is illustrated in Fig.5 with a buffer volume of 800 L, where uniform mixing between flow-in
liquid nitrogen and liquid nitrogen inside the buffer is assumed. As seen in Fig.5, the buffer pressure
collapses during the first a few seconds due to the introduction of sub-cooled liquid nitrogen (the
buffer normally operates with saturated nitrogen). The bubble temperature drop due to the pressure
collapse requires the addition of fast grounding switches to avoid damaging the dielectric insulation.

The stored energy inside the cable due to the fault has to be extracted from the system before the
cable can be re-energized. With the refrigeration power designed for the normal operating mode, the
time duration to cool the cable back down to the normal operating mode has been predicted. An
estimated 7 hours is required using the available refrigeration power of 5 kW. The cool down time
can be reduced to about 4 hours if an additional 2kW of refrigeration power is added to the system.

5. Conclusion
A general fault management scheme for a cold dielectric HTS cable has been presented. The scheme
can be used to handle both local and through faults. The thermal calculation of fault conditions
demonstrated that the model is useful to provide information for the cable and cooling system design.

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Reference
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