Active Damping for Electromagnetic Transients in Superconducting Systems

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Abstract—The use of superconductors for power transmission has been studied for decades. The lossless nature of the superconducting cables makes the system less stable operationally since the damping normally provided by resistive losses is eliminated. Breaker actions during routine system operations or in response to faults can trigger high frequency oscillations between the inductances and capacitances in the system. These capacitances are either power factor correction capacitors or parasitic phase-to-phase or phase-to-ground capacitances in the lines or cables. The resulting transients are referred to as electromagnetic transients and can often see 100% or greater over-voltages. In a system using conventional conductors, the series resistance will damp these oscillations within a number of 60 Hz cycles. In a superconducting system, these oscillations will persist, with only the light damping from the frequency dependent resistance of the superconductors, creating a long-lasting distortion on voltage and current. Many of the traditional methods to damp transient oscillations can be used but they won’t cover every situation effectively. Power electronic converters could also be used to damp these oscillations. Either a shunt- or a series-connected converter could be used. However, the series-connected converter would need to carry the full line current at all times, but a shunt-connected converter need be used to damp oscillations only when they occur. Key issues are rating the converter and reducing energy losses.

I. INTRODUCTION

The discovery of high temperature superconductivity [1] sparked renewed interest in its application to the power area. One such application, low voltage power transmission, could have a significant impact on the layout of power grids in the future. A superconducting power system would operate at optimum generator voltages, resulting in a single voltage level from generation to distribution subsystems. There would no longer be a need to step up to high voltage levels for long distance transmission because IR losses would have been eliminated from the lines. Low voltage operation eliminates the need for high voltage insulation and large transformers [2,3]. A superconducting power system could have either ac or dc transmission and distribution. Both have their advantages and disadvantages.

Implementing a system using direct current transmission eliminates losses resulting from eddy currents in the metal matrix surrounding the superconductor [4]. There will be significant added costs up front for converters and a further penalty for converter losses. However, this is offset by the enhanced ability to control system operation. Such a system is referred to as a low voltage direct current (LVdc) transmission system.

The lossless nature of the superconducting cables creates new problems because eliminating losses also eliminates the damping normally provided by resistive elements. Breaker actions during routine system operations or in response to faults can trigger high frequency oscillations between the line and transformer inductances and capacitances from power factor correction capacitors or parasitic phase-to-phase or phase-to-ground capacitances in the cables. The resulting transients are referred to as electromagnetic transients and can often see 100% or greater over-voltages. In a system using conventional conductors, the series resistance will damp these oscillations within a few 60 Hz cycles. In a superconducting system, these oscillations will persist, with only the light damping from the frequency dependent resistance of the superconductors, creating a long-lasting distortion on voltage and current. Loads will also provide some damping to these oscillations but oscillations on the transmission system will persist. Many of the traditional methods to damp transient oscillations can be used but they won’t cover every situation effectively. Power electronic converters could also be used to damp these oscillations. This paper will explore these options for ac and dc systems.

II. TRANSMISSION SYSTEMS

A. AC Power Systems

AC power systems tend to be connected in a meshed network, having parallel current paths between most system buses. Power is usually generated at 12kV to 24kV by synchronous generators. The voltage is then stepped up to higher levels by transformers for long distance transmission, typically in the 132kV to 500kV range. The voltage is stepped down again for distribution to local loads in a distribution system branching out from the transformer substation. Distribution voltages often range from 13.2kV to 69kV.

Early superconducting systems will probably operate at these same levels. Superconducting cables will probably initially replace existing lines to increase the current capability of a given corridor. Eventually, the step up to higher transmission voltage levels may be eliminated.

B. DC Transmission Options

Direct current transmission sees limited use at present. It is mainly used to connect asynchronous systems or for high capacity point-to-point transmission over long distances in the form of HVdc transmission systems. These point-to-point lines are typically 300 or more miles long. Most existing systems are two-terminal point-to-point systems due to control limitations that are partly tied to the use...
of line-commutated current source converters. However, voltage source inverter (VSI) based HVdc systems are becoming available, these systems have fewer limitations in system control. Advantages of dc transmission must be balanced against an additional cost for power conversion and the potential complexity of multiterminal systems. Superconducting dc systems also have the same advantage as superconducting ac systems in that neither needs to have the current stepped down to low levels (and the voltage consequently stepped up to high levels) to reduce the IR losses. However, converter performance may be better with higher voltage and lower current levels [4].

Initial application of superconducting low voltage dc (LVdc) systems will probably begin with point-to-point dc systems, such as a high-capacity link into a transmission-limited urban area. The low voltage level allows for simple modular converters at a number of taps. The voltage level may be on the order of 10 kV, eliminating the need for series connection of devices within converters. Simple six-pulse modules could be connected in parallel to achieve a desired current rating. This suggests a system with a large number of “off-the-shelf” mass-produced converter modules. A typical LVdc transmission system could consist of numerous rectifiers feeding hundreds of inverter terminals [4].

III. UNDAMPED OSCILLATIONS FROM TRANSIENTS

Both ac and dc systems are subject to electromagnetic transients. These transients normally result from resonances between capacitances and inductances triggered by sudden changes in operating state on the system [5,6]. These can be resonances dominated by a single frequency, a few frequencies, or a broad spectrum of frequencies, in the case of a transmission line. These frequencies can range from a few Hertz to hundreds of kiloHertz, or even a few MegaHertz for lightning transients.

Slower transients result from sudden changes in load, such as a steep increase in load, load rejection, or inrush currents from motor starting. Motor starting causes the most difficulty with ac systems. However, dc systems, especially multiterminal voltage source inverter based systems, will have more problems with changes in load. If the load at inverter one in the system of Fig. 1 experiences an abrupt increase in load, the initial current will be supplied by the dc bus capacitor on the inverter. The other two inverters are closer electrically to inverter 1 and will supply current to inverter 1 before the rectifiers, dropping the voltage at their capacitors slightly. This triggers a slow resonant oscillation between the inverters, as shown in Fig. 2. Because the lines within have no resistance, there will be no damping of this slow oscillation.

Relatively slow oscillations also arise from electromechanical transients resulting from opening and reclosing faulted lines. When circuit breakers open a faulted line, there is a decrease in the ability to transfer real power from the generators. The generators are unable to respond quickly to this decrease and continue to generate the same total power. The excess power is converted to kinetic energy in the rotor, resulting in an increase in rotor speed.

When the circuit breakers reclose, the system will oscillate as it settles back into a steady-state condition. This is a very lightly damped oscillation in a system with normal conductors because the generator has almost zero damping. In fact, the generator has negative damping at the rotor mechanical resonant frequencies. Superconducting transmission systems have no line resistance. Therefore, they are quite difficult to damp. For a more complete discussion, see [7].

![Fig. 1: Four terminal superconducting LVdc system with VSI's.](image)

The transients from changes in power demand or motor starting tend to cause relatively small oscillations in voltage on the system. More significant transients can arise from routine capacitor and line switching operations. When a transmission line is first energized there will be an inrush current as the electric field builds up, even if the end of the line is open-circuited. This initial current will be $v_{in}/Z_c$ where $v_{in}$ is the line to neutral voltage at the instant that the voltage is applied, and $Z_c$ is the characteristic impedance of the line modes [6]. The voltage surge will also be reflected when it reaches the far end of the line, with the amplitude as much as doubling. The resulting voltage oscillations will bounce back forth down the line until the line resistance dissipates the energy or the energy is transferred elsewhere in the system [5,6]. In a superconducting transmission system, these oscillations will persist because there is no line resistance to damp them out. The frequency-dependent energy dissipation of superconductors will provide light damping that will eventually damp the transient. Fig. 3 shows the voltage at the open end of the transmission line that is energized after 16.67 msec. Notice that the voltages on the three phases differ due to the different voltage amplitude on each phase when the switch closes. The length of the pulses will vary with the length of the line.
Operations that switch power factor correction capacitors in and out of the system also lead to transient voltage oscillations. When the breakers for a capacitor open to switch the capacitor out of the system, the current will cease to flow at the natural current zero. Because the capacitor voltage and current are 90 degrees out of phase, the capacitor remains charged to either the positive or negative peak voltage. When the capacitor is switched back in, the inductance between the capacitor and the source could have as much as twice the system voltage across it, triggering a LC resonance between the system inductance and the capacitor. On the other hand, the breaker may happen to reclose at nearly the same voltage as the capacitor retains, leading to a much smaller transient. The actual applied voltage condition for any given reclosing case is essentially random. Fig. 4 shows a simple example system and Fig. 5 shows the computer simulation of a capacitor in a superconducting distribution system with the breaker opening and then reclosing.

Another class of common transients result from the transient recovery voltage (TRV) when a circuit breaker is opened [5,6]. When the circuit breaker in series with an inductance is opened, for example a circuit breaker that protects a transformer, there will be a transient oscillation between the transformer inductance and the parasitic capacitances of the windings.

A. In DC Systems

Damping can be added to a dc system with a simple modification to the inverter control scheme. The inverters normally operate in a current control mode, with the current set point computed to maintain the proper power flow to the ac system. The current control scheme compares the measured current on the dc side of the inverter to the set point and varies the phase command that is sent to the switching devices. Damping can be obtained by adding the dc bus capacitor current to the summation. The capacitor current is the derivative of the dc bus voltage. Fig. 6 shows this modified scheme. Fig. 7 shows the results of adding the damping scheme to the case shown in Fig. 2. Notice that the oscillations damp out quickly with the damping feedback loop added. This method is only effective if the switching frequency of the converter is higher than twice the resonant frequency of the system. In a dc transmission or distribution system, the inductances of long lines and the capacitances needed for large inverters produce oscillations at a resonant frequency that a converter in 6 step (360 Hz switching for a 60 Hz system) switching mode can damp.

B. In AC Systems

The methods traditionally used to reduce transients in ac power systems will also help in superconducting systems. For example, switching a pre-insertion resistor with \( R = Z_c \) when reclosing into a line will damp much of the voltage oscillations by absorbing the reflected waves when they return to the sending end. A damping resistor across the circuit breaker can reduce the TRV to a minimal level as well. Using electronic controls on the switches for the power factor correction capacitors can ensure that the capacitors are reinserted with essentially zero voltage across the breaker. However, these methods may not cover every case. There will be cases where active damping is necessary.

Fig. 7: Computer simulation results showing dc terminal voltages following a 50% increase in load at Inverter #1 with damping.
Active methods for damping transients have also been used or proposed for conventional power systems. At the transmission level, these have been limited to the slower electromechanical transients. HVdc converters have damped dynamic swings on ac systems, most notably on the Pacific Intertie. In addition, flexible ac transmission (FACTS) devices provide fast enough control to damp dynamic swings and control the distribution of power flow between parallel lines [8,9]. At the distribution level, active power filters cancel harmonic currents by injecting currents 180 degrees out of phase with the harmonic currents [10,11].

Converters to damp transient oscillations in a superconducting system require a sufficient switching frequency to be able to damp the voltage or current oscillations. Converters based on thyristors such as the static VAr compensator [9] and the thyristor controlled series capacitor [8,9] use 60Hz switching schemes and are too slow. Converters such as the static compensator (STATCOM) [8,9], the synchronous static series compensator (SSSC) [9,12], and the unified power flow controller (UPFC) [9], as shown in Fig. 8-10, will be more effective. Each of these converters injects a controlled voltage source into the line. The STATCOM acts as a shunt voltage source, the SSSC creates a series voltage source and the UPFC combines both. Unlike the FACTS applications where the goal is to be able to steer real power, the converter rating needed to provide damping can be much lower, on the order of a few hundred kW. This allows the use of pulse width modulated (PWM) converters with switching frequencies in the 25 kHz range to effectively damp typical resonant frequencies. The same converter configurations can be used at the distribution level. Converters along these lines are part of the Custom Power family of converters which include the DSTATCON [11] and the dynamic voltage restorer (DVR) [11,13]. In fact, these converters can already have some ability to damp slower transients because they are designed to regulate load voltage.

Fig. 8: Synchronous Static Compensator (STATCOM)

Fig. 9: Synchronous Series Compensator (SSSC)

Fig. 10: Unified Power Flow Controller

V. CONCLUSION

Electromagnetic transients appear on power transmission systems, including superconducting transmission systems, for several reasons. Among these are normal breaker operations, generator response to reclosing operations, and routine insertion and removal of capacitance. Transmission systems having resistance can damp out these transients within a few 60 Hz cycles. However, eliminating the resistance, as is done in a superconducting system, also eliminates the damping necessary to attenuate these transients. Therefore, damping must be intentionally added.

Methods to add damping include the following:

a. Modify the control scheme, as in the case of a dc system supplied by a controlled rectifier,

b. Use a preinsertion resistor,

c. Employ active power line filters based on HVdc or apply FACTS or Custom Power devices to the purpose

Observing bandwidth requirements is important when adding active damping to superconducting systems.

REFERENCES


