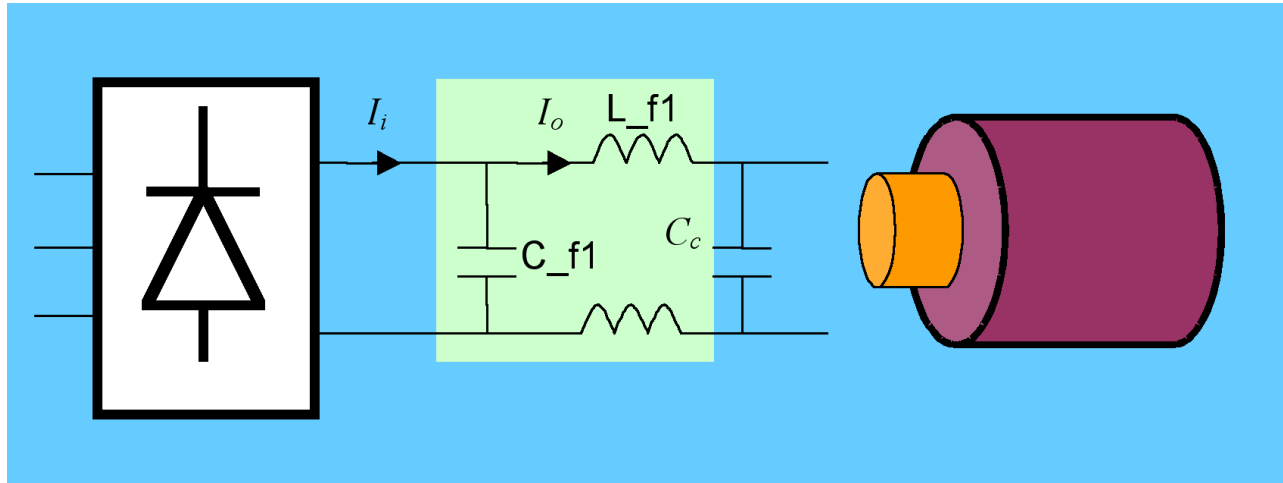


Program on Technology Innovation: Transient Response of a Superconducting DC Long Length Cable System Using Voltage Source Converters



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PRODUCT DESCRIPTION

This report supports development of a superconducting, long-distance, high-power capacity dc transmission system configured with multiple taps such that power can be easily be injected from generating plants and removed to serve loads all along the cable. The technology that will enable the construction of such a system is based on so-called “voltage source converters.” The superconducting cable used for transfer of the power will have zero dc conduction losses. These technologies, when commercially available, could make a high-voltage dc system perform in ways similar to present-day ac systems by facilitating tapping of the dc circuit. This would make dc more competitive with ac for high-power corridor applications.

Results and Findings

This study was performed to develop information needed to design superconducting dc cables. However, it can also be used by utilities considering high-voltage dc applications using voltage source converters as an alternative to the conventional line-commutated current-source converter systems. To provide performance trade-off information to guide the design of a superconducting cable, simplifying control systems were simulated, and protective features normally incorporated in the converters were not included. The simulation was also based on a point-to-point, two-terminal dc link to facilitate understanding of the basic control issues. Extensions to a multiterminal dc system are discussed to the degree that the results can be extrapolated to such systems, and recommendations are made for the next steps in the development of a commercially viable system with multiple on and off ramps to the cable.

Challenges and Objectives

The report is assumed to be used by engineers and researchers involved in the development and design of dc superconducting cable systems. The subject of the control of power flows on a very long superconducting dc cable with multiple taps is complex. It was necessary to begin with a conceptually simple feasibility study to identify transient events to which the cables might be exposed. Further studies will be needed before the interface requirements between the converters, the ac system, and the dc cable are fully understood and equipment can be designed and built. A significant challenge was the nonexistence of a computer model of a superconducting dc cable for use in the simulation program. Instead, the study was performed based on an extremely low loss conventional cable, and the results must be interpreted accordingly.

Applications, Value, and Use

Long-distance, high-capacity power transmission circuits operating at power levels possibly around 10,000 MW per circuit might be needed to bring power from remote sources such as large wind farms to urban load centers. Ultrahigh-voltage ac or dc transmission lines would be

the conventional solution. However, using superconducting cables, underground power using superconducting dc cables could be viable alternatives to high-voltage overhead lines in the near future. If the cables are interfaced with voltage source converters, it should be possible to connect many converters to the cable, all along the cable route, which removes a frequent barrier to application of high-voltage dc for transmission applications. This report sets forth a method of analysis and establishes some fundamental facts that will be needed in subsequent research and development efforts.

EPRI Perspective

This study was one of several efforts in a project undertaken to achieve a feasible engineering design at a conceptual level of a high-power superconducting dc cable using voltage source converters in a long-length, multiterminal configuration. The unique role of the Electric Power Research Institute (EPRI) in the achievements of the study was the ability to bring together and lead a collaborative team of experts who had both utility business understanding as well as specific expertise in key technical areas. The study establishes a basic understanding of and initiates the design process for resolving the operational issues associated with the interactions between the cable and the converters. One of the goals was to uncover specific concerns that might affect the design of the cable itself and to assist researchers in making trade-off decisions regarding its optimization. Thus, the results of the study should be considered by future cable designers and by those who are focusing their efforts on the design and control of the voltage source converter. The study has only scratched the surface of the rather significant research and development challenges, particularly in the areas of system dispatch, control, reliability, and contingency operations. Nevertheless, it provides a good foundation for future research and puts EPRI in a position of being able to effectively lead and/or collaboratively assist in that effort.

Approach

The simulations of a voltage source converter system based on an extremely low loss underground cable as an approximation for a superconducting dc cable reported here were built using a commercially available power system simulation program called PSCAD. The converters were assumed to be pulse-width-modulated voltage source converters. The system studies covered normal start and stop operations, power up and down ramps, and various fault scenarios. The studied faults included short circuits to ground in the sending and receiving ac systems and short circuits across the cable terminals on the dc side.

Keywords

High-voltage dc transmission
Multiterminal dc system
Pulse-width modulation
Superconducting cable
Voltage source converter

EXECUTIVE SUMMARY

This report contains the results of a study of a superconducting dc cable system using a power system simulation tool called PSCAD®. A study was performed by Los Alamos National Laboratory (LANL) in the 1970s that covered a low temperature superconducting dc transmission cable utilizing Current Source Converters. This study was performed to understand how Voltage Source Converters (VSC) might facilitate the design and construction of a multi-terminal high voltage superconducting dc system assumed to carry about 10,000 MW. The simulations were based on a point-to-point HVDC system since the extension of the simulation into three or more terminals was not feasible with the available resources. However, the results from the simulations have been used to extend the lessons learned from the two terminal simulations to multiple converters. It is envisioned that 30 to 40 converters might be connected to one cable where the rated power for the cable is, as indicated above, 10,000 MW.

The simulation comprised two VSCs with basic controls. The converters were assumed to be operating with Pulse Width Modulation (PWM) using a base switching frequency equal to nine times the fundamental, 60 Hz network frequency. The switching frequency was selected to achieve simplicity in the models and not necessarily because it is expected that it will be used for a commercial application. New VSC concepts are emerging with different performance attributes, so if a system as envisioned will be built sometime in the future, it would probably be based on newly developed converter topologies.

The modeled system did not incorporate numerous protection features that are utilized in commercially operating VSC schemes. First, this would require a very detailed converter model. Second, the study focused on the cable, assuming that the converters would have to be adapted to meet the performance requirements of the cable be constrained by converter limitations. Therefore, the simulation does not represent a finished converter design. This model has been built and used primarily to study faults in the system such as cable short circuits and ac system faults of various kinds. It has also been used to study harmonic injection from the converters into the cable.

Two terminal VSC based systems are already in operation in many parts of the world. The results and analysis of the simulation results show that it appears quite feasible to build multiterminal systems based on VSC converters. Specifically, the following conclusions have been reached:

1. Steady state harmonic injection into the cables can be managed to an arbitrary level using harmonic filters.

-
2. Starting the DC system requires charging of the dc system's capacitances to a level close to rated voltage before starting the converters to avoid high charging currents and overvoltages on the dc side that result from the large inrush currents.
 3. The charging of the DC system can be from a Current Source Converter (CSC), which conceivably could be a converter used at a large generating plant that does not need reverse power operation.
 4. The power rate-of-change should be limited to avoid injecting losses into the superconducting DC cable. However, the converters are not the limiting factor on how fast the power through the cable can be increased.
 5. AC system voltage sags and short circuits are common mode stresses on the DC cable system, since these can affect many converters connected electrically close to each other such that a voltage sag in one can impact other converters in approximately the same way. Such sags could seriously affect the availability of a multi-terminal dc system if they impact the dc system such that the power taken out of the dc system exceeds the power injected.
 6. Fast acting, semiconductor based DC circuit breakers will be needed to disconnect converters from the dc circuit in case of cable and converter station short circuits.

Further studies are needed to extend the study into three or more terminals to understand the complexities and to develop solutions to the identified problem areas.

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1

INTRODUCTION

Electric power transmission lines are used to move electric power from where power generation resources are available at an attractive price to where there is a demand for electric power. However, both the demand for electric power and the availability of power generation are not constant, but vary with time of day, day of the week and seasons. Some regions have maximum power demand during the winter when the need for space heating is significant, whereas other regions need most of the generation capacity during the summer when air-conditioning systems are heavily utilized. Some regions depend on hydro generation to a large degree, which is limited during dry seasons but abundant in the spring and early summer when snow melts, causing heavy run-off. To maximize the utilization of the costly generation facilities as well as of seasonably cheap energy, the electric power system incorporates long distance, high power transmission lines to move large amounts of power between generating plants and load centers. An example of this application is the ac and dc transmission system that connects the Pacific Northwest, rich in hydropower plants, to Southern California. Import of power from Canada into the New England area is another example of distant hydropower being used to supplement fossil-based power generation in the Northeastern parts of the United States.

Moving power between the East and West coasts of the United States to share generation capacity during the peak power periods has been discussed for a long time. However, the distance between the East and West coasts of the United States and the associated costs of building interconnecting transmission lines has so far inhibited the construction of the lines needed to take advantage of time differences in the peak demands for electric power. Conceivably, this could change if generation of electric power shifts towards more reliance on renewable energy sources and nuclear power, because many of the so-called green technologies are either not dependable or systematically unavailable. An example of the latter is solar power generation, which is unavailable at night or during cloudy weather conditions. Also, wind power may not be available for long periods when winds are typically light, or the winds may be too strong for generation of power during stormy conditions. Thus, when the available generation is low in one area, sharing the generated power from another area could be beneficial. This study of a superconducting dc cable envisions a system of interconnected generators and loads covering a very large area, potentially with intercontinental dimensions. It also envisions the use of the dc cables interconnecting a large number of converter stations to rectify the generated ac power and inverting the dc power to ac to feed the loads.

A study was performed by Los Alamos National Laboratory (LANL) in the 1970s that covered a low temperature superconducting dc transmission cable utilizing Current Source Converters [7]. In the present study, the converter topology for a superconducting dc cable system is assumed to be a multiterminal dc system based on VSC technologies suitable for connection to 115kV to 230kV ac systems [1]. This facilitates using air insulated converters operating at relatively low

dc voltages and high currents, which should be feasible when the conductors are superconducting. A suitable power rating for a converter terminal would be about 200MW, which could feed loads much closer to the load centers than would be possible if 1000 to 2000MW converters were to be used. Such power levels typically require connections to 500kV to 765kV ac systems, which would require one or two step-down transformers, introducing additional losses between the ac connections points and the load centers.

Current source converters (CSC), which are typically used for high power dc systems, would be very difficult to operate with a large number of terminals. In particular, small CSC systems connected to a high power dc system are likely to cause severe disturbances into the dc system in case of an ac system disturbance at the connection point of the small CSC converter [5]. If VSC converters are used for most of the connected converters,¹ it would make the dc system operate similar to existing ac systems. That is, it would be easy to connect an additional terminal to the cable so that expansion or extension of the areas served through the cable would be relatively easy. Furthermore, in a VSC dc system, power flow direction can be changed by reversing the current flow. That is, it does not require switching the voltage polarity of the cable or reconnection of the converters by means of reversing switches. The loading of the converters could be handled with relative ease as long as the total amount of load does not exceed the available generation. That is, the dispatching of generation and loads would be almost the same as for today's ac systems. However, there are numerous technical issues that need to be studied in some detail before a superconducting dc cable power transmission system can be realized. Some of the issues are:

1. The control requirements for the converters to ensure that the power transmission system is stable and reliable. This must include studies of interactions between the connected converters on the dc side as well as interactions between converters that are closely coupled to each other on the ac side.
2. Losses in the superconducting component of the dc cable that result from changing current levels, which arise as a result of the cyclic, particularly sudden, variations in the demand for power.
3. The impact of power system faults in the ac systems connected to the dc cable, which might upset the power flows in the entire interconnected power system.
4. The impact of faults in the system of dc converters and the dc cable itself, which could lead to loss of the power fed to the load centers as well as over-frequency in the connected generating stations.
5. How to dispatch and account for the power transmitted over the dc cable.
6. Development of new technology for protection of the dc cables and for isolation of faults in the dc power transmission system.

There is limited experience in building very long dc cable systems. The link from Norway to the Netherlands, the longest in the world at present, includes an approximately 600 km long cable. In

¹ Large sending end (rectifier) terminals operating with no need to receive any power might be connected to the dc cable in a system using primarily CSC converters.

addition, if the Baku system in South East Asia had been built, it would have incorporated a very long dc cable. These systems are conventional point-to-point dc transmission links using current source converter technologies. Not much is published about the performance of the Norway to the Netherlands system, but it is well understood that the large cable capacitance leads to some significant control problems. This study of a superconducting dc cable system was conducted to develop an understanding of some of the fundamental aspects of an extremely low loss, long distance dc cable transmission system. This included:

- Energizing the superconducting dc cable.
- Connection and disconnection of converters to the dc cable.
- Loading (increase of the dc current) and unloading of the dc system.
- Harmonic injection into the dc cable, since this leads to power losses and heating of the superconducting dc cable.
- Grounding and insulation requirements for the dc cable as a result of transient overvoltages.
- Loss of generation and load rejection of the cable system.
- AC system faults.
- DC cable faults.

This study is intended to illustrate the interactions between a system of VSC converters and a superconducting dc cable. The modeled converters and cable do not represent a finished design of the system, but only highlight design trade-offs between converters and the modeled cable. Therefore, the modeled VSC converters do not incorporate protective features normally included in VSC systems to prevent over-currents in the semiconductor valves. Neither do the models include protective features to block the valve groups in response to serious ac and dc disturbances. The study only models a point to point dc system, but the lessons learned from the simplified system used in this study are used to extrapolate to a multiterminal dc system.

2

SIMULATION SETUP

A simplified ac-dc superconducting dc cable transmission system was simulated using available components in the PSCAD® computer program. The assumption for the dc cable system is that there will be many converters connected to the cable. However, to develop a reasonable understanding of the dc transmission system, it was necessary to start with a smaller system. Therefore for this study, a two terminal, point-to-point system rated about 1,000 MW was selected. This would be the equivalent of five 200 MW converter terminals connected to the same point on the cable.

Cable Model

The PSCAD® program had no built-in model for superconducting cables. Therefore, a cable model had to be created from available ac cable system models.

Cable Structure

The superconducting dc cable considered in this study is a coaxial cable with a construction shown in Figure 2-1. The cable has two conductors; an innermost superconductor (referred to as inner conductor or IC) separated from an outer superconductor (referred to as outer conductor or OC) by an insulation layer. This insulation is assumed to be capable of withstanding the voltages that appear between the IC and OC. The cable is contained inside a corrugated metallic sheath (referred to as metallic sheath or MS).

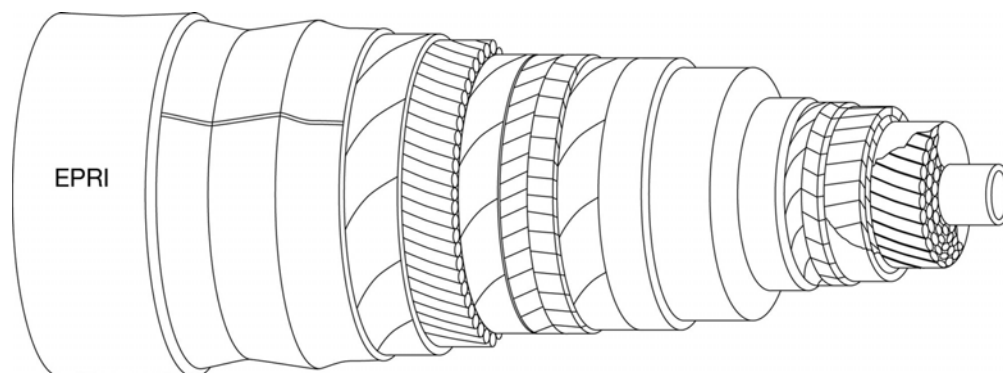


Figure 2-1
Superconducting DC cable

For the sake of this study the cable is assumed to be a coaxial cable with two concentric annular conductors (IC and OC) contained inside a stainless-steel MS, which is solidly grounded.

The cross-section of the cable used for the transient study is shown in Figure 2-2. In order to model superconductivity with reasonable accuracy using a conventional simulation tool, the dc resistivity, ρ_1 , of the two annuli conductors is taken as $10^{-12} \Omega\text{m}$.² The metal sheath resistivity, ρ_2 , is considered to be equal to stainless steel ($\sim 3 \times 10^{-8} \Omega\text{m}$). The relative electrical permittivity, ϵ_r , and relative magnetic permeability, μ_r , of the cable's insulation material are assumed to be 2.5 and 1.0, respectively.

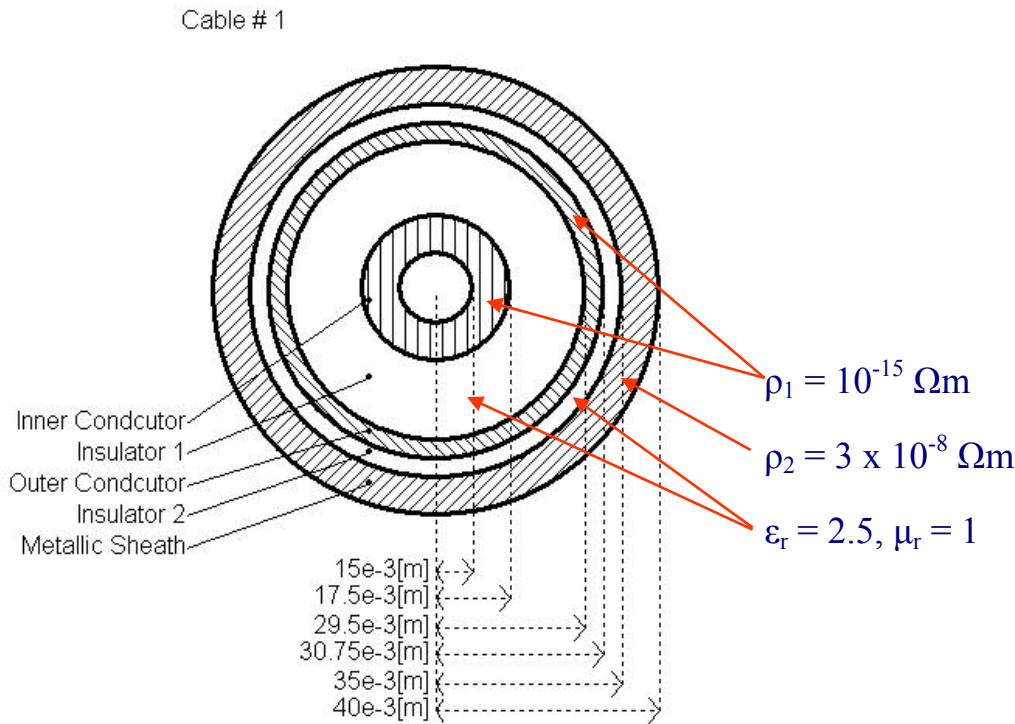


Figure 2-2
Coaxial cable cross-section (not to scale)

The cable is modeled using a transmission line distributed impedance equation for a coaxial cable. These equations have been studied in detail. Schelkunoff [3] presented an in-depth study of coaxial cables and developed accurate equations for high frequency studies. Wedepohl [4] further developed simplified equations suitable for modeling traveling waves of coaxial cables. These equations are used to develop frequency domain equations for the transmission system. The cable characteristic admittance can be calculated using the series impedance and shunt admittance of the dc cable. Figure 2-3 shows the characteristic admittance of IC and OC (shown as Insulator 1 and Insulator 2 respectively).

² This resistivity is 17,200 lower than copper. Still, the dc resistance of the conductors is higher than for a superconducting cable for which the resistance is zero; but the ac resistance is underestimated.

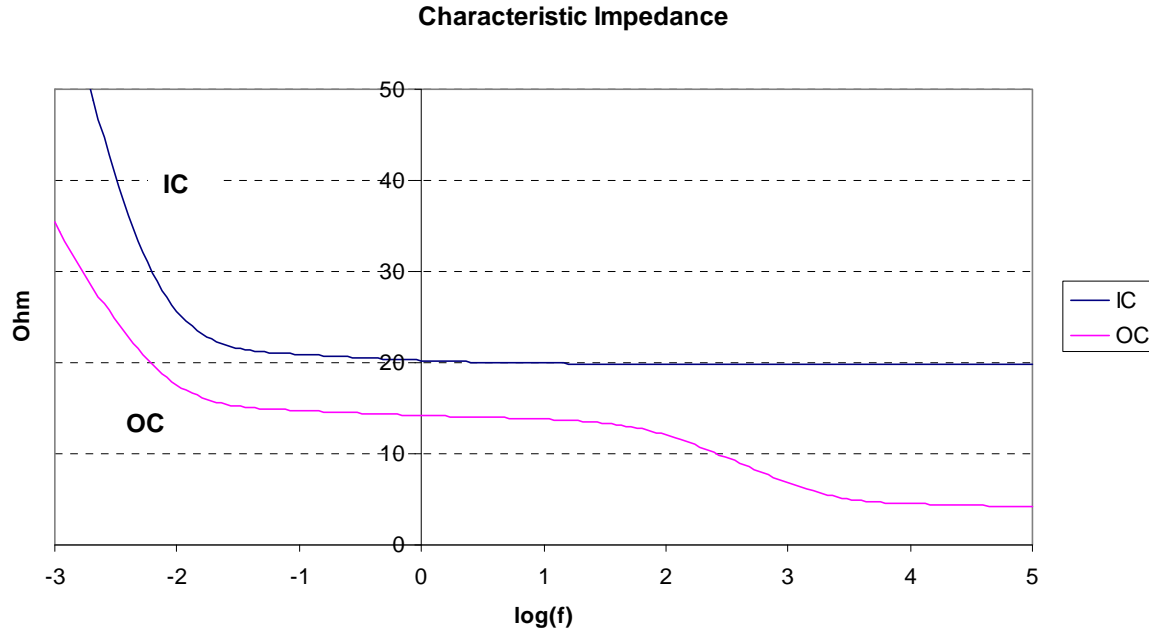


Figure 2-3
Cable characteristic admittance

For the sake of brevity and in order to gain some insight into the cable characteristics, basic equations for capacitance and inductance of simple coaxial cable were investigated.

The capacitance between the IC and OC, C_1 , can be determined by the following well-known formula and use of the information provided in Figure 2-2; i.e. $r_1=17.5$ cm, $r_2 = 29.5$ cm, $\epsilon_r = 2.5$ $\epsilon_0 = 8.85 \times 10^{-12}$ F/m, and $\epsilon = \epsilon_r \times \epsilon_0 = 2.21 \times 10^{-11}$ F/m.

$$C_1 = 2\pi\epsilon \left[\ln\left(\frac{r_2}{r_1}\right) \right]^{-1} = 2.663 \times 10^{-10} \text{ F/m}$$

The mutual inductance between the IC and OC can also be derived using the dimensions and physical properties presented in Figure 2-2: $\mu_r = 1.0$, $\mu_0 = 4 \pi \times 10^{-7}$ H/m, $\mu = \mu_r \times \mu_0 = 4 \pi \times 10^{-7}$ H/m.

$$L_1 = \frac{\mu}{2\pi} \ln\left(\frac{r_2}{r_1}\right) = 1.044 \times 10^{-7} \text{ H/m}$$

The velocity of propagation of an electromagnetic wave along the line is $\sqrt{\epsilon \cdot \mu} = \sim 1.9 \times 10^8$ m/s, and thus it takes ~ 10.6 ms for an electromagnetic wave to travel along the 2,000 km length of the line.

A detailed analysis of a coaxial cable structure involves the inclusion of series resistance, self-inductance of various levels, and the effect of time-varying magnetic fields on the inductances and resistances. Such a derivation was used to develop the model used in the simulation throughout this study.

Cable Loss

Power loss due to ac harmonics (in watts per meter per length) of the superconducting dc cable is represented as.³

$$P \cong 4 \cdot 10^{-7} \sum_{all_n} \omega_n \cdot I_n^2 \text{ W/m.}$$

where ω_n is the harmonic frequency in radians per second, and I_n is the amplitude of the harmonic current in amperes.

The permissible loss per unit length of the cable is assumed to be 0.5 W/m. However “the operating power limit, 0.5 W/m, which is determined by the steady-state cooling requirements, may be exceeded for short periods when the ac or dc systems are disturbed.”⁴

In order to study cable power loss, a new terminology based on commonly used Total Harmonic Distortion (THD) is introduced: *Weighted Total Harmonic Distortion (WTHD)*.

Using the terminology as defined below, loss per length of 0.5 W/m provides an upper limit for *WTHD* measurement as follows:

$$P \cong 4 \cdot 10^{-7} \sum_{all_n} \omega_n \cdot I_n^2 = 4 \cdot 10^{-7} \cdot I_{dc}^2 \cdot \sum_{all_n} 2\pi \cdot f \cdot n \cdot \left(\frac{I_n}{I_{dc}} \right)^2 = 4 \cdot 10^{-7} \cdot I_{dc}^2 \cdot 2\pi \cdot f \cdot WTHD^2 < 0.5$$

where

$$WTHD = \sum_{all_n} n \cdot \left(\frac{I_n}{I_{dc}} \right)^2 .$$

Therefore

$$WTHD < \sqrt{\frac{0.5}{8\pi \cdot f \cdot 10^{-7} \cdot I_{dc}^2}} .$$

Thus for $f = 60$ Hz and at full load, where $I_{dc} = 12.5$ kA, $WTHD < 0.465\%$. Thus a $WTHD = 0.4\%$ is satisfactory at steady state full load. Based on this criterion, acceptable system response and other specifications such as required filter can be determined.

Converter Station Models

The VSC converters are modeled using six switching devices with parallel diodes and snubber circuits [6]. The sending end and receiving end converters are connected through the 2,000 km length of dc cable. Each converter is connected through a step-up transformer to 115 kV systems. The ac systems are assumed to be Thevenin equivalent ac sources.

³ Communication with William Hassenzahl (Refer to EPRI Report 1020458, Chapter 6 [8])

⁴ Ibid

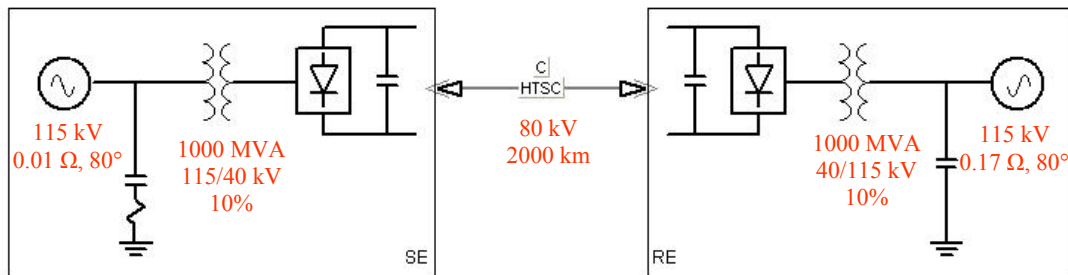


Figure 2-4
System under study

The rated voltage of the dc cable is assumed to be 80 kV, with 12.5 kA rated current for transfer of 1 GW power. The actual cable may be rated as much as 10 GW, but it is assumed that no single terminal will be rated over 1 GW. The converter side transformer voltages are adjusted in such a way that the converters' modulation index will be about 80% under steady state conditions.

Converter Model

As mentioned above, the modulation carrier frequency, m_f , is selected as nine times the fundamental frequency; i.e. 540 Hz. This is a compromise between having a converter that requires a minimum amount of filtering while the losses are not excessive. There are active developments of VSC converters around the world, so it is assumed that other low loss VSC topologies will emerge that satisfy the need for low loss converters in a superconducting dc system.

The basic rectifier's electrical diagram is shown in Figure 2-5. As shown in this figure, the converter is connected to the low voltage windings of the transformer. It is assumed that the inductance of the converter transformer can serve as the commutating reactance (boost or buck inductance) of the converter, although this might cause unacceptable dielectric stresses on the transformer's windings. If this is the case, a separate reactor and low pass filter might need to be inserted between the converter valves and the transformer.

The converter dc rails are connected to a dc capacitor (C_{fl}), which is connected between nodes n1 and n2. The HTSC terminals (C1 and S1) are connected through an inductance (L_{f1}) or through a filter to the dc rail capacitor.

As also shown in Figure 2-5, the HTSC outer conductor is solidly grounded through a negligible 1 mΩ resistance, at the rectifier or sending end (it is floating at the inverter or receiving end) of the dc link.

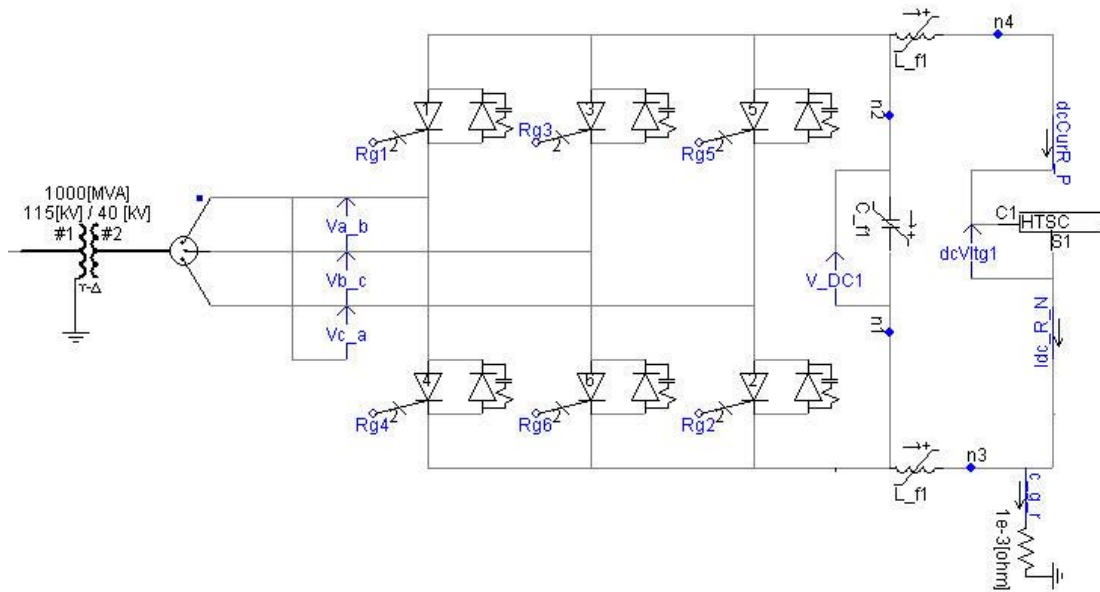


Figure 2-5
Rectifier electrical diagram

The dc rail capacitor C_{f1} , connected across the converter output, provides a low impedance path for harmonics generated by the converter. In addition, the series inductance L_{f1} ,⁵ connected in series between the HTSC and the converter, provides high impedance to current harmonics and partially blocks current harmonics from flowing into the HTSC. The combination of C_{f1} and L_{f1} serves as a low pass filter for the dc cable to avoid injecting high frequency ac harmonics into the cable, which can cause unacceptable losses in the cable. Additional filters to attenuate primarily 120 and 360 Hz harmonics, which can also cause unacceptable cable losses, are probably also necessary, as will be discussed later in this report.

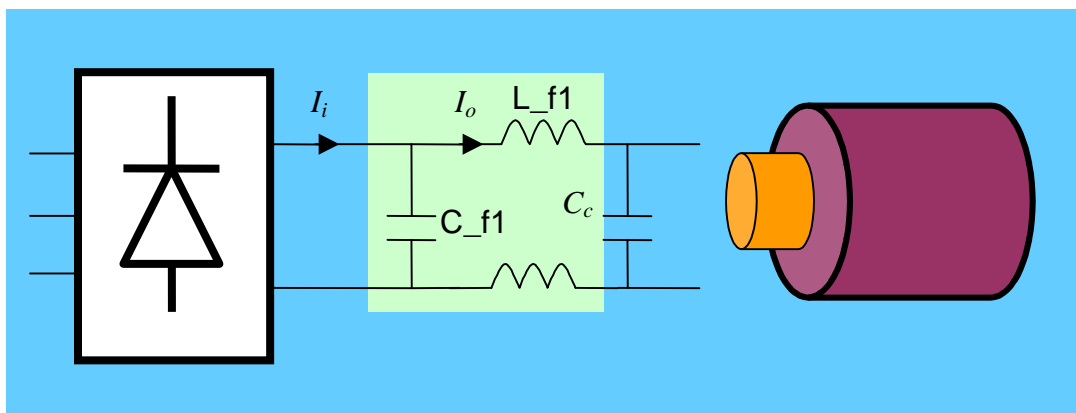


Figure 2-6
Cable interface filter

⁵ Or through a filter.

The capacitance C_c , shown in Figure 2-6, represents the equivalent capacitance between the cable's inner and outer conductors. The general form of LC filter gain, the ratio of current magnitude into the cable (I_o) to magnitude of converter current (I_i), is shown in Figure 2-7. As shown in this figure, the LC filter has almost a constant gain G_{low} at frequencies below f_c , and has an attenuation equal to -20 dB/decade for frequencies above f_c . Thus, a large dc rail capacitance can reduce the harmonics below f_c .

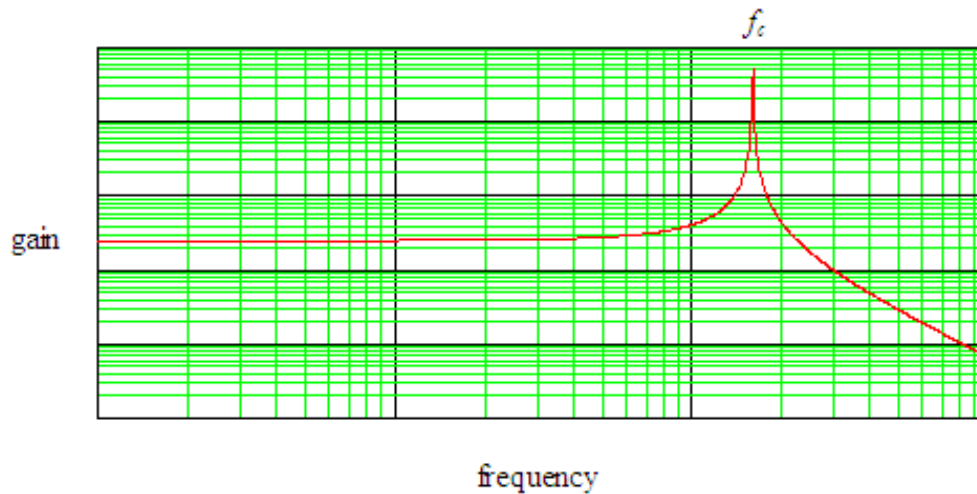


Figure 2-7
LC filter transfer function

The constant gain G_{low} and the frequency f_c are calculated as follows:

$$f_c = \frac{1}{2\pi} \sqrt{\frac{C_{fl} + C_c}{L_{fl} \cdot C_c \cdot C_{fl}}} \quad G_{low} = \frac{C_c}{C_{fl} + C_c}$$

The f_c frequency of the LC filter can be adjusted by varying the LC filter's inductance or capacitance.

A practical design criterion for the dc rail capacitor is: energy stored in the capacitor in terms of electric charge is between 2 to 5 milliseconds of the transmitted power [2].

$$\frac{1}{2} C_{fl} \times V^2 = P_{dc} \times time$$

Therefore, for $P_{dc} = 1$ GW, and $V_{dc} = 80$ kV voltage across the capacitor, the dc rail capacitor should be chosen between $625 \mu\text{F}$ to $1,560 \mu\text{F}$.

The electrical diagram of the receiving end station is identical to the sending end station. However, unlike the rectifier station, the outer conductor of the HTSC is floating at the inverter station. It has been assumed that grounding of the neutral side of the dc cable at one point only

will be a requirement in order to obtain permits for the system. This will eliminate the possibility for dc currents to be injected into the ground from this system. However, it is assumed that the outer pipe will be continuously grounded with cathodic protection systems used to minimize the risk of corrosion to the pipe as is typical for pipelines. In order to model this floating effect, the outer conductor at an inverter station is connected to ground through a 1 MΩ resistance.

Control System Model

Basic controls for turning the power semiconductors on and off, voltage, current, and active and reactive power controls have been implemented in the models. The control loops have been tuned to make the system operate, but the control systems have not been optimized and therefore should not be assumed to represent the conditions of an actual system. No automatic protective features have been included in the model. Such features have to be manually set prior to beginning simulation runs.

The rectifier end controller (see Figure 2-8) adjusts the dc voltage across the cable to 1 pu (80 kV) and the input reactive power of the converter to the set value. The following shows the basics of the rectifier control scheme. The phase angle (δ) controls the active power flow into or out of the cable. The assumption for the rectifier side is that the rectifier operates with a constant voltage irrespective of the power flow through the rectifier terminal. The modulation index controls the reactive power flow into or out of the ac power system at the connection point. The converter is assumed to be a simple two level VSC operating with a modulation frequency, m_f , of 9 times the ac system frequency. (Please see Appendix A for list of symbols.)

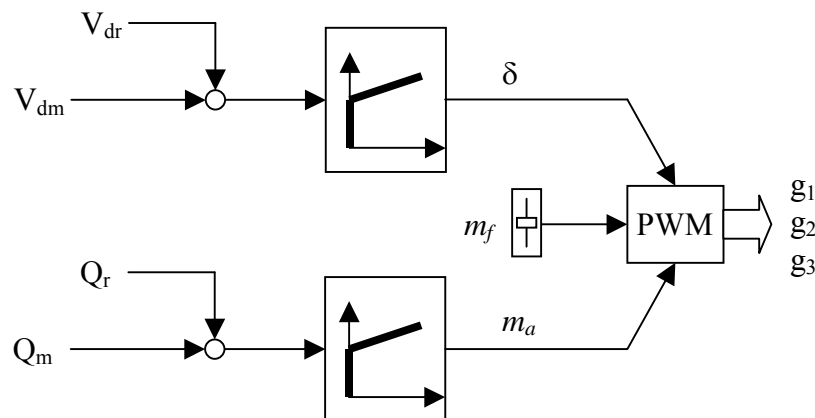


Figure 2-8
Rectifier control scheme

The phase angle at the inverter end is controlled to achieve a constant current flow, which will be equal to a constant power flow if the voltage is held constant.⁶ In this type of system all converters except one, the voltage controlling converter, operates on constant current, which is determined to be equal to the scheduled power divided by the assumed constant voltage. Thus, the voltage controlling converter station, which in an actual system probably will be the largest sending end converter terminal, is operating as if it is an infinite bus able to take up the slack of power demand from all other stations. This is similar to how an ac system operates, with some generating plants that are load followers controlling the ac system's frequency. In this simulation, the inverter end controller adjusts the dc current through the cable to 1 pu (12.5 kA) and is assumed to keep the reactive power injection from the converter close to zero. The basics of the inverter control scheme are shown below.

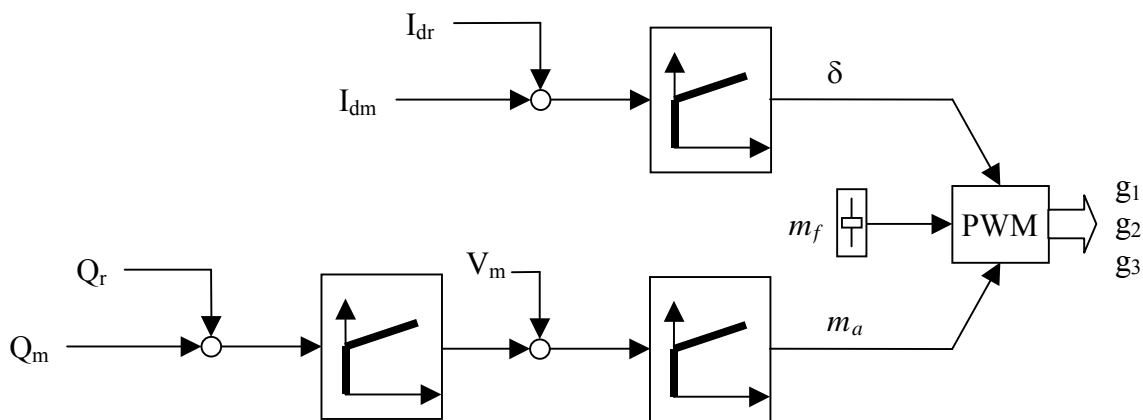


Figure 2-9
Inverter control scheme

⁶ No voltage control loop has been included in the receiving end's control system. Therefore, this converter attempts to draw the set current out of the cable even if the voltage is much below the rated 80 kV level. In an actual system, the output current at the inverter should be reduced if the voltage is excessively low.

3

SIMULATION RESULTS

The first part of the study was to verify that all of the elements worked in the overall system model. The damping in the cable modeled in the system had to be checked, since the losses in the very low loss modeled conductors are higher than the actual ac losses that would be expected in a real superconducting dc cable. (The model estimates ac losses based on a very low resistive, conventional conductor and is not able to match actual losses. DC losses are higher in the model than actual because of assumed very low resistance required by the simulation tool.)

Energizing the Cable

A voltage source converter can be represented by a small inductance in series with a diode at the ac side with a large capacitor on the dc side, as shown in Figure 3-1. Thus, a large inrush current will arise if a breaker is closed to energize the VSC, resulting in a high overvoltage across the capacitor on the dc side. The magnitude of the inrush currents can be very large and can even lead to diode failures if the diodes do not have a sufficiently large current rating to handle the thermal stresses associated with the inrush currents.

There are several ways to avoid or reduce such over currents and overvoltages. One is to include a closing resistor in the breaker, which will reduce the inrush current and therefore reduce the overvoltage associated with the switching. Another way to avoid the overvoltage altogether is to have the dc capacitor pre-charged to a voltage higher than the peak rectified voltage from the ac system side. In this case, there will be no overvoltage at all. However, if the voltage on the dc side capacitor is reduced because of control actions following an ac system voltage sag, an inrush current from the ac system into the capacitor is unavoidable when the ac system voltage recovers from the voltage sag. That is, loss of voltage on the dc capacitor for any reason can lead to large inrush currents into the capacitor. Therefore, the transient power flows associated with ac system disturbances must be carefully studied to ensure that the converter valves are capable of handling transient current flows as well as overvoltages associated with ac system faults. Such dc side oscillations that arise as a result of the transients will also inject losses into the dc cable.

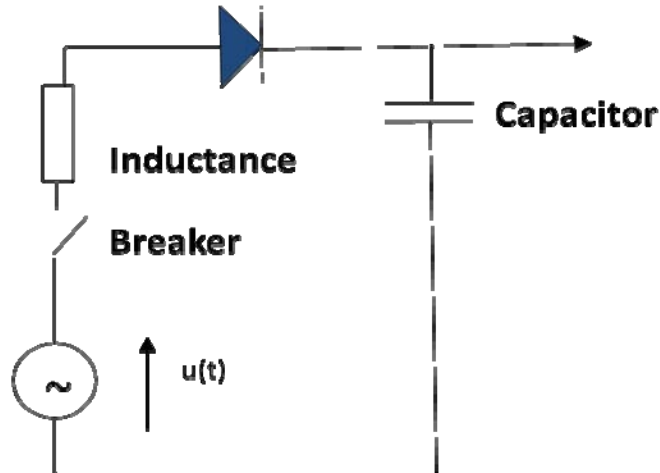


Figure 3-1
Simplified schematic diagram for a VSC converter when energized from an ac system

As is readily apparent from the simple schematic shown in Figure 3-1, a short circuit across the dc capacitor will also result in a short circuit of the ac system behind the diode. This will also result in over current through the diode. The short circuit current is only limited by the system's short circuit impedance, which means that the short circuit current can be very high. The diode current in the circuit as shown in the figure might have to be interrupted by means of the ac circuit breaker, which will take two to three cycles for a typical ac circuit breaker. Thus, the diodes must be able to ride through such an event, or they will have to be bypassed or disconnected using faster switching equipment such as a dc side circuit breaker. This will probably require high current solid state switches or circuit breakers since mechanical switching of high voltage, high current systems is slow. Switching surges will also enter the dc cable, which will result in losses and potentially also overvoltages on the cable's dielectric systems. Therefore, the key to having a well-functioning superconducting dc cable transmission system is to understand the interfacing requirements at the point of connection of the ac/dc converters. Interactions between the converters in a multiterminal system must also be studied, but this is beyond the scope of this study.

Study of Cable Step Voltage Change

The damping of the dc cable as modeled can be studied by introducing step changes into the system and studying the response of the system. The effect of voltage transient across the cable was therefore modeled. It was assumed that the dc cable was pre-charged to a voltage close to nominal dc voltage from another dc source prior to energizing the VSC converter. Thus, the simulation shown in Figure 3-2 first included a ramp from zero dc voltage to 85 kV. Following this, a step voltage change to 170 kV and a step voltage change back to 85 kV are simulated. This simulation shows the reflections and the damping of the low-loss dc cable used to approximate the performance of a real superconducting dc cable. The cable voltage is tapered off to zero at the end of the simulation.

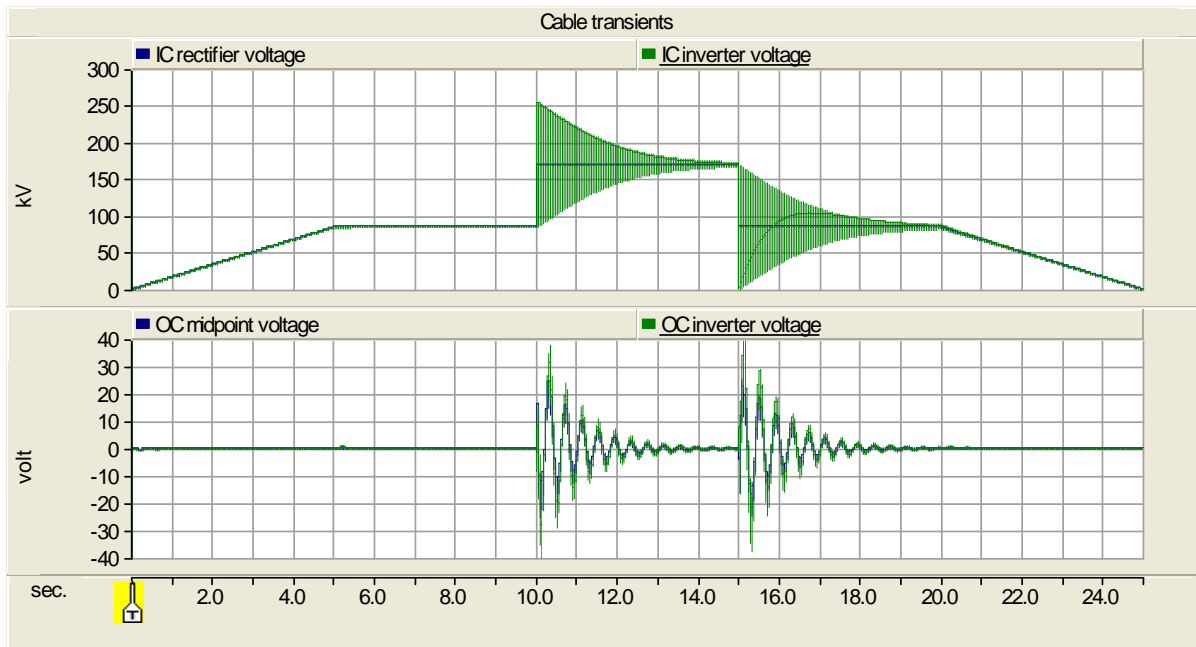


Figure 3-2
Cable voltage transient

The inner conductor swings from 85 to 255 kV (reflection from the open end of the cable leads to twice the voltage or a change of 2×85 kV). The other conductor's voltage remains close to zero volts (a change of less than 50 volts) because the voltage rate of change is slow. This can be seen in more detail in Figure 3-3. The oscillating frequency in the modeled system of the OC to ground is slightly over 3 Hz, whereas the oscillating frequency of the IC to the OC, including the termination capacitors for the converters, is about 20 to 25 Hz. The time constant for the damping of the IC to OC mode is about 2 seconds. The ground mode oscillation has a time constant of about 1 to 1.2 seconds. That is, the modeled cable system has reasonably low losses, although, as mentioned, the ac losses are probably lower in an actual superconducting dc cable.

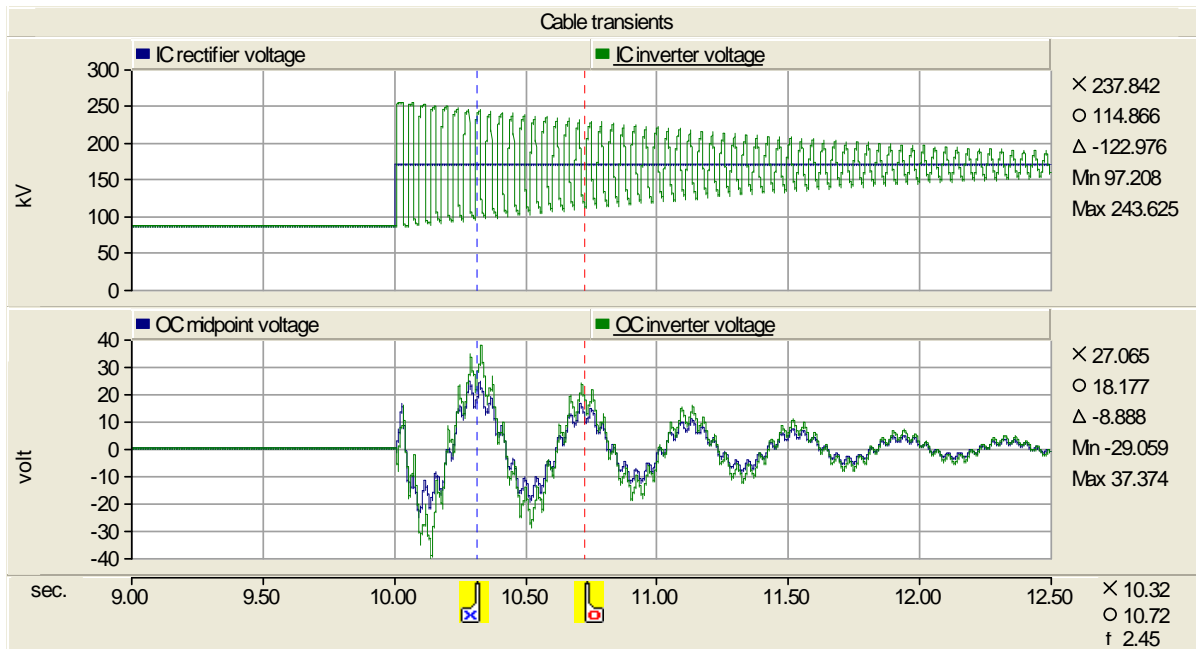


Figure 3-3
Detail of cable voltage transients

Startup, Steady-State Operation and Ramp-Down

A system simulation with 1000 μF dc rail capacitance at each converter station was conducted. The startup and ramp-down cycle was conducted with an order as outlined in Table 3-1. For the simulation it was assumed that the cable had to be charged to close to the nominal dc voltage (80kV) prior to starting the converter operations. This avoids large inrush currents through the converters, which would arise if the cable is fully discharged when the ac converter breakers are closed. In order to get a reasonable simulation time, the cable charge was not optimized, therefore the transients that arise upon closing the ac breakers should be disregarded. The results of the simulation are depicted in Figure 3-4.

The system response, as shown in Figure 3-4, shows that the system ramped up from zero current to 12.5 kA in about one second. The system is not optimized to minimize voltage and current transients since that would require very long computer simulation runs. However, sudden changes in voltage and currents are unavoidable responses to ac system disturbances, so in that respect, the simulation may to some degree represent actual, although infrequent, performance. The system reached steady state and transferred 1 GW of power along the HTSC between 12 and 16 seconds. Figure 3-5 shows the ramp in greater detail.

The ripple currents and voltages during the ramp are shown in Figure 3-6.

Table 3-1
Simulation switching order

Time [s]	Action	Time [s]	Action	Time [s]	Action
0 – 1	Cable charging	1	Rectifier ac breaker closes	3	Sending End (SE) converter de-blocked
5	Inverter ac breaker closed	7	Receiving End (RE) converter de-blocked	10-11	Receiving End (RE) power ramped to 1 pu
16-18	Receiving End (RE) power ramped down to 0 pu	19	Inverter ac breaker opened, converter blocked	19.5	Rectifier ac breaker opened, converter blocked

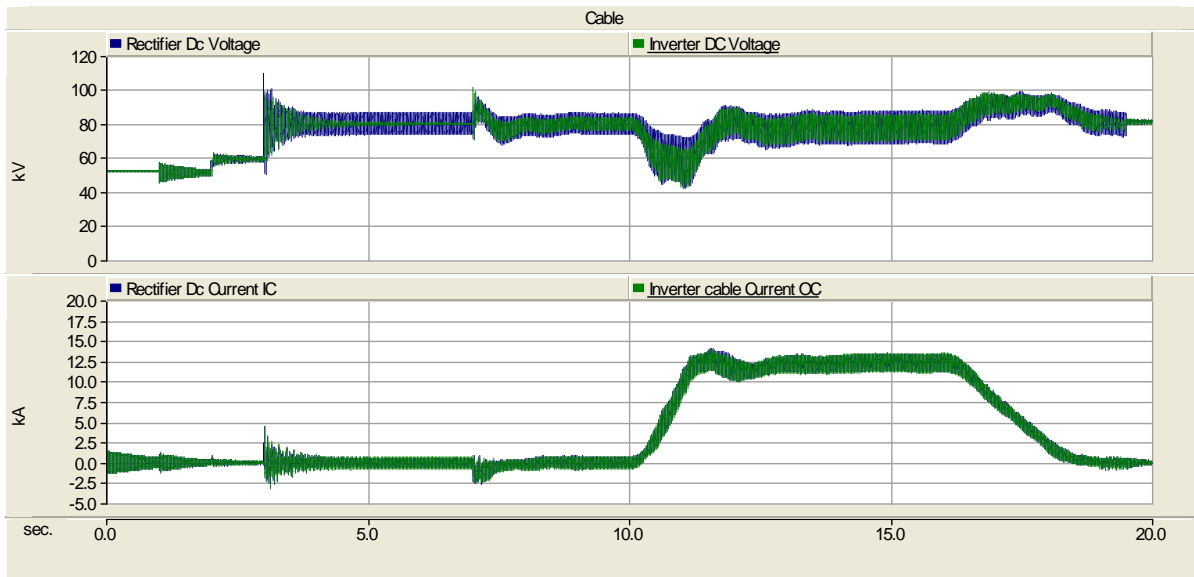


Figure 3-4
System performance during power cycling

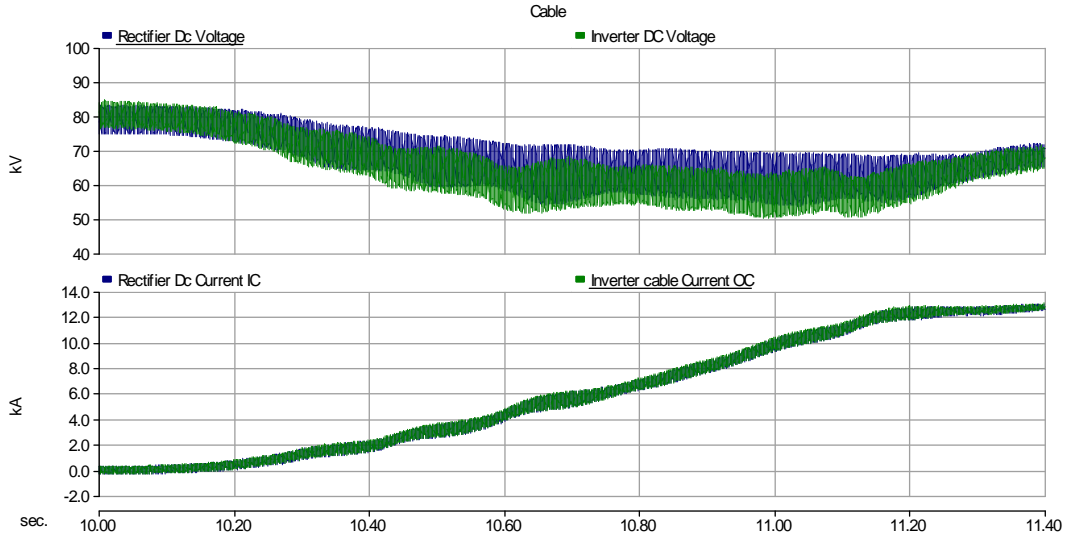


Figure 3-5
Ramp of current from zero to 12.5 kA

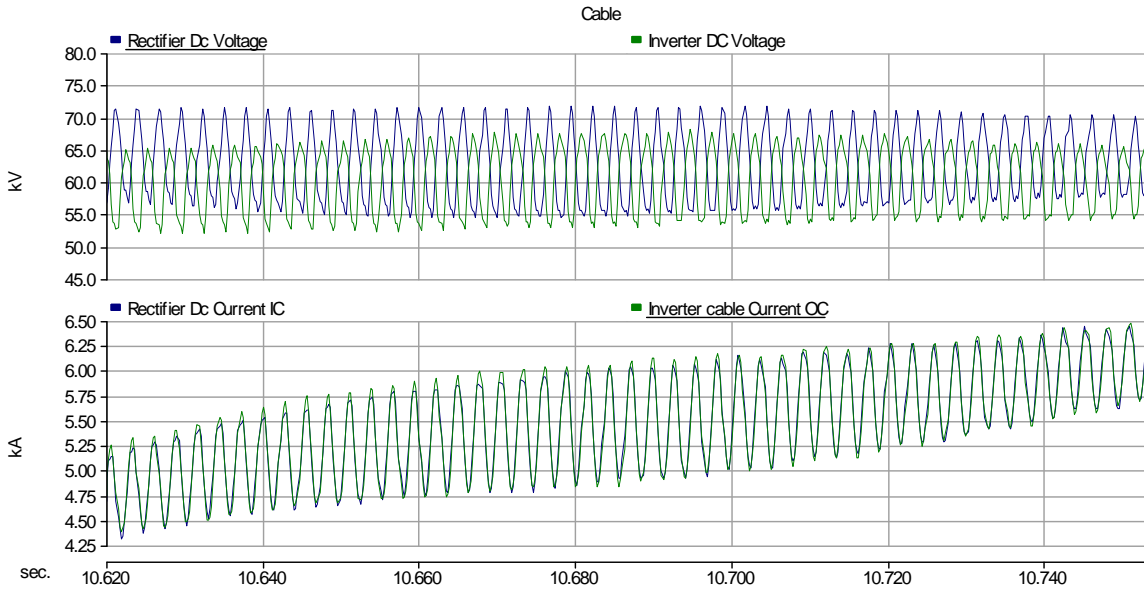


Figure 3-6
Voltages and currents during the power ramp

A more detailed plot covering approximately one-half 60 Hz cycle is shown in Figure 3-7, which shows a large 6th harmonic component in the currents and voltages.

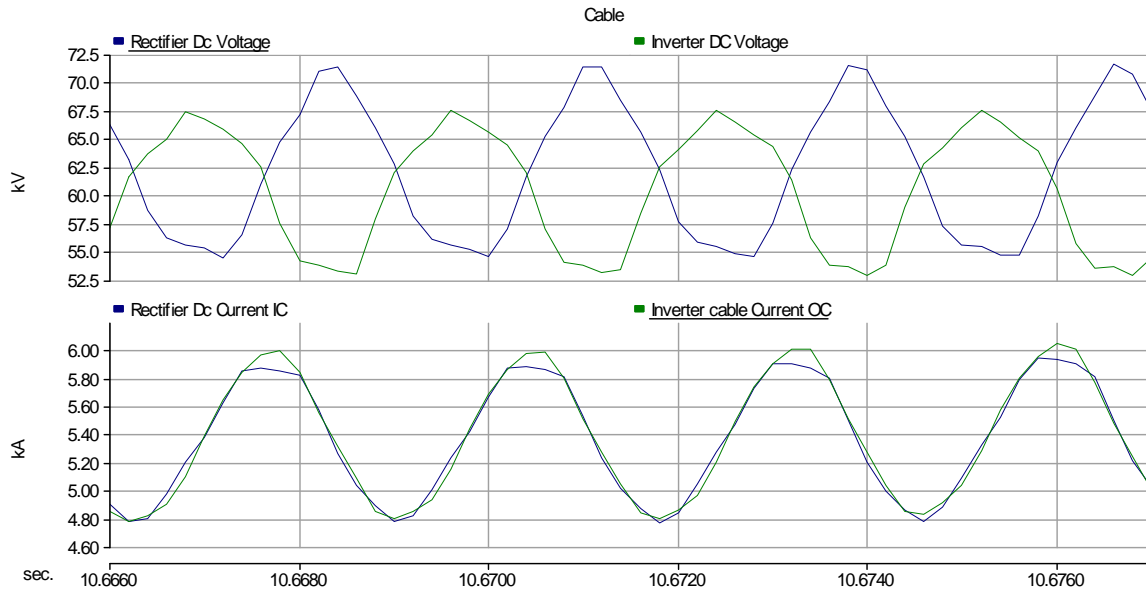


Figure 3-7
One 60 Hz cycle along the power ramp

The 6th harmonic is one of the dominant harmonic frequencies on the dc side, which will have to be attenuated to avoid imposing losses in the cable. A 6th harmonic filter has been included in the simulation but the filter characteristics should be better optimized to reduce the cable losses during power ramps. It is envisioned that a 2nd harmonic filter will also be required to attenuate injected 120 Hz currents into the dc side of the converter during unbalanced operation of the ac system. Such unbalances will arise during unbalanced short circuit faults on the ac side of the converters such as a single phase ground fault. Therefore, simulations were run also with a 120 MVA, 120 Hz filter added across the dc capacitor at the inverter and rectifier terminals. The resulting currents are shown in Figure 3-8 and the harmonic spectrum is shown in Figure 3-9.

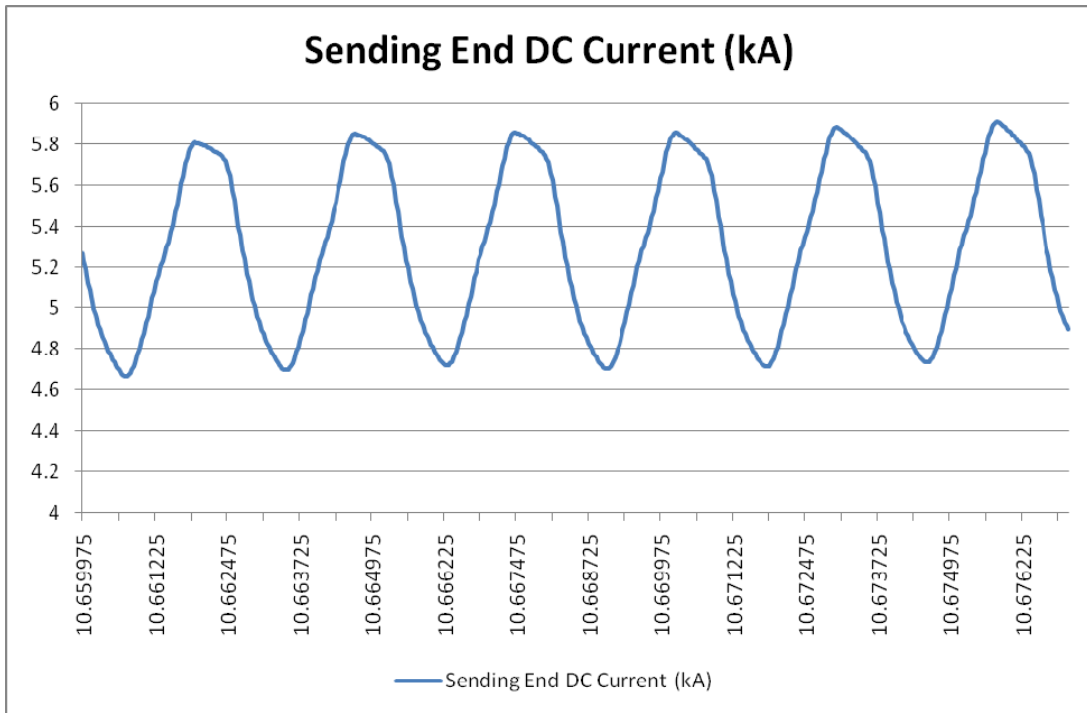


Figure 3-8
Sending end dc current ripple during the power ramp

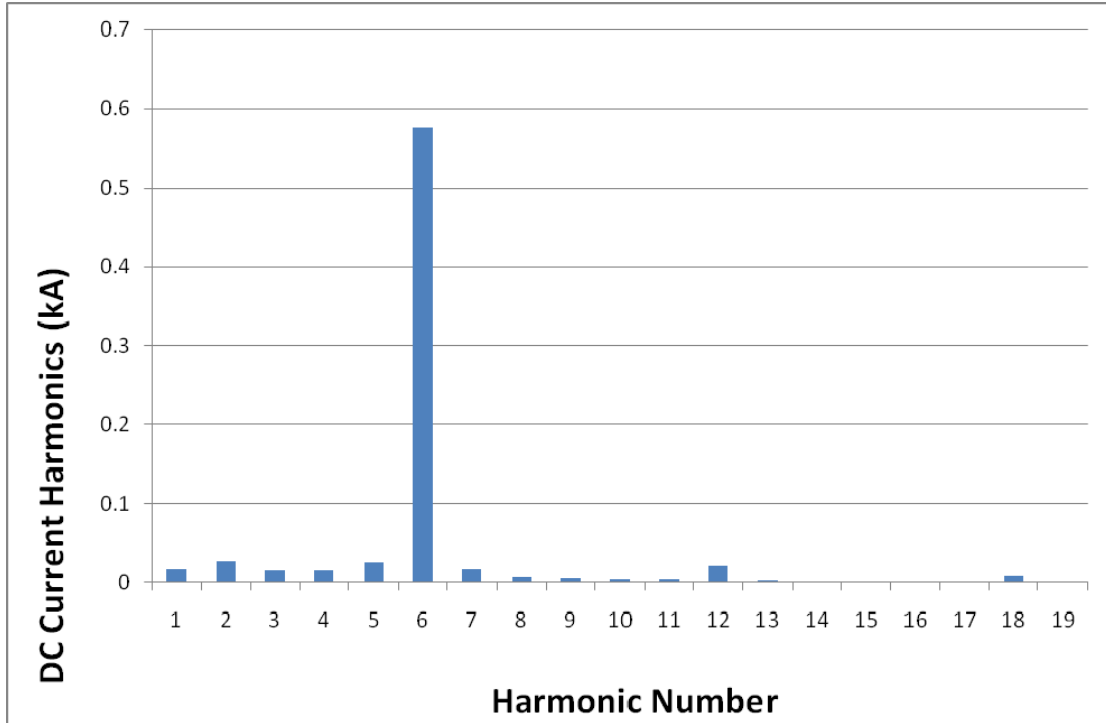


Figure 3-9
Harmonic spectrum of current ripple shown in Figure 3-8

As can be seen in Figure 3-8 and Figure 3-9, the main component in the spectrum is the 6th harmonic. The magnitude of the 6th harmonic component is relatively unchanged, which indicates that some additional damping is still needed in the filters or in the control system to avoid injecting large harmonic currents.

An important parameter of interest is power loss per unit length of the HTSC. The power loss associated with a 500 A 6th harmonic current, using the following formula that will give the loss per meter of superconducting cable, is about 113 W/m or 113J for a one second ramp. This is far above the tolerable level, which is assumed to be 0.5 W/m for continuous operation.

$$P(\text{W/m}) = \frac{\mu_0}{2\pi} I_c^2 \cdot \sum_{\text{all}_n} \omega_n \cdot \frac{I_n^2}{I_c^2} = \frac{\mu_0}{2\pi} \sum_{\text{all}_n} \omega_n \cdot I_n^2$$

Steady state harmonics are important to understand since this determines the steady state cooling requirements for the superconducting cable system. Figure 3-10 shows steady state operation at a 12.5 kA dc current (1 pu. dc power transfer). As shown in Figure 3-11, the dominating harmonic frequency in this case is the 6th harmonic. The losses associated with these currents are about 27 W/m, which is still too high for the cable. Assuming that the spectrum stays unchanged, the harmonics need to be attenuated by almost an order of magnitude to get below the 0.5 W/m acceptable for the cable. Therefore, an improved filtering arrangement was studied.

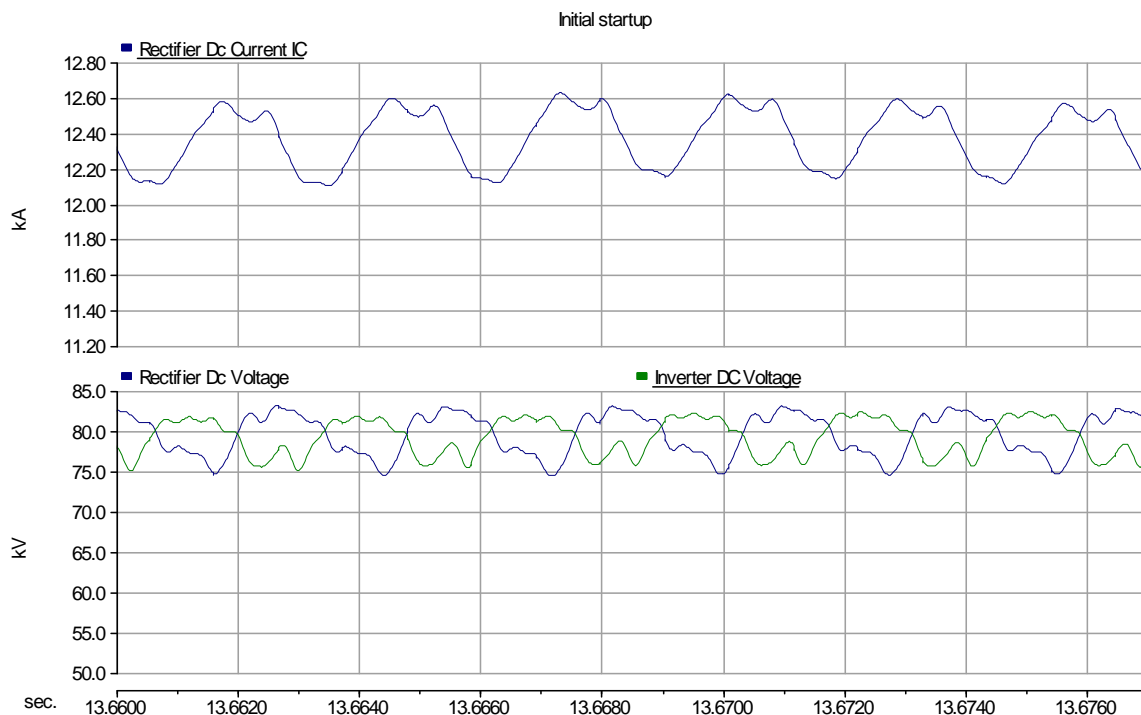


Figure 3-10
DC voltage and current ripple at the sending end converter terminal

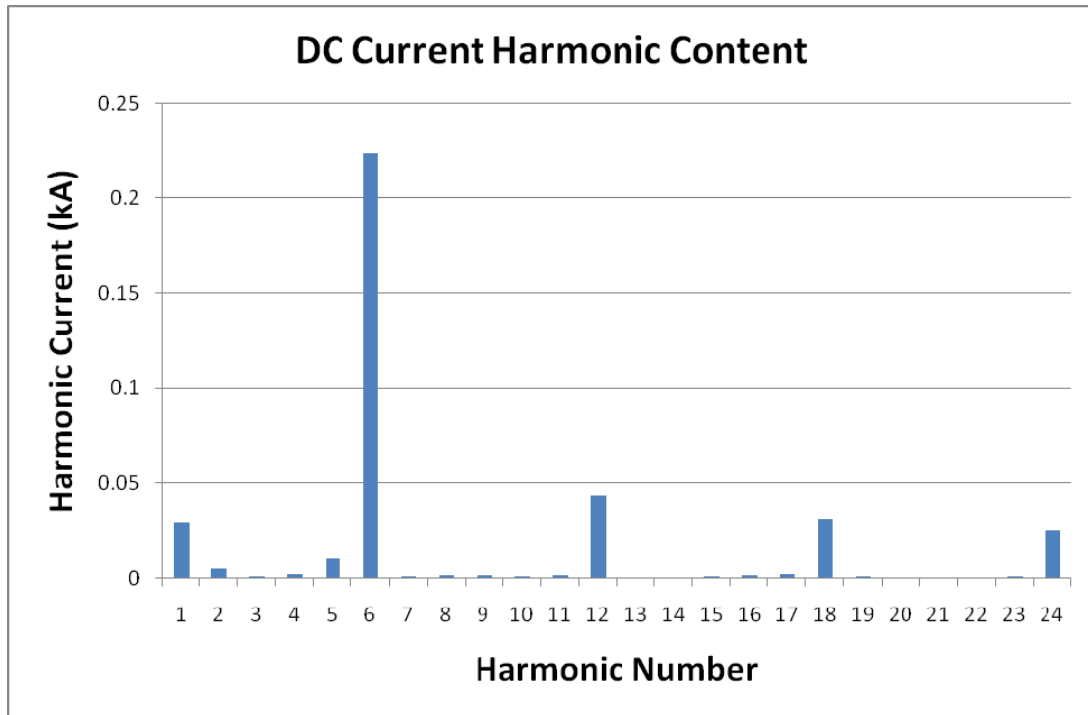


Figure 3-11
Steady-state dc cable current harmonic spectrum

Better attenuation of the converter harmonics can be achieved by using a balanced “I-type” filter between the dc capacitor and the cable. The filter must be balanced, because current harmonic injection into the superconducting neutral side of the cable and ground would cause losses and generate heat in this part of the cable. Thus, it is not sufficient to limit the harmonic currents flowing between the center and neutral conductors of the cable. A schematic of the studied filter is shown in Figure 3-12. This filter consists of a 120 Hz branch to attenuate 120 Hz voltages injected into the dc side of the converter from an unbalanced 60 Hz ac network. It also has a 360 Hz branch to attenuate the fundamental dc side 6th harmonic frequency.

The characteristic of the filter is shown in Figure 3-13. The filter characteristics calculation assumes that the cable can be represented by its surge impedance, which is a real impedance of about 20 Ω . The inductances on both sides of the tuned filter branches provide impedance towards the dc side converter capacitor as well as the cable capacitance. Because of these inductances, the reflection coefficient changes from a short circuit to a high impedance, which will cause the voltage magnitude of an incoming surge to double for a few milliseconds as the wave is reflected.

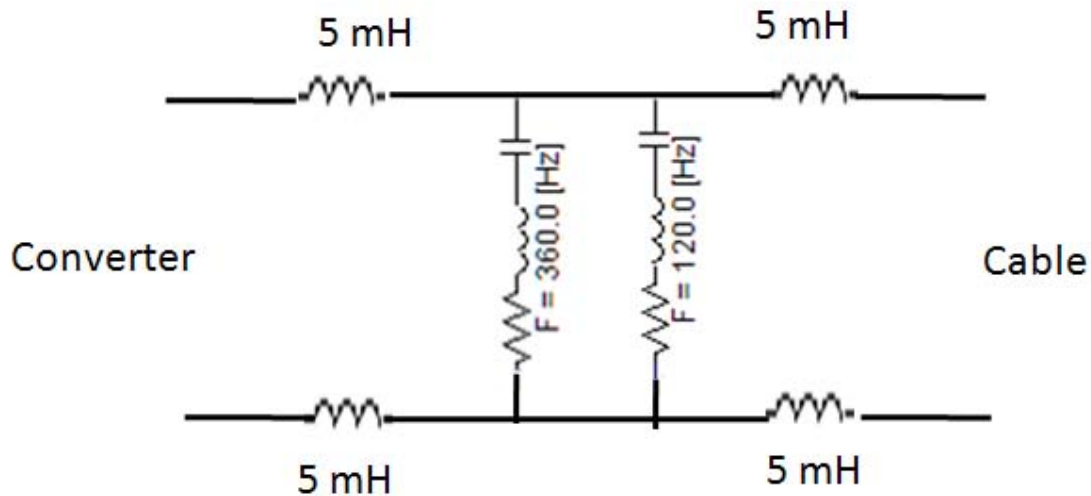


Figure 3-12
Balanced four pole filter for attenuation of 2nd and 6th harmonics

Using the new filter, the harmonics injected into the cable are shown in Figure 3-14. The losses are reduced to 0.88 W/m. However, a significant contributor to the losses is a 60 Hz component, which probably arises as a result of the gain introduced by the filter below 120 Hz. If the filter were to be optimized, this component could be eliminated or substantially reduced. If this were to be the case, the losses would be reduced to 0.27 W/m, which for this power level is below the limit of 0.5 W/m.

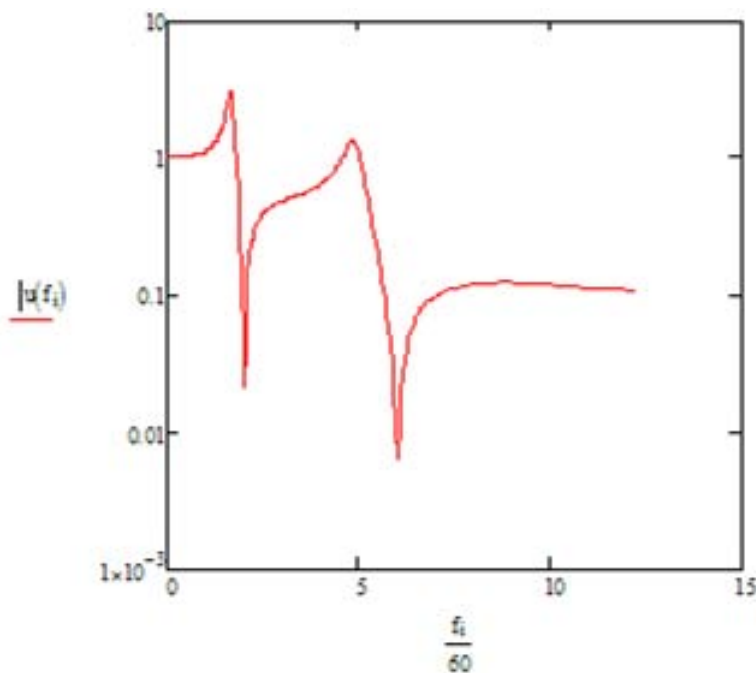


Figure 3-13
Impedance as a function of frequency for the filter shown in Figure 3-12

Extension to Multi-Terminal Systems

In a multiterminal system with a large number of converter stations connected to the cable, it is envisioned that the largest converter terminal would be 1000 MW or less. Thus, the harmonics injected from a single terminal should be much less than the 0.5 W/m. The harmonics from the different converters will also be attenuated in the cable. This means that the injected harmonics will combine with the attenuated harmonics injected from other terminals. Therefore, for each multiterminal system, the losses in the cable as a result of such harmonic injections need to be studied in detail to ensure that the cable losses are not excessive at any point along the length of the cable. The loss evaluation part of this study is included here only to show that the steady state harmonic injection can be limited to meet the design criteria for the superconducting cable.

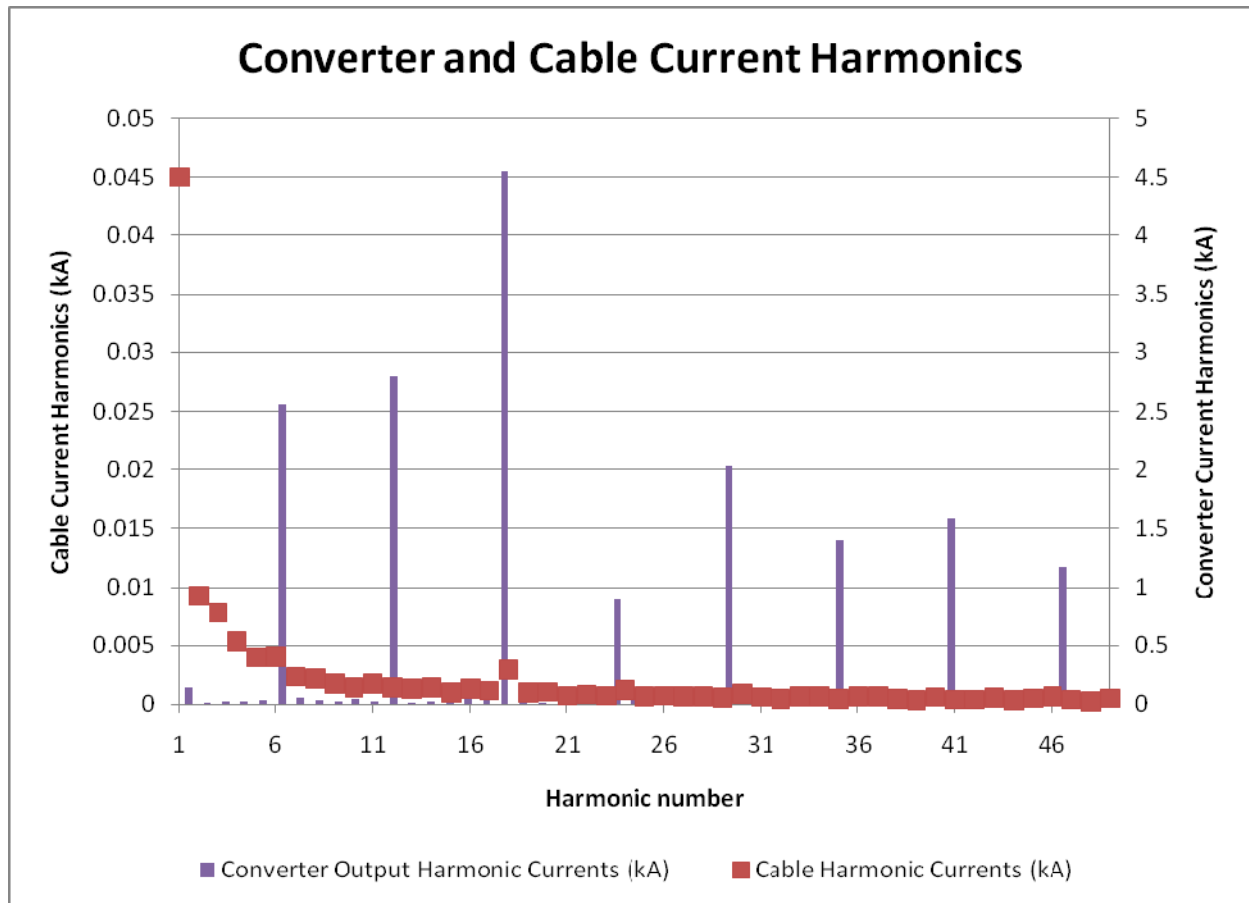


Figure 3-14
Converter and cable harmonics with the balanced I-type filter

Comments on dc-Side Harmonics

The harmonic spectrum of the converter for a constant dc voltage with a PWM with carrier frequency of m_f is fairly well known, with the first two ac-side voltage harmonics as $f.(m_f \pm 2)$ on the ac side for a constant dc voltage. In this derivation, the dc rail capacitor is assumed to be infinitely large to maintain a constant dc voltage, although this is an approximation since in an actual VSC system with a finite dc rail capacitance, the dc voltage is not constant. The dc current is as follows [2]:

$$i_D(t) = k_a(t) \cdot i_a(t) + k_b(t) i_b(t) + k_c(t) \cdot i_c(t)$$

Where $k_i(t)$ is the switching function for the converter valves and $i_i(t)$ is the instantaneous current in the ac phase.

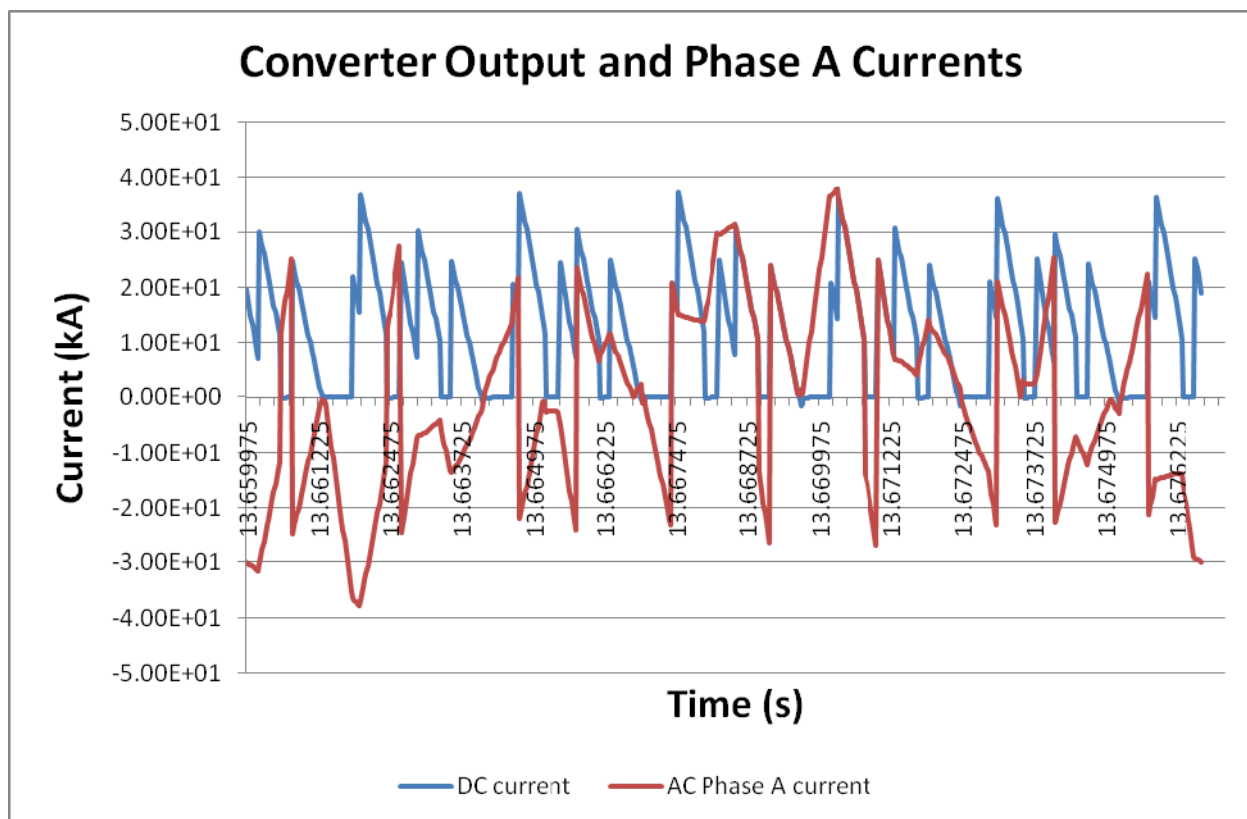


Figure 3-15
One phase of the ac current and the output current from the converter

The dc-side harmonics for a rectifier operation can be explained using converter behavior to ac side harmonics. The converter maps a positive phase sequence (PPS) harmonic from the ac-side to one harmonic less on the dc side, and maps a negative phase (NPS) sequence harmonic from the ac-side to one harmonic more on the dc side (see Figure 3-16).

In case of a VSC using a synchronized PWM switching sequence, the ac side voltage at no-load is theoretically free from harmonics. However, it can also be assumed that the ac side voltage of the converter is compensated with the converter's characteristic harmonics: i.e. harmonics equal to the negative of the converter characteristic harmonics can be assumed to have been added to the ac side and canceled these characteristic current harmonics. Using this analogy, and assuming that the assumed compensating harmonics do not interfere with the PWM switching sequence, the dc side effect of these harmonics can be determined. The first two harmonic voltages to be considered are m_f-2 and m_f+2 . For m_f chosen as a multiple of three, the two harmonics m_f-2 and m_f+2 are positive and negative sequence respectively. The positive sequence voltage m_f-2 is modulated on the dc side to m_f-3 and the negative sequence voltage m_f+2 is modulated to the dc side to m_f+3 . For $m_f = 9$ they would become 6th and 12th harmonics.

This reasoning can be extended to the second ac side harmonic band: $2m_f \pm 1$. The $2m_f-1$ and $2m_f+1$ are the negative and positive sequence respectively, so each is modulated to the $2m_f$ (18^{th}) harmonic.

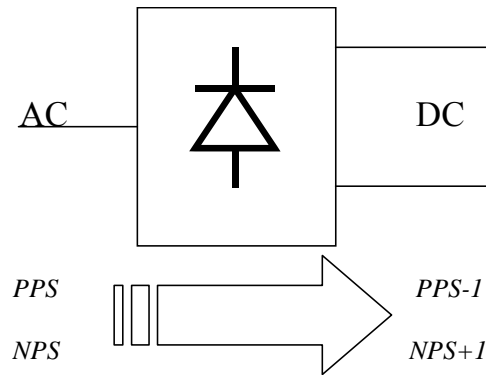


Figure 3-16
Harmonics transfer through a converter

The harmonic spectrum of the currents shown in Figure 3-15 is shown in Figure 3-17. The dc current is about 12.5 kA and the amplitude of the dominating 6th harmonic in the dc current is about 225A, or about 1.8%.

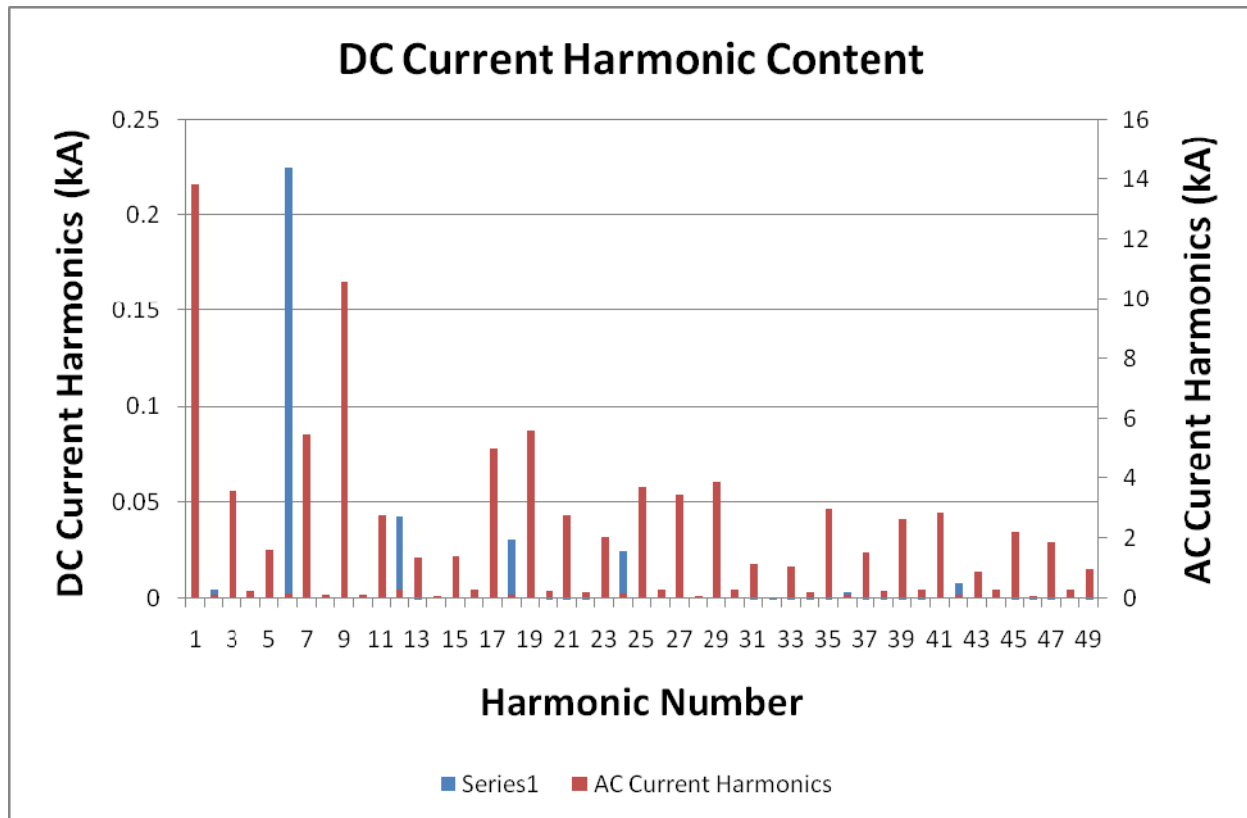


Figure 3-17
Harmonic spectrum under steady state conditions when operating at 1 p.u. load

Sudden Load Drop

The effect of sudden load drop was investigated by opening the receiver side's ac breaker. This breaker was opened at 16.0 seconds after the system had reached steady state conditions and was transferring 1 GW of power. As can be seen in Figure 3-18, the instantaneous power surplus at the inverter end results in a sudden voltage increase across the cable. In this simulation run there were no arresters included to limit the overvoltages. The cable voltage swings up to 250 kV, and a ringing frequency of about 11 Hz is observed at the cable ends. This event shows that the stored energy in the inductance of the cable is converted to stored energy in the cable and the filter capacitors. The inductive energy stored in the cable is trapped between the inverter diode and the rectifier. As can also be seen in Figure 3-18, the rectifier is sending some of the excess energy back into the ac system, which reduces the dc cable voltage, and the system eventually settles at 80 kV voltage and zero current flow. However, this leads to very large peak currents in the semiconductor switches. These currents are too large for the switches to handle, so in an actual converter installation, over current protection features of the valves would shut off the valves before the current reaches excessive levels. This simulation shows the operation of the converters without any such constraints. The cable losses (i.e., in an actual superconducting cable these ac losses would normally be encountered when superconducting materials are exposed to alternating fields) eventually cause the oscillation to die down.

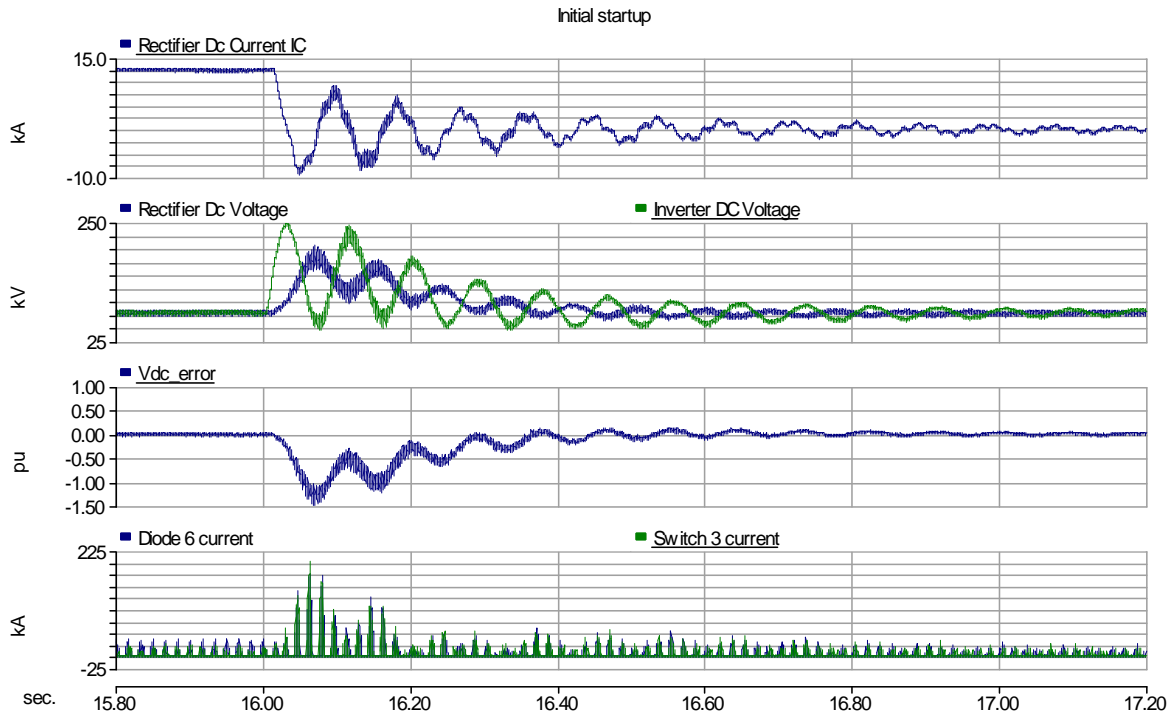


Figure 3-18
Currents and voltages after opening the ac breaker at the inverter

In an actual system, overvoltage protection will also be used to limit the cable overvoltages. Figure 3-19 shows the same event but with arresters installed at both the sending and receiving end converter terminals. The dc current goes to zero in less than 0.5 seconds and the overvoltages are limited. The oscillations are well damped by means of the arresters. Figure 3-20 shows the energy absorbed by the arresters. The inverter arrester will absorb 200 MJ during this event, which requires a substantial bank of MOV arresters.

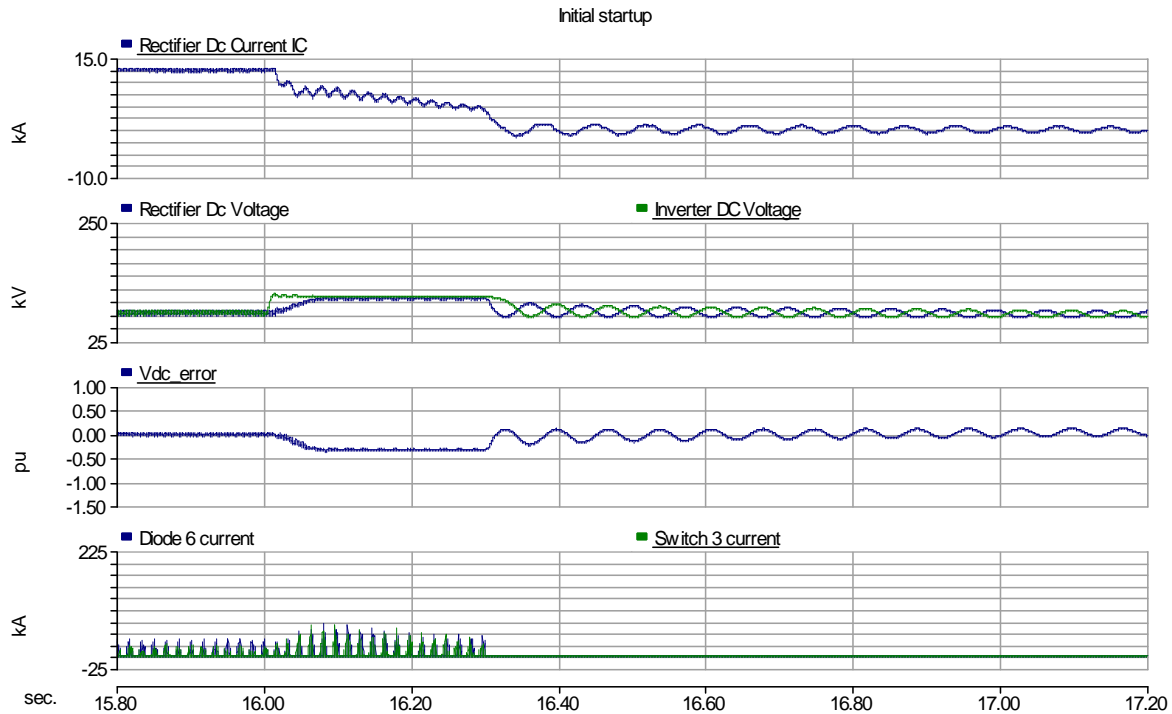


Figure 3-19
Opening of the receiving end ac breakers with MOV arresters installed at both ends of the cable

The opening of the sending end ac breaker is fairly benign for the cable as shown in Figure 3-21. The system voltage collapses because the receiving end's converter (inverter operation) drains the power from the cable while the diodes in the sending end converter are freewheeling and therefore continue to provide a path for the direct current. However, the receiving end converter has to be blocked because it cannot operate into the ac side with zero dc voltage. As soon as the inverter valves are blocked, the trapped magnetic energy in the cable will cause the system to behave in a similar way to the case of opening of the receiving end ac circuit breaker as described above.

Simulation Results

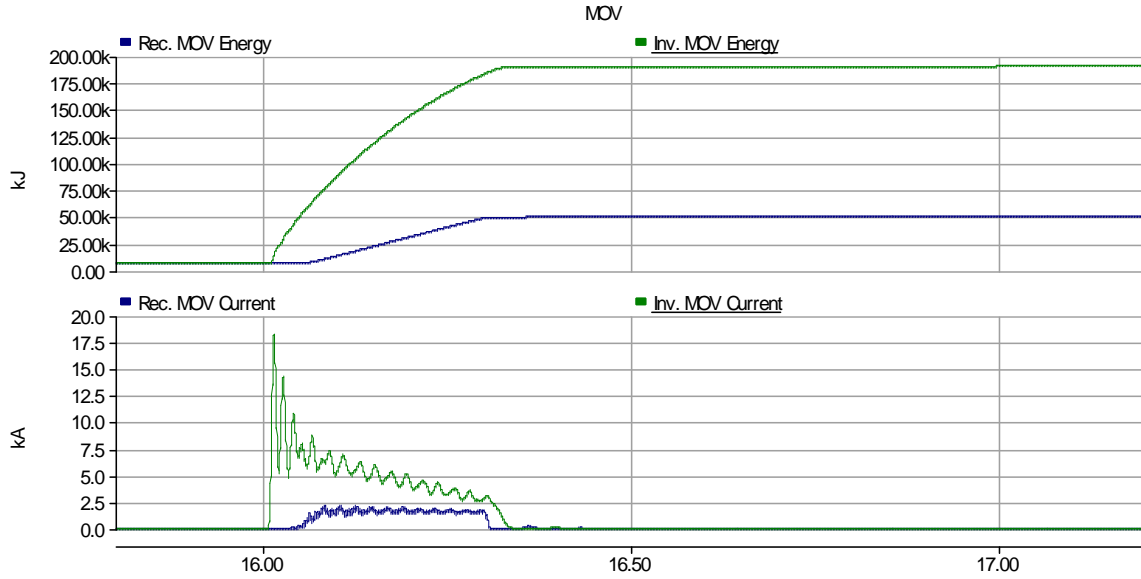


Figure 3-20
Energy absorbed by the MOV arresters

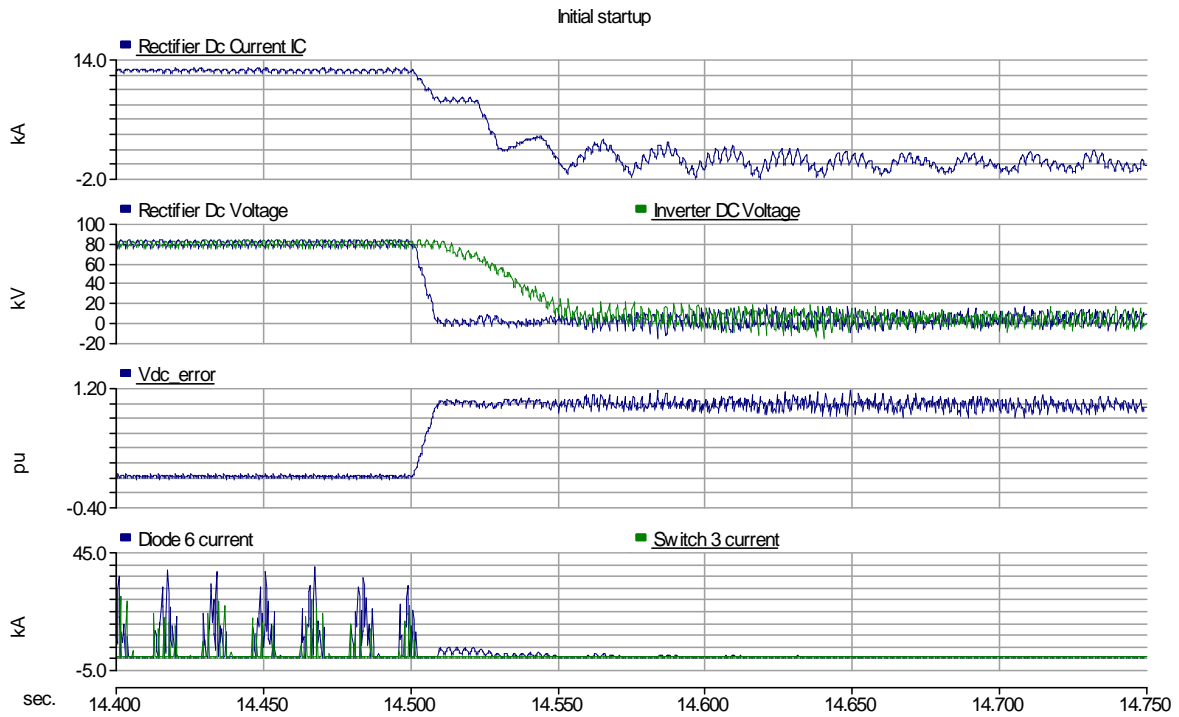


Figure 3-21
Opening of the sending end's circuit breaker without blocking the receiving end converter

Extension to Multi-Terminal Systems

A multi-terminal superconducting cable transmission system is assumed to have many connected converters. The example shown above for a two terminal system could be viewed to represent a blackout in an area fed by five converters, each rated 200 MW. The energy stored in the cable's inductance is:

$$W = \frac{LI^2}{2}$$

If it is arbitrarily assumed that the cable current drops from 100% to 90% as a result of the ac system disturbance (e.g., one of the five terminal drops to half current), the energy that has to be transferred from the cable inductance to the other operating terminals will be 19% (1 minus 0.81) of the total magnetic energy in the cable for the cable segments affected by the change. Since it is also assumed that all but the voltage controlling sending end converter will be controlled on constant current, the increased voltage associated with the drop in the dc current will automatically lead to higher output power from the receiving end converters. Therefore, the magnetic energy released in the cable will flow into the ac systems where it will be readily absorbed. Thus, the arrester duties will only be severe if the entire power transmitted through the dc cable needs to be dissipated in the arresters, which should be an unlikely event although the arrester banks have to be designed to handle this contingency.

Another assumption made for control of the multiterminal dc system studied here is that the voltage controlling converter or converters will adjust their voltage set point such that if the demand for power is increased, the voltage set point will be reduced, and if the demand for power is reduced, the voltage set point will be increased. That is, the voltage control loop will have a droop characteristic such that the loss of the largest rectifier terminal should not cause a collapse of the system, and the loss of the largest inverter terminal will lead to redistribution of the loads and generation such that a new equilibrium is found that satisfies the power schedules. The dynamics of such a control system will require further studies.

Voltage Sag

Voltage sags caused by ac system short circuits can affect a large geographic region. Symmetrical ac system faults are relatively easy to deal with by using the normal controls used for voltage source converters. However, unsymmetrical ac voltages, such as those arising from ac system short circuits to ground, lead to injection of second harmonics into the dc side of the converter. This leads to losses in the superconducting cable that might lead to quenching of the super conductive material if not controlled. Also, it leads to over current in the converter valves. Unsymmetrical ac system voltages caused by single phase short circuits to ground are also most frequent, which makes it important to find solutions for how to handle the voltage sags caused by such faults.

For the superconducting dc cable transmission system envisioned here, there will be many converter connections to the dc cable, which could simultaneously experience voltage sags. From the ac system point of view, it would not be desirable to shut down the dc power system during such faults and then go through a restart when the ac faults are cleared, because the power levels transferred through the dc cable are assumed to be very large and the losses imposed on the dc cable by rapid current changes would impose severe thermal stresses on the cable.

Voltage sags are also a common mode disturbance that will affect converters connected to all of the converters in the vicinity of the disturbance. Therefore, even if the dc cable system was comprised of redundant dc cables with their own sets of connected converters, the sag will affect both systems equally. The potential for a loss of all power from both dc cables at the same time would impose unacceptable stresses on the ac systems served by the cable. It would probably be acceptable and necessary to have those converters that are close to the ac system fault shut down momentarily while the fault is being cleared, under the assumption that the converters would be able to restart quickly after the fault. Therefore, it would be desirable to have the converters be able to operate through voltage sags possibly as large as 50%.

Large 2nd harmonic filters could be used to control the losses in the cable, but not the over current in the converter valves. However, this is an expensive solution, so it would be desirable to find a control system approach to minimize the harmonic voltage injection into the cable and also the over current in the valves. Controlling the gating on and off of the individual converter valves might be an approach to maximize the positive sequence voltage and current flowing into the cable and to minimize the negative sequence currents and voltages as seen by the cable. Such special control features are reportedly used in some commercially operating VSC systems. However, such modification of the basic control system is not easy to implement, therefore only the use of a 120 Hz filter has been investigated here. The effect of single-phase voltage sag manifests itself as a fundamental negative sequence on the ac side. The negative sequence is then transferred to the dc side as a second harmonic component. Figure 3-22 shows the spectrum of the cable dc current for a 20% sag in the phase “a” voltage⁷ at the receiving end of the cable system and Figure 3-23 shows the dc side cable current and voltage for this voltage sag. Figure 3-24 shows the matching sending end (rectifier) behavior. No 120 Hz filter is included in these simulation runs.

⁷ A 20% drop in one phase represents a positive sequence voltage of 93% and a negative sequence voltage of 7% on the converter side of the transformers since the converter transformer blocks the zero sequence component. The negative sequence component is causing the 120 Hz ripple in the dc voltage and current.

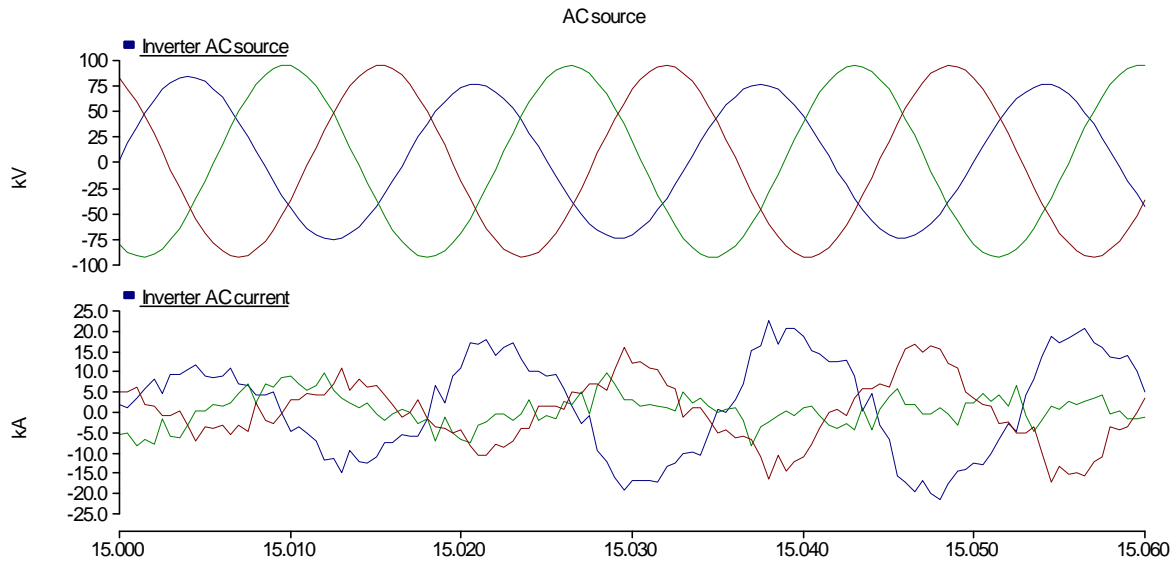


Figure 3-22
Receiving end ac voltages and currents after a 20% drop in the voltage of phase a

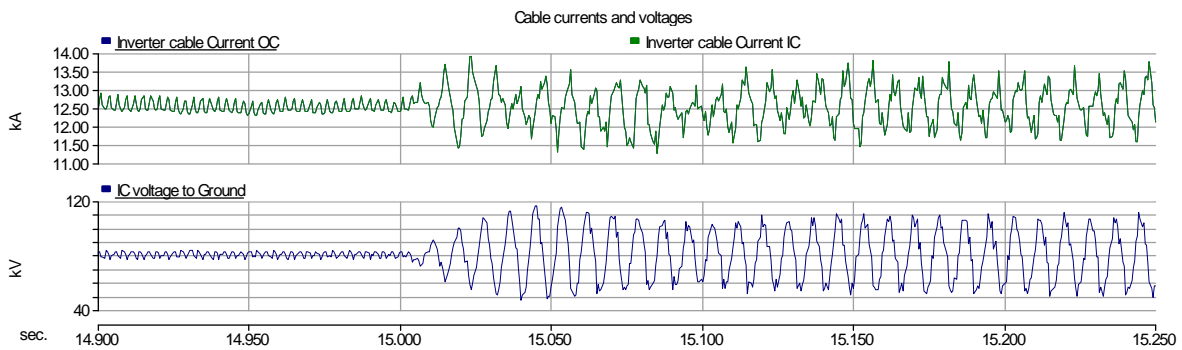


Figure 3-23
Receiving end cable current and voltage for a 20% drop in the ac voltage

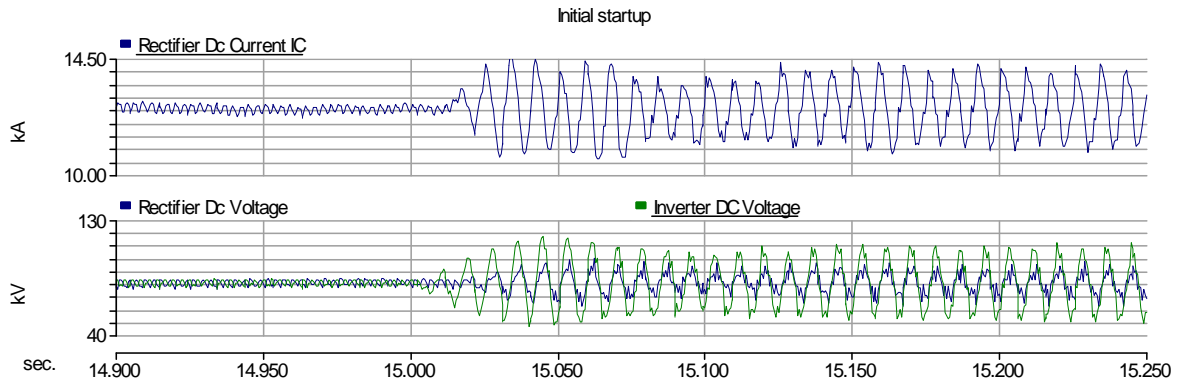


Figure 3-24
Sending end current and voltage with the inverter side voltage overlaid

Figure 3-25 shows the harmonic spectrum in the inverter current during the voltage sag. The dominating harmonic is the second at 120 Hz. The losses based on the calculated spectrum are estimated to be about 114 W/m, which is 230 times the allowable cable loss for continuous operation. These losses will typically only last for about 10 cycles, since this is the normal time for clearing a stuck breaker pole using breaker failure backup relaying systems. This should limit the power dissipation to about 20 J/m.

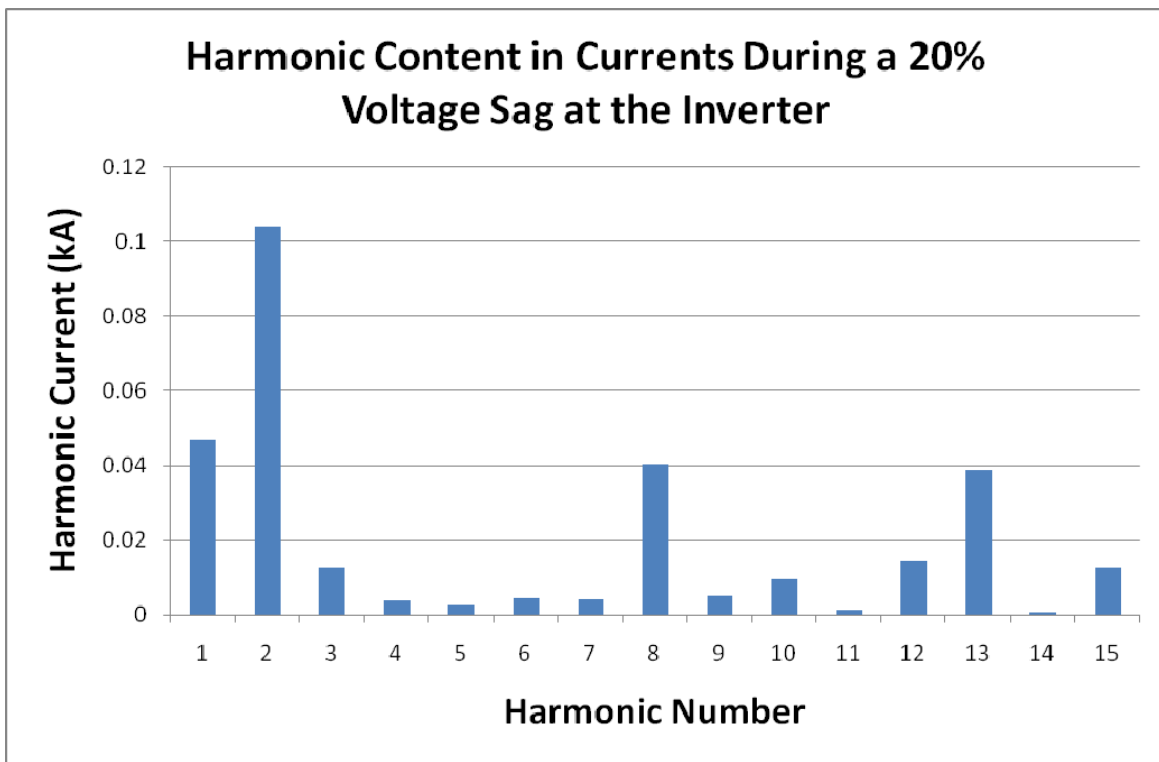


Figure 3-25
Harmonic content of the inverter current for a 20% voltage sag

As mentioned above, one way to reduce the injected second harmonic into the cable is to use a 2nd harmonic filter across the dc output bus of the converter. Figure 3-26 shows the receiving end ac system voltages and currents for a 20% voltage sag on one phase at the receiving end converter. The first 5 cycles after the initiation of the fault do not appear to be significantly different from the currents seen in Figure 3-23, but after the initial transient, the injected cable currents are significantly reduced. A reduced Q-value of the 120 Hz filter might provide faster response and more attenuation of the initial transient. However, after the initial 5 cycles, the 120 Hz current injection into the cable is substantially reduced. Figure 3-27 shows the switch and diode currents for the same event and the cable voltages and currents are shown in Figure 3-28. The graphs show the system response for about 10 cycles, which is approximately equal to the time it takes to clear a stuck breaker in a typical ac system. The currents in the two harmonic filter banks are shown in Figure 3-29. The harmonic spectrum for the harmonic currents injected into the cable is shown in Figure 3-30. The spectrum shows that the 2nd harmonic filter works well. It is very likely that a combination of valve controls to limit the second harmonic injection into the dc side and a 2nd harmonic filter will be the optimal solution.

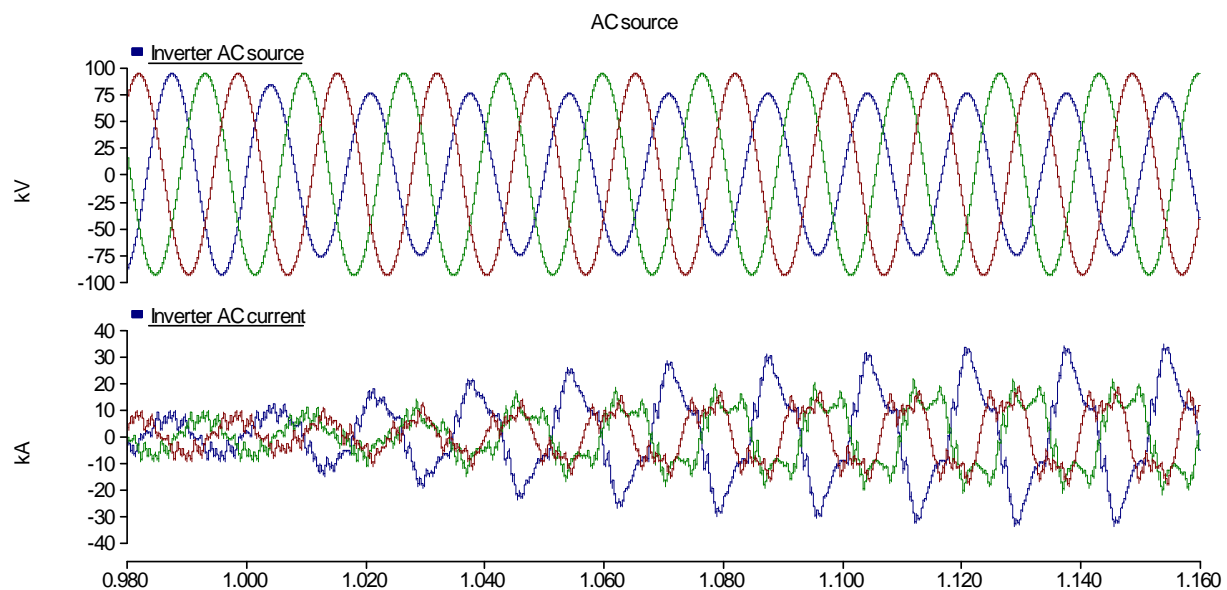


Figure 3-26
20% voltage sag on phase a at the receiving end with 120 Hz filter and no blocking of the converter

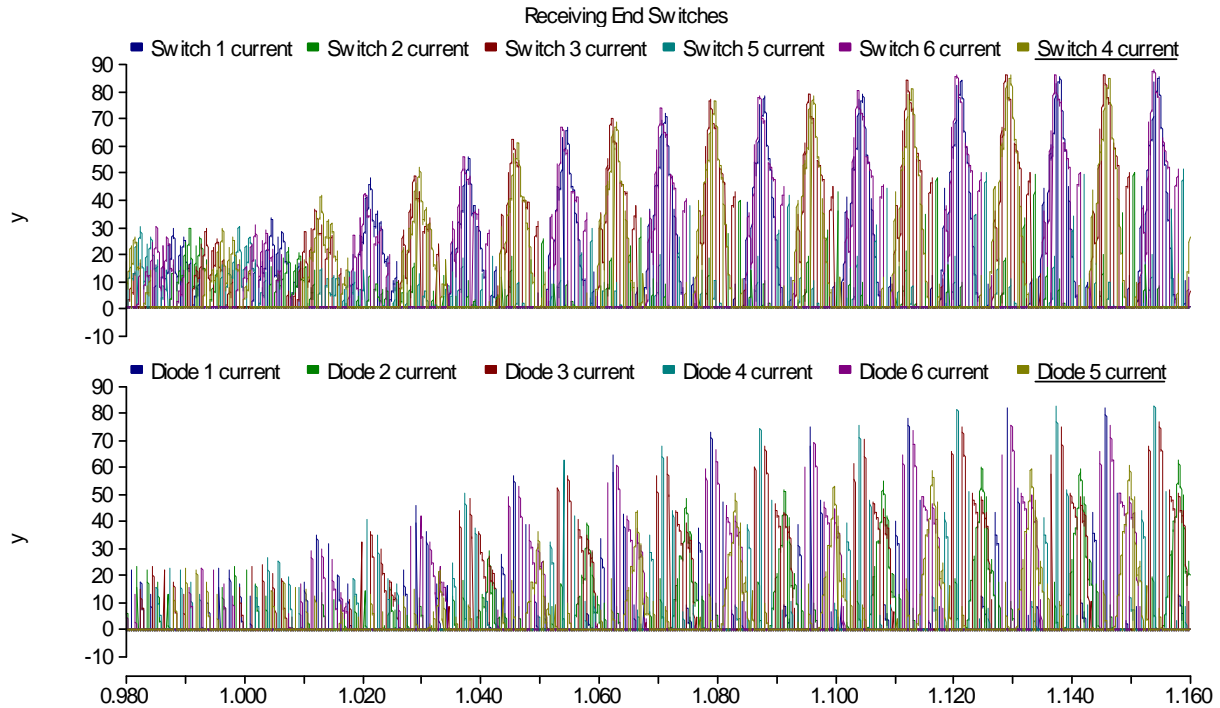


Figure 3-27
Switch and diode currents for a 20% voltage sag on phase a at the receiving end with 120 Hz filter and no blocking of the converter

The duty for the diodes and switches is illustrated in Figure 3-27. While the currents are significantly increased during the sag, the valves should be designed to ride through this level of ac voltage drop for at least 10 to 15 cycles. Larger voltage sags are likely. If the sag is large, it is probably not economical to maintain converter operation and a temporary blocking of the converters is probably necessary. However, fast restart (deblocking) of the converters at the end of the fault will be required. Such an event will lead to the dc current first going to zero and then returning back to the pre-disturbed level when the ac system recovers. This will induce losses in the cable, so it is important to maintain normal dc current for as deep a sag as possible to avoid introducing higher than necessary cable losses.

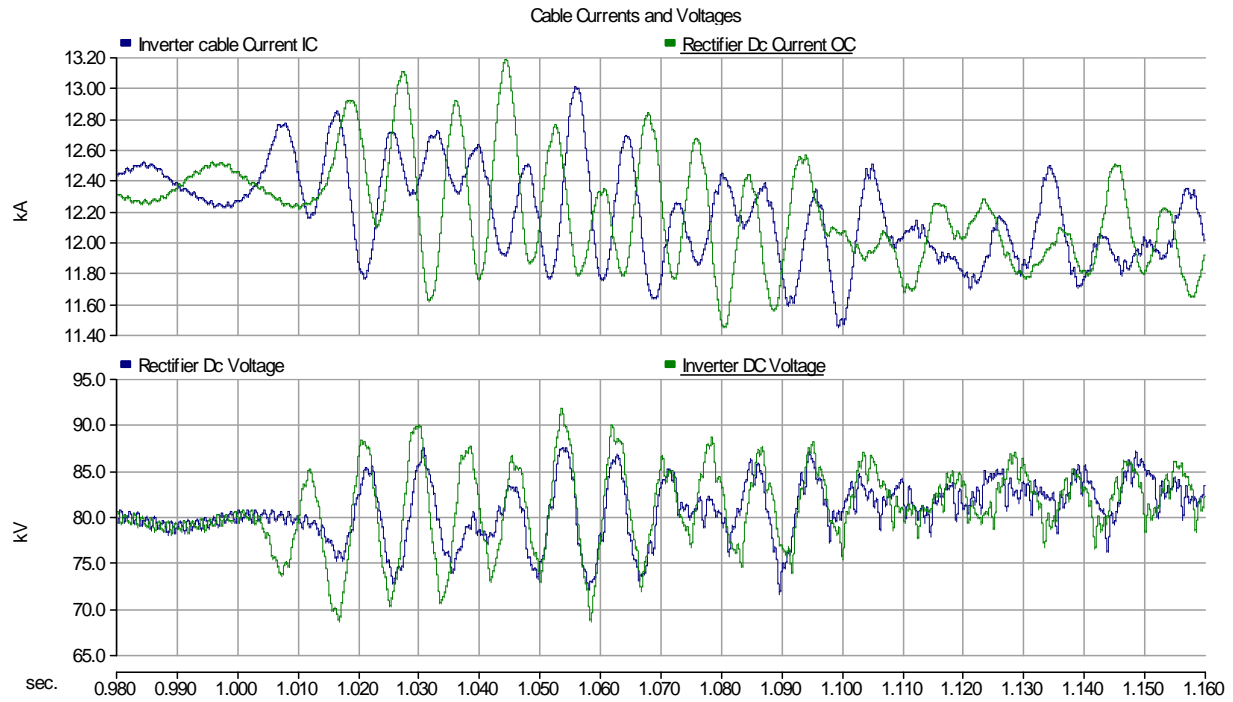


Figure 3-28
Cable voltages and currents for a 20% voltage sag in the ac system at the receiving end

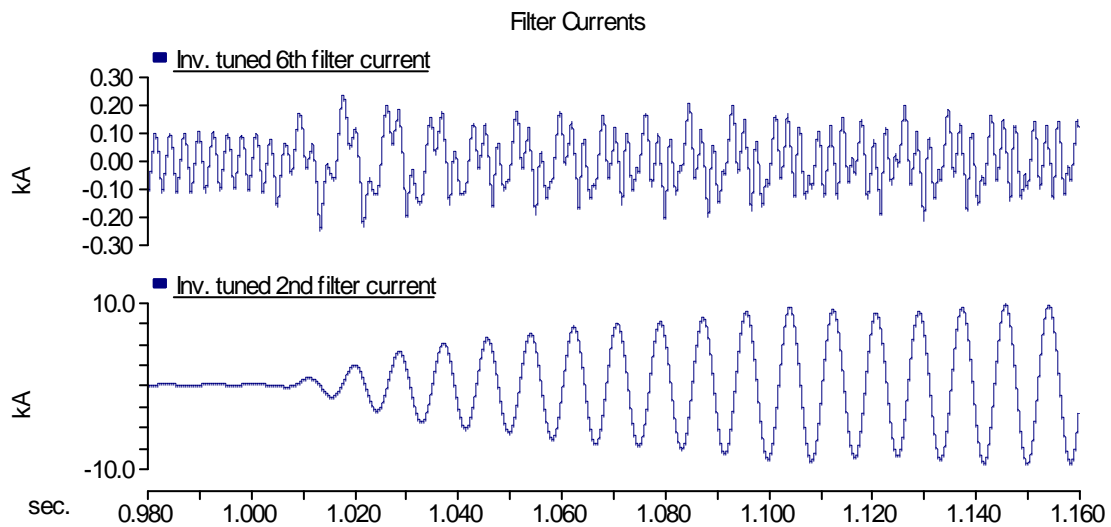


Figure 3-29
Receiving end filter currents for the 20% voltage dip at the receiving end

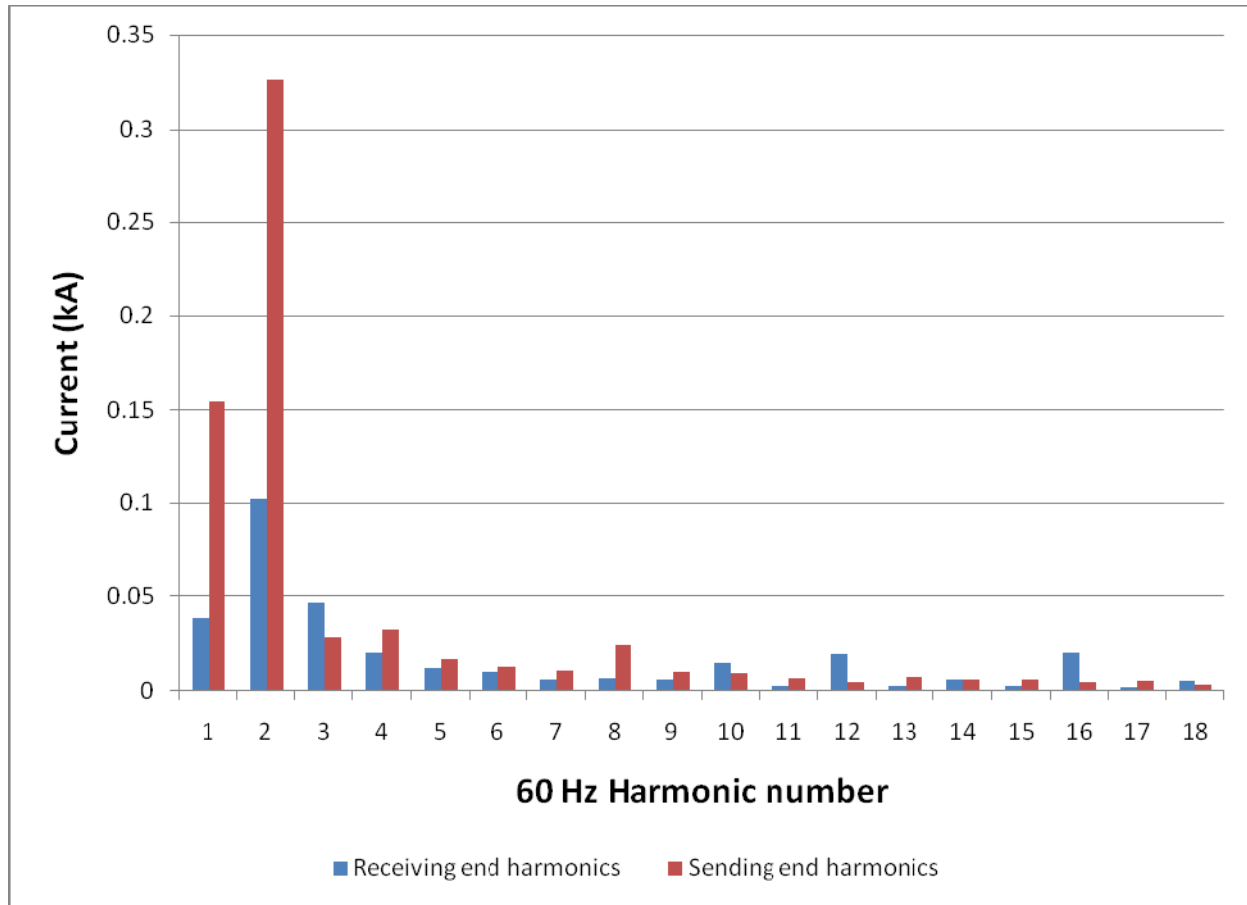


Figure 3-30
Current harmonic spectrum for the cable current with a 20% voltage sag on one phase

The cable losses estimated for the spectrum shown in Figure 3-30, which represents the steady state harmonic injection after the initial transient has subsided, are estimated to be less than 2 W/m at the receiving end and less than 10 W/m at the sending end. This indicates that there is an amplification of the harmonics injected from the receiving end at the sending end. This has not been explored further. While this is still above the allowable 0.5 W/m, it is closer to being tolerable. If the fault lasts for only a fraction of one second, it might be sustainable.

Voltage sag down to 50% of nominal ac system voltage on one phase is shown in Figure 3-31.⁸ In this case a 2nd harmonic filter was also assumed to have been added at both ends of the cable. Again, this simulation shows that the initial phase of this event causes large transient currents and voltages at both ends of the cable. This disturbance causes very high diode and switch currents, so the over current protection features of typical IGBT or GTO based valves can be assumed to operate and block the converter. The trade-off between valve ratings, control features and main circuit filters will need further study.

⁸ A 50% drop in one phase represents a positive sequence voltage of 86% and a negative sequence voltage of 17% on the converter side of the transformers since the converter transformer blocks the zero sequence component.

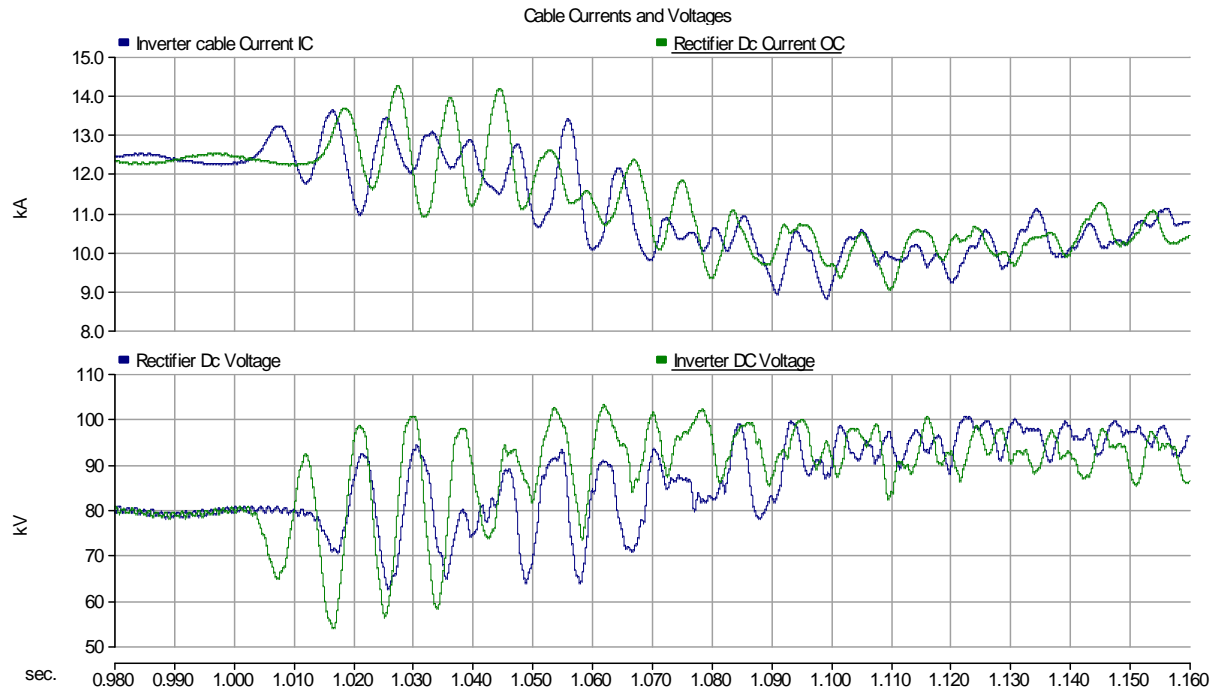


Figure 3-31
A 50% sag on one phase at the receiving end with 2nd harmonic filters

A 23% voltage sag at the rectifier end is shown in Figure 3-32. This figure shows the cable currents and voltages during the first 12 cycles after the fault. This rectifier is controlled to keep the voltage constant and therefore responds differently to the disturbance than the inverter, which is controlled on constant current. A large 120 Hz transient voltage first appears across the cable terminals. This is followed about 20 milliseconds later by the transient reflected from the sending end of the cable. This type of fault typically represents backup clearing of a stuck breaker, which typically is cleared in about 10 cycles.

Simulation Results

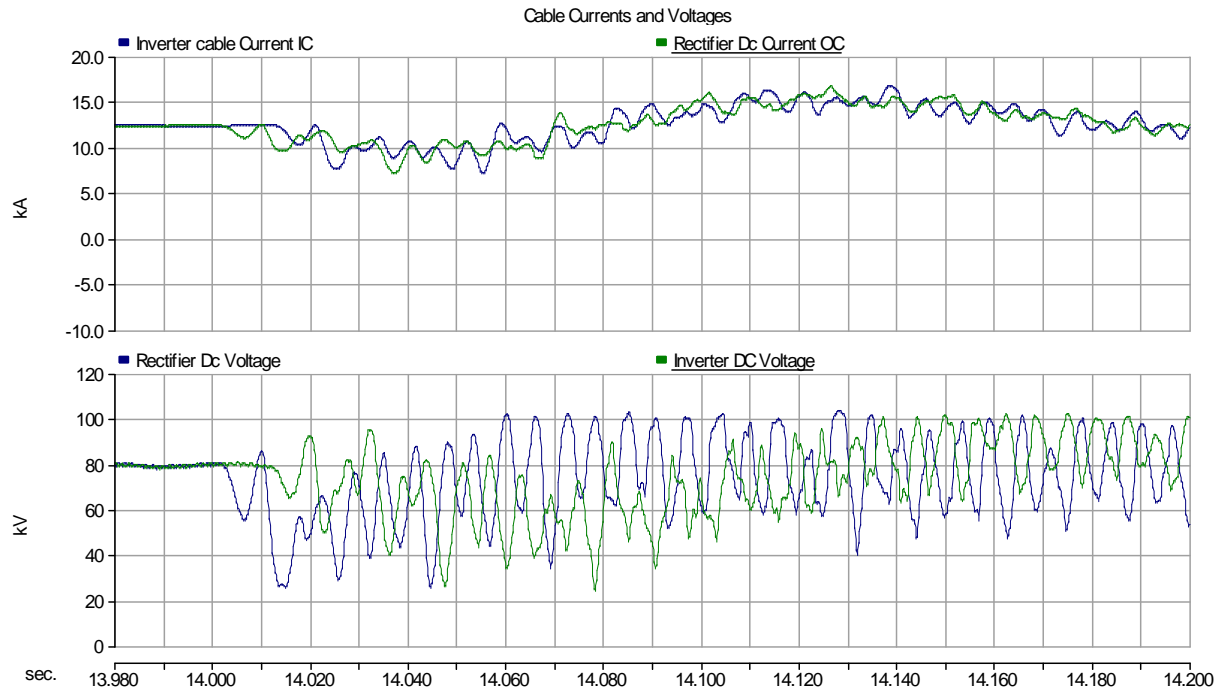


Figure 3-32
A 23% single phase voltage sag at the rectifier terminal

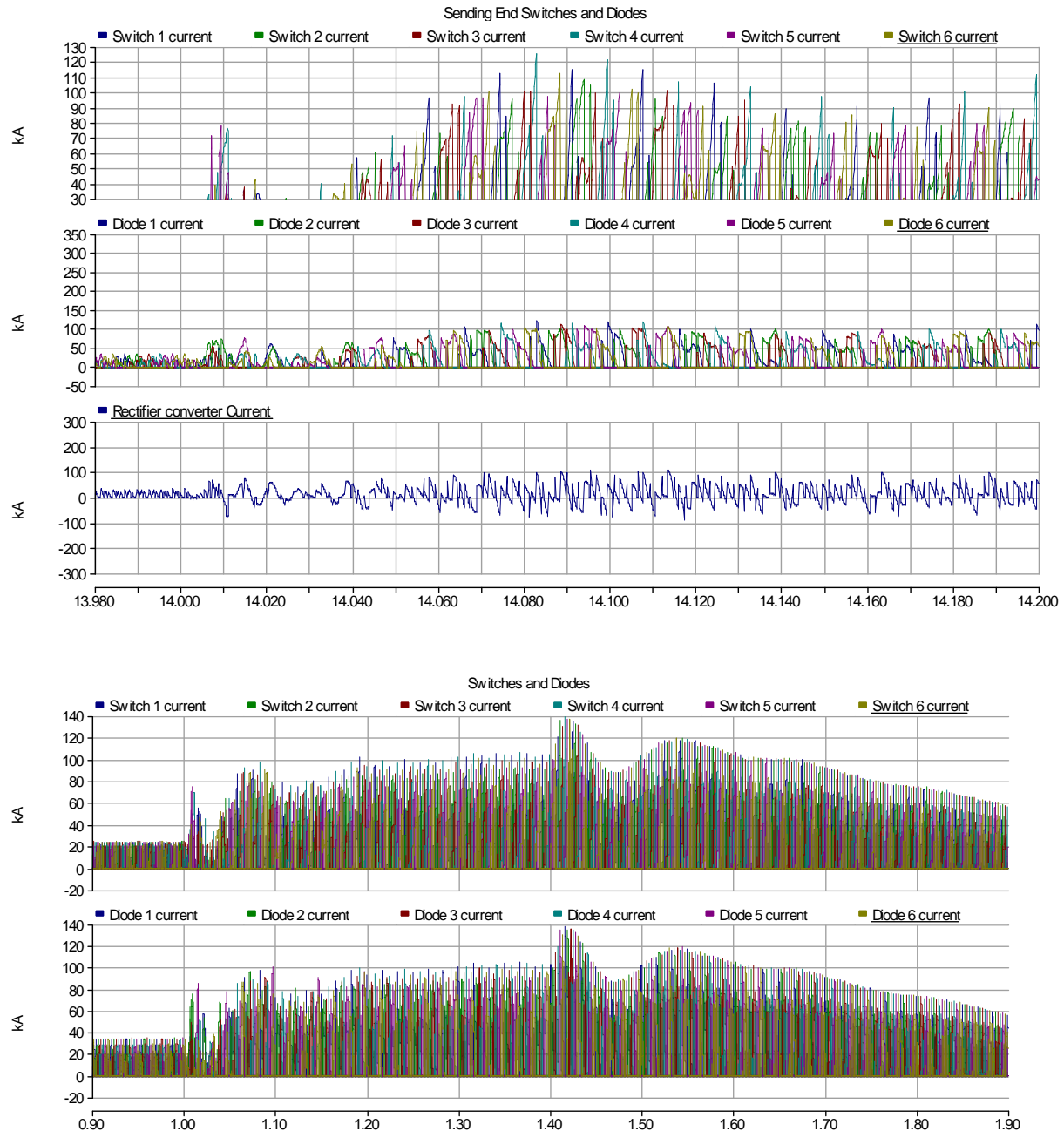


Figure 3-33
Diode, switch and dc output currents during and after the voltage sag event

The current duty of the diodes and switches during and after the sending end's voltage sag event are shown in Figure 3-33. One reason for the large diode currents is that the voltage across the converter's output capacitor drops dramatically as a result of the imposed 2nd harmonic voltage. This leads to high inrush currents from the ac side. Since the inverter continues to operate and draw power out of the cable, the dc voltage at the sending end drops, requiring larger current inflows through the diodes to maintain the voltage. Limiting the allowable voltage drop at the

receiving end would be one way to reduce the duration of any significant voltage sag from the converter at the receiving end. This should be possible to include in the control system of a receiving end converter.

AC System Faults

Because voltage sags have a significant impact on the performance of the dc cable system, a low impedance ac system fault at the connection point of the cables has also been studied. If it is assumed that there are two converters at one point in the ac system, each connected to a different superconducting dc cable, and an ac system short circuit occurs on the bus used to feed one of the converters, both converters will see zero bus voltage until the short circuit is cleared. The converter without a short circuit should recover after the fault has cleared and the power transmission should then resume. A three phase short circuit at the sending end is shown in Figure 3-34. The simulation is set up such that the receiving end converter is blocked before the cable charge is drained. (In a two terminal system as simulated here, the converter at the other end of the cable has to be blocked or the voltage on the cable will collapse, causing over currents in the converter if it is allowed to operate with zero dc bus voltage. Therefore, blocking the unfaulted converter is necessary.) The oscillations between the capacitors in the two ends of the cable and the cable inductance are unavoidable. Therefore, the cable has to endure these losses without going normal. As can be seen in Figure 3-35, in this case, the system shuts down relatively smoothly. The diodes in the converter valves can be freewheeling, which can be seen in the figure. If needed, dc breakers can be inserted into the positive and negative terminals of the converter since switching at zero current is feasible. However, these breakers can also be made using antiparallel connected thyristors or IGBT devices if current zero crossings are unreliable, requiring semiconductors that can self-commutate.

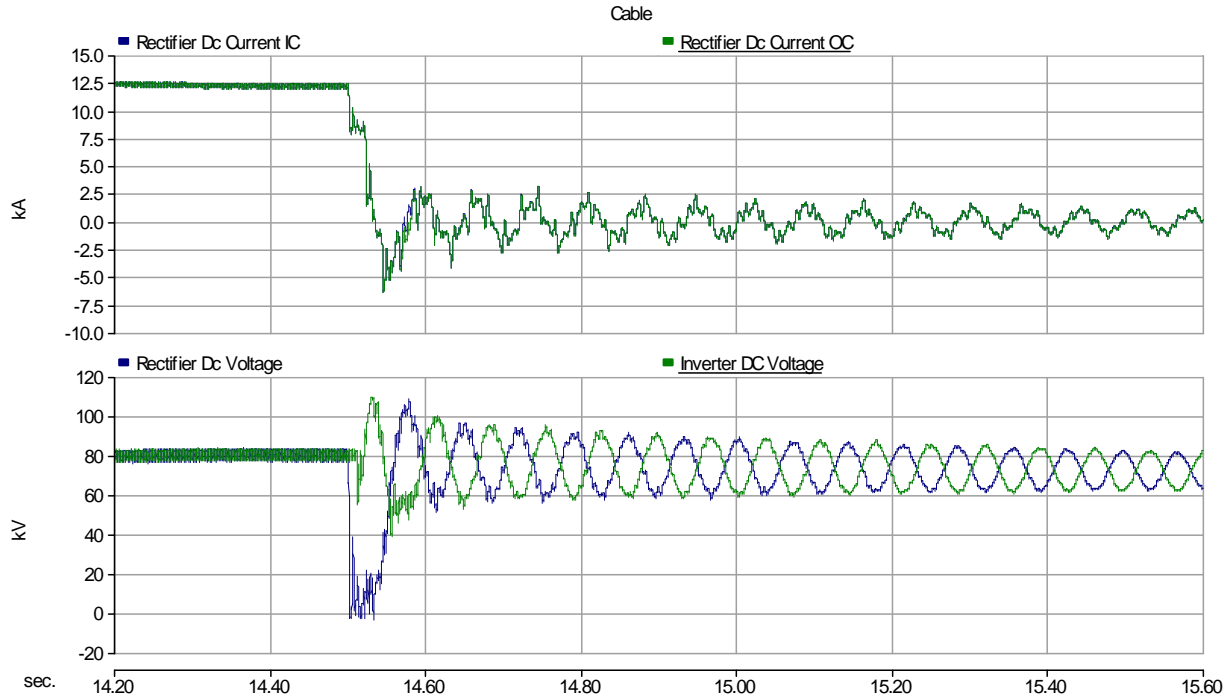


Figure 3-34
Three phase bus short circuit at the sending end

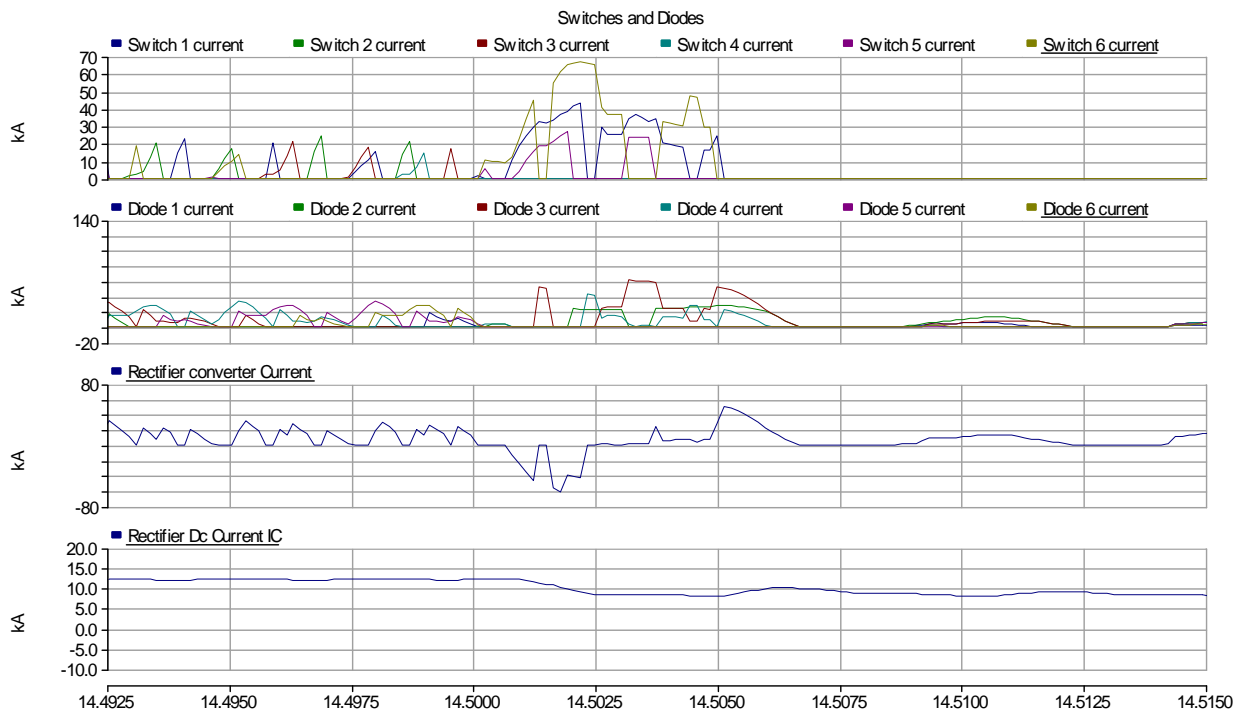


Figure 3-35
Sending end converter currents prior to and just after the application of the three phase bus fault

A three phase short circuit at the receiving end of the cable is shown in Figure 3-36. The inverter is now operating into a short circuit on the ac system, and therefore has to be blocked. The energy stored in the inductance of the dc cable is dissipated in the MOV arrester at the inverter end, which limits the overvoltage imposed on the receiving end converter. High over current arises in the sending end converter valves, as can be seen in Figure 3-37, but the diodes can freewheel as necessary after the sending end converter has been blocked. Approximately 10 cycles after the fault was applied, the fault clears and the system can restart. This simulation shows that the system can recover and be up to the pre-fault power level very quickly after the receiving end ac voltage recovers.

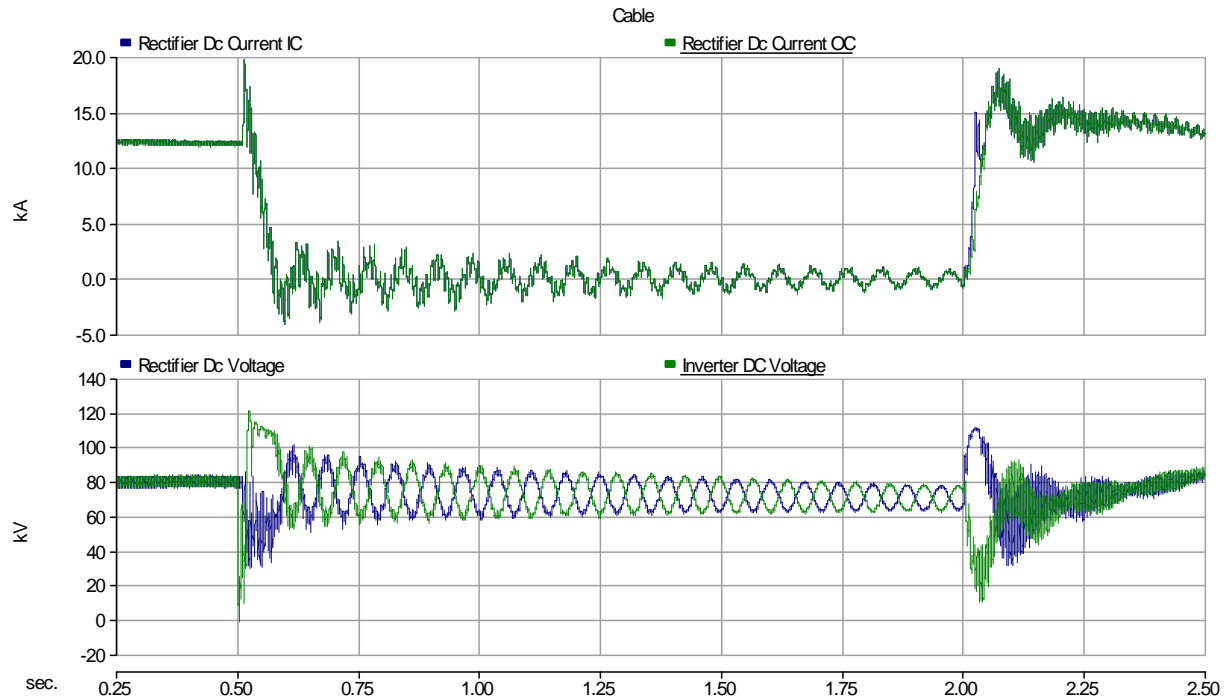


Figure 3-36
Three phase bus short circuit at the receiving end's ac bus

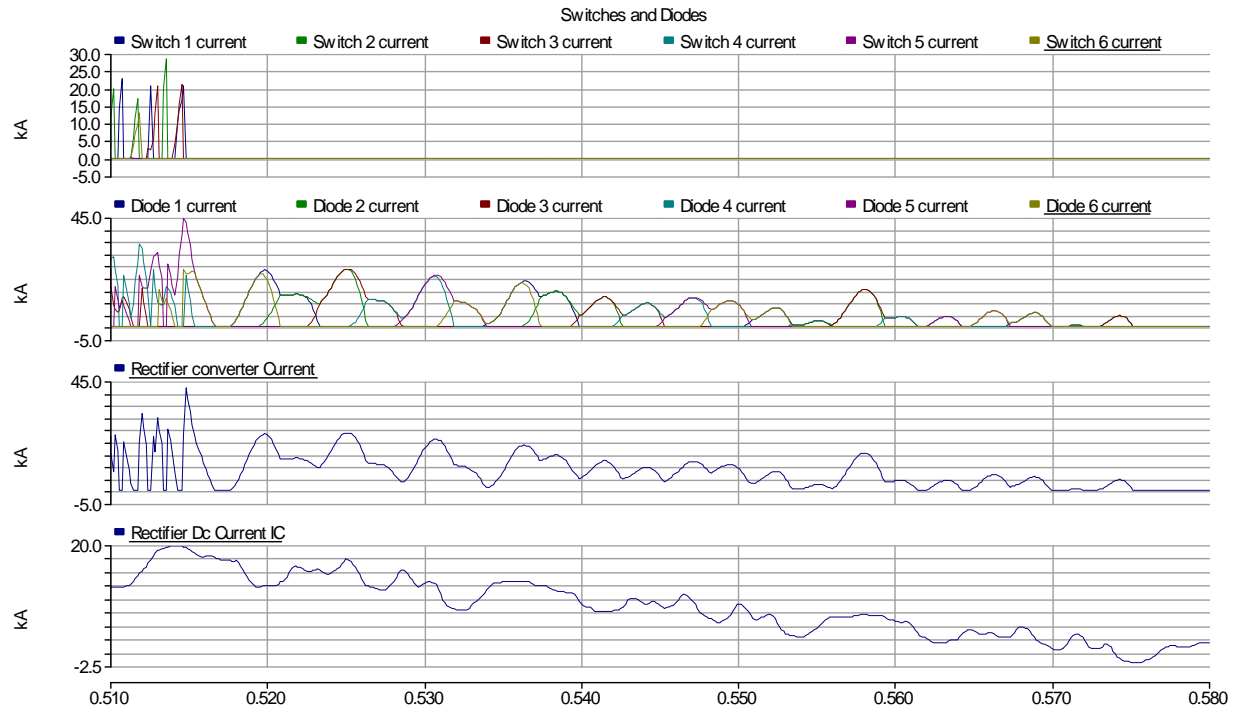


Figure 3-37
Sending end converter valve operation during the initial phase of the bus fault at the receiving end

A special case is a short circuit inside the converters. Figure 3-38 shows a three phase short circuit between the sending end's transformer and the converter. The simulation shows that if the converters are quickly blocked, the cable capacitance will not be discharged, so the dc voltage stays relatively unchanged. As shown in Figure 3-39, the energy stored in the cable's inductance will be dissipated in the arresters.

Simulation Results

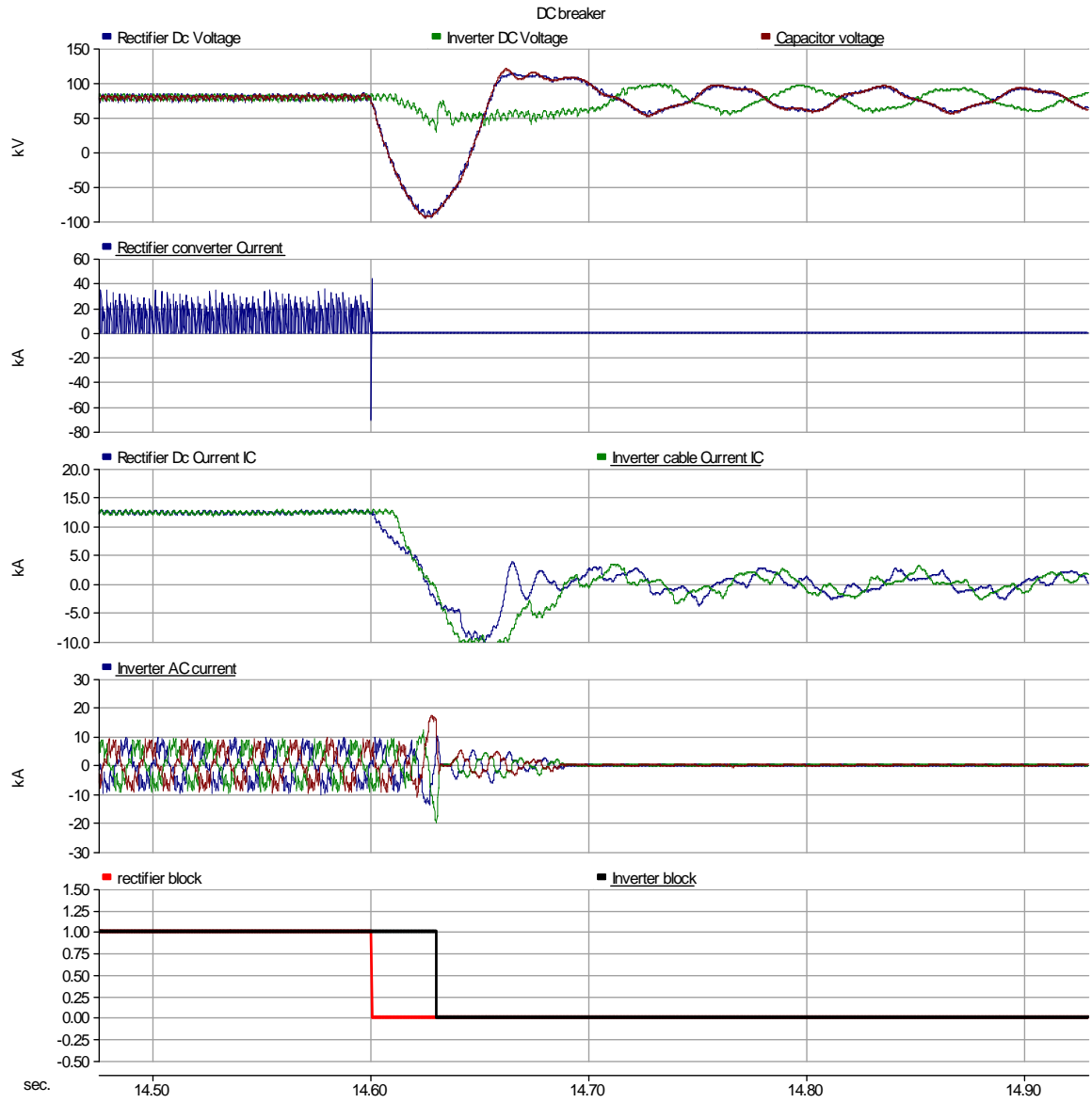


Figure 3-38
Three phase short circuit on the converter side of the sending end's transformer

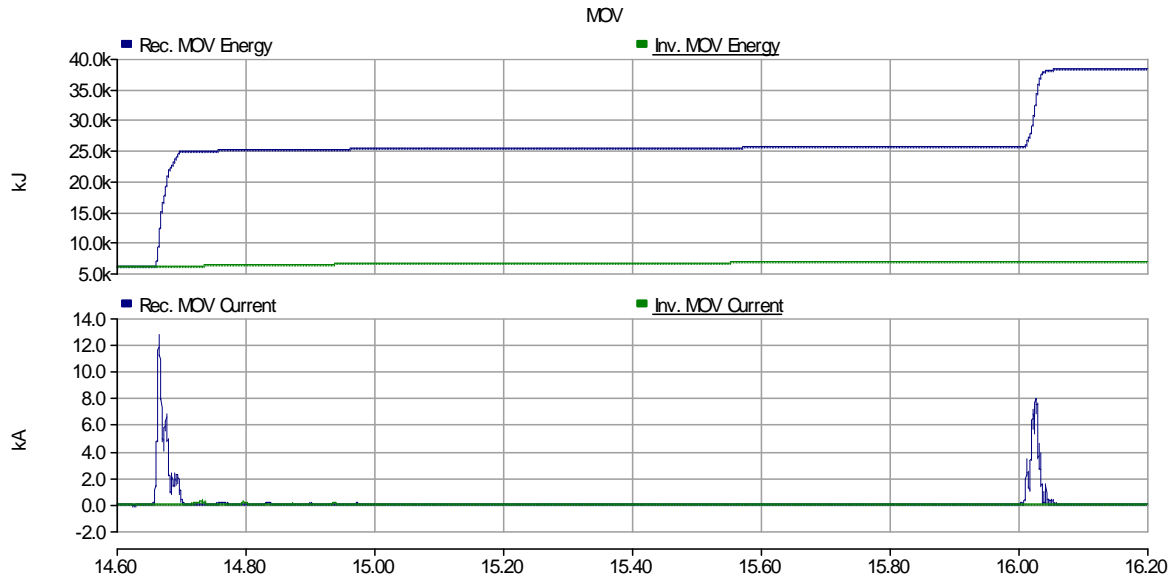


Figure 3-39
MOV energy dissipation for the case shown in Figure 3-38

Extension to Multi-Terminal Systems

A solid three-phase short circuit at a converter bus is the worst case ac voltage sag. Such events are rare but do happen. This simulation shows how the system might behave for such an event. It also shows that the ac and dc power system can recover quickly after the event if the voltage on the dc cable is maintained close to the nominal voltage. However, the transient currents and the associated cable losses might impose a severe thermal stress on the cable. The power ramp upon system recovery can be slowed down, but the abrupt changes when the fault occurs are unavoidable.

Voltage sags caused by single phase faults in the ac system occur frequently. A short circuit involving one or more phases can depress the voltage over a wide area. Assuming that a significant fraction of the power carried over the superconducting dc cable is delivered to a major metropolitan area through five or more converter stations, all of these converters can be affected by a single short circuit event that affects one or more phases. The result can be a temporary interruption of the power from the cable into the load area if the converters are blocked. This will result in rapid changes of the current flowing in the cable.

The changes in the current flows change the energy stored in the cable's inductance. This released energy has to be diverted into other loads or recovered by the generators. The control strategy for the dc system has to be selected such that the disturbance to the operating converters is minimized, and to enable fast recovery of the power flows when the disturbing short circuit is removed. This study has shown that there are important tradeoffs between the ratings of the converter valves to enable the system to ride through the voltage sag, the losses caused by the

transient power flows in the cable, and the use of main circuit harmonic filters. Advanced converter firing schemes could be devised and are reportedly in use for existing VSC systems to reduce the need for filters, but such schemes have not been possible to demonstrate in this simulation.

In a system of many converters connected to the same or two parallel dc cable circuits, an ac voltage sag may affect the converters connected to both cables. In this case, a large sudden load drop will arise. Or if the affected station or stations are injecting power into the cable, there might be insufficient power injected to serve all the loads, in which case the system would collapse, which is unacceptable. Even if there are two parallel cables each feeding half the load or supplying half of the power injection, as has been assumed for this study, both cables would be affected because an ac system disturbance is a common mode event that affects the converters connected to both cables. That is, for this event there is no redundancy in the system that can prevent the impact on both cables.

If the disturbance is at a voltage controlling generating station, the loss of voltage control would be serious and would either lead to overvoltage of the system if there is too much power injected or undervoltage if the total load exceeds the available injected power. One possible way to avoid this is to have one or more rectifier stations pick up more load if the voltage collapses or shed power injection if the voltage exceeds a setpoint. A possible implementation of this strategy is illustrated in Figure 3-40. It is assumed that the voltage controlling station has a droop characteristic as shown in the solid line of the figure. The droop can be more or less steep. The droop will lower the injected voltage and therefore lower the power output to all connected loads in proportion to the voltage change. This should redistribute the available generation so that all loads get most of their scheduled power delivery. If the voltage controlling converter reaches its rated load, the voltage will begin to go down and then an alternate voltage controlling station should pick up the slack. Similarly, if the voltage controlling converter is lost, the alternative voltage controlling converters will automatically switch over to the voltage control mode, which should prevent a collapse of the system. However, the voltage controlling converters must be electrically sufficiently far from each other to prevent both from being affected by a single ac system disturbance. If this is the case, the dc systems should be able to ride through severe ac system disturbances without causing a collapse of the dc systems.

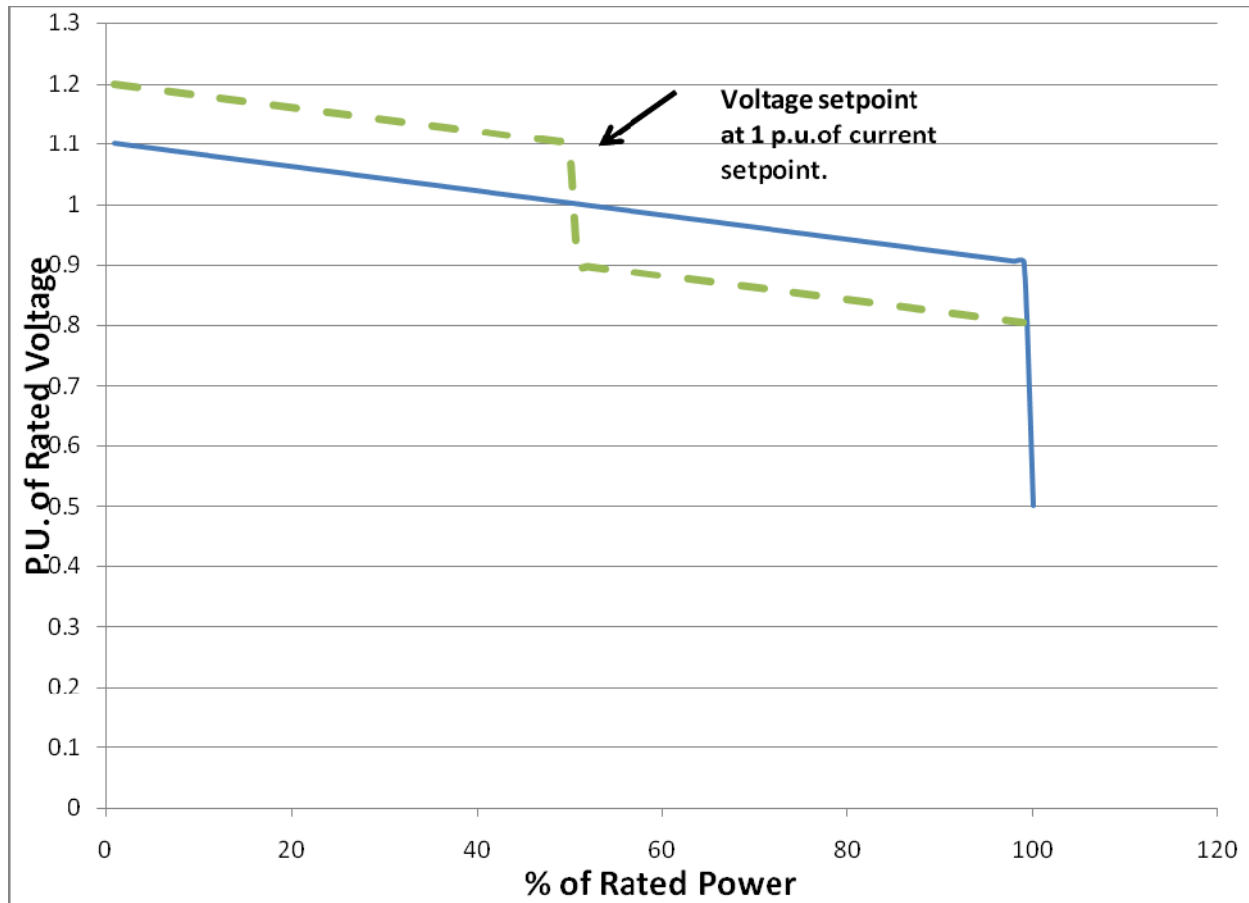


Figure 3-40
Conceptual voltage control strategy to avoid voltage collapse of the dc system

DC Cable Fault

The effect of a dc cable fault was studied and the results are described below. The inverter end of the cable is shorted while the system is transferring 1 GW at steady state conditions. Figure 3-41 shows the current at the sending end and the voltages at the two ends of the cable. The short circuit at the receiving end causes a wave to travel towards the sending end, where it is reflected back towards the receiving end. Because in the modeled system, the voltage source converter is terminated in a large capacitor, the reflection causes a current doubling when the wave reaches the sending end converter. The reflected wave is about 7.5 kA, so the surge impedance for the cable is about 21 Ω . Because the sending end converter is not de-energized, the current continues to flow and doubles at the sending end every 20 milliseconds. Eventually the front of the wave is less sharp, indicating that the higher frequency components of the wave are attenuated. At the time of the reflections, a voltage transient is observable. A short voltage reversal pulse appears in the voltage trace. This is as expected because the system has a small inductance⁹ inserted

⁹ In this simulation, the inductance is chosen to be 2 mH inserted in both the pole and the neutral conductors.

between the dc bus capacitor and the cable. At the receiving end, short circuit currents are being fed to the short circuit. Even if the sending end converter is blocked, fault currents are being fed via the diodes in parallel with the switching semiconductor devices to the fault. The short circuit needs to be isolated from the rest of the dc system to prevent failure of the semiconductor devices in the converter valves.

In the system as modeled, the cable is only solidly grounded at one point. As has been shown in the LANL report [7], a short duration transient voltage arises between the neutral conductor and the outer, grounded shield at the point where the fault occurs.¹⁰ The model used for this simulation is not suitable for studying very short duration transients, since the minimum step between calculations is much longer than the time step required for studying microsecond or sub-microsecond transients, but the results of the LANL study can be used to gain the needed understanding of the short duration cable transients.

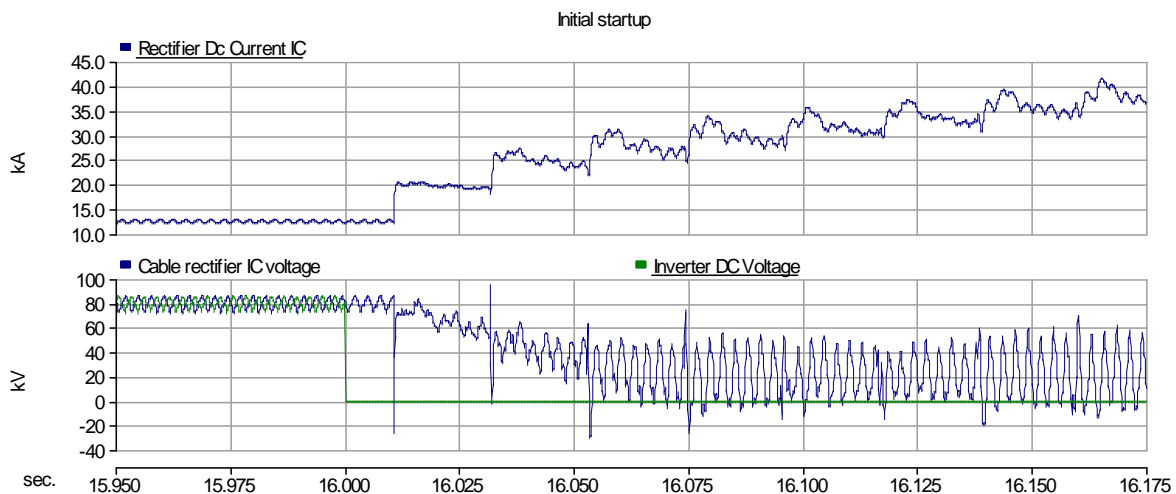


Figure 3-41
Cable short circuit at the receiving end

The current through the diodes of the converter bridge cannot be interrupted except by means of a circuit breaker.

The oscillatory discharge of the cable causes power dissipation in the cable. The main component of the oscillation is about 9.4 Hz and the oscillation decays exponentially with an attenuation factor of about 0.5. The harmonic spectrum for the discharge is shown in Figure 3-42. The losses dissipated in the cable during the first 50 cycles of this oscillatory discharge have been estimated to be about 50 J/m.

¹⁰ See section 3.1.3 on page 29 of the LANL report [7].

If an ac breaker is used in combination with blocking the sending end converter, the cable's voltage and current flowing into the cable can be seen in Figure 3-43. The converter currents are shown in Figure 3-44. This simulation result shows that there is a tradeoff between the over current rating of the converter valves and the required response speed of the short circuit detection function and breaker operation.

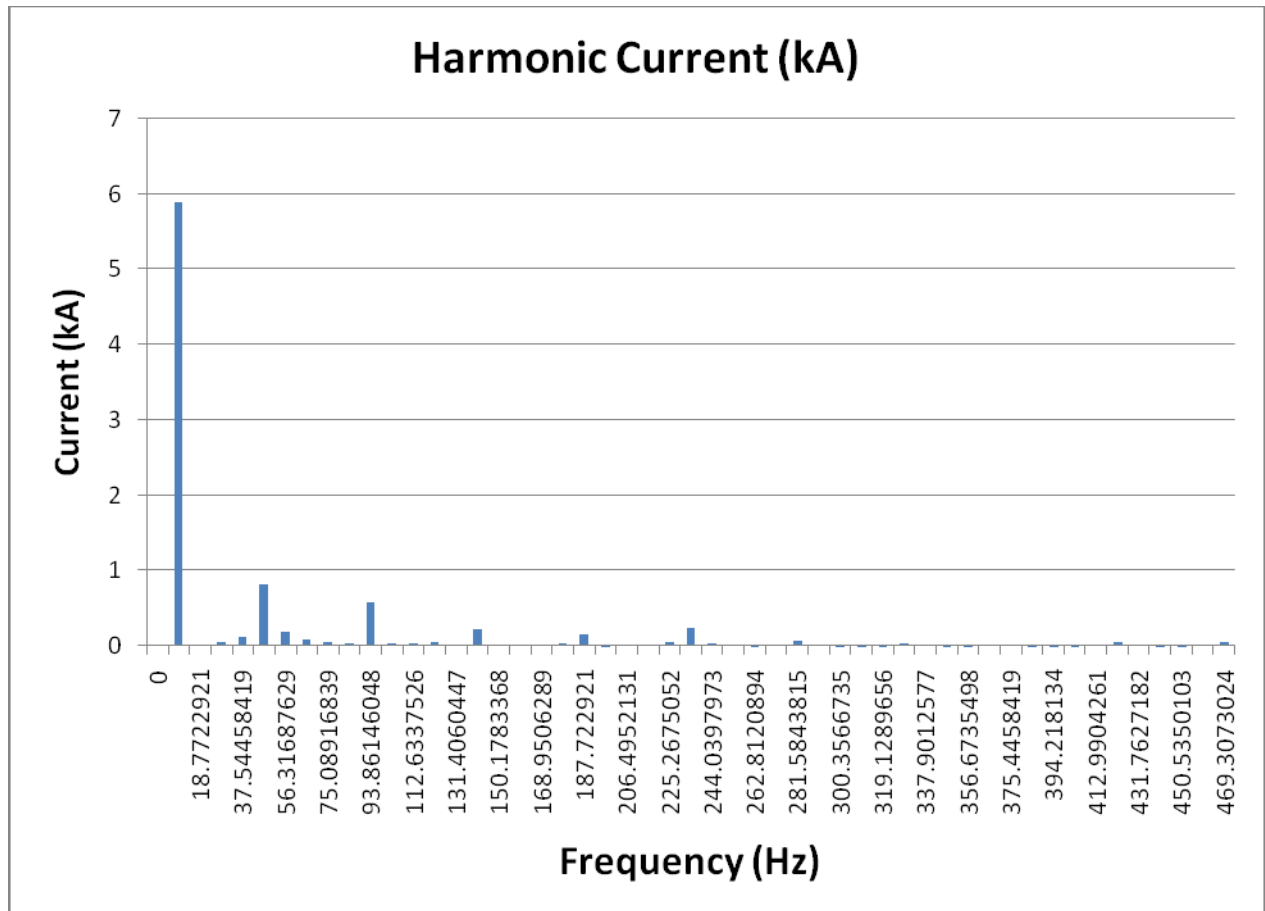


Figure 3-42
Harmonic spectrum for the discharge shown in Figure 3-41

Simulation Results

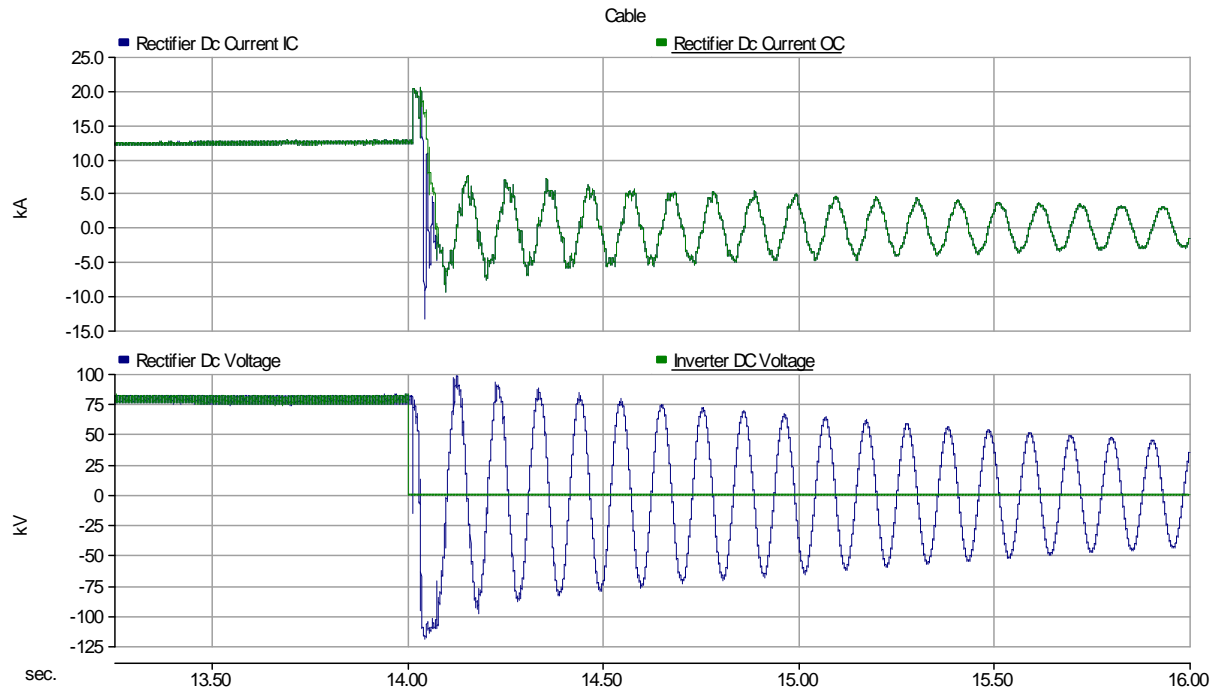


Figure 3-43
Sending end voltage and current for a short circuit of the cable at the receiving end cable termination. DC breaker opens 25 ms after the fault is applied.

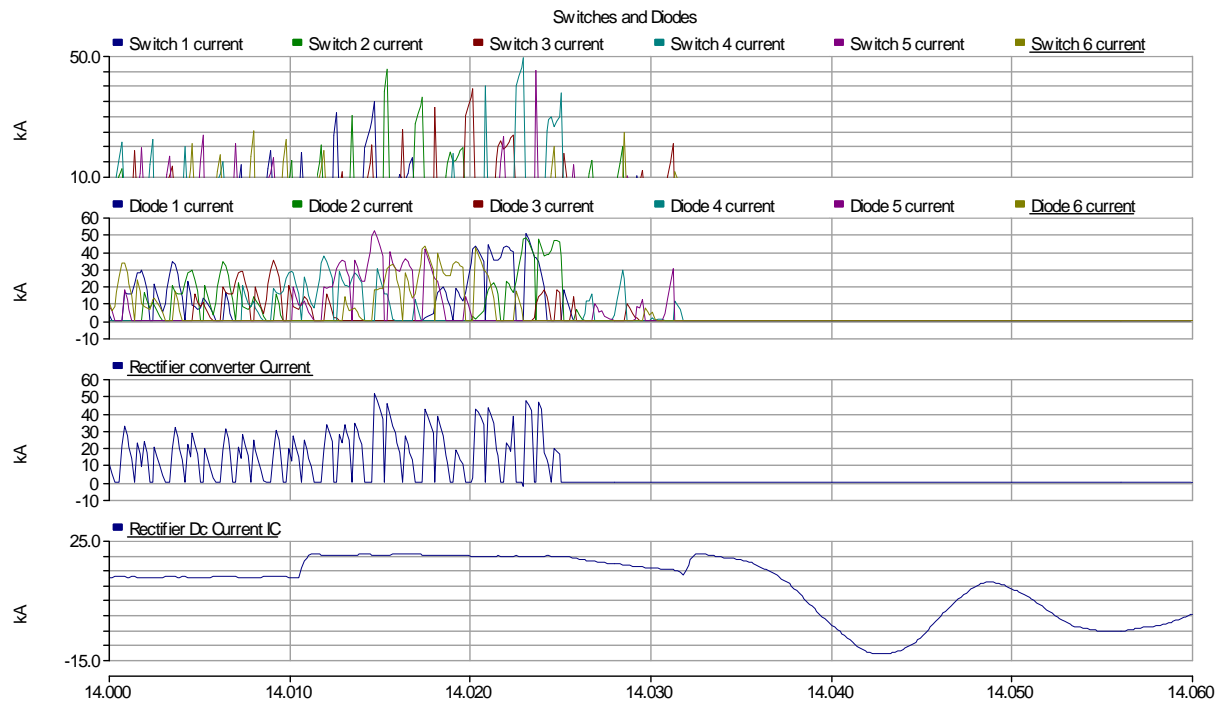


Figure 3-44
Converter currents for the case shown in Figure 3-43

The voltage and current recorded at the cable termination of the receiving end is shown in Figure 3-45. As can be seen in the figure, the discharge current from the dc capacitor is very large because the simulated fault is a zero impedance fault right at the point where the cable is terminated. The current magnitude would be reduced if the fault was applied some distance away from the terminal, but it would still be high.

This simulation has been run with the assumption that the converter is blocked within about 10 ms and the ac breaker is opened within three cycles after the short circuit has been applied. This causes very high currents to flow through the semiconductor switches and diodes. The switching devices can be turned off faster than assumed in this simulation by blocking the switching in response to over current detection. However, the current flow through the diodes cannot be turned off. Thus, even in this case, fast acting dc breakers would be needed or the diodes will have to be made to sustain the over current duty until the ac breaker opens.

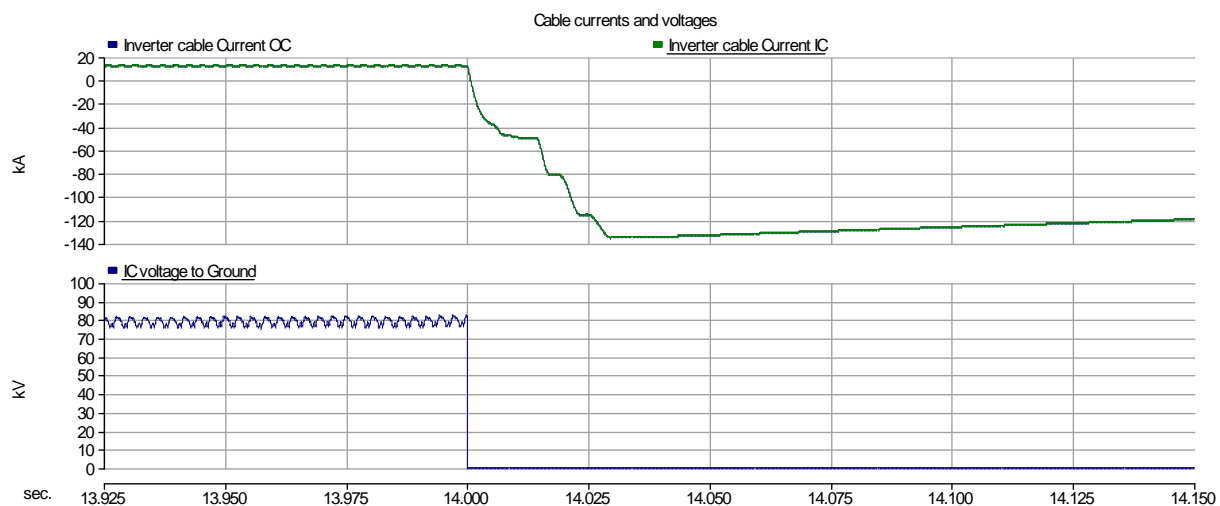


Figure 3-45
Receiving end voltage and current

If fast detection of cable short circuits and dc breakers is used at both the sending and receiving ends of the cable, the valves do not see any significant over-current on either end of the cable. A simulation of such a case is shown in Figure 3-46.

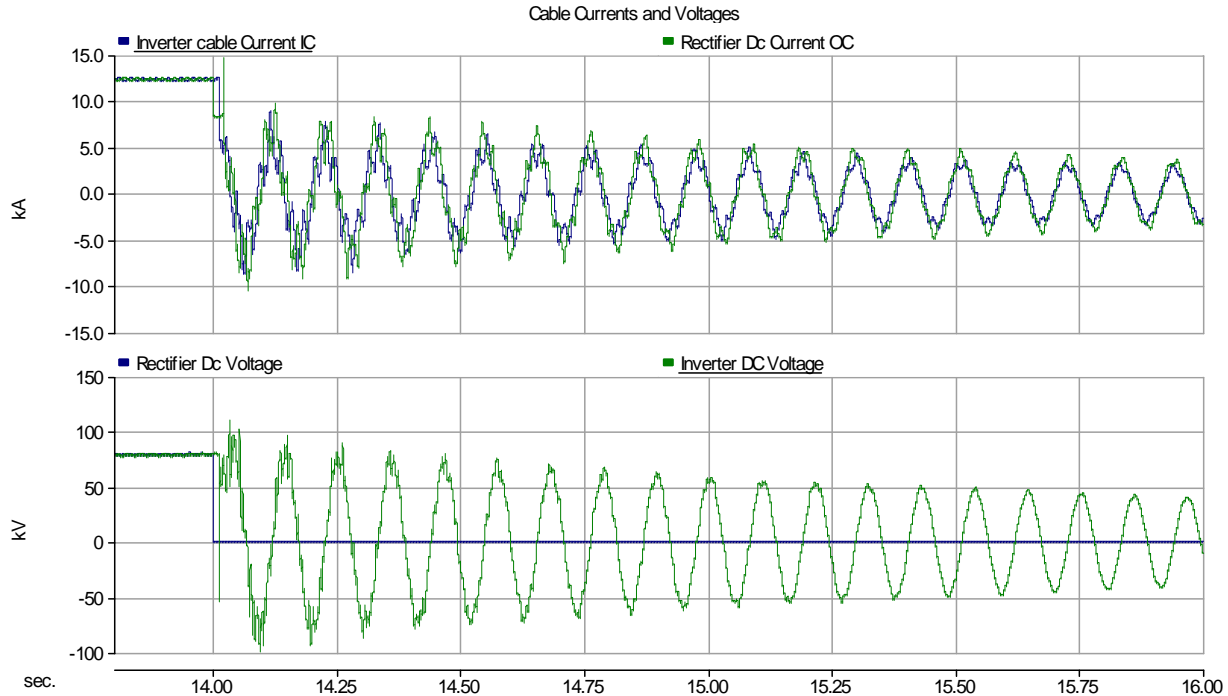


Figure 3-46
Short circuit across the dc cable at the sending and of the cable

In this simulation, the improved filters with 2nd and 6th harmonic filter branches as shown in Figure 3-12 have been used. It was also assumed that the sending end converter is blocked within 3 ms after the short circuit is applied and the dc breaker is opened at the same time. This simulation also assumes that a solid state, self-commutated circuit breaker is used.

The dc breakers were inserted between the converter's output reactors and the cable terminals. One breaker pole was placed between the center conductor in the cable and the converter and the other breaker pole is between the neutral conductor and the neutral side of the converter. However, the breakers can be inserted anywhere between the converter bus and the cable. If a breaker is inserted between the valves and the dc bus capacitor, the energy stored in the bus capacitor and the filters will be dumped into the dc side fault, which causes extra losses in the cables. For other disturbances it might be advantageous to have the capacitor connected to the cable side when the dc breaker is open, since then the capacitor can be charged to nominal dc voltage from the dc side. In that case, closing the ac breaker and energizing the converter valves will not cause any inrush currents. These trade-offs need further study.

The valve and converter output currents at the sending end can be seen in Figure 3-47. Similarly, at the receiving end, the converter was assumed to be blocked within 3 ms after the short circuit is observable at the receiving end and a fast acting dc breaker was opened at the receiving end to prevent the diodes in that converter from feeding the fault. The switch duties can be seen in Figure 3-48. As can be seen in this figure, the over current levels in the valves are quite moderate.

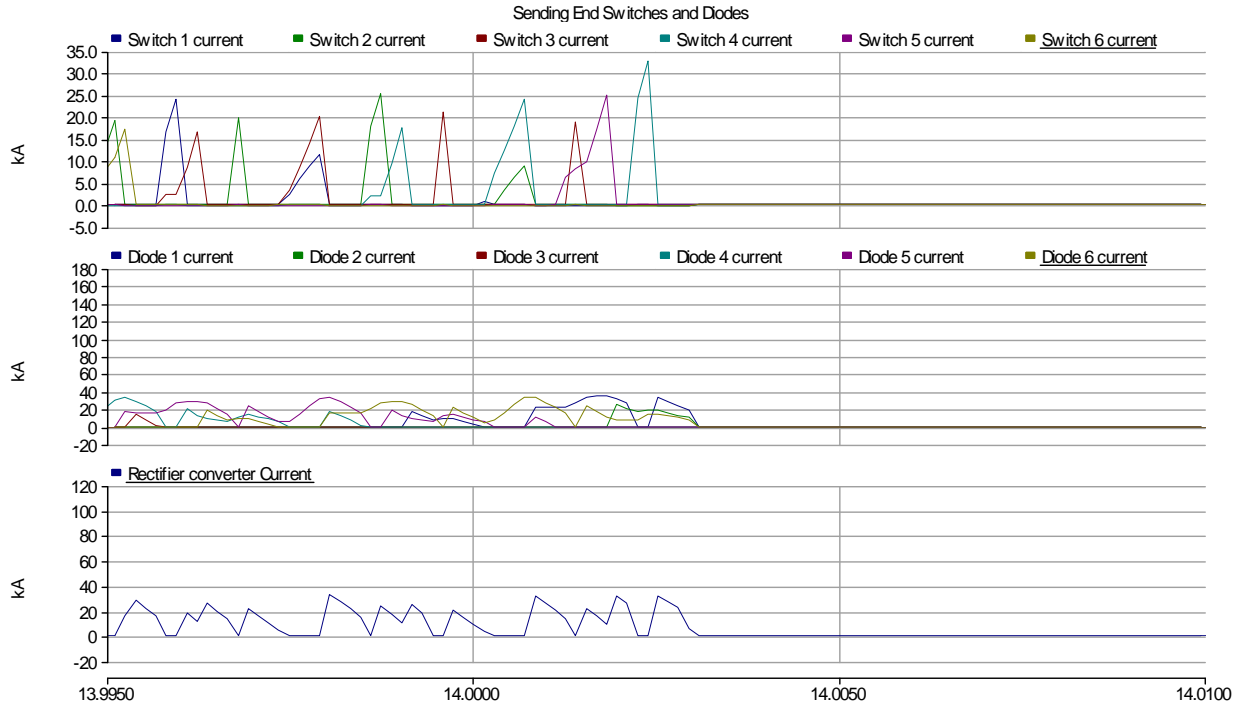


Figure 3-47
Sending end semiconductor valve and dc output currents

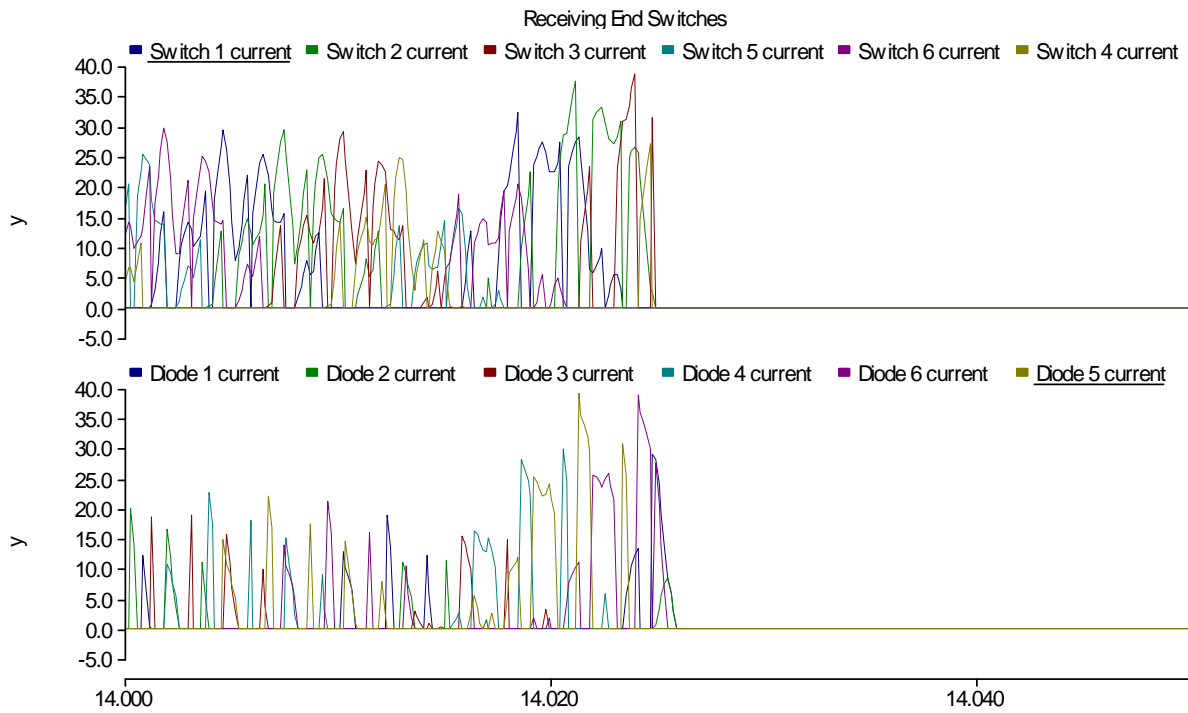


Figure 3-48
Receiving end semiconductor valve currents

Extension to Multi-Terminal Systems

This study has shown that dc fast short circuit detection combined with dc circuit breakers is needed in a multiterminal system. For simpler point to point systems, other approaches such as a large smoothing reactor to limit the current rate of rise in case of a short circuit on the dc side of the converters might work. However, for very large currents such as those assumed to pass through the dc cable, this will probably not be practical. The study also shows that on the dc side, the currents flowing into a short circuit will be very large, since the cable has a low surge impedance and will therefore not limit the current to levels that are close to the rated current of the cable. Therefore, it might be necessary to install fault current limiters to prevent the superconducting cable from being severely damaged by the short circuit currents. Circuit breakers at points where the cable might branch out to feed a tap along the main cable route or to sectionalize the cable in case of cable faults might be beneficial, as well. This requires further studies.

This study has assumed that the dc system is comprised of two parallel cables each carrying half the load. In such a system, for all cable faults, one half of the power is lost all across the system and switching over to the unaffected cable within a reasonably short time would be necessary. It has been assumed that this can be accomplished in about one second.

A loop configuration is also possible in which the converters are connected to one cable but looped back to the beginning, thereby forming a closed loop. In a loop system, a cable fault would affect all of the converters connected to the cable until the fault is cleared. Therefore, in such a system the cable needs to be frequently sectionalized to avoid a complete collapse of the entire dc system in case of a cable fault. At minimum, a breaker is needed on both sides of any connection point in case of a short circuit inside the converter. Furthermore, in a loop system, the power to one load area would be completely lost in case the cable fails close to the point of connection, unless a dc breaker is placed such that only 50% of the dc power injected or taken out of the cable is lost for every possible cable fault. If all of the power is lost into an area, a severe outage affecting that area could occur. Breaker failure backup equipment would also be needed in case a breaker fails to open when needed, since otherwise a single equipment failure could lead to collapse of the entire dc power system.

This short discussion of the radial and looped systems has been included here only to illustrate that it is a complex problem. The tradeoffs between a loop system and a redundant cable system are not possible to understand without a detailed study.

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SUMMARY

This study explored several aspects of VSC converters if applied in a superconducting HVDC transmission assumed to be configured as a multiterminal system carrying about 10,000 MW. The simulation comprised two VSCs with basic controls configured as a two-terminal system. The converters were assumed to be operating with Pulse Width Modulation (PWM) using a base switching frequency equal to nine times the fundamental, 60 Hz network frequency. The switching frequency was selected to achieve simplicity in the models and not necessarily because it is expected that it will be used for a commercial application. The modeled system did not incorporate numerous protection features that are utilized in commercially operating VSC schemes. First, this would require a very detailed converter model. Second, the study focused on the cable, assuming that the converters would have to be adapted to meet the performance requirements of the cable and not be constrained by converter limitations. Therefore, the simulation does not represent a finished converter design.

The following areas were studied:

1. Harmonic injection from a PWM type converter into the cable.
2. The stresses imposed on the superconducting cable when the cable is first energized and during power ramps for increasing or decreasing of the power transferred through the superconducting cable.
3. The transient current changes resulting from various fault conditions. These included ac system faults as well as short circuits of the superconducting cables at the ends at the interface between the converters and the cables ends.
4. The injection of power frequency harmonics into the cables during asymmetrical ac system faults, which leads to high levels of second harmonic currents into the cables, which causes power losses that increases the temperature of the superconducting cable.

The results and analysis of the simulation results show that it appears quite feasible to build multiterminal systems based on VSC converters. Specifically, the following conclusions have been reached:

1. Steady state harmonic injection into the cables can be managed to an arbitrary level using harmonic filters. As a minimum a 6th harmonic filter is required to limit the injected fundamental harmonic frequency from a three-phase converter.
2. Starting the DC system requires charging of the dc system's capacitances to a level close to rated voltage before starting the converters to avoid high charging currents and overvoltages on the dc side that result from the large inrush currents.

3. The charging of the DC system can be from a Current Source Converter (CSC), which conceivably could be a converter used at a large generating plant that does not need reverse power operation.
4. The power rate-of-change should be limited to avoid injecting losses into the superconducting DC cable. However, the converters are not the limiting factor on how fast the power through the cable can be increased.
5. AC system voltage sags and short circuits are common mode stresses on the DC cable system, since it can affect many converters connected electrically close to each other such that a voltage sag in one can impact other converters in approximately the same way. Such sags could seriously affect the availability of a multi-terminal dc system if they impact the dc system such that the power taken out of the dc system exceeds the power injected.
6. AC system voltage sags are frequently asymmetrical, which will introduce second harmonics into the dc side or cable. Control features to limit the injection of second harmonics into the cable can be used but for simplicity, in this study only the use of main circuit filters tuned to the second harmonic frequency were applied.
7. Short circuits on the dc cable side of the system will lead to high over currents through the diodes of the converter valves. The breakers on the ac side of the converter transformers would not be sufficiently fast to interrupt the currents before the valves might be thermally damaged. Also, the valves might have to carry the cabled currents almost continuously until the energy in the cable has been dissipated, which also might impose unacceptable stresses on the valves. Therefore, as the study shows, fast acting, semiconductor based DC circuit breakers will be needed to disconnect the converters from the dc circuit in case of cable and converter station short circuits.

Further studies are needed to extend this study into three or more terminals to understand the complexities and to develop solutions to the identified problem areas.

As mentioned above, the study system was configured as a two terminal system in order to understand the fundamental operating characteristics of a VSC type dc transmission system. This system was simplified further by not including any over current protective features of the converter valves. This approach was selected because in a superconducting system at extremely high power levels, the power transmission must be maintained even during system disturbances in the ac systems connected to the cable via the converters. The proper trade-off between features needed to protect the converter valves from overloading and the features needed to prevent quenching or overheating of the superconducting cable can only be understood if first it is understood what the effects of disturbances are on each of the elements of the superconducting transmission system. Thus, before a final design is reached there must be an iterative process requiring trade-offs between costs and performance for both the cable and the converters to reach an economic optimum, which should be the subject of future studies.

The simulation incorporated a basic control system to enable power to flow between the sending and receiving end converters. The control system was not optimized but appeared to be reasonably stable and sufficiently fast for a practical application. Further optimization must ensure that the control system provides proper stability margins, and takes into account

interactions between the dc and ac system, between the cable and the converters, and between converters themselves. Further, the control system needs to be studied and optimized to enable extension of the two-terminal system to an N-terminal system where N could be 20 to 30 converter terminals.

New VSC concepts are emerging with different performance attributes, so if a system as envisioned will be built sometime in the future, it would probably be based on newly developed converter topologies, which will have lower losses but also different performance characteristics. Obviously, for each new converter topology that emerges, detailed studies need to be performed before the trade-offs between the performance of the converter and the cable can be understood.

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A

LIST OF SYMBOLS, ACRONYMS AND ABBREVIATIONS

Symbols

Ω	Resistance in Ohms
ϵ_r	Relative dielectric constant
μ_r	Relative permeability
ρ	Resistivity
m	Meter
f	Frequency in hertz
$g_{1,2,3}$	Rectifier gate control signals (per phase)
L	Inductance
ω	Frequency in radians per second
ω_n	Harmonic frequency in radians per second
I	Current
I_{dr}	Inverter dc current set point
I_{dm}	Inverter dc current measured
I_n	Amplitude of the harmonic current
V_m	Inverter dc voltage measured
n	Harmonic number
m_a	Modulation index
m_f	Modulation frequency
Q_r	Rectifier reactive power set point
Q_m	Rectifier reactive power measured
C_{fl}	DC rail capacitance
L_{fl}	DC series inductance
$R_{g(x)}$	Semiconductor device gate for device (x)

List of Symbols, Acronyms and Abbreviations

dcCurr_p	Positive dc current
dcCurr_n	Negative dc current
V _{dr}	Rectifier dc voltage set point
V _{dm}	Rectifier dc voltage measured
V _{DC(x)}	DC voltage pole (x)
V _{x-y}	Voltage between phase (x) and (y)
f _c	Cut off frequency
δ	Phase angle
Q	Reactive power
J	Joules (watt-seconds)

Acronyms and Abbreviations

AC	Alternating current
DC	Direct current
CSC	Current Source Converter
VSC	Voltage Source Converter
kV	kilo-Volt
kA	kilo-Ampere
km	kilometer
MW	Mega-Watt
SCDC	Superconductor DC cable
IC	Inner conductor
OC	Outer conductor
MS	Metallic sheath
Ωm	Ohm meter
ms	millisecond
s	second
F	Farad (unit for capacitance)
C	Capacitance
P	Power
H	Henry (unit for inductance)

PPS	Positive phase sequence
NPS	Negative phase sequence
PWM	Pulse width modulation
THD	Total harmonic distortion
WTHD	Weighted total harmonic distortion
Hz	Hertz (unit for frequency)
GW	Giga Watt
mΩ	Milli-ohm
HTSC	High temperature superconducting cable
G	Gain
pu	Per unit
μ	Micro (10^{-6})
Q	Quality factor
HVDC	High Voltage Direct Current
LANL	Los Alamos National Laboratory

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