Transient Analysis of a 150 kV Fault Current Limiting High Temperature Superconducting Cable

Vandana S. Mehairjan[1], Marjan Popov[2], Alex Geschiere[1], Will L. Kling[3]

***Abstract*—The interconnection of electrical power systems and the increase in power demand leads to higher fault current levels and transport capacity bottlenecks. The smart-grid vision and the newest Fault Current Limiting High Temperature Superconducting (HTS) cable technologies, can offer solutions for these issues. The Alternative Transient Program (ATP) is applied to investigate the behavior of a 150 kV FCL HTS cable in an existing power network. The case study shows that fault currents can be suppressed leading to a decreasing dynamic short-circuit current withstand. Furthermore, the generator terminal voltage and the Transient Recovery Voltage (TRV) have been analyzed. In this paper the network model and the simulation results will be presented and explained.**

***Keywords*: Fault Current Limiting, High Temperature Superconducting, Transient Recovery Voltage, Short-circuit Currents, ATP-EMTP, High Voltage**

I. Introduction

THE demand for electric power is growing and electrical power networks are becoming more interconnected. This is a trend in many countries of the world and it is caused by increased customer requirements and advanced technological improvements. In order to meet the ever-increasing energy demand, the integration of new power sources in the grid is necessary. The short-circuit current withstand capability of system components are often exceeded when a new power plant is connected with conventional cables to an existing grid, due to the increase of the short-circuit current contribution. It is also a big challenge to increase the amount of generated power due to bottlenecks such as voltage fluctuations, high fault current levels and reactive power.
Furthermore, the existing power grid is becoming an aging infrastructure, the transport capacity is increasing and the grid is also facing environmental issues like CO_2- emissions, EM-emissions and visual impact (overhead lines, despite their efficiency). This asks for an efficient underground infrastructure, but bulk transportation through conventional cables will cause high reactive power consumption. Taking into account all these obstacles, problems and limitations, the great challenge lies in the design of a network with a smooth voltage profile and limited short circuit currents. The smart-grid vision and the newest Fault Current Limiting (FCL) High Temperature Superconducting (HTS) cable technologies, can offer solutions for these issues.

Devices and techniques such as circuit breakers, fuses, air-core reactors, employing high-impedance transformers, bus-splitting (system configuration) and fault current limiters (FCLs) have been applied to limit the available short-circuit currents [1]. Due to the progress that has been made in the development of superconducting materials, it is possible to commercialize FCL HTS cables. This technology has many advantages because it is possible to transport much more power at lower voltage levels, having very low energy losses, limiting the short-circuit current and no negative thermal influences on other infrastructures. The FCL HTS cable limits fault currents, without energy losses, during normal operation due to a smart non-linear cable resistance. Under fault conditions the non-linear resistance of the cable is inserted into the power network to limit the short-circuit current. The transition from the superconducting to the normal-state, the so-called quench, takes place automatically [9].

In order to fulfill the growth of the demand of electricity, new generation plants will be connected to the transmission power system by implementing FCL HTS cable technology to the network. This physical Fault Current Limiting (FCL) cable property is analyzed for the connection of a power plant with a 150 kV FCL HTS cable to the 150 kV transmission network. An ATPdraw model is developed by applying MODELS language based on the $R \sim I_t$ characteristics of FCL HTS cable. Short-circuit current analysis are carried out for this model, with and without the FCL HTS cable. For this model, the generator terminal voltage and the Transient Recovery Voltage (TRV) have been analyzed.

II. Fault Current Limiting High Temperature Superconducting Material

A. Physics of High Temperature Superconducting cables

HTS-cables use tapes made of superconducting material as

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current carrying elements. These elements can carry a current with practically zero losses as soon as their temperature falls below a temperature known as the "critical temperature" (T_c). The value of T_c depends on the type of superconducting material that is used for the HTS-tapes. Nevertheless, this physical phenomenon is influenced also by two other conditions: the current density and the magnetic field. The superconducting state is achieved, when the temperature, current and magnetic field are below their critical values: T_c (critical temperature), I_c (critical current) and H_c (critical magnetic field). This behavior is schematically depicted in Figure 1.

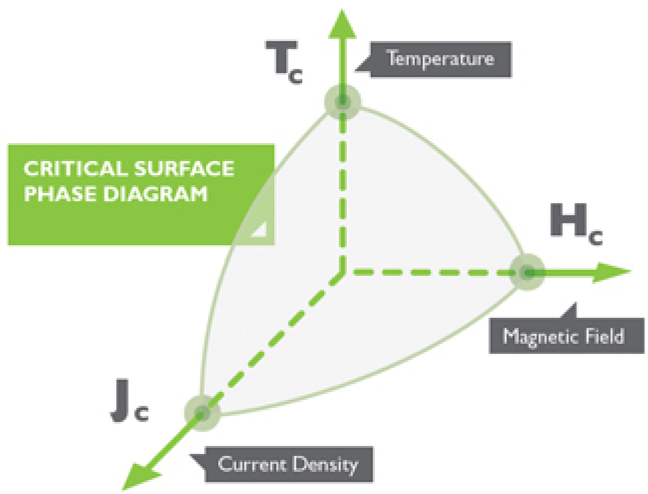

Figure 1: Critical surface diagram (source: www.supercables.com)

C. Principle designs HTS cables

Superconducting power transmission cables are available in two types; warm and cold dielectric type. The manufacturing process of the "warm dielectric" HTS cable is in principle not difficult, apart from the conductor. Its design is comparable to the design of the conventional cables, whether it is the oil-filled or synthetic type. In the "warm dielectric" type the electric insulation (dielectric) is located outside the cryogenic cold part of the cable. Even though the design of this type is relatively simple and has similarities to "older"/conventional cable technologies, there are quite a lot of disadvantages, for example higher electric losses, higher inductance, required phase separation to limit the effects of eddy current heating and control the production of stray electromagnetic fields (EMF) in the vicinity of the cable.

HTS cables available today are commonly referred to as "cold dielectric" HTS cables. The main reason for this description is due to the fact that the dielectric, or electrical insulation, of the cable is located inside the cable structure.

In principle the manufacturing of the "warm dielectric" type is less complicated than the "cold dielectric" type, because the design is very close to that of conventional cables. The complicated and expensive manufacturing of the "cold cables" is caused by the structure of two superconductive components (internal and external circuit). Since the design is not common, it practically doubles the cost of the cable in comparison with the "warm dielectric" design. But this pays itself back in the advantage of canceling out the magnetic field outside the cable and so reducing losses [8].

III. SYSTEM MODELING

The150 kV grid is fed via a 23/150 kV step-up transformer. This voltage level is chosen, because it is possible to apply and analyze the 150 kV FCL HTS cable in a power system. The application of the HTS cables in the power network is interesting for voltage levels from 10 kV to 150 kV. Due to the high ampacity, higher voltage levels are not necessary [1].

In the simulation model, the 150 kV network will be represented as an infinite powerful grid to which a 23 kV generator is connected through a step-up transformer. The 150 kV FCL HTS cable model is connected between the 23/150 kV transformer and the 150 kV network (shown in Figure 2).

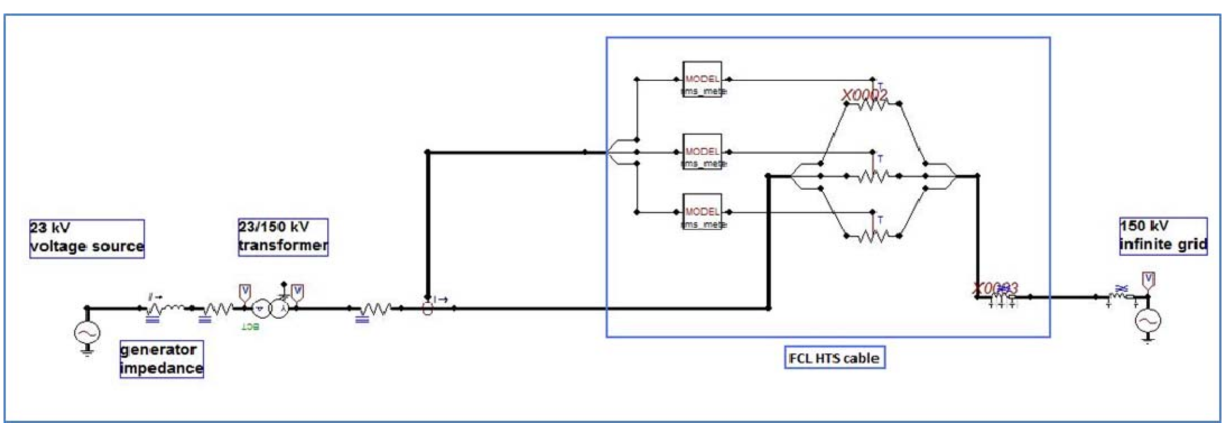

Figure 2: Studied network model in EMTP-ATPDraw

The system is studied for power frequency. The wavelength of the sinusoidal currents and voltages is large compared with the physical dimensions of this network (cable length approximately 300 m). Logically, the network will be modeled by applying lumped elements and the travel time of the electromagnetic waves does not have to be considered. This makes it possible to model the network by using standard ATP components [7].

The generator is modeled as a voltage source and a RLC source impedance. Elements AC 3-ph type 14 (voltage source) and RLC 3-ph (impedance) are applied to represent the 23 kV generator and the generator impedance, where

$$Z_{generator} = \sqrt{\left(X_d^{"}\right)^2 + R^2}$$

R is the equivalent resistance and $X^{"}_d$ is the sub-transient reactance of the generator. For the determination of the interrupting capacity of circuit-breakers, the sub-transient reactance of the generator is used to obtain the initial current flowing on during the occurrence of a short-circuit current.

The BCTRAN supporting routine is used to model the three-phase Δ/Y connected 23/150 kV transformer. For this routine, the test data for both the exciting test and the short-circuit test at the rated frequency are used. Excitation and short-circuit losses are taken into account by this transformer model. If zero sequence data is available, these can also be inserted in the model. For this study, it must be noted that only positive sequence parameters are used for the transformer model.

The 150 kV infinite grid is modeled as a feeding voltage source (AC 3-ph type 14) and an impedance (RLC 3-ph). This is done in a way that the short-circuit withstand current is above 40 kA_{rms} (specification of the grid).

An ideal three-phase switch is applied to simulate a three-phase fault to earth. During normal operation, the switch is open and at a certain instant the switch will be closed. Depending on the fault location the fault current will be limited.

In ATP the cable is modeled by applying standard ATP-, TACS- and user specified components, by using MODELS.

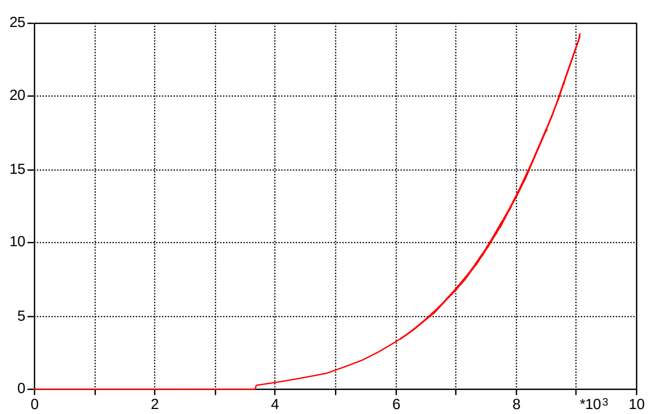

Figure 3: $R_t \sim I_{rms}$ characteristic (y-axis resistance in Ω; x-axis: t in s)

The fault current behavior of the superconducting cable is described as a non-linear resistance (depicted in Figure 3) and standard cable capacitance and inductance. The non-linear resistance is constructed by applying MODELS and TACS. In MODELS an algorithm is programmed to calculate the non-linear resistance of the cable, which is related to the momentarily current [2].

$$R_t = 10^{-3,555} \left|I_t\right|^{0,1699} \qquad (I_t < I_c)$$

$$R_t = 10^{-18,041} \left|I_t\right|^{4,9090} \qquad (I_t > I_c)$$

$$I_c = 1,3 I_{nom}$$

The fault current will be limited when it exceeds the so-called critical current of 3.67 kA. The absolute momentarily current is used for the determination of the non-linear resistance of the superconducting cable. This non-linear resistance is the output of MODELS and it is controlled by a TACS-controlled current-dependent resistance. Depending on the value of the momentarily current, the non-linear resistance will be low or will increase. The transition from the superconducting state to the non-superconducting state, is modeled by making use of an "if-then-else" function in MODELS. The cable capacitance and inductance are modeled by using a standard π-circuit component, defined in ATP per unit length.

Due to the resistive power dissipation in the cable, the energy is transferred into heat energy. The influence of the heat on the current limiting behavior of the cable is neglected in this research.

IV. Case Study Simulation Results

Simulations were carried out with a three-phase short circuit created at 100 ms (t = 0 ms at the beginning of the simulation). The total simulation time 250 ms and the time step was 2.5 μs in order to properly see the transient. The operation current during normal operation is 2 kA. The FCL HTS cable is assumed to be homogeneous along its length.

Three-phase fault short-circuit currents are simulated for the studied network, with and without a superconducting cable. Two options with the superconducting cable are analyzed, a three-phase fault between the infinite grid and the cable and a three-phase fault between the transformer and the cable [3], [5].

A. Three-phase fault simulation between the 150 kV grid and the 150 kV FCL HTS cable

In the case of a three-phase short circuit fault between the 150 kV grid and the 150 kV FCL HTS cable, the fault current flowing from the generator to the point of the fault will be investigated. After the fault occurred, without the 150 kV FCL HTS cable, the peak value of the fault current fed by the 23 kV generator reaches 13.7 kA (Figure 4). With a 150 kV FCL

HTS cable installed in the power system, the peak fault current was limited to 7.7 kA (Figure 5), which is only four times higher than the nominal current of the FCL HTS cable. After a cycle the fault current was further reduced to 6.7 kA.

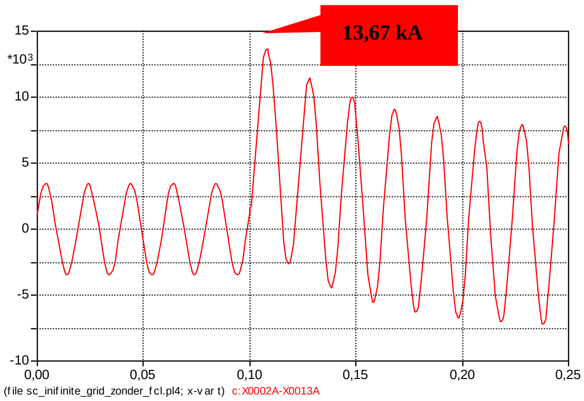

Figure 4: Three-phase fault to earth **without** 150 kV FCL HTS cable for phase A (x-axis: time in s and y-axis: current in A)

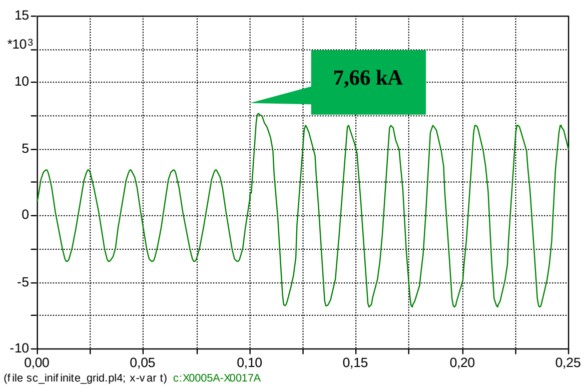

Figure 5: Three-phase fault to earth **with** 150 kV FCL HTS cable for phase A (x-axis: time in s and y-axis: current in A)

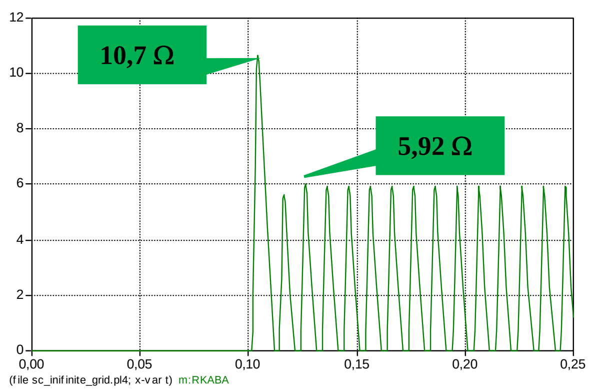

Figure 6: Non-linear resistance of 150 kV FCL HTS cable as a function of time, during a fault between cable and infinite grid (y-axis: non-linear resistance in Ω; x-axis: t in s)

The superconducting state of the cable decreases and the resistance increases non-linearly. For the type of superconducting material that is used for this research, the highest value of the resistance becomes in this case slightly higher than 10 Ω, at the maximum value of the fault current and around 6 Ω, during steady-state value of the fault current. These values are marked in Figure 6 and will be used for the TRV analysis.

The voltage across the generator terminals, at the instant of the fault occurrence is simulated in (Figure 7). It can be seen that the voltage at the generator terminals is lower at the instant of the fault occurrence. Hence, there is no danger for the generator windings and insulation.

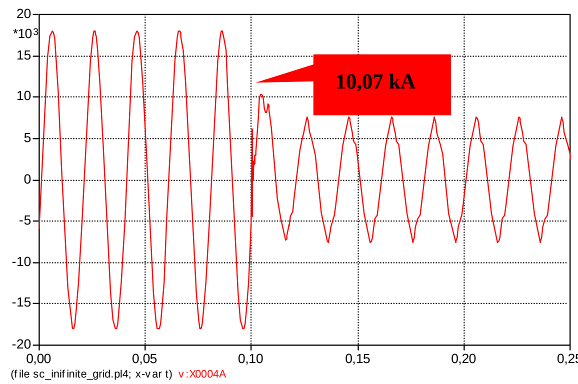

Figure 7: Voltage across the generator terminal, during a fault between cable and infinite grid (y-axis: voltage in kV; x-axis: t in s)

B. Three-phase fault simulation between the 23/150 kV transformer and the 150 kV FCL HTS cable

In this case of a three-phase short circuit fault between the 23/150 kV transformer and the 150 kV FCL HTS cable will be analyzed. The fault current flowing through the cable to the point of the fault will be fed by the 150 kV grid. In case of a fault without a FCL HTS cable, the peak value of the fault current fed by the grid reaches 101.7 kA. With the use of a 150 kV FCL HTS cable installed in the power system, the peak fault current is limited to 10.7 kA, which is nearly 10 times lower than the fault current without a FCL HTS cable, which is limitation of almost 90%. These results are shown in Figure 8 and 9 respectively. The peak fault current in this case is only five times higher than the nominal current.

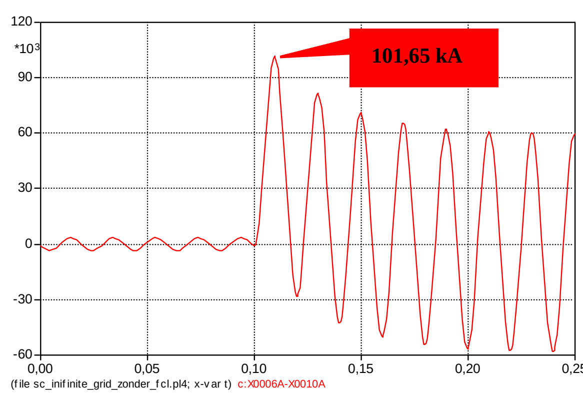

Figure 8: Three-phase fault to earth **without** a 150 kV FCL HTS cable for phase A (x-axis: time in s and y-axis: current in A)

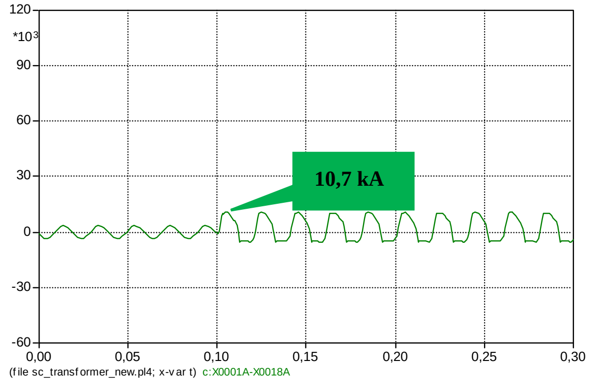

Figure 9: Three-phase fault to earth between the 23/150 kV transformer **with** a 150 kV FCL HTS cable for phase A (x-axis: time in s and y-axis: current in A)

When the value of the momentary peak current exceeds the critical current (Ic), a transition takes place in the FCL HTS cable. The superconducting state of the cable decreases and the resistance increases non-linearly. For this fault study the non-linear resistance is 55 **Ω**, at the maximum peak value. This result will be applied for the TRV analysis.

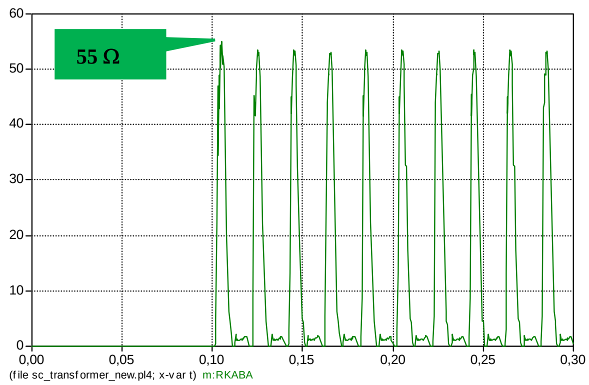

Figure 10: Non-linear resistance of 150 kV FCL HTS cable as a function of time, during a fault between cable and transformer (y-axis: non-linear resistance in Ω; x-axis: t in s)

C. Transient Recovery Voltage Analysis

In order to analyze the behavior of transients in the studied network, the fundamental principles of the black-box arc model of circuit-breakers is applied to explain the fault current limiting effect of the cable [6]. The general Mayr model is used to represent the arc [4], when a fault current is disconnected is:

$$\frac{1}{g}\frac{dg}{dt}=\frac{1}{\tau}\left(\frac{ui}{P}-1\right)$$

Where g - the arc conductance, u – arc voltage, i – arc current, τ – the arc time constant and P – the cooling power.

From the Mayr model, the arc conductance is calculated and implemented as a non-linear resistance in the network. In this way, the interruption capabilities of the circuit breaker to disconnect the fault currents are studied.

At a certain moment the circuit breaker is triggered to switch off the fault current, by opening the breaker contacts. A successful interruption of the short-circuit current takes place at current zero, as it can be seen in Figure 11.

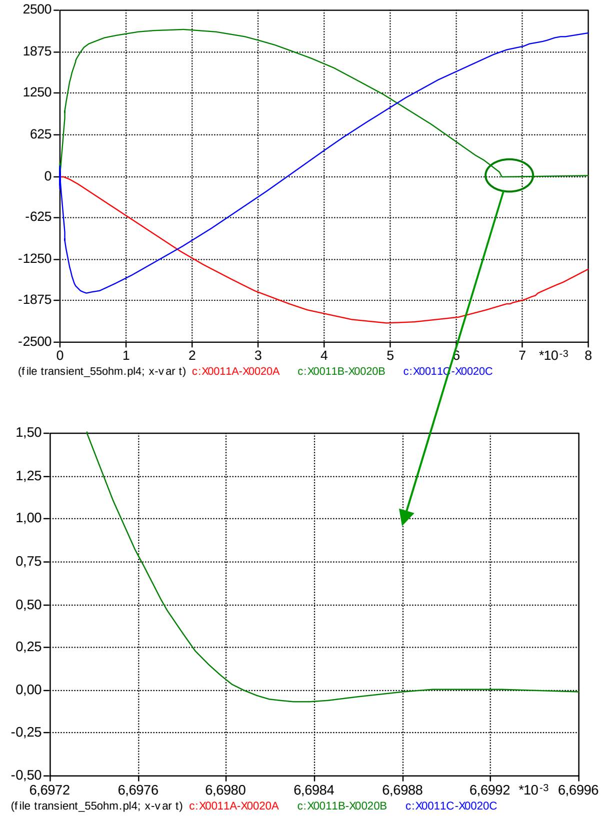

Figure 11: Fault clearing of phase B and post-arc current R= 55 Ω (x-axis: time in s and y-axis: current in A)

The fault current flowing through phase B is the first pole to clear (green line in Figure 11). Considering this, the expectation is that the TRV will occur in phase B. In (Figure 12) the overvoltage that arises after the circuit breaker of phase B is open, is depicted. By using this plot, two points are chosen to calculate the steepness (du/dt) of the TRV. As it can be seen from these results the du/dt of the TRV is 2.3 kV/μs. To verify this result, it is compared with the IEC 62271-100 standard.

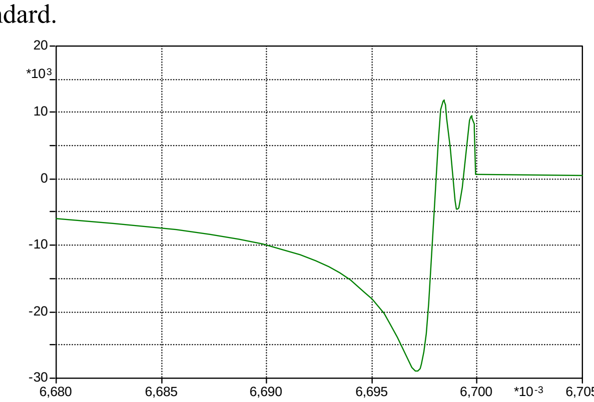

Figure 12: TRV phase B for R = 55 Ω (x-axis: time in s; y-axis: voltage in V)

For this comparison IEC test duty T10 is used, because the maximum fault current (2,5 kA green line in Figure 9) is about 4% of the full short-circuit current (40 kA). The standard TRV parameters are grouped for certain values, being 10%, 30%, 60% and 100% of the maximum short-circuit current rating for the specified voltage level of 245 kV. In the IEC standards, these current values are referred to as test duties and the corresponding TRV parameters are tabled for these duties [62271-100]. For test duty T10, 12,6 kV/µs is the maximum RRRV that is allowed for a voltage rating of 100 kV and above. Since the du/dt is 2,3 kV/µs (for this calculation), the T10 test duty fulfills the IEC specified values. Proceeding with the same method of RRRV calculation, the identical steps are done for R = 10 Ω and R = 5.9 Ω. For this simulation with R = 10 Ω the du/dt = 3.9 kV/µs. Comparing the RRRV with the standard value that is allowed by the IEC the calculation fulfills the required value. For this case, IEC test duty T30 is used, because the maximum fault current (10 kA) is about 25% of the full short-circuit current. For test duty T30, 5 kV/µs is the maximum RRRV that is allowed for a voltage rating of 100 kV and above. This means that the du/dt = 3.9 kV/µs (for this calculation) is within the limits based on the requirements of the standard. For the final simulation with R = 5.9 Ω the du/dt = 5.6 kV/µs. Comparing the RRRV with the standard value that is allowed by the IEC, the calculation fulfills the required value. For this case IEC test duty T60 is used because the maximum fault current (18 kA) is about 45% of the full short-circuit current, and the permissible slope is 3 kV/µs which is lower than 5.6 kV/µs.

V. Conclusions

The main goal of this research is to analyze the effect of a 150 kV Fault Current Limiting High Temperature Superconducting Cable due to a new generator connection to the power network. For the analysis an approximation has been made for the non-linear characteristic.

When the fault is between the infinite grid and the 150 kV FCL HTS cable, the major contribution to the three-phase fault current is coming from the grid. The scarce portion results from the 23 kV voltage source, flowing through the 150 kV FCL HTS cable. The latter current is limited from 13.7 kA_{peak} (*without* superconducting cable) to 7.6 kA_{peak} (*with* superconducting cable). When the fault is between the 23/150 kV transformer and the cable, the fault current is limited from 101.7 kA_{peak} (*without* superconducting cable) to 10.7 kA_{peak} (*with* superconducting cable).

For the TRV analysis, three resistance values of the FCL HTS cable have been used; these values were calculated during the second study of the three-phase fault current (55 Ω; 10.7 Ω and 5.9 Ω). For these resistances the TRV analysis are done and compared with the standard value that is allowed by the IEC. Except for R = 5.9 Ω, the calculations fulfill the IEC specified values.

VI. References

[1] A. Geschiere, D. Willén, E. Piga, P. Barendregt, I. Melnik: Optimizing cable layout for long length High Temperature Superconducting Cable. Cigré B1-307, 2008.

[2] G. Del-Rosario-Calaf, A. Sumper, X. Granados, A.Sudria-Andreu: Grid impact analysis of a HTSC cable by using an enhanced conventional simulator, *IOP Publishing; 9th European Conference on Applied Superconductivity, 2010. Volume 234, Part 3.*

[3] J.J. Grainger, W.D. Stevenson, JR.: *Power System Analysis.* : McGraw-Hill International Series, 1994.

[4] L. van der Sluis: *Transients in Power Systems.* Sussex : John Wiley, 2002.

[5] IEC. *IEC 60909-0 Calculation of currents.* Geneva : IEC, 2001. IEC 60909-0.

[6] M. Popov: Modeling of non-linear elements by ATP-EMTP, *Proceedings of the* EEUG Meeting, Izmir, Turkey, 2008.

[7] L. Prikler, H. Kr. Høidalen: *ATPDraw for windows* Trondheim: 1998.

[8] Cigré Study committee SC21 HV Insulated Cables: *High Temperature Superconducting Cable System.* Italy : Cigré, June 2003. 229.

[9] Lin Ye, A.M. Campbell: *Case study of HTS resistive superconducting fault current limiter in electrical distribution systems.* China and Cambridge : Elsevier ScienceDirect, 2007.

VII. Appendix

Table I. Circuit Data

DATA PARAMETER	VALUE
Generator	
Nominal voltage	23 kV
Resistance per phase	0,0265 Ω
Inductance per phase	0,858 mH
Transformer	
Power	535 MVA
Ratio	23/150 kV
Group	dY_G 30
Iron losses	300 kW
No load current	0.156 %
Short circuit impedance	12.969%
Copper losses	1100 kW
Infinite grid	
Nominal voltage	150 kV
R_+	0.2062 Ω
R_0	0.6 Ω
L_+	6.56 mH
L_0	18 mH
C_+	1.0e-5 µF
C_0	1.0e-5 µF
Cable data	
Z_+	50 Ω
Z_0	30 Ω
v_+	1.5e8 km/s
V_0	1.3e8 km/s
Circuit breaker	
τ	0.4 µs
P_0	50 kW