HTS-FCL EMTDC Model Considering Nonlinear Characteristics on Fault Current and Temperature

Jae-Young Yoon, Seung-Ryul Lee
Korea Electrotechnology Research Institute

Abstract. One of the most serious problems of the KEPCO system is a higher fault current than the CB (Circuit breaker)’s SCC (Short Circuit Capacity). There are so many alternatives to reduce the higher fault current, such as the isolation of bus ties, enhancement of the CB’s SCC, and the application of HVDC-BTB (Back to Back) or FCL (fault current limiter). However, these alternatives have drawbacks from the viewpoint of system stability and cost. As superconductivity technology has been developed, the resistive type (R-type) HTS-FCL (High Temperature Superconductor Fault Current Limiter) offers one of the important alternatives in terms of power loss and cost reduction in solving the fault current problem. To evaluate the accurate transient performance of R-type HTS-FCL, it is necessary for the dynamic simulation model to consider transient characteristics during the quenching and the recovery state. Against this background, this paper presents the new HTS-FCL EMTDC (Electro-Magnetic Transients including Direct Current) model considering the nonlinear characteristics on fault current and temperature.

1. Introduction
If a fault occurs in the power system, the circuit breaker promptly separates the fault location from other system areas. To perform this action successfully, the capacity of the circuit breaker has to be bigger than the fault current magnitude. However, owing to the enlargement of the scale of power systems, the fault current is larger, and it could exceed the breaking capacity. In this case, the fault current magnitude should be controlled to foster the stable operation of the power system. There are many alternatives to reduce the increased fault current, such as the isolation of bus ties, enhancement of the SCC of circuit breakers, the application of HVDC-BTB (Back to Back) and FCL (fault current limiter), but these alternatives present problems of enormous expense growth, or the degradation of system stability [1-3].

The development of HTS-FCL is currently underway worldwide through HTS technology, and attempts to apply it to power systems are continuing. R-type HTS-FCL has a large reduction effect, without the level of system stability degradation compared to other alternatives. Also, its costs are relatively lower than HVDC BTB or breaking capacity increasing [4, 5]. Dynamic behavior, and its control effect, has to be confirmed under various operating conditions for the application of R-type HTS-FCL.

To evaluate the accurate transient performance of R-type HTS-FCL, it is necessary for the dynamic simulation model to consider transient characteristics during the quenching and the recovery state. Against this background, this paper presents the HTS-FCL EMTDC model for R-type HTS-FCL.
considering the nonlinear characteristics on fault current and temperature when quenching and recovery phenomena by fault current injection and clearing occurs. Thus, the developed HTS-FCL EMTDC dynamic model has been used to simulate the quenching and the recovery phenomena, and to confirm the effectiveness of applying this to a simulated test power system similar to the real conditions of power systems.

2. THE DEVELOPED HTS-FCL EMTDC MODEL

If a power system is in the normal operational state, HTS-FCL resistance can be maintained at nearly zero because of superconducting characteristics. However, if a fault current over critical quenching current flows, HTS-FCL resistance will increase by the quenching resistance. This means that the HTS-FCL can control the fault current below the specific values by inserting quenching resistance. Basically, whether or not the quenching status is reached is dependent upon the current magnitude and temperature. In a practical concept, the status variation of HTS-FCL resistance is co-related to several factors, such as the peak magnitude of fault current, the integration of fault current, fault current per second and the temperature of HTS-FCL. This paper introduces a generic model to simulate the superconducting, the quenching and the recovery state for R-type HTS-FCL. Fig. 1 represents the dynamic characteristics of the developed HTS-FCL, depending on fault current and other factors. The overview of mathematical modeling is as follows.

\[
I_x = I_{x0} \times (K_1 T_{x0} + K_2 T_{x0} + K_x)
\]
\[
I_y = I_{y0} \times (K_1 T_{y0} + K_2 T_{y0} + K_y)
\]
\[
I_z = I_{z0} \times (K_1 T_{z0} + K_2 T_{z0} + K_z)
\]
\[
VINT_{x0} = VINT_{y0} \times (K_1 T_{x0} + K_2 T_{y0} + K_x)
\]
\[
VINT_{y0} = VINT_{x0} \times (K_1 T_{y0} + K_2 T_{x0} + K_y)
\]
\[
VPT_{x0} = VPT_{y0} \times (K_1 T_{x0} + K_2 T_{y0} + K_x)
\]

**Figure 1.** Dynamic characteristics of the developed HTS-FCL

2.1. Equations of temperature dependence for basic parameter

In this paper, the HTS-FCL model is developed considering temperature dependence in the quenching and the recovery status. The basic equation of the developed model considering temperature dependence is as follows.

\[
I_x = I_{x0} \times (K_1 T_{x0} + K_2 T_{x0} + K_x)
\]
\[
I_y = I_{y0} \times (K_1 T_{y0} + K_2 T_{y0} + K_y)
\]
\[
I_z = I_{z0} \times (K_1 T_{z0} + K_2 T_{z0} + K_z)
\]
\[
VINT_{x0} = VINT_{y0} \times (K_1 T_{x0} + K_2 T_{y0} + K_x)
\]
\[
VINT_{y0} = VINT_{x0} \times (K_1 T_{y0} + K_2 T_{x0} + K_y)
\]
\[
VPT_{x0} = VPT_{y0} \times (K_1 T_{x0} + K_2 T_{y0} + K_x)
\]
\[ VPT_{w} = VPT_{w0} \times (K_{1}T_{w} + K_{2}T_{w} + K_{3}) \] (7)

\[ T_{e} = \frac{T}{T_{c}} \] (8)

Where,

- \( T_{w}, T_{c}, T_{0} \): Per unit, surrounding, and base temperature.
- \( I_{w}, I_{c}, I_{0} \): Steady state, quenching and recovery current.
- \( VINT_{w}, VINT_{c} \): Integration value of fault current for quenching and recovery current [kA-sec].
- \( VINT_{w0}, VINT_{c0} \): Base integration value of fault current for quenching and recovery current.
- \( VPT_{w0}, VPT_{c0} \): Integration value of fault current per second for quenching and recovery current.
- \( VPT_{w}, VPT_{c} \): Base integration value of fault current per second for quenching and recovery current.
- \( K_{0}, K_{1}, K_{2} \): Temperature coefficients.

2.2. Superconducting state and the resistance value

If Eq. (9) is satisfied, the superconducting status will be maintained and the resistance value is nearly zero.

\[ I_{\infty} \leq I_{c} \] (9)

\[ HTS_{SR} = R_{SR} \text{ (constant value)} \] (10)

Where,

- \( HTS_{SR} \): HTS-FCL resistance during superconducting state.

2.3. Quenching state and the resistance value

If all equation (11)-(14) are satisfied, the HTS-FCL should be quenched and the resistance value will be a quenching design value. The quenching resistance will increase with the specific characteristics. In this paper, the exponential function is used to describe the quenching resistance from zero (superconducting resistance) to the specified value.

\[ I_{\infty} \geq I_{0} \] (11)

\[ \int I_{\infty} dt \geq VINT_{w0} \text{ for } T_{0} \leq T \leq T_{e} \] (12)

\[ \int I_{\infty} dt \geq VPT_{w0} \text{ for } T_{0} \leq T \leq T_{e} \] (13)

\[ HTS_{QR} = (T - T_{0}) \times I_{rms} \times \exp(kT) \] (14)

Where,

- \( T_{0}, T_{R} \): Quenching and recovery starting time.
- \( HTS_{QR} \): HTS-FCL resistance during quenching state.

2.4. Recovery state and the resistance value

If equation (15) and (16) are satisfied, the HTS-FCL must be recovered after the quenching state is completed, and the resistance value will be back to a superconducting value of nearly zero. The
recovery resistance will decrease with the specific characteristics. In this case, exponential function is introduced from the quenching resistance to zero (superconducting resistance) and the resistance equation of recovery state is shown in (17).

\[
I_i \leq I_{\text{rms}} \leq I_v \tag{15}
\]

\[
\frac{K_v \int_0^t I_v dt + K_q \int_0^t I_q dt}{T - T_v} \leq V_{\text{PTT}} \quad \text{for} \quad T \geq T_v \tag{16}
\]

\[
HTS_{RR} = (T_R - T_Q - T + T_R) \times I_{\text{rms}} \times \exp(-kT) \tag{17}
\]

Where,

\( HTS_{RR} \): HTS-FCL resistance during/after recovery state.

This paper developed the EMTDC dynamic model of R-type HTS-FCL depending on the above equations using by UDM (user defined model) developing option within EMTDC. Fig. 2 describes this model. Also, main parameters, which influence the dynamic behaviors of HTS-FCL controlling the fault current, are presented in Fig. 2.

![Figure 2. Dynamic model of developed HTS-FCL](image-url)

If necessary, for the EMTDC model of Fig. 2, non-linear characteristics as equation (18) could be structured to change the HTS-FCL resistance with fault current, temperature and other factors during the quenching and the recovery process. Also, it can be designed to add alterations of function and input factors. This means that we can change the detailed transient function for the dynamic behavior of HTS-FCL resistance because the actual transient characteristics of HTS-FCL resistance during the quenching and the recovery phenomena are not clear at this stage, and the dynamic performance is not the same for different types of HTS-FCL.
\[ R = f(I_F, \text{Temperature}, \text{Other factors}) \]  \hspace{1cm} (18)

Where,
\[ R : \text{HTS-FCL resistance.} \]

3. CASE STUDY FOR POWER SYSTEM APPLICATION

3.1. Analysis overview

We analyzed the dynamic performance of the EMTDC model developed in this paper and verified the effectiveness of this model. The overview of the test system, basic data and the analysis case are specified. We constructed the test system as Fig. 3, which has the basic characteristics of the KEPCO system to verify the effectiveness of the EMTDC dynamic model developed in this paper. This test system reflects exactly the actual system state for 154kV overhead transmission lines and 154kV/22.9kV conventional/superconducting cable with R-type HTS-FCL to reduce fault current, and other power equipment, which represent the whole power system. It can be simulated under the various operational states for the test power system by changing the basic data. Specially, we notified the characteristics of HTS-FCL on temperature and fault current.

3.1.1. Model parameter

In this paper, to verify the test power system, the basic data of R-type HTS-FCL included in test power system is shown in Table I. All HTS-FCL in this paper are 3-phase equipment, not single-phase.
Table 1. HTS-FCL parameters

| Parameter name | Parameter value of HTS-FCL 1 and 2 | Parameter value of HTS-FCL 3 |
|----------------|-----------------------------------|-------------------------------|
| $I_{LO}$ [kA]  | 0.3                               | 0.5                           |
| $I_{RO}$ [kA]  | 50                                | 5.0                           |
| $R_{SL}$ [Ω]   | 0.001                             | 0.001                         |
| $R_{QL}$ [Ω]   | 10                                | 10                            |
| $T_{QL}$ [sec] | 0.05                              | 0.05                          |
| $T_{RF}$ [sec] | 0.2                               | 0.1                           |
| Temp [°C]      | 20.0                              | 20.0                          |
| $VINT_{IQ0}$ [kA-sec] | 0.001                         | 0.001                         |
| $VINT_{IR0}$ [kA-sec]  | 0.001                  | 0.001                        |
| $VPT_{IQ0}$ [kA-sec/sec]  | 5.0                   | 5.0                        |
| $VPT_{IR0}$ [kA-sec/sec]  | 0.5                   | 0.5                        |

3.2. Analysis results

In this paper, the developed model has many parameters, which is quenching resistance, fault current, temperature, and so on. Table II shows the difference of analysis results for the base case study, which the resistance of HTS-FCL is changed. The base case study means that the 3-phase fault occurs on the 154kV bus in the case of HTS-FCL applied at the 154kV bus. Table II describes the analysis results when the quenching and recovery starting current are changed. In Table II, IF is a three-phase RMS fault current, IFCL is a three-phase RMS fault current in back of HTS-FCL 3, and $I_{max}$ is the maximum of a instantaneous value when a three-phase fault is occurred in 154 kV bus. It shows that the higher the quenching resistance, the smaller the fault current. We can see from the analysis results, for the base case study with HTS-FCL, that the maximum and steady-state RMS fault current is noticeably smaller than when quenching resistance is a higher.

Table 2. Analysis results when quenching resistance changes

| Quenching resistance | IF [kA]  | IFCL [kA]  | $I_{max}$ [kA] |
|----------------------|----------|------------|----------------|
| 1                    | 87.14    | 85.90      | 121.20         |
| 3                    | 74.49    | 72.98      | 100.94         |
| 5                    | 66.75    | 65.05      | 87.64          |
| 10                   | 54.59    | 52.86      | 70.06          |
| 15                   | 46.81    | 44.99      | 62.28          |
| 20                   | 41.10    | 40.36      | 56.40          |
| 30                   | 34.24    | 34.41      | 48.65          |
| 50                   | 27.59    | 27.68      | 39.15          |
| 70                   | 25.79    | 24.81      | 33.68          |
| 100                  | 23.43    | 22.46      | 30.52          |

*) IF: Total Fault Current
    IFCL: Fault Current flowing into FCL

Fig. 3 and 4 shows some useful simulation results including fault current, integrated values for quenching and recovery and related factors in case of the developed HTS-FCL depending on fault current, temperature, and other factors is applied in test power system. A simulation results is changed by a parameter value of the developed HTS-FCL model. Especially, response characteristics are affected by temperature coefficients.
4. CONCLUSIONS

This paper develops the EMTDC dynamic model of HTS-FCL resistance and evaluates the analysis results by applying it to a test power system representing similar characteristics to the KEPCO system. Here are the overall research results.

- We analyzed the dynamic behavior of HTS-FCL resistance, and developed the generic EMTDC dynamic model. Also, we verify the effectiveness of the developed model by applying it to the test power system.
- As the analysis results of the basic case, having HTS-FCL or not, the fault current could be reduced below the breaking capacity if HTS-FCL is applied.
This paper simulates the nonlinear characteristics of HTS-FCL, but the accurate equation describing actual nonlinear characteristics is not clear at this stage. Therefore, it is necessary to study the nonlinear characteristics itself.

Furthermore, additional research on the optimum setting of HTS-FCL parameters, such as quenching resistance and critical quenching current for practical power system application, is necessary.

5. REFERENCES
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