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R-type HTS-FCL EMTDC Transient Model Considering Quenching and Recovery Characteristics

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Abstract-- One of the most serious problems in the operation of the KEPCO system is a higher fault current than the circuit breaker SCC (Short Circuit Capacity). There are many alternatives to reduce the increased fault current, such as the isolation of bus ties, enhancement of the circuit breaker SCC, and the application of HVDC-BTB (Back to Back) and FCL (fault current limiter). However, these alternatives have drawbacks from the viewpoint of system stability and cost. As superconductivity technology has been developed, the resistance type HTS-FCL (High Temperature Superconductor Fault Current Limiter) offers one of the most attractive alternatives in solving the fault current problem. To evaluate the accurate transient performance of resistance type HTS-FCL, it is necessary for the dynamic simulation model to consider transient characteristics during the quenching and recovery state. Against this background, this paper presents the EMTDC model for resistance type HTS-FCL, considering the nonlinear characteristics of final resistance value when quenching and recovery phenomena by fault current injection and clearing occurs.

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 exceeds 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 (High Temperature Superconductor-Fault Current Limiter) is currently underway worldwide through HTS technology, and attempts to apply it to power systems are continuing. Resistance 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 resistance type HTS-FCL, it is necessary for the dynamic simulation model to consider transient characteristics during the quenching and recovery state. Against this background, this paper presents the EMTDC model for resistance type HTS-FCL considering the nonlinear characteristics of the final resistance value when quenching and recovery phenomena by fault current injection and clearing occurs. Thus, the EMTDC dynamic model has been developed to simulate the quenching phenomena of R-type HTS-FCL, and to confirm the effectiveness of applying this to a simulated system similar to the real conditions of power systems.

2. TRANSIENT MODEL OF R-TYPE HTS-FCL

If power is in the normal operational state, HTS-FCL resistance can be maintained at nearly zero because of superconducting characteristics. However, if the fault current is 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, quenching and recovery state for R-type HTS-FCL. Fig. 1 represents the dynamic characteristics of HTS-FCL resistance, depending on fault current (IF_RMS) and other factors. The overview of mathematical modeling is as follows.

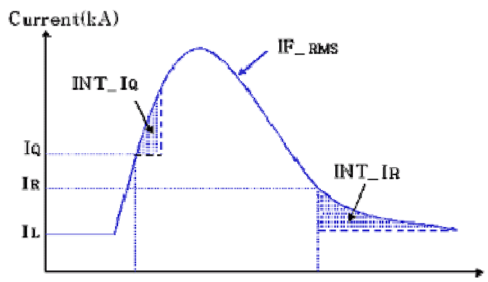

Fig. 1. Dynamic characteristics of HTS-FCL resistance

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2.1. Equations of temperature dependence for basic parameter

$$T_{PU} = \frac{T}{T_0} \quad (1)$$

$$I_L \ or \ I_Q \ or \ I_R = I_{L0} f(T_{PU}) \ or \ I_{Q0} f(T_{PU}) \ or \ I_{R0} f(T_{PU}) \quad (2)$$

$$\text{ex)} \ I_L = I_{L0} f(Tpu)$$

$$VINT_{IQ} = VINT_{IQ0} \times f(T_{PU}) \quad (3)$$

$$VINT_{IR} = VINT_{IR0} \times f(T_{PU}) \quad (4)$$

$$VPT_{IQ} = VPT_{IQ0} \times f(T_{PU}) \quad (5)$$

$$VPT_{IR} = VPT_{IR0} \times f(T_{PU}) \quad (6)$$

Where, T_0, T: Base and operational temperature

I_L, I_Q, I_R : Steady state, quenching and recovery current

I_{L0}, I_{Q0}, I_{R0} : Base steady state, quenching and recovery current

$VINT_{IQ}$, $VINT_{IR}$: Integration value of fault current for quenching and recovery (kA-sec)

VPT_{IQ}, VPT_{IR} : Integration value of fault current per second for quenching and recovery (kA-sec/sec)

2.2. Superconducting state and resistance

If Eq. (7) is satisfied, the superconducting status will be maintained and the resistance value is nearly zero.

$$I_{RMS} \leqq I_{L,MAX} \quad (7)$$

$$FCL_R \cong 0.0 \quad (8)$$

2.3. Quenching state and resistance value

If all Eqs. (9)-(11) 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. For example, the exponential function, from zero (superconducting resistance) to quenching resistance.

$$I_{RMS} \geq I_Q \quad (9)$$

$$\int_{t_Q}^{t} I_{RMS} \, dt \geq VINT_{IQ} \quad \text{for } t_Q \leq t \leq t_R \quad (10)$$

$$\frac{\int_{t_Q}^{t} I_{RMS} \, dt}{t - t_Q} \geq VPT_{IQ} \quad \text{for } t_Q \leq t \leq t_R \quad (11)$$

$$HTS_R = f(I_F, t) \quad \text{ex)} \ HTS_R = (t - t_Q) \times I_{RMS} \times \exp(-kt)$$

Where, HTS_R: HTS-FCL resistance during quenching state

2.4. Recovery state

If Eqs. (12)-(13) 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. For example, exponential function, from quenching resistance to zero (superconducting resistance).

$$I_L \leq I_{RMS} < I_Q \quad (12)$$

$$\frac{K_Q \times \int_{t_Q}^{t_R} I_{RMS} \, dt + K_R \times \int_{t_R}^{t} I_{RMS} \, dt}{t - t_Q} \leq VPT_{IR} \quad (13)$$

$$\text{for } t \geq t_Q$$

$$HTS_R = f(I_F, t) \quad (14)$$

$$\text{ex)} \ HTS_R = (t_R - t_Q - t + t_R) \times I_{RMS} \times \exp(-kt)$$

Where, HTS_R : HTS-FCL resistance during/after recovery state

This paper develops the EMTDC dynamic model of HTS-FCL resistance depending on the above equations. 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.

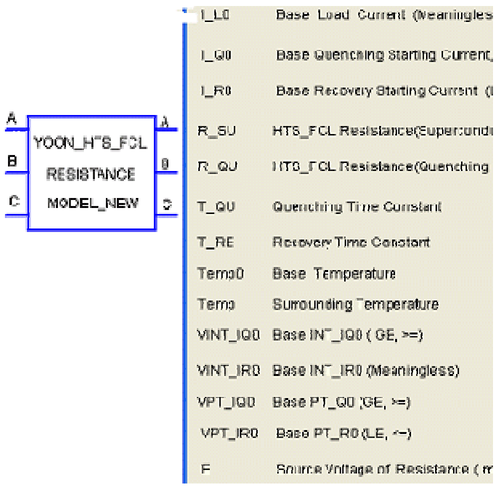


Fig. 2. Dynamic model of HTS-FCL resistance

If necessary, for the EMTDC model of Fig. 2, non-linear characteristics as Eq. (15) could be structured to change the HTS-FCL resistance with fault current, temperature and other factors during the quenching and recovery process. Also, it can be designed to add alterations of function and input factors. This means that we can change the detail transit function for the dynamic behavior of each HTS-FCL resistance because the actual transient characteristics of HTS-FCL resistance during quenching and recovery phenomena are not clear at this stage, and the dynamic performance is not the same for different types of HTS-FCL.

$$y = f(I_F, \ Temperature, \ Other \ Factors) \quad (15)$$

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 HTS-FCL resistance to reduce fault current, and other power equipment, which represent the whole power system. It can be simulated under the various operational states for test power systems by changing the basic data.

3.2. Analysis results

The basic data of HTS-FCL resistance is described in

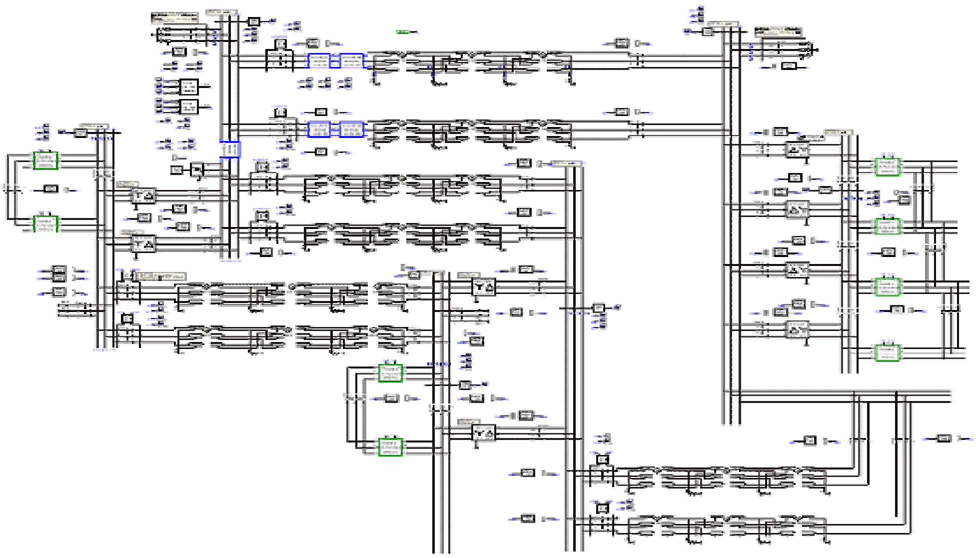


Fig. 3. Test power system representing KEPCO system

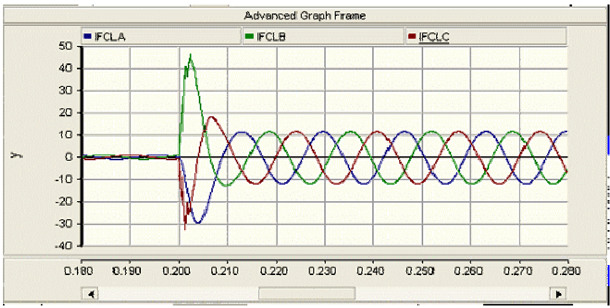
Table I, Table 2 shows the difference of analysis results for the base case, whether HTS-FCL applies to 154kV bus or not. The base case means that the 3-ph. fault occurs on the 154kV bus in the case of HTS-FCL applied at the 154kV bus. We can see from the analysis results, for the base case with HTS-FCL, that the peak and steady-state RMS fault current is noticeably smaller than for the base case without HTS-FCL. When comparing the analysis results, the peak fault current reduces from 151.3(kA_peak) to 46.4(kA_peak) in the case of having HTS-FCL with basic data.

TABLE I
Basic data of HTS-FCL resistance

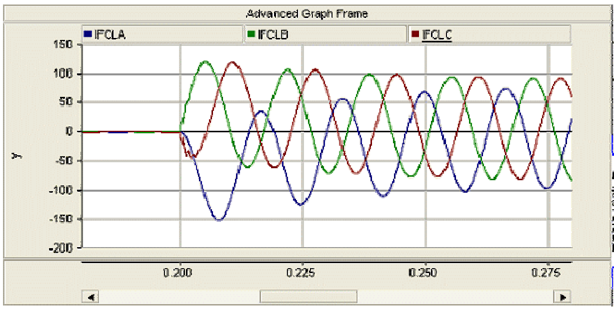
Data	Base Data	Remark
I_L0	0.5 [kA]	Base Load Current
I_Q0	8.0 [kA]	Base Quenching Starting Current
I_R0	0.5 [kA]	Base Recovery Starting Current
R_SU	0.001	HTS_FCL Superconducting Resistance
R_QU	10.0	HTS_FCL Quenching Resistance
T_QU	0.01	Quenching Time Constant
T_RE	100	Recovery Time Constant
Temp0	20.0	Base Temperature
Temp	20.0	Surrounding Temperature
VINT_IQ0	0.001	Base INT_IQ0
VINT_IR0	100	Base INT_IR0
VPT_IQ0	5.0 [kA]	Base PT_IQ0
VPT_IQ0	100 [kA]	Base PT_IR0

TABLE II
Analysis result for base case

CASE	IFCL_peak(kA)	IFCL_rms
Base case with HTS-FCL	46.4(kA_peak)	8.4(kA_rms)
Base case without HTS-FCL	151.3(kA_peak)	62.1(kA_rms)



(a) Fault current with HTS-FCL (Base case)



(b) Fault current without HTS-FCL (Base case)

Fig. 4. Fault current comparison with/without HTS-FCL for base case

As a case study, quenching resistance (R_QU), and quenching starting current can be varied within a limited range. Table III describes the analysis results when the quenching resistance and quenching starting current are changed. It shows that the higher the quenching resistance, the smaller the fault current.

TABLE III

Analysis result when quenching resistance changes

CASE	IFCL_peak(kA)	IFCL_rms
Base case with HTS-FCL R=0(Ω)	151.3(kA_peak)	62.1(kA_rms)
Base case with HTS-FCL R=1(Ω)	100.5(kA_peak)	47.8(kA_rms)
Base case with HTS-FCL R=5(Ω)	59.9(kA_peak)	16.1(kA_rms)
Base case with HTS-FCL R=10(Ω)	46.4(kA_peak)	8.4(kA_rms)
Base case with HTS-FCL R=20(Ω)	34.3(kA_peak)	4.3(kA_rms)
Base case with HTS-FCL R=50(Ω)	21.4(kA_peak)	1.7(kA_rms)

4. Conclusion

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 result 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 characteristic 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 characteristic 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.

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