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Resistive Hts-Fcl Emtdc Modeling By Using Probabilistic Design Methodology

Jae-Young Yoon*, Jong-Yul Kim* and Seung-Ryul Lee*

Abstract - Nowadays, one of the serious problems in the KEPCO system is a much higher fault current than the SCC (Short Circuit Capacity) of the circuit breaker. Since superconductivity technology has become more developed, the HTS-FCL (High Temperature Superconductor-Fault Current Limiter) may become an attractive alternative to solving the fault current problem. In order to achieve the best performance, the parameters of HTS-FCL should be designed optimally. Under this setting, this paper presents the optimal design method of parameters for resistive type HTS-FCL using the Monte Carlo technique.

Keywords: HTS-FCL, Monte Carlo Simulation, Optimal design, PSCAD/EMTDC

1. Introduction

Along with power system development, fault current has increased, leading to short circuit capacity being exceeded in the KEPCO transmission system. This results in very serious problems from the viewpoints of system planning and operation [1]. Various countermeasures such as separation of busbars and lines, enhancement of circuit breaker's short circuit capacity, application of fault current limiter and BTB (Back-to-Back) HVDC systems can be alternatives [2]. Each of these alternatives has drawbacks from the perspective of system stability or effectiveness of fault current reduction, etc. But, as HTS technology has developed, the HTS-FCL can be the most effective alternative to reduce the fault current as compared with other countermeasures in terms of system stability, cost effectiveness and fault current reduction [3-6].

In order to apply the HTS-FCL to a practical power system, the simulation results of transient behavior including steady state, quenching and recovery state are needed. Also, it is necessary for the dynamic model to represent overall phenomena in order to obtain the simulation results, and the optimal design of the HTS-FCL parameter should be performed to maximize the effect of fault current reduction and maintain the stability of the power system when fault occurs. Therefore, the optimal design method of parameters for resistive type HTS-FCL using the Monte Carlo technique is presented and a typical case study is performed to confirm the effectiveness of this method with a typical power system model that is similar to the practical system under the various conditions in this paper.

2. Parameter of Resistive Type HTS-FCL

HTS-FCL has a zero resistance under static conditions. But, if fault current exceeds the critical value, known as quenching state, the resistance of HTS-FCL increases and the fault current is limited to a certain specified value. The fault current reduces below the critical value after HTS-FCL operates and fault clears. After that, the characteristics of HTS-FCL are recovered by reducing the resistance to zero.

The important parameters required for representing the dynamic characteristics of HTS-FCL are described in Table 1. Among the parameters in Table 1, the operation characteristics of HTS-FCL are dependent on design parameters such as R_FIN (Final resistance value), I_OP (Initial operating current), and T_FCL (time constants).

Table 1 General definitions of HTS-FCL parameter

Parameter	Definitions	Remarks
CB_{SCC}	SCC of circuit breaker (kA)	SCC: Short Circuit Capacity
I_FCL	Fault current flowing into HTS-FCL	
I_OP	Initial operating current of HTS-FCL (kA)	upper limit: (SCC - Margin) lower limit: (Max. load current +Margin)
R_FIN	Final resistance value in quenching state(Ω)	dependent on CB_{SCC} and I_OP
T_FCL	Time constants of HTS-FCL(msec)	
T_REC	Recovery time of HTS-FCL(msec)	related to reclosing

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* Power System Research Group, Korea Electrotechnology Research Institute (KERI), Changwon, 641-420, Korea (jyyoon@keri.re.kr, yjkim@keri.re.kr, srlee@keri.re.kr)

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These parameters have the reverse characteristics to determine the magnitude of fault current. For example, if the R_FIN is larger, I_OP is smaller or T_FCL is shorter than others, the effectiveness of HTS-FCL at reducing the fault current becomes higher and higher. But, even if these three parameters are well-designed by prescribed values, the overall effect of HTS-FCL is dependent on the stochastic characteristics of mutual effect of each parameter. Therefore, it is necessary to consider the stochastic characteristics of HTS-FCL parameters for optimal design.

3. Emtdc Model Of Hts-Fcl

This paper presents the transient model of HTS-FCL considering static and quenching state by Fig. 1.

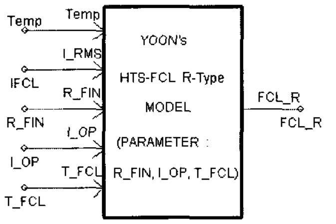


Fig. 1 Transient model of resistive HTS-FCL model

When fault occurs, the resistance of HTS-FCL changes from zero to finite final resistance value. This change of resistance of HTS_FCL is dependent on various parameters described in Table 1 such as fault current (I_FCL), final resistance value (R_FIN), initial operating current (I_OP), temperature (Temp), and time constant of HTS-FCL (T_FCL) as shown in Fig. 1. The fault resistance of HTS-FCL can be described by Eq. (1).

$$
\begin{aligned}
&FCL\_R = R\_FIN \times R\_OUT \\
&R\_OUT = Temp + IF + Other \\
&IF = \frac{1}{T\_FCL} \int_{T_0} (I\_RMS - I\_OP)\, dt, \qquad (1) \\
&if \;\; I\_RMS \geq I\_OP
\end{aligned}
$$

where, FCL_R : Resistance value of HTS-FCL
Temp : Impact factor of temperature
Other : Other factor if necessary
IF : Integral value of the fault current which exceeds I_OP

4. Design Method of Optimal Parameter

Monte Carlo Simulation is one of the optimal design methods applied to the case in which input parameters have stochastic characteristics and mutual dependency. So, Monte Carlo Simulation is a probabilistic method considering the input parameter as a random variable and can be used by effectiveness methodology to design optimal parameter of HTS-FCL. In this paper, R_FIN and I_OP are considered as random variables and the design procedures as shown in Fig. 2 are as follows.

(Step 1) Setting up the upper and lower limit of R_FIN, I_OP and T_FCL. In this study, three types of probability distribution are used. This means that sequential, normal and random distribution can be applied as a probability density function.

- Final resistance value as a random variable $10 \leq$ R_FIN ≤ 60 (Ω)
- Initial operating current as a random variable $5 \leq$ I_OP ≤ 10 (kA)
- Time constants for case study $0.001 \leq$ T_FCL ≤ 0.01 (sec)

(Step 2) Select T_FCL within lower and upper limits.

(Step 3) Generate random value for R_FIN, I_OP using random generator within upper and lower limits.

(Step 4) Carry out the EMTDC simulation of the model system, which has the value of R_FIN, I_OP and T_FCL selected in step 2 and step 3.

(Step_5) Confirm the steady state continuous fault current flowing into HTS-FCL (I_FCL).

(Step_6) Repeat step 3 to step 5. After several trials, go to step 2.

(Step_7) Analyze simulation results and determine the combination of R_FIN, I_OP, which has the minimum I_FCL for a given T_FCL.

I_FCL is relative to FCL_R and FCL_R is a function of R_FIN, I_OP and T_FCL as shown in Eq. (2).

$$FCL\_R = f(R\_FIN, I\_OP, T\_FCL) \qquad (2)$$

Therefore, we can select the combination of R_FIN, I_OP, which has the minimum I_FCL among many combinations generated by the random generator.

The above design method (step 1 to step 6) is carried out using PSCAD/EMTDC Multi-Run Control as shown in Fig. 2.

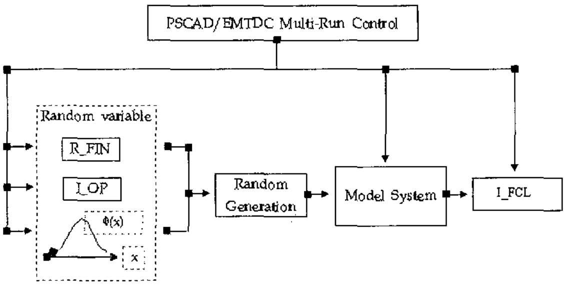


Fig. 2 Overview of Probabilistic analysis

5. Analysis Results

5.1 Overview of analysis

5.1.1 Model system

The model system of Fig. 3 is presented to confirm the effectiveness of this method. This model system represents characteristics similar to the KEPCO 154kV system, which has a similar average short circuit capacity, overhead line, cable configurations, etc.

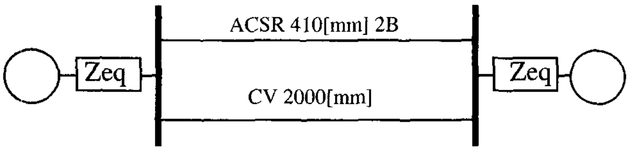


Fig. 3 Model system for KEPCO 154kV system with resistive HTS-FCL

5.1.2 Model system data

Basic data to analyze the model system with HTS-FCL are as follows.

- Equivalent source of sending and receiving end 1.02∠10°(PU) and 1.0∠0°
- Source impedance: 2.223(Ω)∠85.0°(in sending and receiving end)
- Overhead line: ACSR 410[mm^2]x2B, frequency independent, non-transposed model (10.0km)
- Cable line: F 2000[mm^2], frequency independent, non-transposed model (10.0km)
- Random variable (R_FIN & I_OP): with limits specified in step 1

5.2 Case study results

5.2.1 Base case

Fault study in the model system is performed as the following upper and lower limits of random variables.

- $10 \leq$ R_FIN ≤ 60 (Ω)
- $5 \leq$ I_OP ≤ 10 (kA)

The input parameter of these random variables varies based on three different methods of 100 cases.

- Sequential : Input parameter varies step by step for each case
- Normal : Input parameter varies by normal distribution
- Random : Input parameter varies by random generator

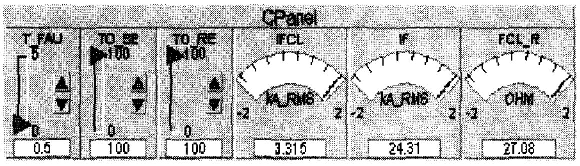
The study results of the base case When T_FCL is 0.002 are described in Table 2. It signifies that the steady state continuous fault current in the case of sending the bus 3-phase fault has a minimum value of R_FIN(57.3Ω) and I_OP (5.0kA) when a random generator is used to determine the input parameter. When HTS-FCL doesn't exist, the total steady state continuous fault current is 50.0kA. These results confirm the effectiveness of HTS-FCL in reducing the fault current.

Generally speaking, a minimum value is expected when the R_FIN is 60.0(Ω) and I_OP is 5.0(kA). However, it proved to be inaccurate via sequential simulation. This is caused by the complex and mutual effect of random variables. If R_FIN is 60.0(Ω), I_FCL (fault current flowing into HTS-FCL) goes down more rapidly under the critical value (I_OP= 5.0 kA) as compared with other specific cases. HTS-FCL is no longer able to operate as a countermeasure of fault current reduction in this case.

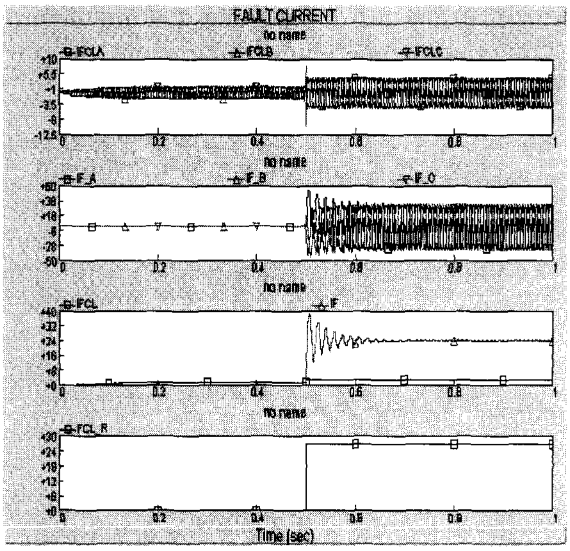
Table 2 Study results of basic case

CASE	Optimal parameter	Results			Remarks
		I_F (kA)	I_FCL (kA)	FCL_R (Ω)	
No HTS-FCL		50.0			Without HTS-FCL
T_FCL = 0.002 (sec)	R_FIN = 57.0(Ω) I_OP = 5.0(kA)	24.3	3.31	27.1	Sequential
T_FCL = 0.002 (sec)	R_FIN = 56.1(Ω) I_OP = 5.1(kA)	24.3	3.37	26.6	Normal distribution
T_FCL = 0.002 (sec)	R_FIN = 57.3(Ω) I_OP = 5.0(kA)	24.3	3.30	27.2	Random

*) I_F: Total fault current, I_FCL: fault current flowing into HTS-FCL , FCL_R: Final fault resistance



(a) Fault current and final resistance with HTS-FCL(Sequential case)



(b) Fault current and final resistance with HTS-FCL (Sequential case)

Fig. 4 Basic study results with HTS-FCL(Fault occurs T=0.5sec)

5.2.2 Case study

In this paper, some cases with different time constants of HTS-FCL are analyzed. The overall study results are described in Tables 3 and 4. Just as in the case of the above study results, the optimal parameter is dependent upon the complex and mutual effect of random variables.

Table 3 Case study results with various T_FCL (input parameter varies sequentially)

CASE	Optimal parameter	Study results		
		I_F (kA)	I_FCL (kA)	FCL_R (Ω)
T_FCL = 0.001 (sec)	R_FIN = 59.0(Ω) I_OP = 5(kA)	24.18	3.05	29.5
T_FCL = 0.003 (sec)	R_FIN = 56.0(Ω) I_OP = 5(kA)	24.44	3.56	25.2
T_FCL = 0.005 (sec)	R_FIN = 59.0(Ω) I_OP = 5(kA)	24.61	3.89	23.0
T_FCL = 0.01 (sec)	R_FIN = 60.0(Ω) I_OP = 5(kA)	24.89	4.38	20.4

Table 4 Case study results with various T_FCL (input parameter varies randomly)

CASE	Optimal parameter	Study results		
		I_F (kA)	I_FCL (kA)	FCL_R (Ω)
T_FCL = 0.001 (sec)	R_FIN = 59.9(Ω) I_OP = 5.0(kA)	24.16	3.00	29.96
T_FCL = 0.0015 (sec)	R_FIN = 51.4(Ω) I_OP = 5.25(kA)	24.29	3.27	27.4

6. Conclusion

This paper presents the optimal design method of resistive type HTS-FCL using the Monte Carlo technique. The overall study results show that the optimal parameter is dependent on the complex and mutual effect of random variables. The effectiveness of HTS-FCL is confirmed in the model system with characteristics similar to the KEPCO 154kV system. As a consequence, it is expected that resistive HTS-FCL can be one of the most effective alternatives to reduce the fault current. A detailed study for the comparisons with other alternatives countermeasures in terms of system stability, cost effectiveness and fault current reduction is needed.

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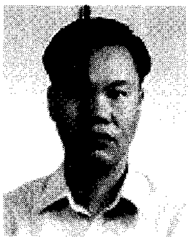
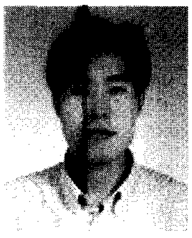


Jae-Young Yoon
He received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from Pusan National University. He is currently employed by the Korea Electrotechnology Research Institute (KERI) as Head of the Power System Group. His current research interest is in the areas of power system interconnection between countries and system application of HTS equipment, such as cables, transformers and fault current limiters



Jong-Yul Kim
He received his B.S. and M.S. degrees in Electrical Engineering from Pusan National University and is currently employed by the Korea Electrotechnology Research Institute (KERI). His research interests are in the areas of power system analysis, superconducting devices and AI to power systems

Seung-Ryul Lee
He received his B.S. and M.S. degrees in Electrical Engineering from Korea University and is currently employed by the Korea Electrotechnology Research Institute (KERI). His research interests are in the areas of power system analysis and application of HTS devices such as fault current limiters, cables and transformers.