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Parameter Design Using Probabilistic Methodology For Resistive HTS-FCL

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Abstract-- **Nowadays, one of the serious problems in KEPCO system is much higher fault current than the SCC(Short Circuit Capacity) of circuit breaker. As the superconductivity technology has developed, the HTS-FCL(High Temperature Superconductor-Fault Current Limiter) can be one of the attractive alternatives to solve the fault current problem. But the parameters of HTS-FCL should be designed optimally to have the best performance. Under this background, this paper presents the optimal design method of parameters for resistive type HTS-FCL using Monte Carlo technique.**

1. INTRODUCTION

As the power system has developed, the fault current increases, then the short circuit capacity can be exceeded in KEPCO transmission system. This comes up to a real serious problem of system planning and operation viewpoints.[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 system can be alternatives.[2] All of these alternatives have drawbacks of viewpoint on system stability or effectiveness of fault current reduction and etc. But, as the 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 practical power system, the simulation results of transient behavior including steady state, quenching and recovery state is 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 HTS-FCL parameter should be performed to maximize the effect of fault current reduction and maintain the stability of power system when fault occurs. Therefore, it is presented the optimal design method of parameters for resistive type HTS-FCL using Monte Carlo technique and the typical case study is performed to confirm the effectiveness of this method with typical power system model which 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 the static conditions. But, if fault current exceeds the critical value, called 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 as a zero.

The important parameters to represent the dynamic characteristics of HTS-FCL are described in Table I. Among parameters in Table I, the operation characteristics of HTS-FCL are dependent on design parameters such as R_FIN (Final resistance value), I_OP (Initial operating current), T_FCL (time constants). These parameters have the reverse characteristics to determine the magnitude of fault current. For example, as the R_FIN is larger, I_OP is smaller or T_FCL is shorter than others, the effectiveness of HTS-FCL to reduce the fault current is higher and higher. But, even if these three parameters are well-designed by prescribed value, 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.

TABLE I
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

3. EMTDC MODEL OF HTS-FCL

This paper presents the transient model of HTS-FCL considering static and quenching state by Fig. 1. 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 I such as fault current(I_FCL), final resistance value(R_FIN), initial operating current(I_OP), temperature(Temp), time constant of HTS-FCL(T_FCL) as shown in Fig. 1. The fault resistance of HTS-FCL can be described by Eq. (1).

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

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

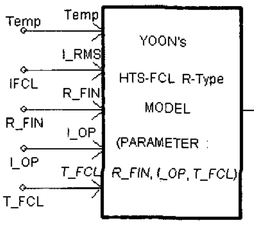


Fig. 1. Transient model of resistive HTS-FCL model

4. DESIGN METHOD OF OPTIMAL PARAMETER

Monte Carlo Simulation is one of the optimal design method applied to the case that 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 is used. This means that sequential, normal and random distribution can be applied as probability density function.

○ Final resistance value as a random variable :
$10 \leq R\_FIN \leq 60\ (\Omega)$

○ Initial operating current as a random variable :
$5 \leq I\_OP \leq 10\ (kA)$

○ Time constants for case study :
$0.001 \leq T\_FCL \leq 0.01\ (sec)$

(step_2) Select T_FCL within lower and upper limit.

(step_3) Generate random value for R_FIN, I_OP using random generator within upper and lower limit.

(step_4) Carry out the EMTDC simulation of 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) Analysis of simulation results and determine the combination of R_FIN, I_OP which has the minimum I_FCL for given T_FCL.

I_FCL is relative to FCL_R and FCL_R is 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 combination of R_FIN, I_OP which has the minimum I_FCL among many combinations generated by 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.

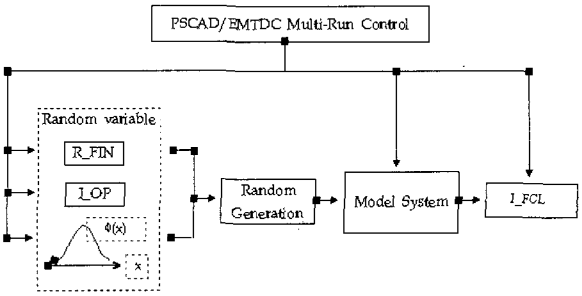


Fig. 2. Overview of Probabilistic analysis

5. DESIGN METHOD OF OPTIMAL PARAMETER

5.1. Overview of analysis

5.1.1. Model system

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

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)

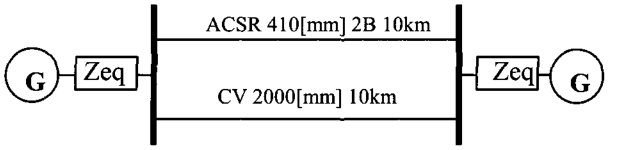


Fig. 3. Model system for KEPCO 154kV system with resistive HTS-FCL

- ○ 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 model system is performed as the following upper and lower limits of random variables.

- ○ $10 \le$ R_FIN ≤ 60 (Ω)
- ○ $5 \le$ 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

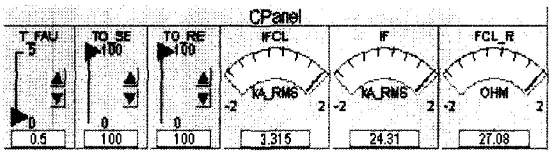
When T_FCL is 0.002, the study results of this base case are described in Table II. It means that the steady state continuous fault current in the case of sending bus 3-phase fault has a minimum value of R_FIN(57.3Ω) and I_OP (5.0kA) when random generator is used to determine the input parameter. When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

Generally speaking, it is expected to have a minimum value when the R_FIN is 60.0(Ω) and I_OP is 5.0(kA). But, 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 operate as a countermeasure of fault current reduction in this case.

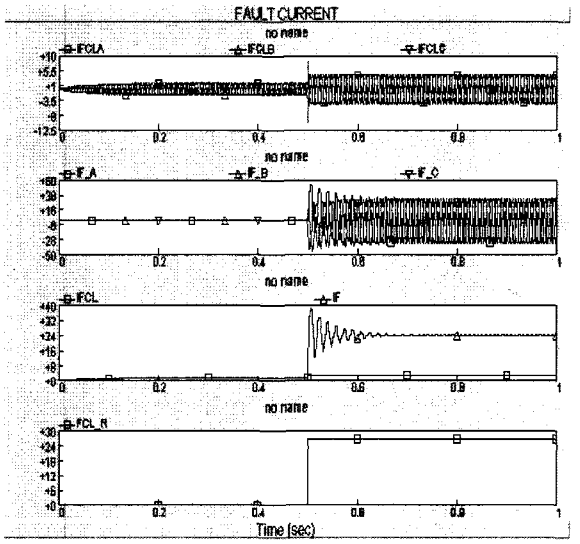
TABLE II.
STUDY RESULTS OF BASIC CASE

CASE	Optimal parameter	Results I_F (kA)	 I_FCL (kA)	 FCL_R	Remarks
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(Ω)	Sequential
T_FCL= 0.002 (sec)	R_FIN = 56.1(Ω) I_OP = 5.1(kA)	24.3	3.37	26.6(Ω)	Normal distribution
T_FCL= 0.002 (sec)	R_FIN = 57.3(Ω) I_OP = 5.0(kA)	24.3	3.30	27.2(Ω)	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 Table III and IV. Same as the above study results, the optimal parameter is dependent on the complex and mutual effect of random variables.

TABLE III
CASE STUDY RESULTS WITH VARIOUS T_FCL(INPUT PARAMETER VARIES SEQUENTIALLY)

CASE	Optimal parameter	Study results			Remarks
		I_F(kA)	I_FCL (kA)	FCL_R	
T_FCL=0 .001 (sec)	R_FIN = 59.0(Ω) I_OP = 5(kA)	24.18	3.05	29.5(Ω)	
T_FCL=0 .003 (sec)	R_FIN = 56.0(Ω) I_OP = 5(kA)	24.44	3.56	25.2(Ω)	
T_FCL=0 .005 (sec)	R_FIN = 59.0(Ω) I_OP = 5(kA)	24.61	3.89	23.0(Ω)	
T_FCL=0 .01 (sec)	R_FIN = 60.0(Ω) I_OP = 5(kA)	24.89	4.38	20.4(Ω)	

TABLE IV
CASE STUDY RESULTS WITH VARIOUS T_FCL(INPUT PARAMETER VARIES RANDOMLY)

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

6. CONCLUSION

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

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