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Application Simulation of a Resistive Type Superconducting Fault Current Limiter (SFCL) in a Transmission and Wind Power System

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Abstract

Due to the increased fault-level currents, superconducting fault current limiter (SFCL) is more likely to penetrate into a low voltage and medium voltage transmission network to improve their stability and lower the electric devices capacity. Therefore it is important to model a SFCL in power system to analyze its performance and study its characteristics. In this paper, a simulation model for a resistive type SFCL consisted of YBCO tapes is developed using Matlab/Simulink software. This model will take into account SFCL's internal electromagnetic behavior by coupling its internal resistance and the current density characteristics based on the *E-J* power law. Finally, the SFCL simulation model is applied in a transmission and a wind farm power grid, respectively. Different fault limiting scenarios are investigated and the results show that the SFCL is effective in limiting fault currents with a maximum of 50% in transmission lines, particularly for wind farm networks.

Keywords : Resistive type superconducting fault current limiter (SFCL); simulation; transmission lines; wind farm; YBCO.

1. Introduction

Superconducting fault current limiter (SFCL) is a mature and near-market technology. A variety of SFCL technologies that utilize unique and novel approaches for limiting the fault currents are now in the prototype stage of development and, if successful, will soon be ready for grid deployment[1]. Since the utility of large-scale distributed generation (including those based on renewable-based energy) and a greater level of interconnection between transmission and distribution lines become more and more popular in the power grid nowadays, the power grid inevitably experience some short-circuit fault events. So the operation limits of the normal electric devices would be exceeded and raise a requirement to

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reinforce the power networks at a high cost.

SFCL is a self - triggering and fail - safe device as long as the superconductor is capable of handling the fault currents when it turns to a normal state and recovering to the superconducting state. They are ideal to manage the short-circuit current to an appropriate level to protect the transmission line and reduce the burden on circuit breakers. Therefore, the integration of SFCL into such power networks is an attractive alternative because the economical property. . It is important to model a SFCL and study its performance for the application in the different scenarios of power system.

An electro-magnetic model of a bifilar resistive SFCL based on *E-J* power law considering the thermal characteristic of superconducting tape is set up and packaged into an application model using Matlab/Simulink software. Then, this SFCL model is applied in a power system with short-circuit fault in a traditional transmission lines and wind farm networks. The results validate the multidisciplinary simulation model of the SFCL, and more importantly, the application potential of SFCL systems in a power grid.

2. Electromagnetic Coupling Mathematical Model of SFCL

The electromagnetic model of a SFCL is built firstly based on the resistive type limiter. Figure 1 shows the basic operating principle of this bifilar non-inductive SFCL in a circuit [2].

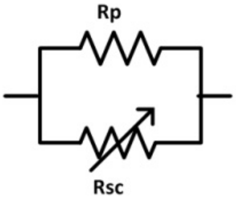


Fig. 1. Resistive type SFCL.

It could be noted that the resistive type SFCL is a variable resistor when connecting in the power network. Therefore, the structure of one variable resistor R_{sc} in parallel with a fixed resistor R_p is proposed for a SFCL model to limit the current when a fault happens in the power networks.

A high temperature superconducting (HTS) SFCL is composed of high temperature superconducting tapes, the resistivity of the tape is a binary function of temperature and current density and its variation is very complex [3]. Changes in temperature and the current variations will lower the critical current of the HTS tape. The calculation formula of the HTS SFCL resistivity ρ is expressed in (1)-(3) [4]:

$$\rho=\begin{cases} 0 & (J<J_c, T<T_c) \\ \rho_c (J/J_c)^{\,n-1} & J>J_c, T<T_c \\ \rho_{HTS}(T) & (T>T_c) \end{cases} \quad (1)$$

$$\rho_c = E_c / J_c \quad (2)$$

$$J_c \quad J_{c0}(\overset{=}{T_c} - T)/(T_c - T_{op}) \quad (3)$$

Where, ρ_c , T_c and J_c are the critical resistivity, the critical temperature and the critical current density (the subscript *c* means the critical value for the specific parameter) respectively, J_{c0} is the critical current density at 77 K, *n* is the exponential index and named *n*-value which is one of the most important properties of a superconductor, T_{op} is the operation temperature.

The resistivity of the stabilizer of HTS tape is a function of temperature, as in (4):

$$\rho_{HTS}(T)=\begin{cases}-3.2783+0.07031T\ 10^{-9}\Omega\cdot\mathrm{m} & (77\,\mathrm{K}<T<180\,\mathrm{K})\\ -3.1737+0.06965T\,10^{-9}\Omega\cdot\mathrm{m} & (T>180\,\mathrm{K})\end{cases} \tag{4}$$

For a high temperature superconductor, the mathematical relationship between the electric field E and the current density J of the superconducting material could be expressed in (5) [5]. It could be found that with an increase of current density, the voltage would increase exponentially. The conversion speed of a superconductor state is very fast when the n-value is large.

$$E \quad E_0\left(\frac{J}{J_c(T_{op})}\right)^n \tag{5}$$

3. Simulation Modelling of A SFCL in Matlab/ Simulink

Figure 2 shows the simplied model built on the platform of Matlab/Simulation. To simply the eletromagnetic model and increase computation speed, a fixed number of 21 was chosen as the n-value.

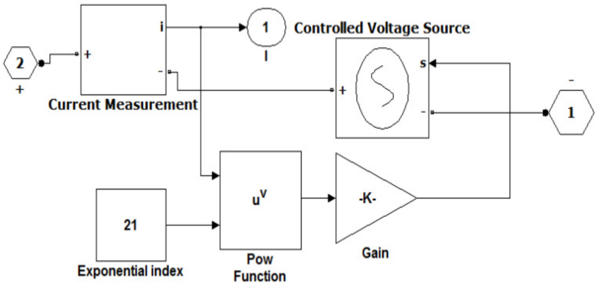


Fig. 2. Electromagnetic model of SFCL based on Matlab/Simulink.

As shown in Figure 2, a current measurement block and a controlled voltage source block are adopted in this subsystem to imitate the E-J power law. When an E-J relationship converts to a V-I relationship, there will be a coefficient appearing to reflect the specific parameters of the superconducting material. So a ‘gain’ block in this system is necessary.

The ampere meter constantly measures the current I in the circuit, which is also the current density J flowing through the SFCL, and an exponential calculation is operated for the current, whose index number is a constant (*e.g.* 21) in this case. Finally the controlled voltage source receives the result of the calculation as the input and outputs the terminal voltage V of the SFCL. So by using this algorithm, the function of a variable resistor of a SFCL has been accomplished.

4. Application Simulation and Analysis in Different Power Systems

4.1. Application in Transmission Power Grid

A SFCL model is integrated into a practical power system to simulate its performance in a grid. Figure 3 shows a schematic diagram of the SFCL applied to a normal transmission power system. Figure

4 is the application simulation system in a three-phase transmission line with SFCL.

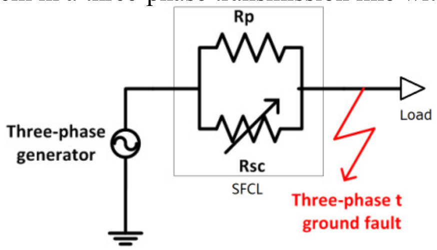


Fig. 3. Schematic diagram of the SFCL in a transmission system.

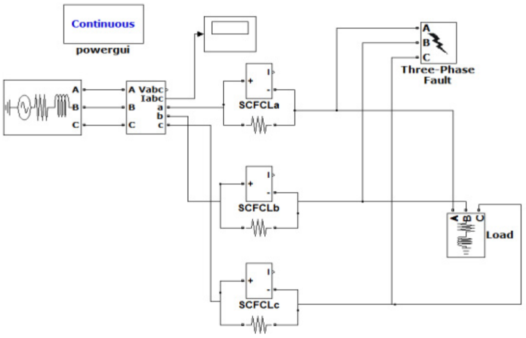
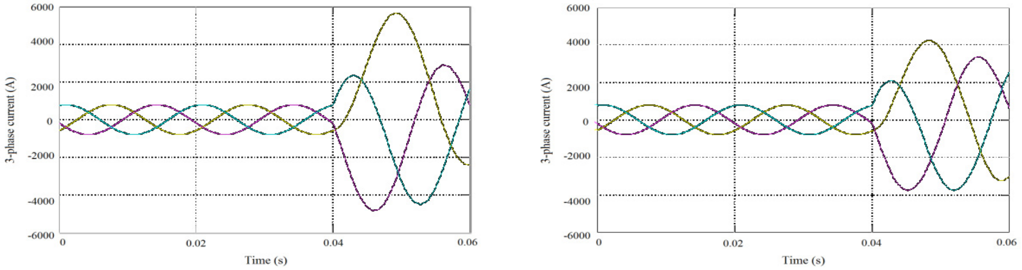


Fig. 4. Simulation system of the SFCL in a 3-phase transmission grid.

As shown in Figure 4, the simulation power system includes a power generator, a load and a SFCL. A three-phase to ground fault has been triggered at time 0.1 s and lasts till the end of the simulation. The SFCL and its shunt resistor have been in series to the output side of the generator in order to protect the generator or other electric devices from overcurrent when any fault happens.



(a) (b)

Fig. 5. Three phase current simulation waveforms: (a) without SFCL; (b) with SFCL.

Figure 5 shows the three-phase current waveforms in the simulation with and without SFCL when a three-phase fault occurs. From Figure 5, it could be noted that when there is no SFCL applied in the distribution power system, the peak value of the three-phase fault current could be as high as about 6 kA. However, when with SFCL, the same distribution system would have a peak fault current of only about 4 kA. Therefore the SFCL effectively limits the peak value of the fault current by about 33 %, as shown in Table 1.

Table 1. Current limitation rate in a transmission simulation system

Item	Current Peak value under normal operation	Current Peak value during fault	Rate of limitation
without SFCL	800 A	6000 A	0
with SFCL	800 A	4000 A	33.3 %

4.2. Application in a Wind Farm grid

Due to the rapid development of renewable energy generation in recent years, the number of wind farms connected to power grids has been significantly increased. Thus the SFCL in such a renewable generation system would provide a valuable role for its current limiting characteristics when connected to a power grid. The wind turbine generation simulation system has been built in Matlab/Simulink. Figure 6 shows the schematic diagram of the specific SFCL applied to a wind turbine system. And Figure 7 shows the simulation system in a wind farm networks with SFCL.

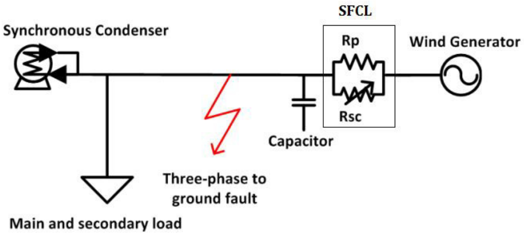


Fig. 6. Schematic diagram in wind farm power system with a SFCL.

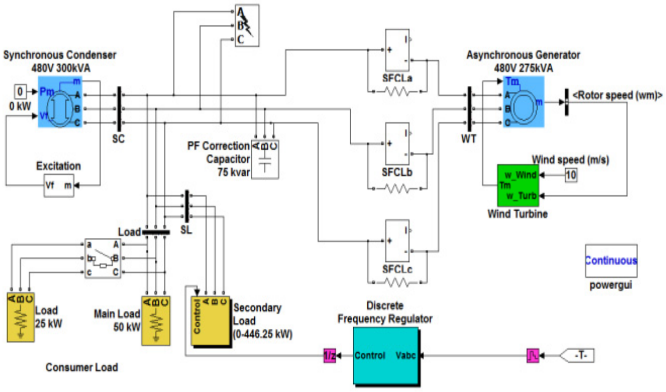
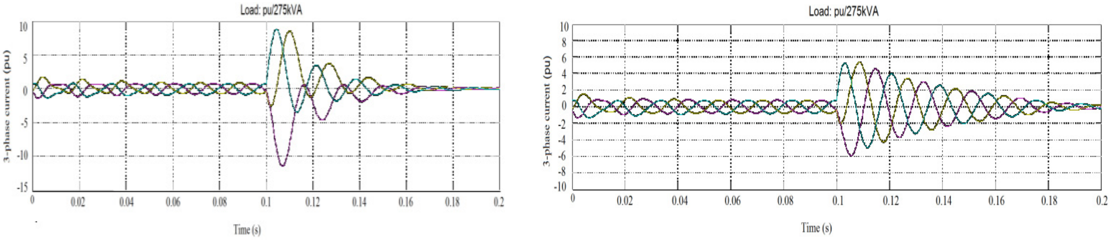


Fig. 7. Simulation system model with SFCL in a wind turbine generation system.

As shown in Figure 7, there is a wind power generator supplying power for one main load and a secondary load in an isolated network. A three-phase to ground fault has occurred at 0.1 s in the transmission lines between the turbine generator and loads. Three SFCLs have been installed at the output side of the wind generator to protect the generator from overcurrent caused by the short-circuit fault. Figure 8 shows the three-phase current waveforms when the SFCL was and was not applied.

By comparing the three-phase currents, it could be noted that without SFCL the peak value of the fault current reaches about 10 pu, while with SFCL it is only about 5 pu. Therefore, a SFCL could effectively limit the peak value of the fault current by about 50 %, as shown in Table 2.



(a) (b)

Fig. 8. Current simulation waveforms: (a) without SFCL; (b) with SFCL

Table 2. Current limitation rate in a wind farm simulation system

Item	Current Peak value under normal operation	Current Peak value during fault	Rate of limitation
without SFCL	1.5 pu	10 pu	0
with SFCL	1.5 pu	5 pu	50 %

5. Conclusion

A multidisciplinary model of a bifilar resistive SFCL considering the electromagnetic properties of YBCO superconducting material is developed in the Matlab/Simulink environment. This SFCL model can show its internal electromagnetic behavior which is influenced by the variation of the operation condition. This packaged SFCL model is integrated in the power systems of both traditional transmission lines and wind farm networks. The current simulation results validate the multidisciplinary design of the SFCL and the application potential of SFCL in a power grid.

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