Safe Operation Improvement of an Electrical Power System by Superconducting Fault Current Limiters

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Abstract: As microgrid grows and will become more interconnected, high short-circuit current level is a serious problem, which will threaten the safe and stable operation of power system. Superconducting fault current limiter (SFCL) is mainly used to solve the problem and can limit a prodigious short-circuit current to a lower level so that the protection devices can be operated safely. This paper is aimed towards the problem of utilizing SFCL with the purpose of safe operation enhancement of medium-low voltage microgrid network. The power grid model was built by using Simulink and SimPowerSystem blocks in Matlab according to the actual power system. In the case of interconnection power grid with different voltage levels, an appropriate resistance value could be obtained by analyzing the relationship between fault current reduction and the resistance value of SFCL in the same voltage level. The investigation on how to use SFCL to limit fault current level was conducted by utilizing the built model. The power grid fault occurred in middle or low voltage distribution network was simulated and the impact of SFCL on fault current reduction was evaluated.

Key Words: Microgrid, Fault Current, Smart Grid, Distributed Generation, Superconducting Fault Current Limiter

1 INTRODUCTION

With the development of our society and the power grid, the consumption of electricity has continued to increase and the infrastructure of power grid has become more complex. For these reasons, smart grid has been proposed to be a bright vision of the future power grid, which can manage the power consumption in real time and be more environmental, flexible and reliable than traditional power system [1]. In a smart grid, microgrid technology is an effective way to promote the development of renewable energy resources. However, one critical problem of integration of new energy is the excessive fault current due to the DGs within electric power grid [2].

When the short circuit current exceeds a certain level, a series of problems will take place during the construction and operation of power system. Microgrid may or may not be connected to the conventional power grid, but the integration of different kinds of DGs and loads with safety should be satisfied [3]. Short circuit current contains extremely high energy, and may damage electrical equipment. When the fault current level increases more than the cutoff value of associated power device, all devices must therefore have a power rating that can withstand the short circuit current. Typically, when a fault occurs, the circuit breaker has a response time delay that allows initial two or three fault current cycles to pass through before getting activated [4]. But circuit breakers, sometimes, fail to deal with the high strength of fault current, so they cannot break off and force the system to crash.

Current limiting devices are becoming more and more important due to the connection of DGs, whose access capacity can lead to a higher fault current level. With the advantages of fast response time and automatic recovery features that other current limiting devices dont have, SFCL can integrate detection, triggering and limiting current in one device, and becomes one of the most ideal current limiting devices. SFCL is an innovative electric equipment and can effectively reduce the current level within the first cycle of fault current [5].

The effect of SFCL on voltage sag was analyzed according to fault location, SFCL's resistance value, and the length of loop system when a SFCL was installed in a radial or loop power distribution system [6]. Reference [7] presented SFCL in a low voltage AC microgrid for its fault transient suppression. The performance and positioning of DC SFCL in a low voltage DC microgrid and AC SFCL in AC microgrid [9] have been investigated. Reference [10] analyzed the working capability of SFCL in a test-bed microgrid. In this paper, the application of SFCL to limit the fault current of medium-low voltage microgrid network and the issue of current limiting impedance of SFCL in the interconnection power grid with different voltage levels are discussed. The article is organised in the following manner. In Section II, we build the model of the power system in MATLAB/SIMULINK, and discuss how to select a suitable resistance value of SFCL. In Section III, how to limit the short circuit current of the power grid and the simulation analyses in different cases are discussed. Section IV is the conclusion.

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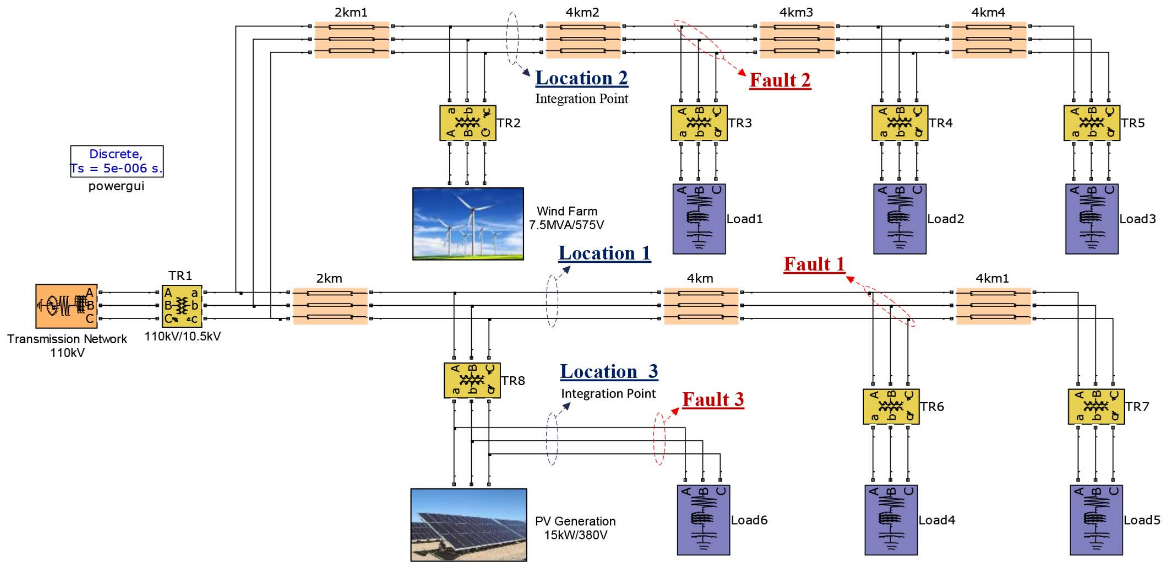

Figure 1: Power System Model Designed in MATLAB/SIMULINK

2 TECHNICAL ANALYSIS

2.1 Power System Model

Figure 1 shows the power system model designed in MATLAB/SIMULINK. The low voltage microgrid integrated with solar power generation, and the medium voltage microgrid integrated with a wind farm, all of these DG units are connected to the power grid through inverters. A 15kW PV generation is connected to the low voltage distribution network through the LC filter. The working voltage is 380V and this voltage is chosen by considering the actual operation voltage of low voltage AC power network. The wind farm consisting of five 1.5 MW wind turbines is connected to 10.5 kV distribution network through transformer TR2.Wind turbines using a doubly-fed induction generator(DFIG) consist of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter modeled by voltage sources. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. At the substation(TR1), the power system voltage is stepped down to 10.5 kV from 110 kV transmission network. Power loads are indicated with the symbols of load1 to load5(2 MW each) are being supplied by separate branch networks. In order to facilitate the simulation analysis, the impedance of the power line with shorter length is equivalent into the short circuit resistance and the load power of load6 is relatively smaller than that of others.

2.2 SFCL Model

The function of SFCL is to limit short circuit current by inserting equivalent current limiting impedance quickly when electric power grid fault occurs. At the same time, current limiting resistance can reduce the switch condition of fault current of circuit breaker, so as to improve the impact of short-circuit fault on power network. The new type resistance SFCL that is small size and light weight has simple principle and structure, which not only can improve the operation performance of electric power line but also can promote the operation reliability of power system, so it has a broad application prospect. During normal operation, based on the zero resistance phenomenon of superconductivity [11], the superconducting part is in its superconducting state and the normal operation current passes with theoretically no loss because of the SFCL's low-loss nature. In the case of a short-circuit, the critical current of the superconductor is exceeded and the superconductor undergoes a transition to its normal state, so a certain value of nonlinear resistance is produced by self-sensing and self-triggering [12].

The SFCL does not have switching impulse during the dynamic process since it has not any moving mechanical part and the self-triggering. This will thereby increase the chance of quickly achieving successful fault current interruption. The SFCL could offer a solution for controlling short circuit current level in utility distribution and transmission networks [13]. The superconducting element, played the role as a nonlinear variable resistance, is inserted directly in series with the power line to be protected. It uses a transition from superconducting-state to normal-state, so as to limit the fault current level. This not only can protect the electrical equipment, but also can effectively cut off the circuit breaker of the faulty line.

The resistive type SFCL was designed to be a nonlinear resistance evolution as a function of time [14]. Based on the experimental studies for superconducting elements being applied in the actual power distribution system [6], its mathematical model can be expressed as follows:

$$R(t)=\begin{cases} 0 & (t<t_0) \\ R_n[1-exp(-\frac{t-t_0}{\tau})]^{\frac{1}{2}} & (t_0\leqslant t<t_1) \\ a_1(t-t_1)+b_1 & (t_1\leqslant t<t_2) \\ a_2(t-t_2)+b_2 & (t_2\leqslant t<t_3) \\ 0 & (t\geqslant t_3) \end{cases} \quad (1)$$

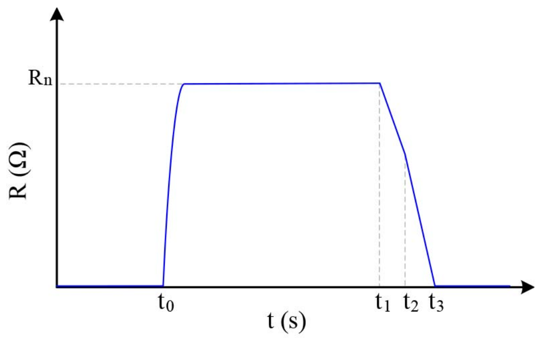

Figure 2: Quenching and Recovery Characteristics of SF-CL

Table 1: Fault Current Changes in Case of Fault 1

	Transformer 1		Wind Farm		PV Generation	
SFCL 1	Affect	%	Affect	%	Affect	%
Location 1	Decreased	77.78%	Decreased	41.21%	Decreased	73.15%

Where R_n and τ represent the impedance being saturated at normal temperature and time constant, respectively. In addition, t_0, t_1, and t_2 represent quench-starting time, the first recovery-starting time, and the secondary recovery-starting time, respectively. As showed in Figure 2, it exhibits the detailed quenching and recovery characteristics of resistive type SFCL. Considering the thermal environment and the system parameters, the SFCL's recovery time may be less than 0.5s [15], so as to match up the reclosing time of power grid.

2.3 Resistance Analysis of SFCL

With the continuous development of new energy, a variety of DGs with different capacities will be connected to power network. Each distributed power supply will increase the short-circuit current, which will change the original fault current level of power system. When a fault occurs in a power system, the use of SFCL to limit the current is becoming increasingly important because of the connection of DGs, whose access capacity can result in a high fault-current level. But how to choose an appropriate value of current limiting resistance of SFCL in the interconnection power grid with different voltage levels is a problem. When a fault occurs, according to the demand for fault current reduction of power system, the current limiting resistance of different voltage levels should not be the same. In the case of medium-low voltage distribution network integrated with DGs, this paper proposes to analyze the relationship between the fault current reduction of the maximum short-circuit current source and the resistance value of SF-CL in the same voltage level. In the power grid model of this paper, the fault position may occur in the medium or low voltage distribution network. In these two cases, the same analysis method is used.

When a fault occurs in the medium-voltage microgrid network, as showed in Figure 1, fault currents from Transformer 1, wind power as well as PV generation will flow

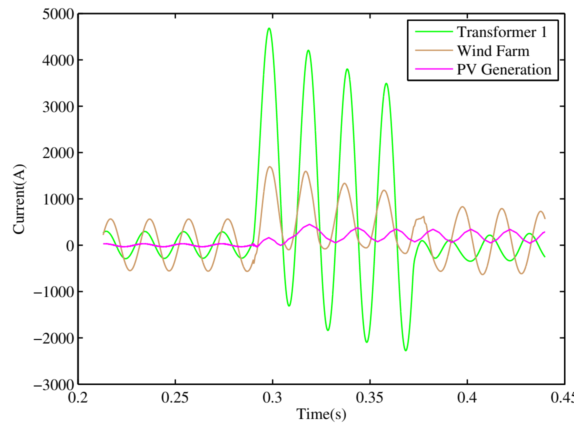

Figure 3: Comparison of Fault Currents in Case of Fault 1

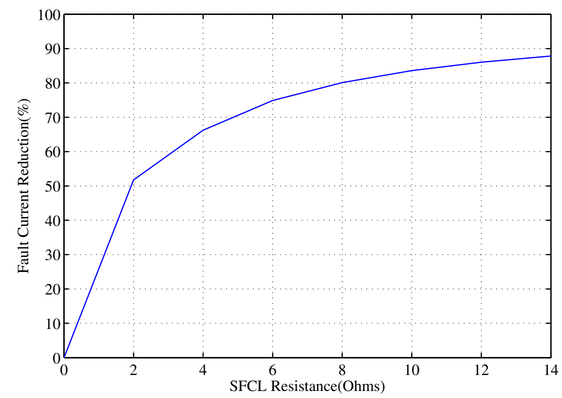

Figure 4: Relationship Between Fault Current Reduction and SFCL Resistance in Case 1

towards the fault point. Figure 3 displays a comparison of fault currents in case of fault 1, the short-circuit currents of the transformer 1, wind power and PV generation significantly increase. When the three-phase short-circuit fault (Fault 1) occurred, the installation location (Location 1) of SFCL was used to analyze this situation. Due to the maximum short-circuit current of transformer 1 was obviously larger than that of other distributed generations, so this paper analyzed the relationship between the fault current reduction of transformer 1 and the SFCL resistance of location 1. With the increase of current limiting resistance, as showed in Figure 4, current limiting effect is more obvious. When the resistance is 7 ohms, as showed in table 1, it is obvious that the current limiting effect of transformer 1 is the best. Within the first half cycle, the maximum fault current of transformer 1 is decreased by nearly 80% to a low current level.

When three-phase grounding fault happened in the low-voltage microgrid network, as showed in Figure 1, the analysis range changed to consider the transient performance of transformer 8 and solar power generation. In this case, the same analysis method that was used in the medium-voltage microgrid network was adopted. The relationship

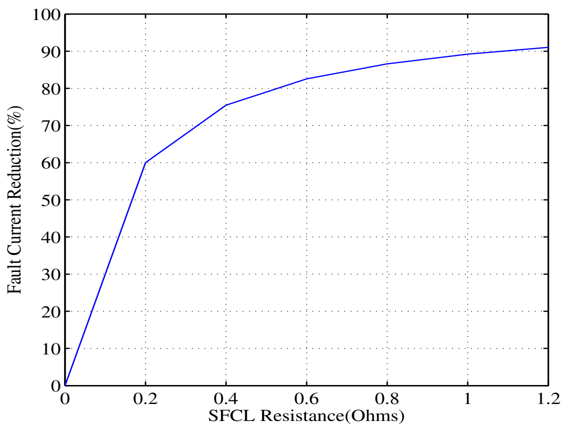

Figure 5: Relationship Between Fault Current Reduction and SFCL Resistance in Case 2

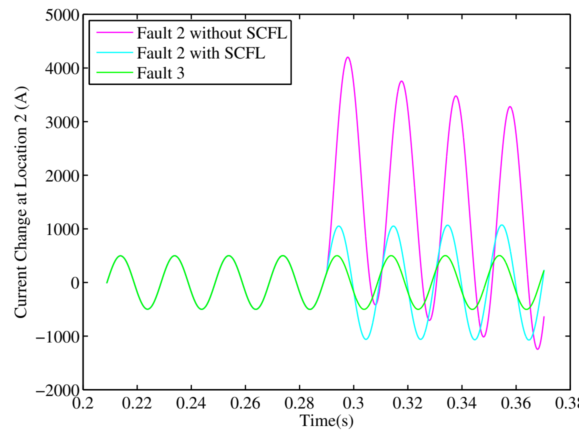

Figure 6: Current Comparison of Installation Location 2

between the fault current reduction of transformer 8 and the SFCL resistance of location 3 is shown in Figure 5, the current limiting effect is more obvious when SFCL resistance increases. Based on the demand for current limiting of electric power system, a suitable resistance value could be chosen in the actual application process according to the relationship between fault current reduction and SFCL resistance in different voltage levels.

3 COMPREHENSIVE APPLICATION

Investigation on how to use SFCL to limit the fault current level is of great importance for dynamic performance improvement of power network. Strategic and economic location of SFCL in power network which limits all fault currents and has no negative effect on the DG source is the location of integration point[8],[9]. In the medium-low voltage microgrid network, as showed in Figure 1, the positions of integration points of PV generation and wind power are adopted to install SFCLs to reduce the short-circuit current of the power grid. The installation locations of SFCLs are marked as Location 2 and Location 3, and the power grid faults are marked as Fault 2 and Fault 3. As three-phase-to-ground fault has the most serious impact on power grid, so all faults select this kind of short circuit fault.

3.1 Current Comparison of Installation Location 2

When a fault occurs in the medium-voltage microgrid network, the integration point of wind power generation is used to limit the short circuit current of the power grid. As Figure 1 shows, Location 2 was installed with SFCL and fault may occur in the medium or low voltage distribution network.

Figure 6 shows the compared short-circuit currents of Installation Location 2. After fault 2 occurred, without the SFCL, the peak value of fault current could reach 4200A in the first half cycle. With the SFCL installed, the maximum short-circuit current was limited to about 1000A within the first half of the cycle, this current is only two times the peak value of the normal operation current. It can be seen from the graph, the fault of the low-voltage microgrid network

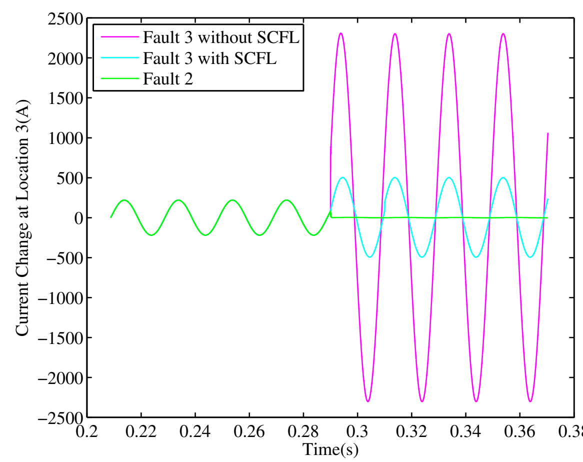

Figure 7: Current Comparison of Installation Location 3

is comparatively a small fault, which has little impact on the current change of medium voltage distribution network when Fault 3 occurred in the low voltage customer side distribution network. From the simulation results, after the quenching of SFCL, the limitation resistance will quickly rise up to limit current in the first cycle and can significantly reduce the short circuit current of medium-voltage microgrid network.

3.2 Current Comparison of Installation Location 3

In the case of a fault occurs in the low-voltage microgrid network, the same analytical method is adopted to simulate the impact of SFCL on fault current reduction of the power grid. As Figure 1 shows, the integration point (Location 3) of PV generation is used to limit the short circuit current and fault may happen in the medium or low voltage distribution network.

Compared fault currents of installation location 3 are showed in Figure 7. When a three-phase-to-ground fault (Fault 3) happened in the low voltage distribution network, without the SFCL, the peak value of fault current could reach 2300A in the first half cycle. With the SFCL installed, the maximum short-circuit current was limited to about 500A within the first half of the cycle, this current is only more than two times the peak value of the normal operation current. From the picture, we can also see the fault of medium voltage distribution network is comparatively a big fault, which has an obvious impact on the current change of the low-voltage microgrid network when Fault 2 occurred. Based on the simulation results, it can be observed the use of SFCL can significantly reduce the short circuit current to a low level. An important aspect to be noted here is that the impacts of faults in medium and low voltage distribution network are significantly different to each other. When the SFCL is strategically located at the integration point of DG, the fault current reduction is also achieved. Thus, the practical application of SFCL can consider the integrated strategy of this paper as a reference in the interconnected power network with different voltage levels.

4 CONCLUSION

This paper presented how to utilize SFCL to achieve the fault current reduction in medium-low microgrid network. The model of power system was established and the transient analysis for SFCL installed in medium or low voltage distribution network was performed. It has been observed that the resistance values of SFCLs shouldnt be the same in different voltage levels of power grid and an appropriate resistance value can be achieved by analyzing the relationship between the fault current reduction of the maximum short-circuit current source and the resistance value of SFCL. Simulations show that SFCL not only can limit fault current level to a suitable value, but also can improve the operation dynamic of interconnection power network with different voltage levels. The research in this paper can be used as a reference for engineering practice, which provides a feasible integrated strategy for the continuous development of power grid technology.

REFERENCES

[1] R. Strzelecki, G. Benysek, Power Electronics in Smart Electrical Energy Networks, New York: Springer, 2008.

[2] J. Driesen, P. Vermeyen, R. Belmans, Protection issues in Microgrids with multiple distributed generation units, in Proc. Power Convers. Conf., 2007.

[3] T. Jamasb, W. J. Nuttall, M. G. Pollitt, Future Electricity Technologies and Systems, Cambridge: Cambridge Univ. Press, 2006.

[4] S. Sugimoto, J. Kida, H. Arita, C. Fakui, T. Yamagiwa, Principle and characteristics of a fault current limiter with series compensation, IEEE Trans. Power Delivery, Vol.11, No.2, 842-847, 1996.

[5] T. Jamasb, W. J. Nuttall, M. G. Pollitt, Future Electricity Technologies and Systems, Cambridge: Cambridge Univ. Press, 2006.

[6] J. F. Moon, J. S. Kim, Voltage sag analysis in loop power distribution system with SFCL, IEEE Trans. Appl. Supercond., Vol.23, No.3, 2013.

[7] T. T. Lv, Y. B. Duan, Y. L. Gong, Analysis of micro-grid based fault transient and its suppression, Power System Protection and Control, Vol.39, No.2, 102-107, 2011.

[8] U. A. Khan, W. J. Shin, J. K. Seong, S. H. Oh, S. H. Lee, B. W. Lee, Feasibility analysis of the application and positioning of DC HTS FCL in a DC microgrid through modeling and simulation using Simulink and SimPowerSystem, Physica C Superconductivity, Vol.21, 1322-1326, 2011.

[9] U. A. Khan, J. K. Seong, S. H. Lee, S. H. Lim, B. W. Lee, Feasibility Analysis of the Positioning of Superconducting Fault Current Limiters for the Smart Grid Application Using Simulink and SimPowerSystem, IEEE Trans. Appl. Supercond., Vol.21, No.3, 2165-2169, 2011.

[10] S. R. Khuntia, S. R. Samantaray, Analysis of resistive SFCL in a test-bed microgrid, Ain Shams Engineering Journal, Vol.53, No.3, 883-892, 2015.

[11] H. K. Onnes, The resistance of pure mercury at helium temperature, Comm Phys Lab Univ Leiden, Vol.12, 120-122, 1911.

[12] M. Noe, M. Steurer, High-temperature superconductor fault current limiters: concept, applications and development status, Supercond Sci Technol, Vol.20, No.3, 15-29, 2007.

[13] R. Schwall, WTEC panel report-Superconducting fault current limiter, WTEC Hyper Librarian, 1997.

[14] Y. Lin, K. P. Juengst, Modeling and simulations of resistive type superconducting fault current limiter, IEEE Trans. Appl. Superconduct., Vol.14, No.2, 839-842, 2004.

[15] C. A. Baldan, J. S. Lamas, C. Y. Shigue, E. R. Filho, Fault current limiter using YBCO coated conductor-the limiting factor and its recovery time, IEEE Trans. Appl. Supercond., vol.19, no.3, 1810-1813, 2009.