PERFORMANCE ANAYLSIS OF ACTIVE TYPE SFCL TO REDUCE OVER VOLTAGES AND OVER CURRENTS IN DISTRIBUTION NETWORKS WITH DG UNITS

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ABSTRACT: The introduction of various distributed generated units into the power distribution network has caused the increase in the fault currents magnitudes and induction of over voltages under abnormal conditions. System protection has become increasingly challenging in these systems. Among the countermeasures to solve this problem, the super conducting fault current limiter (SFCL) has been noticed as the promising and feasible solutions.

In this paper a voltage compensation type active SFCL is introduced into the distribution network consisting of DG units and its effects are studied through theoretical derivation and simulation. The active SFCL consists of an air-core superconducting transformer and PWM converter. By changing the converters output current the equivalent impedance of active SFCL can be regulated for current limitation and possible voltage suppression. The suppression characteristics of active SFCL at different DG locations and fault positions are studied through MATLAB simulation. The results show that active SFCL suppresses the short circuit currents and over voltages induced by 3phase to ground fault effectively and power system safety and reliability can be improved.

Key words – Distributed generation (DG), distribution system, over voltage, over currents Voltage compensation type active superconducting fault current limiter (SFCL)

1. INTRODUCTION: Due to increase in demand and consumption of electrical energy, distribution systems are growing and changing significantly. Global demand for electricity is projected to double by 2050 continuing the trend from the previous 40 years**.** In response to ever growing needs for electricity, Technical advancements and promotions of various types of renewable energy generation have also led to a large number of distributed generators (DG's) connected to the power grids. The introduction of DG into distribution network may bring lots of advantages, such as emergency backup and peak shaving. However, the presence of these sources will lead the distribution network to lose its radial nature: As a result, the potential short-circuit current levels increase substantially, approaching the limits of the devices in existing distribution systems. Besides when single phase ground fault happens in distribution system with isolated neutral, over voltages will be induced on the other two healthy phases, and in consideration of the installation of multiple DG units, the impacts of them on the distribution networks insulation stability and operation safety should be taken into account seriously. Aiming at the mentioned technical problems and the urgency of increasing fault current problems, applying superconducting fault current limiter (SFCL) may be feasible solution

For the application of some type of SFCL into a distribution network with DG units, a few works have been carried out, and their research scopes mainly focus on current-limitation and improvement of protection coordination of protective devices [4]–[6]. Nevertheless, with regard to using a SFCL for suppressing the induced overvoltage, the study about it is relatively less. In view of that the introduction of a SFCL can impact the coefficient of grounding, which is a significant contributor to control the induced overvoltage's amplitude; the change of the coefficient may bring positive effects on restraining overvoltage.

We have proposed voltage compensation type active SFCL, and analyzed the active SFCL's control strategy and its influence on relay protection [8, 9]. In this project, taking the active SFCL as an evaluation object, its effects on the fault current and overvoltage in a distribution network with multiple DG units are studied. In view of the changes in the locations of the DG units connected into the distribution system, the DG units' injection capacities and the fault positions, the current limiting and overvoltage-suppressing characteristics of the active SFCL are investigated in

II.THEORITICAL ANALYSIS

A) ***Structure and principle of SFCL:*** As shown in Fig. 1(a), it denotes the circuit structure of the single-phase voltage compensation type active SFCL, which is composed of an air-core superconducting transformer and a voltage-type PWM converter. L_{s1}, L_{s2} are the self-inductance of two superconducting windings, and Ms is the mutual inductance. Z_1 is the circuit impedance and Z_2 is the load impedance. L_d and C_d are used for filtering high order harmonics caused by the converter. Since the voltage-type converter's capability of controlling power exchange is implemented by regulating the voltage of AC side, the converter can be thought as a controlled voltage source Up. By neglecting the losses of the transformer, the active SFCL's equivalent circuit is shown in Fig. 1(b).

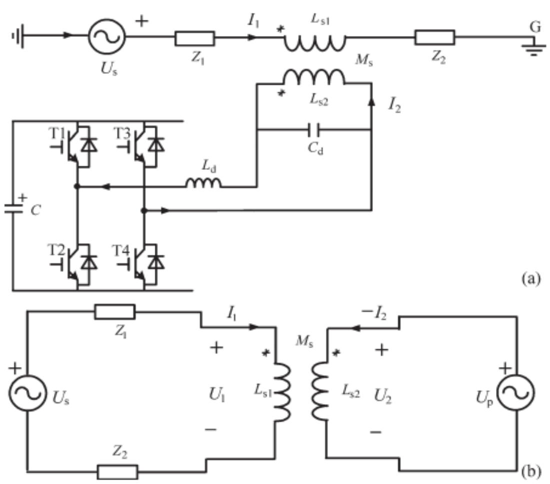

Fig 1 : single phase active type SFCL a) circuit structure b) equivalent circuit

In normal (no fault) state, the injected current (I_2) in the secondary winding of the transformer will be controlled to keep a certain value, where the magnetic field in the air-core can be compensated to zero, so the active SFCL will have no influence on the main circuit. When the fault is detected, the injected current will be timely adjusted in amplitude or phase angle, so as to control the superconducting transformer's primary voltage which is in series with the main circuit, and further the fault current can be suppressed to some extent. Below, the suggested SFCL's specific regulating mode is explained. In normal state, the two equations can be achieved.

$$\dot{U}_s = \dot{I}_1(Z_1 + Z_2) + j\omega L_{s1}\dot{I}_1 - j\omega M_s \dot{I}_2 \quad (1)$$

$$\dot{U}_p = j\omega M_s \dot{I}_1 - j\omega L_{s2}\dot{I}_2. \quad (2)$$

Controlling I_2 to make $j\omega L_{s1}\dot{I}_1 - j\omega Ms\,\dot{I}_2 = 0$ and the primary voltage U_1 will be regulated to zero. Thereby, the equivalent limiting impedance Z_{SFCL} is zero ($Z_{SFCL}=U_1/I_1$), and I_2 can be set as $\dot{I}_2 = \dot{U}s\sqrt{L_{s1}/L_{s2}}/$ (Z1+Z2) k, where k is the coupling coefficient and it can be shown as $k=Ms/\sqrt{L_{s1}\,L_{s2}}$. Under fault condition (Z_2 is shorted), the main current will rise from I_1 to I_{1f}, and the primary voltage will increase to U_{1f}.

$$\dot{I}_{1f} = \frac{(\dot{U}_s + j\omega M_s \dot{I}_2)}{(Z_1 + j\omega L_{s1})} \quad (3)$$

$$\dot{U}_{1f} = j\omega L_{s1}\dot{I}_{1f} - j\omega M_s \dot{I}_2 = \frac{\dot{U}_s(j\omega L_{s1}) - \dot{I}_2 Z_1 (j\omega M_s)}{Z_1 + j\omega L_{s1}} \quad (4)$$

The current-limiting impedance Z_{SFCL} can be controlled in:

$$Z_{SFCL} = \frac{\dot{U}_{1f}}{\dot{I}_{1f}} = j\omega L_{s1} - \frac{j\omega M_s \dot{I}_2 (Z_1 + j\omega L_{s1})}{\dot{U}_s + j\omega M_s \dot{I}_a} \quad (5)$$

According to the difference in the regulating objectives of I_2, there are three operation modes:

1) Making I_2 remain the original state, and the limiting impedance $Z_{SFCL-1}=Z_2\,(j_\omega L_{s1})/(Z_1+Z_2+j_\omega L_{s1})$.

2) Controlling I_2 to zero, and $Z_{SFCL-2}=j\omega L_{s1}$.

3) Regulating the phase angle of I_2 to make the angle difference between $\dot{U}s$ and $j\omega M_s\,\dot{I}_2$ be 180∘.By setting $j\omega M_s\,\dot{I}_2 = -c\dot{U}s$,and $Z_{SFCL-3}=cZ_1/(1-c)+j_\omega L_{s1}/(1-c)$.

The air-core superconducting transformer has many merits, such as absence of iron losses and magnetic saturation, and it has more possibility of reduction in size, weight and harmonic than the conventional iron-core superconducting transformer [11], [12]. Compared to the iron-core, the air-core can be more suitable for functioning as a shunt reactor because of the large magnetizing current [13], and it can also be applied in an inductive pulsed power supply to decrease energy loss for larger pulsed current and higher energy transfer efficiency [14], [15].
There is no existence of transformer saturation in the air-core, and using it can ensure the linearity of ZSFCL well.

III) Applying the SFCL into a Distribution Network with DG

As shown in Fig. 2, it indicates the application of the active SFCL in a distribution network with multiple DG units, and the buses B-E are the DG units' probable installation locations. When a single-phase grounded fault occurs in the feeder line 1 (phase A, k1 point), the SFCL's mode 1 can be automatically triggered, and the fault current's rising rate can be timely controlled. Along with the mode switching, its amplitude can be limited further. In consideration of the SFCL's effects on the induced overvoltage, the qualitative analysis is presented. In order to calculate the over voltages induced in the other two phases (phase B and phase C), the symmetrical component method and complex sequence networks can be used, and the coefficient of grounding G under this condition can be expressed as $G=-1.5m/(2\ +m)\pm j\sqrt{3}/2$, where $m=X_0/X_1$, and X_0 is the distribution network's zero-sequence reactance,$X_1$is the positive-sequence reactance [16].

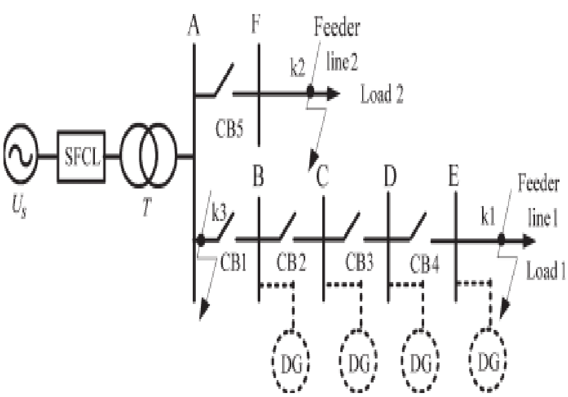

Fig 2 : application of SFCL into distribution network

IV. MATLAB/SIMULINK RESULTS:

For purpose of quantitatively evaluating the current limiting and overvoltage-suppressing characteristics of the active SFCL, the distribution system with DG units and the SFCL, as shown in Fig. 3 is created in MATLAB.

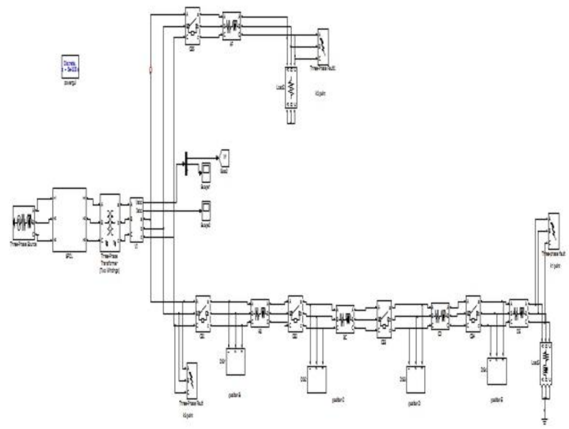

Fig 3: simulation diagram of proposed system

The proposed system is composed of 5MVA, 35KV conventional power plant composed of 3-phase synchronous machine, connected by 35km long 10.5KV distributed parameters transmission line through a step down transformer of 35KV/10.5KV. The ends of the transmission lines are connected with 50ohm and (10+j12)ohm. The SFCL is installed in the behind of the power supply *U*s, and two DG units are included in the system, and one of them is fixedly installed in the Bus B(named as DG1). For the other DG, it can be installed in an arbitrary position among the Buses C–E (named as DG2). The model's main parameters are shown in Table I. To reduce the converter's design capacity [17], making the SFCL switch to the mode 2 after the fault is detected, and the detection method is based on measuring the main current's different components .For the purpose of quantitatively evaluating the current limiting and over voltage suppressing characteristics of the active SFCL. The distribution system with DG units and the SFCL as shown in the figure .The performance analysis of active SFCL in the proposed system in two cases They are

Case 1: fault at single point at a time

Case 2: fault at two points simultaneously

CASE 1: FAULT AT SINGLE POINT AT A TIME

I) **Over voltage suppressing characteristics of the active SFCL**: Supposing that two DG units are operating at B and C positions, a fault is created at the location k1 point (phase-A is shorted), and the fault time is t = 0.2 sec, the simulation is done. The DG2 is respectively installed at the buses C, D, and E positions and the simulation is performed without SFCL. Figure 4 shows the over voltage characteristics of the distribution system with DG units at different positions with fault at k1 point without SFCL. The peak amplitudes without SFCL will be respectively 1.14, 1.23, and 1.29 times the nominal value. Now when the active type SFCL is placed in the distribution system and the same simulation procedure is repeated as done without SFCL. Figure 5 shows the over voltage suppression characteristics with SFCL. The corresponding drops in the voltages are 1.08, 1.17, and 1.2 of the nominal value.

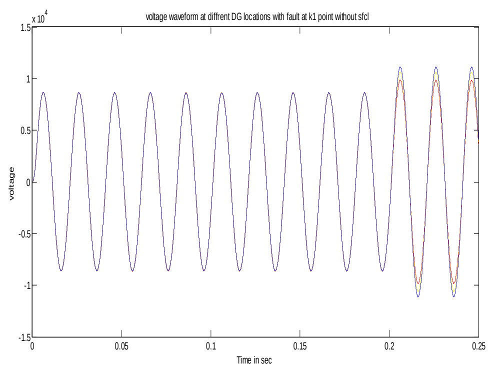

Figure 4: voltage characteristics at different DG locations with fault at k1 point without SFCL

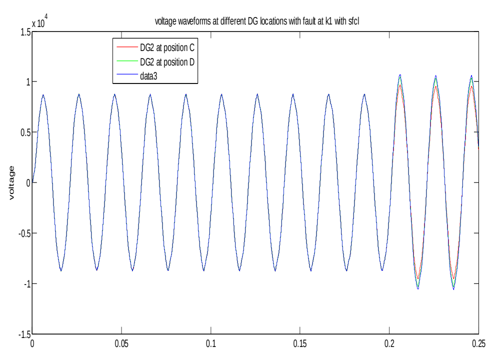

Figure 5: voltage characteristics of the bus A under different DG locations at k1 with SFCL

During the study of the influence of DGs, the two DG units are located in the buses B and E, and the other fault conditions are unchanged. Along with increase of DGs capacity the overvoltage will be accordingly rise, and once the DG capacity is equal to the capacity the overvoltage will exceed acceptable limit (1.3 times). But, if the active SFCL is put into use, the limit-exceeding problem can be solved effectively.

II) Current-limiting characteristics of the SFCL: By observing the voltage compensation type active SFCL's installation location, it can found out that this device's current-limiting function should mainly reflect in suppressing the line current through the distribution transformer. There upon, to estimate the most serious fault characteristics, the following conditions are designed: the injection capacity of each DG is about 100% of the load capacity (load 1), and the two DG units are separately installed in the buses B and E. Moreover, the three-phase fault occurs at k1, k2, and k3 points respectively, and the fault occurring times is t = 0.2sec. Hereby, the line current characteristics are imitated in the following sections

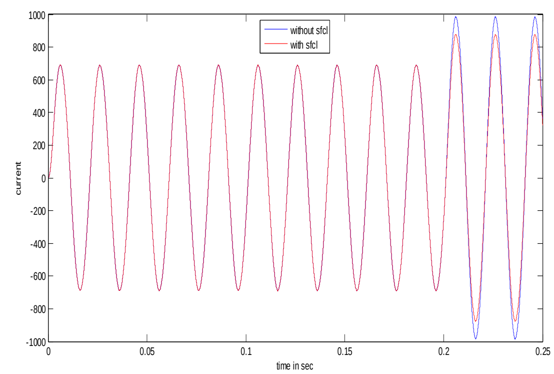

figure6: current limiting characteristics of active SFCL under fault at k1 point and DG1 and DG2 at B and C positions

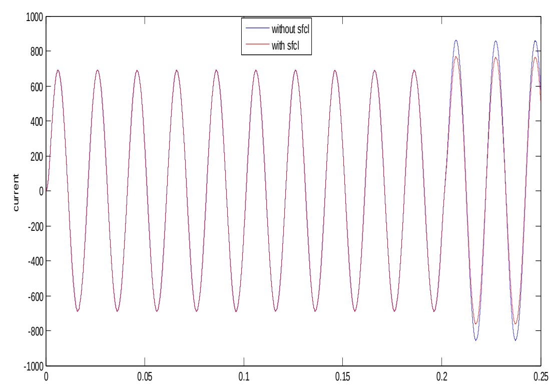

figure7: current limiting characteristics of active SFCL under fault at k2 point and DG1 and DG2 at B and C positions

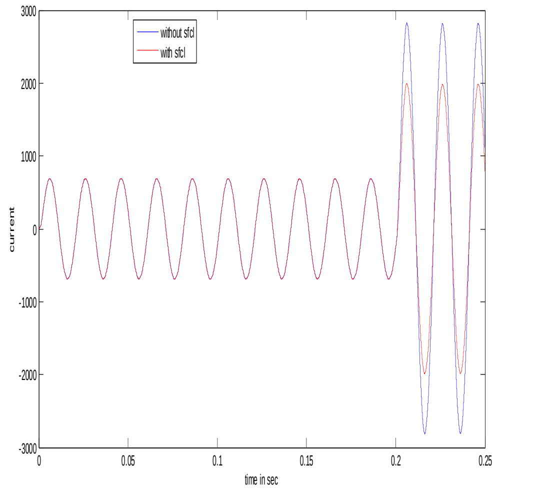

figure8: current limiting characteristics of active SFCL under fault at k3 point and DG1 and DG2 at B and C position

From all the above three current limiting characteristics of SFCL it can be observed that along with the decrease with the distance between fault point and SFCL position, the limiting capability of SFCL can be increased to about 9 to 10%.

CASE 2) FAULTS AT BOTH K1 AND K2 LOCATIONS:

In this section the fault is applied at k1 and k2 points simultaneously and voltage suppression and current limiting characteristics are observed with

1) Single SFCL at the distribution substation
2) Two SFCLs at a time i.e. one at distribution substation and another at DG.

Voltage suppression characteristics:

Figure 8 shows the voltage characteristics of the system when a 3 phase short circuit is applied at both k1 and k2 locations simultaneously at t=0.2 sec.

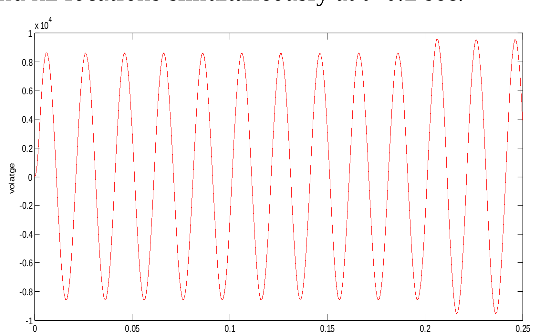

Figure 9: voltage characteristics without SFCL, with fault at both k1 and k2 points

Here the voltage increases beyond the nominal value which can be observed from the figure i.e. the characteristics beyond t = 0.2sec.

This over voltage is limited by using the active type SFCL in the system. Figures9 and 10 shows the voltage suppression characteristics with single active SFCL and two SFCLs

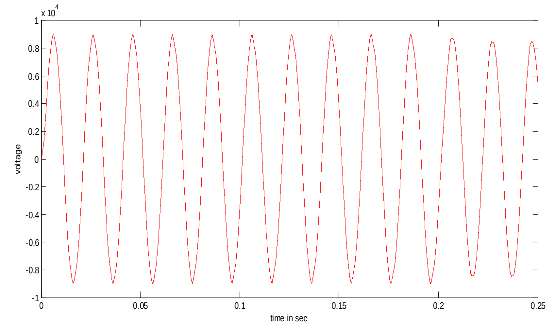

Figure 10: voltage characteristics with one SFCL, with fault at both k1 and k2 points

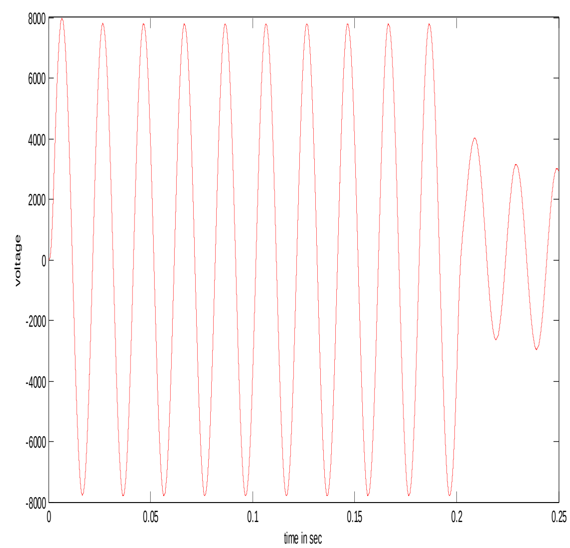

Figure 11: voltage characteristics with two SFCLs, with fault at both k1 and k2 points

Current suppression characteristics:

Here in this section the current limiting characteristics of active SFCL are analyzed when faults are simultaneously applied at k1 and k2 points. The following figure 11 shows the fault current waveform when 3phase short circuit is applied at k1 and k2 locations.

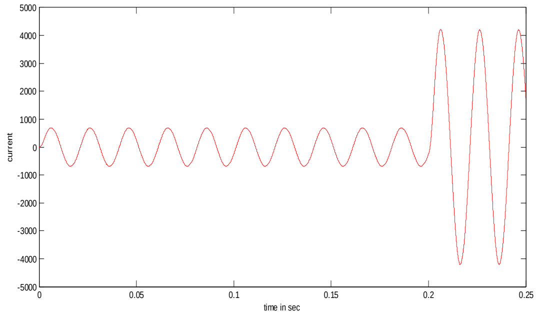

Figure 12: fault current characteristics without SFCL, with fault at both k1 and k2 points

Here from the above figure it can be seen that the fault current is about 4150A. In order to limit this high fault current we use one active type SFCL in the system and two SFCLs in the system. The figures 12 and 13 show current limiting characteristics by using single SFCL and two SFCLs respectively.

From the above figure 5.16 it can observed that the fault current is limited to about 3900A when single SFCL is used at the distribution substation and from figure 5.17 it is seen that the fault current value is reduced to about 1800A i.e. nearly half of the value of fault current is limited.

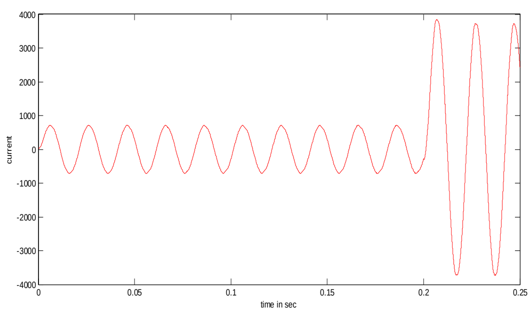

Figure 12: fault current characteristics with one SFCL, with fault at both k1 and k2 points

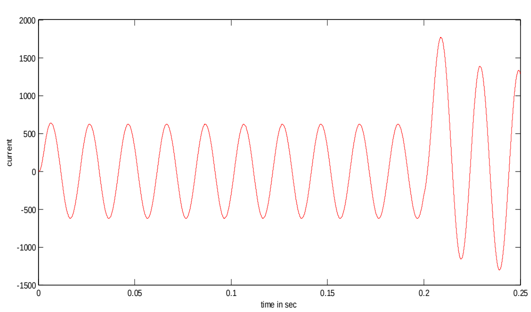

Figure 13: fault current characteristics with two SFCLs

6.1 Conclusion

In this project, the application of the active SFCL into in a power distribution network with DG units is investigated. For the power frequency overvoltage caused by a single-phase grounded fault, the active SFCL can help to reduce the overvoltage's amplitude and avoid damaging the relevant distribution equipment. The active SFCL can as well suppress the short-circuit current induced by a three-phase grounded fault effectively, and the power system's safety and reliability can be improved. Moreover, along with the decrease of the distance between the fault location and the SFCL's installation position, the current-limiting performance will increase. By using active SFCL along with the DG the over current and over voltage characteristics can be further reduced to a great extent when the fault is created in the two lines.

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