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A Fuel Cell based SFCL for Improving Electric Power System Security and Reducing Fault Currents

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Abstract— **Power system faults are a typical occurrence today. A striking electrical gadget called a superconducting fault current limiter was developed to address the issue of extremely high fault current in the power system. In this article, the performance of a superconducting fault current limiter with existing switchgear is investigated. Simulink is used to model a resistive type SFCL initially. An air-core superconducting transformer and a PWM converter make up the active SFCL. By modifying the converter's output current, the magnetic field in the air-core can be controlled. Next, the equivalent impedance of the active SFCL may be tuned for current restriction and potential overvoltage suppression. This paper uses MATLAB to construct and simulate a revolutionary fuel cell-based SFCL. The simulation results show that by limiting the fault current and overvoltage, the active PV-based SFCL can help to prevent damage to the power system.**

Index Terms: PV, superconducting fault current limiter (SFCL), DG, Fault.

INTRODUCTION

Distributed generation (DG), which produces electricity from numerous tiny energy sources and is becoming one of the primary components in distribution networks to feed electrical loads, is becoming more popular due to rising consumption demand and the high cost of natural gas and oil [1]–[3]. A distribution network may gain many benefits from the addition of DG, including peak shaving and emergency backup. The distribution network will lose its radial characteristics as a result of the existence of these sources, and the fault current level will rise. In addition, when a single-phase grounded fault occurs in a distribution system with an isolated neutral, over voltages will be induced on the other two health phases. Because multiple DG units will be installed, the effects of the induced over voltages on the insulation stability and operation safety of the distribution network should be carefully considered. Applying a superconducting fault current limiter (SFCL) may be a workable solution to the technical issues outlined.

A few studies have been conducted for the introduction of a certain type of SFCL into a distribution network with DG units, and their research areas mostly centre on current-limitation and improving the coordination of protective devices [4]–[6]. However, there hasn't been a lot of research done on employing an SFCL to suppress the resultant overvoltage. The change in the coefficient may have a favourable impact on reducing overvoltage since the introduction of an SFCL might affect the coefficient of grounding, which plays a vital role in regulating the induced overvoltage's amplitude.

In earlier work [7], we presented the voltage compensation type active SFCL and examined its control scheme and impact on relay protection. Additionally, an 800 V/30 A laboratory prototype was created, and its operating characteristics were successfully confirmed [10]. The impacts of the active SFCL on the fault current and overvoltage in a distribution network with numerous DG units are examined in this research using it as an assessment object. The current-limiting and overvoltage-suppressing properties of the active SFCL are thoroughly examined in light of the changes in the locations of the DG units connected to the distribution system, the DG units' injection capabilities, and the fault positions.

THEORETICAL ANALYSIS

Structure and Principle of the Active SFCL:

A voltage-type PWM converter and an air-core superconducting transformer make up the circuit construction of the single-phase voltage compensation type active SFCL, as shown in Fig. 1(a). Two superconducting windings' self-inductances are Ls1 and Ls2, and their mutual inductance is Ms. Z1 is the impedance of the circuit, while Z2 is the impedance of the load. For filtering high order harmonics produced by the converter, Ld and Cd are used. The converter can be considered a controlled voltage source Up since the voltage of the AC side is controlled in order to execute the voltage-type converter's ability to control power exchange. Fig. 1 displays the active

SFCL's equivalent circuit while disregarding the transformer's losses (b).

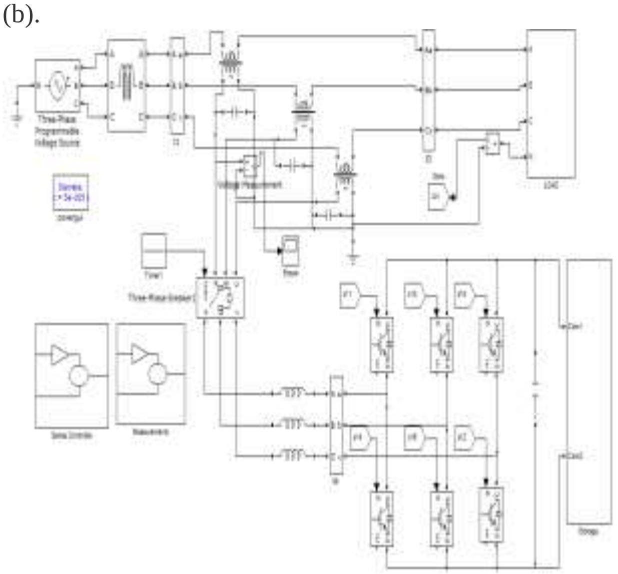

Fig. 1. Three-phase voltage compensation type active SFCL.

The magnetic field in the air-core can be corrected to zero in a normal (fault-free) condition by controlling the injected current (I2) in the secondary winding of the transformer to maintain a specific value, meaning that the active SFCL will not affect the main circuit. When a defect is found, the injected current is promptly modified in amplitude or phase angle to control the primary voltage of the superconducting transformer, which is connected to the main circuit, and to some extent suppress the fault current.

Below is an explanation of the particular regulating mode of the proposed SFCL. The two equations are achievable in a normal state.

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

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

Controlling I_2 to make $j\omega L_{s1}\dot{I}_1 - j\omega M_s\dot{I}_2 = 0$ 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 $\dot{I}_2 = \dot{U}_s \quad L_{s1}/L_{s2}/(Z_1 + Z_2)k$,

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

$$\begin{aligned}\dot{U}_{1f} &= j\omega L_{s1}\dot{I}_{1f} - j\omega M_s\dot{I}_2 \\ &= \frac{\dot{U}_s(j\omega L_{s1}) - \dot{I}_2 Z_1(j\omega M_s)}{Z_1 + j\omega L_{s1}}.\end{aligned} \qquad (4)$$

where k is the coupling coefficient and it can be shown as $k = M_s/\sqrt{L_{s1}L_{s2}}$.

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}.

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

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

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 set- ting $j\omega M_s\dot{I}_2 = -c\dot{U}_s$, and $Z_{SFCL-3} = cZ_1/(1-c) + j\omega L_{s1}/(1-c)$.

The air-core superconducting transformer has many advantages over the traditional iron-core superconducting transformer, including the absence of iron losses and magnetic saturation, as well as higher potential for size, weight, and harmonic reduction [11], [12]. The enormous magnetising current of the air-core can make it more suited for use as a shunt reactor when compared to the iron-core [13], and it can also be used in an inductive pulsed power supply to reduce energy loss and increase energy transfer efficiency [14], [15]. Since there is no transformer saturation in the air-core, utilising it can effectively guarantee ZSFCL linearity.

B. 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

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. Further, the amplitudes of the B-phase and C-phase over voltages can be described as.

$$U_{BO} = U_{CO} = \sqrt{3}\left|\frac{\sqrt{G^2 + G + 1}}{G + 2}\right| U_{AN} \qquad (6)$$

where U_{AN} is the phase-to-ground voltage's root mean square (RMS) under normal condition

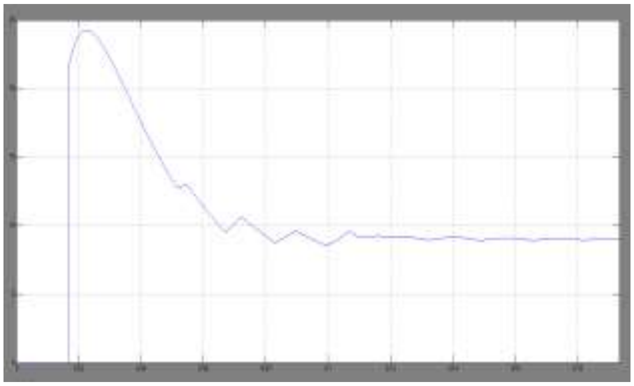

Fig. 3. Relationship between the reactance ratio *m* and the B-phase overvoltage

It denotes the connection between the reactance ratio m and the B-phase overvoltage, as seen in Fig. 3. It should be noted that the reactance ratio m is typically greater than four for distribution systems with isolated neutral points. The addition of an active SFCL will increase the power distribution network's positive-sequence reactance in a fault state as compared to the absence of one. Installing the active SFCL can assist in lowering the ratio m because X0 /(X1 + ZSFCL) X0 /X1. Then, from the perspective of using the recommended device, it can reduce the overvoltage's amplitude and increase the safety and dependability of the system.

The specific effects of the SFCL on the fault current and overvoltage may also differ depending on the locations of the DG units connected to the distribution system, their injection capacities, and the locations of the faults, all of which are replicated in the simulation analysis.

SIMULATION ANALYSIS

The distribution system comprising DG units and the SFCL, as shown in Fig. 2, is developed in MATLAB with the intention of quantitatively analysing the current-limiting and overvoltage-suppressing properties of the active SFCL. Two DG units are part of the system, and one of them is permanently located in the Bus B. The SFCL is installed behind the power supply Us (named as DG1). It can be installed for the other DG anywhere between Buses C and E. (named as DG2). Table I displays the key parameters of the model. Making the SFCL transition to mode 2 after the issue is discovered may diminish the converter's design capacity [17], and the fault detection mechanism is dependent on measuring the main current's different components by Fast Fourier Transform (FFT) and harmonic analysis.

Characteristics of the SFCL

The simulation is performed with the DG2 installed in each of the Buses C, D, and E, and the three cases are referred to as case I, II, and III. Assuming that each DG's injection capacity is approximately 80% of the load capacity (load 1), that the fault location is at k1 point (phase-A is shorted), and that the fault time is t = 0.2 s, Figure 4 displays the overvoltage-suppressing properties of the SFCL as well as waveforms with and without the SFCL.

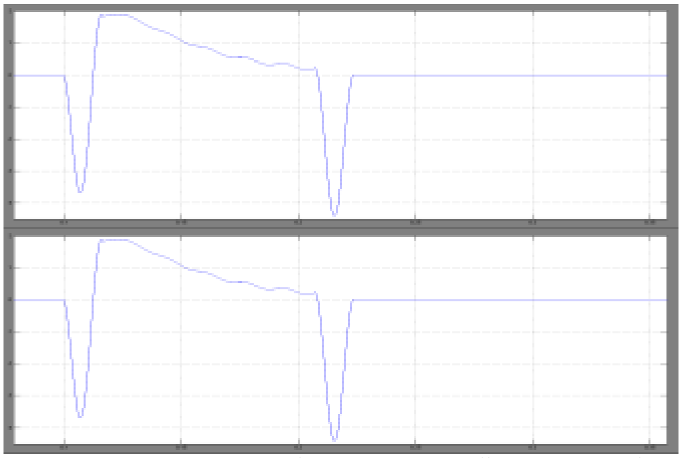

Fig. 4. Voltage characteristics of the Bus-A under different locations of DG units. (a) Without SFCL and (b) with the active SFCL

both are listed. For situations I, II, and III, the overvoltage's peak amplitude will be, respectively, 1.14, 1.23, and 1.29 times of normal value without SFCL, and the corresponding times will decrease to 1.08, 1.17, and 1.2 once the active SFCL is applied.

The adjustable range of each DG unit's injection capacity is assumed to be between 70% and 100% of the load capacity (load 1) during the study of the impact of the DG's injection capacity on the overvoltage's amplitude. The two DG units are assumed to be located in Buses B and E, and the other fault conditions are left unchanged. Table II illustrates the overvoltage's amplitude characteristics in this context. The overvoltage will climb in step with an increase in the DG's injection capacity, reaching an unacceptable level once the injection capacity is equal to or greater than 90% of the load capacity (1.3 times). However, the limit-exceeding issue can be efficiently resolved if the active SFCL is used.

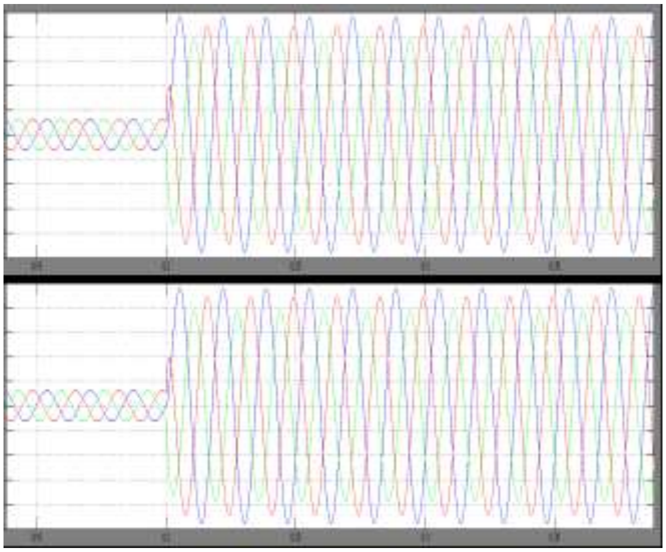

Fig. 5. Line current waveforms when the three-phase short-circuit occurs at k3 point. (a) Without SFCL and (b) with the active SFCL.

A. Characteristics of the SFCL with Fuel Cell:

It may be determined by looking at the installation site of the voltage compensation type active SFCL that this device's current-limiting function should primarily reflect in stifling the line current through the distribution transformer. The following conditions are designed after that in order to estimate the most critical fault characteristics: The two DG units are individually installed in the Buses B and E, and each DG has an injection capacity that is about 100% of the load capacity (load 1). Additionally, the three-phase fault occurs at sites k1, k2, and k3 in that order, with a t = 0.2 s fault occuring time. In this way, the features of the line current are mimicked.

The line current waveforms with and without the active SFCL when the three-phase short-circuit occurs at k3 point are depicted in Fig. 5. The first peak value of the fault currents (iAf, iBf, and iCf) can be restricted to 2.51 kA, 2.69 kA, and 1.88 kA, respectively, after installing the active SFCL, as opposed to 3.62 kA, 3.81 kA, and 2.74 kA under the condition without SFCL. The predicted fault currents will be reduced at rates of 30.7%, 29.4%, and 31.4%, respectively.

Figure 6 displays the SFCL's current-limiting capabilities when the fault is at the k1 point or k2 point, respectively (selecting the phase-A current for an evaluation). The current-limiting ratio will rise from 12.7% (k1 point) to 21.3% when the distance between the fault location and the SFCL installation position decreases (k2 point).

In addition, the natural reaction, which is a part of the fault current, is a DC wave with exponential decay whose starting value is directly related to the fault angle. In other words, the peak amplitudes of the short-circuit current will differ depending on the initial fault angles. utilising the programme

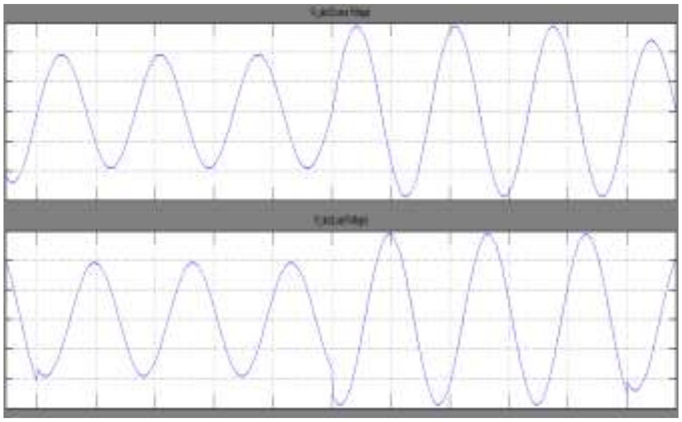

Fig. 6. Active SFCL's current-limiting performances under different fault locations. (a) k1 point and (b) k2 point.

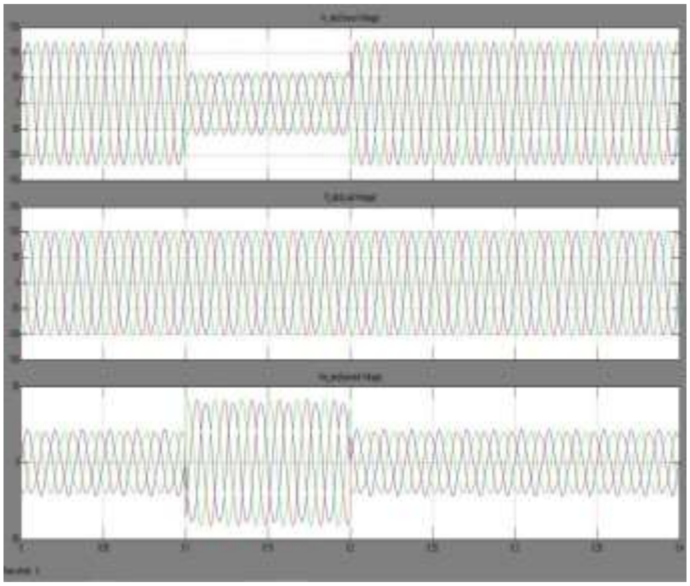

Fig. 7. Fuel Cell Based SFCL

In Fig. 7, where the fault is located at k3 point, it is examined how the initial fault angle affects the peak amplitude of the A-phase short-circuit current of the active SFCL. It is clear that when the fault angle is around 130°, both with and without the SFCL, the peak amplitude of the short-circuit current will be at its lowest value. The power distribution system can quickly achieve the steady transition from the normal state to the fault state at this fault angle.

CONCLUSION

The use of the fuel cell-based SFCL in a power distribution network with DG units is examined in this research. The Fuel Cell based SFCL can assist in lowering the overvoltage's amplitude and preventing damage to the relevant distribution equipment when it results from a single-phase grounded fault. The safety and dependability of the power system can be increased because to the active PV based SFCL's capacity to efficiently suppress the short-circuit current caused by a three-phase grounded fault. Additionally, the current-limiting performance will improve as the distance between the fault and the PV-based SFCL installation point decreases.

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