Modeling and Analysis of Resistive Type Superconducting Fault Current Limiters for Coordinated Microgrid Protection

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***Abstract*-- The penetration of distributed generation (DG) through microgrid systems is increasing continually to meet growing energy demand. The energy delivered through microgrids has increased the overall reliability of power systems, but at the same time protection issues are observed. These problems need to be addressed in order to facilitate smooth operation of power system. Superconducting fault current limiters (SFCLs) provide unique protection features to electrical power system during various fault conditions. The paper describes modeling, characterization, and implementation of SFCL to enhance the transient stability of power system. The system is modeled and developed in MATLAB/ Simulink environment and the performance of proposed model is validated through simulation results. It is also shown that proposed SFCL provides means of better relay coordination during various fault conditions. This is achieved by incorporating well-calculated design parameters of SFCL and its placement at optimal location.**

***Keywords*: superconducting fault current limiter (SFCL), distributed generation (DG), microgrid (MG), fault current, protection.**

I. Introduction

As the countries develop and living values improve, energy demand grows significantly resulting in increased number of power plants and influx of electrical interconnections. With these increasing energy needs and reducing dependency on conventional power generation technologies, the microgrid systems integrated with distributed energy resources (DER) are being developed. The integration of DERs in electrical power distribution system (EPDS) give rise to diverse levels of fault current and may interrupt coordination of protection system [1]. The increased interconnections of modern electrical power system among distributed and centralized power resources may cause complicated short circuit scenarios. A short circuit fault in electrical power system affects the continuity of supply and hazardous for equipment.

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The electrical system's strength against a fault can be enhanced by applying superconducting fault current limiter (SFCL) which has the prospective capabilities to suppress critical fault current and protect the relevant equipment against any worst condition. Due to their unique features (e.g. very quick response, high reliability because of independent operation from external signals, minimal self-recovery time, no wearable parts, energy efficiency, etc.), SFCL are promising candidate for their increased role in power systems [2]. The well-known fast protection feature of SFLCs is due to HTS (high temperature superconducting) materials. In general, an SFCL offers superior technical performance to limit fault currents in comparison to conventional protective approaches. The SFCL shows high impedance during fault period and negligible impedance during normal operating conditions in the circuit [3]. The resistive and inductive are two basic types of SFCLs. In resistive type SFCLs, the superconductor is directly connected in series to the line to be protected. On the other hand, in the inductive type SFCLs, the superconductor is magnetically coupled with the line. Under normal operation, SFCLs have negligible influence on a power system. In case of fault, they limit short-circuit current to a value close to nominal current. With discovery and advancement in HTS materials, SFCLs have strong potential for power system applications due to their numerous advantages [4].

There is significant literature which has looked into the use of SFCL for power system stability. In [5] the results show that the power quality is significantly enhanced by use of SFCLs. The SFCLs limit the fault currents and controls voltage sags on other feeders connected to power transformer. In addition, the stresses on other equipment (transformers, circuit breakers, etc.) are greatly reduced, and this prolongs the useful life of the equipment. The use of SFCLs to handle asymmetrical fault current has been addressed in [6].

Fault currents in power systems always create troubles and adversely affect system's performance and efficiency. The performance of advanced power systems is more vulnerable to these conditions because they incorporate intermittent and comparatively weak distributed generation (DG). The conventional protection schemes cannot operate efficiently in EPDS integrated with DG because of bidirectional power flows and uncertain current and voltage levels under fault conditions. Therefore, it is required to develop new protection schemes for protecting MG and

EPDS integrated with DG. Amongst various protection schemes, inclusion of SFCL is a promising solution for MG protection. An SFCL offers several advantages for power system protection especially for EPDS integrated with DG because it has negligible power loss and high initial fault current limiting capability usually at first half cycle [2], [7].

The relevant literature shows that the protection of MG is not achieved with the same methodologies that have been used to protect conventional distribution systems [8], [9]. In general, the MG can operate in both the grid-connected mode and the islanded mode, whereas the overcurrent relays (OCRs) are set for higher fault currents under grid-connected mode, but under islanding operation the response is slow. These relays cannot operate reliably because of low fault current contribution from DG [10]. When an EPDS is integrated with multiple DG units as MG, and a short circuit fault occurs in the upstream or downstream network, the MG may be tripped off due to protection equipment setting and poor fault-ride-through (FRT) capabilities of some DG units [11]. Therefore, the protection equipment design parameters are modified for DER integrated with EPDS.

In this study, we have considered some practical scenarios which can be observed in actual microgrid systems. The fault current level varies significantly during grid-connected and islanded modes of microgrid. This results in increased complexity for reliable operation of protection system. There are several protection methodologies proposed in literature to address this problem [12]. This paper proposes modeling and use of SFCL to increase transient stability of integrated power system and to achieve relay coordination of microgrid in both grid-connected and islanded modes of operation.

The organization of rest of the paper is as follows: in section-II SFCL is modeled and analyzed in MATLAB/Simulink environment and its various characteristics are explained. This section also shows the development of coordinated protection system capable to work in both modes of microgrid operation. In section III, test system is presented and simulation results are discussed. The conclusion of paper is presented in section-IV.

II. Modeling and Analysis

This section has been divided into three sub-sections which describe fundamental principle of resistive SFCL, modeling and characteristics of resistive SFCL using MATLAB, and development of protection relaying system to best work with developed SFCL.

A. Fundamental Principle of Resistive Type SFCL

A resistive type SFCL is merely a length of superconductor which is connected in series with a line to limit high fault currents. This class of current limiters is based on the physical properties of an oxide ceramic superconductor connected in series with the system. In the normal operating condition, this behaves nearly perfect electrical conductor without ohmic resistance. If the passing current exceeds the current carrying capacity of the oxide ceramic material (which happens during short circuit conditions), it suddenly drops its superconducting property and reverts rapidly to its normal state (i.e. its impedance increase to a defined value). In this way, by shaping up as a high ohmic resistance in the network, resistive type SFCLs limit the short-circuit current in the first half-wave. The oxide ceramic elements of the SFCL, whose temperature rises briefly during the limiting process, automatically revert to the superconducting state after cooling back to normal operating temperature.

Generally resistive SFCL works on a zero resistance principle. i.e. during normal condition when value of current and temperature are below their critical values I_c and T_c respectively, the value of resistance is zero. During fault condition this value of I_c and T_c increases above their critical values and hence, there is transition from superconducting to normal state, which cause the increase in resistance value with increased current. In this way current limitation takes place in resistive SFCL.

The relation among temperature, magnetic field, and current density, known as T-B-J characteristics of superconductor, describe the behavior of superconducting materials. These show significant physical property of SFCL performance and give idea of three states of actual superconductors with different power laws. These sates are superconducting state (E_1), flux flow state (E_2), and normal conducting state (E_3), as shown in Fig. 1. Such parameterization in general holds for all types of high temperature superconducting (HTS) materials [13].

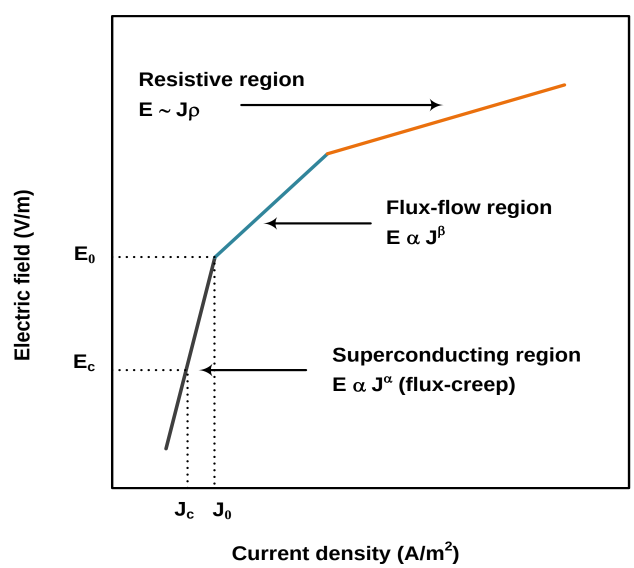

Fig. 1. Characteristic curve and states of SFCL

B. Modeling and Design Characteristic

As mentioned earlier, the working of resistive type SFCL is divided into three regions. Each region has its own physical characteristics which can be expressed by mathematical equations [14].

The superconducting state E_1 is expressed in (1), where J_c

is the critical current density, E_c is the critical electrical field intensity defined at $E_c = 1\mu V/cm$ of superconducting material and $J_c(T)$ is temperature dependent current density by an exponential power law.

$$E_1 = E_c \left(\frac{J}{J_c(T)}\right)^{\alpha T} \quad (1)$$

The exponent α (T) is derived as

$$\alpha(T) = \max[\beta, \alpha'(T)] \quad (2)$$

Whereas,

$$\alpha'(T) = \frac{\log\left(\frac{E_0}{E_c}\right)}{\log\left[\left(\frac{J_c(77k)}{J_c(T)}\right)^{(1-\frac{1}{\beta})}\left(\frac{E_0}{E_c}\right)^{\frac{1}{\alpha(77k)}}\right]} \quad (4)$$

The flux flow state (E_2) is expressed as,

$$E_2 = E_o \left(\frac{E_C}{E_O}\right)^{\beta/\alpha(77k)} \frac{J_c(77k)}{J_c(T)} \left(\frac{J}{J_c(77k)}\right)^{\beta} \quad (4)$$

And the normal conducting state (E_3) is given by (5) as,

$$E_3 = \rho(T_c) J \quad (5)$$

Whereas, ρ is the normal resistivity and T_c is the critical temperature of the HTS material.

The calculated values of E_1, E_2, *and* E_3 gives the variable impedance of resistive type SFCL and characterizes the non-linearity of HTS material.

We modeled resistive type SFCL using parameters shown in Table I.

TABLE I
SFCL MODEL PARAMETERS

Parameter	Value
alpha_77K	6
beta	3
Critical current density at 77K, A/m^2	1.5e^7
Critical temperature, K	95
$\rho(T_c)$, Ωm	1e^{-6}
E_0, V/m	0.1
E_c, V/m	1e^{-4}
Length of super conductor, m	50
Diameter of super conductor, m	0.004
Area of super conductor, m^2	1.2566e^{-5}

Before implementing the modeled SFCL in test system, the functionality of developed model was first tested by applying a current from 0 amps to 3000 amps and values of various SFCL parameters were evaluated as shown in Fig. 2. The values of SFCL resistance, temperature of SFCL due to high magnitude of passing current, and developed electric field show validity of modeled SFCL. The value of resistance is almost zero in superconducting state (state 1) of SFCL. In this region, the temperature is nearly 77F and electric field intensity is also negligible. As the value of current exceed about 600A, the resistance of SFCL increases and electric field builds up. In the 2nd state of SFCL, the value of resistance exceeds enough to significantly reduce the fault current. The normal conducting state (state 3) has the maximum resistance and hinders fault current the most.

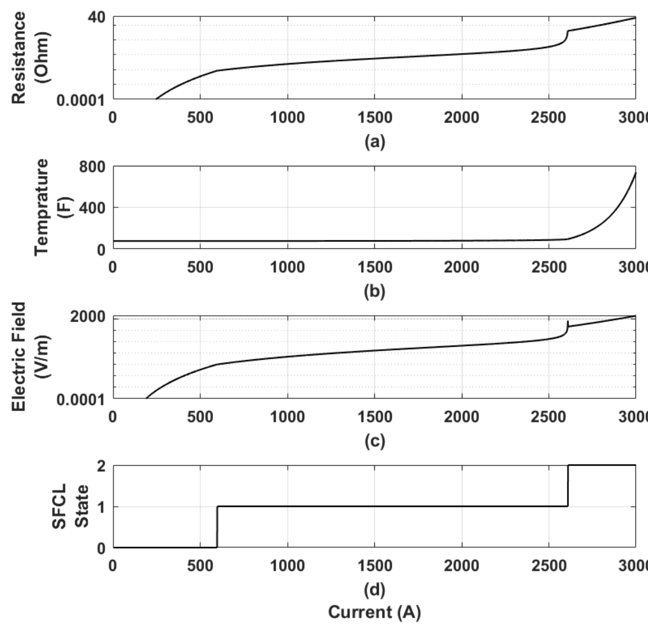

Fig. 2. Effect of current on SFCL parameters. (a) The resistance of SFCL increases with applied current (b) The temperature of SFCL (c) Electric field intensity (d) States of SFCL

C. Development of Protection System

As mentioned in Section-I, the protection of MG integrated with DERs is a challenging area. Since there is significant difference between fault currents during grid-connected and islanded modes, therefore, special attention is required when protection schemes for such microgrids are developed. In this work, we exploit the use of external device (i.e. SFCL) to obtain the protection objective. It is proposed that fault current during grid-connected mode should be limited by proper design and placement of SFCL such that it matches the fault current level during islanded mode. By achieving this, a uniform relay setting can work in both grid connected and islanded modes. For protection of test system (presented in section-III), we calculated the SFCL design parameters and placed it at the location where protection objective can be achieved. In this subsection, details of modeled relay and trip characteristics of important breakers are provided.

The overcurrent relay (OCR) is installed in electrical power system for primary and/or backup protection. It operates instantly or with a preset time delay when the fault current exceeds a preset value and disconnects the fault section from the system by tripping the associated circuit breaker. In order to validate protection coordination with SFCL, we have modeled a relay in MATLAB with three relaying elements (instantaneous, inverse time, and definite time) which are built-in to commonly available digital relays. The interface of modeled relay is shown in Fig. 3. For inverse time characteristics, IEC 60255-3 type C curve has been adopted whose trip time can be calculated by (6), where I is the current flowing through circuit, I_p is pick-up value (or plug multiplier setting, PMS) of current, and T_p is time dial setting of the relay.

$$T = \frac{80}{(I/I_p)^2 - 1} . T_p \qquad (6)$$

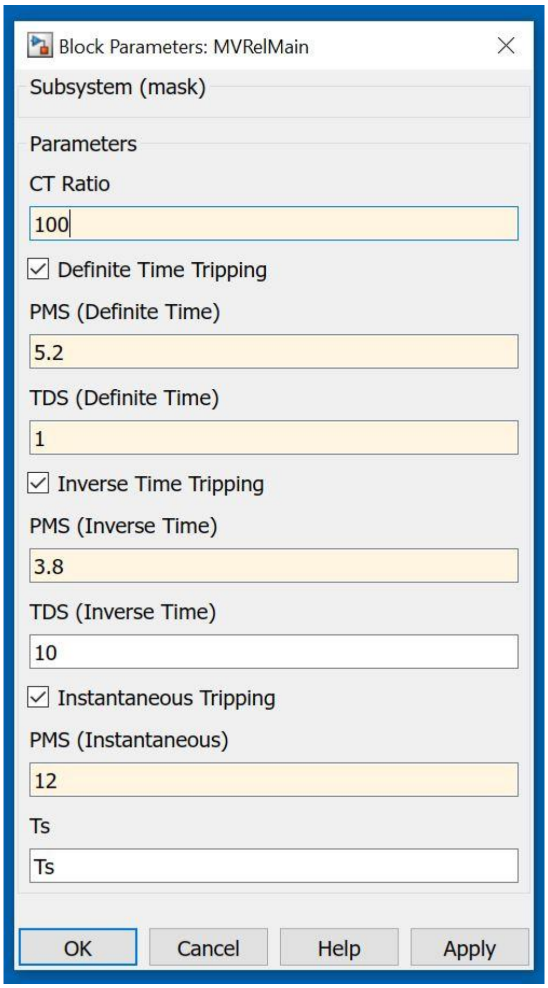

Fig. 3. The user interface of modeled relay

For test system (shown in Fig. 5), appropriate relay coordination has been developed for proper operation of protection system. The tripping characteristics of three important breakers (outgoing breaker of 4 MVA PV array, main breaker of MV named as MV Br, and outgoing breaker of utility) of system are shown in Fig. 4. The lower current setting of utility breaker is due to the fact that the utility side voltage is high. The utility breaker is not shown in test system of Fig. 5.

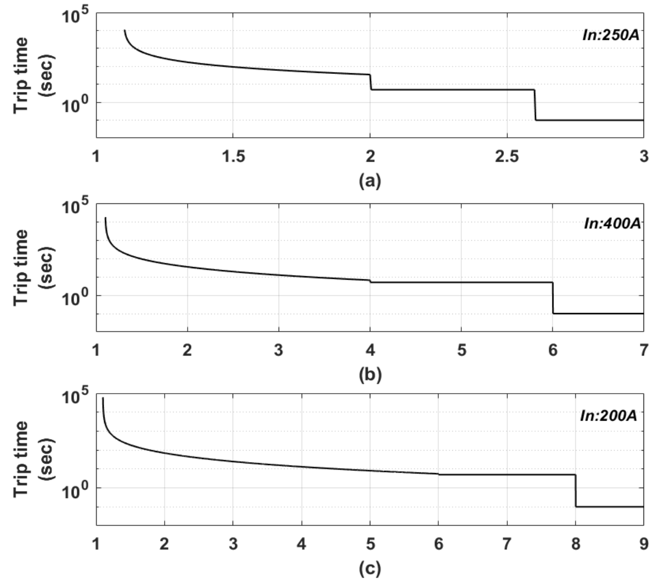

Fig. 4. Trip time characteristics of three important breakers of test system (a) trip characteristics of 4 MVA PV array outgoing breaker (b) trip characteristics of MV breaker (c) Trip characteristics of utility breaker

III. Test System and Simulations Results

The single-line diagram of the test system considered in this study is illustrated in Fig. 5. The system has been adopted from [15] and only medium voltage (MV) side has been considered which is relevant to our study. The parameters of test system are summarized in Table II. The main utility grid is connected to a distribution network consisting of electrical loads and two DGs through a 10 MVA 35 kV/10 kV transformer. The rated capacities of PV system and diesel generator are 4-MVA and 7-MVA respectively. The placement of SFCL near M1 yields optimal results in this study. The impact of SFCL placement at various locations of microgrid has been discussed in [7].

To verify the performance of developed model of SFCL and proposed protection strategy, the fault F1 has been considered with and without SFCL in grid-connected and islanded modes. The details of these simulations are described below.

Table II
Test System parameters

Parameter	Value
Utility Voltage and VA	35kV, 100MVA
Transformer Ratio	35 /10 kV
PV Capacity	4 MVA
Diesel Generator Capacity	7 MVA
Line Positive Sequence Resistance	0.38Ω/km
Line Positive Sequence Reactance	0.45Ω/km
Line Zero Sequence Resistance	0.76Ω/km
Line Zero Sequence Reactance	0.32Ω/km
Load 6	5MVA
Load 7	1 MVA
Load 8	5 MVA

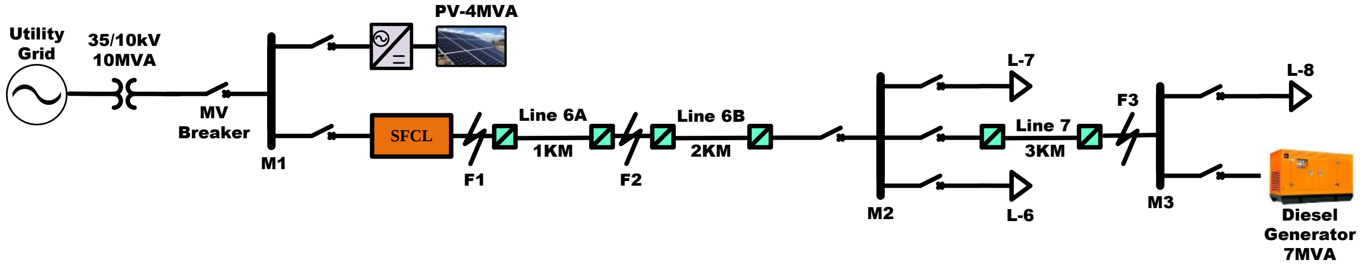

Fig. 5. Test microgrid

A. Case 1: F1 in grid-connected mode without SFCL

In this situation, the contribution of fault current is from utility as well as distributed resources as shown in Fig. 6. In this case, the fault current is very large which is dangerous for electrical equipment and needs earliest possible tripping.

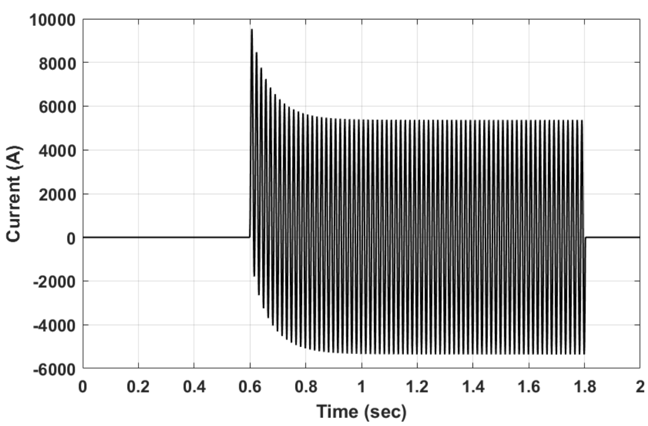

Fig. 6. Fault current in case of F1 in grid-connected mode without SFCL

B. Case 2: F1 in grid-connected mode with SFCL

As shown in Fig. 7, the fault current is reduced to lower level very quickly due to increased resistance of SFCL. The advantage of SFCL is well recognizable over here. This is the reason why SFCLs lessen the stress on circuit breakers [16] and transformers [17] by limiting fault currents.

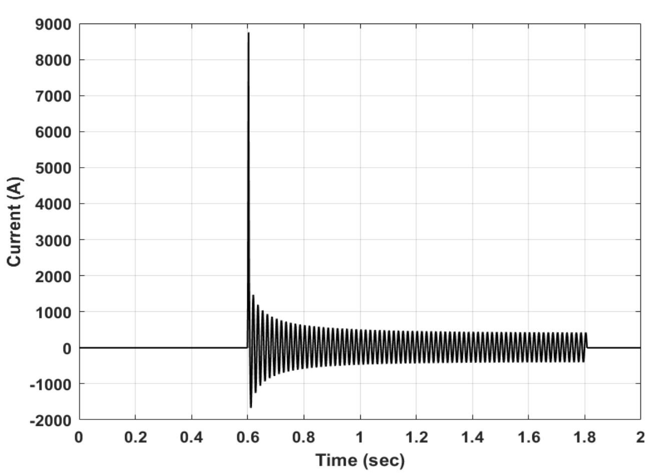

Fig. 7. Fault current in case of F1 in grid-connected mode with SFCL

C. Case 3: F1 in islanded mode with and without SFCL

The level of fault current in case of islanded mode is shown in Fig. 8. The level of fault current is considerably less due to no contribution from utility and limited fault current capacity of distributed energy resources. The fault current in islanded mode during F1 fault is small enough that it is not limited by SFCL. Hence, fault current shown in Fig. 8 is same in case of SFCL installed or otherwise.

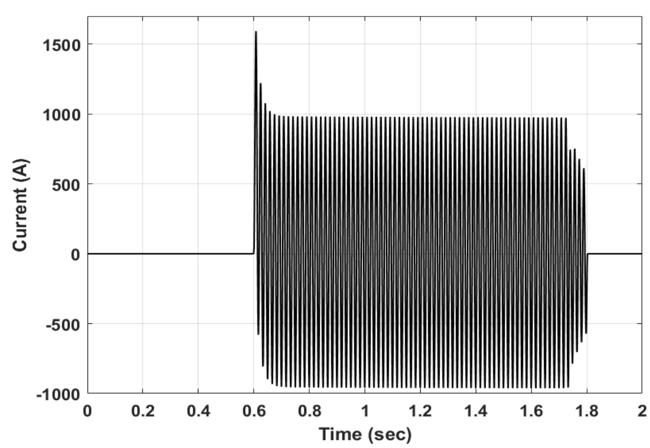

Fig. 8. Fault current in case of F1 in islanded mode

From Fig. 7 and Fig. 8, it is notable that fault current level in grid-connected mode with SFCL is comparable with fault current level in islanded mode. This helps in achieving uniform relay setting in both modes. On the other hand, there is significant difference in fault current levels when fault occurs in grid-connected mode without SFCL as observed in Fig. 6 and Fig. 8.

IV. Conclusion

Superconducting fault current limiter is a promising device that can limit the fault current levels. This feature of SFCL can be utilized for coordinated protection of microgrid during various modes. This paper presents a comprehensive study on the basic principle, modeling, and performance analysis of resistive type SFCL. In this work, a protection strategy that exploits the use of SFCL is proposed and analyzed for microgrid protection. The proposed strategy is capable of working in both modes of microgrid operation and does not require any advanced or complicated system configuration. As shown in the paper, the proposed model of SFCL can help in improving system's transient stability. It does not only limit the initial short circuit fault current but also lowers the stress on other protection and operational equipment as well.

The developed model of SFCL and proposed coordinated microgrid protection scheme is evaluated on a test system. The results show that overall performance of SFCL and proposed scheme is very promising.

V. References

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