

DESIGN AND ANALYSIS OF FAULT CURRENT LIMITER BASED ON THE SUPERCONDUCTING PRINCIPLE IN THE SMART GRID SYSTEMS

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Abstract

This paper presents a simulated analysis for the first time using the MATLAB Simulink tool prototype model to find the best configuration of the Superconducting Fault Current Limiter (SFCL) Impedance method. The goal here is to maintain the short circuit current within the circuit breaker's power. To improve the reliability of the power system, various forms of decentralized generation plants (DGP) can be connected to the traditional electric grid (PS). Interconnected Decentralized Generation (DG) to an existing electric system provides a variety of benefits, including increased distribution system reliability, enhanced power quality, and decreased short circuit current, which can damage protective equipment. Since it gives virtually zero resistance in a steady-state, the Superconducting Fault Current Limiter (SFCL) is an ideal technology for reducing the magnitude of fault current (FC) in PS. Finally, the SFCL technique was used in the conventional grid interconnected with the wind farm to determine its optimal location in the smart grid (SG) with DG. However, we investigate the best location for SFCL in the smart grid, and our findings show that SFCL at the integrating point is the right alternative.

Keywords: Unsymmetrical fault, Distributed Generation (DG), Superconducting fault limiter (SFCL), Transient Recovery Voltage (TRV), Smart grid (SG)

Introduction

Including India, the world energy demand is rising at a high pace, and power demand is higher than the availability of power due to increased society, air conditioners, big televisions, and more electronic devices. The size of both electric grid and non-conventional energy generation systems increases with the substantial increase in electricity

requirements (Noe and Oswald, 1999), (Kovalsky, 2005). Increased distribution system reliability, improved power quality, and lowered short circuit current, which can harm protective equipment, are all advantages of linking Decentralized Generation (DG) to an existing electric system. The probability of a fault incident efficient for causing

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unrecoverable and severe harm to a wide range of power equipment, or even a system collapse, has increased hastily due to the stubborn increase of De-centralized Generations (DCG), like as photovoltaic cell (PVC), solar power generation (SPG) and wind farms Generation (WFG). The Transmission System Operators (TSO) are not concerned about this issue, as the increased fault current has a negative effect on the entire PS's fidelity and security. Many traditional methods have been used in many industries to decrease the fault current's severity, such as split bus bars system, fuses, and higher impedance transformers. However, the power system's efficiency can degrade these devices and increase power loss (Blair *et al.*, 2013; Bock *et al.*, 2014; Kim *et al.*, 2014). The most economical solutions for correcting the issue of rising fault current are the SFCL. SFCL provides insignificant voltage drops and energy losses under normal working conditions. SFCL's theory is based on superconductivity. It determines that as far as current (I), temperature (T), and magnetic field density (Jc) are below their rated value, any superconducting material is at the superconducting point. However, suppose some of the relevant parameters like Jc, critical Tc, and Hc, that characterize the switching from the superconducting state to the ideal working state has overreached. In that case, RSFCL adds impedance to the circuit to reduce the fault current magnitude (Hwang *et al.*, 2012; Shu *et al.*, 2014; Khuntia and Samantaray, 2015). With the AC microgrid providing a wind farm, the comprehensive power system model was introduced. For the serious faults with the various SFCL structures, the transient analysis was performed. It is optimal to find the strategic location of SFCLs in power systems from the simulation results, which restricts all irregular FCs and has no negative impact on DG resources (Jo *et al.*, 2012). The different SFCLs can be categorized as Impedance type SFCLs, iron core type SFCLs, and inductive type SFCLs. This paper modeled the resistive form of SFCL in MATLAB/Simulink (Nagarathna *et al.*, 2015).

The present paper is structured as follows: The model of the AC resistive SFCL is defined in Section 2, and the equal-area criterion is used for stability analysis based on its correct value during a fault. Section III presents the simulation results to illustrate the efficacy of the proposed ZSFCL within acceptable variables, including a similar test at the delivery system's level identical to the real environment. Finally, Section IV gives the conclusions.

Simulation Set-Up

To develop and implement the SFCL model, the MATLAB/Simulink/Simpower model is selected in this paper. An entire smart grid power network consisting of wind farm model integrated transmission, generation, distribution, and SFCL model has also been applied in Simulink/Simpower system. This software has multiple benefits over its present simulation software (such as PSPICE, EMTF) due to its flexible analysis, open architecture model, and robust command-line interface.

Conventional Power Grid

MATLAB/Simulink/SimPower System has also launched a full SG electric power network (EPS), including generation stations (GS), transmission stations (TS), and distribution systems (DS) with an interconnected wind farm (WF) model. Figure1 indicates the PS model with fault and SFCLs positions. The power system model consists of a three-phase synchronous machine, a 100 MVA traditional power plant linked to a 132 kV, 200 km long TL, 132 kV dispersed-variables TL by a step-up transformer (TR1). The Stepdown transformer (TR2) is used for stepping down the voltage from 132 kV to 33 kV at the substation (Jo *et al.*, 2012), (Elsamahy *et al.*, 2011). High power loads in the industry (6.0 MW) and small power residential loads (1.5 MW each) are being provided by individual branch networks (BN) distributor's center, as indicated in Figure1.

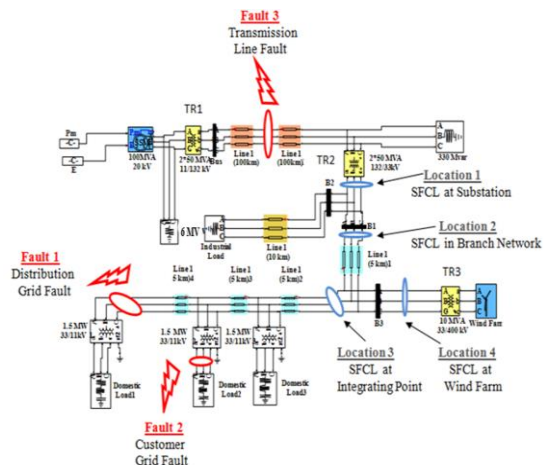


Figure 1. Model of Power System designed in Simulink with fault and SFCLs positions.

AC Microgrid

The AC microgrid has a wind farm plant, a combination of three wind turbines in a constant velocity induction generator. Three fixed-speed induction-type wind turbines with 5MVA, 3MVA, and 2MVA ratings comprise the 10 MVA wind farm. In MATLAB/Simulink, the wind turbine generation scheme was simulated. The AC microgrid working voltage is 33kV, which is the standard transmission voltage in INDIA. The 10 MVA wind farm shown in Figure 2 is connected to a 400-kV distribution system through a 210-km 33kV feeder to provide power to a 100-kV grid (Hwang *et al.*, 2012; Shu *et al.*, 2014).

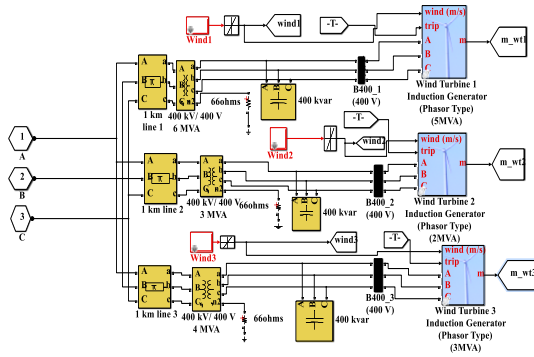


Figure 2. Simulink Model of 10 MVA Wind Farm Station.

Resistive SFCL Simulink model

The MATLAB/Simulink/Simpower system uses the Impedance SFCL model to design and implement it. In high-temperature SFCL, the high-temperature superconducting tapes were used in which tape resistivity is a binary function of current density and temperature, due to which it isn't easy to adjust (Kozak *et al.*, 2012a; Baldan *et al.*, 2013; Mukoyama *et al.*, 2013). The resistance of SFCL's mathematical model is given by Equation (1);

$$Z = \begin{cases} 0 & (J < J_{cd}, T < T_{cr}) \\ Z_{cr} \left(\frac{J}{J_{cd}} \right)^{s-1} & (J > J_{cd}, T > T_{cr}) \\ Z_{HTS}(T) & (T > T_{cr}) \end{cases} \quad (1)$$

Where Z_{cr} and J_c is written as;

$$\begin{cases} Z_{cr} = \frac{E_c}{J_{cd}} \\ J_c = J_{c0} \end{cases} \quad (T_{cr} - T)/(T_{cr} - T_{op}) \quad (2)$$

The z_c , J_c and T_c, T_{op} is the operating temperature, whereas s is the exponential index in the above mathematical model given by Equation (2). There are several parameters for the Impedance SFCL design, out of which only four basic parameters are used (Choi *et al.*, 2005; Xin *et al.*, 2012; Kozak *et al.*, 2012b; Lee *et al.*, 2012; Bahramian *et al.*, 2021).

In Table 1, the ZSFCL Variables with their values are shown. The SFCL is operating at a voltage of 33kV. The maximum impedance value will vary between 20 and 27 times. Figure 3 shows the single-phase resistive form SFCL model produced by the Simulink/SimPower System. The RSFCL Simulink model determines the passing current's mean square value and then compared it with the critical current or trigger specified in the MATLAB function program (Kraemer *et al.*, 2012; Martini *et al.*, 2012; Wojtasiewicz *et al.*, 2012; Zhang and Dougal, 2012). If the superconducting material YBCO and passing current temperature is below a critical temperature, then the RSFCL impedance increases to a maximum value. In Figure 3, I is termed as the mean square value of the passing current. T is termed as the temperature of YBCO superconducting material, and Z is higher or lower impedance depending on the operating conditions of ZSFCL. YBCO's critical temperature is 93K, or -183°C as defined in MATLAB ZSFCL algorithm (Lee *et al.*, 2008; Kim *et al.*, 2013).

Table 1. Fundamental Variables of Ac Rsfcl.

S. No	RSFCL Variables	Values
1.	Switching Time	1.990ms
2.	Lower Impedance	00.01Ω
3.	Higher Impedance	20.01Ω
4.	Reeling Time	10.05ms
5.	Activating current	600A

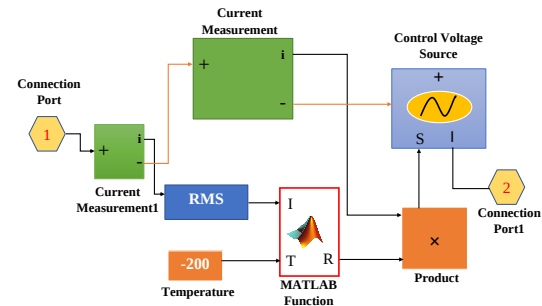


Figure 3. Simulink model of a single-phase Impedance SFCL.

In a fault state, the voltage is decreased, and the regulated voltage block is used to remunerate for the issue of sag in voltage. The multiplication of impedance and flowing current has been implemented as an input to the regulated voltage source. The system stands by until the recovery time when a current passing magnitude goes below the switching current level and then finally goes into a steady state. The three-phase resistive type model of SFCL is a combination of the three single phases SFCL used in subsequent models (Yang *et al.*, 2017; Bernstein and Noudem, 2020; Farzinfar and Jazaeri 2020; Nourmohamadi *et al.*, 2020).

Result and Discussion

Analysis in a normal state without SFCL

When no fault is introduced in the proposed system and no SFCL has been placed, the traditional grid system interconnected with the WF is stable. The current waveforms obtained via scope for proposed buses (B, B1, B2, and B3) were investigated. Figure 4 demonstrates the variation of all the currents for various buses.

Comparison of different bus currents in fault condition without SFCL

The fault was first introduced to the distribution system (DS), then to the customer grid (CG), and then to the transmission line (TL). In all cases, the FC level, as shown in Figure 5, Figure 6, and Figure 7, is different.

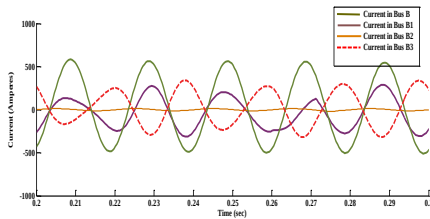


Figure 4. Comparison of the current level at the buses in normal condition.

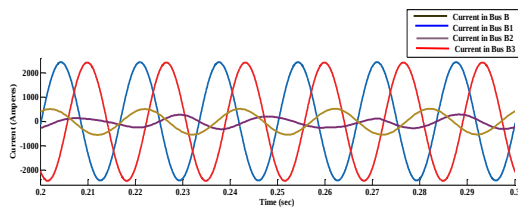


Figure 5. Comparison of current when the fault is in distribution grid without SFCL.

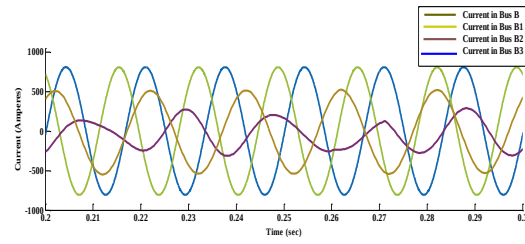


Figure 6. Comparison of current when the fault is in customer grid without SFCL.

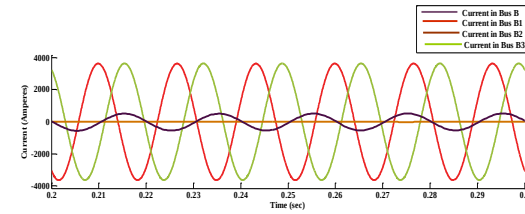


Figure 7. Comparison of current when the fault is in transmission line without SFCL.

The current magnitude was calculated when SFCL is positioned at different locations on the various buses B, B1, B2, and B3. Figure 8 displays various buses' waveform with a fault in DG and RSFCL at the substation (position 1). The wind farm's fault current (Bus B3 current) is appeared to be raised, and the FC level at B3 is greater than the 'No RSFCL' situation.

The empirical findings show that instead of decreasing, the placement of SFCL in Position1 and

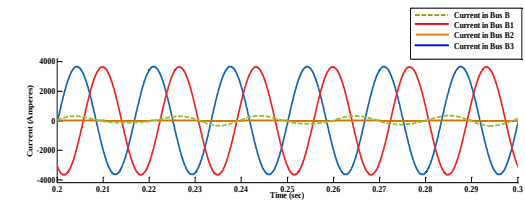


Figure 8. Comparison in current level with SFCL at substation and fault in DG.

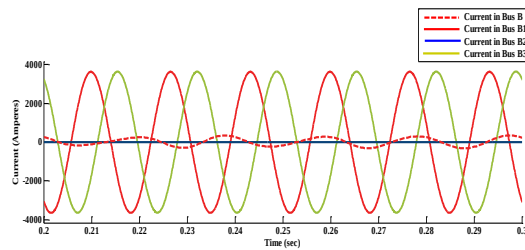


Figure 9. Comparison in current with SFCL in branch network and fault in DG.

Position 2 has raised the fault current in DG. This unexpected rising in fault current in the wind farm is due to the abrupt shift in the power grid's impedance as shown in Figure 9.

The contribution of FC in bus B3 from the WF has been decreased, and the FC is less than the situation of 'No SFCL' as shown in Figure 10. The implementation of two SFCLs at the substation (position 1) and SFCLs at the WF (position 4) was also combined, and the contribution of the fault current coming from the WF was measured and shown in Figure 11. When a 3-phase-to-ground (PG) fault is started in the DG (fault 1), the fault current coming from the WF at bus B3 for different SFCL locations is found to vary abruptly and is plotted as shown in Figure 12. As ZSFCL is placed at the integration point (position 3) of WF with the power grid, the FC coming from WF has been successfully decreased. The ZSFCL decreases the FC from the WF by 66 percent and reduces the fault current from traditional power plants because

RSFCL is put in the straight direction of every FC that flows to fault 1. The 40 percent decrease in fault current has also adhered with dual RSFCL mounted at Position 1 and Position 4. However, it is uneconomical and technically not feasible to place two SFCLs.

Table 2 indicates the magnitudes of the WF fault current (measured at TR3 output) with and without SFCL at various locations and the distribution grid fault. It is inferred from Table 2 that this case is position 3, the optimal location for SFCL implementation.

Table 2. Windfarm fault current when the fault in DG, for different SFCLs locations.

S. No.	With/without RSFCL	Current (Amp)
1.	Without RSFCL	2400A
2.	RSFCL (position 1)	3600A
3.	RSFCL (position 2)	3200A
4.	RSFCL (position 3)	800A
5.	RSFCL (position 1 and 4)	1400A

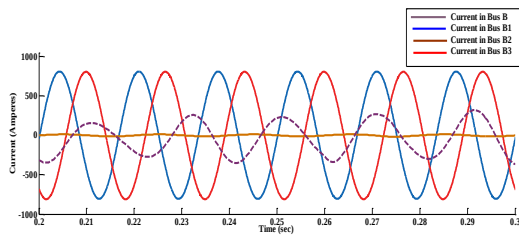


Figure 10. Current comparison with SFCL at integration point and fault in DG.

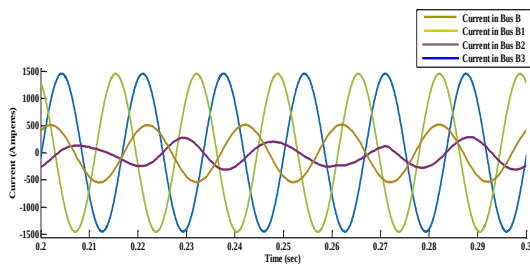


Figure 11. Comparison in current with SFCL in branch network and fault in DG.

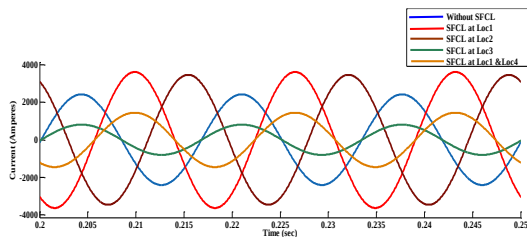


Figure 12. Current comparison in wind farm fault current with SFCLs and fault in DG.

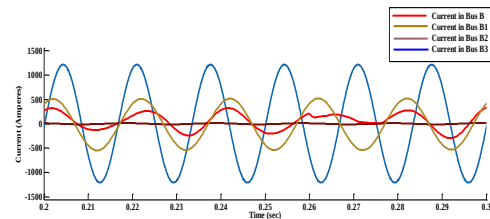


Figure 13. Current comparison with RSFCL at substation and fault in CG.

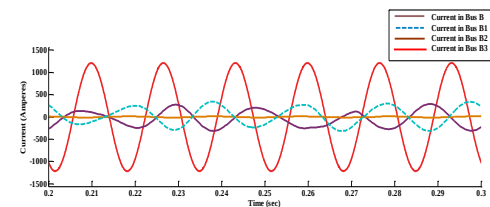


Figure 14. Current comparison with RSFCL in branch network and fault in CG.

Fault in customer grid (fault 2) with SFCLs at different positions

Similarly, fault 2 is minor since it occurs at the end of the low voltage customer side distribution. The current magnitude was calculated when RSFCL is positioned at different locations on the various buses B, B1, B2, and B3. Figure 13 displays the present waveform of various buses at Substation with a customer grid (CG) fault and RSFCL (position 1). FC's contribution from the WF (current in Bus B3) is found to be raised, and the level of FC at B3 is higher than the situation of 'No RSFCL.' as shown in Figure 14.

In this case, the comparison of all current buses shown in Figure 15 shows the SFCL located at position 3. The wind farm FC contribution has been decreased, and the FC's severity is smaller than the situation of 'No RSFCL.'

Two RSFCLs at the substation (position 1) and an SFCL at the wind farm (position 4) were also considered, and the FC contribution from the wind farm was analysed and shown in Figure 16.

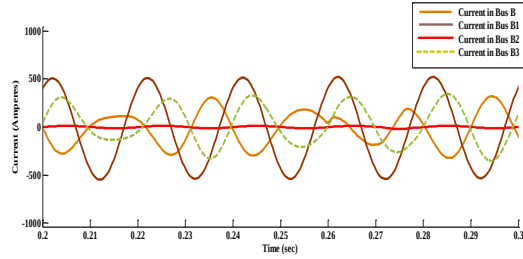


Figure 15. Current comparison with RSFCL at integration point and fault in CG.

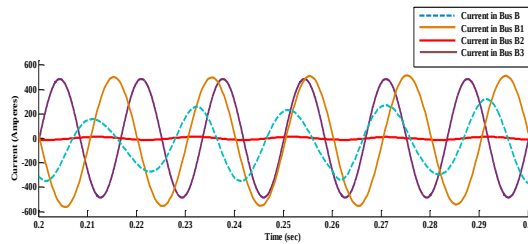


Figure 16. Current comparison with SFCL in positions 1 and 4, with the fault in CG.

The 3-phase-to-ground fault was initiated in the CG, the fault current flowing towards the wind farm for various SFCL positions (fault 2) has been considered in this case. The simulation results are close to what we have seen in the DG case (Fault 1). Once again, we got the suitable result as shown in Figure 17, when a single SFCL is placed at position 3, which is the integration point of the DG with the WF.

Fault in the transmission line (fault3) with SFCLs at different positions

In this case, the fault in the transmission line (TL) is introduced, the fault current coming from the traditional power plant with interconnected wind farm plant can flow to the fault point. The seldom occurring TL fault, resulting in severe fault currents. The wind farm fault current travels through the substation in the opposite direction and the fault position's transmission line. The current magnitude was calculated when SFCL is positioned at different locations on the various buses B, B1, B2, and B3.

Figure 18 displays the present waveform of various buses with TL fault and SFCL at the substation (position 1) compared to the last findings obtained from DG and CG faults.

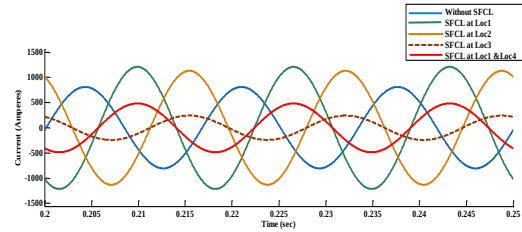


Figure 17. Current comparison of the wind farm fault current at different SFCL positions when the fault in CG.

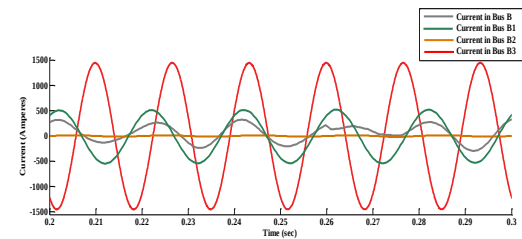


Figure 18. Current comparison with SFCL at substation and fault in TL.

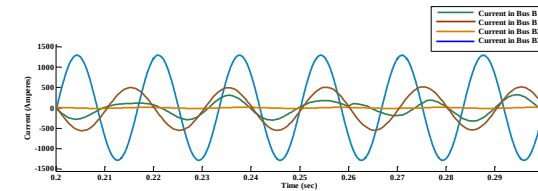


Figure 19. Current comparison in TL with SFCL in network branch and fault.

The waveform of current at different buses with TL fault and SFCL in the branch network and the integrating point is shown in Figure 19 and Figure 20. The contribution of the wind farm fault current (current in Bus B3) has increased the severity of the fault current and is now higher than the 'No RSFCL' condition. Figure 21 shows how installing two SFCLs at the substation (position 1) and SFCLs at the wind farm (position 4) reduced the wind farm's fault current contribution.

Table 3 shows the different SFCL location of wind farm fault current magnitude in case of a fault in customer grid.

The placement of SFCL at position 1, position 2, decreases the magnitude of the fault current when faults occur in the TL, but the placement of SFCL at position 3 increased the magnitude of the fault

current, as shown in Figure 22. In this case, the best position for SFCL installation is location 1 and location 2. The magnitudes of the wind farm fault current without and with SFCL at different locations with TL fault are shown in Table 4. It is inferred from Table 4 that the best position for SFCL placement is position 1 and position 2. The output of SFCL at this position is better than that of dual SFCL placement at position 1 and position 4 because multiple SFCLs are expensive and less effective than a single SFCL strategically placed in a smart grid.

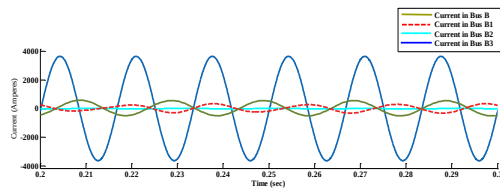


Figure 20. Current comparison with SFCL at integration point and fault in TL.

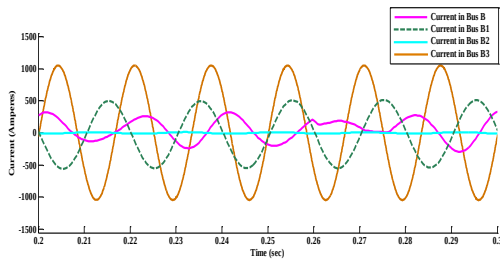


Figure 21. Current comparison with SFCL at the substation and WF with the fault in TL.

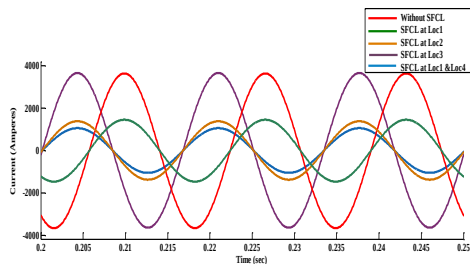


Figure 22. Fault case comparison for SFCLs position of the wind farm fault current.

Table 3. Various SFCL location of wind farm fault current magnitude in case of a fault in customer grid.

S. No	With and without RSFCL	Current(A)
1.	Without RSFCL	900
2.	RSFCL in position 1	1400
3.	RSFCL in position 2	1200
4.	RSFCL in position 3	400
5.	RSFCL in position 1 and 4	600

Table 4. For various SFCL position current magnitude value in TL fault condition.

S. No	With/without SFCL	Current (Amp)
1.	Without SFCL	3500A
2.	SFCL (location 1 and 4)	1300A
3.	SFCL (location 1)	1500A
4.	SFCL (location 2)	1400A
5.	SFCL (location 3)	3500A

The Reduction in WF fault current for various SFCLs positions was summarized in Table 5.

Conclusion

The SFCL is an emerging technology that offers the benefits of limiting power systems with a large short-circuit current. In this paper, a new model was proposed and simulated for resistive SFCL. SFCL's 3 phase resistive Simulink model has been developed. This resistive model was then positioned with an ac microgrid in an optimized traditional grid system to determine the optimal position of SFCL. As three phase faults occur in the distribution grid, the presence of SFCL at locations 1 and 2 increases the fault current. SFCL, on the other hand, reduces the fault current at locations 3, 1, and 4. The magnitude of the fault current increases again if the presence of SFCL at locations 1 and 2 fails in the customer grid, but SFCL at locations 3, 1, and 4 does not decrease the fault current. SFCL at location 2, location 1, and location 4 decreases the severity of the fault current when the transmission line fails, but SFCL at location 3 increases the fault current. The fault current limiter is improved and optimized by 66, 70 and 63% for different fault condition of Distribution grid (DG), Customer Grid (CG) and Transmission Line (TL) respectively. So SFCLs

Table 5. Percentage change in wind farm fault current due to SFCL installed locations.

S.No.	SFCL Positions	Fault Condition					
		Distribution Grid (DG)		Customer Grid (CG)		Transmission Line (TL)	
	SFCL Positions	%	Affect	%	Affect	%	Affect
1.	Position 1	39 %	Increased	55 %	Increased	59 %	Decreased
2.	Position 2	33 %	Increased	36 %	Increased	62 %	Decreased
3.	Position 3	66 %	Decreased	70 %	Decreased	1 %	Decreased
4.	Position1 and Position 4	40 %	Decreased	37 %	Decreased	63 %	Decreased

would be the ideal solution from an economic point of view for a smart grid.

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