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Impact of Active Superconducting FCL on Distance Protection in Nine Bus

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Abstract: ***In this paper, Active Superconducting Fault Current Limiters (ASFCLs) has been introduced in the existing nine bus ring system to validate prompt reduction in fault current magnitude. Instigation of FCL in rapidly expanding transmission and distribution network supports existing installed equipment. ASFCL uses converter in association with superconducting transformer to decrease fault current with its inception instantaneously. In nine bus ring system, with and without ASFCL, various faults are simulated, sampled and processed using MATLAB/Simulink. The mitigation of current during LG fault has been observed to be effective with ASFCL placement near the generating buses in the existing system. This inclusion of ASFCLs in the existing system appends the impedance seen by the distance relays affecting its characteristics operation and the protection scheme. Resistance, reactance, impedance and phase angle as seen by the relay have been computed using fundamental component of the voltages and currents, extracted by applying Discrete Fourier Transform (DFT) on sampled data. The change in the impedance and its component have been tabulated and plotted without and with ASFCL for different types of fault with respect to distance between fault points and relay location. The zone settings of protected transmission line, need to be modified as per appended reactance and impedance seen by distance relay with inclusion of SFCL to prevent maloperation.***

Keywords: Active SFCL, distance protection, fault current limiters, fault simulation, nine bus system.

I. INTRODUCTION

With rapid growth in power demand, size and number of generating stations has increased along with expansion of interconnections. The complex network leads to escalation of fault current beyond the capabilities of the existing equipment having thermal and dynamic effects on existing substation equipment and may cause damage to them [1]. The relays at these existing substations mal operates for higher levels of fault current than rated value due to CT saturation. This current inflammation for short duration may lead to displacement of coils in transformer due to thermal and mechanical forces on its windings [2].

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By increasing short-circuit (SC) impedance of transmission line (TL), fault currents can be restricted artificially. Many conventional solutions are available for limiting the current over-duty, which comprises system reconfiguration, bus splitting of existing substation and up gradation of multiple circuit breakers as per the new short circuit values. These solutions are expensive and have many drawbacks i.e. augmentation in system losses, voltage regulation issues and reduction in power system reliability as well as stability as tabulated in Table I [3].

Table I: Different solutions for limiting fault current [3]

Solution	Advantage	Disadvantage	Expense
Bus splitting	Separates sources of fault current	Separates sources of load current from load centres and decrease system reliability	High if not already installed
Multiple CB Upgrades	Direct solution with no adverse effects	Difficult to schedule outages	Depend on type of CB
New Substation	Good for future growth	Costly and time taking process for installation	Most expensive solution
Sequential Breaker tripping	No Major hardware installation required	Impact of fault gets expanded to wide range of the system	Low
Current limiting Reactors	Easy to install	Causes instability in system along with voltage drop and power losses	Medium to low
Fuse	Simple and reliable	One time use. Manual replacement is done	Low
FCL	Instant reduction of fault current magnitude	Resetting of existing protection schemes	High

An alternate way to limit the SC current is by incorporating fault current limiters (FCL) in existing system, at appropriate locations [4]. The current is reduced by FCL only for duration of fault without increasing the impedance of system under normal operating conditions ensuing to its conducive utilization [3, 5].

Several types of FCL have been evolved in past decade, which include dc biased iron core, resonant, bridge, resistive and active SFCL, with evolution of superconducting materials, cryogenic system, magnetic technologies and power electronics applications [6-11].

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With the employment of SFCL, at the sending end of TL, the change in voltage as well as current of the system gets reflected in impedance seen by relay at existing locations, resulting in loss of coordination between protective schemes [12-14]. Thus, tripping characteristics of relay needs to be modified as per the updated value of system parameters with inclusion of SFCL.

In this paper, active SFCL have been modeled using MATLAB/Simulink and their effect on voltage and current profile in standard nine bus ring system has been studied. Impact of limiter inclusion in the system on distance protection schemes has been analyzed as well. In Section (II), the brief review of FCLs has been done and in Section (III) operating principle of ASFCL has been described. Its impact on distance protection scheme due to incorporation in the system has been analyzed in Section (IV), subsequent with conclusion in Section (V).

II. FAULT CURRENT LIMITERS

FCL functioning is rapid and self-regulating in confining fault current transients to CB rated parameter. Employment of FCL is for protecting system till the initiation of circuit breaker (CB) assigned to it. Activation of CB depends on the tripping signal received from relay, which needs the sensing time, while limiter response is solely determined by magnitude of fault current in system. For system refurbishment functioning of both involve few cycles. For short-time faults, limiter recurs to its low-impedance state, depending on its recovery time, after current shrink i.e. healthy condition is reinstated. For permanent faults, FCL remains in state of high impedance, till the arc extinguishes between contacts of circuit breaker.

The characteristics of Ideal FCLs are as follows:

- Exhibit zero impedance during normal operating condition (healthy system). However, this condition cannot be fully meet by practical FCL systems but can reach near to it
- Zero power loss during normal condition
- Limit the rate of increase of current immediately within first cycle of the fault occurrence
- Impose high impedance instantly during fault occurrence
- Improve voltage profile of the system
- Quick and automatic recovery after fault clearance
- Minimal impact on existing protective schemes
- Require less maintenance
- Low weight and smaller in size
- No or only few auxiliaries

FCL are categorized as passive or active as per the impedance realization by the network as stated in [5]. Employment of passive FCLs escalates the system impedance under normal as well as faulted situation whereas active type levy insignificant impedance during healthy condition and increases rapidly with inception of fault.

Development in semiconductor technology for high power switches such as IGBT, IGCT etc. of higher voltage as well as current capacity aided in deployment of solid state FCLs (SSFCL). They are categorized into three major types, namely, series switch (SS), resonant and bridge type [15]. SSFCL includes a bidirectional restrained semiconductor switch in addition to bypass circuit. This circuit consists of parallelly connected normal state, fault current and bypass over voltage protection along snubber circuit.

Current fed switch arrangement is utilized for Bridge type FCL realization. The switches current rating is determined by fault current and system voltage maximum value. The operating principle of the limiter depends on incorporation of dc current source with the line connected in series. In practical purpose, reactors are used as current source because which it possess some disadvantages. It includes saturation of the inductor used during high voltage resulting in failure in accomplishing current limiting properties. There is a notable loss during normal operating condition. The switches used (generally diodes) should have the capabilities to withstand the current flowing during normal as well as in faulted condition. ZnO is used for overvoltage protection along with providing path to reactor for discharging at the instant of CB opening. Solid state switches in Resonant FCL reconfigure its network into either normal or faulted state. Else normal condition and fault current bypass elements are utilized individually. The by-pass CB is open during healthy condition due to which the inductor/reactor and capacitor are in resonance. During fault condition, the capacitor is by passed, injecting the reactor in transmission line, which further limits fault current. Zero series impedance is achieved by employing the line frequency tuned Series resonant circuit. When fault occurs, the tuning is disturbed and conditions for circuit to be in resonance is no more. This introduces high additional impedance to the existing TL. These FCLs reduce fault currents with no interruption capability.

Current limiters have upgraded with advancement in superconducting materials manufacturing technology. Superconducting FCL (SFCL) is an inventive solution, having many benefits. The current magnitude is restricted within the first cycle of fault inception. This results in system reliability and transient stability improvement. Several current limiters have evolved with various circuit designs using superconducting materials. Resistive, inductive, bridge and active are different forms of SFCL [7-10].

III. ACTIVE SFCL

Active SFCL (ASFCL) consists of PWM controlled converter along with superconducting air core transformer. Transformer primary is in series with transmission line. One end of three single phase transformer secondary is connected to converter and other ends are grounded [16-17]. Hence, the mutual inductance amid the phases has been neglected.

Proper switching of the controlled switches aids in sustaining synchronization with protection schemes as well as subduing harmonic contents. Reduction in energy losses and weight owing to exclusion of iron core are the major advantages of air core superconducting transformer as compared to conventional one [18]. The decision of healthy or faulty state relies on amplitude of current computed. The equivalent circuit of three-phase ASFCL is depicted in Fig. 1.

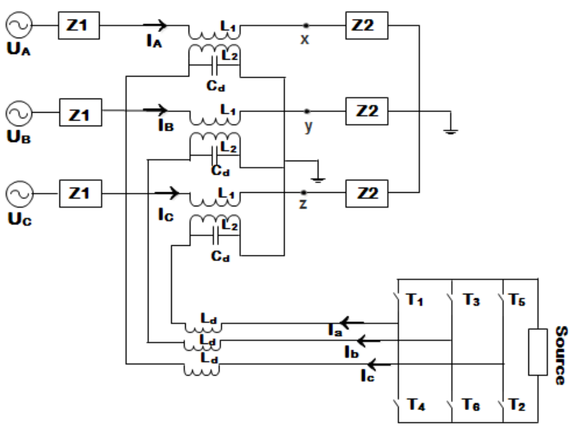

Fig. 1: Structure of three phase ASFCL

The input to the converter is via superconducting transformer. U_A, U_B, U_C are voltage sources, I_A, I_B, I_C are circuit's line current. I_a, I_b and I_c are converter's output current. During normal state, Converter output current is maintained to compensate transformer's core magnetic field to almost zero. C_d and L_d are utilize for filtering the harmonics created by the converter.

The Fourier series of the instantaneous current for phase A of a Y- connected load to the converter can expressed in (1).

$$I_a = \sum_{n=1,2,3..}^{\infty} \frac{4I_L}{n\pi} \sin\frac{n\pi}{3} \sin n\left(wt+\frac{\pi}{6}\right) \tag{1}$$

Considering the circuit shown in Fig. 2, the phase A voltage can be indicated as (2)

$$U_A = I_A(Z_1 + Z_2) + jwI_A L_1 - jwMI_a \tag{2}$$

Where,

Z_1 = circuit impedance

Z_2 = load impedance

M = mutual inductance between transformer windings

Under normal operating condition, the limiting impedance (Z_L) should be equal to zero. Therefore,

$$jwI_A L_1 - jwMI_a = 0 \tag{3}$$

Output current of converter in original state is given in (4) [16]:

$$I_a = \frac{I_A L_1}{M} = \frac{U_S L_1}{(Z_1+Z_2)M} \tag{4}$$

In Fig. 1, LG fault (phase A) at location x has been taken as sample derivation and same can be replicated for other phases. After insertion of fault, line current in phase A will increase from I_A to I_{Af}, assuming remaining phases to be unaffected.

Substituting I_{Af} in place of I_A in (2), I_{Af} can be given as (5)

$$I_{Af} = \frac{U_A + jwMI_a}{Z_1 + jwL_1} \tag{5}$$

Eq. (5) infers that controlling I_a can regulate I_{Af}.

The three modes for controlling I_a is given by:

Mode 1- When I_a is in original condition, as per (4)

$$I_{Af} = \frac{U_A}{Z_1 + Z_L} \tag{6}$$

Where,

$$Z_L = jwL_1\left(1 - \frac{I_A}{I_{Af}}\right) \tag{7}$$

Mode 2- Regulating amplitude of I_a to zero. SC current would be given as

$$I_{Af} = \frac{U_A}{Z_1 + jwL_1} \tag{8}$$

Hence,

$$Z_L = jwL_1 \tag{9}$$

Mode 2 exhibits better limiting effect owing to higher magnitude of complex Z_L as compared to mode 1.

Mode 3- Regulating the phase angle of I_a by making jwI_a lead by 180 with respect to U_A. The equivalent Z_L can expressed as (10)

$$Z_L = jwL_1 + \frac{jwMI_a}{I_{Af}} \tag{10}$$

The limiting effect is best in mode 3 amongst the three discussed. Therefore, the same has been implemented in the bus system considered. ASFCL has been modelled according the circuit depicted in Fig. 1 using Matlab/ Simulink where IGBT are used as converter switches. The rating of the superconducting transformer has been considered as given in [19].

IV. DISTANCE PROTECTION

The impedance and its components (i.e. reactance and resistance) measured between fault point and location of relay is the key factor for the working of distance relays. Its basic working principle is depends on ratio of voltage to current at relaying point as well as the angle between them and is varying depending on the location of the fault [20, 21]. Distance relay operates instantaneously, if the measured quantity is less than zone 1 set value (Z_{set}) else with definite time delay for other zones of protection.

For distance relay operation:

$$|Z_M| \leq |Z_{set}| \tag{11}$$

$|Z_M|$ - impedance measured by the relay

$|Z_{set}|$ - set value of impedance for zone 1

With the insertion of SFCL in the existing system, pre-defined impedance for zone1 (Z_{set}) protection of the transmission line has to be modified as Z_{new} (12)

$$Z_{new} = Z_{set} + Z_{SFCL} \tag{12}$$

To avoid under reach condition caused by inclusion of SFCL, relay setting for zone 1 operation should modified as per Z_{new}. The effect of Z_{SFCL} would also reflect in the other zones of relay setting. Now, the condition of relay operation should based on (13):

$$|Z_M| \leq |Z_{set}| \tag{13}$$

Removal of dc offset and higher order harmonics are required for measurement of seen impedance by the relay at the system frequency. The real and imaginary components of fundamental frequency voltage and current have been extracted using Discrete Fourier Transform (DFT) as per following equations:

$$V_s = \frac{\sqrt{2}}{N} \sum_{m=0}^{N-1} \left(v_m \sin\frac{2nm}{N}\right) \tag{14}$$

$$V_c = \frac{\sqrt{2}}{N} \sum_{m=0}^{N-1} \left(v_m \cos\frac{2nm}{N}\right) \tag{15}$$

$$I_s = \frac{\sqrt{2}}{N} \sum_{m=0}^{N-1} \left(i_m \sin\frac{2nm}{N}\right) \tag{16}$$

$$I_s = \frac{\sqrt{2}}{N} \sum_{m=0}^{N-1} \left(v_m \cos\frac{2nm}{N}\right) \tag{17}$$

Where,

N is the number of samples distributed uniformly over the full cycle data window. v_m and i_m are sampled values of voltage and current respectively.

The implementation of different types of distance relays require various parameters as resistance (R), reactance (X), impedance (Z) and angle (Φ) depending on its individual characteristics.

These parameters can computed from the real and imaginary components of the extracted fundamental frequency voltage (14-15) and current (16-17) as follows (18-22)

$$Z = R + jX = \frac{V_S + jV_C}{I_S + jI_C} = \frac{(V_S I_S + V_C I_C) + j(V_C I_S - V_S I_C)}{{I_S}^2 + {I_C}^2} \quad (18)$$

Therefore,

$$R = \frac{V_S I_S + V_C I_C}{{I_S}^2 + {I_C}^2} \quad (19)$$

and

$$X = \frac{V_C I_S - V_S I_C}{{I_S}^2 + {I_C}^2} \quad (20)$$

$$Z = \frac{V}{I} = \frac{\sqrt{{V_S}^2 + {V_C}^2}}{\sqrt{{I_S}^2 + {I_C}^2}} \quad (21)$$

$$\emptyset = \tan^{-1}\frac{X}{R} \quad (22)$$

The computed quantities (19-22) as seen by the distance relay get modified with inclusion of SFCL in the system, as depicted in (12). Therefore, the reach of relays needs modification for different zones of protected transmission line to maintain the same range of operation. The zone setting of the distance relay without SFCL would cause under reach operation with inclusion of the SFCL in the protected section [22].

V. RESULT AND DISCUSSION

Standard nine-bus ring system has been modeled in Matlab/Simulink environment and depicted in Fig. 2. Bus1 has been considered as swing bus. Bus2 and 3 are PV buses. Bus 5, 6 and 7 are load buses. The SFCLs are placed at all the generator buses to have its maximum effectiveness on the bus system considered. Swing bus generator is rated at 16.5kV and 500 MVA. The other generators considered are of 18 kV, 192 MVA, p.f. 0.85 and 13.8 kV, 128MVA, p.f. 0.66. The respective transformers are of rating 100, 150 and 100 MVA. The TL voltage is 230 kV and system frequency is 50 Hz.

The impact on voltage and current waveforms with ASFCL incorporation in the system has been scrutinized by measuring the reduction of current during LG fault carried at locations 1, 2 and 3 as illustrated in Fig.2. The distance relay revised parameters have been estimated for faults in the TL at varying distances, with the inclusion of ASFCL.

The performance of the system without and with inclusion of ASFCL for LG fault in phase A at locations near to generating ends has been analyzed. The voltage and current waveforms of faulty phase at Bus1 (relay location), for LG fault at Fault3 (near bus4) has been depicted in Fig. 3(a) and (b) respectively. The preferred action of limiter for fault period has been observed, to decrease the fault current magnitude and enhance the voltage profile.

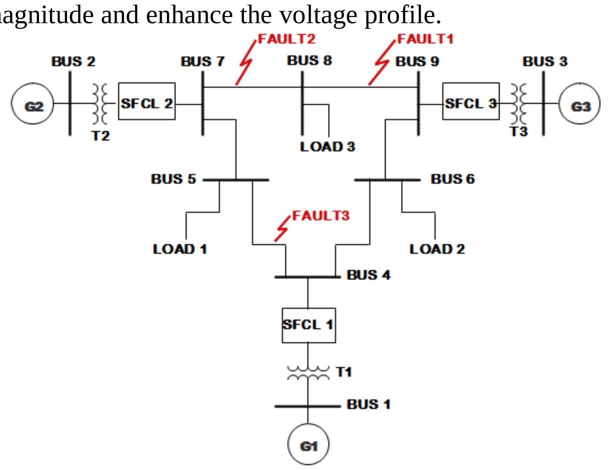

Fig. 2: Nine-bus ring system with SFCL [23]

The depletion in the current amplitude of the defective phase is significant as seen from Bus1 with ASFCL as shown in Fig. 3(b).

The impact of ASFCL in peak value percentage reduction of fault current in the model considered for Fault 1-3 have been tabulated in Table II. The simulated observations as seen from bus1 for different fault locations (fault2 & fault3) are similar, therefore, only fault2 (near bus7) measurements has been depicted in Fig. 4(a) & 4(b). Voltage dip for the fault distant from the bus1 is relatively low due to distance as well as presence of sources near to it (Fig. 4(a)). The same effect can be perceived for the current waveforms.

Table II: Reduction in fault current with inclusion of ASFCL

Fault position	Fault Current (KA)		% Reduction
	Without SFCL	With ASFCL	With ASFCL
Fault1	13.62	10.59	22.79%
Fault2	13.9	10.81	22.75%
Fault3	29.9	19.46	34.79%

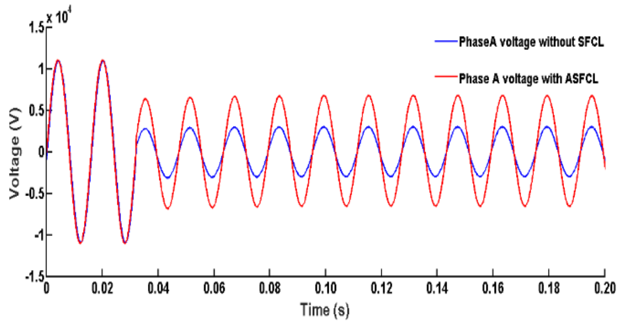

Fig. 3(a): Phase A Voltage at Bus1 for LG fault for Fault3

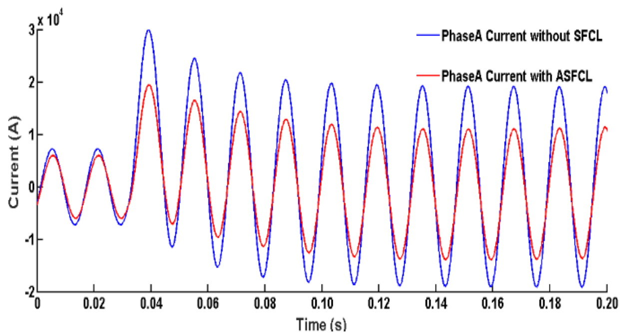

Fig. 3(b): Phase A fault current at Bus1 for LG fault at Fault3

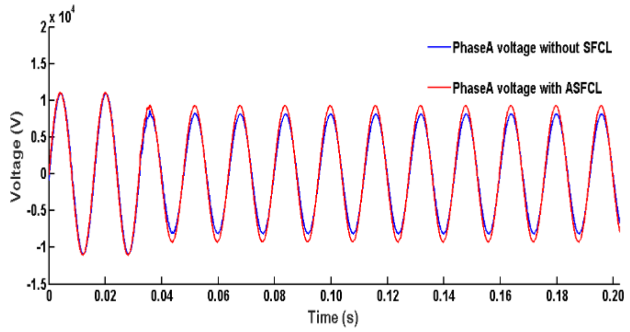

Fig.4(a): Phase A voltage at Bus1 for LG fault at Fault2

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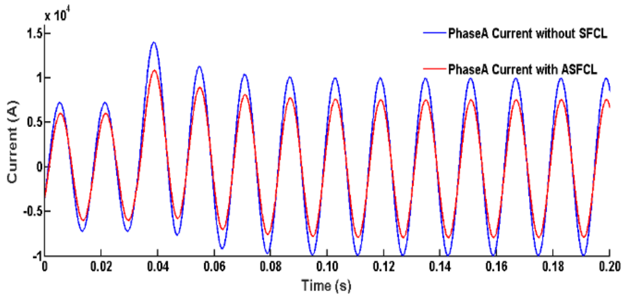

Fig. 4(b): Phase A fault current at Bus1 for LG fault at Fault2

The working of distance relay depends on the measured impedance and components between the fault location and its placement. However, due to implementation of limiters (ASFCL) in the existing system, the impedance measured by the relay at generating buses gets modified and may cause maloperation in selection of protected zones. Thus, the distance relay settings need to be modified for different zones.

For extraction of system frequency signals at 50 Hz using DFT, the data has been sampled at 20 kHz frequency i.e. 400 samples per cycles. Sine and cosine components of voltages and currents have been calculated using the sampled data. With the help of (19)-(22), R, X, Z and Phase angle has been computed. The value of resistance (R), reactance (X), impedance (Z) and phase angle seen at Bus1 for LG fault in phase A without and with ASFCL for different distances from Bus4 to Bus5 has been tabulated in Table III and graphical representation of the same has been illustrated in Fig 5.

Figs. 5(a-d) show the change in the value of resistance, reactance, impedance and phase angle due to implementation of ASFCL during LG fault (fault3) at different distances as seen from Bus1. The measured resistance before and after implementation of ASFCL is almost similar as windings of air core superconducting transformer have negligible resistance. Significant change has been observed in reactance, impedance and phase angle due to air core reactance of transformer attached in series with transmission line. When fault occurs, the limiter comes into existence resulting increase in the overall reactance of the system which further modifies the net impedance and phase angle.

For LLG fault and LLLG, the impedance and phase angle measured at Bus1 without and with the limiter at same distance as LG fault has been tabulated in Table IV & V and plotted in Fig 6(a-b) & Fig. 7(a-b) respectively. The impedance and phase angle plot of three phases coincides with each other (Fig. 7(a-b)), hence, only phase A has been shown. The results are similar for all types of simulated faults, thus, the distance relay settings should be modified as per (12) for all the zones of protection.

The effective insertion of SFCL aids in lessening in amplitude of fault current in initial cycles of its occurrence, ensuing transient stability enhancement and reliability of system. It also prevents CT saturation and other protection relays maloperation in the expanded transmission and distribution network.

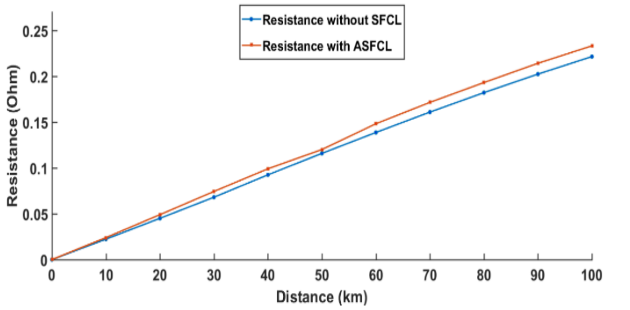

Fig. 5(a): Resistance seen at Bus1 at various distances for LG fault (Fault3)

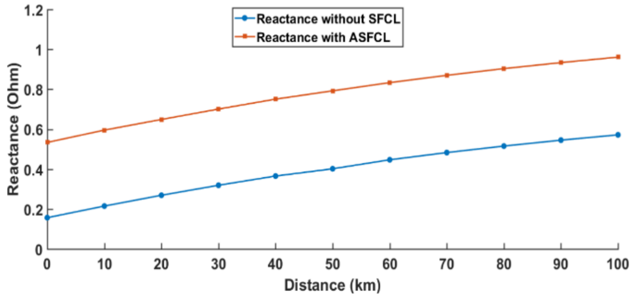

Fig 5(b): Reactance seen at Bus1 at various distances for LG fault (Fault3)

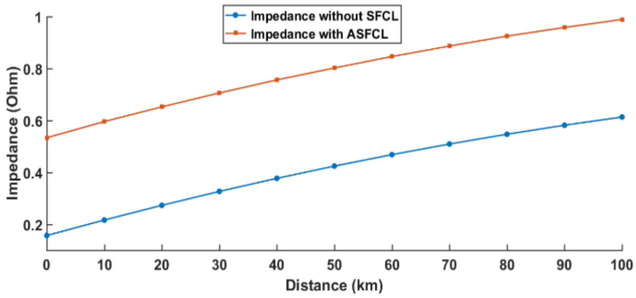

Fig. 5(c): Impedance seen at Bus1 at various distances for LG fault (Fault3)

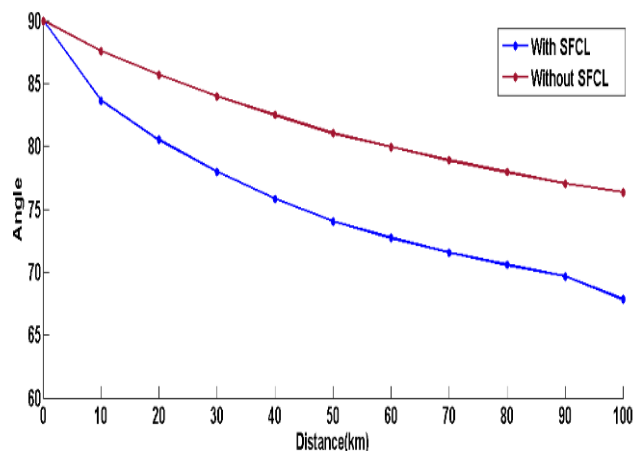

Fig. 5(d): Angle at Bus1 at various distances for LG fault (Fault3)

Table III: Values of impedance and its components of faulted phase (phase A) without and with ASFCL at different distances from Bus1 for LG fault at Fault3

Distance (seen from Bus 1) (in km)	Without ASFCL				With ASFCL			
	R(Ω)	X(Ω)	Z(Ω)	Φ	R(Ω)	X(Ω)	Z(Ω)	Φ
0	0	0.157	0.157	90	0	0.534	0.534	90
10	0.024	0.215	0.2163	83.63	0.025	0.595	0.596	87.59
20	0.045	0.269	0.273	80.50	0.049	0.649	0.652	85.68
30	0.068	0.319	0.326	77.96	0.074	0.701	0.706	83.97
40	0.092	0.365	0.377	75.85	0.099	0.751	0.756	82.49
50	0.115	0.402	0.424	74.03	0.125	0.792	0.806	81.03
60	0.139	0.447	0.468	72.72	0.148	0.834	0.846	79.93
70	0.161	0.483	0.509	71.56	0.171	0.870	0.887	78.88
80	0.182	0.516	0.547	70.57	0.193	0.904	0.925	77.94
90	0.202	0.545	0.582	69.66	0.214	0.934	0.958	77.05
100	0.233	0.572	0.613	67.83	0.233	0.961	0.989	76.37

Table IV: Values of impedance of faulted phases (phase A & B) without and with ASFCL at different distances from Bus1 for LLG fault at Fault3

Distance (seen from Bus 1) (in km)	Phase A impedance (Ω) during LLG fault		Phase B impedance (Ω) during LLG fault		Phase A phase angle during fault		Phase B phase angle during fault	
	without ASFCL	with ASFCL	without ASFCL	with ASFCL	Without ASFCL	With ASFCL	Without ASFCL	With ASFCL
0	0.157	0.534	0.157	0.534	90	90	90	90
10	0.201	0.578	0.214	0.596	81.40	87.02	88.84	89.42
20	0.244	0.619	0.267	0.651	76.47	84.35	87.64	88.59
30	0.285	0.661	0.319	0.705	73.08	82.39	86.58	87.97
40	0.324	0.697	0.367	0.577	70.75	80.69	85.46	87.34
50	0.360	0.732	0.413	0.804	69.14	79.38	84.57	86.79
60	0.395	0.767	0.456	0.849	67.74	78.10	83.58	85.80
70	0.425	0.798	0.498	0.891	66.72	76.97	82.72	85.17
80	0.457	0.828	0.537	0.933	65.91	76.19	81.96	84.57
90	0.486	0.855	0.573	0.968	65.27	75.44	81.16	84.01
100	0.512	0.881	0.607	1.003	64.74	74.83	80.43	83.64

Table V: Values of impedance of faulted phases without and with ASFCL at different distances from Bus1 for LLLG fault at Fault3

Distance (seen from Bus 1) (in km)	Phase A impedance during LLLG fault		Phase A phase angle during fault	
	Without ASFCL	With ASFCL	Without ASFCL	With ASFL
0	0.157	0.534	90	90
10	0.199	0.578	86.26	88.61
20	0.241	0.622	83.68	87.51
30	0.281	0.663	81.81	86.19
40	0.319	0.703	80.41	85.04
50	0.356	0.740	79.13	84.56
60	0.391	0.776	77.74	83.63
70	0.423	0.810	77.07	82.87
80	0.456	0.842	76.54	82.21
90	0.486	0.873	75.93	81.83
100	0.5148	0.900	75.39	80.94

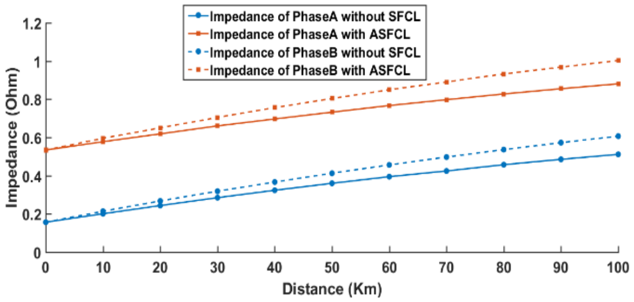

Fig: 6(a): Impedance seen at Bus1 at various distances for LLG fault at Fault3

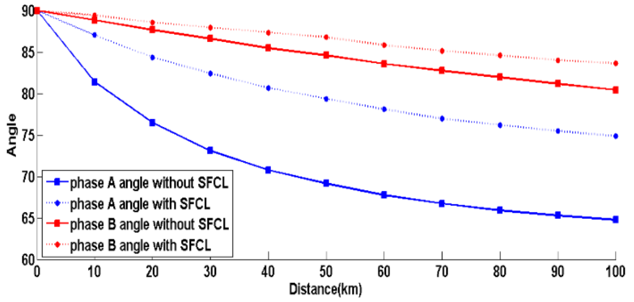

Fig. 6(b): Angle at Bus1 at various distances for LLG fault (Fault3)

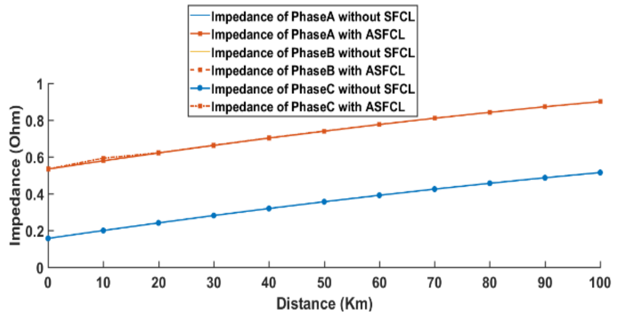

Fig. 7(a): Impedance seen at Bus1 at various distances for LLLG fault at Fault1

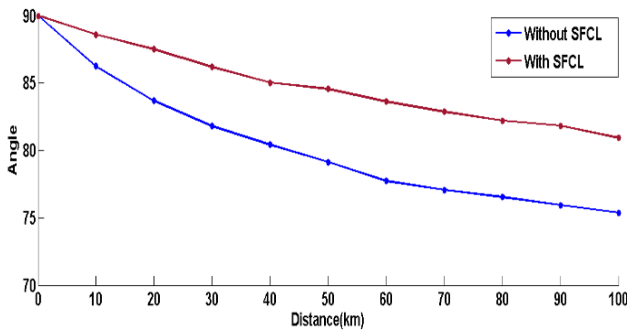

Fig. 7(b): Angle at Bus1 at various distances for LLLG fault (Fault3)

VI. CONCLUSION

The working of Active SFCL in nine bus ring system for LG fault has been investigated. The diminution in fault current magnitude is observed to be noteworthy due to presence of ASFCL for LG fault at different location in the system considered. The impact on distance protection with inclusion of ASFCL has been analyzed using simulation results. Applying DFT, fundamental component of the voltage and current have been extracted and are employed for the calculation of resistance, reactance, impedance and phase angle as seen by the relay. Submission of ASFCL has influence over other protective schemes present in the system as net impedance and its components seen by relays get altered because of impedance inserted by limiter for period of fault. The resistance remains unaltered due to superconducting transformer windings. The reactance and impedance increase due to air core reluctance of the ASFCL transformer and in turn alters phase angle seen by the relay. The existing distance relay settings need to be modified as per the updated value of impedance and reactance with inclusion of ASFCL to prevent maloperation for different zones.

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