Performance Analysis of Voltage Sag Compensation Using Super Conducting Fault Current Limiter for R & RL Loads

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Abstract-
Potential fault current levels in power grids is approaching, and may eventually exceed, the short-circuit-current limits of existing protection devices. Alternative to expensive system upgrades of protection devices, Fault Current Limiters (FCL's) provide less cost solutions to prevent old protection devices and other equipment on the system from being damaged by excessive fault currents. The proposed structure prevents voltage sag and phase-angle jump of the substation PCC after fault occurrence. This paper proposes a new series type fault current limiter (FCL) that uses a resistor in series with a inductor. The proposed FCL is capable of limiting the fault current magnitude near to the pre-fault magnitude of distribution feeder current by placing the mentioned resistor in the structure of the FCL.In this paper, the improvement of the voltage sag is analyzed according to the fault location, resistance value of SFCL, and the length of the loop power distribution system. First, a resistor-type SFCL model is used using the MATLAB/SIMULINK. Finally, when the SFCL is installed in the radial or loop power distribution system with various lengths, voltage sags are evaluated according to various fault locations. The results of voltage sag analysis in the loop system are compared with the voltage sags in radial power distribution system. In extension to the work discussed in paper the system can be tested under different Loading conditions and a

study on positioning of super conducting fault current limiter can be analyzed.

Index Terms—Loop power distribution system; superconducting fault current limiter (SFCL); voltage sag

I. INTRODUCTION

In today circumstances, rapid development of power network cause the fault current of the system increased greatly. The levels of fault current in many places have often exceeded the withstand capacity of existing power system equipment. As implication to this matter; security, stability and reliability of power system will be negatively affected [1]. Thus, limiting the fault current of the power system to a safe level can greatly reduce the risk of failure to the power system equipment due to high fault current flowing through the system. Because of that, there is no surprise to fault current limiting technology has become a

hotspot of fault protection research since this technology can limit the fault current to a low level[2,3].
This huge short circuit current of higher capacity system is limited by fault current limiters which can be an alternative solution rather than replacing existing switchgear. High fault current can be limited to a level of highest designed short circuit current rating of presented switchgear. It creates a cost-effective way to improve the power system capacity keeping switchgear unchanged. Thus, the fault current limiter can be an excellent technique to protect power system equipments.SFCL can limit the fault current in power

system using the increased resistance caused by quenching characteristics of superconducting elements. In addition, SFCL can improve voltage quality not only in faulted phase but in non-faulted phase when a 1 phase to ground fault is occurred. The assessment method of voltage sag using the Information of Technology Industry Council curve is presented in Reference [1] when SFCL is applied to power distribution system. The parallel connection of radial systems via the SFCL which can make voltage dips less severe is presented in Reference [2].

The improvement of voltage sags caused by decreased fault current is presented in References [3] and [4]. These studies dealt with the voltage sags in the power distribution system with SFCL. However, voltage quality such as voltage sag and overvoltage in faulted and non-faulted phase has been not dealt with. The magnitude of sag, whereas it may worsen the duration of sag because of the delayed trip time of a protective device by the decreased fault current. These effects of SFCL on voltage sags should be evaluated. Also, power distribution system will be changed to loop system such as microgrid or smart grid. Thus, effects of SFCLs should be evaluated and analyzed when SFCLs are installed in radial and loop power distribution system according to the location and impedance of SFCL, the length of feeder, and location of fault. However, the overall effects on voltage sag were not dealt with in the above mentioned studies.

In this paper, we assess the impact of SFCL on voltage sags in radial and loop power distribution system. In Section II, we model a resistor-type SFCL. In Section III, the voltage sag occurred by fault current is explained. In Section IV, we evaluatethe voltage sag magnitude according to the fault location and resistance of SFCL in radial and loop power distribution system.
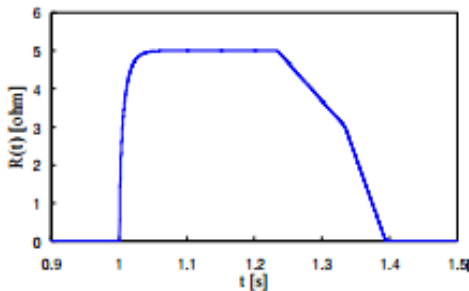

Fig. 1 Quenching and recovery characteristics of SFCL

II RESISTIVE-TYPESFCL

Many SFCL models have been developed. In this paper, we use resistive-type SFCL based on [1], [5]–[10] which represents the experimental studies for superconducting elements of SFCL being applied to Korean power distribution systems. The impedance of SFCL according to time t is given at (1), where R_n and T_F represent the impedance being saturated at normal temperature and time constant, respectively. In addition, t_0, t_1, and t_2 represent quench-starting time, the first recovery-starting time, and the secondary recovery-starting time, respectively.

$$R(t) = \begin{cases} 0 & (t < t_0) \\ R_n \left[1 - \exp\left(-(t - t_0)/T_F\right)\right]^{1/2} & (t_0 \leq t < t_1) \\ a_1(t - t_1) + b_1 & (t_1 \leq t < t_2) \\ a_2(t - t_2) + b_2 & (t \geq t_2) \end{cases} \quad (1)$$

Fig. 1 represents quenching and recovery characteristics of the SFCL shown. When a reclosing scheme is 2 Fast 1 Delay (2F1D). When a fault is occurs in a power distribution system, the resistance of SFCL increases.

TABLE I
PARAMETERS OFMODELEDSFCL

Parameter	$R_n\,[\Omega]$	T_F	$a_1\,[1/s]$	$a_2\,[1/s]$	$b_1\,[\Omega]$	$b_2\,[\Omega]$
Value	variable	0.01	-80	-160	R_n	$R_n/2$

If a recloser is tripped, SFCL is recovered. The scheme is repeated two times more. The used values for parameters are shown in Table I. The recovery time of SFCL is set to the value less than 0.5 s based on [9], because the reclosing time of power distribution system in Korea is 0.5 s.

III.VOLTAGE SAGS IN POWER DISTRIBUTION SYSTEM

When faults occur in power distribution system, the automatic recloser or circuit breaker with over-current relay (OCR) and reclosing relay will open to clear the fault and automatically reclose after a time delay. This reclosing behavior can take place several times in an effort to establish a continuous service when a temporary fault occurs [11].The voltage sag generally happens from fault. In case 1 in Fig. 2(a), if a temporary

fault occurs between CB and recloser, the reclosing operation of the OCR of breaker will be successful and the momentary interruption will occur. In this case, the customers at feeder 1 (faulted feeder) will experience voltage sag and a momentary interruption. The customers at feeder 2 (neighbor feeder) will experience the voltage sag during the fast-trip time of the OCR and this is shown in Fig. 2(b).

However, if a permanent fault is occurs, the reclosing operations will be failed and the reclosing operation will be finally locked out. In this case, the customers in feeder 1 will experience three voltage sags, two momentary interruptions and a sustained interruption. The customers in feeder 2 will experience two voltage sags during the fast-trip time of OCR and one voltage sag during the delay-trip time of OCR when reclosing scheme of OCR is 1F1D; this is shown in Fig. 2(c).during a fault. In case 2 in Fig. 2(a), all sequences and phenomena is equal to that of case 1 such as the number of voltage sags, momentary interruptions, and sustained interruption except the fault clearing time of recloser instead of OCR. In other words, if a temporary fault is occurs, the customers at feeder 2 will experience the voltage sag during the fast-trip time of recloser instead of OCR, so on. As presented above, the automatic reclosing scheme in power distribution systems can produce various voltage sags to the customers on the neighbor feeder. Moreover, the number of neighbor feeder is about 6 to 10 while the number of faulted feeder is only one. Generally, a voltage magnitude at bus of secondary-side of main transformer (MTr.) during fault can be represented as equation (2) if fault impedance is ignored, a type of fault is 3-phase fault, and source voltage is 1.0 p.u.

$$V_{bus} = \frac{Z_{line}}{Z_{source} + Z_{MTr} + Z_{line}} \quad (2)$$

Where Z_{source}, Z_{MTr}, and Z_{line} are source impedance, transformer impedance, and line impedance from source to faulted location, respectively. Equation (2), also, can approximately represent the voltage magnitude at customers on all neighbor feeders. In this paper, the voltage magnitude is focused than sag duration.
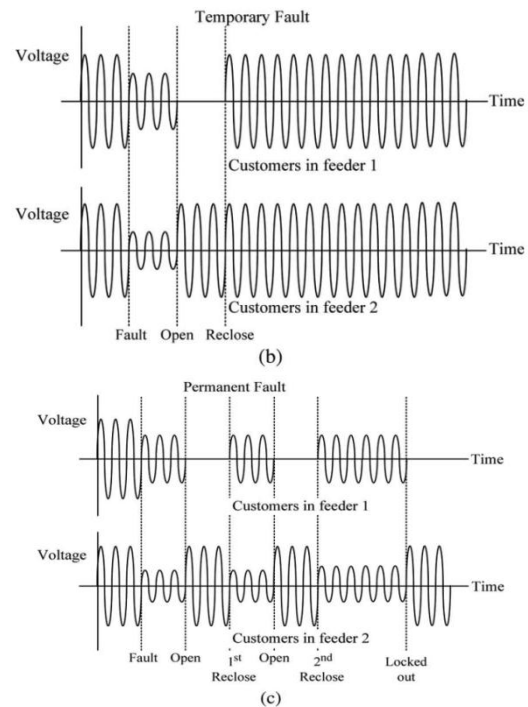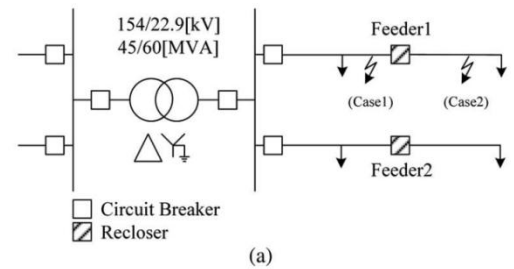

Fig. 2 Voltage sag in power distribution system d. (a) Power system configuration, (b) voltage sags of customers (temporary fault), and (c) voltage sags of customers (permanent fault).

IV ASSESSMENT OF IMPACT OF SFCL ON VOLTAGE SAGS

If SFCL is installed at the starting point of feeder, (2) is changed to equation (3) during fault.

$$V_{bus} = \frac{Z_{SFCL} + Z_{line}}{Z_{source} + Z_{MTr} + Z_{SFCL} + Z_{line}} \quad (3)$$

The voltage sag is improved more than the case without SFCL. To evaluate the improvement of voltage sag, the radial and loop power distribution system is modeled and the various cases are studied.
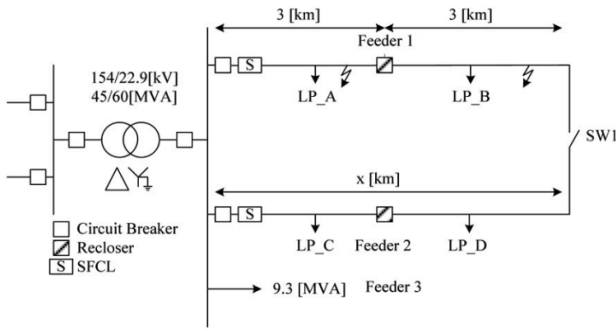
Fig. 3. Power distribution system model

TABLE II
POWER DISTRIBUTION SYSTEM DATA

	Data
Source	154 kV, 100 MVA, j4 Ω
M. Tr	154/22.9 kV, 45 MVA, j15 %
Line impedance	Z_0=10.8+j23.6 %/km
	Z_1=3.48+j7.44 %/km
Line length	F1 : 3 km, 3 km
	F2 : x km (variable)
Load	F1 : LP_A=3 MVA, LP_B=4 MVA
	F2 : LP_C=5 MVA, LP_D=5 MVA
	F3 : 9.3 MVA

TABLE III
CASES FOR VOLTAGE SAG SIMULATION

	Cases	SFCL Ω	Fault location	x km	Fault type
SW1 open	Case1-0	No	1, 2, 3, 4, 5, 6 km	6	
	Case1-1	0.5			
	Case1-2	1			
	Case1-3	1.5			
	Case1-4	2			3phase fault
SW1 Closed	Case2-0	No	1, 3, 6 km	2, 4, 6	
	Case2-1	0.5			
	Case2-2	1			
	Case2-3	1.5			
	Case2-4	2			

A. Power Distribution System Model
Fig.3 represents the power distribution system model with SFCL and interconnecting switch to simulate voltage sags. Table II shows the data of Fig. 3.

B. Case Studies
Total 10 cases of contingency analysis are studied as shown in Table III. Case 1-x is for radial distribution system and Case 2-x is for loop distribution system. The resistance of SFCL ranges from 0 to 2Ω and the fault location is 1 to 6 km. The length of feeder 2 varies 1 to 6 km at loop distribution system.

V. MATLAB/SIMULINK RESULTS

Here the simulation is carried out by different cases they are 1) Radial distribution system Fault location without and with SFCL 2) loop distribution system Fault location without and with SFCL 3) radial distribution system Fault location without and with SFCL of R and RLC loading conditions4)loop distribution system Fault location without and with SFCL of R and RLC loading conditions 5). With Series Type FCL System for Minimizing the Voltage Sag.

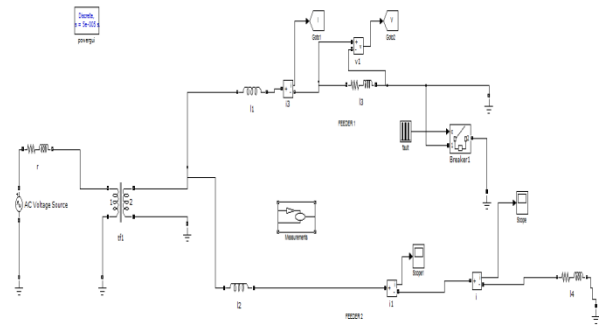### Case-1 Radial Distribution System Fault Location Without and With SFCL

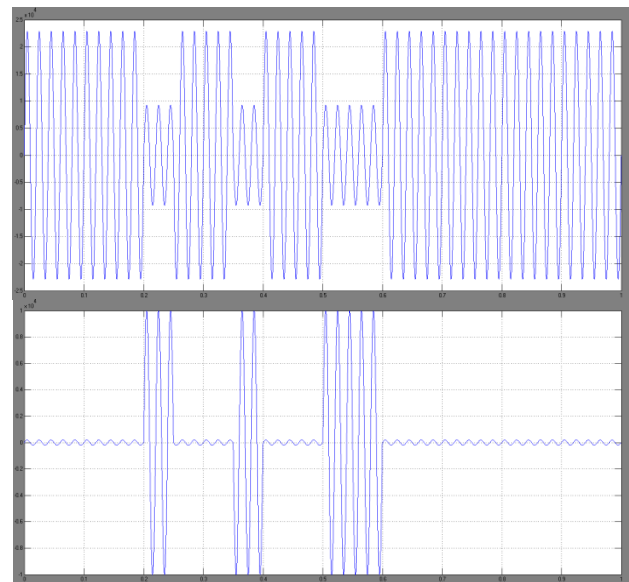Fig.4 Matlab/simulink model of radial distribution system Fault at 3 km location without SFCL

Fig.5 Voltage and current wave in radial distribution system Fault at 3 km location without SFCL
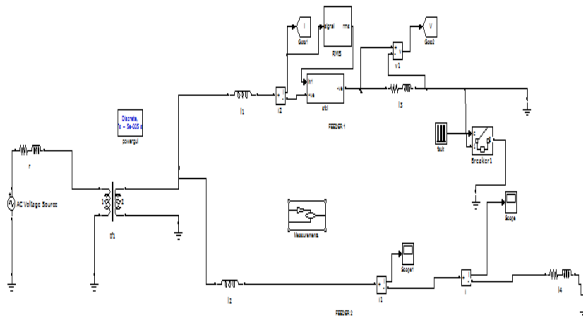
Fig.6 Matlab/simulink model of radial distribution system Fault at 3 km location with SFCL
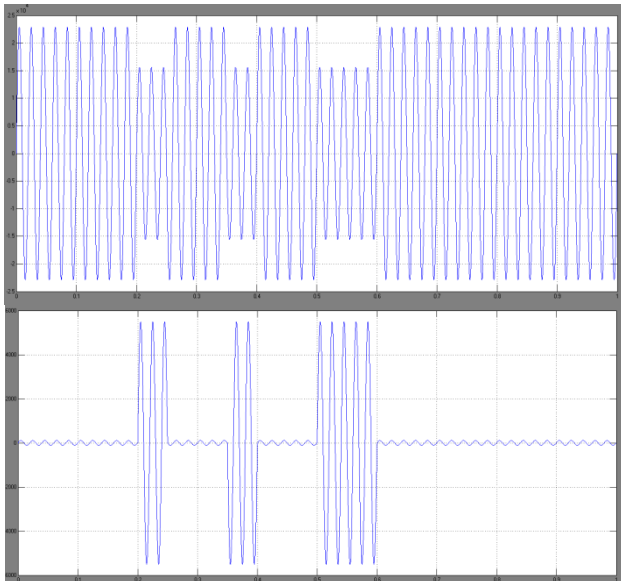

Fig. 7 Voltage and current wave in radial distribution system fault at 3 km location with SFCL

Case-2 Loop Distribution System Fault Location Without and With SFCL
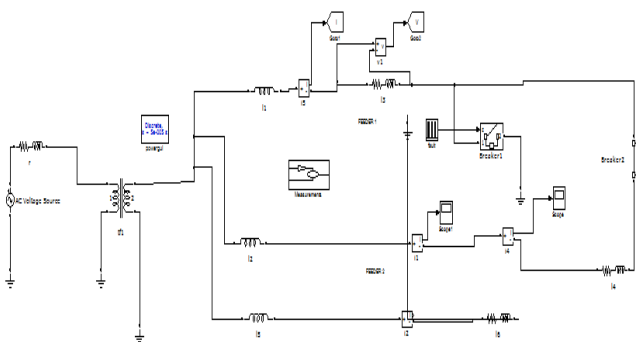

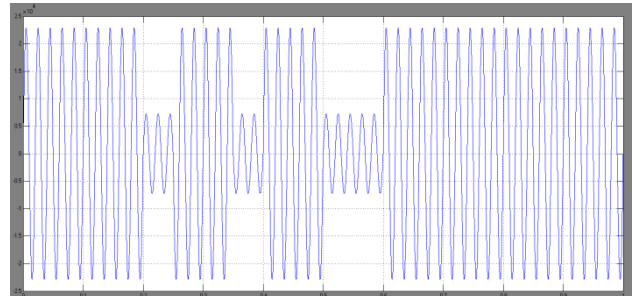Fig.8 Matlab/simulink model of loop distribution system Fault location without SFCL

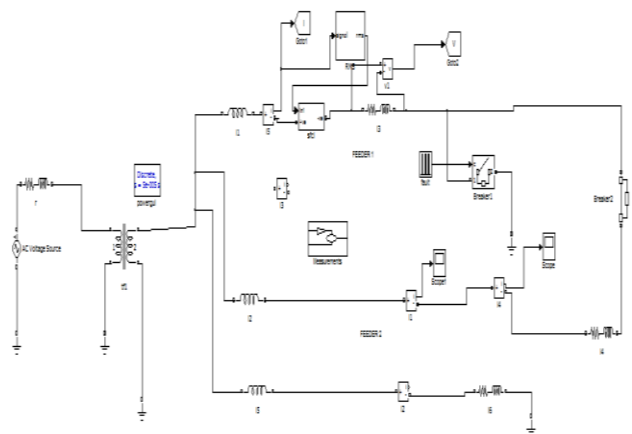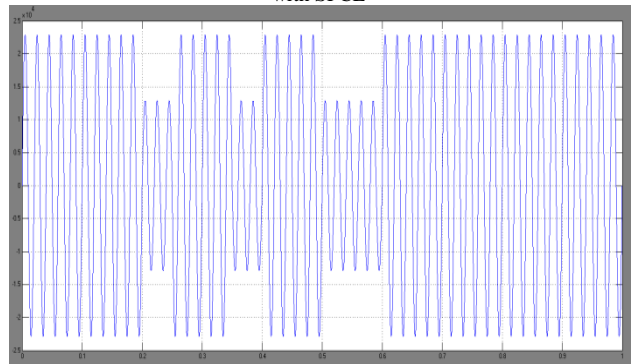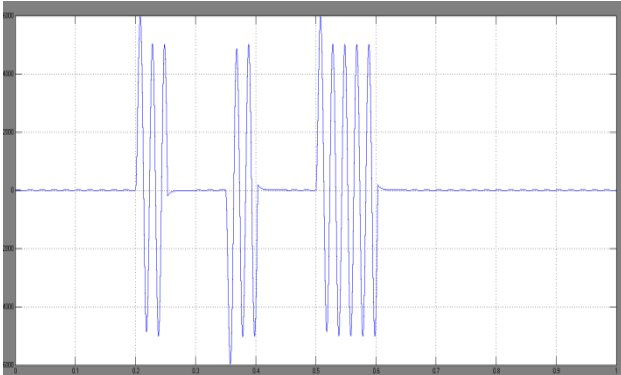Fig.9 Voltage and current wave in loop distribution system Fault at 3 km location without SFCL

Fig.10 Matlab/simulink model of loop distribution system Fault location with SFCL

Fig. 11 Voltage and current wave in loop distribution system fault at 3 km location with SFCL

Case-3 Radial Distribution System Fault Location Without and With SFCL of R Load
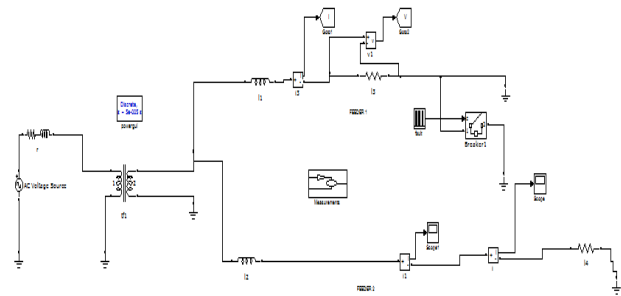

Fig.12 Matlab/simulink model of radial distribution system fault location without SFCL of R load
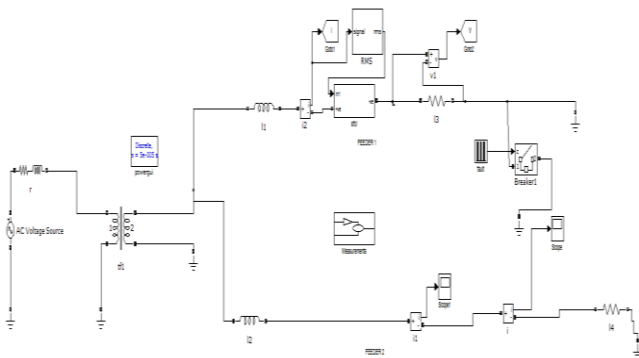

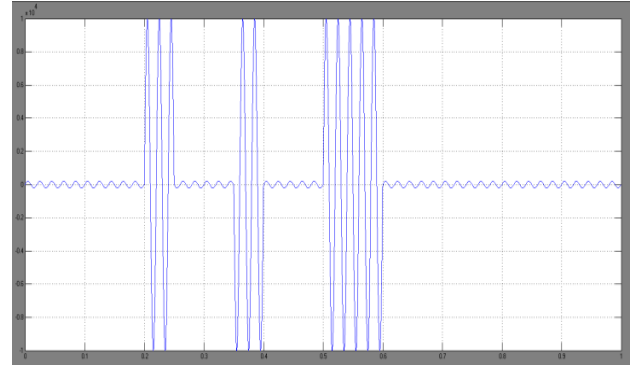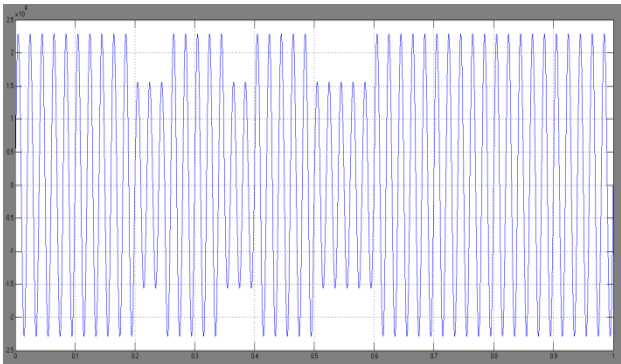Fig.13 Matlab/simulink model of radial distribution system fault location with SFCL of R load

Fig. 14 Voltage and current wave in radial distribution system fault at 3 km location with SFCL of R load

Case-4 Loop Distribution System Fault Location without SFCL Of R and RLC Loading Conditions
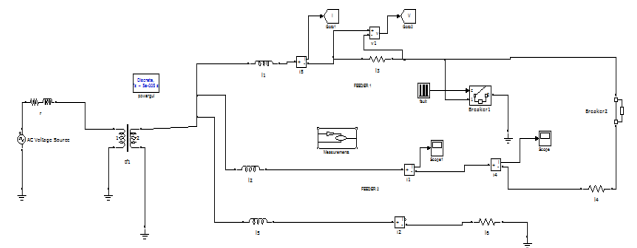

Fig.15 Matlab/simulink model of loop distribution system Fault location without SFCL of R load
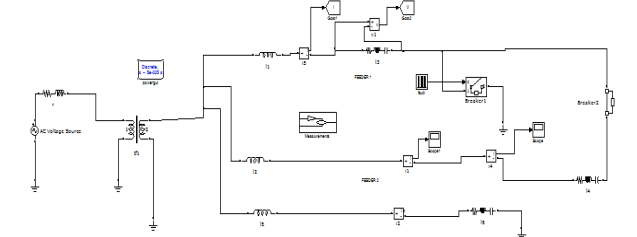

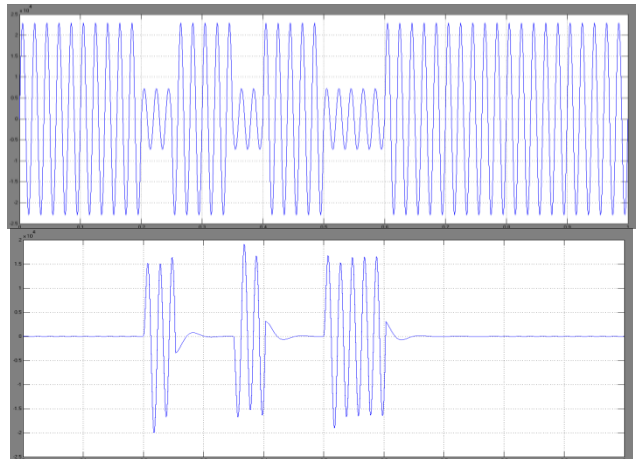Fig.16 Matlab/simulink model of loop distribution system Fault location without SFCL of RLC load

Fig.17 Voltage and current wave in loop distribution system Fault at 3 km location without SFCL of R and RLC loading conditions

Case 5: With Series Type FCL System for Minimizing the Voltage Sag
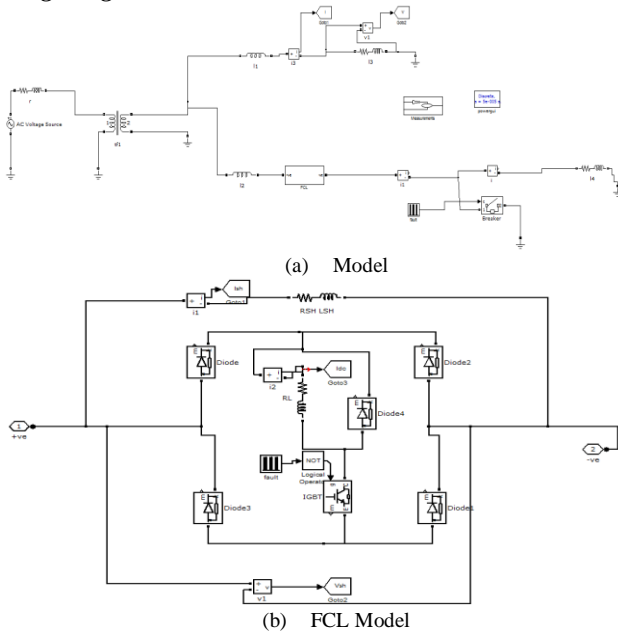

(a) Model

(b) FCL Model

Fig.18 shows the Matlab/Simulink Model of Series Type FCL System for Minimizing the Voltage Sag
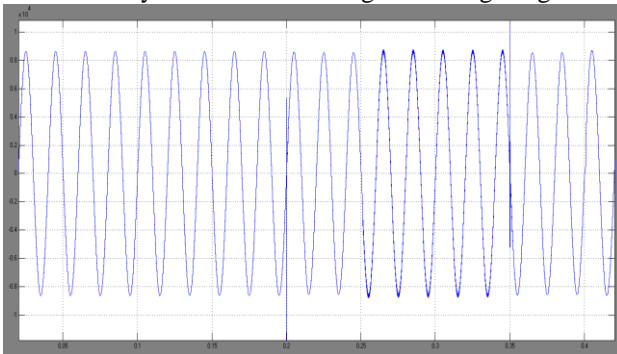

Fig.19 PCC Voltage

Fig.19 shows the PCC Voltage of Series Type FCL System for Minimizing the Voltage Sag.

VI. CONCLUSION

The simulations performed prove the method effectiveness, as well as the possibility of building the 'FCL' with commercially available components. The main concept of this proposed converter is simulated at different loading conditions like R and RLC to check the performance of with and without SFCL conditions. The effect of SFCL on voltage sag is analyzed when a SFCL is installed to a radial and loop power distribution system. Firstly, resistor-type SFCL and radial/loop power distribution system are modeled. The simulation results found that the voltage sags at loop distribution system is mores ever than radial distribution system by the increased fault current. Moreover, the results of simulation represent the SFCL with bigger resistance is needed to improve the voltage sags in loop system. These all results verified through Matlab/simulink software.

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