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# Voltage Sag Analysis in Loop Power Distribution System with SFCL

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*Abstract*— **In this paper, the effects of a superconducting fault current limiter (SFCL) installed in loop power distribution systems on voltage sags are assessed and analyzed. The power distribution system will be operated to a type of loop. In this case, voltage drops (sags) are severe because of the increased fault current when a fault occurs. If SFCL is installed in the loop power distribution system, the fault current decreases based on the location and resistance value of the SFCL, and voltage sags are improved. 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 PSCAD/EMTDC. Next, the loop power distribution system is modeled. 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.**

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

## I. Introduction

Over the past decades, superconductivity techniques have been very grown in various areas. Especially, superconducting fault current limiters (SFCLs) have been developed and are put to practical use in power distribution systems in Korea. SFCL decreases fault current and reduce an adverse effect on power systems, ultimately can make the capacity of circuit breakers small. Moreover, SFCL can provide additional advantage as the improvement of voltage sags [1]. Reference [1] presented the assessment method of voltage sag using the Information of Technology Industry Council (ITIC) curve when SFCL is applied to a radial power distribution system. Reference [2] presented the parallel connection of radial systems via the SFCL which can make voltage dips less severe, [3-4] present the improvement of voltage sags caused by fault current decreased by installing fault current limiter.

Voltage sag is evaluated by magnitude and duration. In general, the series-connected impedance such as SFCL improves 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 smartgrid. 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.

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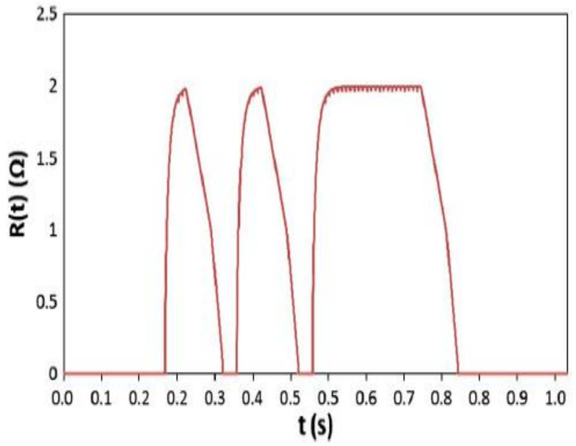


Fig.1.Quenching and recovery characteristics of SFCL.

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 evaluate the voltage sag magnitude according to the fault location and resistance of SFCL in radial and loop power distribution system

## II. Resistive-Type SFCL

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.

$$R(t)= \begin{cases} 0 & (t<t_o) \\ R_n[1-\exp(-(t-t_o)/T_F]^{1/2} & (t_o\le t<t_1) \\ a_1(t-t_1)+b_1 & (t_1<t<t_2) \\ a_2(t-t_2)+b_2 & (t\ge t_2) \end{cases}$$

TABLE-I
PARAMETER OF MODELED SFCL

| 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 | $R_n$ | $R_n/2$ |

reclosing scheme is 2 Fast 1 Delay (2F1D). When a fault is occurs in a power distribution system, the resistance of SFCL increases. 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 0.5s based on [9], because the reclosing time of power distribution system in Korea is 0.5s.

## 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.

Also, when a fault occurs, the customers at each feeder experienced the various magnitude of voltage according to many factors such as line impedance, fault location, types of fault, and so on.

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.

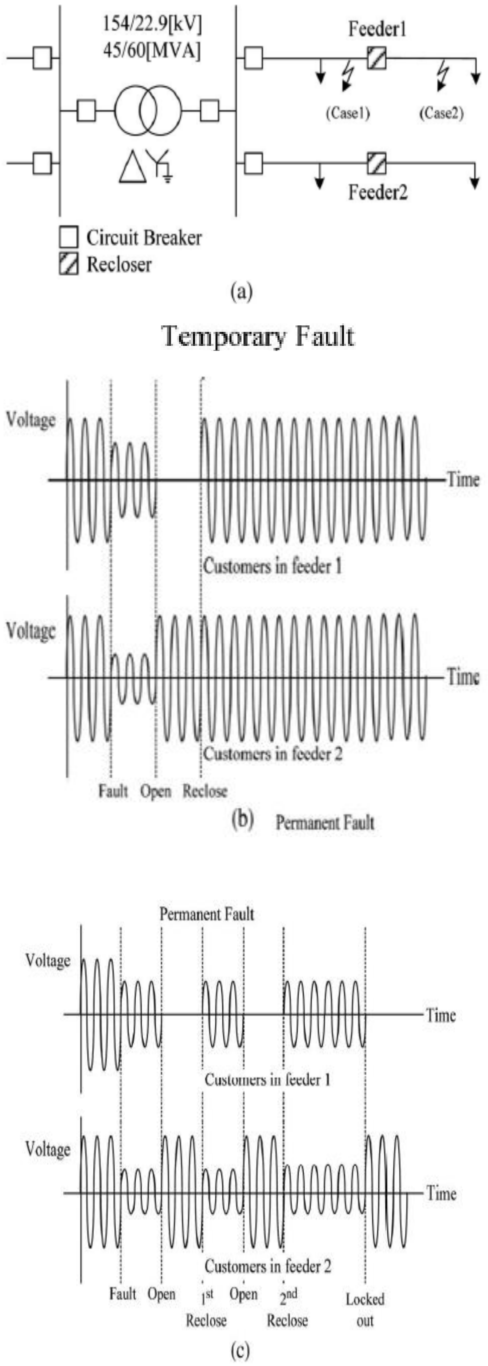


Fig. 2. Voltage sag in power distribution system d. (a) Power system configuration,

## 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.

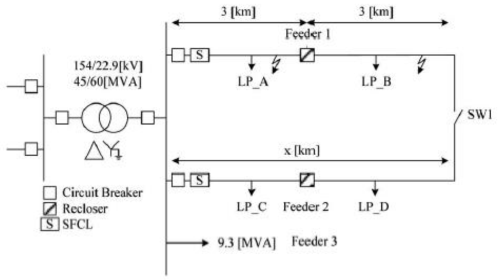


Fig. 3. Power distribution system model.

$$v_{bus} = \frac{z_{line}}{z_{source} + z_{MTr} + z_{line}} \quad (2)$$

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.

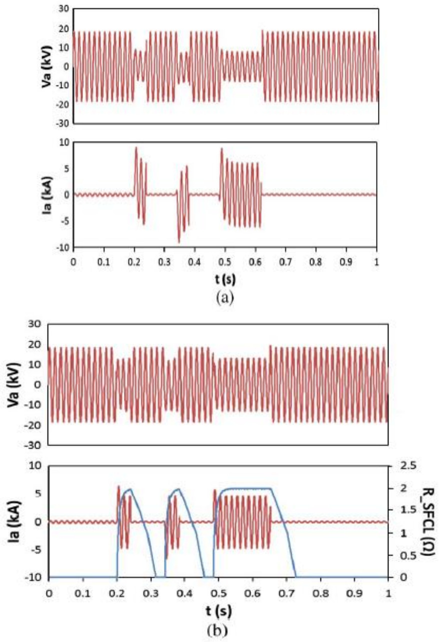


Fig. 4. Voltage and current wave in radial distribution system. (a) Fault at 3 km location without SFCL and (b) fault at 3 km location with SFCL of 2 Ω. TABLE-II
POWER DISTRIBUTION SYSTEM DATA

| | Data |
|---|---|
| Source | 154KV,100MVA,j4Ω |
| M.Tr | 154/22.9KV,45MVA,j15% |
| Line Impedance | $Z_0$=10.8+j23.6%km |
| | $Z_1$=3.48+j7.44%km |
| Line length | F1:3km,3km |
| | F2:x km(variable) |
| Load | F1:LP_A=3MVA,LP_B=4 MVA |
| | F2:LP_C=5 MVA,LP_D=5MVA |
| | F3:9.3MVA |

### *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.

TABLE-III
CASES FOR VOLTAGE SAG SIMULATION

| cases | SFCL Ω | Fault location | x Km | Fault type |
|---|---|---|---|---|
| SW1 open case 1-0 | No | 1,2,3,4,5,6 km | 6 | 3 phase fault |
| case 1-1 | 0.5 | | | |
| case 1-2 | 1 | | | |
| case 1-3 | 1.5 | | | |
| case 1-4 | 2 | | | |
| SW1 Closed case 2-0 | No | 1,3,6 km | 2,4,6 | |
| case 2-1 | 0.5 | | | |
| case 2-2 | 1 | | | |
| case 2-3 | 1.5 | | | |
| case 2-4 | 2 | | | |

### *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 2 Ω and the fault location is 1 to 6 km. Fig. 4 represents the voltage and current wave form when a fault occurs at 3 km location of feeder 1 from a bus in radial distribution system with (a) no SFCL (b) 2 Ω SFCL. The voltage magnitude is improved from 42.82% to 71.30% during fault.

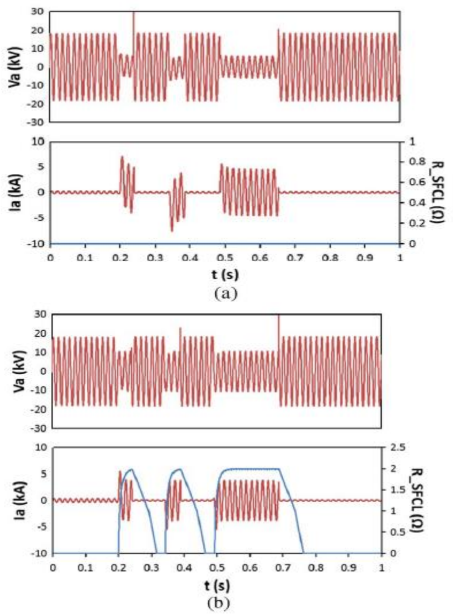


Fig. 5. Voltage and current wave in loop distribution system. (a) Fault at 3 km location without SFCL (*x* = 2 km) and (b) fault at 3 km location with SFCL of 2 Ω (*x* = 6 km).

Voltage magnitudes for all cases are represented at Tables IV and V. In radial system, Table IV, when a SFCL is not installed, the fault location has much effect on the voltage magnitude.

Table IV
Voltage Magnitude according To Fault Location and SFCL'S Resistance for Case1

| Fault Location | No SFCL | 0.5Ω | 1Ω | 1.5Ω | 2Ω |
|---|---|---|---|---|---|
| 1 km | 19.83 | 34.57 | 49.92 | 62.04 | 69.60 |
| 2 km | 33.18 | 42.92 | 53.78 | 63.19 | 70.68 |
| 3 km | 42.82 | 49.92 | 57.87 | 65.12 | 71.30 |
| 4 km | 50.08 | 55.56 | 61.57 | 67.36 | 72.45 |
| 5 km | 55.71 | 60.11 | 64.89 | 69.52 | 73.69 |
| 6 km | 60.25 | 63.81 | 67.67 | 71.45 | 75.00 |

Table V
Voltage Magnitude according To Fault Location, Length Of Feeder 2, And SFCL'S Resistance For Case 2

| Fault Location | X km | No SFCL | 0.5 Ω | 1 Ω | 1.5 Ω | 2 Ω |
|---|---|---|---|---|---|---|
| 1 km | 2 | 18.09 | 29.68 | 40.72 | 49.49 | 56.46 |
| | 4 | 18.48 | 30.70 | 42.36 | 51.29 | 58.18 |
| | 6 | 18.79 | 31.32 | 43.54 | 52.70 | 59.75 |
| 3 km | 2 | 32.26 | 37.67 | 43.70 | 49.73 | 55.36 |
| | 4 | 35.00 | 40.25 | 46.20 | 52.00 | 57.32 |
| | 6 | 36.57 | 41.97 | 48.08 | 53.80 | 58.97 |
| 6 km | 2 | 28.74 | 36.10 | 43.46 | 50.12 | 55.99 |
| | 4 | 38.76 | 43.15 | 47.92 | 52.86 | 57.56 |
| | 6 | 44.01 | 47.45 | 51.45 | 55.52 | 59.51 |

Also, the resistance of SFCL has a more effect on the voltage magnitude when a fault occurs at near location from the bus. The voltage magnitude at loop system is small compared with radial system because of the voltage drop at main transformer by sum of fault current at feeder 1 and feeder 2. In loop system, the length of feeder 2 has a effect on the voltage magnitude when a fault occurs at the location far from the bus at feeder 1.

Moreover, SFCL of 2 Ω does not improve needed to improve the voltage sag in loop system as much as radial system. The voltage sag as much as radial system.

## V. Conclusion

In this paper, 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. Next, 10 case studies are simulated using PSCAD/EMTDC. Voltage magnitudes are analyzed according to fault locations and SFCL's resistance values, and the lengths of loop system. The simulation results found that the voltage sags at loop distribution system is more severe 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.

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