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Mitigation of Distributed Generation Impact on Protective Devices in a Distribution Network by Superconducting Fault Current Limiter*

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ABSTRACT

Protection of radial distribution networks is widely based on coordinated inverse time overcurrent relays (OCRs) ensuring both effectiveness and selectivity. However, the integration of distributed generation (DG) into an existing distribution network not only inevitably increases fault current levels to levels that may exceed the OCR ratings, but it may also disturb the original overcurrent relay coordination adversely effecting protection selectivity. To analyze the potentially adverse impact of DG on distribution system protective devices with respect to circuit breaker ratings and OCR coordination fault current studies are carried out for common reference test system under the influence of additional DG. The possible advantages of Superconducting Fault Current Limiter (SFCL) as a means to limit the adverse effect of DG on distribution system protection and their effectiveness will be demonstrated. Furthermore, minimum SFCL impedances required to avoid miss-operation of the primary and back-up OCRs are determined. The theoretical analysis will be validated using the IEEE 13-bus distribution test system is used. Both theoretical and simulation results indicate that the proposed application of SFCL is a viable option to effectively mitigate the DG impact on protective devices, thus enhancing the reliability of distribution network interfaced with DG.

Keywords: Overcurrent Relay (OCR); Distribution Protection Coordination; Distributed Generation (DG); Fault Current; Superconducting Fault Current Limiter (SFCL)

1. Introduction

In recent years, mainly due to environmental concerns and in preparation for an expected shortage of traditional fossil fuel based energy, distributed generation (DG) based on renewable energy sources is attracting more and more attention. The advantages of introducing DG into a distribution system are generally called "system support benefits" such as voltage support, improved power quality, loss reduction as well as transmission and distribution capacity release [1]. However, there are several disadvantages introduced by DG. For instance, the increasing fault current levels may exceed the current ratings of circuit breakers (CBs), which lead to the need for expensive upgrading of CBs [2]. Another impact of DG is the disturbance on existing protection coordination. Since distribution systems are for the predominant part of radial structure, the inverse time Overcurrent Relays (OCRs) [3] are the most applied protection device in distribution systems. However, when DGs are installed in a distribution system, the typical one-direction nature of power flow can be lost. In such case, there is a risk of existing relay coordination to be disturbed or even becoming ineffective [4].

Several possible solutions have been proposed to overcome the above problems, such as upgrading circuit breakers, installing microprocessor based recluses [5], employing adaptive protection [6], decreasing the generation capacity of DGs or even cut off the DGs from the main grid during fault conditions [7]. These methods are complex and expensive, and in many cases put constraint in using DG capacity and limiting the benefits from DG units.

As will be shown in this paper, Superconducting Fault Current Limiter (SFCL) can be used to minimize the adverse impact of DGs on distribution system protection. SFCL represents a near-zero impedance during normal operating conditions, thus causing a negligible voltage drop and power loss. However, during fault condition, it introduces high serial impedance limiting the short- cir-

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cuit current flowing though the SFCL. Therefore SFCL in series with DG units are able to decrease the adverse impacts of DG to the distribution system protection during network faults.

This ability as well as the minimum SFCL impedance requirements during fault conditions is analyzed in this paper, which is organized as follows. Section 2 analyses the effect of DG on the protection coordination of distribution systems. In Section 3, the functioning principle of SFCL is analyzed and its mathematical model is established. In Section 4, a case study is used to investigate the impact of SFCL on protection of distribution systems with DG with respect to CB fault current levels and coordination of OCRs. Finally, the conclusions are given in Section 5.

2. Impact of DG on Overcurrent Relay (OCR) Coordination

2.1. Principle of OCR

The protective devices in a power system are used to operate CBs correctly to detect and clear faults with minimum customer interruption and as quickly as possible. Inverse time OCRs are most commonly used in a radial distribution system. The operating time of OCRs is inversely proportional to the current flow I through the relay exceeding the pick-up current threshold $I_{pick\text{-}up}$. The tripping time $t_{trip}(I)$ is given by the following equation, where *TDS* is the time-dial setting, which adjusts the time-delay curve between minimum and maximum curves for the particular relay. Here *A*, *B*, *p* and *K* are constants that represent different types of OCR:

$$\begin{cases} t_{trip}(I) = TDS \times (\dfrac{A}{M^{p} - 1} + B) + K \\ M = I / I_{pick-up} \end{cases} \quad (1)$$

Results presented in this paper were obtained using $A = 3.922$, $B = 0.0982$, $p = 2$ and $K = 0$ based on the "very inverse type OCR" defined by IEEE Std. C37. 112-1996 [8]. For this study *TDS* values are taken from an interval between 0.5 and 11s, which are used to tune response times at same current levels.

For systems with multiple installed OCRs, relays installed in series should be coordinated to ensure relay response in a specified operation sequence, that is to say, primary relay near the fault location is supposed to trip first, and the back-up relay is supposed to trip only in case of a primary relay fails. This is to ensure maximum selectivity and to limit the number of customers affected by the required de-energization of sections of the network. Therefore, the Coordinated Time Interval *CTI*, specifying the time between the primary relay's tripping time $t_{trip,primary}$ and the back-up relay's tripping time $t_{trip,back\text{-}up}$ is defined as follows:

$$CTI \le t_{trip,back} - t_{trip,primary} \quad (2)$$

Typical *CTI* values range between 0.2 s and 0.5 s. For the results presented in this paper *CTI* values are set to around 0.25 s. Value for $I_{pick\text{-}up}$ and *TDS* are chosen according to the magnitude of load and fault current flowing through each OCR and the required operating times to clear the corresponding fault. The selection of these two values should satisfy the following conditions:

- The primary relay must trip over the level of 1/3 of minimum fault current of the back-up relay;
- The *CTI* between primary and back-up relays are set around 0.25 s and must be over 0.2 s to avoid miss-tripping.

2.2. Analysis of DG Impact

When DGs are integrated into a distribution system, the Thévenin impedance seen from a possible fault location will decrease and thus the corresponding fault current level will increase, which may exceed the interrupting capacity of the installed CBs. For example, when a fault F_1 occurs in **Figure 1**, the fault current flowing through CB_2 (I_{CB_2}) is calculated as:

$$I_{CB_2} = I_s + I_{DG} \quad (3)$$

where, I_s is the fault current flowing through CB_2 from the source feeder before the presence of DG, then the resulting I_{CB_2} will be greater than I_s with help of I_{DG} supplied by DG. Therefore, in some cases the fault current I_{CB_2} in the system with DG may exceed the rated current of the specific CB, which is selected in accordance with I_s.

Additionally, the application of DG in a distribution network may cause wrong relay coordination. For instance, the OCRs R_1, R_2 and R_3 in **Figure 1** have been coordinated properly for a fault at F_1 and F_2.The operating time of R_2 is larger than that of R_3 by a certain *CTI* value while the operating sequence for relay R_1 and R_2 is similar. However, when DG is connected, the coordination between these two pairs of relays (R_1-R_2 and R_2-R_3) is likely to be disturbed by the decreasing operation time of R_2 and R_3, which is determined by the increasing fault current flowing through them. Therefore, the *CTI* between R_2 and R_3 may decrease and *CTI* between R_1 and R_2 may increase.

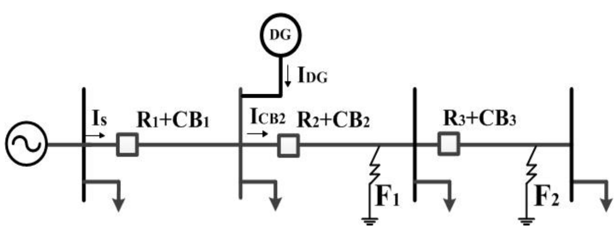

Figure 1. DG impact analysis.

3. Application of SFCL

A Fault Current Limiter (FCL) is a device for detecting, triggering and limiting fault currents in power systems. An ideal FCL works in low impedance at standby state thus causes little contribution to power loss of a healthy system. However, it rapidly converts to a high impedance when a fault occurs, decreasing the fault current. Among all types of FCL, the usefulness and usability of Superconducting Fault Current Limiters (SFCLs) are widely investigated due to the advantage of inherent self-triggering, fast response and self-recovery. The quenching and recovery characteristics of a resistive type SFCL can be described as follows:

$$R_{SFCL}(t)=\begin{cases}0 & t<t_f \\ R_n\left[1-\exp\left(1-\dfrac{t-t_f}{T_F}\right)\right]^{\frac{1}{2}} & t_f<t<t_r \\ a(t-t_r)+b & t>t_r\end{cases} \quad (4)$$

In Equation 4 R_n refers to the maximum resistance of the specific SFCL, T_F refers to the time constant of transition from the superconducting state to the non-superconducting state, while t_f and t_r are the time intervals for SFCL starting quenching and starting recovery respectively. Variables a and b are constants related to recovery characteristic.

The impact of the SFCL on a connected DG unit during fault conditions is determined by its current limiting performance on the DG current. A model of DG-SFCL unit has been developed in the environment of PSCAD/EMTDC [9], based on the mathematical model defined by Equation 4. To illustrate the SFCL performance **Figure 2** depicts the DG fault current contribution I_a resulting from a simulated fault in the network, with I_{a0} depicting the non-limited DG fault current contribution as a reference. Here, the quenched impedance of SFCL is selected equals to the line impedance of the small system.

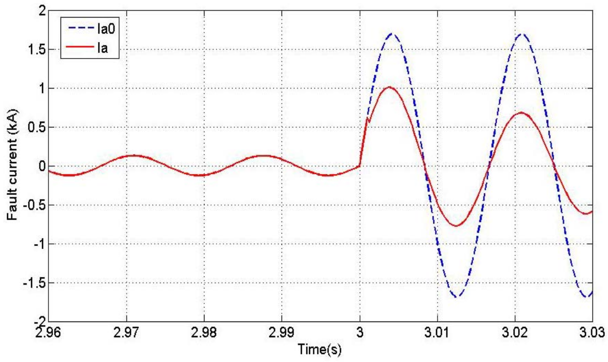

Figure 2. DG fault current limitation by a SFCL.

As can be seen in **Figure 2,** the peak value of fault current I_{a0} before the installation of a SFCL (approximately 1.8 kA) is more than 10 times of the normal operation current (the magnitude is around 150 A). By installing a SFCL in series to the DG, this fault current peak can be limited by around 50% (being reduced to about 1 kA) of its non-limited value. Note that the current limiting performance greatly depends on the non-superconducting impedance of SFCL, which will be discussed later on.

4. Case study

4.1. IEEE 13-bus Distribution Network

The test network used in this study is 4.16kV IEEE 13-bus distribution network, which is a radial unbalanced power system with three-phase, two-phase and single-phase lines as well as unbalanced wye load and delta load [10]. **Figure 3** shows the single-line diagram of 13-bus system protected by 10 protection units (OCRs and CBs).

The system configuration, line impedance and load data with no DG are given by IEEE PES Distribution Systems Analysis Subcommittee [10]. The first step of the study carried out for this paper was to calculate the load and fault currents, in purpose of determining the operating times and required *CTI* between each pair of OCRs based on the two conditions described in Section 2. The second step consisted of introducing an additional three-phase load S= (600+j30) kVA at bus 680 and an additional 660kVA wind turbine at bus 675 to supply the increasing power. This changes the power and current flows, leading to fault current increasing and disturbance of the protective coordination between some pairs of relays during fault conditions. As the final step, a model of SFCL is developed and added to the DG connection.

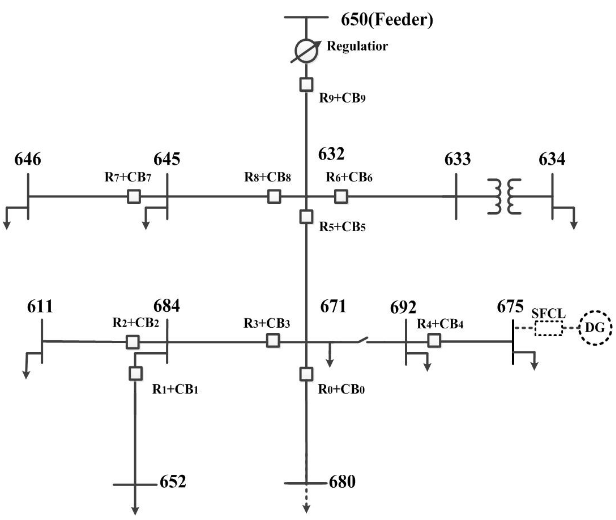

Figure 3. IEEE 13-bus distribution network [10].

The purpose is to investigate its performance during faults by minimizing the DG's adverse impact on protection coordination.

4.2. DG and SFCL Impact on CB Fault Currents

The required rated current level of CB is determined by the highest fault current that might have to be cleared by it. In this section, some simulations are carried out to analyze the impact of DG and SFCL to the fault current, when faults occur at the terminal of each CB. **Table 1** shows the highest RMS value of the fault currents flowing through CB1, CB2, CB3, CB7 and CB8, for the proposed distribution network without DG, with DG and with DG-SFCL unit.

As shown in **Table 1**, SFCL can decrease the fault current effectively for all CBs while comparing without a use of SFCL. As the SFCL is installed in series with DG unit, it is used to limit the DG current contribution to the main grid during a fault. Its current limiting performance turns out to be better for those CBs that located closer to it. This can also be observed in **Table 1** that the current limiting performance is more significant for nearby CBs (CB_1, CB_2 and CB_3). Moreover, the limiting performance is highly affected by the parameter of SFCL (R_{SFCL}). **Figure 4** shows the relationship between fault current (RMS) and SFCL resistivity (R_{SFCL}). It can be observed that the fault current limiting performance becomes better with increasing resistivity of the SFCL.

4.3. DG and SFCL Impact on OCR Coordination

As the load and the fault current of this 13-bus network can be calculated, the OCRs are modified in accordance with the pre-defined $I_{pick\text{-}up}$ and *TDS*, aiming at setting *CTIs* of each pair of OCRs around 0.25s and in the range between 0.2s and 0.5s. However, when a DG is connected into the network, the protection coordination will be disturbed. In purpose of investigating the changes, a number of simulations in PSCAD/EMTDC environment have been carried out. The results of three-phase and single line to ground faults at the terminal of different buses before and after the introduction of DG are shown in **Tables 2** and **3** respectively. For a fault occurrence at

Table 1. Fault current of each CB (kA).

CB	No DG	with DG		with DG and SFCL(R_{SFCL}=2pu)	
		Current	increase rate	Current	increase rate
CB_1	2.34	2.71	15.8%	2.48	6.0 %
CB_2	2.32	2.65	14.2%	2.48	6.9 %
CB_3	2.68	3.17	18.3%	2.90	8.2 %
CB_7	3.61	3.80	5.3%	3.71	2.8 %
CB_8	4.30	4.58	6.5%	4.44	3.2 %

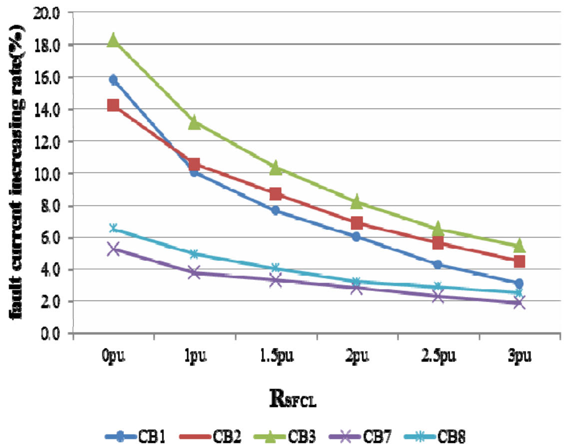

Figure 4. Fault current limiting effect of SFCL.

Table 2. Setting value of each OCR (three-phase faults).

Fault Location	Relay No.	Without DG		With DG	
		Trip time(s)	*CTI*(s)	Trip time(s)	*CTI*(s)
680	R_0	0.160		0.155	
	R_5	0.385	0.225	0.385	0.230
675	R_4	0.109		0.109	
	R_5	0.337	0.228	0.337	0.228
692	R_5	0.285		0.285	
	R_9	0.568	0.283	0.568	0.283
633	R_6	0.129		0.129	
	R_9	0.342	0.213	0.342	0.213

Table 3. Setting value of each OCR (single-phase faults).

Fault Location	Relay No.	Without DG		With DG	
		Trip time(s)	*CTI*(s)	Trip time(s)	*CTI*(s)
652 (A-G)	R_1	0.555		0.400	
	R_3	0.793	0.238	0.581	**0.181**
684 (A-G)	R_3	0.606		0.430	
	R_5	0.831	0.225	0.735	0.305
646 (B-G)	R_7	0.620		0.543	
	R_8	0.838	0.218	0.743	0.200
645 (B-G)	R_8	0.601		0.527	
	R_9	0.873	0.272	0.832	0.305
611 (C-G)	R_2	0.575		0.421	
	R_3	0.818	0.243	0.608	**0.187**
684 (C-G)	R_3	0.645		0.470	
	R_5	0.881	0.236	0.800	0.330
646 (C-G)	R_7	0.634		0.568	
	R_8	0.866	0.232	0.784	0.216
645 (C-G)	R_8	0.612		0.550	
	R_9	0.845	0.233	0.828	0.278

bus 680, R_0 works as the primary relay while R_5 is the back-up relay. The coordinated conditions of primary and back-up relays are similar for faults located at other buses in **Tables 2** and **3**.

It can be seen from **Tables 2** and **3** that most of CTIs, especially for faults close to the DG are affected by the presence of DG. The values of CTIs may increase or decrease with respects to their locations and distance to the DG unit as analyzed in Section 2. In this case, the increasing *CTIs* are still in the range and need no adjustment. However, among those decreased CTIs, the *CTI_1,3* (phase A) and *CTI_*2,3 (phase C) drop below 0.2s, which is out of the acceptable range. Therefore, the coordination of these two pairs of OCRs needs to be restored, e.g. by means of a SFCL.

Figure 5 shows the improvement of these two *CTIs* when a SFCL is installed, where $R_{SFCL} = 2\text{pu}$. Under the presence of a SFCL, both of these two *CTIs* have been improved to over 0.2s, which satisfy the range requirement mentioned in Section 2. In addition, the contribution of SFCL to the improvement of the *CTIs* is more significant when the OCR pairs are located closer to the DG-SFCL unit. For instance, compared with *CTI_*1,3 (increasing by 0.034s), *CTI_*7,8 (phase C) just increases from 0.200s to 0.209s under the same situation.

To further investigate the relationship between different values of SFCL parameter R_{SFCL} and *CTIs*, R_{SFCL} is set to 1pu, 1.5pu, 2pu, 2.5pu, and 3pu. The simulation results are shown in **Table 4**. It is found that the larger the SFCL resistivity, the closer is the *CTIs* to their previous determined setting values (see **Table 3**).

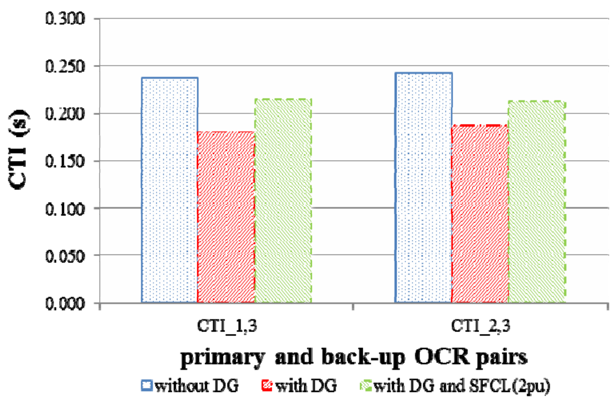

Figure 5. Comparison of CTIs.

Table 4. Comparison of CTIs with different value of RSFCL.

R_{SFCL}	0pu	1pu	1.5pu	2pu	2.5pu	3pu
CTI_1,3	0.181	0.198	0.208	0.215	0.221	0.226
CTI_2,3	0.187	0.199	0.206	0.214	0.219	0.224

With the last part of this study, the minimum value of R_{SFCL}, which improves all *CTIs* to the range between 0.2s and 0.5 s should be determined. As can be observed in **Table 4**, when R_{SFCL} set as 1pu, *CTI_*1, 3 and *CTI_*2, 3 are slightly under 0.2s, while when $R_{SFCL} = 1.5\text{pu}$, both of them are over 0.2s. Therefore, some specific tests were carried out to find the minimum value of R_{SFCL} in the range between 1pu and 1.5pu. The results turn out that when R_{SFCL} is set to 1.1pu, *CTI_1, 3* (phase A) and *CTI_2, 3* (phase C) are equal to 0.200s and 0.201s respectively, both of them are in the required range. At the same time, all of the increasing *CTIs* are under 0.5s. In other words, for this case study, a minimum value 1.1pu is needed for R_{SFCL} to avoid any alteration of the original OCR settings.

5. Conclusions

The application of DG in a distribution network increases the fault current level and disturbs the protection coordination. To overcome these problems, this paper proposed a resistive type of SFCL to mitigate the adverse impact of DG to the protective devices in a radial distribution network. Simulations on the IEEE 13-bus distribution test network are carried out by using PSCAD/ EMTDC software. For this study, the issues of CB rating current levels and OCR coordination are considered. Particularly, the fault current flows through CB at the tripping moment is used to evaluate the current limiting performance while the *CTIs* between the primary and back-up OCRs operating times are used to investigate the SFCL behavior on OCR restoration. Besides, the minimum parameter of the proposed SFCL is also determined to avoid wrong coordination of all the OCR pairs. Results show that the proposed SFCL installation in series with a DG unit is able to effectively limit the fault current and at the same time improve the *CTIs* to its required value.

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