Analysis on Protection Coordination of Protective Devices With a SFCL Due to the Application Location of a Dispersed Generation in a Power Distribution System

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***Abstract*—The increase of various dispersed generations (DGs) such as wind power and solar cell in a power distribution system has been reported to increase the short-circuit current. In addition, the introduction of the DG in a power distribution system is expected to affect the operation of the protective device as well. The superconducting fault current limiter (SFCL), which has been continuously studied for the reduction of the circuit breaker's power burden, recently starts to be noticed as effective method to solve the fault current problem due to the introduction of the DG. Since the fault current limiting operation of the SFCL and the operations of the protective devices such as the over-current relay or the recloser are affected by the application location of the DG, the study on the protection cooperation of the protective devices with the SFCL considering the application location of the DG in a power distribution system is firstly required.**

In this paper, the protection coordination of the protective devices with a SFCL due to the application location of a DG in a power distribution system was analyzed. The experimental circuit to simulate the DG and the protective devices was designed and realized by using the power electronic switches. With the power distributed system assembled with the DG, the protective devices and the SFCL, the short-circuit tests were carried out. The lower resistance generation of the SFCL due to the decrease of the feeder current in case that the DG was applied into the middle point of the fault feeder was analyzed to cause the fault current not to decrease, which the lock-out operation of the recloser was confirmed to be less delayed compared to other application locations of the DG in a power distribution system.

***Index Terms*—Dispersed generation (DG), protection coordination, short-circuit current, superconducting fault current limiter (SFCL).**

I. INTRODUCTION

WITH the increased awareness for the energy problem such as the environmental pollution and the global warming, the efforts to utilize the renewable energy such as wind power and solar cell effectively have been made. In addition, the environmental limitation of the generating plant and the efficient supply of the electric power have promoted the introduction of the dispersed generation (DG) using renewable energy into a power distribution system [1]–[4]. However, introduction of numerous DGs with larger capacity has been reported to cause the increase of the short-circuit current as well as the maloperation of the protective devices and the deterioration of the power quality [3]–[5]. As one of the countermeasures to solve the problem of the fault current due to the introduction of the DG in a power distribution system, the superconducting fault current limiter (SFCL) has recently been taken into consideration [5]–[9]. Nevertheless, the studies for the effective SFCL's application for the protection coordination of the protective devices considering the application location of the DG in a power distribution system have been rarely progressed.

In this paper, the protection coordination of the protective devices with a SFCL due to the DG's application location such as the primary bus line, the middle point of the fault feeder and the middle point of the sound feeder of the power distribution system was analyzed through the short-circuit tests for the simulated power distribution system, which was comprised of the protective devices, the SFCL and the DG. In addition, the effect of the application location of the DG on the resistance generation of SFCL during the fault period was described through the analysis on the experimental results. The operation time of the recloser (R/C), in case of the DG applied into the middle point of the fault feeder, was confirmed to be less affected by the SFCL compared to other application locations of the DG in a power distribution system.

II. CONFIGURATION OF POWER DISTRIBUTION SYSTEM LINKED BY DG

Fig. 1 shows the configuration of the power distribution system with a SFCL, which is installed in the entrance of each feeder, and a DG linked to the bus line (DG_1), the middle point of fault feeder (DG_2) and the middle point of the sound feeder (DG_3), respectively. Instead of the several feeders, two feeders are represented for the simplicity, which are protected by the circuit breakers (CBs) through the operation of the over current relays (OCRs). The branch lines from each feeder are protected by the R/Cs as indicated in Fig. 1.

To investigate the effect of the SFCL application on the operation of the protective devices and the protection coordination between the protective devices due to the application location

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Manuscript received September 11, 2011; accepted December 06, 2011. Date of publication December 12, 2011; date of current version May 24, 2012. This work was supported in part by the National Research Foundation of Korea (NRF) Grant funded by the Korea government (MEST) (2011-0000891).

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Digital Object Identifier 10.1109/TASC.2011.2179509

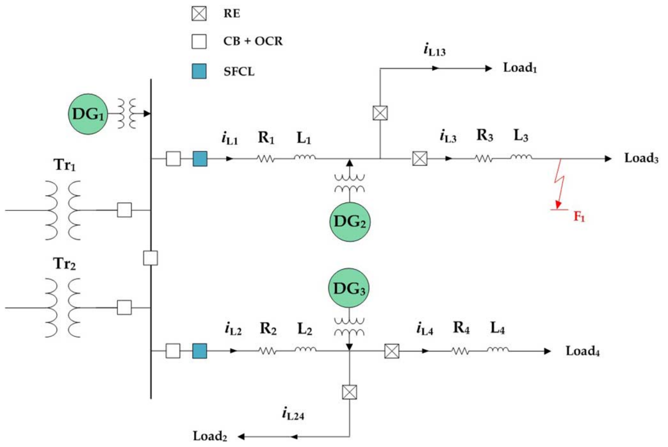

Fig. 1. Schematic configuration of experimental circuit for the protective coordination analysis in a power distribution system with a SFCL, which is applied into the entrance of each feeder, and a dispersed generation linked to the bus line (DG_1), the middle point of the fault feeder (DG_2) and the middle point of the sound feeder (DG_3), respectively.

TABLE I
SPECIFICATIONS OF COMPONENTS COMPRISING POWER DISTRIBUTION SYSTEM

Transformer 1, 2 (Tr_1, Tr_2)	**Value**	**Unit**
Capacity	5	kVA
Voltage of primary side	200	V
Voltage of secondary side	60	V
Distribution line	**Value**	**Unit**
$R_1 + X_1$, $R_2 + X_2$	0.097 + j0.686	Ω
$R_3 + X_3$, $R_4 + X_4$	0.140 + j1.033	Ω
Load	**Value**	**Unit**
Load_1	8 + j1.885	Ω
Load_2	10 + j1.885	Ω
Load_3	40 + j1.885	Ω
Load_4	5 + j1.885	Ω

TABLE II
SETTING PARAMETERS OF PROTECTIVE DEVICES AND SFCL

OCR	**Value**	**Unit**
Pickup current for instantaneous operation	25	$\mathrm{A_{rms}}$
Pickup current for a definite time delay operation	10	$\mathrm{A_{rms}}$
Lever	0.4	
R/C (Recloser)	**Value**	**Unit**
Number of reclosing events	1	
Reclosing interval times	0.2	s
Pickup current	10	$\mathrm{A_{rms}}$
Lever for fast curve	0.5	
Lever for slow curve	0.5	
SFCL	**Value**	**Unit**
Material	YBCO	
Manufactured form	Thin film	
Critical current	19	A
Critical temperature	87	K
Shunt resistance	1.15	Ω

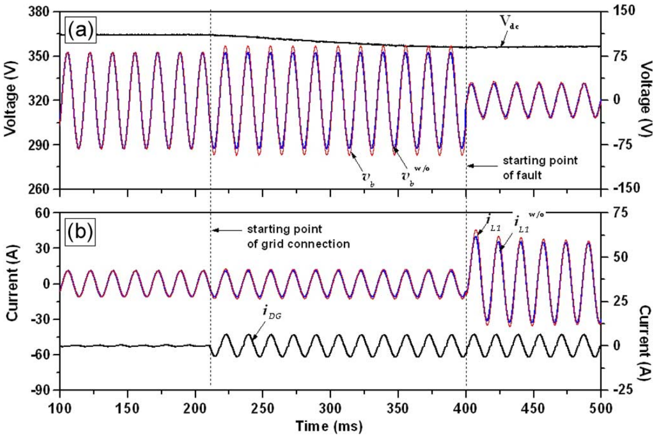

Fig. 2. Voltage and current waveforms before and after the fault occurs in a power distribution system either linked by the dispersed generation or not. (a) Input voltage of dispersed generation (v_{DC}) and bus voltage $(v_{\mathrm{b}}, v_{\mathrm{b}}^{\mathrm{w/o}})$. (b) Feeder currents $(i_{\mathrm{L1}}, i_{\mathrm{L1}}^{\mathrm{w/o}})$ and output current of a dispersed generation (i_{DG}).

of a DG in a power distribution system, the short-circuit test at load side location of the feeder 1, which is designated with F_1 in Fig. 1, was performed. In the short-circuit tests, for the easy adjustment of the resistance generation of the thin film type SFCL after the fault occurrence, the connection of the shunt resistance was considered and the shunt resistance of 1.15 Ω was connected in parallel to the SFCL.

The detailed specifications of the components comprising the tested power distribution system where the DG was applied into the bus line (DG_1), the middle point of the fault feeder (DG_2) and the middle point of the sound feeder (DG_3) as indicated in Fig. 1 are shown in Table I. The reclosing event of the R/C was set to occur one time for scale-down of its operation time and other setting parameters of the protective devices including the SFCL are listed in Table II.

Fig. 2 shows the bus voltages and the feeder currents before and after the fault occurs for two cases. One is the power distribution system linked by the DG in its bus line, one of the DS's application locations, and the other is not linked by the DG. In Fig. 2, the superscript "w/o" within the voltage and the current variable names $(v_{\mathrm{b}}^{\mathrm{w/o}}, i_{\mathrm{L1}}^{\mathrm{w/o}})$ represents the variable ones in the system without the DG. As seen in Fig. 2, the rise of both the bus voltage (v_{b}) and the feeder current (i_{L1}) after the DG is linked to the system can be observed. The feeder current (i_{L1}) in case that the fault happens in the power distribution system linked by the DG is confirmed to be eventually more increased than the current $(i_{\mathrm{L1}}^{\mathrm{w/o}})$ in the system unlinked by the DG.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Through the short-circuit tests in the load side point of the feeder 1, which was displayed with F_1 in Fig. 1, the dependence of the protective devices on the SFCL's application in a power distribution system where the DG was introduced in its different locations was investigated.

Fig. 3 shows the current waveforms flowing into the CB and the R/C in the fault feeder and their integral values considering the SFCL's application in case that a short-circuit occurs in the power distribution system where the DG is linked to its bus line. In case that the SFCL was not applied, after its fast and slow operations, the lock-out operation of the R/C, which means the permanent separation of the fault section, was observed to occur at 829 milliseconds. In case that the SFCL was applied, on the other hand, the lock-out operation of the R/C was seen to be completed at 904 milliseconds, which took more time than the

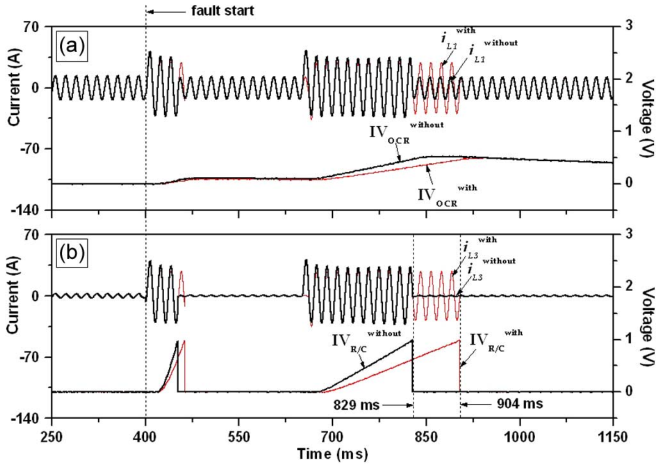

Fig. 3. Current waveforms and integral values of protective devices considering the application of the SFCL in case of the occurrence of the short-circuit in a power distribution system with a dispersed generation (DG_1) linked to a bus line. (a) Current waveform $(i_{\mathrm{L1}}^{\mathrm{with}}, i_{\mathrm{L1}}^{\mathrm{without}})$ and integral value $(\mathrm{IV}_{\mathrm{OCR}}^{\mathrm{with}}, \mathrm{IV}_{\mathrm{OCR}}^{\mathrm{without}})$ of OCR. (b) Current waveform $(i_{\mathrm{L3}}^{\mathrm{with}}, i_{\mathrm{L3}}^{\mathrm{without}})$ and integral value $(\mathrm{IV}_{\mathrm{R/C}}^{\mathrm{with}}, \mathrm{IV}_{\mathrm{R/C}}^{\mathrm{without}})$ of recloser.

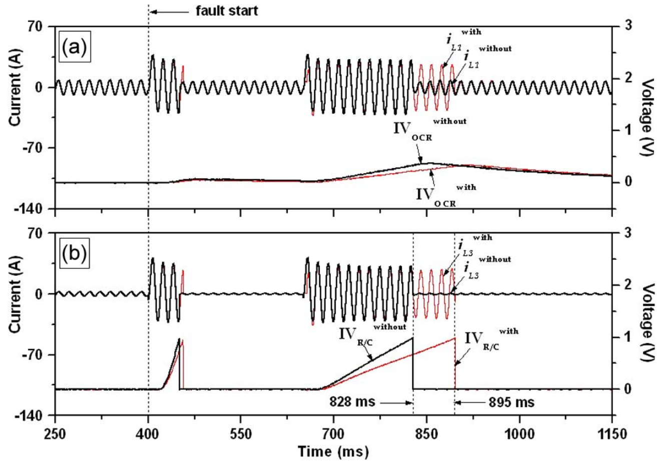

Fig. 4. Current waveforms and integral values of protective devices considering the application of the SFCL in case of the occurrence of the short-circuit in a power distribution system with a dispersed generation (DG_2) linked to a middle point of the fault feeder. (a) Current waveform $(i_{\mathrm{L1}}^{\mathrm{with}}, i_{\mathrm{L1}}^{\mathrm{without}})$ and integral value $(\mathrm{IV}_{\mathrm{OCR}}^{\mathrm{with}}, \mathrm{IV}_{\mathrm{OCR}}^{\mathrm{without}})$ of OCR. (b) Current waveform $(i_{\mathrm{L3}}^{\mathrm{with}}, i_{\mathrm{L3}}^{\mathrm{without}})$ and integral value $(\mathrm{IV}_{\mathrm{R/C}}^{\mathrm{with}}, \mathrm{IV}_{\mathrm{R/C}}^{\mathrm{without}})$ of recloser.

case without the SFCL and resulted from the fault current limiting operation by the SFCL's application. As the second application location, in case that the DG was linked to the middle point of the fault feeder, which was designated with DG_2 in Fig. 1, the current waveforms of the CB and the R/C in the fault feeder and their integral values were displayed in Fig. 4. Compared with the DG linked to the bus line, the lock-out time of the R/C in case that the DG was linked to the middle point of the fault feeder in the power distribution system with the SFCL was shortened as 895 milliseconds, which was confirmed to be resulted from the reduction of the fault current limiting effect by the SFCL. In other words, the application of the DG into the middle point of the fault feeder was thought to cause the current flowing into the drawing point of the fault feeder to decrease, which lead to lower resistance generation of the SFCL and thus, the lock-out time of the R/C in the system with the DG applied into the middle point of the fault feeder was not much delayed.

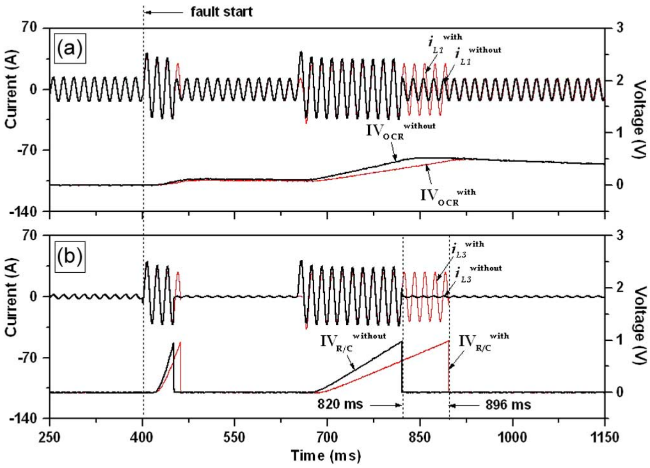

Fig. 5. Current waveforms and integral values of protective devices considering the application of the SFCL in case of the occurrence of the short-circuit in a power distribution system with a dispersed generation (DG_3) linked to a middle point of the sound feeder. (a) Current waveform $(i_{\mathrm{L1}}^{\mathrm{with}}, i_{\mathrm{L1}}^{\mathrm{without}})$ and integral value $(\mathrm{IV}_{\mathrm{OCR}}^{\mathrm{with}}, \mathrm{IV}_{\mathrm{OCR}}^{\mathrm{without}})$ of OCR. (b) Current waveform $(i_{\mathrm{L3}}^{\mathrm{with}}, i_{\mathrm{L3}}^{\mathrm{without}})$ and integral value $(\mathrm{IV}_{\mathrm{R/C}}^{\mathrm{with}}, \mathrm{IV}_{\mathrm{R/C}}^{\mathrm{without}})$ of recloser.

In case that the DG is linked to a middle point of the sound feeder, as the DG's another application location, the current waveforms and the integral values of the protective devices due to the SFCL's application were shown in Fig. 5. The lock-out time of the R/C in case of the SFCL's application was seen to be similar to the case that the DG was linked to the middle point of the fault feeder, which was also thought to cause the current in the drawing point of the fault feeder to increase more compared to previous two application locations of the DG $(\mathrm{DG}_1, \mathrm{DG}_2)$. Therefore, the operation of the R/C's lock-out was analyzed to be relatively quickly completed although the resistance generation of the SFCL was expected to be larger.

To analyze the operation of the R/C resulted from the resistance generation of the SFCL due to the application location of the DG in the power distribution system, the voltage and the current of the SFCL were measured and the resistance generation curves of the SFCL including the operation signals of the R/C were compared.

Fig. 6 shows the current waveforms and the operation signals of the R/C including the resistance curves of SFCL due to the application location of the DG in a power distribution system immediately after the short-circuit happens. The upper number "1", "2" and "3" included in each variable name in Fig. 6 represent the application location of the DG, which corresponds to the bus line, the middle point of the fault feeder and the middle point of the sound feeder, in sequence.

The amplitude of the resistance curve of the SFCL in case that the DG was applied into the middle point of the fault feeder could be seen to be lower compared to other application locations of the DG, which was resulted from the reduction of the current flowing into the drawing point of the fault feeder as expected from the previous analysis in Fig. 4.

Fig. 7 show the variation of current waveforms and integral values of protective devices including the resistance curves of

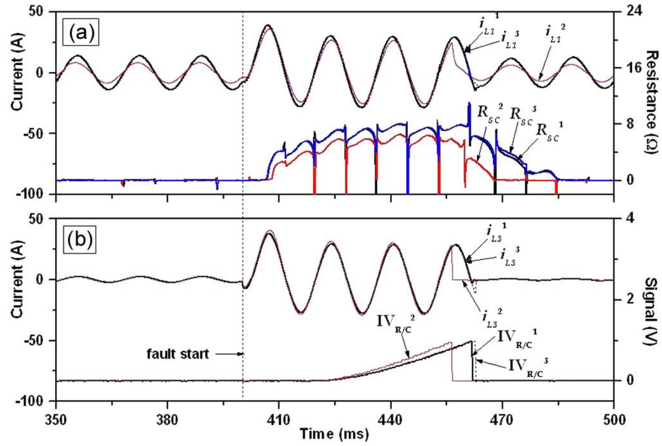

Fig. 6. Variation of current waveforms and integral values of protective devices including the resistance of SFCL due to the application location of the dispersed generation in a power distribution system immediately after the short-circuit happens. (a) Current waveforms of OCR $(i^1_{\rm L1}, i^2_{\rm L1}, i^3_{\rm L1})$ and resistance curves of SFCL $(R^1_{\rm SC}, R^2_{\rm SC}, R^3_{\rm SC})$. (b) Current waveforms $(i^1_{\rm L3}, i^2_{\rm L3}, i^3_{\rm L3})$ and integral values $({\rm IV}^1_{\rm R/C}, {\rm IV}^2_{\rm R/C}, {\rm IV}^3_{\rm R/C})$ of recloser.

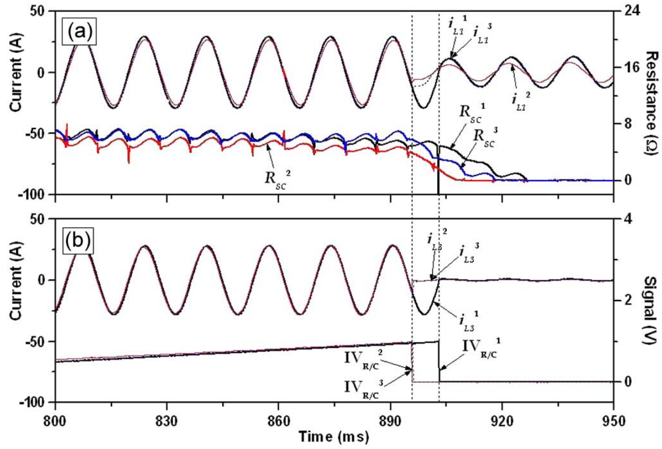

Fig. 7. Variation of current waveforms and integral values of protective devices including the resistance curves of SFCL due to the application location of the dispersed generation in a power distribution system before and after the recloser locks out after the short-circuit happens. (a) Current waveforms of OCR $(i^1_{\rm L1}, i^2_{\rm L1}, i^3_{\rm L1})$ and resistance curves of $(R^1_{\rm SC}, R^2_{\rm SC}, R^3_{\rm SC})$. (b) Current waveforms $(i^1_{\rm L3}, i^2_{\rm L3}, i^3_{\rm L3})$ and integral values $({\rm IV}^1_{\rm R/C}, {\rm IV}^2_{\rm R/C}, {\rm IV}^3_{\rm R/C})$ of recloser.

SFCL dependent on the application location of the DG in a power distribution system before and after the R/C locks out after the short-circuit happens. As expected in Fig. 5, the amplitude of the resistance curve of the SFCL in case that the DG was applied into the middle point of the sound feeder could be confirmed to be similar to the case that the DG was applied into the bus line. Especially, the larger current flowing into drawing point of the fault feeder in case that the DG was applied into the middle point of the sound feeder could be confirmed to contribute to the fast lock-out operation of the R/C, which can be observed to be almost the same as the case of the DG's application into the bus line.

From the above analysis, the operation of the protective devices was analyzed to be affected by the application location of the DG in the power distribution system due to the different fault current limiting effects of the SFCL and thus, the study for the effective protection coordination of the protective device with the SFCL considering the DG's application location in the power distribution system is expected to be progressed in the future.

IV. CONCLUSION

In this paper, the protection coordination of the protective devices with a SFCL due to the DG's application location in a power distribution system was analyzed. As the typical application location of the DG in a power distribution system, the bus line, the middle point of the fault feeder and the middle point of the sound feeder were considered. In case that the DG was applied into the middle point of the fault feeder, the current flowing into the drawing point of the fault feeder during the fault period was seen to be decreased, which caused the lower resistance generation of the SFCL and thus, prevented the lock-out operation of the R/C from being delayed. On the other hand, the lock-out operation of the R/C in case that the DG was applied into the middle point of the sound feeder could be analyzed to be relatively quickly completed due to the larger feeder current in spite of the larger resistance generation of the SFCL.

In the future, the analysis results for the effective protection coordination of the protective device with the SFCL considering the DG's application location in the power distribution system will be shown.

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