Journal of Electrical Engineering & Technology (2024) 19:4607–4614
https://doi.org/10.1007/s42835-023-01642-5

ORIGINAL ARTICLE

Fault Analysis of the Mid-point Grounding with Capacitors in Unipolar LVDC System

Seung-Taek Lim[1] · Ki-Yeon Lee[1] · Dong-Ju Chae[1] · Chan-Hyeok Oh[1] · Sung-Hun Lim[2]

Received: 29 September 2022 / Revised: 13 August 2023 / Accepted: 25 August 2023 / Published online: 5 September 2023
© The Author(s) under exclusive licence to The Korean Institute of Electrical Engineers 2023

Abstract

Low voltage DC (LVDC) systems have been gaining increasing attention for improving energy efficiency and electrical safety. Compared to AC systems, using LVDC systems in residual households present many advantages, such as low energy conversion losses in home appliances operated with DC power. Thus, there have been many studies aimed at developing LVDC systems. Among them, the grounding system of LVDC system is a different research field because there are many differences from AC systems. In particular, the DC grounding system has different characteristics in terms of sensing, corrosion, etc. Therefore, this study presents an analysis of the fault characteristics in unipolar LVDC systems when a combination of capacitors and resistors were used as a mid-point grounding. Through fault tests according to the element configurations of mid-point grounding and the fault resistance, the change in the fault current characteristics caused by capacitor discharging could be confirmed. Through the analysis, it is considered that mid-point grounding with resistors and capacitors has many benefits, such as better human safety and system protection.

Keywords Capacitor · DC grounding · Fault test · Low voltage DC (LVDC) · Mid-point grounding · Unipolar system

1 Introduction

A low voltage DC (LVDC) system has higher energy efficiency than an AC system and can minimize power conversion loss caused by the integration of renewable energy sources [1–3]. Thus, LVDC systems have been highlighted as next generation energy systems. However, owing to a short period of research and lack of real-life utilization, the verification of LVDC systems have not been achieved. Moreover, LVDC systems are difficult to commercialize owing to the lack of standardization.

Until now, most related studies have predominantly considered energy efficiency, energy conversion, and protection relay algorithms in LVDC systems. References [4, 5] proposed protection algorithms for unground LVDC systems using discrete wavelet transform (DWT) to detect the pole to ground fault for renewable distribution power source. References [6, 7] are present power conversion systems, such as the design of a dual active bridge (DAB) converter and converter LC filter or operation strategy for efficiency. Meanwhile, there is insufficient research related to connection with ground.

Power systems have various configurations, such as TT, IT, and TN depending on the configuration of the ground system [8]. In particular, in the case of a unipolar DC power system, which has polarity, additional cases can be configured, and each system has different characteristics based on the grounding system [9, 10]. Consequently, different grounding systems require different protection algorithms and devices [5, 11].

To adapt the appropriate protection technique, various grounding configurations have been analyzed, and the mid-point grounding system is among them [12, 13]. Reference

✉ Seung-Taek Lim
jstyim@kesco.or.kr

Ki-Yeon Lee
lkycj@kesco.or.kr

Dong-Ju Chae
chaedju@kesco.or.kr

Chan-Hyeok Oh
dhcksgur@kesco.or.kr

Sung-Hun Lim
superlsh73@ssu.ac.kr

[1] Electrical Safety Research Institute, Korea Electrical Safety Corporation, Wanju, Korea

[2] Department of Electrical Engineering, Soongsil University, Seoul, Korea

[14] summarizes various grounding methods, such as direct grounding, resistive grounding, mid-point grounding, diode grounding, and thyristor grounding, and compares their characteristics. Mid-point grounding is characterized by easy fault detection and a low earth voltage.

However, the mid-point grounding system has not been sufficiently studied in terms of its fault characteristics. Hence, this paper presents an analysis of the form of LVDC grounding using capacitors for use in the consumer stage. The mid-point grounding is constructed using resistors and capacitors to prevent loss in the normal state. A hardware-based experiment was conducted to verify the fault characteristics of the capacitor-based mid-point grounding method.

2 Grounding in Unipolar DC System

2.1 Classification According to IEC Standard

In IEC 60364, a power system is classified according to earthing at source and earthing in the distribution (exposed-conductive-parts). The representative systems are TT, IT, TN-C, TN-S, and TN-C-S. An AC system, which has a neutral point, can be easily classified based on above. However, the 2-wire DC system (unipolar system), which does not have a neutral point, cannot be easily classified based on the existing standard. Therefore, in some studies, high resistances have been used to make an artificial neutral point. However, the grounding system involves current flowing through the resistances, generating a loss (heat) in the normal state. Consequently, the biggest advantage of the LVDC system, efficiency, deteriorates. To solve the problem, diodes, thyristors, etc., have been proposed in previous studies.

2.2 Mid-point Grounding Using the Capacitors and Resistors

In unipolar DC systems, IT system has been mainly studied because of the reliability of the power supply. However, the only method to detect the first fault involves using insulation monitoring via an insulation monitoring device (IMD) because the residual current is extremely low. However, the detection time of the IMD depends on the line capacitance and fault resistance. Therefore, detection time is inconsistent and takes a long time (seconds to minutes). Based on the above reasons, it is considered that the IT grounding configuration is not appropriate for an LVDC system used in residual households. To improve detection, the mid-point grounding system is analyzed in this paper. Figure 1 shows three types of mid-point grounding systems composed of resistors and capacitors.

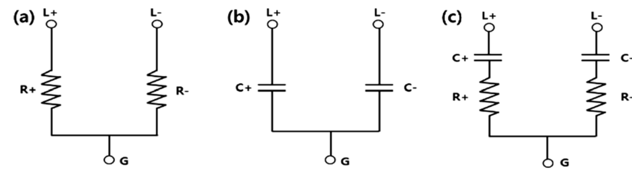

Fig. 1 Types of mid-point grounding for unipolar LVDC systems

Figure 1a shows the mid-point grounding configuration composed of two resistors. It has the advantage of easily detecting a leakage current and lowering the ground potential by half, but has the disadvantage of causing a loss due to the continuous flow of current in normal state. Figure 1b shows the configuration composed of two capacitors. It is lossless in normal state and lowers the ground potential by half, but has the disadvantage of having a high initial fault current, requiring extra protection methods for short duration of the leakage current discharge. Moreover, the configuration has a danger factor because they generate extremely large impulsive fault currents in the event of a short circuit. Figure 1c shows the configuration composed of two resistors and capacitors. In addition to being lossless in normal state and lowering the ground potential by half, it can control the initial fault current by changing the resistance and capacitance. However, depending on the configuration of the resistors and capacitors, it has the disadvantage of requiring additional protection techniques to detect and trip the limited and short fault current.

In this study, the capacitors, which is considered as OPEN state in steady DC circuit, was used to block the current and reduce the loss in normal state. The resistor and capacitor are in series and an artificial neutral point was grounded on earth, as shown in Fig. 1c. By using the resistance and capacitor in series, the capacitor discharging current can be reduced when a fault occurs.

In this case, the approximate fault current of the capacitor discharge can be obtained using Eq. (1), as specified in IEC 61660-1. The peak value is expressed using Eq. (2) [15]

$$i_C(t) = I_{pc} e^{-t/\tau} \tag{1}$$

$$I_{pc} = k_c \frac{E_c}{R_{CBr}} \tag{2}$$

Here, τ, k_c, E_c, and R_{CBr} denote the time constant, coefficient, capacitor voltage before the fault, and equivalent resistance, respectively. From Eq. (1), in a mid-point grounding system, the resistors and capacitors are related to the time constant of the capacitor discharge current as a fault current. From Eq. (2), it can be known that the capacitor discharge current is inversely proportional to the equivalent resistance because the system voltage is constant. A

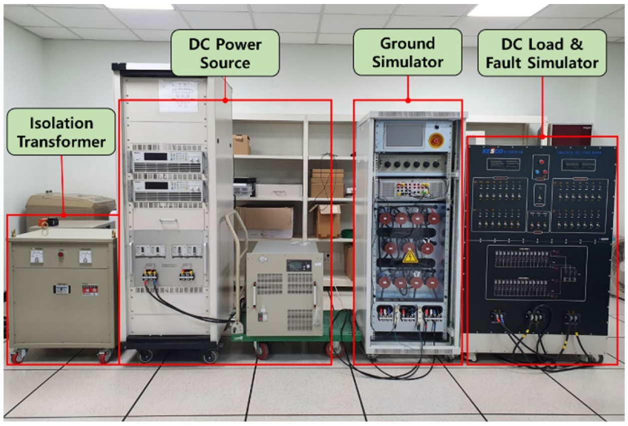

Fig. 2 Test-bed for the verification fault test

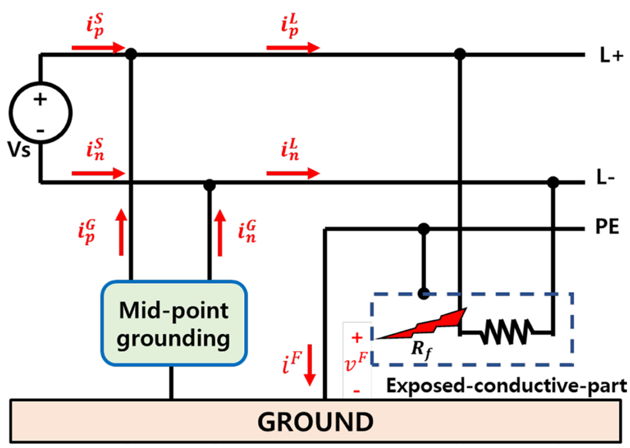

Fig. 3 Simplified configuration of the fault test

hardware test was performed to confirm the fault characteristics of the capacitor mid-point grounding system.

3 Verification Based on the Fault Test

3.1 Configuration of the Test-Bed

Figure 2 shows the experimental test-bed composed of an isolation transformer for isolating the test system from the AC system, DC power source, load, ground simulator for changing the ground type and mid-point system, and fault simulator. Here, the ground simulator can change a mid-point grounding system that can change the resistance and capacitance.

The simplified simulation circuit is illustrated in Fig. 3, and the specific parameters are listed in Table 1. The main DC power voltage was selected as 380 [V], which is mainly being studied in residual LVDC systems. To verification

Table 1 Parameters of the fault test

Component	Value	Unit
V_s	380	[V]
R_f	38, 380	[Ω]
Load	380	[Ω]
Mid-point grounding		
R	100, 1000	[Ω]
C	0 (short), 3, 30	[μF]

Table 2 Test conditions of the resistance and capacitance

Cases	Conditions	
	R [Ω]	C [μF]
1	100	30
2	100	3
3	100	–
4	1000	30
5	1000	3
6	1000	–

characteristic of the mid-point grounding system, the permanent fault between positive pole (L+) and exposed-conductive-part connected with the protective earth (PE) conductor line occurred at 0.00 [s] with fault resistance R_f.

The measuring points are marked. The lower subscripts ‘p’ and ‘n’ indicate positive line and negative line and the upper subscripts ‘S’, ‘L’, ‘G’, and ‘F’ indicate source, line, ground, and fault point, respectively.

Based on experimental safety and practicality, the six cases specified in Table 2 were conducted to analyze the characteristics of the mid-point grounding system according to conditions of the resistance (R) and capacitance (C) in the mid-point grounding. For the resistance and capacitance, 100 [Ω], 1000 [Ω], and 3[μF], 30[μF] were used, respectively. Cases 3 and 6 only used resistors for the mid-point grounding.

3.2 Result and Analysis of the Fault Test

The fault test was performed using the above conditions, and the fault current characteristics and fault current path were analyzed. In particular, the capacitor discharge current was analyzed based on the peak current and time constant. Here, according to IEC 60479-2, the time constant (T) indicates the time required for the amplitude of an exponentially decaying quantity to decrease to 0.3679(= 1/e) times the initial amplitude. The shock-duration of the capacitor discharge, which affects humans during electric shocks, is equal to the DC current with 3 T divided by root 6 of peak current value [16, 17]. Therefore, based on the time constant, the

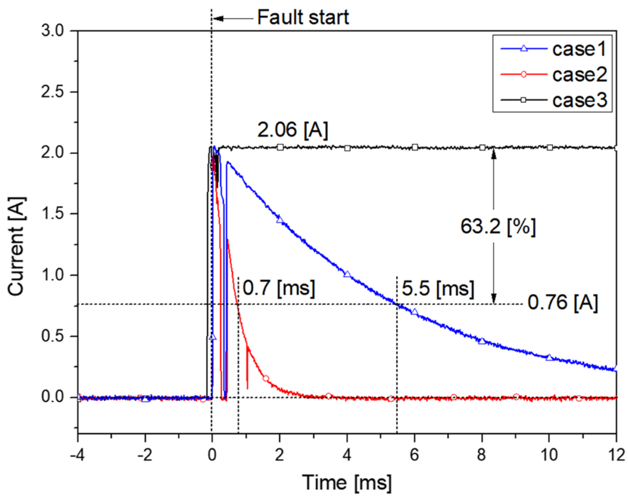

Fig. 4 Waveforms of the fault current for Case1, Case2, and Case3 with fault resistance of 38 [Ω]

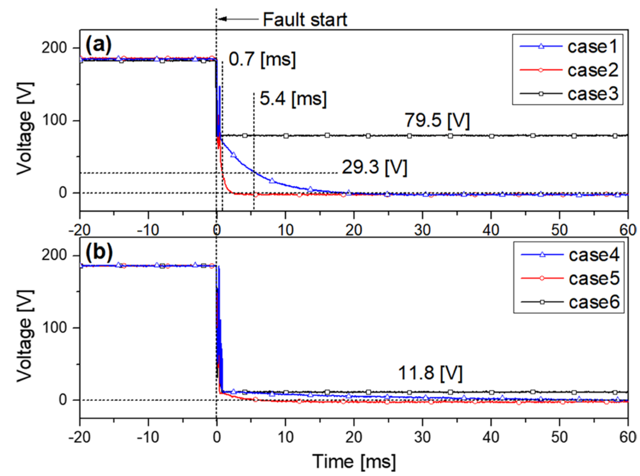

Fig. 6 Waveforms of the fault point voltage according to cases with fault resistances of 38 [Ω], **a** R = 100 [Ω], **b** R = 1000 [Ω]

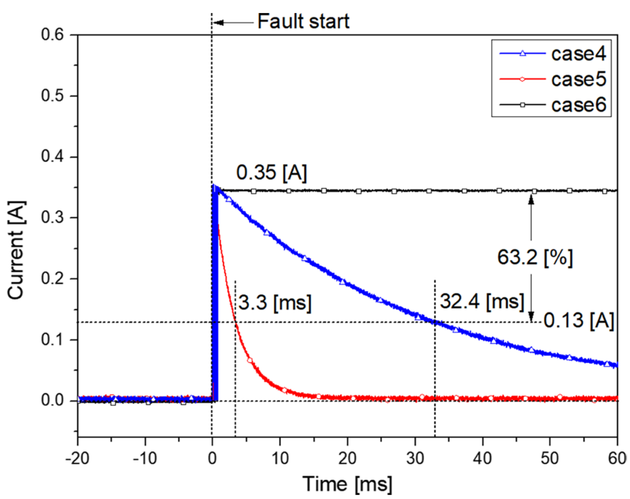

Fig. 5 Waveforms of the fault current for Case4, Case5, and Case6 with fault resistance of 38 [Ω]

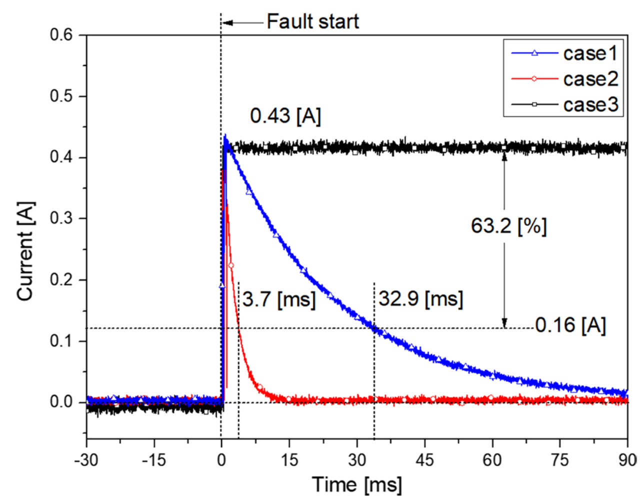

Fig. 7 Waveforms of the fault current for Case1, Case2, and Case3 with fault resistance of 380 [Ω]

minimum operating time of protective equipment, such as residual current devices, can be researched in future works.

Figure 4 illustrates the fault current through the PE line when the resistors in the mid-point grounding and fault resistance are 100 [Ω] and 38 [Ω], respectively. The peak current is approximately 2.06 [A] and it is 0.76 [A] at the time constant of the peak value in the cases that use the capacitor. In Cases 1 and 2, the time constants are 5.5 [ms] and 0.7 [ms]. In the case that only uses the resistance (Case3), there was no decaying and fixed fault current flow.

Figure 5 illustrates the fault current through the PE line when the resistor in mid-point grounding and fault resistance is 1000 [Ω] and 38 [Ω], respectively. The peak current is approximately 0.35 [A] and it is 0.13 [A] at the time constant in the cases that entail the capacitor. In Cases 4 and 5, the time constants are 32.4 [ms] and 3.3 [ms]. In the case using only the resistance, there was no decaying and there was a fixed fault current.

The voltage of the fault point is shown in Fig. 6 when the fault resistance is 38 [Ω]. As the resistance increases from 100 to 1000 [Ω] in the mid-point grounding configuration, the initial voltage of the fault point, before decaying because of the capacitors, decreases from 79.5 to 11.8 [V]. Although the resistance in mid-point grounding system is 10 times, it can be known that the fault current is not a 0.1 times difference because of the change in the initial fault point voltage according to the resistor in mid-point grounding.

Figure 7 shows the fault current through the PE line when resistors in mid-point grounding and fault resistance are 100 [Ω] and 380 [Ω], respectively. The peak current is approximately 0.43 [A] and it is 0.16 [A] at the time constant of the peak value in the cases using the capacitor. In Cases 1 and 2, the time constants are 32.9 [ms] and 3.7 [ms], respectively. In cases using only the resistance, there was no decaying and there was a fixed fault current flow.

It can be confirmed that the peak fault current decreases by approximately 0.2 times, from 2.06 to 0.43 [A], compared to Fig. 4, with a fault resistance of 38 [Ω].

Figure 8 shows the fault current through the PE line when resistors in mid-point grounding and fault resistance are 1000 [Ω] and 380 [Ω], respectively. The peak current is approximately 0.21 [A] and it is 0.08 [A] at the time constant in the cases using the capacitor. In Cases 4 and 5, the time constants are 65.1 [ms] and 6.7 [ms], respectively. In cases using the resistance only, there was no decaying and there was a fixed fault current flow.

It can be confirmed that the peak fault current decreases by approximately 0.6 times, from 0.35 to 0.21 [A], compared to Fig. 5, with a fault resistance of 38 [Ω]. It can also be confirmed that by using the higher resistance as mid-point grounding from 100 to 1000 [Ω], the variation of fault current according to the fault resistor was reduced.

The voltage of the fault point is shown in Fig. 9 when the fault resistance is 380 [Ω]. As the resistance in the mid-point ground changed from 100 to 1000 [Ω], the initial voltage of the fault point, before decaying due to the capacitors, decreased from 162.8 to 79.9 [V]. It can be known that the fault current was not a 0.1 times difference, although the resistors in the mid-point grounding system were 10 times higher because of the change of the initial fault point voltage according to the resistor in mid-point grounding.

In cases with capacitors, the decaying was like the time constant of the current discharge, but in the cases using only a resistor, there was no decaying. The voltage at the time constant in the cases using the capacitor were approximately 59.9 [V] and 29.4 [V], and they take similar time as the current discharge.

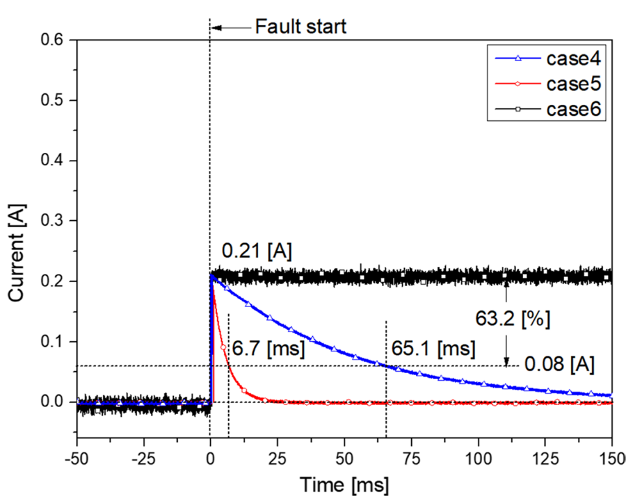

Fig. 8 Waveforms of the fault current for Case4, Case5, and Case6 with fault resistance of 380 [Ω]

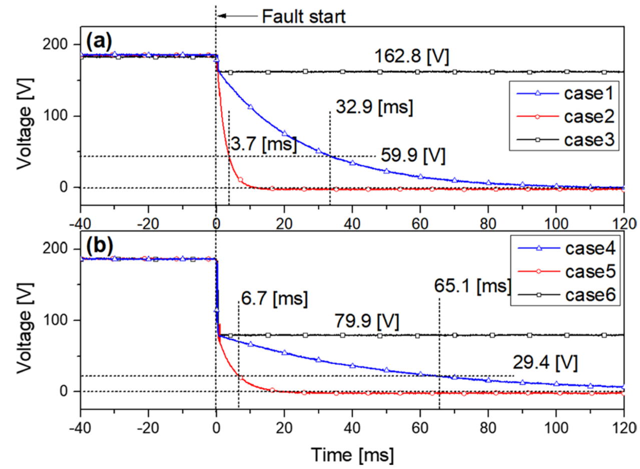

Fig. 9 Waveforms of the fault point voltage according to cases with fault resistance of 380 [Ω], **a** R = 100 [Ω], **b** R = 1000 [Ω]

Theoretically, the time constant of the discharge current in the RC circuit is expressed as a product of the resistance and capacitance. The theoretical and test time constants are summarized in Table 3. The theoretical values only consider the resistance and capacitance in the mid-point grounding system because it is difficult to know the other values.

Overall, it can be known that the time constants from the experiment are longer than those from the theoretical analysis because they were affected by other elements, such as line impedance, load, parasitic capacitance, and so on.

It was shown that, as the fault resistance increased by 10 times in the case with a low resistance (100 [Ω]) in the mid-point grounding system, the time constant was changed dramatically by six times or more. On the other hand, as the fault resistance increased by 10 times in case with large resistor (1000 [Ω]) in mid-point grounding system, the time constant changed by approximately two times. The change of the time constant caused by the fault resistance was decreased. In particular, the test with a large resistance in the mid-point grounding system and small fault resistance

Table 3 Time constant of the theoretical and fault test according to the resistance and capacitance in the mid-point ground system

R [Ω]	C [μF]	Theoretical time constant [ms]	Test time constant [ms]	
			Rf = 38 [Ω]	Rf = 380 [Ω]
100	30	3.0	5.5	32.9
100	3	0.3	0.7	3.7
1000	30	30.0	32.4	65.1
1000	3	3.0	3.3	6.7

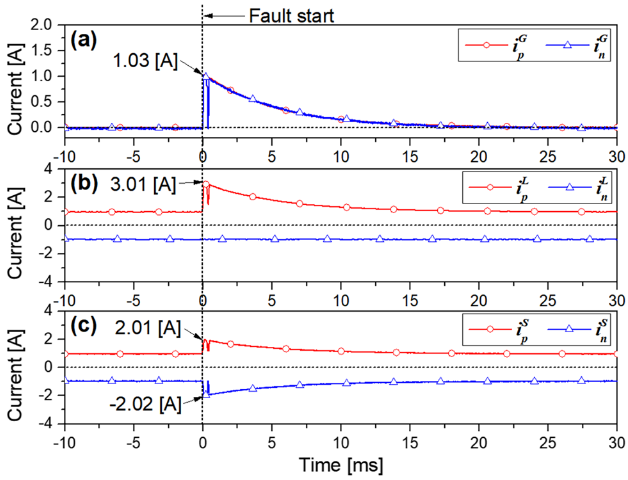

Fig. 10 Waveforms of the fault current flow in LVDC systems with mid-point grounding for Case1 **a** current flowing in the resistance in the mid-point grounding **b** current flowing in the load distribution line, **c** current flowing in the power source line

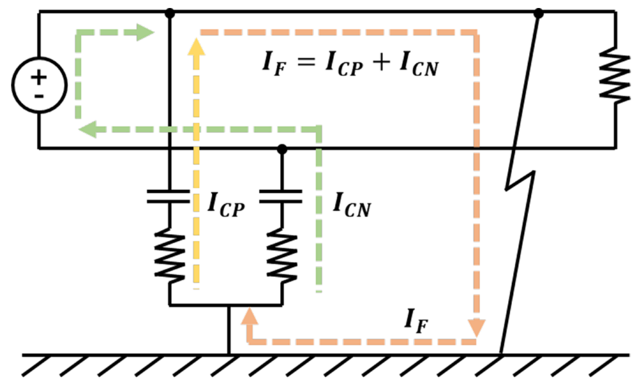

Fig. 11 Fault current path of the capacitor's discharge in mid-point grounding when the fault occurred

has a time constant similar to that of the theoretical time constant of RC discharge.

Accordingly, it is confirmed that the effect of other elements, such as fault resistance, was reduced by using a large resistance in the mid-point grounding system.

Figure 10 shows the fault current flow in an LVDC system with mid-point grounding using Case1. The fault current path is confirmed when the capacitor discharge occurred.

Figure 10a shows the positive (i_p^G) and negative (i_n^G) capacitor discharge current in the mid-point grounding system. The fault current increases from 0 to 1.03[A] at the positive and negative poles, respectively. Figure 10b shows the positive(i_p^L) and negative(i_n^L) line currents in the load distribution line. The positive line current increases from 1 to 3.01[A] at the positive pole. It increases by 2.01 [A], which is similar to the sum of discharge current from the capacitor discharge at the positive and negative sides. On the other hand, there was little change in the negative line current. Figure 10c shows the positive (i_p^S) and negative (i_n^S) line current in the source side. The current in the positive line changes from 1 to 2.01[A] and the current in negative line changes from -1 to -2.02[A] at the negative pole.

As a similar current change appeared in source side line and above fault flows, it is considered that the discharge current from the negative capacitor flows to ground through the power supply side of the positive load distribution line. Moreover, it is also considered that the discharge current from the positive capacitor flows to the ground through the negative load distribution line, as shown in Fig. 11. Here, I_{CP}, $I_{CN,}$ and I_F denote capacitor discharge current at positive line, capacitor discharge current at the negative line, and fault current, respectively.

It is confirmed that there is no fault current flowing on the negative line of the load side with respect to the mid-point grounding and that the magnitude of the leakage current is sufficient to trip the residual current device (RCD) based on the mid-point grounding parameters. Accordingly, RCD that is not available for traditional IT grounding can be used.

As confirmed by experimental results, since the magnitude and duration of the fault current change depending on the parameters of the midpoint grounding, it is necessary to select an appropriate operation value for the RCD.

4 Conclusion

This paper analyzed the fault current characteristics of using a midpoint grounding system in a unipolar IT system. Through fault experiments, it was confirmed that the safety in terms of electric shock is increased by reducing the voltage between the line and the ground when using the midpoint grounding system, and that protection against electric shocks and leakage currents can be provided using RCDs, which was not available in existing IT systems.

Moreover, it is found that the fault characteristics differ depending on the configuration of the midpoint grounding system. More specifically, if the intermediate point is configured using only a resistor, continuous losses occur at normal times, but when a fault occurs, a fault current is continuously generated, which is easy to detect, but problems such as human health hazards and electrolysis may occur.

On the other hand, if the midpoint is constructed using a resistor and a capacitor, there is no normal loss and an impulse-type fault current is generated during a fault condition. In this case, the parameter selection of the midpoint ground should be considered to use an RCD. It was found that the resistor serves to limit the peak value of the fault current, thereby protecting the safety of the equipment and protecting it from shrinkage, while the capacitor is related to the duration of the fault current, which is related to the ability to enable the operation of the RCD. Therefore, it is considered that the midpoint configuration that uses capacitors and resistors in a combination is a system that can maximize power efficiency, which is the primary advantage of LVDC systems, while reducing the risk of electric shocks.

Based on the analysis, the parameter setting method of mid-point ground system that considers the relationship between the electric shock and grounding type and a protection algorithm that considers the capacitance in an LVDC system will be researched in the future.

Acknowledgements This work was supported by the Energy Efficiency and Resources of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea Government Ministry of Trade, Industry, and Energy (No. 20193810100010).

Declarations

Conflict of interest No institutional conflicts of interest exist. Only financial support for the study was received.

References

1. Gwon GH, Kim DU, Oh YS, Han J, Kim CH (2014) Analysis of efficiency for AC and DC load in LVDC distribution system. In: 12th IET international conference on developments in power system protection (DPSP 2014), Copenhagen, Denmark
2. Alidrissi Y, Ouladsine R, Elmouatamid A, Bakhouya M (2021) An energy management strategy for dc microgrids with PV/battery systems. J Electr Eng Technol 16:1285–1296
3. Morris B, Faheem G, Enrico R, Dario Z (2020) Modeling of LVDC distribution system: an assessment of control, power quality, and DC faults. In: 2020 19th International conference on harmonics and quality of power (ICHQP). IEEE, pp 1–5
4. Lee KM, Kim JW, Park CW (2019) Detection method of pole to ground fault in ungrounded LVDC distribution grid using DWT. J Electr Eng Technol 14(4):1529–1536
5. Seo HC, Gwon GH, Park KW (2023) New protection method considering fault section in LVDC distribution system with PV system. J Electr Eng Technol 18(1):239–248
6. Zhu Z, Xiao F, Liu J, Chen P, Ren Q, Huang Z (2022) Control strategy for bidirectional DC–DC converter based on cascade connection of LC filter and DAB converter. J Electr Eng Technol 17(3):1829–1844
7. Kim SW, Lee HJ, Kim DS (2022) Power converter design based on RTDS implementation for interconnecting MVDC and LVDC. J Electr Eng Technol 17(3):1751–1760
8. IEC, IEC 60364–1 (2018) Low-voltage electrical installations—part 1: fundamental
9. Noritake M, Iino T, Fukui A, Hirose K, Yamasaki M (2009) A study of the safety of the DC 400 V distribution system. In: INTELEC 2009–31st international telecommunications energy conference. IEEE, pp 1–6
10. Joseph SC, Dhanesh PR (2016) LVDC architecture for residential application. In: 2016 IEEE international conference on power electronics, drives and energy systems (PEDES). IEEE, pp 1–4
11. Oh YS, Kim CH, Gwon GH, Noh CH, Bukhari SBA, Haider R, Gush T (2019) Fault detection scheme based on mathematical morphology in last mile radial low voltage DC distribution networks. Int J Electr Power Energy Syst 106:520–527
12. Lim S-T, Lee K-Y, Chae D-J, Oh C-H (2022) Study on the fault characteristics in LVDC system using the capacitor midpoint grounding. In: ICEF 2022 conference, Tashkent, Uzbekistan
13. International Telecommunications Union -Telecommunication Standardization Sector (2012) L. 1200. Direct current power feeding interface up to 400 V at the input to telecommunication and ICT equipment. International Telecommunication Union, Geneva
14. Mohammadi J, Ajaei FB, Stevens G (2019) Grounding the DC microgrid. IEEE Trans Ind Appl 55(5):4490–4499
15. International Electrotechnical Commission (1997) Short-circuit currents in DC auxiliary installations in power plants and substations–part 1: calculation of short-circuit currents. Standard IEC, 61660–1
16. IEC, IEC 60479–1 (2018) Effects of current on human beings and livestock-part 1: general aspects
17. IEC, IEC 60479–2 (2017) Effects of current on human beings and livestock-part 2: special aspects

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Seung-Taek Lim He received the B.S. and M.S. degrees in electrical engineering from Soongsil University, Seoul, Korea, in 2016 and 2018, respectively. He is currently a senior researcher in the Electrical Safety Research Institute of Korea Electrical Safety Corporation (KESCO) since 2018.

Ki-Yeon Lee He received the B.S. and M.S. degrees in electrical engineering from Incheon National University, Incheon, Korea, in 2002 and 2004, respectively. He received the Ph.D. degree in IT Applied System Engineering from Jeonbuk National University, Jeollabukdo, Korea, in 2020 He is currently a head researcher in the Electrical Safety Research Institute of Korea Electrical Safety Corporation (KESCO) since 2004.

Dong-Ju Chae He received the B.S. and M.S. degrees in electrical engineering from Korea University, Seoul, Korea, in 2008 and 2011, respectively. He is currently a senior researcher in the Electrical Safety Research Institute of Korea Electrical Safety Corporation (KESCO) since 2014.

Chan-Hyeok Oh He received B.S., M.S. and Ph.D. degrees in electrical engineering from Chonnam National University, Gwangju, Korea, in 2015, 2017 and 2022, respectively. He is currently a senior researcher in the Electrical Safety Research Institute of Korea Electrical Safety Corporation (KESCO) since 2022.

Sung-Hun Lim He received his B.S., M.S., and Ph.D. Degrees from Chonbuk National University, Jeollabukdo, Korea in 1996, 1998, and 2003, respectively. Currently, he is a Professor in the Department of Electrical Engineering at Soongsil University, Seoul, Korea.