A Study on Protective Coordination for Low Voltage DC Last Mile Distribution System

G. H. Gwon, C. H. Noh, J. Han, J. I. Song, Y. S. Oh, M. O. Khan, S. Zaman, M. Mehdi, C. H. Kim

***Abstract*— Since the debate between Thomas Edison and Nikola Tesla, most of the power system have operated on AC. In the past, the power conversion in AC power transmission with high voltage level using AC transformer was easier than that in DC power transmission due to the lack of power electronic device technologies. These days, however, DC power system is readily available due to development of the technology related to power converter with high performance. Especially, the rapid increase of the DC based digital load and the interconnection of distributed generation with DC output lead to an interest in Low Voltage DC (LVDC) distribution system to achieve the high efficiency. Although the LVDC distribution system has many advantages, there are still some challenges such as protection system. This paper, therefore, discusses the protection system and protective coordination among several protective schemes in LVDC distribution system.**

***Keywords*: EMTP, low-voltage DC distribution system, protective coordination, protection system.**

I. Introduction

RECENTLY the penetration levels of local Distributed Generation (DG) and digital load have grown in the distribution system. In conventional AC power system, it causes the power loss when they are connected to AC distribution system since it needs several power conversion stages. As a countermeasure, the DC distribution system is proposed in several researches [1-5]. In DC distribution system, DG such as PV based on DC output power can be interconnected to grid through reduced power conversion stages because of the absence of DC to AC inverter. For the digital load such as personal computer and monitor based on DC power, it needs an adapter composed of AC/DC rectifier and it causes the power loss. In this case, DC distribution system can provide the improved power efficiency due to the elimination of rectifier [6]. Although the DC distribution system has these advantages, there are still some challenges such as protection system [7]. To provide the protection system with high reliability for DC distribution system, it needs the use of qualified protection method such as Over-Current Relay (OCR) and Under-Voltage Relay (UVR) based on non-communication.

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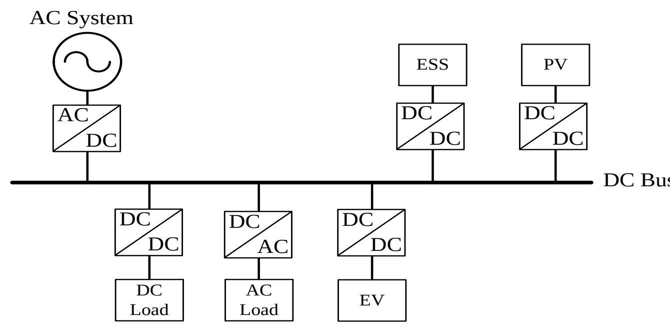


Fig. 1. The block diagram of LVDC distribution system.

This paper discusses the proper protection system and the protective coordination among several protective schemes, especially, in Low Voltage DC (LVDC) last mile distribution system. This paper shows the fault characteristics for the distribution line and the DC load. And then the possible protection schemes are discussed, and the protective coordination between both protective system are proposed. Finally, this study has conducted to verify the proposed protective coordination scheme in LVDC last mile distribution system using ElectroMagnetic Transients Program (EMTP) simulation.

II. LVDC Distribution System

In this section, we describe the elements and the layout of LVDC distribution system in which the power is supplied from AC system. Electronic power converters are main elements in LVDC distribution system, as shown in Fig. 1, to supply the voltage with proper magnitude level. In this system, the AC/DC converter provide the distribution voltage and DC/DC converter supplies the customer voltage for end-use device. According to Low Voltage Directive (LVD) 2006/95/EC, the voltage level of 1500V is allowed in LVDC distribution system [8]. This paper, therefore, assumes that the line voltage and customer voltage lever are set as $1500V_{DC}$ and $380V_{DC}$, respectively. Furthermore, several DGs and Energy Storage System (ESS) can be connected to this system through only one DC/DC converter so that this system can achieve high efficiency. In addition, we don’t need to consider

TABLE I
NOMENCLATURE OF PARAMETER

Parameter	Meaning
R and L	Equivalent resistance and inductance
I_0 and V_0	Initial capacitor current and voltage
δ	$R/2L$
ω_0	$\sqrt{\delta^2+\omega^2}$
ω	$\sqrt{(1/LC)-(R/2L)^2}$
I_0'	Initial current value of inductor
α	Phase A voltage angle
β	$\arctan(\omega/\delta)$
φ	$\tan^{-1}(\omega_s(L_g+L)/R)$
φ_0	Initial phase angle
τ	$(L_g+L)/R$ (L_g: grid inductance)
ω_s	Synchronous angular frequency
I_m and I_{m0}	Grid current magnitude and initial grid current

the synchronization of DG when it is reconnected to the LVDC distribution system because of the absence of phase angle and frequency elements in DC system.

III. FAULT CHARACTERISTICS

As mentioned above, the LVDC distribution system has many advantages. However, there are still some challenges such as protection system to implement this system. In this section, we discuss whether the conventional protection scheme is appropriate to LVDC distribution system and try to find out better solution for protection. In order to consider protection system, we should analyze the fault characteristics in LVDC distribution system. The following discussion, thus, presents the fault characteristics focused on the electronic power converter.

When a fault occurs in distribution line, the short circuit current flows into the fault location through AC/DC converter. Fig. 2 shows the circuit of the typical Voltage Source Converter (VSC)-based AC/DC converter. After a fault occurs, all switches in AC/DC converter are off by the internal protection. At this time, the output capacitor (C) discharges the current with high magnitude into distribution line rapidly as shown in Fig. 3(a). In this case, the current (i_C) and voltage (V_C) of output capacitor are calculated using (1) and (2) [9]. The nomenclature of parameter is tabulated in Table I.

$$i_C = C\frac{dV_C}{dt} = -\frac{I_0\omega_0}{\omega}e^{-\delta t}\sin(\omega t-\beta)+\frac{V_0}{\omega L}e^{-\delta t}\sin\omega t \quad (1)$$

$$V_C = \frac{V_0\omega_0}{\omega}e^{-\delta t}\sin(\omega t+\beta)-\frac{I_0}{\omega C}e^{-\delta t}\sin\omega t \quad (2)$$

After discharging of the output capacitor, the short circuit current from AC side is conducted through anti-parallel diodes as shown in Fig. 3(b). The fault current of DC feeder (i_L) and the phase current on a leg of converter (i_a) are expressed as (3) and (4), respectively [9]. In this case, if the short circuit

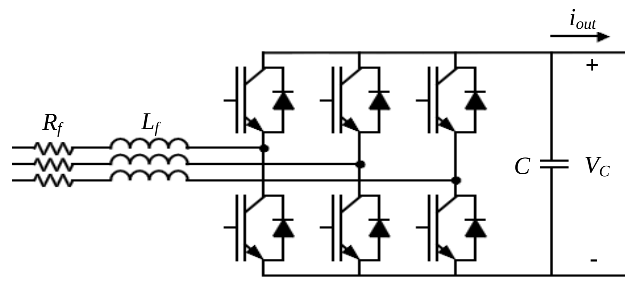
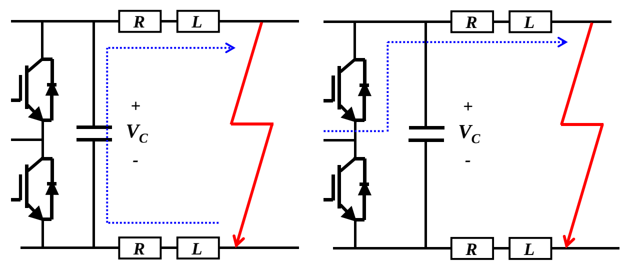


Fig. 2. The circuit of VSC-based AC/DC converter.



(a) (b)

Fig. 3. The path of short circuit current in VSC-based AC/DC converter: (a) capacitor discharging current and (b) short circuit current after capacitor discharging.

current with high magnitude flows into anti-parallel diodes for a long time, the diodes can be damaged. As a result, AC/DC converter might be broken down and it is impossible to operate normally after fault clearing.

$$i_L = I_0' e^{-(R/L)t} \quad (3)$$

$$\begin{aligned} i_a &= I_m\sin(\omega_s t+\alpha-\varphi) \\ &\quad +(I_{m0}\sin(\alpha-\varphi_0)-I_m\sin(\alpha-\varphi))e^{-t/\tau} \end{aligned} \quad (4)$$

From the above analysis for fault characteristics, we can draw the conclusion that the fault should be cleared before the fault current flows into anti-parallel diodes. In other words, the fault detection scheme has to operate for discharging of the output capacitor. It, therefore, needs very fast fault detection method and high speed circuit breaker to protect the LVDC distribution system. The suitable fault detection methods will be discussed in next section.

The DC circuit breaker requires two issues mainly. One is the fast fault clearing since the circuit breaker should operate quickly before the output capacitor discharges fully. The other is the extinction of arc. The DC circuit breaker should be able to extinguish the arc by force because of the absence of zero-crossing in DC system. Recently, to satisfy these issues, Solid State Circuit Breaker (SSCB) has been developed. It is possible to clear the fault in micro seconds. It, however, causes the conducting loss because the circuit breaker consists of semiconductors and thus the normal current flows through it. As a countermeasure, the hybrid circuit breaker has been developed to reduce the conducting loss. In conclusion, we

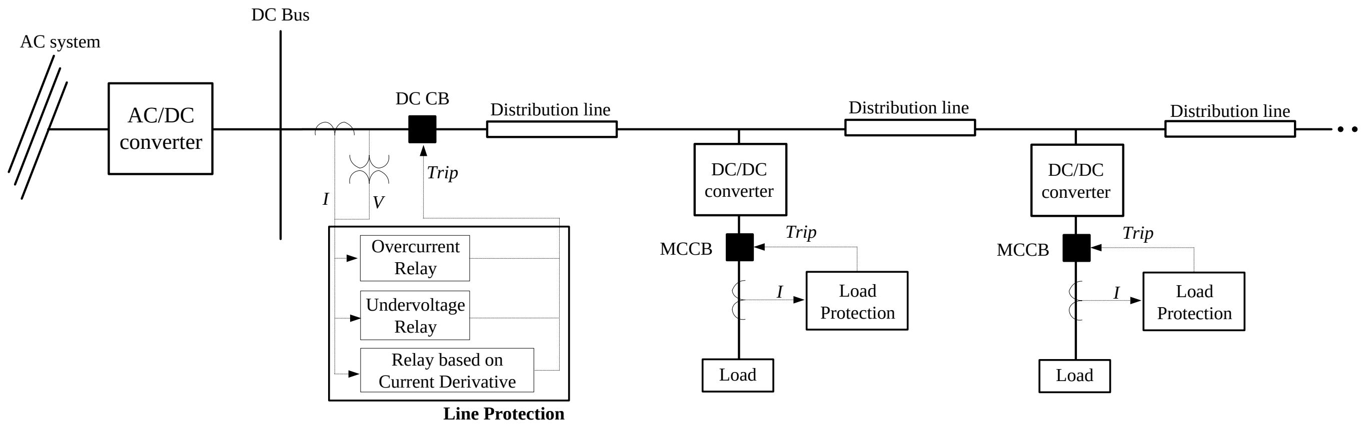


Fig. 4. The proposed protection system in LVDC last mile distribution system.

TABLE II
PARAMETER OF MODEL SYSTEM

Parameter	Value and Type
Line voltage	1500V_{DC}
Customer voltage	380V_{DC}
AC/DC converter	3-phase SPWM AC/DC converter with the output capacitor of 9000μF
DC/DC converter	Buck converter (1500V_{DC} to 380V_{DC}) With the output capacitor of 2000μF
Distribution line	PI line model (R: 0.164Ω/km, L: 0.26mH/km, C: 0.29μF/km)
Load	Total 100kW

can implement the high speed protection system by using these SSCBs.

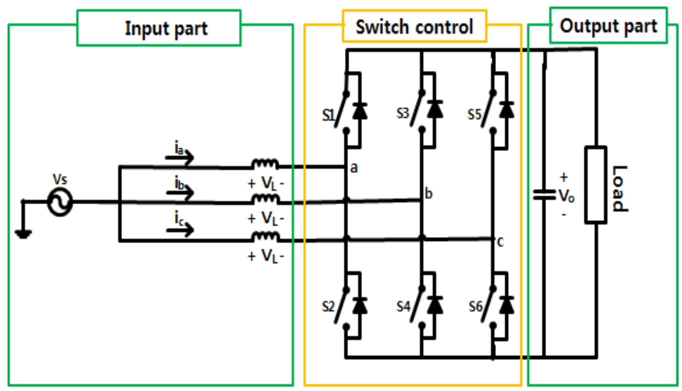
IV. PROTECTION SYSTEM IN LVDC DISTRIBUTION SYSTEM

A. Modeling of the LVDC Last Mile Distribution System

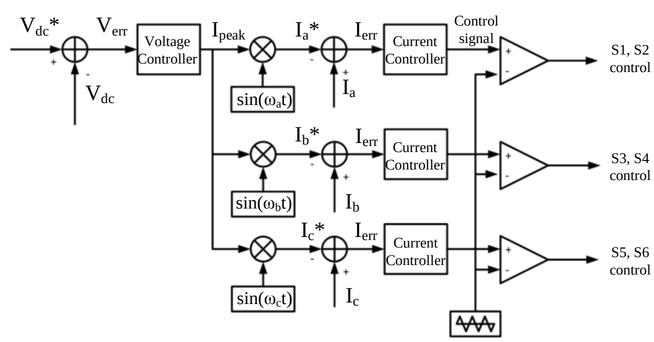
This paper has conducted to model the LVDC last mile distribution system using EMTP. This system consists of AC/DC converter, distribution line, DC/DC converter, DC load, and so on, as shown in Fig. 4. The details are tabulated in Table II. Fig. 5 shows the topology of the AC/DC converter and the control block diagram based on Sinusoidal Pulse Width Modulation (SPWM) control. In EMTP simulation, the converter is modeled using the Transient Analysis of Control System (TACS) element and MODELS function, which is the user defined model based on Fortran interface. This EMTP does not provide the model of power electronic converter and semiconductor switch. Therefore, the semiconductor switch is modeled using an antiparallel diode element and TACS-controlled TYPE 13 switch, which has on/off action according to control signal. This signal is generated through MODELS.

B. Protection Scheme in LVDC Last Mile Distribution System

This paper focuses on the protection system in last mile distribution system. We, therefore, divide it into the line protection and load protection as shown Fig. 4. For each protection system, we consider several fault detection methods,



(a) Circuit of full bridge AC/DC converter



(b) Block diagram of three-phase SPWM converter control

Fig. 5. Topology of three phase SPWM AC/DC converter

which are used in conventional AC system, to verify whether they are suitable to protect the target. To obtain the high feasibility, we discuss not an adaptive and communication-based method but the conventional fault detection methods such as over-current and under-voltage relaying schemes.

For the line protection, as above mentioned, the output capacitor discharges when a fault occurs in distribution line. The fault current with high magnitude flows through distribution line rapidly. Furthermore, the fault loop impedance varies according to the fault location and fault resistance. It means that it causes the sudden rise and different peak of fault current. The fast non-unit protection scheme, therefore, is required. The OCR and UVR of non-unit protection can be one of good solution for the line protection.

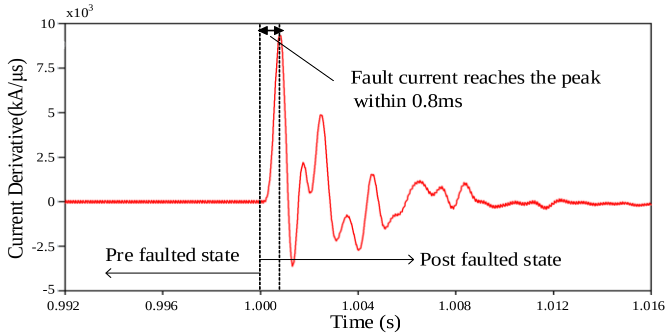


Fig. 6. The waveform of current derivative measured in DC circuit breaker.

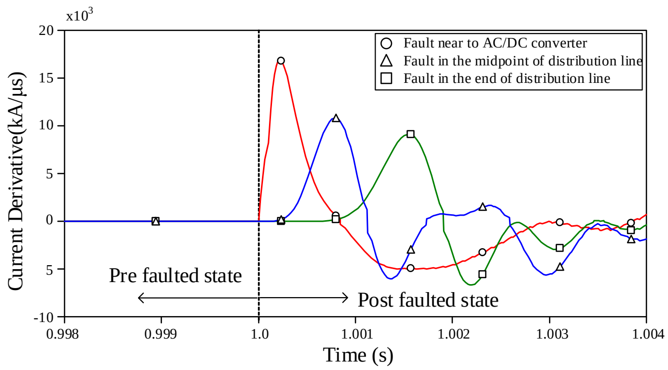


Fig. 7. The waveform of current derivative according to fault location.

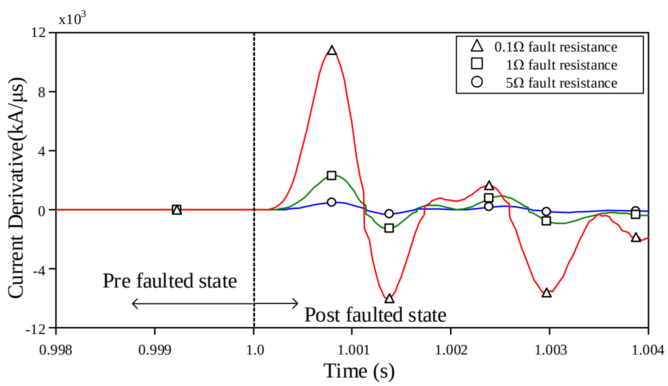


Fig. 8. The waveform of current derivative according to fault resistance.

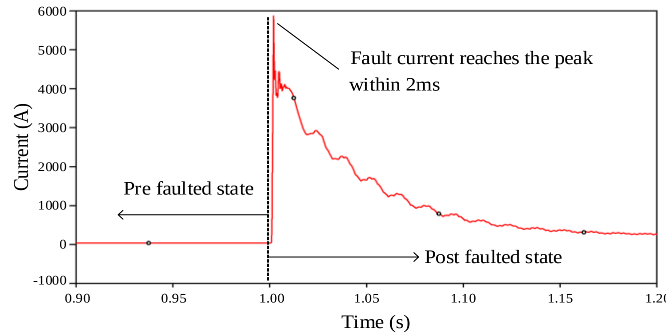


Fig. 9. The waveform of current measured in DC circuit breaker.

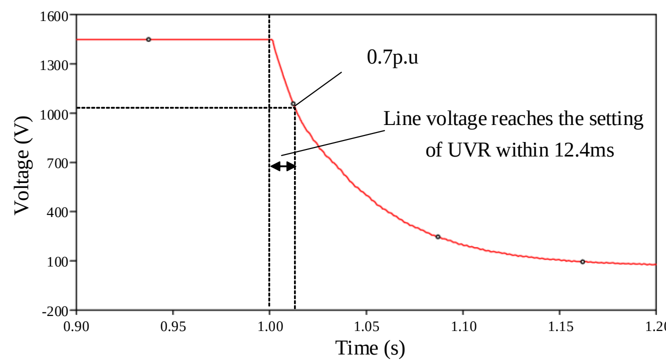


Fig. 10. Pole-to-pole voltage measured in DC circuit breaker.

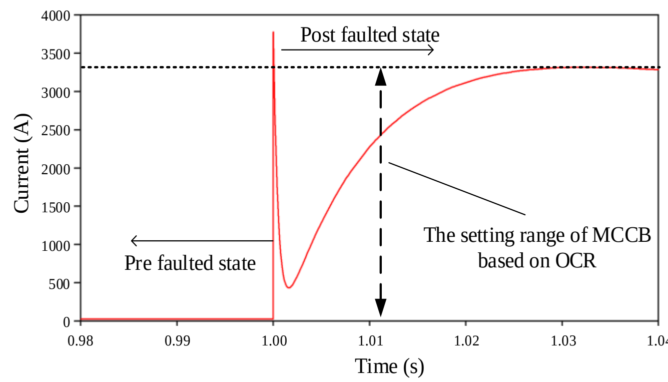


Fig. 11. Waveform of current measured in MCCB for load fault.

Both method, however, might be improper for converter protection due to the sharp increase of discharging current. Thus, the relay using current derivative, which means the slope of current, can apply to line protection since it has very fast response to discharging current of output capacitor. The OCR and UVR can be used as backup protection to achieve the redundant protection. Figs. 6 to 11 show the simulation result using EMTP for the model of Fig. 4. From the simulation results, we can see that the current derivative reaches the peak faster than the others. And this peak value differs according to the system and the fault conditions. Figs. 7 and 8 show the current derivative according to the fault location and resistance. They show that the peak value can be different duet to the fault conditions, which cause the different fault loop impedance. Although the time of fault detection depends on the performance of protective relay, the current derivative is possible to provide the fast fault detection relatively for a same protective relay.

For the load protection, we can use the Molded Case Circuit Breaker (MCCB) based on over-current relaying to detect and clear the fault occurred in load side. When a fault occurs in the load side, the output capacitor of DC/DC converter discharges. The fault current, however, is smaller than that of the line fault because of the small output capacitor of the DC/DC converter and low voltage level relatively. The MCCB based on OCR, therefore, is proper to block the load fault. Fig. 11 shows the fault current when the fault occurs in the load. The fault current rises suddenly due to the output capacitor and then it increases again. At that time, the MCCB will be operate to clear the fault.

C. Protective Coordination Between Distribution Line and Load Protection

In the previous subsection, we discussed the line and the load protection. For these systems, if the load protection fails to block the load fault, the line protection should operate as

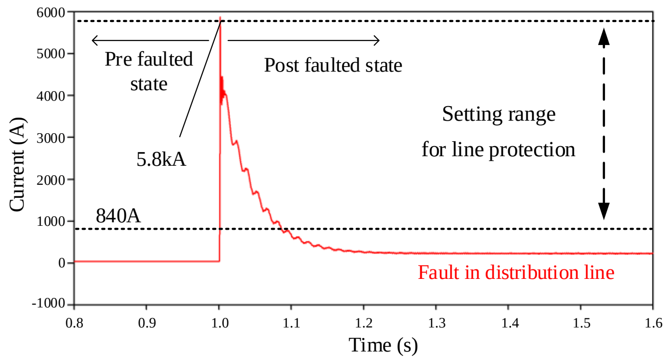


Fig. 12. The fault current measured in DC circuit breaker for line fault.

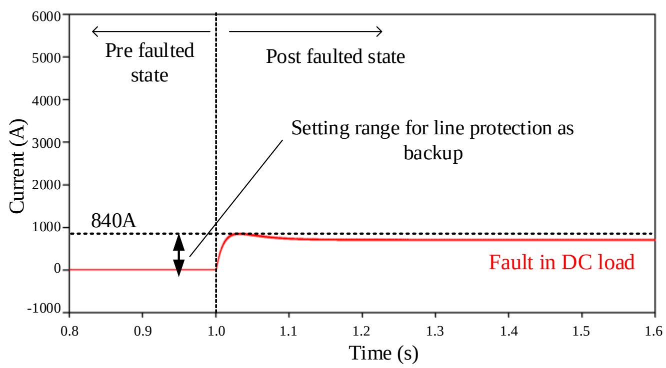


Fig. 13. The fault current measured in DC circuit breaker for load fault.

backup protection to prevent the extension of load fault. Furthermore, the line protection has to operate for only line fault. Low pickup setting in the line protection causes mal-trip of circuit breaker for load fault and then all loads experience the interruption. We, therefore, need to consider the protective coordination between both protection systems.

In Figs. 12 and 13, which show the fault current according to the fault location, if the line protection system has too low pickup value, it might cause mal-operation. The setting value of the line protection should be bigger than the peak of fault current in case of the load fault. Also, the line protection system should have the setting with a low pickup value and delayed time to operate as backup.

D. The Setting of Protection System

From the above simulation results, we can know that the selection of proper setting is quite important for the presented protection systems. The setting value, however, depends on the system and fault condition. Therefore, it needs to draw the proper setting from the system study in order to construct the effective protection system. In general, 0.6 - 0.8p.u. is typical setting for UVR protection [10]. For current derivative protection, it needs to consider the peak value of current derivative according to the fault location and resistance when the system operator selects the setting. It is because that too high setting makes it difficult to detect the fault current. As expressed as (5), therefore, the setting ($di/dt_{setting}$) should be smaller than the minimum peak ($di/dt_{line\ fault,min}$) of current derivative, which is obtained by considering the fault location and resistance.

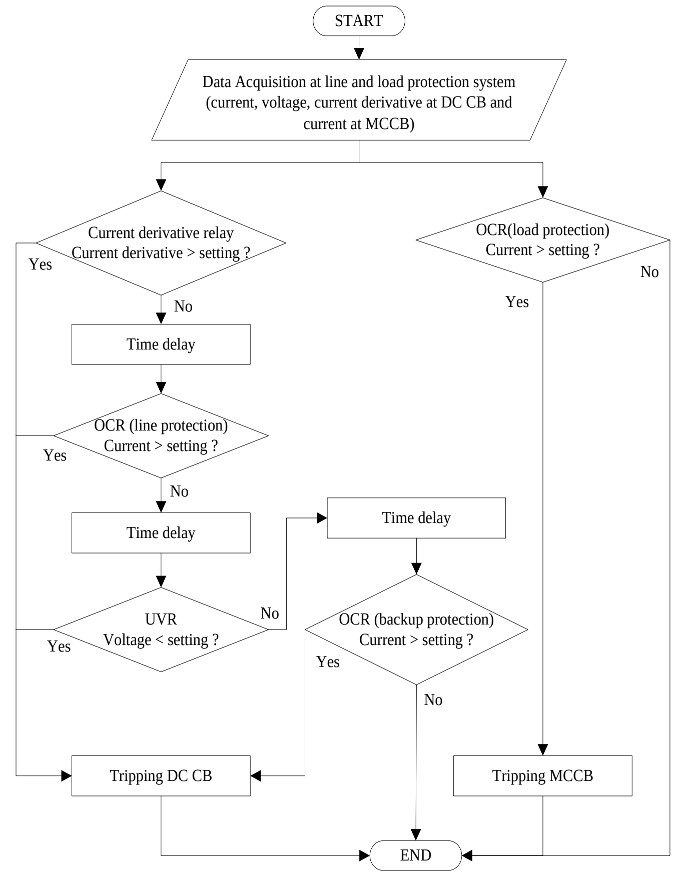


Fig. 14. The flowchart of protective coordination between line protection and load protection.

$$di/dt_{setting} < di/dt_{line\ fault,\min} \tag{5}$$

For OCR protection, the pickup value ($i_{setting,OCR}$) should be set bigger than the fault current ($i_{load\ fault}$) measured in line protection when the fault occurs in DC load side. And also, the pickup value should be smaller than the peak of fault current ($i_{line\ fault,peak}$) for line fault. The range of this value can be expressed as (6).

$$i_{load\ fault} < i_{setting,OCR} < i_{line\ fault,peak} \tag{6}$$

In case of load protection, the typical pickup value of DC MCCB for the instantaneous trip is about 900 – 1400% of the rated current [11]. It is expected to be proper for DC load protection. Fig. 14 shows the flowchart of the suggested protective coordination system between both protection systems. This protective coordination is essential for high reliability of protection system. The important thing here is that these settings can be changeable according to system condition or system operator.

V. Conclusions

This paper discusses the protection system and protective coordination in LVDC last mile distribution system because it is a vital element to implement the those system. Firstly, we have analyzed the fault characteristics in DC distribution system considering power electronic device. From this analysis, we have drawn the conclusion that the fault should be cleared faster than AC system. We, thus, have proposed line and load protection system based on current derivative relay, OCR, and UVR. Finally, the protective coordination between two protection systems is considered to block the unintended interruption due to mal-operation of relay and to provide backup protection. This study contributes to improved stability and high reliability of the LVDC last mile distribution system.

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