A Reliability Analysis of Low Voltage DC Distribution

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***Abstract*— DC-based power system has paid attention as a solution that can provide improvements in energy efficiency. However, the researches that have been performed to construct Low Voltage DC (LVDC) distribution system are not yet suitable for practical use. This paper presents a reliability analysis for an LVDC distribution system that is conducted according to the DC/DC converter arrangement. In order to analyze conduct an accurate analysis of the reliability, power quality and voltage drop constraints are additionally considered. The reliability analysis is conducted for an LVDC distribution system with loop and proceeded step by step. First, LVDC distribution systems are modeled, and then the ElectroMagnetic Transients Program (EMTP) is used to conduct simulations. Next, the minimal cut-set method is used for the results of the simulation to draw up the reliability block diagrams. Finally, the Customer Interruption Cost (CIC) is calculated by applying the Customer Damage Function (CDF) and load capacity, which is used to analyze the reliability. The results of reliability analysis show that LVDC distribution system with loop in Distributed Converter (DC) type is more reliable than in Centralized Converter (CC) type.**

***Keywords*: Centralized converter type, Customer interruption cost, Distributed converter type, Low Voltage DC distribution system, Power quality, Reliability, Voltage drop constraint.**

I. Introduction

NOWADAYS, DC power system is receiving an increasing amount of attention because of the increased interests in energy efficiency. In the past, the conventional AC power system was considered to be the only solution because of the serious downside of DC power system such as voltage transformation. However, this issue has been solved by developing power electronic devices. Furthermore, the energy efficiency can be improved by reducing the stage of power conversion if both the distributed generations that generate DC outputs and the DC-based digital loads belong to DC power system [1]. As a result, a High Voltage DC (HVDC) transmission system has been applied in a practical power system to transmit electricity over a long distance [2]. On the other hand, it is difficult to construct Low Voltage DC (LVDC) distribution system since standards and researches on LVDC distribution system are not still enough.

This paper presents a reliability analysis for an LVDC distribution system that was conducted by taking into consideration power quality and the arrangement of DC/DC converters. The power quality was relatively insignificant factor for the conventional reliability analysis [3]. However, it should be taken into account in LVDC distribution system since digital loads and power electronic devices are sensitive to variations in the voltage. Moreover, the DC/DC converter arrangement is considered since no research has yet been conducted on how DC/DC converters affect the reliability of power system. In addition to both issues mentioned above, voltage drop constraint on lines is also contemplated referring to [4], which could increase the practicality of the reliability analysis. The following explains the reliability of LVDC distribution system is analyzed by reflecting on the three factors mentioned above: power quality, the arrangement of DC/DC converters, and voltage drop constraint.

II. Low Voltage DC (LVDC) Distribution System

A. The layout of the LVDC distribution system

LVDC distribution system can be constructed using the same layout as an AC distribution system such as radial, loop, and etc. Although a radial type is the most widely used to distribute power, when a fault occurs, there is a serious drawback in that all customers behind a fault location could experience an interruption [5]. On the other hand, a loop distribution system can mitigate this problem by using a tie switch to make it possible to supply customers deviously when a fault occurs [5]. A tie switch of a loop system is normally open (N/O) so that the loop system operates as radial system in a normal state. If a fault occurs on a line, however, tie switch closes and then links the end of two lines. That is, the configuration of LVDC distribution system becomes loop only in the fault state. This system has an advantage in that increases system reliability by only applying tie switch.

B. Classification of the LVDC distribution system according to the arrangement of DC/DC converters

A step-down transformer is used for voltage transformation in conventional AC distribution system. However, the LVDC distribution system includes additional components such as an AC/DC converter and a DC/DC converter. In general, an AC/DC converter is installed behind a transformer in order to rectify AC to DC. A DC/DC converter is used to step down DC voltage level, and it can be arranged in two different ways.

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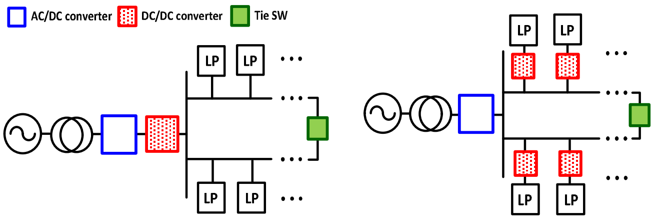
The first one involves installing one DC/DC converter behind AC/DC converter, which is called 'Centralized Converter (CC) type'. Note that AC/DC converter cannot output lower DC voltage than AC peak value by itself. Therefore, DC/DC converter should be used together. The other setup involves arranging DC/DC converter in front of each customer, which is called 'Distributed Converter (DC) type'. Fig. 1 shows a configuration of the LVDC distribution systems with loop according to the arrangement of DC/DC converters.



(a) CC type (b) DC type

Fig. 1. Configuration of an LVDC distribution system with loop according to the arrangement of DC/DC converters.

III. Analysis of LVDC Distribution System

A. *Modelling of LVDC distribution system*

In this section, two LVDC distribution systems with loop are modeled using the ElectroMagnetic Transients Program (EMTP). In the two modeled LVDC distribution systems, Load Points (LPs) can be supplied through several steps. First, 22.9kV voltage, transmitted from utilities, is stepped down by transformer and then rectified to 1500V_{DC} voltage by AC/DC converter. This rectified voltage should be converted to 380V_{DC} by a DC/DC converter to fulfil customer demand. Therefore, voltage level on distribution line can be different according to the arrangement of DC/DC converters. While 380V_{DC} voltage is excited on distribution line in CC type as DC/DC converter is installed behind AC/DC converter, 1500V_{DC} voltage is energized on distribution line in DC type since each DC/DC converter steps down in front of LPs.

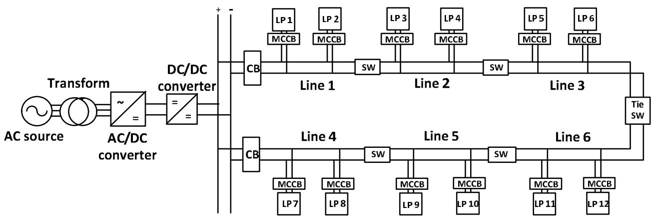


Fig. 2. Modeled LVDC distribution system with loop in CC type.

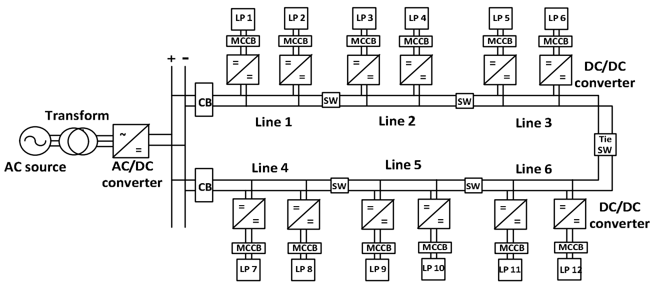


Fig. 3. Modelled LVDC distribution system with loop in DC type.

In the LVDC distribution system models that are considered, it is assumed that line length between loads is 100m and the capacity of each LP is 25kW. The protection scheme based on the AC distribution system is applied to modeled systems as one for LVDC distribution system are not set up yet. Applied protection schemes are as follows.

• Internal faults of converters: In general, a converter is designed with built-in protective system to protect itself against internal faults. Therefore, in this case, it is assumed that converters should interrupt themselves against internal faults.

• Distribution line fault: When a fault occurs on distribution line, a circuit breaker (CB) and switch (SW) are assumed to operate based on the operation sequence of a recloser and sectionalizer as provided by Korea Electric Power Corporation (KEPCO). When a line fault is detected, CB opens first. Then, the corresponding SWs operate to isolate the fault location. Finally, both CB and tie switch are simultaneously closed.

• Fault on LPs: In this case, protection scheme is also based on AC distribution system. Molded Case Circuit Breaker (MCCB) interrupts the fault on LPs.

B. *Analysis of simulation results*

The previous section described two LVDC distribution system with loop according to the DC/DC converter arrangement. The reliability of LVDC distribution system is analyzed in this section by conducting the simulation with the modeled systems. The simulation consists of two parts. The first part involves analyzing the impact that faults have on LPs and how the corresponding protective devices operate. The interruption area can be classified into sustained interruption or instantaneous interruption. The former is the resulted from isolation of fault section using SW or MCCB, and the latter occurs as a result of the voltage dip and operation of the CB. The important thing is to understand the relationship between fault location and interruption on any LP when classifying interruption area as it is closely related to the analysis results.

TABLE I
The Classification of Interruption Area on LPs Depending on Fault Location in CC Type

Load Point / Fault Location	LP1 & LP2	LP3 & LP4	LP5 & LP6	LP7 & LP8	LP9 & LP10	LP11 & LP12
Transformer	S	S	S	S	S	S
AC/DC converter	S	S	S	S	S	S
DC/DC converter	S	S	S	S	S	S
Line 1	S	I	I	-	-	-
Line 2	I	S	I	-	-	-
Line 3	I	I	S	-	-	-
Line 4	-	-	-	S	I	I
Line 5	-	-	-	I	S	I
Line 6	-	-	-	I	I	S

TABLE II
THE CLASSIFICATION OF INTERRUPTION AREA ON LPS DEPENDING ON FAULT LOCATION IN DC TYPE

Fault Location \ Load Point	LP1 & LP2	LP3 & LP4	LP5 & LP6	LP7 & LP8	LP9 & LP10	LP11 & LP12
Transformer	S	S	S	S	S	S
AC/DC converter	S	S	S	S	S	S
DC/DC converter	Only related LP experiences sustained interruption.					
Line 1	S	I	I	D	D	D
Line 2	I	S	I	D	D	D
Line 3	I	I	S	D	D	D
Line 4	D	D	D	S	I	I
Line 5	D	D	D	I	S	I
Line 6	D	D	D	I	I	S

Simulation results are explained in Table I and Table II, which show the interruption area depending on fault location and correspond to CC type and DC type, respectively. Each letter (S, I, and D) in the table stands for sustained interruption, instantaneous interruption, and voltage dip defined in IEEE standard. In addition, hyphen (-) means that there is no impact of faults.

When a fault occurs in transformer and AC/DC converter, all of the LPs encounter a sustained interruption for both CC type and DC type. However, the impact by resulting from line fault is different for each case. In DC type, LPs in the faulted distribution line experience interruption as shown in Table II (sustained interruption for corresponding LPs, instantaneous interruption for other LPs). All LPs in the adjacent distribution line experience voltage dip. In contrast, for CC type, there is no impact on all LPs in the adjacent distribution line even if the impact on LPs in the faulted distribution line is same as that for DC type. Moreover, the impact of internal faults on DC/DC converter is different depending on the arrangement of DC/DC converters as well. For CC type, all of the LPs in the system experience sustained interruption while only related LP is under interruption for DC type.

The next part involves checking whether the voltage drop constraint on distribution line is violated or not in LVDC distribution system with loop. That is because all LPs in modeled systems should be supplied with voltage level within voltage drop constraint specified on [4]. In normal state, two modeled systems are designed to meet voltage drop constraint. When a fault occurs on line, however, some LPs could violate regulation due to change in the equivalent impedance. It means that some of the LPs cannot be fed with proper voltage level under faults even if a tie switch is closed. From this perspective, the results of reliability analysis based on the first part can be more practical. Table III shows voltage level on LPs in LVDC distribution system for both CC type and DC type under a pre-fault state. Table IV and Table V present voltage level on each LP under post-fault state, providing information on the violation of voltage drop constraint. These simulation results present only the fault on distribution line since the violation of voltage drop constraint does not occur under faults on other components. LV customers should be fed within the allowable variation range of customer voltage level as ± 10% reflecting voltage drop constraint specified in [4].

TABLE III
VOLTAGE LEVEL ON LPS IN LVDC DISTRIBUTION SYSTEM UNDER PRE-FAULT STATE AND POST-FAULT STATE

Load Point \ Type	CC type	DC type
LP1	371.4[V_{DC}]	381.2[V_{DC}]
LP2	363.4[V_{DC}]	
LP3	357.0[V_{DC}]	
LP4	352.3[V_{DC}]	
LP5	349.1[V_{DC}]	
LP6	347.5[V_{DC}]	
LP7	371.4[V_{DC}]	
LP8	363.4[V_{DC}]	
LP9	357.0[V_{DC}]	
LP10	352.2[V_{DC}]	
LP11	349.1[V_{DC}]	
LP12	347.5[V_{DC}]	

TABLE IV
VOLTAGE LEVEL ON LPS IN LVDC DISTRIBUTION SYSTEM IN CC TYPE UNDER POST-FAULT STATE

Load Point \ Fault Location		Line1	Line2	Line3	Line4	Line5	Line6
Voltage under Post-Fault state [V_{DC}]	LP1	0	377.8	374.5	366.4	368.8	371.5
	LP2	0	376.1	369.5	353.3	358.0	363.4
	LP3	302.5	0	366.2	341.8	348.9	357.1
	LP4	303.9	0	364.5	331.8	341.3	352.3
	LP5	306.6	326.4	0	323.3	335.3	349.1
	LP6	310.8	327.9	0	316.3	330.9	347.5
	LP7	366.4	368.8	371.5	0	377.8	374.5
	LP8	353.3	358.0	363.4	0	376.1	369.5
	LP9	341.8	348.9	357.1	302.5	0	366.2
	LP10	331.8	341.3	352.3	303.9	0	364.5
	LP11	323.3	335.3	349.1	306.6	326.4	0
	LP12	316.3	330.9	347.5	310.8	327.9	0

TABLE V
VOLTAGE LEVEL ON LPS IN LVDC DISTRIBUTION SYSTEM IN DC TYPE UNDER POST-FAULT STATE

Load Point \ Fault Location		Line1	Line2	Line3	Line4	Line5	Line6
Voltage under Post-Fault state [V_{DC}]	LP1	0	381.5	381.5	381.4	381.4	381.4
	LP2	0	381.5	381.5	381.4	381.4	381.4
	LP3	381.5	0	381.5	381.4	381.4	381.4
	LP4	381.5	0	381.5	381.4	381.4	381.4
	LP5	381.5	381.5	0	381.4	381.4	381.4
	LP6	381.5	381.5	0	381.4	381.4	381.4
	LP7	381.4	381.4	381.4	0	381.5	381.5
	LP8	381.4	381.4	381.4	0	381.5	381.5
	LP9	381.4	381.4	381.4	381.5	0	381.5
	LP10	381.4	381.4	381.4	381.5	0	381.5
	LP11	381.4	381.4	381.4	381.5	381.5	0
	LP12	381.4	381.4	381.4	381.5	381.5	0

As shown in Table III, the voltage level on all LPs meets the condition for the voltage drop constraint in a pre-fault state. In the post-fault state, however, the shaded LPs in CC type violate the condition for the voltage drop constraint due to the increase in the equivalent impedance as shown in Table IV. Whereas all LPs in DC type meet the condition of voltage drop constraint as shown in Table V. That is because each DC/DC converter in front of LPs always keeps voltage level constant (about $380V_{DC}$). The LPs that violate this condition are considered to undergo a sustained interruption when the reliability of the LVDC distribution system is analyzed.

IV. Reliability Analysis of LVDC Distribution System

A. Customer Interruption Cost (CIC)

In general, the reliability of power system is analyzed by using reliability indices such as System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). However, these indices are not suitable to evaluate instantaneous interruption due to power quality phenomena since they are calculated according to the long-term data. In the case of LVDC distribution system, instantaneous interruption can't be ignored because multiple digital loads that are sensitive to power quality phenomena are included. In this paper, the concept of Customer Interruption Cost (CIC) is therefore introduced. This index can evaluate the cost from an interruption of the LPs by power quality and power supply phenomena [6]. It is represented as (1).

$$\mathrm{CIC} = \mathrm{CDF} \times \mathrm{U}_i \tag{1}$$

Customer Damage Function (CDF) means the cost function per unit power for the interruption duration, which is represented in Table VI [7]. Other values that are not provided in this table are decided as linearized values based on specific values.

TABLE VI
Customer Damage Function (CDF) according to Load Type

Load types	Cost per unit power for the duration of interruption [$/kW]			
	1min	20min	60min	240min
Residential	0.004	0.071	0.442	4.079
Large	1.160	2.777	4.482	10.186
Small	0.568	2.667	4.158	15.511
Official	0.032	0.284	1.145	5.010
Commercial	0.678	4.173	13.050	46.281

The unavailability (U_i) refers to the period for specific customers to be unable to have a normal supply for a year, which is shown in (2). λ_i and r_i mean the failure rate and Mean Time To Repair (MTTR) of components *i*, resulting in interruption for the respective customers [6]. These data are referenced from [8].

$$\mathrm{U_i} = \sum \lambda_i r_i \tag{2}$$

The CIC of LVDC distribution system is calculated step by step as shown in Fig. 4.

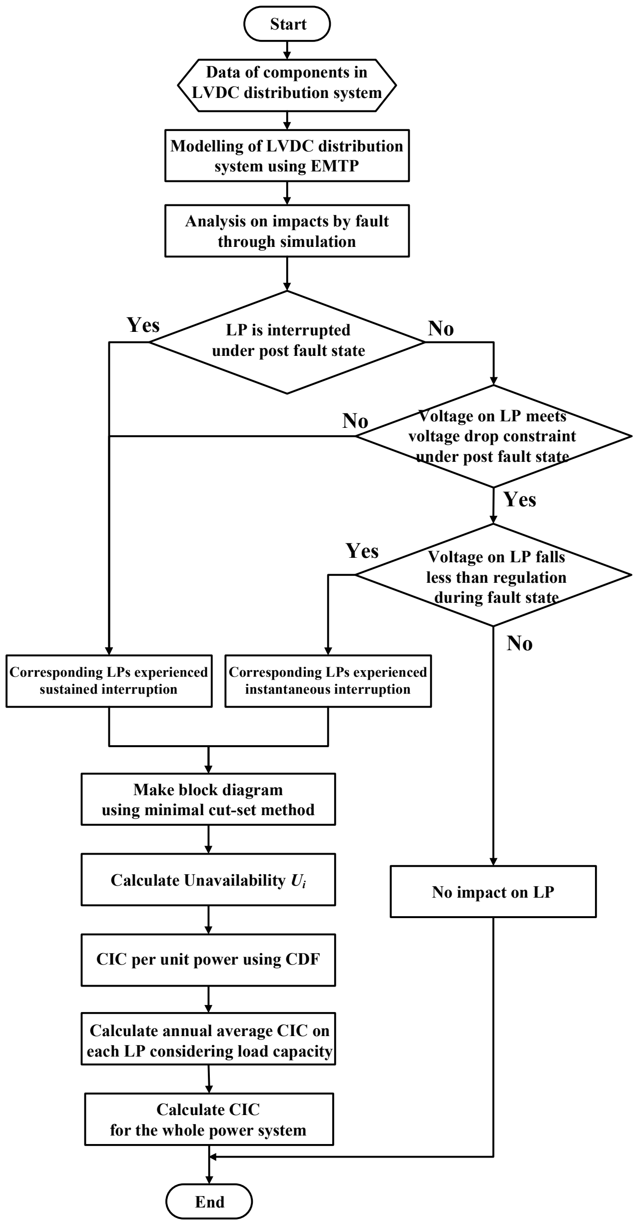


Fig. 4. Flowchart to calculate CIC of LVDC distribution system.

The details for each of the steps are as follows.

- Step 1: In this step, impacts due to faults on LVDC distribution system are analyzed through simulation that uses the EMTP. In the previous section, the subject for simulation process and results are discussed in detail.
- Step 2: Based on the simulation results, the reliability block diagram is drawn up through the minimal cut-set method. The minimal cut-set method is defined for the analysis by using the set of components that cause an interruption on for

customers when a fault occurs [9]. Reliability block diagram is helpful to gain an intuitive understanding of the relationship among the components and LPs. Fig. 5 shows an example of reliability block diagram meaning that LP 2 experiences interruption due to the fault on line 2 and DC/DC converter.

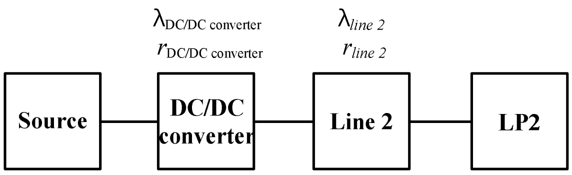


Fig. 5. An example of reliability block diagram.

• Step 3: The sets of reliability block diagram and (2), U_i on each of the LPs is calculated. If U_2 (U_i on LP2) is calculated in the example in Step 2, it is expressed as (3).

$$U_2 = \lambda_{DC/DCconverter} r_{DC/DCconverter} + \lambda_{line2} r_{line2} \quad (3)$$

• Step 4: CDF in Table VI is applied to the U_i that is calculated for each LP. We can get interruption costs per unit power on all LPs through this step.

• Step 5: Annual average interruption costs on each LP are acquired by applying load capacity (20kW).

• Step 6: CIC for the entire LVDC distribution system is calculated according to the sum of annual average interruption costs on each LP that are given in Step 5. CIC can be divided into CIC for sustained interruption and CIC for instantaneous interruption, each of which are utilized in the reliability analysis of LVDC distribution system.

B. A reliability analysis of LVDC distribution system

In this section, the reliability of LVDC distribution system is analyzed according to the arrangement of DC/DC converters. As mentioned above, instantaneous interruption resulting from power quality phenomena and voltage drop constraint are additionally considered in the reliability analysis. The following figures show the interruption cost that are calculated within the given conditions. Fig. 6 presents total interruption costs for LVDC distribution system with loop. Fig. 7 and Fig. 8 show sustained interruption cost and instantaneous interruption cost for LVDC distribution system with loop, respectively.

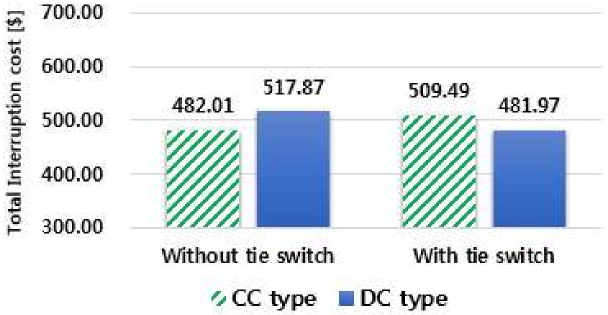


Fig. 6. Total interruption cost of LVDC distribution system with loop.

We reach several conclusions from Fig. 6. The first one is that CC type is more reliable than DC type if a tie switch is not applied to LVDC distribution system. According to [8], failure rate and MTTR are proportional to voltage level on line so that failure rate and MTTR of DC type are higher than the ones for CC type, which is the reason why the results come out as shown on left side of Fig. 6. Next, there are changes in the total interruption cost when a tie switch is applied. As mentioned above, a tie switch of LVDC distribution system with loop should be closed when a fault occurs on distribution line in order to improve the system reliability. However, in the case of CC type, voltage level on some LPs violates voltage drop constraint. Therefore, the total interruption cost for CC type becomes larger if the tie switch operates properly as shown in Fig. 6. On the other hand, in the case of DC type, voltage level does not violate voltage drop due to the presence of DC/DC converter in front of each LP. That is, the total interruption cost of DC type becomes lower when a tie switch is included. In conclusion, the LVDC distribution system with loop in DC type is more reliable than one in CC type as shown on the right side in Fig. 6.

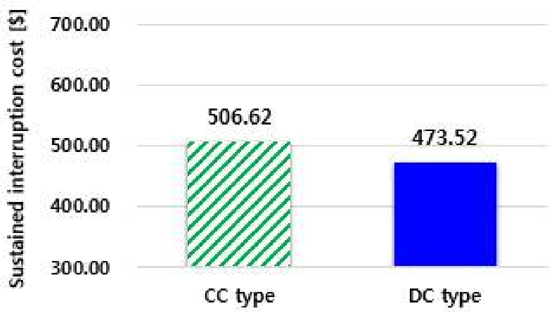


Fig. 7. Sustained interruption cost of LVDC distribution system according to the arrangement of DC/DC converters.

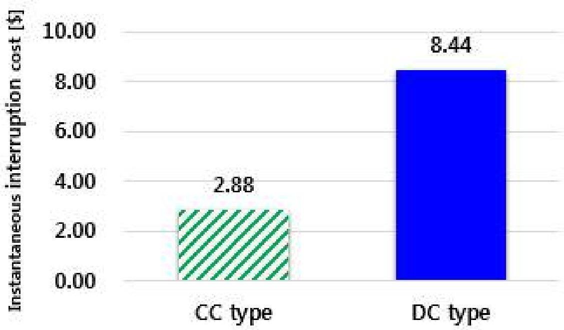


Fig. 8. Instantaneous interruption cost of LVDC distribution system according to the arrangement of DC/DC converters.

The results in Fig. 7 come out by reflecting on voltage drop constraint. Its tendency is similar to the results on right side in Fig. 6. In contrast, the results in Fig. 8 show the opposite tendency when considering the instantaneous interruption due to power quality phenomena. This means an impact resulting from power quality phenomena including voltage dip on LVDC distribution system is more severe in DC type as a result of the impacts of line fault on AC/DC converter. If a line fault occurs, the equivalent resistance decreased, and AC/DC converter recognizes the state where the total load capacity increases. It could result in AC/DC converter losing control, resulting in voltage dip. The possibility that an AC/DC converter loses control can be decided by the relationship between load capacity and voltage: The higher voltage level on line, the more frequent a failure occurs in the AC/DC converter, which explains the results are as shown in Fig. 8.

In conclusion, DC type should be adopted to improve the reliability of LVDC distribution system with loop. Moreover, we can be sure that there are many advantages to operating LVDC distribution system in terms of the power loss, voltage drop, and cross-sectional area of conductor since voltage level energized on distribution line in DC type is higher than that in CC type. However, we should also consider the disadvantages of using DC type such as characteristics of power quality as shown in Fig. 8. Therefore, the countermeasures to restrict damages due to power quality phenomena should be taken into account to construct LVDC distribution system with loop in DC type.

V. CONCLUSION

This paper discusses the reliability of LVDC distribution system with loop according to the arrangement of DC/DC converters: CC type and DC type. A reliability analysis is conducted by taking into account power quality and voltage drop constraint as well. CIC is used in reliability analysis and is appropriate to evaluating the interruption costs even for a short duration. In order to calculate CIC of LVDC distribution system, the modeled LVDC distribution systems are simulated by using EMTP first of all and then reliability block diagrams are drawn up based on simulation results. Next, the U_i is calculated by using reliability block diagram. Finally, CIC is calculated by applying CDF and load capacity on LP. The results of reliability analysis of LVDC distribution system based on CIC are summarized as follows.

· In order to improve the reliability of LVDC distribution system, a loop-type system layout is adopted using a tie switch. It works well in DC type while the reliability of CC type is degraded as a result of the voltage drop constraint. Moreover, we can guess that there is advantage to operating power system because of the higher voltage level on distribution line for DC type. Therefore, we can be sure that DC type offers acceptable performance for LVDC distribution system with loop.

· Since LVDC distribution system in DC type operates at higher voltage level, it is subject to interruption due to power quality phenomena including voltage dip. It means that countermeasures to mitigate the adverse effects from power quality phenomena should be researched and applied when constructing LVDC distribution system in DC type.

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