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Short-Circuit Protection For MV & LVDC Grid

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Abstract— A DC medium voltage (MV) and low voltage (LV) power distribution network will be proposed and the protection aspects will be discussed in this paper. This paper is mainly focused on the short-circuit overcurrent protection system of the future MV/LVDC distribution network. The proposed MV/LVDC distribution network would be modeled using PSCAD. Positive phase to ground faults normally observed in the unipolar network will be simulated and analyzed. Typical response times to clear the different types of short-circuit fault would be estimated. The response time will be compared with proposed tripping time.

Keywords— DC-DC converter, DC distribution, DC grid protection, DC relay, HVDC, IGBT, LVDC, MVDC, Overcurrent protection.

I. INTRODUCTION

High-voltage (>65 kV) direct current (HVDC) transmission line has been adopted in many countries such as China, US and Russia for many years, for lower electrical losses, less capital costs, ease of control, etc. Unlike the HVDC, the medium and the low voltage (MV/LV) DC distribution is a new distribution concept.

Many studies [1–2] have reported that the DC distribution scheme could not only offer lower losses and cost, but it could be also more reliable. In recent times, MV/LVDC distribution system studies and research is significantly increasing, in order to make the system more reliable, economical and sustainable. This paper therefore will discuss how the proposed short-circuit protection technique is able to isolate the fault for future MV/LVDC distribution network.

The remainder of the paper is organized as follows. The MV/LVDC distribution network and the state-of-the-art literatures are introduced in section II. Section III describes the possible faults in the MV/LVDC network. Protection aspects of the MV/LVDC network are discussed in section IV. The PSCAD MV/LVDC system model is described in section V. Detailed case-studies of the fault is described with simulation results in section VI. Discussions on the results are mentioned in section VII, followed by conclusion in section VIII.

II. MV/LVDC DISTRIBUTION

MV/LVDC distribution can be identified by means of voltage rating:

- MVDC is rated from 1500 VDC to 22 kVDC,
- LVDC is typically rated below 1500 VDC.

The MV/LVDC networks can further be classified into unipolar and bipolar system. In the unipolar system, the loads are connected to the DC voltage line and the neutral pole, common voltage rating being 1500 VDC.

Two unipolar systems can be combined to become a bipolar system. Two voltage levels, ± 750 VDC and the neutral pole are normally used in the bipolar system. The loads can be connected to the system in multiple ways, such as,

- Between the positive pole and the neutral
- Between the negative pole and the neutral,
- Between the positive and the negative pole.

Unlike long HVDC links, short distance of the MV/LVDC distribution network may be subjected to higher initial cost due to the expensive DC converters. However, large varieties of low-cost converters are coming to the market rapidly. This will indirectly make the power electronics converter price more attractive. Therefore, in near future, the lower cost of the converter station and the equipment are expected to bring down the initial cost, making the DC distribution system more competitive, compared to the AC counterpart.

With regard to the abovementioned benefits, the MV/LVDC distribution networks are being adopted for applications like data centre, train/traction, marine, etc. [3–4]. Engineers use MV/LVDC voltage to support different type of sensors, motor/drives and electronics appliances in their system. The MV/LVDC network is also considered for the renewable energy infeed, such as the PV and the wind energy at the MV/LV level to cut down the fossil fuel power consumption.

LVDC network is particularly being considered for utilization in homes, e.g., for computing, LED lighting, etc., improving the AC-DC conversion losses. Nuutinen et. al. [5] reported new technologies to transmit electric power supply to the end customer with more reliability, easy control and less outages. After several years of research, new LVDC network was successfully implemented in Finland in 2005 [6–7]. It demonstrated how the DC voltage could improve the power quality, with lower power losses in the distribution network [6].

III. SHORT-CIRCUIT FAULTS IN MV/LVDC DISTRIBUTION NETWORK

To ensure reliable operation of the MV/LVDC network and protection of the vital power electronic components, it is important to implement fast DC fault detection system, to isolate the faulty zones. This would prevent the fault current from flowing into the circuit, preventing any damage to the equipment and network failure. DC distribution network fault current protection

is new to the power industry, as there are not many MV/LVDC distribution networks today. Therefore, any standards, regulation, guides are missing from authorities like IEC, IEEE, etc., while those are well established for AC distribution [8].

Previous researches [6–7] have indicated that the following types of common short-circuit faults normally occur in the DC network:

- i. Short-circuit in a positive pole
- ii. Short-circuit in a negative pole
- iii. Short-circuit between +ve/-ve to neutral pole
- iv. Positive pole to earth fault
- v. Negative pole to earth fault
- vi. Neutral pole to earth fault.

IV. SHORT-CIRCUIT PROTECTION IN MV/LVDC DISTRIBUTION NETWORK

To ensure reliable operation of the MV/LVDC network and short-circuit protection of the vital power electronic components, it is important to implement fast, intelligent fault detection and effective protection system.

Many works [1–2, 9–10] have proposed how to design and implement an effective protection system to ensure reliable operation of the MV/LVDC network. Circuit-breaker (CB) and fuses are the common protective devices to be used in the future DC grid to break the fault current in the network [12]. However, there is a challenge for circuit breaker to break the DC circuit current, as the DC current flows in a constant direction. More energy may require to open the breaker isolation mechanism. Fast acting DC solid state fault isolation electronic devices could be an alternative because it is able to perform softer and faster switching than conventional CB [13].

The schemes proposed in the paper will broadly leverage the AC time-overcurrent principles, taking into consideration differences between the AC and the DC systems (e.g., absence of current zero crossing, etc.). One of the main focuses of the work is to implement fast acting solid state isolation devices into the distribution network. It will be compared with the conventional CB with default setting.

However, the MV/LVDC distribution system is more complex than the traditional 22 kV/0.4 kV AC distribution system. DC distribution system can be constructed with different topologies such as unipolar and bipolar system. This study would concentrate on unipolar 750 VDC systems. The hypothetical LVDC system will be fed by a 10 kV DC network from nearby MVDC grid network. The energy is transmitted through a high power DC-DC converter located at the customer substation. The power supply shall be converted to 750 VDC via converter for customer need. Simulation results using PSCAD [11] are reported in the following section.

V. MV/LVDC SYSTEM MODEL

Fig. 1 shows the block diagram of the proposed MV/LVDC distribution network. In Fig. 1, the circuit

indicated as ‘Customer 1’ will be observed and studied further. The distribution network for ‘Customer 1’ comprises of MV switchgear, DC-DC converter [3], LV switchgear, and DC load. Among all the equipment, the DC-DC converter would have significant impact on the system. Therefore, it would be discussed briefly.

Fig.1. Block diagram of proposed MV/LVDC grid.

The DC-DC converter schematics diagram is shown in the dashed box in Fig. 1. The converter consists of the insulated-gate bipolar transistor (IGBT) 1 to 4, high frequency transformer (ratio of 10 kVDC to 750 VDC), a bridge diode and an output filter. The full-bridge DC-DC power converter with the isolation transformer is able to step down the time varying input voltage to the desired output voltage level.

The isolation full bridge DC-DC converter uses solid-state devices as the switches to control the output voltage. Each switch in the converter is comprised of series of IGBTs. Pulse width modulation (PWM) controller and two gate drivers would be used to control the IGBT switches. The PWM pulse generator is rated at 50% duty cycle and 2 kHz switching frequency. Two pulses will be generated to turn on and off the diagonally opposite switches in a portion of each half-cycle of the switching frequency. DC Power will be transferred from the source to the high frequency transformer through the conduction of a pair of IGBT switches,

Isolation transformer will step the voltage down by a factor of approximately 13. Isolation transformer may provide better conversion optimization and minimize the stress imposed on the IGBT and the diodes. The diode bridge rectifies the 750 VDC supply from the secondary winding of the transformer. The output ripple voltage will be filtered by the capacitor.

Fig. 2. Modeling of MV/LVDC distribution network.

Fig. 2 shows the modeling of the future MV/LVDC distribution network using PSCAD [11]. Parameters for each component are listed in Table I.

TABLE I. BLOCK DIAGRAM OF PROPOSED MV/LVDC GRID

Parameter	Value
DC voltage Source	10 kVDC
Transformer rated MVA	1.8 MVA
Primary Voltage rating	10 kVDC
Secondary Voltage rating	0.750 kVDC
DC Load	1 ohm

VI. MV/LVDC GRID FAULT CASE STUDY

A. Line-to-Ground fault

The proposed short-circuit fault in the modeled DC grid is +750 VDC pole-to-ground short. The possible location of the fault could be at the following locations:

- Grid intake
- DC load.

Fault simulation is carried out for a period of 1 second using PSCAD/EMTDC [11]. The simulation will be conducted along with fault created from fault logic recommended by PSCAD/EMTDC [11].

The first set of positive pole to ground short-circuit is placed between the grid intake and DC-DC converter (refer to Fig. 3 for more details). The fault happened at 0.3s at the grid intake and the clearing time is 100ms. Do note that network is simulated without any protection devices. The current and the voltage waveforms are shown in Fig. 4 and Fig 5. Fig. 4 indicates that the fault current amplitude at 10 kVDC grid intake increases from 0.25 per unit (p.u.) to 7p.u. at the grid intake. The fault causes a severe current increase (refer to Fig. 4). The fault creates a voltage drop at the secondary winding of the isolation transformer (refer to Fig 5).

B. Low Impedance Ground Fault

To investigate the low impedance ground fault at the DC load feeder, fault will be registered near the DC load. It can be observed that a large fault current will

Fig. 3. Fault at 10 kVDC grid intake.

Fig. 4. Amplitude (p.u.) of the fault current at grid intake and DC load.

Fig. 5. Amplitude (p.u.) of voltage at grid intake and DC load.

flow to the ground during the fault. The fault current increases to approximately 16 times near the resistive load which is rated at 750 VDC. This can be observed from the simulation results shown in Fig. 6 (current), and Fig. 7 (voltage). The simulation analyses the net-

work condition when fault occurred at DC load during 0.3s. Fault is cleared at 0.4s.

Fig. 6. Amplitude (p.u.) of the fault current at grid intake and DC load current during low impedance ground fault.

Fig. 7. Amplitude (p.u.) of the voltage at grid intake and DC load during low impedance ground fault.

VII. DISCUSSION ON PROTECTION REQUIREMENT

The following comments are cited on the proposed MV/LVDC distribution network, fault analysis, results for the possible protection requirements.

- From the above case studies, MV grid intake and DC load feeder must be protected against short-circuit current. The high fault current not only can damage the connected equipment, moreover cause power outage to the distribution network. To provide adequate fault current protection, each circuit in the network should be equipped with a CB for

automatic interruption of supply in the event of fault occurred.

- DC CB especially for MV/LV side is not in general commercially available like the AC circuit breaker. However, these should be available in future.
- Besides the CB, solid state fault isolation devices are the alternative protective device which could be used. The main advantage of these devices is the ability to break the short-circuit current very fast.
- Distribution network should also be protected from the overload. It can be achieved by installing the CB in the main incoming circuit. The rated current of the circuit would allow the circuit to carry current continuously. From the simulations, it would not trip if the current passing through it is typically in the range of 105% to 113% of the rated current. The circuit should be opened if the current is 1.13 to 1.5 times with respect to the rated current. The values are obtained from several simulations.
- The protection time will be determined in future, following further analysis and analysing the timing requirements from the circuit breaker side.
- Fast fault detection in the MV and the LVDC grid could be done using the wavelet transform (WT). WT is effectively applied for fault detection in HVDC [14–15], and HVAC [16–20] applications.
- Directional protection only from current for MV distribution automation is a growing field [21–26]. Such technologies [21–26] with adjustment for DC grid applications could be applied in future for MV & LVDC as well.

Table II summarizes the location of the circuit breaker and isolation time with respect to the fault in the network, based on different simulations.

TABLE II. PROPOSED LOCATION OF CIRCUIT-BREAKER AND TRIPPING TIME

Description (Location of the proposed circuit breaker)	Circuit breaker tripping time
+750 VDC pole-to-ground faults at 10 kVDC feeder (location of CB: 10 kVDC feeder)	Tripping time is less than 0.1s in view of fault current is more than 6 time. (instantaneous trip)
+750VDC pole-to-ground fault at 750VDC feeder (location of CB: 750VDC feeder)	Tripping time is less than 0.1s in view of fault current is more than 16time. (instantaneous trip)

In the following section, we will discuss about the impact to the network if protective devices are added at the DC load.

A. Circuit-breaker added to the DC load

Fig. 8 shows the proposed CB location in details. Fault simulation similar to mentioned at section VI-B, has been carried out. Minor disturbances could be observed in Figs. 9 and 10, after the fault is isolated by the

CB. The fault has been detected at 0.3014s and signal is sent to the CB trip coil to open the circuit. CB opened at 0.31s.

Fig. 8. The proposed circuit breaker location with the DC load.

Fig. 9. Amplitude (p.u.) of fault current at the grid intake and DC load, during low impedance ground fault, after circuit breaker is installed.

Fig. 10. Amplitude (p.u.) of voltage at the grid intake and DC load, during low impedance ground fault, after circuit breaker is installed.

B. IGBT- Isolation switch added to the DC load

Several issues have been raised against the use of CB to interrupt the short-circuit current in MV/LVDC network [13]. One of the significant issues is that the conventional AC or DC CB is based on thermal/ magnetic mechanism to break the short-circuit. It generally requires relatively long tripping time. Therefore, solid state isolation devices such as IGBT has been proposed to incorporate with the CB to clear the fault.

Fig. 11 shows the location of the IGBT isolation switch in details. Fault simulation similar to mentioned at section VI-B, has been carried out. No significant disturbances could be observed in Figs. 11 and 12, after the fault gets isolated by the IGBT – isolation switch. The fault has been detected at 0.3014s, and the signal is sent to the IGBT to block the fault current. Fault is isolated at 0.3016s.

Fig. 11. The proposed IGBT isolation switch location at DC load.

Fig. 12. Amplitude (p.u.) of fault current at the grid intake and DC load during low impedance ground fault after IGBT – isolation switch is installed.

VIII. CONCLUSIONS

In this paper, a future MV/LVDC distribution scheme has been proposed. A key requirement for future DC grid is the protection. DC distribution protection is new to the power industry, as there are not many MV/LVDC networks today.

In this paper, a realistic MV/LVDC distribution grid is modelled using PSCAD [11]. In the proposed DC grid, DC-DC converter will be implemented to replace the traditional AC transformer in distribution network. Different faults and type of protection has been simulated using PSCAD. Type of protective devices and isolation time has also been estimated.

Fig. 13. Amplitude (p.u.) of voltage at the grid intake and DC load during low impedance ground fault after IGBT – isolation switch is installed.

Different types of short-circuit faults, e.g., pole to ground and low impedance ground faults are simulated and analysed. Further analysis is done on the impact to the network if protective devices are added at the DC load. Faster response could be achieved if IGBT isolation switches are used than circuit-breakers to isolate the fault near the DC load.

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