Investigation of Different System Earthing Schemes for Protection of Low Voltage DC Microgrids

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Abstract

DC microgrids are expected to play an important role in maximising the benefits of distributed energy resources in future low carbon smart power systems. One of the remaining complex challenges is the requirement for effective DC protection solutions. The advancement of DC protection is hindered by the lack of good understanding and development of reliable and effective earthing schemes which can enable safe and secure operation of DC microgrids in both on-grid and off-grid modes. Therefore, this paper discusses different DC microgrid earthing opportunities, and comprehensively evaluates through detailed simulation studies the influence of different earthing methods on the fault behaviour of DC microgrid. A transient model of an active DC microgrid is developed in PSCAD/EMTDC and used for the paper studies.

1 Introduction

Recently, there has been an increase of interest in Low Voltage Direct Current (LVDC) microgrids. Enhanced controllability, power quality and energy efficiency have promoted the interest in this field. DC microgrids require fewer conversion stages to host distributed energy resources in comparison to AC systems. The voltage regulation and power balancing are more controllable in DC systems [1,2]. DC microgrids have already been introduced for several applications such as data centres, information communication systems and electric ships. Usually DC microgrids accommodate renewable energy resources such as Photo-Voltaic (PV), Battery Energy Storage Systems (BESS), Electric Vehicles (PHEV) and loads directly or through power electronic converters. For those interfaced by converters such as DC renewable resources and in many case, no transformer isolation between are used. This is driven by the need for cost and size reduction of the installation. However, such technologies can pose safety and common-mode noise challenges if the earthing of the microgrid is not properly designed. Moreover, most work found in the literature and on existing trials of DC distribution have not demonstrated different DC earthing systems with different methods on a similar DC microgrid to find the best protection strategy.

The main contribution of this paper is to provide an overview and comparison of different earthing methods whilst keeping the earthing tethered to the negative pole. Furthermore, a transient simulation for pole to ground faults in a DC microgrid network is performed with different earthing methods in order to investigate fault behaviour.

The paper is organised as follows. Section 2 presents the different DC microgrid configurations. Section 3 the earthing configurations and requirements for DC microgrid are presented. A simplified DC microgrid model is presented in Section 4. In Section 5 the simulation analysis. Finally, the discussion of the results and conclusion of the presented work are drawn in section 6 and 7.

2 DC Microgrid Configurations

There are a number of configurations that have been reported in the literature [3], the most relevant to this study are investigated here. These include radial configuration and ring configuration. Each connection scheme has their pros and cons. Moreover, based on these connection schemes different DC microgrid configuration can be possible.

A. Radial configuration

In this configuration, the single DC bus is commonly used for DC microgrid, and it can be considered as the basis of multi-bus network. The single DC bus can be regarded as unipolar or bipolar depending on its application and requirements. This type of configuration can be implemented in residential building where low voltage DC is preferred to correspond to the voltage level of different appliances, and to limit any extra DC-DC conversion. The radial DC microgrid configuration has a number of advantages such as simplicity and different voltage levels (bipolar scheme) can be provided. However, the radial DC bus configuration is not flexible during fault conditions. If a single fault occurs in the network, it will affect all customers connected to the single DC bus [3].

B. Ring or loop configuration

The ring or loop configuration is developed to overcome the limitation of the radial configuration and to increase the flexibility of the system during the fault. It can consist of two or more paths between the AC grid interface and the loads. At both ends of each DC bus, Intelligent Electronic Devices (IEDs) are used to control each bus and their interface with other connecting buses [4]. This type of configuration is

implemented in urban and industrial environments. The main merit of this topology is that a high reliability and redundant operation is provided. When a fault occurs in the DC bus, the IED first detects and isolates the faulty bus from the network and then the load power turns to be supplied through an alternative heathy path [3].
For the purpose of this study and due to its simplicity, a radial configuration has been used in the test DC microgrid model.

3 Different Earthing Schemes

This section discusses standard functional earthing arrangements and safety requirements for DC microgrids in accordance to the IEC60479. Also a number of different DC earthing methods are investigated in this section.

3.1 Standard DC System Earthing Arrangements

According to IEC 60479-1, in 2-wire DC systems, it is recommended to earth the negative pole instead of the positive pole. This is because, earthing the positive pole drives the fault current direction to flow "upwards" through the heart which can cause higher risk of the ventricular fibrillation. The heart threshold for ventricular fibrillation when enduring an upwards current is half compared with a "downward" fault current that can be caused through earthing the negative pole [5]. Therefore, upwards current needs to be interrupted quicker and may require faster protection devices to detect and interrupt the fault.
International standard IEC-60364 has classified three types of earthing systems using two-letter codes TN, TT and IT. The first letter represents the connection type between the power system supply to the earth, which can either be T (direct connection of one point to earth) or I (all live parts isolated from earth, or one point connected to earth via a high impedance). The second letter denotes the connection type between the customer installations and the earth, which is either T (direct connection of the electric device to the local earth) or N (direct connection of the electrical device to the earth point of the power system, either as a separate protective earth conductor or combined with the neutral conductor) [6].
These earthing schemes have different fault characteristics and influence the setting and configuration of the protection system in different way. Therefore, a number of factors including maximisation of personal safety (i.e. reduce the touch voltage), minimisation of stray current (i.e. reduce the leakage current to the soil), fault detection, and minimisation of common-mode noise between AC and DC should be taken into consideration when designing and selecting DC earthing schemes [7].
In the case of TT earthed system, as shown in Figure 1(a), there are two earthing points, one from the system side and the other from the customer side. The fault loop has a large impedance which make the faults do not migrate between the supply and the customer's installation.

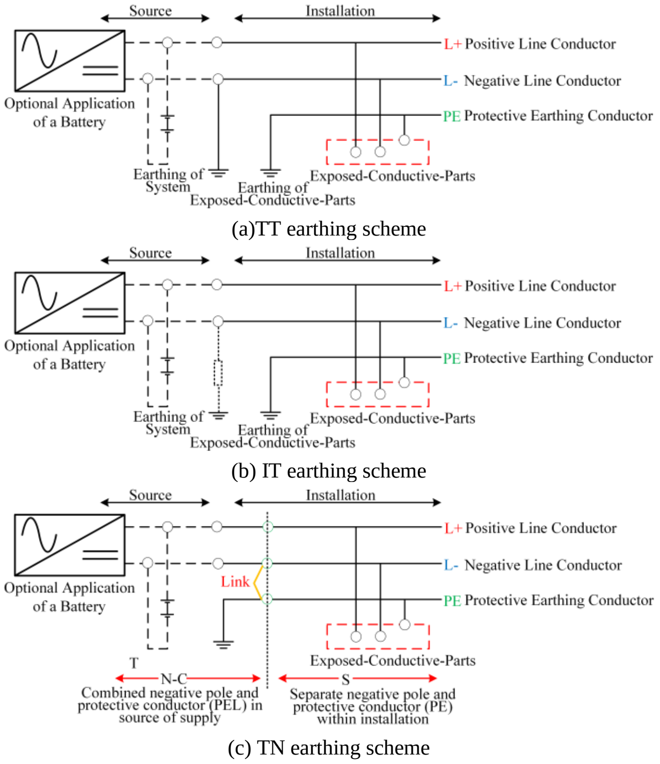

Figure 1: DC microgrid earthing schemes[8].

In the case of IT earthed system, the power negative line is earthed via a high resistance as or completely unearthed as shown in Figure 1(b). The fault current is very low due to the high resistance in the fault loop, which make it a suitable choice for reducing the touch voltage under the first fault but makes the fault more challenging to detect. The problem arises during the second ground fault in a different conductor of the same system, which drives a pole to pole fault with large fault current through the path created by the combination of the first and the second faults, resulting in a risk to personnel safety [9]. IT earthed systems are usually galvanically isolated from the customer, therefore, devices such as isolation monitoring are required to detect earth faults. On the customer side, the system can be configured as a TN to allow the use of suitable DC residual current devices (RCDs) to ensure the personal safety when the faults occur.
The TN earthed systems are sub-classified into TN-C, TN-S and TN-C-S as shown in Figure 1(c). TN-S and TN-C-S earthed schemes are widely used in existing systems. The exposed conducting parts and lines are connected to the ground through associated midpoints. Normally, detection of faults in a TN earthed system is simple, this is because the fault loop has low grounding resistance. The personal safety can be met since the touch voltage may exceed its acceptable threshold. The challenge of selecting one of these earthing schemes is coupled with the safety requirements, which can involves a trade-off between cost of insulation of materials and the protection devices costs.

3.2 Different DC Earthing Methods

Different DC earthing methods with fault current paths following a positive pole to ground fault are shown in Figure 2. The first method is solid earthing of the negative pole (L-) point (I). The second method is earthing the L- point through high resistance (II). The other methods are made by earthing the L- point using capacitive impedance or capacitor in parallel with diodes as shown (III) and (IV) in Figure 2 respectively. All these different earthing methods in addition to floating (completely unearthed method) are considered in the study of the paper.

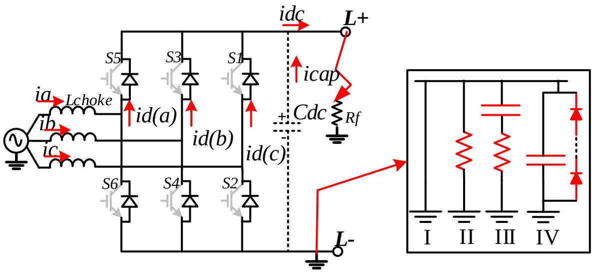

Figure 2: Current path of the fault current after L_+-G fault occurs with different earthing methods

3.3 Safety Requirements for DC Microgrid

This section presents DC safety requirements according to the IEC60479 and IEC60364 standards. The discussion in the section includes the risk of electric shock and the effect of corrosion due to different DC earthing. In addition to these, the common available safety standards to alleviate the risk of electric shock and corrosion effects are also discussed.

A. Risk of electric shock

The risk of electric shock can arise in faulted electrical systems when exposed conductive segments become 'live'. To mitigate this risk, these segments need an effective earthing and fault detection protection system that can quickly resolve the fault before public or livestock are affected [10]. IEC60479 characterizes the effects of electric currents on humans as shown in Figure 3 [10]. The level of the current flowing through the human body relies on its impedance and the touch voltage of the live equipment. Four time-current regions are categorized, these include DC-1, where minor sensations are felt, DC-2 where muscles may involuntary contract, DC-3 strong muscle contractions and adverse heart effects are experienced, and DC-4 critical effects can be done which can result in death depending on exposure to the current [10]. It is therefore essential to select DC voltage levels and protection device such as residual current devices with sufficiently short interrupting time that restrain exposure to body currents. It is suggested in [11] that voltages under 50V DC do not present danger to humans, this assumes a body impedance of 1 kΩ and a threshold current of 50 mA.

B. Corrosion effects

To date, there is no specific standards that mention or offer recommendations regarding the mitigation of electrolytic corrosion effects. However, the IET's "Practical Considerations for DC Distribution" proposes the IT earthing arrangement naturally reduces the earth current during faults and thus is more protective of adjacent metalwork than the TT earthing arrangement [12]. However, IT earthing system is not common in public networks, unless galvanic isolation is used between the supply and the end users. The BS EN 50162 standard provides detailed guidance for the protection against corrosion caused by stray currents from direct current systems. Nevertheless, this standard considers more about the traditional uses of DC power, and possibly needs an update that combines the recent development in LVDC distribution applications such as microgrids and building level distribution [13,14]. The −48 V telecom standard uses an earthed positive pole to mitigate against electrolytic corrosion; however, it not recommended at high voltage levels and considered more dangerous from the safety perspective[15].

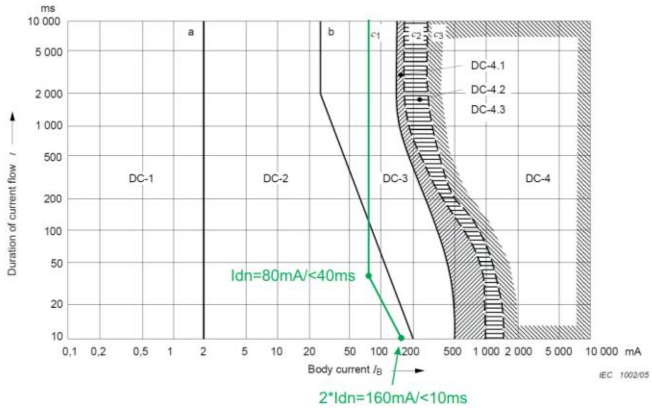

Figure 3: Characteristic curve of body current/duration of current flow[10].

4 DC Microgrid Test System Description

The test network is based on a typical microgrid DC network, which has been adopted from [16]. The DC network is connected to a secondary substation of 11/0.4 kV transformer by two-level voltage source converter (VSC) and modelled in PSCAD/EMTDC as shown in Figure 4. The VSC converter provides 750V DC voltage at the point of common coupling (PCC) [17]. A 1 km feeder is modelled with resistor connected in series with an inductor (R=0.164 Ω/km-L=0.24 mH/km) [18]. The DC microgrid supplies a DC load 8kW through bi-directional DC/DC converters. A 10kW PV and 7.8kWh battery storage are connected to the DC customer bus. The DC customer is supplied by 200V DC. The main AC-DC converter operates in DC voltage control mode to maintain the DC voltage at 750V DC using commonly outer DC voltage and inner current control loops [19]. A solar PV array system interfaced via a DC-DC boost converter is modelled and connected to the customer DC bus. The PV generator is set to operate at its peak power point. A Buck-Boost DC-DC half bridge converter is modelled to interface the BESS on the customer side. A boost mode is activated when the battery operates in the discharge stage. While a buck mode is activated when the battery operates in the charge stage. More details on the model of the battery converters are given in [16]. The DC microgrid test system parameters are illustrated in Table 1.

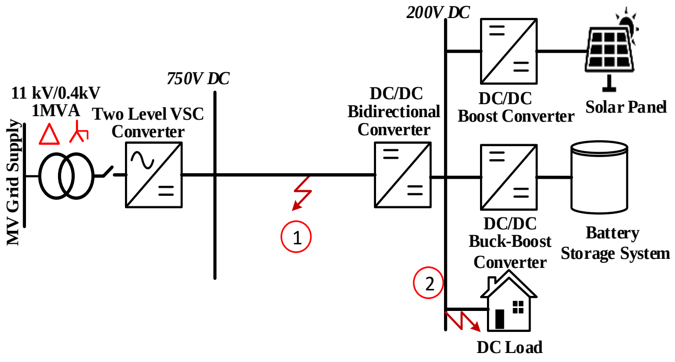

Figure 4: DC microgrid test network.

Table 1: DC Microgrid Test System Parameters [16]

Parameter	Value
AC supply	11 kV
Transformer X/R	5
Fault level	156 MVA
Transformer capacity	1 MVA
Choke Inductance [*LChoke*]	0.003 H
DC-Link Capacitance[*Cdc*]	3300 µF
LVDC main voltage	750V (pole-to-pole)
R and L of LVDC cable	0.164 Ω/km, 0.24 mH/km
Cable length	1 km
PV generation	10 kW
Battery system	7.8 kWh
DC loads	8 kW

5 Simulation Analysis

This section investigates the performances of the test DC microgrid network with different earthing methods as shown in Figure 2. A DC positive pole to ground (L_+-G) fault is applied at the main feeder of the DC microgrid and at DC customer side (shown as location 1 and 2 in Figure 4). Each fault is initiated at time t=0.5s with fault resistance (R_f) of 0.01 Ω and lasts for 100ms. The response in each earthing case is discussed as follows.

5.1 Case I: negative pole (L-) is solidly earthed

Before the fault at location 1 as shown in Figure 4 is initiated, the grid side AC voltages (V_{gabc}) are displaced by a DC voltage of magnitude (V_{dc}) with respect to ground in the normal operation. Whereas under the faulted condition, the DC link voltage (V_{dc}) is completely collapsed and the grid side voltages (V_{gabc}) are actually devoid of dc offset voltage as shown in Figure 5(a). In this arrangement the capacitor of VSC converter is completely discharged with transient fault current of dc link side (I_{dc}) of 1.7 kA peak. This is followed by forward biased of the antiparallel-diodes, resulting in uncontrolled steady state fault current to be passed from the AC grid to the fault point as shown in Figure 5 (b). The fault current contributions ($I_{dc\text{-}Customer}$) are coming from the PV and BESS on the customer side. The DC/DC bidirectional converters interfacing these devices are modelled without limiting the fault current functionality. The highest current from the PV and the BESS as shown in Figure 5(b) will be supplied under this faulted condition. Thereby, for solidly earthed system, to protect a DC microgrid interfaced by two-level VSC against the overcurrent, fast acting protection schemes are needed to isolate the faulted part in the appropriate timescale. Otherwise, equipment with higher ratings over-dimensioning will be required.

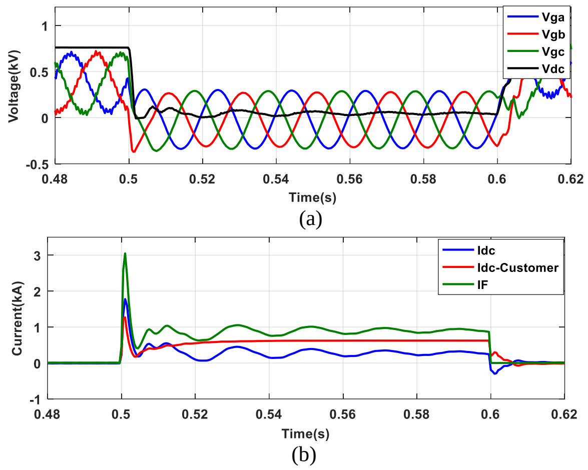

Figure 5: Fault response when L_+-G fault in location 1(a) DC voltage and AC grid voltage responses (b) DC current transient, DC-customer current and total fault current transient.

5.2 Case II: negative pole (L-) is earthed through high resistance

In this case, a high earthing resistor of 50 kΩ is used to earth the L-pole. During the first L_+-G fault at the location 1 and at t=0.45s, the system is maintained continuously operating without any disturbance. This is because, only parasitic capacitance will discharge and they have little energy stored, which makes the fault current hard to notice. However, during second fault (pole to pole fault applied at t=0.5s), the DC link voltage is collapsed. The transient fault current of dc link side (I_{dc}) has reached 1.7 kA peak and customer side ($I_{dc\text{-}Customer}$) is 5 kA as shown in Figure 6. It is concluded that during the first fault with high resistor, the system will promote a safe operation for DC network, since the fault current can be significantly limited by the earthing resistance. However, the risk is raised during the second fault which can create a path for the fault current and lead to the safety issue at the DC system.

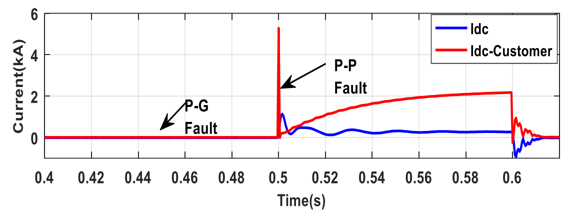

Figure 6: fault current response of DC-link and customer side currents when L_+-G and P-P faults in location 1

5.3 Case III: negative pole (L-) is earthed through capacitor and resistor

In this arrangement a capacitor of 50mF in series with 0.1Ω resistor is connected between the negative pole L- and the earth as depicted in Figure 2. Three different pole to ground faults (L_+-G) located at the beginning, middle and end of the line of the VSC converter are tested. When the L_+-G fault is applied, the capacitor within the earth path has discharged immediately a large transient current. Figure 7 illustrates that the transient current discharged by the earthed capacitor when the L_+-G fault is applied at location 1 (d=0.25km from VSC terminal), (d=0.5km from VSC terminal), and (d=1km from VSC terminal). It can be clearly seen from Figure 7, that the location of the capacitive earthing in respect to the fault location has direct impact on the transient fault current magnitudes. This earthing method provides sufficient current for detecting DC earth faults and operating the associated protection devices such as fuses, breakers, and RCDs.

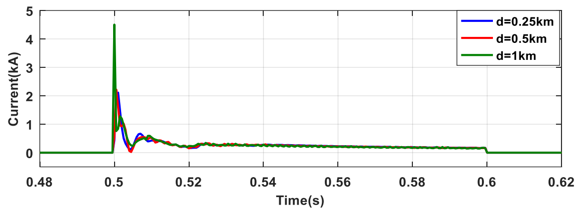

Figure 7: Total fault current response with different line impedance when L_+-G fault in location 1.

5.4 Case IV: negative pole (L-) is earthed through capacitor and diode

The advantage of using a capacitor in parallel with diode for DC earthing is the elimination of DC stray currents during the normal operation, and the provision of an effective earth path under the faulted conditions. This can be achieved by the open circuit that the diode and the capacitor provide during the normal operation, and the short circuit path that the diode will provide when it is operated by L_+-G fault. The closed loop during the fault, leads to discharge the capacitor (I_{cap}) with high transient as shown in Figure 8. In this configuration, the system will automatically be transformed from high impedance to low impedance mode when the fault occurs at the positive pole.

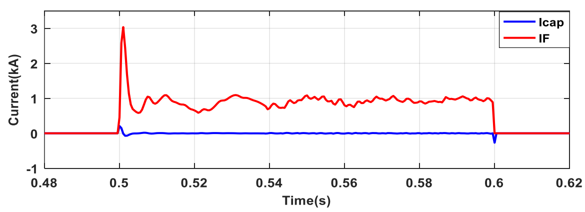

Figure 8: Fault current response of the capacitor, and the total fault current when L_+-G fault in location 1.

5.5 Case V: negative pole (L-) is unearthed (floating)

The DC–DC bidirectional converter used as the customer interface in the previous cases is replaced by a Dual Active Bridge converter (DAB). Basically, the DAB converter has an isolated transformer and better fault management capability [20]. Two pole to ground (L_+-G) faults are applied at both location 1 and location 2 as shown in Figure 4 respectively. Figure 9(a) and Figure 9(b) illustrate the AC grid voltage (V_{gabc}) and the DC current of PV (I_{pv}) and BESS (I_{bat}) when the fault is applied at location 1. The results show that the AC grid voltage is shifted with double the voltage and contained of high frequency harmonics. This can cause a stress on the cable and line connected devices if not designed properly, while no changes are seen in the PV and BESS currents.

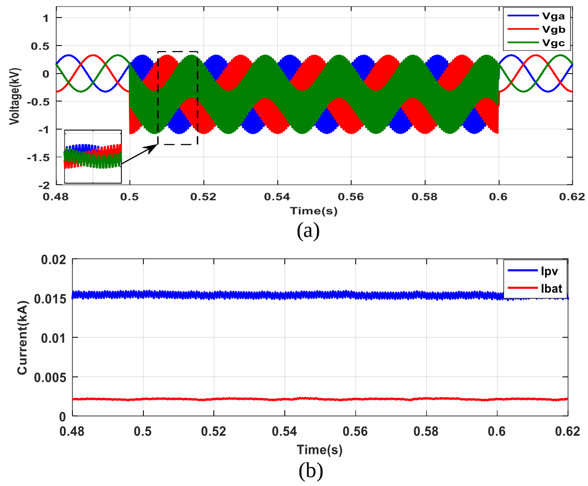

Figure 9: AC grid voltage responses during L_+-G fault in location 1(a) PV and BESS currents response in the customer side (b)

Figure 10(a) and Figure 10(b) illustrate the AC grid voltage (V_{gabc}) and the DC current of PV (I_{pv}) and BESS (I_{bat}) when the fault is applied at location 2. The results show that there are no noticeable impacts on the AC grid voltage profile in this case. This is due to the fault is isolated by the DC-DC converter that has a galvanic isolation transformer. The negative pole of the secondary transformer of the DAB converter is earthed through diode and capacitor, which cause the capacitors of the BESS and PV boost converter to discharge when the fault occurs.

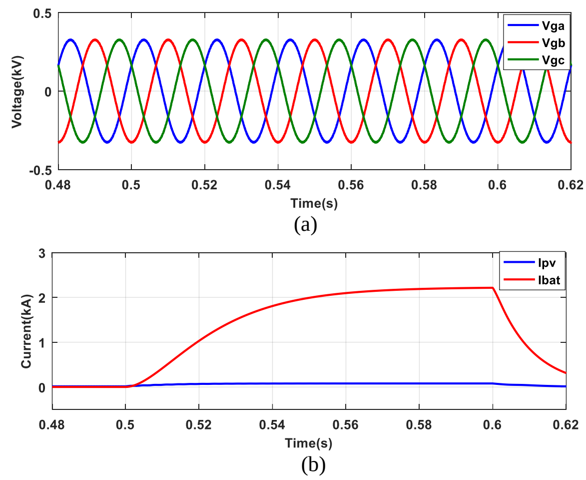

Figure 10: AC grid voltage response during L_+-G fault in location 2 (a) PV and BESS currents response in the customer side (b)

6 Discussion of simulation results

The simulation results show that DC pole to ground fault with solidly earthed configuration allows the fault current to flow from the AC grid through to the VSC converter causing damage to AC side and VSC converter components as well as impose hazard to the DC customer. Thereby, fast acting circuit breakers are recommended with a time scale of millisecond to disconnect the faulted components as soon as the fault is detected to protect the system against overcurrent.

On the other hand, the advantage of high resistance earthing scheme is that no fault current circulates in the network under the first pole to ground fault, as such the faulted line can continue operating in single pole to ground fault. However, fault-clearing action is needed as a second fault will form a double pole to ground, which can cause a very high current. For this type of earthing an isolation-monitoring device is required, in order to detect the first fault. This implies additional cost to the system. The third configuration uses a capacitor earthed through a resistor. The results show that this configuration provides sufficient current to operate the circuit breaker and protect the system. The use of passive devices such as diodes can transform the earthing connection depending on the condition of the system from high impedance to low impedance. This configuration provides the possibility to protect the network from any damage to the devices especially in the islanded LVDC system. In the case of the floating configuration, the use of an isolated transformer provides a safer condition for LVDC system operations, since the ground fault will not flow in the network, which can reduce harmful levels at the DC customer side.

7 Conclusions

DC microgrid distribution networks have the potential to be considered as promising technology for the development in the performance of the LV network. This paper has broadly discussed and investigated different earthing methods for LVDC microgrid network by preforming transient simulations. In this paper capacitive earthing and passive components such as diodes were introduced as possible earthing configurations for LVDC microgrids. Their advantages include the prevention of circulating DC ground current in normal operation, while still presenting low impedance during fault transient. Also, using an isolated transformer, the floating method has no DC fault current path in the network, which consequently prevents component stress caused by a pole to ground fault. Further research should be conducted to evaluate and identify the capacitor size, the number of the earthing points and the location of the earthing points in the network. Further work should be done to evaluate the utilization of the protection devices with active controllable devices in order to switch between different earthing configurations for a LVDC microgrid system.

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