Grounding and safety considerations for residential DC microgrids

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***Abstract*—DC-based microgrids are promising solutions to enhance the energy efficiency, reliability and safety of residential and commercial buildings, as well as to provide more effectively higher penetration of renewable energy resources into the electrical grid. However, despite the great effort that is being done by electronics, telecom/datacom and buildings sector companies and entities upon the standardization of DC distribution networks, the lack of practical experience and safety issues regarding the utilization of DC powered buildings still works against DC adoption. This paper aims to contribute with the discussion about residential DC microgrid safety by evaluating system grounding schemes and its effects on personal safety and endurance to ground faults.**

I. Introduction

Residential and commercial buildings have a great impact on the electricity demand, accounting for over 40% of the total consumption. Therefore, the deployment of power distribution solutions which enable such environments to reduce their energy demand has been the focus of many worldwide Net Zero Energy Buildings (NZEB) initiatives, as the 2007 Energy Independency and Security Act (EISA) in USA and the 2010 Energy Performance in Buildings Directive (EPBD) in the European Union [1], [2]. These initiatives are legal instruments that establish energy management goals and energy performance requirements for buildings, in order to push energy consumption reduction and the substitution of fossil fuels for renewable energy resources. According to the EISA, after 2030, all new U.S. commercial buildings shall fulfill the NZEB concept, *i.e.*, produce locally the energy consumed throughout the year, and up to 2050 all american commercial buildings shall be energy independent [1]. However, the feasibility of NZEB depends on the successful introduction of distributed generation to current installations and a substantial enhancement on energy efficiency in buildings.

DC-based microgrids are a promising alternative to enable the proliferation of net zero energy buildings, since they can increase buildings efficiency, reliability, safety and power quality and also employ renewable energy resources as main local power generation [3]–[6]. DC power distribution provides the elimination of redundant power conversion stages in the building environment, since most electronics and appliances use DC power in some manner or can easily operate with DC voltage input. Moreover, in comparison with alternating current installations, DC distribution yields a significant reduction in cable losses, due to the absence of skin and proximity effect and the lack of reactive power. The savings can reach an overall efficiency increase of 15% to 20% in residential systems and datacenters, considering distribution voltage levels around 380V [7]–[9]. DC microgrids also accomplish a more effective integration with distributed generation and storage devices [3]. DC systems promote a more safer operation as well, since the human body sensibility to DC electrical discharges is substantially lower than to 60Hz AC [10].

A microgrid can be defined as a distribution level network which integrates local loads, distributed generation and storage devices in an independent power system rating up to a few hundreds of kW [11]. The utility grid is interconnected to the microgrid through a single point of common coupling, where energy can be exchanged between both systems. A residential microgrid, sometimes also termed as a nanogrid, can be envisioned as a small scale distribution system which encompass a single residence or a small residential complex with a power demand lower than 100kW [3].

Despite the evident benefits of DC microgrids to the buildings sector and to the electrical utility, AC systems are still preferred for current electrical installation design in buildings and other microgrid setups as well. The main barrier against DC adoption is the lack of standardization, the unavailability of DC compatible products and protection devices and the relative lack of practical experience. To revert this situation, several companies and entities of the buildings and electronics industry have joined to develop standards for DC distribution in residential and commercial buildings [6], [12], [13]. In literature, several propositions for DC residential and commercial microgrid architecture can be found [3]–[5], [12]. Its becoming a common sense that the residential DC microgrid will consist of a main high voltage DC (HVDC) bus of 380V, which interconnects renewable energy resources, storage system, plug-in hybrid electric vehicles (PHEV) and loads through power electronic converters, and 24V or 48V low voltage DC (LVDC) buses supplying household appliances and consumer electronics, as depicted in Fig. 1. A communication network, which links all HVDC power electronic converters, is used to inform a central control system about the operational conditions of the microgrid. The electronic control center (ECC) will gather this information and define optimization energy management routines to be performed by the microgrid. In some situations, the ECC can be integrated

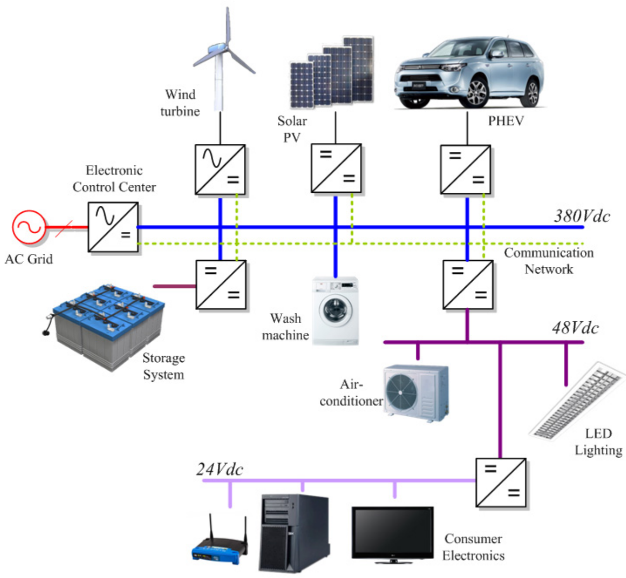

Fig. 1. Diagram of a residential DC microgrid

with the bidirectional converter which interfaces the microgrid and the utility grid [3].

Nevertheless, even through the discussions about the DC microgrid setup are reaching an advanced stage of maturity, some issues regarding DC system safety are still open [10], [14]. The main concern of an electrical installation, either it uses AC or DC voltage, is to ensure human and livestock protection against the hazards of electricity. In order to contribute for a better understanding of the effects of DC microgrid systems on human and system safety, this paper will discuss grounding schemes for residential DC microgrids, focusing on their effect on ground fault currents and electric shock body currents.

In most existing commercial and industrial DC power systems, the grounding of the DC busses assumes a galvanic isolation between the DC and the AC networks, which is achieved through a isolation transformer [10], [15], [16]. Such condition is considered in the discussions and analyzes performed in Section II. However, in low power grid-tie DC power systems, *e.g*, PV distributed generation, in order to reduce cost and size of the installation no transformer is employed, which is particularly appealing for residential microgrids. Although a transformerless DC microgrid architecture is considered for low power residential systems [3], [17], the safety issues produced by the lack of isolation are poorly described and analyzed in literature. This paper addresses this matter in Section III. Section IV presents the conclusions of the work. The simulations presented in Section III consider a 5kW bidirectional grid interface converter which connects a 380V DC bus with an $127V_{rms}$ utility grid. The energy storage system consists of a 12kWh lead-acid battery array and a 5kW converter. A 1,5kWp PV power generation is also considered and the microgrid load is set to 3kW during the simulations.

II. Grounding of isolated DC power systems

Although most power distribution systems are based on 50-60Hz alternating current waveforms, several industrial and commercial systems currently employ direct current. The telecom industry have been using 48Vdc systems for many decades, since at the age of phone manual customer pairs switching, the utilization of low voltage DC was safer for operator staffs and home use [13]. In modern telecom and datacom systems, however, the power consumption of IT equipments does not comply with low voltage DC. New DC distribution standards for the sector are being developed to use 380V or 400V feeders [13]. These high voltage DC systems can produce safety issues concerning electric shocks and fire hazards, therefore recommended grounding practices suggest the employment of high resistance grounding schemes [10], [15].

DC distribution is also present at traction systems to supply electric buses, trams and subways. The electrification of the traction power system generally uses a positive overhead feeder of 750V up to some kV to supply the moving trains and the current return path is closed through the tracks running rails [16]. Ungrounded systems can produce unsafe touch voltages between ground and metallic parts of the carriages, since leakage resistances reduce the isolation level of the return rail. The direct grounding of the negative rail exposes the tracks to corrosion, therefore, to ensure low stray current and reasonable personal safety, the negative rail is grounded through high or low resistance and fault protection relays are used to prevent fault events to produce high touch voltages.

Regarding the buildings sector, DC distribution standards currently in development tend to use different voltage levels along the commercial or residential installation [3], [6]. The american National Electric Code foresees that LVDC systems that employ less than 60V and possess a sufficiently high galvanic isolation from the system main grounding electrode can operate ungrounded, since the risks to human safety are minimized. However, higher voltage systems, as the one proposed for the main residential and commercial buildings DC bus, must be grounded.

Considering that the HVDC bus will present a voltage level around 400V, issues regarding human safety and system behavior during faults arise. A high voltage level can consequently produce the flow of relatively high body currents through direct contact of a person with the DC system live terminals. According to IEC 60479-1 [18], 50% of the population will show a body resistance of 950Ω, considering a longitudinal path (hand-to-hand) when in touch with a 400Vdc potencial. If the current path is transversal to the body (hand-to-feet) this body resistance might be up to 30% lower, *i.e.*, around 665Ω. Depending on the magnitude of the body current, a person will sense different physiological effects, from harmless muscle contractions to cardiac and breathing arrest or ventricular fibrilation, which in most cases can be fatal. Fig. 2, extracted from [18], shows the time/current zones for some main physiological effects of electricity to the human body, considering a longitudinal upward current path, which is more likely to produce ventricular fibrilation than a downward current path. Notice that the border between Zone DC-3 and DC-4 varies among the human population. For 50% of human population zone DC-4 begins at the region defined as DC-4.2. Table I describes the effects related to each zone.

The damage caused by electric shocks in the human body can be minimized through appropriate system grounding,

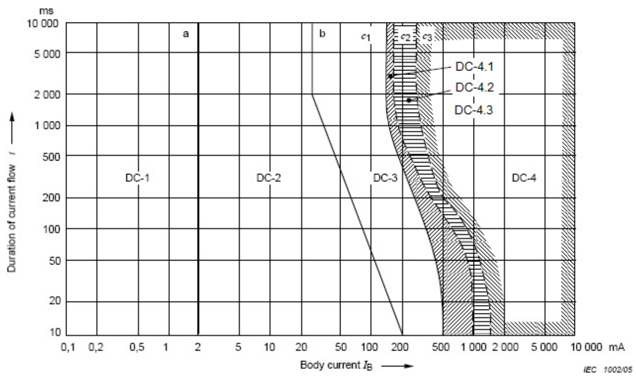

Fig. 2. Conventional time/current zones of effects of d.c. currents on persons for a longitudinal upward current path [18]

TABLE I. TIME/CURRENT ZONES PHYSIOLOGICAL EFFECTS.

Zone	Effect
DC-1	Slight pricking sensation when making, breaking or rapidly altering current flow.
DC-2	Involuntary muscular contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects.
DC-3	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected.
DC-4	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time.

bonding and the employment of protection devices such as residual-current circuit breakers. Assuming that the residential utility connection will be solidly grounded at the point of common coupling a typical unipolar DC distribution system can employ basically two grounding schemes, as depicted in Fig. 3. The TN scheme refers to a solidly grounded DC system and the IT system accounts for the use of grounding resistors, which produces two possible situations: single pole grounding and double pole grounding. The bidirectional grid interface power converter is named BGIC in this paper.

In TN and single pole IT grounding systems, a neutral conductor is provided which can be safely handled by the building occupants. The grounding electrode can be connected either to the positive or the negative DC rail, however for study purposes and simplification this paper will only consider, for this two schemes, negative rail grounding. For the analyzes conducted in this section it was assumed a 380V main DC bus voltage (V_B) and a body resistance (R_B) of 665Ω.

In the TN grounding system, one of the system conductors is solidly grounded, this will set a low impedance path for positive rail ground faults, producing extremely high fault currents, since the current magnitude will mostly depend on the fault impedance. The touch voltage of the positive rail will be equal to the HVDC bus terminal voltage, *i.e.*, 380V, what will produce a body current of 570mA during an electric shock, assuming a hand-to-feet current path. If the duration of the electrical discharge exceeds 200ms, according to Fig. 2, cardiac and breathing arrest, as long as ventricular fibrilation may occur. It can be noticed that the TN grounding system can produce dangerous situations for both the system and personal safety, therefore, the employment of protection devices against

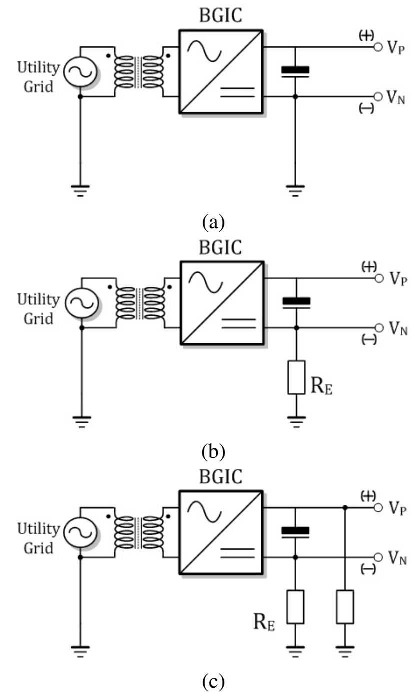

Fig. 3. Isolated DC microgrid grounding schemes. (a) TN system, (b) Single pole IT system, (c) Double pole IT system.

short-circuit and residual currents is mandatory.

In the single pole IT system, the grounding resistor (R_E) will produce a high impedance path for the circulation of both fault and body currents. The magnitude of such currents can be controlled by the grounding resistor, as described in (1) and (2), for ground fault and body current respectively. Considering a maximum body current of 35mA, which will produce no harmful effects on human body even for long exposure, a 10kΩ grounding resistance could be employed. Such resistor will limit the system fault current to 38mA, which allows the installation to maintain operation even at the occurrence of a pole to ground fault.

$$I_{F,sp} = \frac{V_B}{R_E} \quad (1)$$

$$I_{body,sp} = \frac{V_B}{R_E + R_B} \quad (2)$$

The double pole IT system has both rails of the DC bus grounded through high resistance. This grounding scheme does not provide a neutral conductor, since the resistors act as a voltage divider, hence the DC bus rails show a voltage level of $\pm$190V in relation to ground. This voltage reduction, however, will not promote a reduction on the touch voltage and fault or body currents. A ground fault, whether it happens on the negative or the positive rail, will short-circuit one of the grounding resistances producing a condition similar to the one observed in a single pole IT system, therefore both single and double pole IT grounding systems will present the same fault current magnitude. During an electric shock, the body resistance will be associated in parallel with one of the grounding resistors. This will raise the touch voltage close to 380V and the body current will be 35.7mA, slightly higher than in the single pole IT situation. The magnitude of the body current can be estimated by (3).

$$I_{body,dp} = \frac{V_B}{R_E + (R_B \parallel R_E)} \tag{3}$$

It can be concluded that for an isolated DC system, the use of IT grounding schemes will promote a more safe operation for the residential system and its occupants, since the fault and body current can be regulated by the grounding resistances. Moreover, the occurrence of a ground fault will not interfere with the system operation.

III. NON-ISOLATED RESIDENTIAL DC MICROGRIDS

The use of an isolation transformer to interconnect a residential microgrid with the utility associated with single or double pole IT grounding schemes can provide a more safe operation condition for the DC system, as observed in the latter section. However, as many residential systems have a low power demand, the isolation transformer may unnecessarily raise the installation cost and footprint or even affect its economical feasibility. The transformerless connection of DC power systems and distributed generation, generally based on photovoltaics, to the utility grid is allowed in some regulation codes. Moreover, depending on the system power ratings this connection can be accomplished at the low voltage distribution level with single or three phase networks.

The absence of an isolation transformer or any other galvanic isolation between the HVDC bus and the utility grid, which is normally solidly grounded at the point of common coupling, will produce a common mode voltage between the microgrid and the utility grid [19]. The common mode voltage can be generically described as the sum of the utility common mode voltage (V_{scm}) and the microgrid bidirectional grid interface converter (BGIC) common mode voltage (V_{icm}). Three phase and single split-phase distribution networks present a null utility common mode voltage, as discussed in [19]. Asymmetrical single phase distribution, in other hand, will present 60Hz sinusoidal utility common mode voltage with an amplitude equal to half the mains amplitude, *e.g*, a $127V_{rms}$ single phase mains will produce a $63.5V_{rms}$ common mode voltage.

The converter common mode voltage will depend on the converter topology and modulation method. For analysis purposes, consider a two stage full-bridge bidirectional grid interface converter, as proposed in [17], depicted in Fig. 4. The intermediate DC bus voltage (V_{BI}) is 600V and the output voltage (V_o) is regulated to 380V. Fig. 5 shows the DC negative rail voltage (V_N) in relation to ground for unipolar and bipolar PWM modulation methods applied at the AC/DC power stage. The resultant common mode voltage is described in (4) and (5) for the bipolar and unipolar PWM respectively.

$$V_{cm,bip} = V_{scm} - \frac{V_{BI}}{2} + \frac{V_o}{2} \tag{4}$$

$$V_{cm,uni} = V_{scm} - \frac{V_{BI}}{2} + \frac{V_o}{2} - HF_{PWM} \tag{5}$$

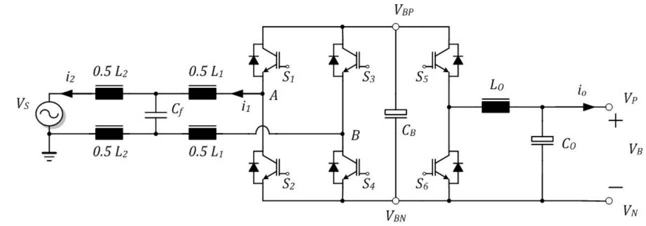

Fig. 4. Two-stage full-bridge BGIC topology.

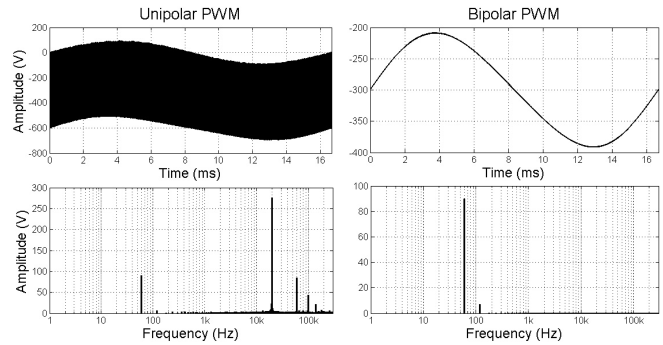

Fig. 5. Common-mode voltage for full-bridge converter unipolar and bipolar PWM modulation.

It can be noticed that in both cases the utility common mode voltage and half the intermediate and output voltages will be present in the DC microgrid common mode voltage. The use of a unipolar PWM introduces high frequency noise (HF_{PWM}) to the common mode voltage related to the harmonics of the PWM carrier and intermodulation components. The high frequency noise can easily be eliminated through the use of common mode filters, as described in [20], [21], or by the employment of modified converter topologies [20]. The utility common mode voltage and the DC component, however, can only be mitigated with the use of a full-bridge second stage and by means of active compensation methods [17]. Fig. 6 presents the BGIC topology considered in this paper. Common mode filters were applied at the utility and DC sides to eliminate high frequency components introduced by each conversion stage. The second stage is controlled in order to produce a 380V regulated DC bus and a null DC side common mode voltage, which means that the DC rails will present a $\pm 190V$ level in relation to the utility ground.

A. Non-isolated systems grounding

The lack of a galvanic isolation prevents a non-isolated DC microgrid to employ solid grounding schemes. In order to provide proper system grounding, the microgrid HVDC bus must employ a IT grounding scheme. Fig. 7 depicts two possible high resistance grounding IT systems to be used with non-isolated unipolar DC microgrids. A simple equivalent circuit can be utilized to represent the behavior of the IT grounded DC system aiding with fault and body current analysis. Fig. 8 depicts such equivalent circuit evidencing the presence of a common mode voltage (V_{CM}) and considering the HVDC bus as two symmetrical ideal voltage sources of 190V, *i.e.*, half the total DC bus voltage (V_B) of 380V.

Fig. 8 shows that for an IT grounded system, regardless of

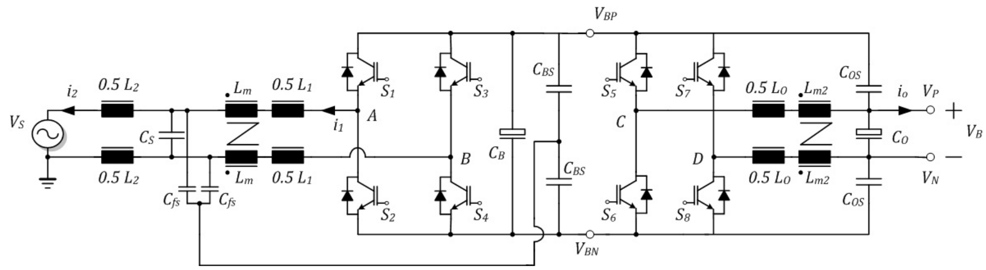

Fig. 6. Two-stage back-to-back Full-bridge BGIC topology with common mode filters in both sides [19].

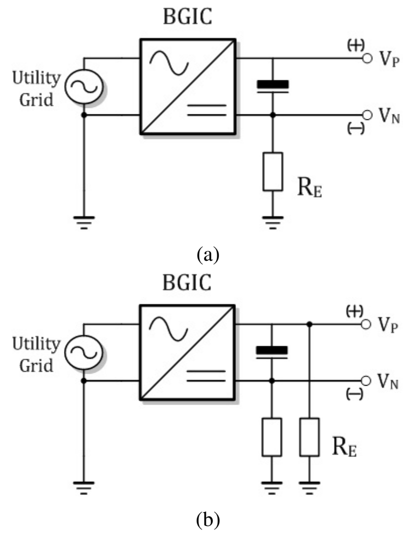

Fig. 7. Non-isolated DC microgrid grounding schemes. (a) Single pole IT system, (b) Double pole IT system.

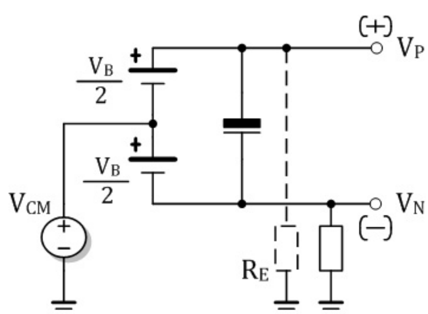

Fig. 8. Equivalent circuit for non-isolated IT grounded systems.

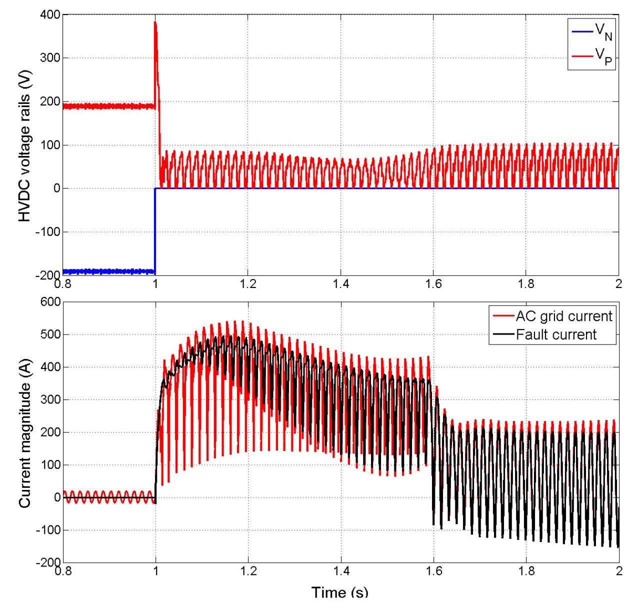

Fig. 9. Simulation results for a ground fault in a non-isolated double pole IT grounded system.

whether it uses a single pole or double pole grounding scheme, the common mode voltage will provide a low impedance path for ground faults which will produce substantially high fault currents, since the current magnitude will mainly depend on the fault impedance and the common mode voltage. Fig. 9 shows the simulation results for a negative rail ground fault in a double pole IT grounded system. Notice that the grid interface converter cancels the common mode voltage through an active compensation technique.

The ground fault short-circuits power switches between the first and second conversion stages of the BGIC. Therefore a current path between both stages is formed whereby the fault current flows. At a first moment, as the fault solidly grounds the negative rail, the common mode voltage compensation system can no longer guarantee a balanced potential between the rails and the ground plane. Immediately after the fault the BGIC second stage control elevates the DC bus voltage level above 400V, however, as the fault current rises, the HVDC bus collapses. It presents in steady state a low voltage DC signal of 51V and an overlapped 60Hz component of 37V. The fault current reaches a maximum peak of 500A, and a transient response which lasts approximately 600ms. In steady state, the fault current will present a sinusoidal 60Hz waveform and a magnitude of 95 A_{rms}. It can be observed that the fault current will flow through the AC utility grid as well, enabling the disturbance detection to be held also in the AC side of the residential microgrid. The simulation verifies that the high resistance grounding will not limit the fault current, hence a non-isolated DC microgrid is not able to maintain operation throughout a ground fault, which demands the employment of protection circuit breakers to clear the fault quickly.

It is interesting to use protection devices at the DC side of the microgrid, since they can isolate faulty circuits from the rest of the system preventing it to interfere with the microgrid operation. DC circuit breakers are available in the market, however they tend to be more costly then their AC counterparts. The use of AC circuit breakers to DC protection is explored in some papers and demands the series connection of multiple poles to enlarge the distance between the circuit breaker contacts, thus improving the device arc quenching capability and voltage rating [4], [22]. Since the fault current will also flow through the AC utility grid, another protection solution is to employ AC circuit breakers at the utility connection point. This allows the use of conventional devices to isolate the microgrid from the utility grid during DC faults, forcing the system to enter islanded operation mode. Once disconnected from the utility grid the microgrid will operate as an isolated system and then the ground fault will be limited by the grounding resistors. Moreover, the fault current will not be able to propagate to the utility system and interfere with other costumer's installations.

Fig. 10 shows the simulation results for the employment of an AC circuit breaker device in the point of common coupling. It can be noticed that the circuit breaker senses the rapid increase in the grid current and quickly unmakes the connection between the utility grid and the microgrid. After the disconnection the DC microgrid behaves as an isolated system, the negative DC rail becomes solidly grounded and the positive rail voltage level raises toward 380V. In islanded mode, the local power generation and storage systems, instead of the utility grid, are responsible for regulating the HVDC bus voltage. Therefore, after the circuit breaker is activated there is a transient of circa 200ms in which DC voltage oscillations can be observed. In steady state, the HVDC bus reaches normal operation unaware of the existence of the ground fault. Nevertheless, the clearance of the ground fault is necessary for the microgrid to operate in grid-tie mode again, since the storage system cannot sustain all residential load for an indefinite period of time. A coordinated protection system may also be used to handle DC bus ground faults. DC circuit breakers shall be utilize to quickly detect and isolate ground faults in the DC distribution network, maintaining a grid-tie operation of the residential system, and whether the DC breakers are not sufficient to prevent the propagation of the fault current to the utility grid, AC circuit breakers shall be used to disconnect both systems.

Assuming that the common mode voltage is mitigated by the common mode filters and the active compensation of the BGIC, the DC rails will present $\pm 190V$ voltage levels. According with [18], the body resistance for such touch voltage, considering a transversal path and 50% of human population will be 892.5Ω. In this situation, the produced body current will be 213mA. For this magnitude, according to Fig. 2, the risk of ventricular fibrilation and therefore death by electrocution is eminent for discharge durations beyond 600ms. The body current can be estimated by (6), since the DC bus has symmetrical rails, a positive or negative rail discharge will produce the same current magnitude, but with opposing polarities.

$$I_{body} = \frac{V_{CM} \pm V_B/2}{R_B} \tag{6}$$

Fig. 11 shows the simulation result for the connection of a 892.5Ω resistor, emulating the body resistance, between the negative rail and the ground plane of a double pole IT grounded system. It can be seen that the electric discharge

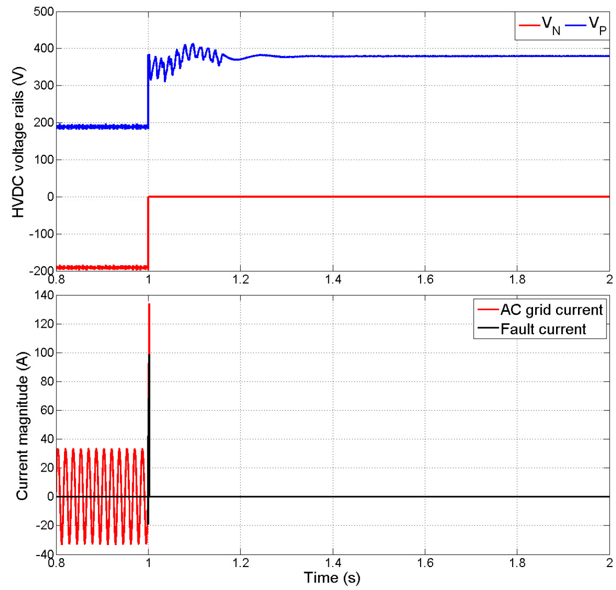

Fig. 10. Simulation results for the employment of AC circuit breakers during a DC ground fault.

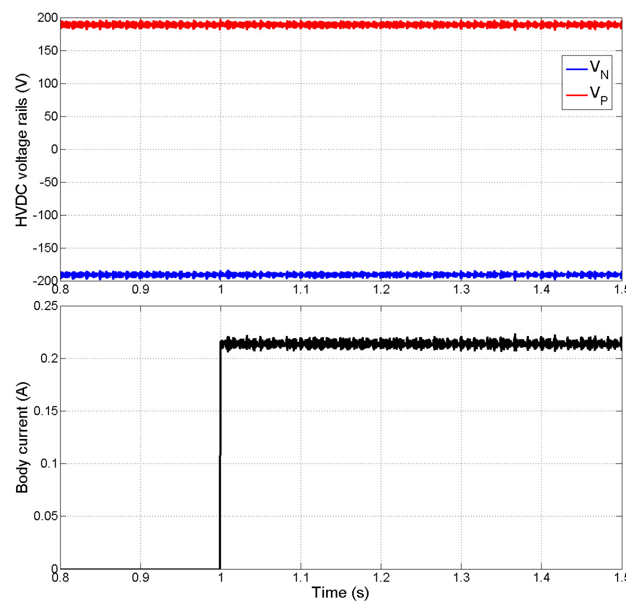

Fig. 11. Simulation results for a electric shock in a non-isolated double pole IT grounded system.

has a magnitude of approximately 215mA, as estimated, and it does not interfere with the system behavior. The simulation results show that, during grid-tie operation mode, the microgrid grounding resistors will not aid nor in fault current limiting nor in body current reduction. Therefore the employment of residual current protection devices is mandatory to ensure personal safety. However, DC residual current devices are not usually available in the market and its conventional AC counterparts can not be applied to this situation since ordinarily a current transformer is used to sense the residual current and thus it will not detect the DC residual current even if it was placed at the point of common coupling.

IV. Conclusion

This paper have discussed the effects of grounding schemes for residential DC microgrids on the system behavior against ground faults and electric shock. In isolated systems, the use of an IT grounding scheme based on high resistance grounding provides a more safe condition for the microgrid operation, since ground fault and body currents will flow through a high impedance path, thus the grounding resistor can be chosen to limit the currents magnitude to unharmful levels. This paper considered $10k\Omega$ resistors which produced body and fault currents around 38mA. In transformerless DC systems, on the other hand, the lack of isolation produces a common mode voltage between the microgrid and the utility grid which, even with the use of IT grounding schemes, common mode filters and compensation techniques, will promote high fault currents and dangerous body currents.

The non-isolated DC microgrid in grid-tie operation mode has not been able to handle the hazards of faults and electric shocks, demanding the employment of protection devices as circuit breakers and residual current devices. Simulations have shown that AC circuit breakers can be used in the AC point of common coupling effectively clearing ground fault current paths, and forcing the microgrid to operate in islanded mode, *i.e.*, as an isolated system, which will limit the fault current magnitude. However, the use of DC side circuit breakers is needed to allow the microgrid to maintain grid-tie operation since the local power generation and storage system cannot sustain the microgrid loads indefinitely. Regarding personal safety, the body current produced during an electric shock can achieve values around 215mA, which can induce ventricular fibrilation for exposures longer than 600ms. In order to ensure a safe environment, protection devices capable of quickly detecting and interrupting residual currents must be used at the DC side of the microgrid. Conventional AC residual current devices cannot be applied due to their measurement system which tends to employ a current transformer for residual current detection, hence not being fit for DC current sensing. Therefore, the development of such devices is still requiring a significant effort from researchers and engineering companies, since these products are still not promptly available in the market.

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