

CONTROL AND PROTECTION OF DC BASED RESIDENTIAL MICROGRID IN LVDC DISTRIBUTION SYSTEM

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ABSTRACT

In this paper, the control and protection of a residential direct current (DC) microgrid (MG) is studied. Of particular interest is an ungrounded building grid, which is also galvanically connected to the supplying low-voltage DC (LVDC) grid. The paper introduces a control strategy for the MG and analyses different faults with PSCAD simulations. A possible protection scheme for the grid is proposed.

INTRODUCTION

A growing and already significant share of modern electrical loads and distributed energy resources are DC based. Hence, DC distribution and building grids offer a natural interface for the devices, reducing the number of power conversions and consequently electrical losses. With a sufficient amount of local energy resources, the building may also operate as an islanded DC MG. Nevertheless, the usage of DC in LV grid and residential premises asks for protection schemes and control strategies, which are particularly designed for DC MGs.

This study focuses on DC-based residential MG, having a connection point to an LVDC distribution system. The ultimate purpose of the study is the analysis of the protection and control of such a residential grid. The analysis is based on a literature review and a PSCAD simulation of the investigated system. The rest of the paper will introduce the studied MG structure and control as they are implemented in the simulations. Furthermore, a protection scheme will be analyzed with the simulation model.

MICROGRID STRUCTURE

The simulations setup is implemented in PSCAD to represent the core components of a residential building grid. These components are an interface converter (IC), photovoltaic (PV) with a converter, battery with a converter, cables, and resistive and constant power loads.

The necessary controls are also modeled for the grid-connected and islanded operation. The structure of the studied grid is presented in Figure 1. Furthermore, the figure indicates the fault locations and measured variables discussed later in this paper.

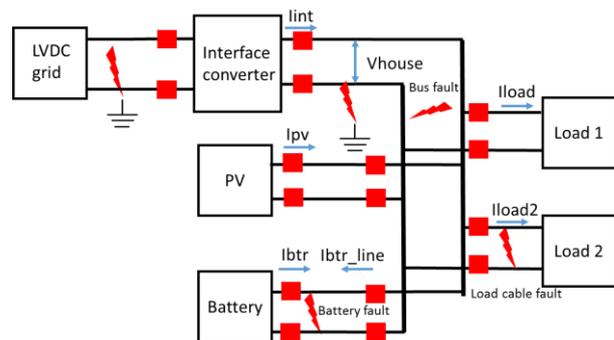


Figure 1: Structure of the studied system with fault and measurement locations. Circuit breaker locations are shown with the red squares.

The IC is a central component in the residential grid. It changes the voltage level for the customer grid, while affecting the overall performance and electrical configuration of the grid. When selecting the converter, several characteristics need to be considered, such as its voltage and current control settings, efficiency, and possible galvanic isolation. Adding a galvanic isolation to the customer connection point is a straightforward approach to simplify the customer grid design. It allows the customer grid to operate as grounded or ungrounded, independent from the distribution grid design. However, in DC grid, the galvanic isolation practically asks for a converter with a high frequency transformer, which complicates the converter design. Thus, non-isolated residential grid is also a viable option but the system protection should be designed accordingly. The study considers a case where the grid is ungrounded and the residential grid is connected to the distribution system through a galvanically non-isolated converter. For the MG, the modeled converters are:

- Interface converter: interleaved half-bridge (HB) non-isolated DC-DC converter
- Battery converter: HB non-isolated DC-DC converter
- PV converter: boost converter

In the studied MG of Figure 1, the LVDC grid feeding the building is modeled as an ideal voltage source with a rated voltage of 750 Vdc and a cable. All the lines in the figure are cables that are represented by a π equivalent circuit. The load 1 is a resistive load and the load 2 a constant power load. The PV and battery are modeled with the models available in PSCAD, while they are connected to the 380 Vdc building grid through their converters.

MICROGRID CONTROL

The IC provides a natural point for the MG formation, as a result of which it should have sufficient functionalities to perform the transitions between grid-connected and islanded operation. Furthermore, the building energy management should be implemented so that the PV generation is rather consumed locally or stored instead of excessive energy exchange with the LVDC grid. Any energy import or export through the IC causes some losses, reducing the building energy efficiency. It probably also increases customer's electricity bill.

The aforementioned challenge is tackled by the control of the building energy resources and converters. The battery converter is mainly responsible for grid-formation and voltage level management in the building. If the voltage level rises or drops due to power imbalance and exceeds certain voltage deadband, the interface converter starts to import or export. Thus, it participates in the power balance management only if power imbalance in the building is great enough. Table 1 summarizes the roles and controls of the interface, battery, and PV converters in both grid-connected and islanded modes. The control strategy has been inspired by, for example, [1].

The transitions between the modes are triggered by the distribution grid voltage if it drops below a defined threshold and when it is again restored. This is to say that the building grid becomes islanded in the case of a loss of the distribution grid voltage. If the voltage remains below the threshold value for a certain time, the interface converter is disconnected from the grid and shut down. In the case of transition from islanded to grid-connected operation, once distribution grid voltage rises above the threshold limit, the converter is connected to the grid and started-up. One should note here that the connection requires auxiliary power circuit to control the contactors. The circuit should be designed so that it remains powered even though there is a long blackout in the distribution system and the local resources in the building become exhausted.

Table 1: Control of the converter and their roles in grid-connected and islanded mode.

	Mode	Role	Controls
Interface	Grid-connected	Maintains power balance by importing and exporting if voltage rises/drops enough	Current, voltage, and droop with a deadband
	Islanded	Disconnected from the distribution and building grids.	-
Battery	Grid-connected	Maintains the voltage level in the building	Current and voltage. Hysteresis between buck and boost mode
	Islanded	Same as grid-connected	Same as grid-connected
PV	Grid-connected	Feeds the PV generation to the building grid	MPPT
	Islanded	Same as grid-connected	Same as grid-connected

MICROGRID PROTECTION

Protection is one challenge related to DC building grids. In general, the protection design aims to ensure human safety as well as protect the network components. Some guidelines are already given in the standardization [2]. For example, in ungrounded systems (IT grounding), touch voltage protection may not require fault clearance after first ground fault. Nevertheless, it is recommended that the first fault is cleared as soon as possible and at least alarm is given. Depending on the protective earth grounding, either TN or TT system clearance times are used for the second fault, that is, 0.1–1 s depending on the voltage level.

Potential protective devices for short-circuits are DC fuses, circuit breakers (CBs), molded case circuit breakers (MCCBs), and solid-state CBs, combined with possible relays. The control of converters can also be utilized to manage fault currents in certain cases. However, the challenge is generally the lack of sufficient fault current to cause the trip of the protective devices. The sizing of the IC's semiconductor components and its control reduces the fault current from the grid. On the other hand, local resources are able to supply fault current. For example, the fault current should be 4–7 times the nominal current of a CB to cause instantaneous trip [3]. In addition to the overcurrent protection, many studies suggest protective devices reacting to the current derivative (di/dt) (see e.g. [4]). A short-circuit in a DC system causes the DC-link capacitors of the converters to discharge, and the current derivative of this discharge current could be employed in the implementation of selective protection. For the ground fault protection of the ungrounded system, insulation monitoring devices (IMDs) can be used to detect the first ground fault and

give an alarm. The challenge with the IMDs is the fault location (and direction, i.e., whether it is in the supply or load side) that they may not be able to identify. However, some solutions are already commercially available.

SIMULATION OF FAULTS

This section discusses about different building grid faults, of which locations are shown in Figure 1. The resulting currents in the system are presented in Figure 2–Figure 4 so that the left-hand side subfigures are zoomed to the initial current transients and the right-hand side subfigures show a longer period. All the faults result in fast current transients and high currents peaks. The level of the constant fault current is mainly dictated by the current control of the IC and the short-circuit current from the battery. Its converter cannot control the fault current.

When a low impedance bus fault occurs in Figure 2 (top), only the cables between the source DC-link capacitors and the fault location limit the capacitor discharge current (I_{btr} and I_{pv} are initially overlapping due to same cable sizes). This results in high current derivatives (more than $1.4 \text{ kA}/50 \mu\text{s}$). When compared with the load cable fault in middle figures, the current derivatives of the interface, battery, and PV converters are way below this value (less than $0.6 \text{ kA}/50 \mu\text{s}$). At the beginning of the cable, instead, the derivative is approximately $1.4 \text{ kA}/50 \mu\text{s}$ (see I_{load2}). Thus, the derivative could be used to achieve selectivity between the bus and load cable faults. On the other hand, overcurrent CBs with time delays could also distinguish the two faults if the load cable protection trips faster than the bus protection. In such a case, the battery and its converter should withstand the fault current until the CB clears the fault. Alternatively, low impedance faults cause the bus voltage to drop so undervoltage relays with time delays could also be an option.

In the case of Figure 2 (bottom), the fault location is at the output terminals of the battery converter with nearly zero impedance between the location and the converter DC-link capacitor. Therefore, the capacitor empties within $50 \mu\text{s}$. For the PV and interface converters, the current derivatives are comparable with the ones in Figure 2 (middle). The faults in the source feeders (cable between the source and the bus) are fed from the source and the bus, i.e., from two directions. The source-side protection sees current derivatives and values greater than in the case of a bus fault and thus its tripping limits can be set accordingly. The bus-side protection, which protects the source cable, needs to react on fault currents flowing to the direction of the source. Thus, it needs to detect whether the fault is on the bus or feeder side. However, if the source cables are short enough, all the faults between the source and the bus could be cleared as bus faults, which simplifies the protection.

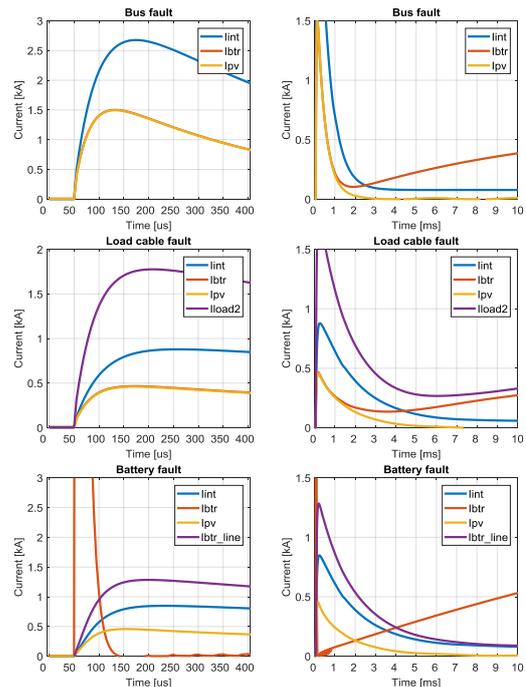


Figure 2: Short-circuit currents when the system is grid-connected. Bus fault (top), load cable fault (middle), battery converter terminal fault (bottom).

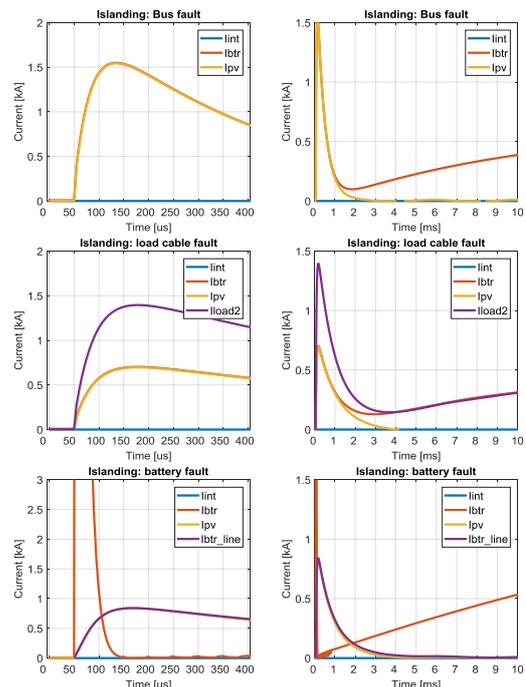


Figure 3: Short-circuit currents when the system is islanded. Bus fault (top), load cable fault (middle), battery converter terminal fault (bottom).

Figure 3 presents similar figures for the bus, load cable, and battery faults when the system is islanded. That is, fault current from the IC is not available. The load cable protection sees now lower current derivative so its setting should be based on the value occurring in islanded operation. In the case of battery fault, the studied system can not continue operation as the PV converter does not

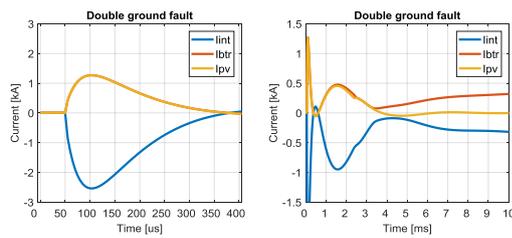


Figure 4: Double ground fault. Faults are on the distribution and building grid side of the IC.

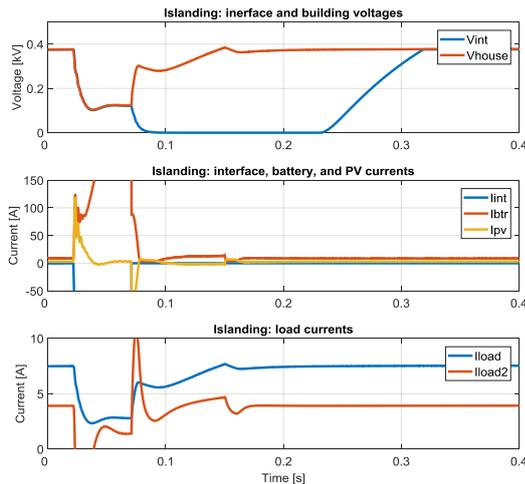


Figure 5: Transition to islanded and back to grid connected operation.

have the grid-forming capability. However, CBs of the battery cable should be set to clear this fault. From the PV and battery, the bus fault causes similar fault as in the case of grid-connected operation.

Figure 4 showcases the fault currents due to double ground fault. These faults could basically be avoided by removing the first ground fault when IMD gives an alarm. The double ground faults can be problematic, since the fault current may pass only part of the poles of the CBs, which can complicate the current interruption. Furthermore, as in the case of the simulated fault, the LVDC grid voltage level can be over the fault location. These aspects should be considered when selecting the protective devices.

Figure 5 show the transitions from the grid-connected mode to islanded and back. The transition is caused by a short-circuit in the distribution grid. First, the building voltage (V_{house}) drops before the interface converter is disconnected from the distribution grid at 0.08 s. It can be seen that there is a high current peak due to the discharge of the DC capacitor. Next, as the in-house voltage becomes lower than the battery voltage, the battery converter loses its control capability and battery discharges a high and constant current to the distribution grid through the anti-parallel diodes of the IC. This continues until the house becomes islanded. Once the islanding occurs, the building grid becomes isolated from

the faulty distribution grid and the battery converter is able to restore the in-house voltage. To preserve protection selectivity, the IC protection should be first to react on this fault. Right after the distribution grid voltage has been restored, the IC connects itself to the grid, charges the grid-side DC capacitor, and starts to charge the household-side capacitor. The charging slowly increases V_{int} until it matches with the in-house voltage level.

CONCLUSIONS

This paper studied a residential DC MG supplied by an LVDC grid. The control of the building grid was introduced and possible grid faults and protection schemes were analyzed. The simulations indicated that a selective short-circuit protection can be achieved with current derivative sensing relays, which detect derivative of DC-link capacitor discharge current. These relays can distinguish the faults at load cables, main bus, distribution grid, or source cables if their derivative settings can be adjusted and they measure the current direction. Use of time delays can help in implementing back-up protection for cable and load protection. Alternatively, selectivity between load feeder and bus faults can be achieved with overcurrent protection if the trip on bus fault is delayed. The challenge with overcurrent protection is the lack of fault current from the distribution grid. On the other hand, current derivative sensing devices are unable to detect overloading or may have difficulties to detect high impedance faults, which need to be cleared by other means. Ground faults can be detected with an IMD, which reduces the risk of double ground fault. The challenge with the IMD is to locate the fault as the building grid is galvanically connected to the distribution grid.

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