GUIDELINES FOR RESIDENTIAL CUSTOMER INTERFACE AND CONNECTION PRINCIPLES IN LVDC GRIDS

Antti ALAHÄIVÄLÄ
VTT – Finland
antti.alahaivala@vtt.fi

Jussi IKÄHEIMO
VTT – Finland
jussi.ikaheimo@vtt.fi

HongJoo KIM
KEPCO – Republic of Korea
hongjoo.kim@kepco.co.kr

Kari MÄKI
VTT – Finland
kari.maki@vtt.fi

Kim FORSSEN
VTT – Finland
kim.forssen@vtt.fi

Jintae CHO
KEPCO – Republic of Korea
jintaecho@kepco.co.kr

Anna KULMALA
VTT – Finland
anna.kulmala@vtt.fi

YoungPyo CHO
KEPCO – Republic of Korea
yp.zo@kepco.co.kr

JuYoung KIM
KEPCO – Republic of Korea
juyong@kepco.co.kr

ABSTRACT

Direct current (DC) grids have potential to improve the energy efficiency of residential buildings but general guidelines and established practices are yet missing for the residential DC grid implementations. Thus, this paper studies potential customer grid topologies in low-voltage DC (LVDC) grid and defines a customer interface for a DC customer. The defined interface together with the grid topologies help in understanding the different aspects of connecting a customer to an LVDC grid, which is the main outcome of the study.

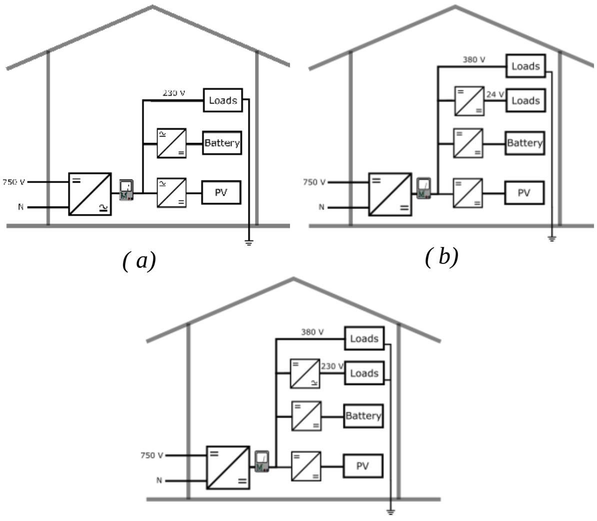
INTRODUCTION

In recent years, DC based low voltage grids have been applied in different electrical systems, ranging from public distribution to residential grids and microgrids [1]. If the distribution systems and building grids will increasingly shift from alternating current (AC) to DC, the customer connection principles need revising. This paper contributes by defining a residential customer interface for LVDC microgrids and by providing a comprehensive introduction on its components and functionalities. The customer interface indicates the point of grid between the distribution system and the customer grid. In addition to the interface, the paper describes possible customer grid topologies that can be connected to the distribution system through the interface. The topologies are mainly distinguished by the type of the in-house electrical system (AC, DC, or their combination). The main focus is on a customer with a DC system in the house.

CUSTOMER GRID TOPOLOGIES

The customer grid within the customer premises can have different electrical systems and topologies. Namely, the systems are AC, DC, or their hybrid (both AC and DC are present in the building). The topology, instead, states how these systems have been organized in the building and how the electricity distribution has been implemented in general. The selection of a suitable topology is dictated by the topology's efficiency, indicating the losses in the building's electrical system; reliability, e.g., a single converter may supply the building and thus, it is critical for continuous supply; and feasibility, i.e., the availability of technology and approaches to actually implement the topology in a residential building. The efficiency, reliability, and feasibility further depend on the type of building and its electrical system, the consumption of the building, possible local resources (e.g. photovoltaic (PV) and battery), used power electronic converters, and available appliances.

The basic structures for three different customer grid concepts are illustrated in Figure 1, where it can be seen how the loads and resources are divided between AC and DC buses. The full AC concept provides rather straightforward option from customer viewpoint, as the electricity delivery is AC inside the building. The LVDC distribution is converted to AC near the consumption point at the customer-end of low-voltage line. Therefore,



(a) (b)

(c)

Figure 1: Illustration of the full AC (a), full DC (b), and hybrid (c) topologies for a residential building.

all the domestic appliances can be used with their commercial power sources. The full DC concept is defined as an approach where the customer building contains only DC supply. This concept provides a great amount of variety in terms of the used DC bus voltages in the building. A hybrid system is characterized by the existence of both AC and DC buses inside a building. Naturally, when AC and DC with different voltage levels and the number of phases are under consideration, numerous topologies become possible.

Topology efficiency comparison

This section provides the comparison of the topologies based on their efficiency, that is, the topologies are compared in terms of the yearly losses due to the needed conversions (e.g. DC to AC, DC to DC). The comparison is performed for two example building types that are an electrically heated detached house and a district heated detached house. The topologies and building types are further compared with and without local generation. Both the building types have several load types (heating, cooking, washing, cooling, electronics, lighting [2]) divided between different buses according to the topologies. Each load type is assigned with a converter, of which efficiency depends on the building topology and the load bus that they are connected to. The conversion efficiencies are attained from the literature and they vary between 0.90–0.97 (see for example [3]).

The calculation of the annual losses consists of the following steps. Firstly, the electricity inputs for all the loads are solved by dividing their yearly consumptions by the conversion efficiency of their power source. Secondly, these solved consumptions are summed for each buses and the total consumption of the bus is divided by the bus-to-bus conversion efficiency. Finally, the input energies of all the bus-to-bus conversions are summed and divided by the efficiency of the interface converter.

The following lists the core observations based on the performed analysis:

- The efficiency of the topologies from the highest to the lowest is as follows: full DC, hybrid, and full AC.
- The utilization of local generation improves the efficiencies because of reduced import through the interface converter.
- The efficiency of DC grid can be improved if devices are designed to use directly the bus voltage levels (e.g. 24 V), which reduces the number of conversions.
- The number of subsequent conversions should be minimized as it affects the building efficiency dramatically (efficiency = efficiency* efficiency* efficiency, e.g. 0.95* 0.95* 0.95 = 0.86).
- The part load efficiency of interface converter (and bus-to-bus converter) should be paid attention. The interface converter can be low-loaded, e.g., at nighttime.

CUSTOMER INTERFACE

Customer interface is commonly defined as the point of common coupling where liabilities of network operator and individual customer meet. Customer interface represents a demarcation point between customer domain (customer loads, generation, storages, management systems, etc.) and external actors (service providers, distribution system operator (DSO), markets and aggregators) [4]. Its practical implementation consists of equipment, communication, software, and functionalities that connect a customer to the electrical grid and enable the customer to participate in its operation and to manage person's own electricity usage. A typical customer connection scheme and the interface are illustrated in Figure 2. The figure depicts the related physical grid infrastructure, information channel, and the division of liabilities. In the case of a LVDC grid, the customer interface contains a converter, which provides the desired voltage level to the customer grid. It may become more central and active component if functionalities, such as metering and protection, will be embedded to it in the future. In the figure's case, there is only one customer behind the converter, which can be the case, for example, with a single detached house. Nevertheless, single converter can also supply several customers.

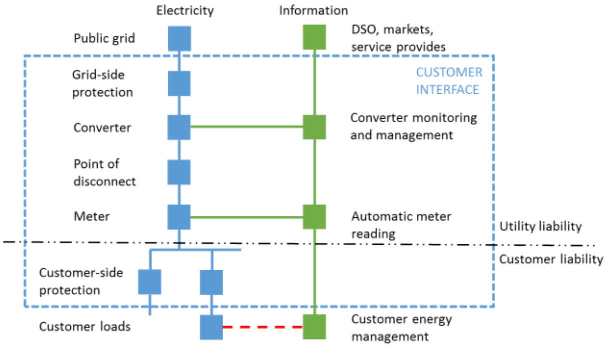


Figure 2: Typical customer connection scheme and the coverage of customer interface.

Interface functionalities

Customer interface should be built to include certain functionalities. These are summarized in the following:

- Energy use measurement for billing purposes
- Power quality measurements for management purposes
- Disconnection point between public grid and customer system
- Protection for separating customer side faults from public system
- Communication enabling information exchange (communication media and protocol)
- Logical interfacing of market controls
- Voltage level transformation if different voltage

levels are used in customer and distribution grids
- Control logic for transitions from grid-connected operation to islanded operation.

Interface components

Based on the interface definition and its functionalities, the main components of the interface are the converter, protective devices, metering devices, and an energy management system (EMS) with a user interface. The following introduces these components.

Converter

The converter is a central component in the customer interface of DC grid, since it affects the overall performance of the customer grid as well as its protection and safety. All the energy a customer needs to import or export flows through the converter, which is why it should operate with good efficiency even if partially loaded. Some other characteristics of the converters that underline their usage are the possible galvanic isolation and the ability to bidirectional operation. 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 grids, the galvanic isolation practically ask for converter with high frequency transformer, which complicates the converter design. In the case of an AC system in the building, 50 Hz isolation transformer is also possible but it increases the interface size and losses [5].

The number of different converter types and topologies is abundant. They all typically have certain advantages and abilities affecting their performance. When selecting the interface converter, it is advisable to pay attention to several aspects, which are discussed in Table 1.

Grid protection

Possible faults or secure threatening situations the interface may encounter as well as protection approaches are listed in Table 2. In addition to the fault protection, circuit breakers (CBs) and fuses should provide protection against overloading. The customer interface converter should be able to feed sufficient fault and load current to enable the operation of the protective devices. It should also be noted that the fault currents in DC grids are likely supplied by several sources, which can be, especially in microgrid application, batteries, distributed generation, and the point of common coupling with the rest of the electrical grid.

The proper planning of grounding and galvanic isolation in a DC grid is essential and it has a central role in the protection design. The grounding affects the transient currents and overvoltages as well as the performance of the protective devices. Grounding in residential low voltage networks is typically implemented as TN-C-S system, for example, in Finland. That is, neutral (N) and protective earth (PE) have a common grounding point. Furthermore, letters C and S indicate that both a common PEN conductor or separate N and PE conductors can be used inside a building. Other possibilities are to ground N and PE separately (TT system) or ground only the PE conductor (IT system) [6].

Table 1: General characteristics of the interface converter and their influences.

Characteristic	***Influence***	***Comments***
Efficiency	Cost-efficiency of the customer grid. Poor efficiency may decrease the advantageous of DC grids.	Partial load efficiency and the load profile of the building should be paid attention to. Modular converter topologies to improve efficiency.
Reliability	Depending on the building grid topology, the converter can be a critical component, of which failure results in blackout.	Use of fault tolerant converter topologies, fault detection and prognoses can improve reliability.
Price	The overall feasibility of the system	Interface converter market is currently niche or nonexistent, which is why the selection may be driven by availability rather than price.
Bidirectional/ unidirectional	Possibility of electricity export from the building to the distribution grid	Unidirectional converter can be sufficient if there is no generation or storage in the building.
Voltage control	Voltage quality within the building. Operation with other converters in the building.	Needs the grid forming capability to provide a stable voltage to the building. Voltage droop may also be needed.
Operation during fault	Fault current available for the in-house short-circuit protection. Possible automatic shut-down in the case of a fault. Reaction during a grid-side fault.	It should also be known how the converter operates during an internal fault. The converter components should withstand uncontrolled fault currents before protection clears the fault.
Galvanic isolation	Grounding and protection of the building grid. Overvoltage and voltage level against ground. Efficiency	Depending on the converter topology, the building grid may supply uncontrolled fault current to the distribution grid during a grid fault.
Rating	Load supplying capability (power rating), current feeding and overloading capability. Voltage range within of which the converter can operate.	Converter should not shut down during typical distribution grid voltage variations. Ratings are closely connected to the converter price.

There is no a direct requirement to isolate the customer network from the distribution system [7]. Principally, the isolation is required if the grounding system changes, e.g., from ungrounded to grounded, but the employed converter topologies can also affect the grounding and isolation solutions. Nevertheless, the grounding of customer network simplifies the protection and enables the use of current TN-C-S system. The grounding also removes possible voltage offsets that can appear due to leakage currents and the modulation of the converters.

Table 2: Customer interface related faults and protection approaches. In table, IMD stands for insulating monitoring device and RCD for residual current device.

	Fault	***Protection***	***Comments***
Grid-side faults	Overvoltage	Surge arrester on the high-voltage side, converter shut-down.	Protect the customer interface converter against climatic and other DC grid overvoltage
	Undervoltage	Converter shut-down	Depending on the converter, the manufacturer gives a certain operation voltage range within of which the converter can operate.
	Short-circuit	CB on the high-voltage side	CB can also enable the converter disconnection, e.g., for maintenance or if the system becomes islanded.
Customer -side faults	Short-circuit (pole to pole)	CB/fuses and converter current limits	Should be installed to protect converters, buses, cables, and loads.
	Ground-fault	IMD (IT system), 30 mA RCD (TT and TN systems), CB/fuses and converter current limits	RCD is used for human and fire protection if leakage currents occur. Correspondingly, IMD monitors potential insulation failures in ungrounded systems. IMD may not be able to detect the direction of the fault.
Converter faults	Switch fault	Converter control functionality, CB/fuses, surge arrester	Converter topology affects its operation in fault situations.

Metering, EMS, and user interface

The main principle is that measurement must always be located exactly at the customer connection point. The converter is likely owned by the DSO who also pays for the conversion losses. Thus, a natural location for the meter is on the customer side of the converter. Nevertheless, modern power electronic converters are not only used for voltage transformation, but they also enable many features typically associated with smart meters. With computing power and bidirectional communication capabilities, these smart converters would enable the constant control of output voltage, power quality data collection, and the maintenance of voltage and frequency quality. Thus, the converter could have a more central role also in the metering in the future.

The user interface (UI) defines all the actions different users are able to perform on the system in day-to-day operation, while providing information on the system state (e.g. real-time energy consumption) for the user. The UI can be connected to an EMS that is used to control the customer's energy consumption (e.g. reduces or shifts it) and maintain good indoor conditions [8]. In context of the DC system, the converter can also run at least a simple EMS application. Another possibility is to use dedicated hardware. In that case, a communication link between the EMS and the converter is still beneficial for load control applications.

CONCLUSIONS

This study focused on the utilization of LVDC grids in a residential building. Three potential customer grid topology concepts were introduced and compared based on their efficiency. A single best customer network topology does not exist but the development should be towards a full DC house if energy efficiency is the main target. In order to connect a DC customer to LVDC grid, the customer interface was studied in this paper. Conventionally, the interface consists of metering and protective devices but in the case of a DC grid, a power electronic converter is required in the network, causing pressure to revise the interface concept. The converter was identified to affect, for example, the system losses, fault currents, grounding, galvanic isolation, and voltage quality. On the other hand, it opens opportunities for metering, control, and protection of the customer grid.

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