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Review article

Is a massive deployment of renewable-based low voltage direct current microgrids feasible? Converters, protections, controllers, and social approach

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ABSTRACT

The main objective pursued by this survey is to debate the feasibility of a new distribution system in low voltage direct current (LVDC) microgrids and its impact on social development. To this end, this study provides valuable information for renewable energy planners and researchers, giving insights or solutions to reduce the transition gap between the current energy network and the future DC energy microgrids. Mainly, this article is divided into interlinking converters, protection schemes, and control systems, which have been analyzed taking into account the technical aspects of an LVDC microgrid as well as the social impact they have in poverty areas. This survey studies how low voltage DC networks can produce social welfare. In short, this paper assess social implications and technical issues, such as low inertia, grounding issues, voltage regulations, arc apparition, etc., providing a different approach to overcome these issues.

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1. Introduction

The European Commission created the European Technology and Innovation Platforms (ETIPs) to deal with the energy model transition. Its primary mission is to guide research, development, and innovation (RD&I) to provide support in European Countries in energy transition through Smart Networks for Energy Transition (SNET) (Intensys4eu, 2020). In their Strategic Research Agenda, they state that "research has to be focused on the low voltage direct current (LVDC) networks where PV and micro-generation should strongly increase their market share by 2035" (European Technology Platform SmartGrids, 2012). The fact that the vast majority of household loads (f.i. low consumption bulbs, TVs, computers, electronic appliances, photovoltaic (PV) generation, electric vehicles, etc.) will be using a DC stage by 2035 must be considered. This brings challenging questions: Is this configuration technically and economically feasible in the near future? Will it impact people's welfare positively?

A group of interconnected loads with Distributed Energy Resources (DER), such as RES and/or ESS within a well-delimited electrical boundary works as a unique controlled system with a utility grid (UG). The majority of the Distributed Generator (DG) is coupled with the low voltage side (Willenberg et al., 2019). Several authors have stated that low voltage microgrids could be one of the most cost-effective solutions to this policy objective (Lotfi and Khodaei, 2017; Nasir et al., 2018; Justo et al., 2013; Backhaus et al., 2015; Sanjeev et al., 2015; Kumar et al., 2017; Williamson et al., 2011). Microgrids emerge as the perfect complement to DERs when increasing the energy system's efficiency (Hesse et al., 2017; Palit and Sarangi, 2014; Gevelt and Holmes, 2015; Ramli et al., 2015; Castillo-Calzadilla et al., 2018; Fregosi et al., 2015; Vossos et al., 2014, 2018; Gerber et al., 2018, 2019) and they offer other advantages and benefits, such as increased quality (Lotfi and Khodaei, 2017; Liu and Li, 2014), improved resiliency (Gerber et al., 2018; Fregosi et al., 2015; Castillo-Calzadilla et al., 2019), cost and transmission loss reduction (Hofer et al., 2017), and other environmental benefits (Mumtaz and Bayram, 2017). For example, Fregosi et al. (2015) achieved efficiency improvements from 6% to 8% in a commercial building. Moreover, Hofer et al. (2017) showed that energy transformation losses can be minimized up to 30% in buildings with a net-zero energy balance for residential use, whereas (Hirsch et al., 2018) stated that losses represent a wastage from 5% to 15% of the energy generation. However, it is highlighted it would depend on the number of back-and-forth conversions. Vossos et al. (2014) claim that it is likely to save about 33% with a total transition to an off-grid DC model. And last but not least, according to Luo and Lie (2019), efficiency is improved by 30% when removing power losses due to the inverter.

Although MGs are a mature technology in LVDC, some challenges must still be overcome. The first one is the differences on how the microgrid connects to the UG (Rehman et al., 2020; Wang and Verbič, 2021; Castillo-Calzadilla et al., 2022). Moreover, there are significant differences on the distribution topologies (Fotopoulou et al., 2021). Another problem is the lack of a voltage standardization (Li et al., 2022). In addition, the lack of mechanic movement on the generation side leads to a decrease in inertia, which is mainly present in systems that depend on solid-state converters for producing electricity (Hailu et al., 2017). In addition, these systems raise problems related to the non-existence of zero crossing and the resistive nature of the DC systems (Sen and Mehraeen, 2019), leading to the apparition of arcs (Li et al., 2021). Finally, there are other problems like: harmonics (Gerber et al., 2022), virtual resistors (Augustine et al., 2016), voltage regulations (Jayan and Ghias, 2022; Jupke et al., 2021), the control of the bidirectional power flow (Baghaee et al., 2020; Zeng et al., 2021; Jayan and Ghias, 2022; Jupke et al., 2021), grid-forming (Chen et al., 2019a; Willenberg et al., 2019; Wang and Verbič, 2021), short circuit (Alluhaidan and Almutairy, 2017), etc.

The main aspiration of this paper is to comprehensively review the pros and cons of LVDC-MGs to help planners and designers to decide what sort of MG is the most suitable. In this document, we will focus on the last three (namely, interlinking converters, protection schemes, and control strategies) as the first four aspects have been already studied (Castillo-Calzadilla et al., 2022). The analysis is made from a technical point of view, but the link between LVDC-MGs and social development and welfare is also analyzed.

The structure of the paper is as follows: In Section 2, the basic configuration of the microgrids studied in this survey is presented. In Section 3, the methodology used to build this survey is explained. In Section 4, the different converters used for interconnecting with the grid are detailed. In Section 5, the most common protection schemes against over-currents, harmonics, low inertia, grounding issues, etc., are analyzed. Control techniques used for this sort of microgrids are introduced in Section 6. Although this is a highly technical survey, it is essential to highlight that it entails a social analysis attempting to link welfare to LVDC-MGs.

Nomenclature

AC	Alternating Current
DAB	Dual Active Bridge
DC	Direct Current
dc	Duty cycle
DER	Distributed Energy Resources
DSO	Distribution System Operators
EMI	Electromagnetic Interference
ESS	Energy Storage System
FCL	Fault Current Limiter
GA	Genetic Algorithm
GD	Gradient Descent
GSC	Grid-Side Converter
GVE	Grid Voltage Error
IGBT	Insulated-Gate Bipolar Transistor
KPI	Key Performance Indicator
LtG	Line-to-Ground
LtL	line-to-line
LtN	Line-to-neutral
LVRT	Low Voltage Ride-Through
MG	Microgrid
MILP	Mixed integer linear programming
MOV	Metal Oxide Varistor
MPPT	Maximum Power Point Tracker
PI	Proportional Integral
PLL	Phase Locked Loop
PSO	Particle Swarm Optimization
PWM	Pulse Width Modulation
RC-BDC	Reflex-Charging-Based Bidirectional DC Charger
RES	Renewable Energy Sources
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SC	Short Circuit
SCC	Short Circuit Capacity
SoC	State of Charge
SSCB	Solid State Circuit Breaker
SST	Solid-State Transformer
SW	Switches
TPC	Three Ports Converter
UG	Utility grid
VC	Virtual-Capacitance
VSC	Voltage source converter
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching

The social linkage between these topics and the welfare of communities which are upon energy poverty is discussed in Section 7. Lastly, Section 8 gathers conclusions and recommendations for future studies.

2. Low voltage direct current microgrids

This section aims to briefly explain the configuration of the LVDC systems that are explored in this survey. There may be different types of classification for these microgrids in accordance of the number of phase (uni-polar, bipolar or multi polar). Nonetheless, this survey will use the one deeply deployed in Castillo-Calzadilla et al. (2022). This features the microgrids in accordance to their interaction with the UG. These are grouped as Grid-connected (red), off-grid (green) mode (Mumtaz and Bayram, 2017; Wang et al., 2018; Castillo-Calzadilla et al., 2018) partially-connected (yellow) (Castillo-Calzadilla et al., 2022). The typical diagram of these system could be found in Fig. 1 While grid-connected grids need to be constantly linked to the UG from the distribution system operators (DSO), off-grids will never be connected to it. Partially connected grids connect and disconnect from the UG depending on its needs. The Fig. 1 shows how the LVDC grids might have a wide variety of energy share, like wind, PV, storage systems from static batteries or movable ones like EVs.

As this paper only deals with interlinking converters, protection schemes and control strategies, each of them will be defined in this introductory section. Their definition and role for these type of systems is stated as follows:

- Interlinking converters: Converters are widely used, as their name hints, to change the qualities/characteristics of a specific signal into another totally different. F.i., this is the case of AC-DC converters where an ever-changing sinusoidal periodic (1/frequency) signal is turned into a DC that lacks frequency and always remains the same. The converters are considered a cornerstone of MGs because they play a crucial role in the performance of DC-MGs as network traders (Ordono et al., 2019) by interconnecting the LVDC-MG with the UG, exchanging energy surpluses, or supplying energy when the network cannot meet its own energy consumption. In this survey, we have classified the converters in accordance with its type and labor in the external interconnection or between buses at different voltage levels.
- Protection schemes: Protection is easily understandable, there are no single systems that do not include these schemes within the microgrids. Power protection is mandatory across the globe for two reasons: to avoid accidents that might cost lives and to keep the operation of these power systems through time, maintaining the resilience against disturbances or instabilities in the network. The protection schemes for LVDC systems are crucial, so this aspect must be strongly considered for network designers and planners. In this paper, we have gathered a wide range of scheme of protections, such as: current based, grounding archetypes, instability issues, and protection devices. To provide reliability and safe to the owners.
- Control strategies: For this study, control comprises strategies that act on different devices of the LVDC microgrid to make their behavior meet the set-point required in a specific moment during operation. These control strategies can be fixed, dynamic, or hybrid. This section tackles the existing issues when dealing with low voltage DC microgrids, either grid-connected or off-grid, such as: low-inertia control, arc-apparition, grid-forming, etc. Each control technique used on this sort of facility is also detailed.

3. Survey methodology

Two queries were performed to systematically retrieve the literature: one for the SCOPUS database and one for WOS (Table 1). The results were combined to remove duplicates (Calzadilla et al., 2022) and were uploaded on https://doi.org/10.5281/zenodo.5914926. Moreover, entries that appeared out of the scope and that were not the focus of this research, such as *grid connections, distribution topologies, voltage standardization*), were removed.

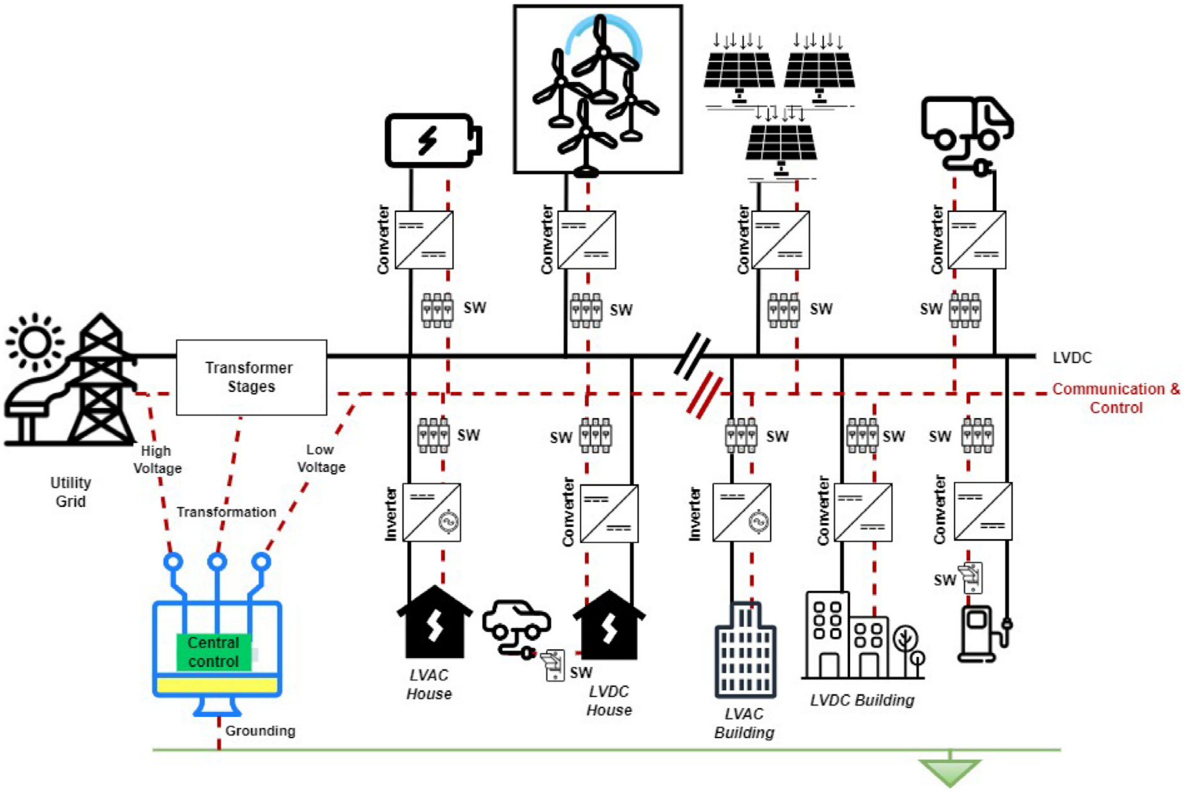


Fig. 1. LVDC microgrids interacting with utility grid.

Table 1
Queries performed on SCOPUS and WOS databases.

Database	Query	Results
SCOPUS	(TITLE-ABS-KEY (“Low-voltage”) AND TITLE-ABS-KEY (“DC”) AND TITLE-ABS-KEY (“microgrid”)) AND (PUBYEAR AFT 2013) AND (LIMIT-TO (SUBJAREA, “ENGI”) OR LIMIT-TO (SUBJAREA, “ENER”))	392
WOS	TI = (“low voltage” AND “DC” AND “microgrid”)	50

Finally, the list was completed with our own set of articles that addressed the subject. In the end, 198 articles were reviewed, and a template was completed with the former points and the solutions proposed and the main conclusions of the reviewed articles related to the scope of the survey (interlinking converters, protection schemes, and control strategies).

4. Interlinking converters

In this part of the survey, a thorough analysis of the power electronic converters implemented at DC-MGs has been carried out. The interlinking converter is a key component for the next generation of DC-MGs because they guarantee power control and they improve the power quality using different ancillary services (Ordono et al., 2019; Iskender and Genc, 2020). These systems can be made using either diodes or thyristors as both are unidirectional. The power flow topologies of diodes and thyristors are highly affected by low order harmonics in the current lines, which come up generally below 2 kHz (Kumar et al., 2017). Generally speaking, the feature that differences converters is that, with diodes, there is no control on the signal conversion, while thyristors are controllable by shooting the gate (changing duty cycle (dc)), helping control the energy conversion process (Bacha et al., 2014). This controlling ability is made using a pulse width modulation (PWM) to modify the converter's dc (Olivares-Rodríguez et al., 2018). Iskender and Genc (2020) highlights the modulation technique: the DC-bus can be supplied by a one-line or two-line AC-DC rectifier in the three-phase configuration. The 12-pulse, half-controlled circuit is the easiest AC-DC topology in low voltage DC grids. The DC-bus circulating current can be restricted by the defined shoot angle of the thyristors. These circuits are biased, which means that one-direction electrons flow only. The secondary windings of the AC-DC circuit are powered by a 3-phase transformer connected in a star and delta configuration to decrease the output DC voltage ripple ratio by producing a phase shift of 30 between the secondary windings.

Another essential feature is the possibility of operating from a single phase to three phases (it is also possible to operate in a greater number of phases). When the system operates in three phases, switches in line 1 to line 3 are controlled by a symmetrical phase shift of 120°. It is worth mentioning that converters are usually controlled under the maximum power point (MPP) approach for extracting as much energy as possible from the renewable source (Liu et al., 2016), which is the case of PV renewable-based LVDC-MGs (Ammous and Morel, 2014). There are about 40 Maximum Power Point Tracker (MPPT) algorithms implemented to maintain the PV-facility operating optimally by re-adapting dc values through their modification, f.i. using PWM, sinusoidal pulse-width modulation (SPWM), etc. Verma et al. (2016). The aspects analyzed in this section are outlined as follows: AC-DC rectifiers, DC-DC converters, DC-AC inverters, switching techniques, issues and variations of DC-DC converters. The converter, rectifier, and inverter are shown in Fig. 1 these are implemented to transform DC voltage into other DC voltage with different levels; to transform AC voltage into DC one to be further stored or supply the DC loads, and to transform DC voltage into AC one to be further poured in the DSO grids or supply the AC loads respectively. Roughly speaking converters are a kind of energy traders for the LVDC systems, they are so capital for these grids that without them would not be feasible the deployment of these cutting-edge grids.

4.1. AC-DC rectifier

There are many aspects that reduce the energy efficiency of power converters. According to Luo and Lie (2019), the low performance (up to 26%) of the traditional AC rectifiers provoke a deteriorated input current waveform drawn from the UG. These diode-based rectifiers have low transmission intervals and the line current is composed by pulses with high harmonic content. The IEEE 519 standard defines the harmonics limits for LVDC systems: individual harmonic 5.0% and total harmonic distortion (THD) 8.0% (Anon, 2014).

Consequently, it is required to minimize the unpure sinusoidal currents of these rectifiers and the harmonics of line current to meet harmonic standards. Furthermore, harmonics reduce the power factor (PF), produce significant losses, and reduce the peak power capacity of the line cabling. Thus, they cause additional losses in capacitors, electromagnetic interference (EMI), and stress the dielectric. These issues are crucial for traditional AC-DC rectifiers. The process of rectification impacts the other customers connected to the same network, reducing the power quality of the grid due to high presence of harmonic. The transformers implemented in distribution are also affected by these significant harmonics currents values, resulting in higher electricity costs (Iskender and Genc, 2020).

There are several solutions to diminish the harmonics from the line, f.i., adding a properly-sized passive filter connected to the direct current connection and/or to the alternating current side of the AC-DC rectifier. A link of capacitance is required to smooth and regulate the output (DC) voltage (Kumar et al., 2017). There is a straight relation between the size of the capacitor filter and the ripple of the system's output (Iskender and Genc, 2020; Mohammadi et al., 2021). Consequently, if the capacitor is big enough, the ripple will vanish. Otherwise, the system will have a voltage with more fluctuations than desired.

These converters are perfectly re-configurable, such as AC-DC rectifiers connected in series to DC-DC converters to meet standards of quality required for the grid. These combinations raise the power factor and reduce harmonic presence in the network. Gerber et al. (2019) claims that there are not many losses in diode bridge rectifiers. Boost rectifiers with power factor correction (PFC) are significantly less efficient. It is stated that electronic equipment is easily downsized by eliminating adaptors, and this will allow the use of DC input, enhancing energy quality and reducing the size of DC condensers.

4.2. DC-DC converter

These type of converters are crucial for the massive implementation of LVDC based systems. Nonetheless, there are still a few issues to overcome before a successful integration of DER and UG. These are harmonics (Eto et al., 2020; Pudota and Srikanth Reddy, 2016), non-zero crossing (Agrawal et al., 2019; Kumar et al., 2017), current ripple (Wang et al., 2018; Jayan and Ghias, 2022), voltage stress (Moradisizkoohi et al., 2018; Wu et al., 2013; Prabhakaran and Agarwal, 2016), etc. The most popular converters are buck, boost, and buck-boost. All of them deliver a DC output after modifying the DC input using dc firing pulses. Due to the usual combination with AC-DC converters (rectifiers), the DC-DC converters inherit some of the rectifiers' issues, like harmonics. This problem is solved by implementing active power filters (Pudota and Srikanth Reddy, 2016). Meanwhile, it is stated that using the shunt active power filter achieves up to 0.99 power factor correction results in almost the ideal threshold (Kumar and Bansal, 2018).

Moreover, a boost converter is designed based on a series of resonant converter schemes (Zhao et al., 2019). It is meant to be a multi-purpose solution used to increase the energy quality and read just the output signal. The proposed boost converter uses a double-firing pulse DC modulation method to step up the voltage. The boost converter reached up to 98.9% of efficiency under rated input voltage conditions. In the way proposed, the output switch-gear performs both the synchronous rectification function and the voltage boost function (Zhao et al., 2019). However, a modular multilevel converter (MMC) that achieves up to 99.4% of efficiency when the main DC-grid is left floating was simulated. It was specially tailored to support LVDC buildings, such as those addressed in this survey (Lachichi et al., 2019).

Although DC-DC converters do not have low frequency problems like AC-DC converters, they do have issues such as the non-existence of natural zero crossing, which is inherent to AC signals. This is known as natural commutation, making switching off the converter difficult. A control strategy with zero circulating power flow (ZCPF) to deal with DC-DC converters was successfully designed and tested. The ZCPF was implemented in a solid-state transformer (SST) and in energy storage devices (ESD), both using the dual active bridge (DAB). This set-up also reduces SST-DAB and ESD-DAB's current stress, and results show net systems efficiency between 90% to 95%, accomplishing the desired purpose (Agrawal et al., 2019).

Meanwhile, a DAB is implemented on the high-voltage section and a buck-boost converter on the LVDC section. This strategy uses the phase-shifting control method with DC adjustment to make bidirectional energy transmission among a triple ports converter (TPC). In the end, the energy transmission features of the TPC resulted in efficiency. The isolated TPC with a low voltage DC-bus was suitable for integrating PV&ESS systems or hybrid ESS at DC-MGs. Furthermore, TPC achieves high power density, power insulation and voltage coupling on both the low voltage and high voltage sides. Additionally, the current ripple and the amount of switching devices are decreased by using an interleaved design and multiplex switch-gear devices on the low voltage side. Based on the results, the power transmission capability and current ripple cancellation have impact on TPC. In the best scenario, a ripple output current of port 1 of only 0.6 A was achieved, unlike the previous 4.5 A with a single filter coil, and after adding the interleaved structure (Wang et al., 2018).

To sustain high efficiency, a new four-port, dual-input, dual-output (DIDO) DC-DC converter topology is proposed to interconnect solar photovoltaic and fuel cell (FC) power sources to a bipolar low voltage microgrid (BDC-MG) (Prabhakaran and Agarwal, 2020). The main benefit of the converter proposed is that it can work in SISO mode (single-input-single-output). In this case, it was tailored to operate in a rated output port of 24 V, enabling the bus to provide 48 V. This converter resulted in a compact-sized unit, less-expensive and effective than its counterparts since it only required two switches and one inductance.

In this regard, Moradisizkoohi et al. (2018) proposed a soft-switched boost converter by adding a build-in double half-bridge. They implemented the voltage booster definition and a double half-bridge rectifier, both integrated at the output to boost the gain of voltage by recycling the leakage energy to the output capacitors. For reducing the voltage stress across switches, diodes, and capacitors, the symmetrical voltage step-up amplifier is implemented in the rectifier phase, which ensures uniform voltage distribution between the output diodes. A boost DC-DC converter coil coupled to reduce the voltage stress was designed (Ai and Lin, 2018). In this paper, the three diodes were working on the ZCS turn-off, thereby, the losses were reduced, and the reverse-recovery problem was avoided. On the other hand, the rate of falling current is properly limited for the leakage inductor. Thus, its reverse-recovery problem is efficiently solved. The two capacitors are part of the clamped circuit, which are connected by a positive pole, resulting in a reduction of voltage stresses, a proper voltage step-up, and improvement of efficiency.

A soft-switching method is defined as ZVS of switches and ZCS of diodes. A technique is proposed for a triple-phase, bidirectional DC-DC converter (Sobrayen and Rathore, 2016). This modulation strategy multiplies the input current and output voltage ripple frequencies by a factor of 3, lowering the filtering needs. This technique is ZCS of all primary switch-gear and ZVS of secondary switch-gear. With no need for active blocking or passive damping, ZCS is accomplished by secondary modulation, which inherently blocks the output voltage reflected from the primary devices, thus removing the problem of voltage spikes associated with current-fed converters. This system is favored by soft-switching commutation and based on the natural commutation of diodes. It remarkably helps to diminish switching losses significantly.

Despite the similarities between Sobrayen and Rathore (2016) and Prajof and Agarwal (2015), a new boost-SEPIC (single-ended primary-inductor converter) interleaved type DC-DC converter is proposed for a +24 V and −24 V bipolar LVDC PV microgrid. A combination in parallel of both boost and SEPIC converter with two outputs for a bipolar LVDC-MG is also proposed. Both Sobrayen and Rathore (2016) and Prajof and Agarwal (2015) worked with low voltage-high-current applications. However, the interleaving effect of the source inductors guarantees a low ripple current drawn from the photovoltaic source, which increases the MPPT efficiency, resulting in good performance of the proposed converter (Prajof and Agarwal, 2015).

A simple decoupling control method for isolated three-port bidirectional converters is proposed for bridging converters in power generation units (Wang et al., 2015). This is a phase-shifting control scheme with a three-port isolated H-bridge converter. By combining this approach and closed-loop strategy of control, the power flow from port 1 to port 2 and from port 1 to port 3 is properly decoupled. This approach is effective for voltage and current tuning in the system and obtains good transient performance under external disturbances, which are quickly controlled to the limits set formerly.

Another research (Lin and Liu, 2018) proposed a parallel full-bridge converter, which has less ripple current and balance load current for LVDC systems. These two full-bridge circuits use the same active switches at lagging-leg. Hence, the lagging-leg switches' ZVS span is enhanced. Current doubler rectifiers are adopted to decrease ripple current on output inductors and capacitors.

Output voltage regulation and low switching loss are reached through the use of a PSPWM (phase shift pulse width modulation) mode. The former studies have shown a wide range of applications for tackling the power-sharing interchange with the MG. A triple active bridge (TAB) DC-DC converter composed for a three-winding transformer and power switches devices made of gallium nitride (GaN) is presented (Yu et al., 2017) as a result of the proposed phase-shift control strategy which consists of a variation of the phase-shift angle among three ports of the converter. The authors concluded that this is perfectly suitable for low voltage distribution due to its high performance lowering the current stress. Therefore, the PV capacitor filter can be reduced because the ripple current drawn from the supply is about zero. In the same line, a capacitor is coupled between the PV module and the DC-DC boost converter to minimize the high-frequency harmonics produced by the DC-AC (inverter) modulation to avoid the introduction of harmonics into UG (Jain et al., 2018).

4.3. DC-AC inverter

Even though this survey is clearly defined to LVDC systems, the use of the inverter (DC-AC) is crucial when interacting with the UG. The DC-AC inverter is the interface between DER such as ESS, PV, wind systems and the UG. The converters (DC-AC inverters) present a lack of grid-forming capability, which raises concerns among designers, operators and others.

Grid-forming converters are raising as an option over grid-following converters because grid-forming are capable to operate steadily in inertia-less grids, like the MGs formed with renewable sources. Renewable systems, like the studied in this paper, have very low inertia or non at all because they lack mechanical parts (rotating mass). Grid-forming converters provide the MG with the voltage and frequency needed for the energy interchange between both systems. Due to the high penetration of DER, grid-following converters tend to fall into unbalances, which can lead to shortage in the grid and reduction in the electricity's quality. Grid-forming converters have arisen to avoid the power unbalances or outages and make the DER integration more friendly (Chen et al., 2019a; Deng et al., 2020). These converters seem to work as gateway between UG and the local MG. A possible workaround to reduce the apparition of the DER grid problems is to use grid-forming converters as voltage sources instead of using external voltage references mainly provided by the UG (Wang and Verbič, 2021).

After analyzing this problem, we have found two main approaches when dealing with grid-forming issues. The first is based on a frequency regulation strategy (Willenberg et al., 2019), and seeks to compensate the power imbalances. This reaches an approximation to frequency operation (50 Hz) of 97% by minimizing the active power of the grid to a minimum and avoiding unnecessary frequency adjustment. The second approach is based on the droop control strategy to minimize the PV DC-bus power oscillation by using fast current limiting avoiding over-current trips during deep voltage drops. The over-current limiting approach is built employing the negative sequence current control to compensate the output currents and finally minimize the DC-bus instabilities (Chen et al., 2019a). According to Chen et al. (2019a), the low-voltage ride through (LVRT) capability is used to deal with grid-forming issues. Nonetheless, this has been oriented to regulate both voltage and frequency under 3-phase symmetrical voltage sags, providing voltage support during grid faults, and diminishing the likelihood of being overloaded (Deng et al., 2020). When the grid voltage drops, the active power is reduced by the controller limiting the current first and maintaining the voltage amplitude to provide more voltage support to the grid and the local load. On the other hand, a detailed analysis of the switching of the voltage source mode and the current source mode of the grid-forming inverter during voltage drops is studied (Zhang et al., 2020). This study presents an universal approach to analyze dynamic characteristics of the grid-forming inverter during and after LVRT. Due to current saturation, the grid-forming inverter is switched from a voltage source to a current source during the LVRT process, then changing the trajectory of the system operating point. This trajectory switching may cause the instabilities. In the experimentation this method was capable to maintain the current saturation state about 0.8 s.

This study (Wang and Verbič, 2021) clearly points at droop approach control strategy as the primary responsible of grid instabilities. Authors of this study revealed that the source of these instabilities are linked to the number of grid-forming inverters. The study conducted concluded the following:

- LVDC feeders working as off-grid mode increase instabilities with the addition of more grid-forming converters;
- The eigenvalue suffers changes during electrical network expansion from a pair of complex eigenvalues associated with the buckling controller to a real eigenvalue basically sensitive to the system size;
- The adjustment of droop and voltage control can reduce the instabilities issues;
- The direct current section voltage regulator is very linked to network stability since this introduces new dominant eigenvalues;
- The supply source would adversely impact stability due to the lack of rapid dynamic response.

A real size experiment conducted by the National Renewable Energy Laboratory (NREL) and General Electric (GE) proved that a wind turbine is capable of providing primary frequency and voltage support (Clark, 2022). This set-up comprises a 5 MW dynamometer that operates as electromotive force, which allowed emulating different grid dynamics. The control restarted the nearby electric network by regulating its output power to act from instantaneous electrical variances. The leaders of the project concluded GE's grid-forming controllers would provide phase-hopping power and inertia similar to that of a synchronous machine, which is a capital feature to add stability to the grid.

Between grid-forming and grid-following, there is a wide gap that is worth highlighting. The main differences are (Yuan et al., 2021; Gao et al., 2022; Deng et al., 2020; Collados-Rodriguez et al., 2021):

- Grid-forming acts like a voltage source whereas grid-following is a current source. A grid-forming voltage source converter (VSC) is predominantly inductive with low amplitude, meanwhile a grid-following VSCs is mainly capable with high amplitude in the middle-frequency.
- Grid-forming converters rely on a LVRT scheme which improves their operation in weak and low inertia grids, meanwhile grid-following converters based on PLL or similar structure are implemented to track the angle, frequency, and voltage of the AC grid.
- Grid-forming control is very linked to the virtual synchronous generator (VSG) control, which enables the converter to mimic the characteristics of synchronous generators to provide inertia and damping for the UG. On the other hand, the grid-following control provides a quick response but lacks inertia for matching to the power grid.
- Grid-forming converters have little signal instability problems. Yet, grid-forming lose the stability in stiff grids, because little phase difference between the converter and grid voltages may lead to large active power fluctuations. On the other hand, grid-following converters lose the stability in a weak power grid because of the asymmetric positive-feedback mechanism introduced by the PLL structure.

It is worth highlighting the difference between the grid (following and forming) converters. Firstly, grid-following converters are strikingly related to produce power that closely follows the frequency and voltage of the overall power grid. The type of grid-following inverter disconnects power when there is a major disturbance or grid outage and wait for a signal that the disturbance has subsided and it is safe to restart.

Grid-following inverters will help recovering the grid after a fault, black-start after a power system outage could pose a challenge for situations where inverter-based generation sources have replaced the majority of synchronous resources. Grid-following inverters may have limited restoration support capabilities because they rely heavily on externally generated voltages and frequencies from synchronous machines to operate. Viewed from the AC output ports, they operate as a current source whose real and reactive output follows the references. On the other hand, inverter-based grid-forming supplies are designed to set the control voltage and frequency autonomously, so they could be designed both to provide black-start capability and to ease network recovery after a blackout. This inverter-based converter, in contrast with grid-following, can be considered as a voltage source on the terminal output (Clark, 2022; Eto et al., 2020).

4.4. Main conclusions

The rectifiers, converters, and inverters, can work as either boosters or reducers of a DC signal which make more suitable pouring into DC distribution. Bridges for converting the AC waveform into DC signal, DC-DC converters to re-adjust the output value Castillo-Calzadilla et al. (2019), and finally taking a DC signal and transforming it to AC respectively are needed. As can be seen Table 2, all former converters have different objectives in a LVDC systems, but all are required to make the massive deployment of this DERs-based electricity scheme. Consequently, DC systems are coming up as the best way to make a much more efficient use of RES.

In summary, we can divide the issues that arise when dealing with the converters into two main groups. Firstly, AC-DC rectifier issues related to ripple and harmonic generation on DC output are usually minimized by implementing strategies supported by active capacitor filters.

Moreover, the main problem of DC-DC converters is the non-zero crossing, which makes the current extinction more challenging. Nonetheless, there are a few other issues such as voltage stress, current stress, maintaining high efficiency without ringing, and spikes, interface RES and ESS units issues, etc. There have been some approaches argued in previous sections to troubleshoot these issues, such as dealing with the voltage stress of switch-gears, which required the active-clamp circuit and the DC control adjustment. Last but no least, switch-gears are more costly than the AC counterparts.

Finally, DC-AC converters (f.i. grid-forming converters) can operate upon strikingly low synchronous converter scheme. Nonetheless, the increasing addition to the systems is not making the system stronger or weaker. As long as these converters starts to replace the synchronous systems, the UG would become unstable (P. Marinakis, 2021). This is may be one of the biggest challenges from the point of view of a future 100% non-synchronous (DER) system based on low voltage DC because it adds more instability to UG.

5. Protection schemes

Working with LVDC makes it necessary to incorporate new safety mechanisms, especially due to the non-zero crossing feature, which makes the interruption or disconnection of the DC line more critical in the event of an unforeseen fault or any safety issue derived from the undesired behavior of some part of the network or parameter variation. This section is structured according to the network parameters used to manage the network's safety, which generally consider disconnecting parts of it such as the line current, the ground connections, the network's stability, or the protection equipment.

Table 2
Main power converters configurations.

Signal implication		Aimed to	Appeal to	Direction
DC-DC Converter	Buck Boost Buck-Boost	to reduce the input voltage to increase the input voltage either to reduce or to increase the voltage	PV systems, Batteries, Fuel-Cells, DC loads	They can operate both in a unidirectional (to connect RES to the distribution grid) or bidirectional way (only for storing energy in ESS) (Guerrero et al., 2017; Liu et al., 2015; Wang et al., 2018; Dantonio et al., 2019; Silva Ortigoza et al., 2017)
AC-DC Rectifier	Half-bridge Full-bridge	to convert half of AC wave into DC one to convert the full AC wave into DC one	Wind-turbines, AC sources, DC loads	Unidirectional to provide the renewable (e.g. wind-turbine) either or fossil (e.g. utility grid) to the distribution system (Zhao et al., 2019; Lin and Wang, 2018; Gorji et al., 2019; Choi et al., 2011; Wu et al., 2016; Emhemed and Burt, 2013)
DC-AC inverter	Half-bridge Full-bridge Grid-forming /following	to convert DC voltage into AC one to convert DC voltage into AC one to restart the utility grid independently and correct the unbalances produced by the lack of synchronous machinery	AC-sources, AC loads	Bidirectional (to connect the MG to utility grid and pour the surpluses either or to supply energy from utility grid to the MG (Karimi et al., 2013; Rigogiannis et al., 2021; Agrawal et al., 2019; Joseph et al., 2017; Deng et al., 2020; Wang et al., 2015)

Although there are standardized protection schemes for AC systems being used at LVDC-MGs, most of them are not valid for LVDC because DC systems contain more hazardous transients than AC (Pramudya et al., 2016). Microgrids, which work as grid-connected and also in off-grid mode, carry more challenges. Therefore, more sophisticated protection schemes are required for the reliable and safe operation of LVDC-MG (Chatterjee et al., 2015). We have gathered all the protection schemes based on sensing and regulating at the low-voltage DC-MG. These had been classified into current-based, grounding types, instability issues, and protection equipment for LVDC-MGs.

5.1. Current-based

As mentioned above, this section has been classified as current-based since the method dealt with presents faults in the current path and short circuit capacity (SSC). SCC can be defined as the inherent robustness or capability of the power system to cope with the product of the short circuit current magnitude and the rated voltage of the short circuit position (Xu et al., 2019). Roughly speaking, this is the protection's size of the elements which are parts of the LVDC-MG to avoid the occurrence of SCs.

5.1.1. Fault in current path

Firstly, a short circuit (SC) is defined as an unwanted connection between two nodes with zero or very low resistance, either by accident or natural causes (Yaqobi et al., 2019). In this survey, these paths are called channels and are used to interface with either LVDC-MG or AC-MGs and other components into the distributed energy resources (DER). Any failure in a current channel might be catastrophic for an LVDC-MG. The most extreme fault can be a SC. However, exceeding the established levels can generate significant problems due to the stressed line, automatic, and unplanned interruption. We can distinguish between detection of the fault and the immediate reaction by interrupting the line flow, stopping propagating the fault to the rest of the network, and finally fixing the network's fault. To each of these aspects, the literature offers mechanisms and strategies which improve the efficiency or speed of these actions (O et al., 2022).

Generally, these channels are made using either flexible cables or copper bars as routers that head the power flow. These channels are protected using breakers for interrupting the current flow during a faulty operation, avoiding damaging them. In this regard, it is claimed that inductances can effectively decrease the current stresses at the lower impact on the steady-state losses (Javed et al., 2019). Yet, the author presents a resistor-based approach to handle this drawback. They stated that the resistive method has a positive effect on limiting and steady state DC current. Nonetheless, it negatively affects the systems since it produces bigger losses than the inductance-based strategy. Thus, by keeping the losses in the systems as low as possible, the superconductivity approach is used to limit the current flow by implementing a fault current limiter (FCL), which eases the alteration of the resistor value, increasing as quick as it is activated and achieving its thermal or current limits.

Meanwhile, a methodology based on the implementation of thyristor for a fast recovery of the systems after an interruption in power supply is adopted (Zhou et al., 2020). This approach has an advantage over the conventional methods because it speeds up the trigger and, thus, reduces the size of the breaker required. Nowadays, solid-state switches such as an insulated-gate bipolar transistor (IGBT), gate turn-off (GTO), silicon-controlled rectifier (SCR), and others, make faster interruptions on the current flow, which is why they are considered the most prominent element on novel LVDC-MGs for protection issues.

However, Alluhaidan and Almutairy (2017) concluded that the use of FCL based on thyristor is unquestionably linked to a controller. This brings a critical disadvantage: a delay when the control makes the decision. This delay is not acceptable in real cases because these systems must operate in real time for safe and reliable operation. On the other hand, Wan et al. (2019) state that FCL could deal with the problem quickly if there were a failure in the channel. To increase the system's effectiveness, using DC breakers is advised to handle the hazardous current in the system. DC breakers differ widely from AC ones since DC circuit breakers must include additional arc extinguishing measures, which usually add mechanisms to elongate and dissipate the electric arc to simplify the shutdown.

In conclusion, FCL protection systems are targeted to cut off and isolate the faulty section of the LVDC-MG to maintain the remaining network working correctly, even when a section has failed (Munasib and Balda, 2016). One strategy to overcome the lack of LVDC breakers is limiting the current variation by combining it with isolating the system. These can successfully surpass the drawback of lacking LVDC breakers. In this way, some researchers have attempted to tackle the issues produced by transients (Wan et al., 2019; Zhou et al., 2020).

5.1.2. Short circuit capacity

This aspect is related to the system's or equipment's capacity to deal with an amount of current produced by a faulty state. Thus, an SC is an undesirable event linked to a sudden spike of current, which lasts more than a transient and might lead to a fire either in the affected section or the entire MG. In this regard, Javed et al. (2019) claimed that there are two kinds of SCs. The first one is positive to negative pole, which is also known as "LtL SC" and the second one is either positive or negative pole to ground SC "LtG SC".

Although some strategies have been defined to reduce the likelihood of an SC occurrence, it is a demanding mission because they do not have occurrence patterns and can happen quite suddenly. When preventing SC current calculation for low voltage DC-MG (Lai et al., 2014), they also demonstrated the method's accuracy, concluding that the shorter it takes to clear the fault (in this case, a SC), the smaller the line fault current is.

It is worth mentioning that DER integration raises the SC likelihood because of the interaction among different elements within the same system. The authors stated that an SC is the most widely-seen requirement for MGs (Kabalci, 2020). The importance of SCC for LVDC-MGs is highlighted because SC rising rates are larger in LVDC systems than in low voltage alternating current (LVAC) systems because of the output capacitors of DC-converters (Virdag et al., 2017; Zhou et al., 2020).

However, this issue must be tackled by implementing the IEC (International Electrotechnical Commission) 61660-1 standard (Electrical, 2016). The standard analyzes in detail how to avoid the SC occurrence (Emhemed and Burt, 2013). Afterward, they remarked that IEC 61660 considers rectifier bridges, stationary ESS, capacitors, and DC motors as sources of failure. When the SC occurs in an LVDC network, the IEC 61660 is effective enough to calculate the steady-state DC current, but it is inaccurate for the transient. The results calculated from IEC 61660 are more conservative than those obtained by simulation, as the latter gives a peak value almost 10% higher than that given by IEC 61660, which also gives a shorter drop time than the simulator. They claimed that the source of the error is that the IEC 61660 corrective factors come from an experimental basis for DC auxiliary installations and not from larger networks (Emhemed and Burt, 2013).

As part of the protocol, the shutdown and isolation protocol for the zone affected must be activated as quickly as possible to avoid propagating the problem to the rest of the system. Once an SC happens, the isolation is based on open circuit control strategy (Javed et al., 2019). The isolated section will not have a current flow because it has been opened. Therefore, there may be a measured voltage between the terminals that tend to be the maximum supplied by the generator.

Furthermore, a modification to effectively isolate LVDC converters that have an over-current vulnerability is presented (Wan et al., 2019). Changing the anti-parallel diode for an emitter turn-off (ETO) or IGBT with proper current shutdown capability is proposed. In the meantime, Pramudya et al. (2016) studied some malfunctions in the LVDC-MG, which were performed at four points of the MG, such as the output of the converter, the consumption points (loads), the output buck converter, and the output of ESS. It is remarkable that the current reduction for all four tests is over 50% on average.

The former two protection schemes are tightly linked to each other. First, a reverse blocked-IGCT (integrated gate-commutated thyristors) is proposed as the switching device which achieves better performance against other devices (Munasib and Balda, 2016). This scheme performed limited conduction losses and high SCC. Afterward, the proposed SC scheme was assessed. FCL performed correctly when a faulty section was found. One drawback was the controller delay on the system. However, it was concluded that this system is perfectly suitable for LVDC microgrids with more than one power converter and source.

5.2. Grounding types

One of the most recurring problems on LVDC power networks is grounding, also known as earthing. Grounding is challenging due to the common interaction with UG (largely AC) and DERs. Kumar et al. (2017) state that grounding an LVDC-MG is harder than its AC equivalent because there are no zero crossing commutation or grounding issues, and corrosion in DC systems seems to be worse.

Grounding schemes are thought to protect the MG against a SC which occurs in the Line-to-Ground (LtG) fault due to the ease with which these types of SC occur due to natural causes. In fact, if compared, the LtG impedance in case of SC is much higher than the Line-to-Line (LtL) impedance (Yaqobi et al., 2019). In this regard, Hirose et al. (2011) concluded that unipolar grounding is established for networks of 24 V and −48 V, and is being widely used at 110 V and 220 V in industrial sectors. They proposed a high-midpoint resistance to decrease the fault grounding currents and increase the safety of the MG. They added that proper management of EMI is required to design a reliable DC grounding system for a safe LVDC-MG (Hirose et al., 2011).

The literature offers a wide range of grounding techniques. There is no consensus on the categorization of these techniques, and each author groups them differently. Mohammadi et al. (2019) tests up to twelve strategies grouped into three clusters according to their performance:

- Ungrounded, bipolar solidly grounded, unipolar parallel resistance grounded, and bipolar resistance grounded. They concluded that these enable LtG fault because of low fault current.
- Unipolar solidly grounded, bipolar solidly grounded, diode-grounded, and thyristor-grounded. They concluded that this group presents large transient discharge currents under LtG faults.
- Unipolar solidly grounded, diode-grounded, thyristor-grounded, and unipolar low resistance-grounded. They demonstrated that this group provides considerable steady-state LtG fault current, requiring quick disclosure and recovery after the faults occurs.

Moreover, Jayamaha et al. (2018) shows six grounding schemes (transformer neutral solidly, negative bus solidly, bus midpoint solidly, negative bus high resistance, bus midpoint high resistance, and center tapped). Five grounding schemes (ungrounded bus, high resistance, bus solid, bus midpoint solid, and reconfigurable) are presented (Jayamaha et al., 2020), while they are reduced to three groups: ungrounded, grounded through a resistor, and solidly grounded systems (Javed et al., 2019). Afterward, IEC (2019) pointed out some grounding schemes that vary among the regions where they were deployed.

Furthermore, if a midpoint is chosen, the designer must consider implementing protection on both sides due to the potential voltage presented. However, this grounding strategy has more advantages in reducing voltage insulation requirements. The potential division of each pole to the ground is half of the LtL potential. The resistance value can be made by a resistor or capacitor dividing it into two poles. Therefore, the series-connected resistor/capacitor is connected to the ground in the midpoint, and the element can blockade the steady-state fault current effectively (Mohammadi et al., 2019).

A grounding scheme is proposed between the AC and the isolated DC sides (Lazzari et al., 2018). The approach demonstrated high performance, isolating only the faulty channel of the LVDC-MG. When a defective section is detected, the front-end-converter (FEC) shuts down, providing the consumption points with electricity, and keeping the line of the zero sequence fault current. The breakers always check the 0 Amperes condition in nodes applying Kirchhoff laws. Otherwise, if any sum differs to zero, the feeder is opened by shutting the faulty current channel. The proposal is constantly sensing the zero current value of the sum of both positive and negative poles, which is similar to the differential methodology (Yuvaraja and Ramya, 2019). The remaining DC-MG is kept, supplied by ESS through a bus distribution. This approach has been tested (Lazzari et al., 2018; Carminati et al., 2014; Yuvaraja and Ramya, 2019). As can be observed, there is a wide range of LVDC-MGs grounding schemes. In this paper, we propose to group them according to their ease of implementation and performance, as shown in Fig. 2, these can be defined as follows:

5.2.1. DC-bus solidly grounded

This scheme is made through a LtG philosophy, with minimal resistance between "line and ground". This type of protection can be seen in Jayamaha et al. (2018), Javed et al. (2019), Mohammadi et al. (2019) and has some advantages such as fast and easy fault detection, easy absorption of peak voltage, less requirement for all the components of the MG insulation, and low grounding cost. On the other hand, the cons of this technique are bigger ground current and larger transient voltage, cable corrosion, and no capability of fault ride-through.

5.2.2. DC-bus high resistance grounded

This grounding scheme is implemented through a LtG philosophy with high resistance between "line and ground". This has been analyzed in Jayamaha et al. (2018), Javed et al. (2019), Mohammadi et al. (2019), Dragičević et al. (2016) and we can highlight some advantages such as high-sensitive ground-fault current, easy detection of bus voltage shift, a guaranteed path for the discharge of current, fast detection, and clearance of faulty operation. Some disadvantages are no common-mode voltage, less-sensitive fault detection for small ground fault currents, non-desired (parasitic) currents energizing metal enclosures of loads, highly-required insulation equipment, large voltage spikes to ground, and the fact that disturbances and noise largely influence the power network.

5.2.3. DC-bus midpoint solidly grounded

This technique includes the "line-to-neutro" (LtN), which provides extra safety, and is not in the other grounding schemes (Jayamaha et al., 2018; Jayamaha et al., 2020; Dragičević et al., 2016). Other advantages are that it adds a high-capacity for detecting ground-fault current, it provides good monitoring schemes to detect high resistance faults, the voltage LtN. It is divided into half from the pole-pole voltage, reduces the insulation requirements, is not tied to LtG steady-state, and has high middle point grounding resistance. On the other hand, this grounding scheme has limitations like low speed for locating faults and high transient voltage in the bus.

5.2.4. DC-bus midpoint high resistance grounded

This technique is focused on LtN, but the ground connection is made through a high resistive value (Jayamaha et al., 2020; Jayamaha et al., 2018; Mobarrez et al., 2017b; Hirose et al., 2011). Its benefits are the easy-detection of pole voltage shift, ease-sensitive ground current, monitoring the insulation, providing fault ride-through ability, low ground-fault current, easy detection of bus voltage shift, limiting ground-fault current in the human body to fewer harm levels, ensuring personnel safety, and eliminating arc flash risk during single ground faults. On the other hand, the drawbacks are a high stray current, high transient overvoltage, the fact that both poles require over-current protection, high susceptibility to noise and disturbances, and the need for a monitoring fault current system.

This approach is focused on detecting abnormal current flows and pouring them into the ground safely. It is carried out following a sequence of steps: sense, locate, isolate, limit, pour, and reconnect the faulty section if it has been recovered without damages (Yaqobi et al., 2019; Munasib and Balda, 2016). In addition, a reliable-safety grounding scheme is highlighted, placing the ground connection on the positive or negative pole or at a midpoint (Mobarrez et al., 2017b).

5.3. Instability issues at LVDC-MGs

In the MGs, one key subject is stability. Avoiding the occurrence of instabilities during energy supply is crucial because these instabilities may damage home appliances (Aaqib et al., 2019). Some of these are represented by disturbance apparition, such as harmonics, virtual resistors, over/under voltages, low inertia, and double-way power flow.

5.3.1. Harmonic issues

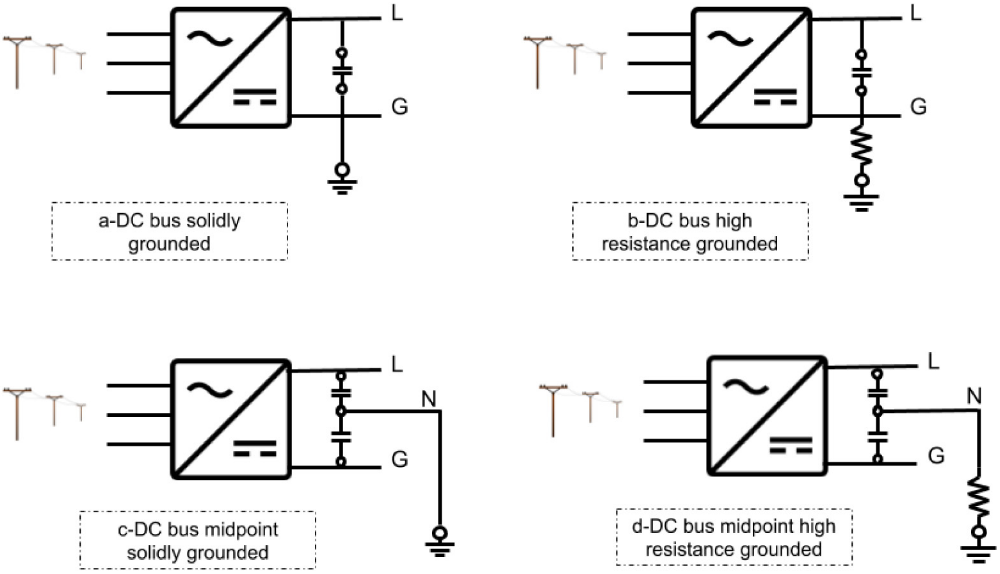
Even though some researchers neglect the harmonic presence in DC systems (Yi et al., 2019), the fact is that there is, and it should be considered. According to Whaite et al. (2015), DC systems do not contain harmonic currents because the DC system frequency is theoretically 0 Hz, and there are no integral multiple frequencies of 0 Hz other than the fundamental. However, on a real scale, the presence of either voltage or current oscillations on an LVDC-MG is like AC harmonics. The apparition of harmonics currents is due to the non-linear loads affecting the true power factor by reducing it.

For DC systems, the harmonic issues appear linked to both oscillatory currents and voltages on DC systems. This is likely transmitted through the DC bus, which operates as a connection between multiple power electronics converters. Current harmonics and circulating currents can come from a DC bus due to the non-linear effects of different power electronic converters. Meanwhile, Jeong et al. (2019) stated that harmonic and EMI issues are produced by the fast switching frequency of the power converters.

Graham (2012) claims that in low voltage DC systems EMI, problematic voltage oscillations and damaging resonance currents can result in harmonics on DC-bus, affecting the whole system. This is more critical when there is an interconnection with UG through inverters. On an off-grid PV facility a significant presence of harmonics induced by the solar PV system is portrayed (Weerakoon et al., 2019). Harmonic filters to the solar PV system's output were introduced, thus reducing the amount of harmonic considerably. Likewise, Ebrahim et al. (2019) stated that integration of PV systems might cause unbalance and voltage fluctuation. Moreover, the deployment of DC native loads with their non-linear behavior adds harmonics to the LVDC-MG. This study proposed a voltage source inverter (VSI) and other advantages that provide harmonics suppression and power factor correction capability at the point of common coupling (PCC). Based on the results, the harmonics have been reduced from 6.7% to 4.78% in a grid-connected system. Frequency issues were found that are produced by the transients, which are instabilities presented in DC systems that generate non-desired oscillation. Though this phenomenon appears mostly at systems that have power interchange with UG, these unlikely arise in off-grid systems as it does not interact with the UG.

5.3.2. Virtual resistor issues

Power converters might lead to instabilities because they may produce a negative input virtual resistor (non-controlled), which might surpass the positive resistor of the filter (composed by inductance-capacitor) at the converters' connection pole (Elsayed et al., 2015). The problem with negative resistors is that it only appears at low frequencies systems. Deng et al. (2019) claimed that negative resistance on LVDC-MG causes instability issues. To diminish it, they have implemented additional damping control (ADC), which successfully corrected the stability issues and improved the system dynamics, keeping a rated power output of 800 V stable and the system safely operating with no disturbances and at a very low control cost. This strategy can automatically generate the additional damping powers through the feedback control for the LVDC system, with any changes on the existing local controllers and their power-sharing references. This proposal was built using Lyapunov as a baseline.



a-DC bus solidly grounded

b-DC bus high resistance grounded

c-DC bus midpoint solidly grounded

d-DC bus midpoint high resistance grounded

Fig. 2. Different grounding schemes in power generation systems.

5.3.3. *Voltage issues*

Another instability problem is produced by both under or over-voltage due to parasitic energy stored on inductors associated with solid-state breakers. Martin et al. (2016) introduced a method to deal with over-voltage problems. Their approach is based on metal oxide varistor (MOV), which rises the value of the resistor at LV and reduces it when the voltage rises. They tested the MOV under 6 different experiments. The MOV-SSCB (solid-state breaker circuit) achieved high performance in all of them, providing the system with a steady behavior. MOV obtained an average of 79.5%, a minimum of 62% in scenario four (MOV Clamp Across Load), and 92% in scenario 6 (MOV and Diode Clamp Across Load), showing its highest protection performance in an actual prototype-based model. Meanwhile, the assessment of the instabilities is carried out, including the under and over-voltage conditions (Aaqib et al., 2019). An under-voltage condition signals that something is wrong within the system. Mostly, it is the product of the over demand of energy, which means a load shift. This can produce overheating because of the large amount of current flowing through. Then, a SSCB-IGBT is proposed to prevent a SC, with the LVDC-MG that acts as a current limiter. Finally, a key part of avoiding the instability issue is selecting the protection component as the carefully determined set-point/threshold for better fault prevention and management. However, it is revealed that instability is responsible for an inductive component in the distribution lines (Mokhtar Yehia et al., 2011). They demonstrated improved network performance by implementing a capacitance-based methodology: the capacitor counteracted inductance in the MG distribution lines, which is the essential factor causing instabilities.

5.3.4. *Low inertia issues*

Low inertia is a critical problem when renewable energies are pouring energy into a UG, as it introduces disturbances to the UG. At the same time, DERs increase their global power exchange, and the rotational inertia of the grids decreases. Usually, in AC power networks, mechanical rotational generators (alternators) are responsible for maintaining the inertia and control of the frequency in the grid. Conversely, renewable grids, generally powered by electronic converters, do not have mechanical movement to stabilize their frequency (Ruiz, 2017). In the AC grid, low inertia leads to frequency problems, whereas in the DC microgrid, it leads to bus voltage instability at the bus (Zhang et al., 2022). To address low inertia problems in DC-MG, a model predictive control (MPC), virtual-capacitance control (VCC) approach for improving low inertia issues in DC microgrids is applied (Yi et al., 2019). This approach of using a set-point of control has been adapted to a virtual-capacitance (VC) across the DC-bus to decrease disturbances in voltage. Moreover, some researchers have agreed that the VC strategy is the best way to troubleshoot low inertial behavior in DC power networks (Ruiz, 2017; Zhang et al., 2022).

To favor the integration of the DERs into the UG, despite the low inertia problem, inertia emulation strategies should be applied to keep the whole system correctly balanced, especially when voltage fluctuations occur. We have divided the strategies against low inertia problems in renewable-based systems into two. On the one hand, wind-energy-based systems have dealt with LV ride-through (LVRT), which keeps the DC-link voltage constant at its threshold value to introduce active and reactive power to the electricity network for the duration of symmetrical or asymmetrical faults (Abdelrahem et al., 2016). Moreover, Yassin et al. (2016) proposed a control scheme for the permanent magnet synchronous generator driven by a variable speed wind-turbine in the event of a network failure as a mismatch occurs within the active generated and delivered power to the grid. This mismatch produces surplus energy, which is stored in the inertia of the turbo-generator to keep the DC-link voltage constant. It is a logic-based strategy acting on the machine-side converter (MSC) instead of the network-side converter (GSC). However, the inertia regulation is performed in the GSC to restore voltage when a grid failure occurs (Marmouh et al., 2019). The use of the MSC is reserved to store an amount of the wind energy in the form of inertia in the drive shaft. The authors highlight the protection against over-voltage, over-current, and improved performance in voltage drops.

Furthermore, the PV-based systems have tackled this problem by emulating the inertia. Implementing strategies of regulation of charge and discharge using a DC-link condenser and adjusting the photovoltaic output in the event of inertia issues a DC-link can be used to attain rated the output. Khazaei et al. (2020) performed an eigenvalue analysis for the sensitivity assessment of the grid stability. Even though the virtual inertia-based PV generation system provides inertia emulation, the inertia coefficient is crucial in the general system's stability. It was concluded that the study could be further widened by assessing the quality (fluctuation) of virtual inertia based on PV facilities when operating in the grid-forming mode. Despite the similarities between Khazaei et al. (2020), and Huang et al. (2018), the latter focused on two off-grid PV parallel farms. A DC-link supported by a capacitor for miming the inertia response was considered in both. Moreover, the phase-locked loop (PLL) parameters are crucial in the instability of PV-inertia systems. The PLL was replaced by a virtual inertia frequency control approach for an off-grid PV system (Huang et al., 2018). It is possible to ensure sufficient energy for the inertial synthesis of PV systems by directly using an inverter on the AC side and simultaneously adjusting the capacitor voltage and the PV output power.

A PV rooftop facility is assessed (Pullaguram et al., 2018). This strategy can efficiently switch from grid-connected to off-grid without affecting the powering of loads. Additionally, Hossain et al. (2018) a control strategy is applied that employs a voltage bandwidth in the DC-bus for maintaining voltage stability based on an inverter inertia approach. In this study, an ESS is used as a barrier against DC-link bus instabilities, and the stored energy to avoid voltage violation of the previously defined bandwidth is exploited. The performance of ESS as an ancillary system is evaluated, and the inertia emulators are supported by an inverter strategy made to respond to the grid frequency and voltage variations when the grid-connected mode is implemented (Pullaguram et al., 2018; Hossain et al., 2018). These former papers resulted in efficient responses to supply during scarce power production or/and absorbing power surpluses from energy generation. A DC-Bus of 350 V was implemented to test a weak DC voltage distribution proposal with a different approach to decreasing the voltage peaks and droops due to low system capacitance (Hailu et al., 2017). It resulted in a DC system with less inertia and low fault current. This facilitates the use of low SC current protection strategies and devices at the expense of control complexities.

All of them have supported the system using an ESS for wind-based implemented batteries (Abdelrahem et al., 2016; Yassin et al., 2016; Marmouh et al., 2019), and in fewer applications into PV-based systems (Pullaguram et al., 2018; Hossain et al., 2018). On the other hand, PV-based systems are largely deployed with the capacitor as DC-link support (Huang et al., 2018; Khazaei et al., 2020).

5.3.5. Bidirectional power flow

This aspect is more important when grid-sharing occurs since several sources are interconnected. As a way to balance energy flows between the AC UG, DC generator, and storing systems, a DC protection is linked to the DC-bus to maintain the DC distribution network under normal operation (Ryu et al., 2015). They limited the DC-bus voltage through LLC, CLLC, and DAB power-isolated converters. The first two controls on the double-way power flow, and the third enable the link and dissociation of the loads and ESS from the DC-bus topology. The three converters regulate the DC bus voltage when the grid is in supply mode and also in generation mode, which are power flows from the grid to the DC bus and vice versa, aligned with the output current status. Additionally, it regulates the charging and discharging currents in accordance to the DC-bus voltage status, like a droop voltage regulator. For example: when the voltage output drops under the threshold limit, in this case, 370 V, the operation varies, and the converter transmits 2.5 kW from the network to the DC-bus. This approach performed correctly because the DC-bus voltage is properly controlled to 380 V, with low ripple voltage.

In this regard, Lai et al. (2018) proposed a high-gain-reflex-charging-based double-way DC charger (RC-BDC) to work at electric vehicles chargers' stations. This system is composed of an unregulated level converter (ULC) and a two-phase interleaved buck-boost charge-pump converter providing a low ripple and high voltage conversion ratio. This system focuses on widening the battery life and increasing the charging efficiency of these storing systems. The ESS consisted of 48 V connected through a 400 V DC-bus. After experimenting, the prototype demonstrated that the designed high gain RC-BDC enhances battery recharging speed by about 12.7% and decreases battery thermal deterioration by 25%. Higher efficiencies for charging of 95.1% and discharging states of 94.2% were achieved.

5.4. Relay, breakers and switches setting

Maybe the biggest weakness of LVDC-MGs is that most protection equipment has been built for AC systems. Some of the elements that protect MGs, such as fuses, breakers, and relays, are shown in Fig. 1. The function of the fuses is to open the circuit after detecting an over-current for a longer transient regime (current-time relationship). Fuses are usually bridged employing a metal hair that rapidly melts (thermal-capacity relationship) when a long-lasting current spike is detected. Usually, fuse protection is used at DC-mobility, ESS-protection, and other low resistive applications (Wan et al., 2019). However, by no means should fuses be implemented as a primary protection element. This is a support for additional protection deployed in LVDC-MG, since in some situations, even the fastest fuse is not fast enough to avoid a more significant failure.

Furthermore, the well-known mechanical breaker is mainly used to support the fuse's works. The SSCB is added (Kabalci, 2020). Breakers are expected to be the cornerstone in the protection of the LVDC system. Breakers are grouped to handle the arc extinction of the current, such as SSCB, hybrid SSCB with mechanical disconnectors, hybrid circuit breakers, hybrid mechanical and solid-state, mechanical passive or active resonance (Wan et al., 2019). Some of them are specially designed to operate under LVAC systems. Nonetheless, they can also give some protection to LVDC-MG. Both SSCB and hybrid circuit breakers are the most appealing protection technologies because the use of power electronics devices helps in current interruption in case of default operation (Moussa et al., 2019). Both technologies are still under assessment for LVDC-MGs. A thyristor-based DC circuit breaker is introduced oriented to reduce the losses during conduction efficiently (Zhou et al., 2020). This shows features such as shorter delay, sharp-rise commutation, compact size, and simple structure. One exciting feature is the reduction of the hot spot due to the non-existence of zero crossing in direct current systems. This is achieved by a low-pass voltage transfer feature and a saturable coil which is used to restrict the switch-on di/dt and prevent from hot spots in the proposed thyristor-based circuit breakers (TBCB). The saturation function also allows a sharp increase in switching current, which can provide a zero crossing for the principal thyristor with a reduced time delay.

There is availability for commercial trading DC breakers from 500 V to 1000 V with a rating current from 1.2 to 7.5 kA (Javed et al., 2019). A wide variety of breakers specially designed for DC application up to 1000 V has been observed (Anon, 2015). It is worth mentioning that the manufacturer offers a series focused on DERs. In this case, PV-MGs have cataloged this series as miniature circuit breakers, which are S200M UC, S800 UC, and S800 PV. Some stress proofs were carried out by testing Eaton's commercial line of DC breakers (Pramudya et al., 2016). The simulation test was based on the Schwarz black box arc model using the information provided by Eaton in its data sheet. The test used the "LtL" principles since the authors considered this the worst possible test scenario. They concluded that it could operate safely in LVDC conditions. In this regard, SSCB are analyzed and a new self-powered SSCB capable of detecting SC in the system by sensing the rate of voltage variation in the terminal of the SSCB was introduced, which is capable of a cut-off up to 180 A at a DC-bus voltage of 400 V within 0.8 s (Shen et al., 2015). Additionally, the self-power feature absorbs energy from the faulty state to activate and open the solid switch. This is possible without requiring any extra/external power supply or wiring. Some other approaches using thyristors like an SCR or IGBT are analyzed for developing SSCB. The commutation at high speed, the operational flexibility, the compact size of the elements, the arc-less operation, and the self-power features make these electronic switches very appealing to the future protection (Wan et al., 2019; Yaqobi et al., 2019).

Moreover, it is important to highlight that protection schemes will vary relying on the type of network (grid-connected or standalone) and the grid topology (bus, ring, etc.). As long as we have seen distribution topology indifferently, the reliability and safe operation of any LVDC system is linked to a well-sized protection scheme. As seen above, some protection schemes have been proposed to avoid shortages and prevent LVDC-MGs from failure. However, even if these strategies are not enough yet, there is still much more to do to achieve a wider stock of LVDC protection strategies and equipment.

5.5. *Main conclusions*

LVDC-MGs can be the most effective, safe, and cost-saving installation in powering houses, buildings, villages, and small cities in the near future. Nevertheless, this will be possible not only if proper protection elements are integrated (Manandhar et al., 2015) but also some issues are overcome that still are considered barriers for direct current systems, like the non-existence of natural zero crossing. There is no way to deploy a safe and reliable system without a sharp-synchronized system based on protection switches for LVDC-MG (Javed and Chen, 2018).

A DC microgrid effectively integrates various sources, energy storage units, and loads at a common DC-side (Khorsandi et al., 2016). Meanwhile, a low voltage system operates up to 1000 VAC or 1500 VDC according to standard *IEC 61643-331*. A LVDC microgrid can operate either connected or isolated from the grid (Mumtaz and Bayram, 2017; Wang et al., 2018). In a grid-connected mode, protection switches are necessary for avoiding the upscale of possible failures in the microgrid toward the UG. In this mode, the MG connects and disconnects from the UG depending on its needs (in this sense, the connection with the UG is mandatory).

One of the most technological challenges for this system is the non-existence of natural zero crossing conversely than AC systems. The absence of zero crossing makes it harder to switch off LVDC-MGs. This is why is it crucial to count on reliable and robust switches, relays, and breakers capable of coping with it safely. Currently, there are professionals seeking solutions to this challenging task. Some are using the same switches and breakers used in AC systems. Others are using a sort of hybrid switches to extinguish the arc-current (electro-mechanics Meckler et al., 2014) by using power semiconductors. Some others are working on developing a new standard of switches for these systems. Oversimplifying, the switched-off of the systems is mostly carried out forcing larger current flows on reverse polarity during an instant of time in order to achieve the zero and shut-down the line (Javed et al., 2019).

Additionally, the soft issues are critical as long as these can produce instability issues in LVDC-MGs. These are electronic oscillations (harmonic, virtual resistor, voltage issues, low inertial behavior and bidirectional power flow) at both lines ends. After comparing with the threshold in the system, they may damage home appliances. Yet, inter-connectivity is one of the most important trade-offs for DER power-sharing. Due to the interconnection, the power flow is bidirectional, which increases the former mentioned issues in the installation control because if there is an interchange of energy into the LVDC-MG, such kind of power flow in two directions emerges among the different components of the utility grid. In this regard, this increases the likelihood of SC by exceeding the SCC that may generate significant problems because the line is forced, automatic, and presents unplanned interruption.

This section summarizes Table 3 all protection strategies used in LVDC networks to interrupt the electricity flow and to maintain the electricity quality. Obviously, these strategies are linked to the LVDC converters that are used in MG (see Section 4) as the main risks of DC powered MGs are the damages of MG components and the potential fire that could cause in facilities. Moreover, the high reliability required in LVDC-MGs will require robust, reliable, efficient, proven, and standardized protection systems. According to Shayeghi and Younesi (2020), the three reliability index for a MG are the SAIDI, SAIFI and ENS, and they clearly improve as the protection systems are better used. Finally, it is clear that as soon as these solutions become reality, they will positively affect the social indicators linked to a communities' access to electric power (''Improved community facilities'', ''Quality of life'', ''Improvement in productivity and time savings'', ''Access to electricity services for all households that want it'').

6. Control strategies

This section explains how some researchers have been dealing with the specific issues of the LVDC system when there is a grid exchanging energy and when it is entirely off-grid. One of the most recurring problems, and the most important one, is voltage droop. Sections 4 and 5 were designed to cope with other issues concerning this sort of system. Fig. 3 gathers the three kinds of controls implemented. These are oriented toward LVDC-MGs implementation to differentiate all of them from AC. In either MVDC or HVDC, the pyramid is being inverted as it is primarily associated with the former systems.

Hierarchical control can be categorized into three levels: primary, secondary, and tertiary. The primary control level uses local information to restore the voltage of the DC-bus. It also damps the oscillations and maintains the adequate distribution of current among the DERs to avoid power imbalances. The secondary control level, which is higher than the primary, balances the voltage deviation caused by the primary controller. The highest level is the tertiary control level, which is responsible for keeping an optimal operation within MGs and the UG and vice versa. It also coordinates the energy storage devices and minimizes the operation costs and the losses of power flow in the system. From primary to tertiary control levels, time scale increases: primary control operates in the range of milliseconds to seconds, secondary control is slower, in the range of minutes, and tertiary control is the slowest one (several minutes to hours) (Feng et al., 2018).

6.1. *Primary control*

As discussed above, the starting level in the hierarchy of control is the primary control. It is usually limited within the MG, as it only considers local variables. It is used for voltage and current management. Among the primary control methods, the most commonly used are droop control, DC-bus signaling, and fuzzy logic. However, droop control stands out above all other methods due to its implementation's simplicity and superior performance (Abhishek et al., 2020; Al-Ismail, 2021).

A droop control-based DC distribution network referred to as grid voltage error (GVE) is proposed (Chen et al., 2019b). This error is calculated using two voltage measures (GV1 and GV2).

Table 3
Main protection schemes.

Signal implication	Feature	Target	Benefits/Means	Disadvantages/Issues	Objective	E.g.
Current-based	Breakers	to interrupt the current flow	avoid the damage, speed up the trigger	produce bigger losses than the inductance-based strategy	These gears can cut off and isolate the faulty section of the LVDC-MG to maintain the remaining network working correctly	Javed et al. (2019)
	Thyristor	to reduce the recovery time of the system	speed up the trigger and, thus, it reduces the size of the breaker required	provides a delay when the control makes the decision		Zhou et al. (2020)
	DC breakers	to increase the system effectiveness	limited conduction losses and high SCC	Handle the hazardous current in the system		Wan et al. (2019)
Grounding types	Grounded by resistor	to reach a high-sensitive ground-fault current	provides a reliable DC grounding system	no common-mode voltage, less-sensitive fault detection for small ground fault currents,	Rounding schemes are thought to protect the MG against a SC which occurs in the LtG	Javed et al. (2019), Mohammadi et al. (2019), Jayamaha et al. (2018)
	Solidly grounded	to reach a fast and easy fault detection	fast and easy detection, easy absorption of peak voltage, less requirement for all the components	low speed for locating faults, high transient voltage in the bus		Jayamaha et al. (2018), Jayamaha et al. (2020), Dragičević et al. (2016)
Stability	Harmonic	to provide harmonics suppression and power factor correction capability	VSI provides harmonics suppression and power factor correction capability	DC systems do not contain harmonic currents because the DC system frequency is theoretically 0 Hz	Avoiding the occurrence of instabilities during energy supply since these instabilities may damage the system	Jeong et al. (2019), Graham (2012), Weerakoon et al. (2019), Ebrahim et al. (2019)
	Virtual resistor	to correct the stability issues and improve the system dynamics	ADC generate the additional damping powers through the feedback control for the LVDC system	Power converters might lead to instabilities due to a negative input resistor (virtual),		Elsayed et al. (2015), Deng et al. (2019)
	Voltage	to increase the resistance value at a low voltage	MOV increases generate the additional damping powers through the feedback control for the LVDC system	under or over-voltage due to parasitic energy stored on inductors associated with solid-state breakers		Martin et al. (2016) (Mokhtar Yehia et al., 2011; Ruiz, 2017; Pullaguram et al., 2018; Hossain et al., 2018)
	Low inertia	to maintain the inertia and control of the frequency in the grid	MPC improves low inertia issues in DC microgrids	when renewable energies are pouring energy into a utility grid, as it introduces disturbances to the utility grid		Zhang et al. (2022), Abdelrahem et al. (2016), Yassin et al. (2016), Marmouh et al. (2019), Khazaei et al. (2020), Huang et al. (2018)
	Bidirectional power flow	to protect the DC distribution system from abnormal operating conditions	A DC-bus protector balances the energy flows between the AC utility grid, DC generator, and storing systems	Occurs since several sources are interconnected		Ryu et al. (2015), Lai et al. (2018)

After obtaining the GVE, they dispatched power for re-adjusting the buses to diminish the GVE deviation of the expected state of the bus. Similarly, a correction drop of voltage is made by adding energy from the ESS, adopting a droop control method based on virtual inertia to stabilize the voltage of the bus during transient states (Han et al., 2019). As in previous papers, Xia et al. (2018) proposes a strategy based on droop control to keep the voltage of the standard bus and, at the same time, perform the power-sharing among the storage. One difference between the last two papers is compensation. While it is made through power-sharing among the four sub-grids designed (Xia et al., 2018), a power injection in the bus to smooth transient behavior is generated (Han et al., 2019).

An adaptive droop control applied to control the current sharing among loads is proposed (Vu et al., 2017). They stabilized the bus voltage in DC-MGs using a model called linear time-varying (LTV) for DC-MGs. In this setup, both the current and the voltage are adjusted. It should be noted that one of the advantages of this control strategy is its flexibility for adjusting both the voltage and the power in the distribution network in real-time.

Nevertheless, these strategies bring a drawback. It is demonstrated in Francés et al. (2018) that the droop control strategy adds a virtual resistive impedance, decreasing the output voltage reference of the converters proportionally to its output current. Afterward, a method of droop control is proposed that automatically changes the droop gain in accordance with the load's size (Khorsandi et al., 2016). This proposal has demonstrated that the voltage regulation and the current sharing are properly achieved as the load is supplied steadily.

A proportional load sharing control based on droop is proposed in Augustine et al. (2016) for LVDC microgrids focused on photovoltaic systems. It consists of DC-DC converters connected in parallel. A proportional–integral–derivative (PID) control is at the core of the proposal. It balances the voltage deviation and the normalized current sharing difference at the output of the converters by calculating the adaptive virtual resistance. Another droop control with virtual impedance is proposed, shortening the adjustment time and eliminating the voltage deviation (Zhang et al., 2019). Following a system fluctuation, the power and voltage of the DC bus reach the reference value at the same time,

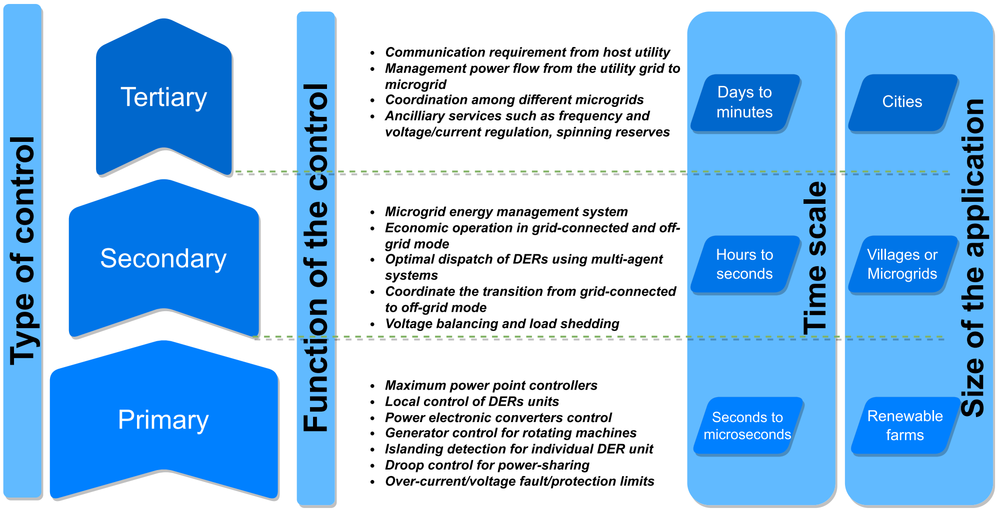


Fig. 3. Different control as well as functions on DER facilities (Feng et al., 2018).

bringing the system to a new stable state. An algorithm prevents a blackout of the system and provides the power balance of the bus. They introduced a disturbance observer (DOB) using a neural network to solve an excess of power peaks and bus voltage. This algorithm makes control simpler and cheaper, and improves the autonomy and stability of the system.

Moreover, Zhao et al. (2017) stated that the use of droop control on a DC microgrid prompts the fast distribution of power and reduces the system's dynamic. This motivated them to use a controlled-virtual resistance for enabling the converter impedance ability to reduce the system voltage droop and improve the pulsation of voltage. They also decreased the influence of a voltage spike, enhanced the damping property, strengthened the system's ability to load, and improved its anti-interference performance by setting up the dynamic virtual resistance.

A simple online adaptive algorithm that updates the droop control resistor as a function of voltage deviation and current difference is presented in Shehata et al. (2019). The proposed control does not need additional measurements or communications among source converters. However, many researchers have been dealing with droop of voltage, and this drawback is still presented in MGs (Peyghami et al., 2017a; Nasir et al., 2016; Agrawal and Gupta, 2019; Khorsandi et al., 2014; Zhang et al., 2019; John et al., 2017; Ingle et al., 2018; Mobarrez et al., 2017a). Finally, Varghese et al. (2016) developed an algorithm to avoid power waste using a droop control technique. This algorithm receives information from sensors to measure when load demand is less, and the battery's storage capacity is exceeded. This way, the power balance into the microgrid is maintained.

Meanwhile, a control strategy for a bipolar (+750 V, −750 V) MGs is proposed (Byeon et al., 2015). This assessment is made for a better interconnection between the UG and DERS. Both buses can be operated individually and can manage a 1500 V DC. They focused their analysis on maximizing the ESS system. ESS control strategy improves all loads' electrical power supply capacity (750 V and 1.5 kV) on grid-connected islanded mode on both sides. In this regard, a clamped converter system for a bipolar (+750 V, −750 V) LVDC distribution is proposed (Kim et al., 2019). It consists of a neutral point control (NPC) of three levels to control the imbalance of the neutral pole. This study has shown its robust operation under various conditions in the LVDC distribution. If the asymmetric load condition is not too large, the DC-link voltage can be regulated to equilibrium by the injected zero sequence voltage. But if the imbalance deviation is higher, the DC-DC converter can reduce the voltage difference between poles to less than 50 V. When a SC condition occurs in either pole, the output current is limited to 120 A by the DC-DC converter, while the output voltage of the other pole is regulated stably at 750 V. If the circuit breaker operation at the positive pole dissipates the SC condition, the positive pole presents the usual regulated output voltage of 750 V. Furthermore, a multiple DC-bus distribution is proposed to solve the power-sharing problem in the DC domain Nimal Madhu et al. (2016). This strategy seeks to control droop voltage on the whole bus. The performance achieved a power loss reduction of 31.6% in a 120 V DC distribution. The bipolar microgrid can efficiently transmit much more power than a unipolar. Also, this type of configuration adds more flexibility by providing three levels of voltage (positive, negative, or double of the two previous) (Mayen and De Jaeger, 2021).

6.2. *Secondary control*

Secondary controllers can be implemented in a centralized, decentralized, and distributed manner. In the centralized control, all sources and loads of the DC-MG are connected through a communication link with a central controller. Although centralized systems provide an acceptable, flexible control action, the fact that they depend on a communication network exposes them to the risk of communication failures, and makes network scaling more difficult. In contrast, decentralized secondary control requires minimal or no communication network. Control is local and based on the available data of the individual modules, thus simplifying the implementation, and enhancing the system's reliability. However, error correction is not optimal due to the absence of global data exchange. Distributed control, in turn, demands a distributed communication network and that control is executed on local variables.

6.2.1. *Centralized secondary control*

As the name suggests, in a centralized control, the loads and generators of the DC-MG are controlled centrally using a communication link. Data from the units are sent to the central controller and the control messages are sent back to the units. Among the most outstanding advantages of centralized control is the controllability and observability of the whole system. However, reliability, flexibility, and scalability are reduced and they may suffer from point of failure issues (Abhishek et al., 2020; Al-Ismail, 2021).

For example, a strategy to compensate for the voltage drop of the primary controller high capacity MGs with long feeders and distributed loads is proposed in Peyghami et al. (2017b). Critical loads are regulated by identifying the critical buses using a modal-based sensitivity analysis. Furthermore, the secondary controller regulates their average voltage by only communicating the voltage of a few buses. Any control strategy can be used to regulate the load voltage of short feeders since voltage drop is negligible. However, a bus-signaling method performed by an energy storage system unit is presented (Wu et al., 2015). A centralized secondary control eliminates the steady state bus voltage deviation. A real-time simulation verified that this control strategy has a good operation in different scenarios of islanded DC-MG systems.

6.2.2. Decentralized secondary control

In a decentralized strategy, all converters are monitored by local controllers. Data of the units are processed locally, and control messages are sent back to the units. In this type of control there is no communication link, which makes it more reliable. Distributed units are independently monitored through their local variables. For example, a decentralized control scheme is proposed in Tah and Das (2016) to improve the accuracy of current sharing and the regulation of voltage. It is implemented at each source together with the basic droop control. The effects of the parameters and loading conditions are analyzed. Similarly, a method is proposed in Gao et al. (2015) for voltage regulation for a droop-controlled DC electrical power system. Although it was originally designed for electric aircrafts, it can also be used in terrestrial DC-MG. No additional communication lines or controllers are required, so modularity is retained. This improves the accuracy of the load sharing under high droop gain conditions while considering the impedance of the wires.

6.2.3. Distributed secondary control

In a distributed secondary control there is no central control unit, but a communication line between adjacent modules. The major benefit achieved is the immunity to the *single point of failure*, which means that the system can continue to operate even if there is a failure on one of the links. The information exchanged between controllers only contains local variables, so the observation of the entire system is limited. One of the strategies to address this approach is through schemes based on average current or voltage sharing. In terms of average current and voltage, proportional-integral controllers are implemented to restore the local DC output voltage and improve the accuracy of the load current sharing (Lu et al., 2013). The control system is local to each converter, and a low bandwidth network is used to exchange the information between converters. Similarly, a low bandwidth communication for a droop-controlled DC-MG is proposed in Wang et al. (2015). Secondary control incorporates slope-adjusting and voltage-shifting approaches to remove the DC voltage deviation and, at the same time, improve the current sharing accuracy.

The use of a control algorithm with no droop for simultaneous load sharing and voltage recovery is proposed in Dong et al. (2019). The system assumes the existence of a communication time-delay. The selection of control parameters is driven by two stability criteria: the upper delay limit obtained by the *linear matrix inequality* for systems with variable time delay, and a delay-dependent stability criterion for fixed-delay systems. The load condition information is shared through an additional communication line to generate a common load condition in each local controller and then compensate voltage deviation and load sharing separately (Yang et al., 2015). At the same time, an energy storage management system is proposed, which simultaneously controls the charge and discharge in the DC-MG and promotes state-of-charge (SoC) equalization between different units. This is achieved using DC bus signaling power management and a secondary control layer for SoC balancing (Oliveira et al., 2016). Also, an average voltage sharing control scheme is proposed in Huang et al. (2014) that ensures a stable current sharing regardless of the loading conditions and fixes the terminal voltage at the nominal value. Secondary voltage controllers are constructed following the anti-windup scheme for a biproper. A low bandwidth communication is used to reduce the voltage bias generated by the resistances of the wires at a given terminal. The average voltage of the MG is regulated, and the output current of the converters is proportionally controlled by using a low bandwidth network, which transmits the information of the currents of the other converters. No voltage information is required (Loh et al., 2016). Cooperative control is another way to address the distributed secondary control. This type of control seeks all nodes to have the same consensus value. A strategy based on integrating the distributed controllers that balance the energy among the energy storage systems is proposed in Morstyn et al. (2015b).

Communication links are only needed among neighboring or adjacent DGs. The dynamic consensus algorithm presented incorporates the mean value of current and voltage of all the distributed units. Communication links are required for the interaction of the distributed units (Meng et al., 2015a). Voltage regulation uses DC electric springs proposed (Chen et al., 2017). A consensus algorithm regulates the bus voltage reference by incorporating the state of charge balancing among the electric springs. The implementation of the secondary controller with a communication triggered by events reduces the communication load (Sahoo and Mishra, 2017a). The states by parameter identification using a projection law are estimated, thus providing load sharing and an average voltage regulation. A voltage regulation and current sharing between multiple agents is achieved by dynamic consensus between its neighbors within a finite settling time (Sahoo and Mishra, 2017b). Meanwhile, a multi-agent collaborative control strategy for managing ultracapacitors and batteries distributed across an MG is proposed (Morstyn et al., 2015a). In this case, the power regulation is provided by the ultracapacitors, while the batteries achieve energy storage with no need for a central controller. In addition, a multi-agent cooperative control strategy achieves a current sharing method for DC-DC converters in input-parallel output-parallel configuration. The information flow among converters is represented as a directed communication graph, and an analytical framework is provided (Behjati et al., 2014).

6.3. Tertiary control

Tertiary control is used for power and energy management in an MG. The main objectives of this control scheme are ensuring optimal storage, scheduling of energy, management of power flow, and minimization of operational costs. Economic and optimization parameters of the MG are monitored. The literature consulted focuses mainly on four optimization algorithms, which will be developed in the following sections.

6.3.1. Mixed integer linear programming

Mixed integer linear programming is a mathematical optimization algorithm in which the objective function and the constraints are linear and some (or all) of the variables are restricted to be integers. It is one of the most used optimization method in general and for implementing tertiary controls in microgrids in particular. For example, a consistent dispatch model with uncertainty constraints is proposed in Qiu et al. (2019) for an islanded AC/DC MG. A mixed-integer problem is used to solve the states of the converter and the generation-load power uncertainties. Moreover, Jabr (2021) presents a mixed-integer formulation based on a conic optimization in order to design a generator droop control. In Su et al. (2021) a dual-solver framework is proposed. The formulation of a scheduling problem is posed using mixed-integer linear programming while the transmission loss problem is formulated using non-linear programming. Finally, Trinh and Chung (2021) presents a strategy for LVDC microgrids. It is based on a smart scheduling of the charging and discharging operations of electric vehicles, which considers the time-of-use electricity rates and the production of DERs.

In any case, this control strategy has its drawbacks. For starters, it can only tackle linear optimization functions with linear constrains. This in general involve a linearization of the objective function that usually increase the number of variables to consider. This, however, makes the formulation of MILP optimization problems very large and thus slow to compute.

6.3.2. Gradient descent

Gradient descent (GD) is an optimization algorithm used to find the local minimum of a differentiable function. The method is used widely in engineering problems (Mehta et al., 2019). In particular, for tertiary controls (Gheisarnejad et al., 2021) propose a novel nonlinear Deep Reinforcement Learning controller to ameliorate the dynamic characteristics of DC-DC buck converters. Moreover, Mcree et al. (2019) implements a control algorithm for the transformer hysteresis based on an iterative GD.

Nevertheless, even as it is known to be optimal in some contexts (Ross, 2019), this methods has its own set of problems. On the one hand, it is a local method, so, unless an heuristic strategy is put into place (which makes the algorithm stochastic), the method only converges to a local minimum. Moreover, it can only be used if both the objective and constrains functions are differentiable and in general involve the computation of he Hessian of the functions, which is not usually a fast task.

6.3.3. Evolutionary algorithm

Evolutionary algorithm are metaheuristic algorithms used to find the solutions to optimization problems. In the literature for control algorithm, two sub-classes are mainly used: Genetic algorithms (GA) and Particle swarm optimization (PSO). On the one hand, GAs are evolutionary algorithms inspired by natural selection. GAs are usually run in three steps: reproduction, crossover, and mutation. To improve the overall efficiency of the system while accounting for the SoC, Meng et al. (2015c) proposes an optimization problem that incorporates the loss of power and the SoC difference into an objective function. The near optimum is sought using a genetic algorithm. In Basati et al. (2016), an optimal droop control scheme controls an islanded MG composed of three DG units and the block of a Battery Energy Storage System (BESS). A genetic algorithm is used to design the optimal droop control for one of the DC-DC power converters. In Meng et al. (2015b), a control approach using an optimization method for maximizing efficiency and minimizing energy losses in paralleled DC-DC converter systems is used. A genetic algorithm is used for searching the optimum.

On the other hand, PSO optimizes a problem by improving a candidate solution iteratively. A set of particles (i.e., the candidate solutions) moves around the search space (as a swarm) to locate the global maximum. An islanded DC-MG made up of a battery, and a super-capacitor is proposed (Vedulla and Mishra, 2017). The tertiary control implements the power flow strategy using a droop control power-sharing method based on optimization. The objective function is formulated as a function of the power loss and the state of charge of the battery. A centralized controller senses the two values, and a PSO solves the objective function. The effect of the impedance of the line is minimized using the PSO algorithm to optimize the voltage reference for two source converters and the droop resistance. Dahiya et al. (2017).

6.3.4. Consensus algorithms

Consensus algorithms can be used to coordinate several distributed generators within an MG. A dynamic consensus algorithm is proposed in a DC MG with multiple parallel conversion systems installed in distributed substations and controlled by droop (Meng et al., 2015a). In this case, the dispersion of the system may make centralized control impractical or costly. The local agents apply the consensus algorithm to know the number of online converters and the total load current. The optimal VR is provided to local controllers using a genetic algorithm. A complete DC MG using a discrete-time approach, and a sensitivity analysis is carried out, which accounts for the effects of the consensus algorithm (Meng et al., 2014). The influence of multiple modeling parameters is studied in depth.

6.4. Main conclusions

As previously seen, and due to the time scale nature of each of the levels, the primary and secondary controls are highly focused on the reliability of power supply and the tertiary (longer time scale, even days) on a cost-effective optimization. Current methodologies for improving microgrid control performance are reviewed in Bidram and Davoudi (2012). Conclusions are drawn that can help establish the impact of each of the levels on the social KPIs considered. Both primary and secondary controls optimize voltage and frequency, maintaining their stability and compensating their deviations. This enhances the social KPIs derived from supply security ('improved community facilities', 'quality of life', 'improvement in productivity and time savings', 'access to electricity services for all households that want it'). The tertiary control level regulates the flow of power between the microgrid and the UG, and enabling an economically optimal operation, positively impacting the 'affordability of electricity rates' and decreasing the environmental impact. As can be seen on Table 4 these three control levels have pros and cons and also important limitations to be considered when designing a LVDC network.

As commented in Section 5.5, microgrid designers interested in considering the social KPIs may find surveys of microgrid controls that have added some features such as the ease of implementation useful. Bharath et al. (2019) produced a summary and comparison of DC microgrid control techniques, including the Implementation Complexity as a factor to be considered. Some methods, such as the Conventional PI Control or the Adaptive-droop strategy of Decentralized Controls, were labeled easy to implement. In the same way, Vandoorn et al. (2013) provided a survey of primary control strategies for islanded microgrids, concluding that the operation without a communication link avoids the complexity of a supervisory system, facilitating the expansion thanks to the plug and play features of the modules. This option is based on droop control, and its ease of implementation helps microgrid designers in improving the social acceptance KPIs.

Furthermore, Unamuno and Barrena (2015) identified and analyzed the strategies of control that can be implemented in hybrid microgrids, concluding that the secondary control strategy must ensure the black start operation and restoration of synchronization in the transition from islanded to grid-connected mode. Without it, it would be hard to keep the microgrid energized. Thus, the secondary control level is fundamental for the reliability of the power supply. This leads to conclude that it impacts positively, to a much greater degree, on all the above-mentioned social KPIs associated with the electricity access within a community with a microgrid operating in islanded mode.

Finally, it should be highlighted that the initial investment in the microgrid is increased by having decided to implement control strategies. As discussed in Section 4.4, there is a trade-off between the cost and the quality. If our goal is to obtain quality benefits in the microgrid, such as the stability or the compensation of deviations in voltage and frequency, then the "Affordability of electricity rates" social KPIs will be harmed.

Table 4
Main control approaches.

Type	Approach	Definition or strategy	Advantages	Disadvantages	E.g.
Primary	Unipolar droop control	The unipolar system is a two-wire system providing either positive or negative voltage	Simple and effective solution for power sharing between all components of the micro-grid. It does not need additional measurements nor communications and is highly reliable and low cost	Poor voltage restoration, low flexibility, poor of load sharing, high voltage deviation and inaccurate current sharing	Augustine et al. (2016), Chen et al. (2019b), Han et al. (2019), Xia et al. (2018), Vu et al. (2017), Khorsandi et al. (2016), Zhang et al. (2019), Shehata et al. (2019), Varghese et al. (2016)
	Bipolar droop control	The bipolar system is a three wire system providing positive and negative voltage poles that share a neutral pole	Higher power dissipation, lower conduction losses, improved user safety and feasible connection	Requires additional power hardware, has a high system cost and is highly complex	Byeon et al. (2015), Kim et al. (2019)
Secondary	Centralized	Data from the units are sent to the central controller and control messages are sent back to units	Good performance, Controllability and Observability	Vulnerable to communication failures and lack of flexibility and scalability	Abhishek et al. (2020), Al-Ismail (2021), Peyghami et al. (2017b), Wu et al. (2015)
	Decentralized	Data from the units are locally processed	Reliability and simple implementation	Sub-optimal error correction	Tah and Das (2016), Gao et al. (2015)
	Distributed	No central control unit but a communication line between neighboring models exits	Immunity to the single point of failures	Requires a distributed communication network	Lu et al. (2013), Wang et al. (2015), Dong et al. (2019), Yang et al. (2015), Oliveira et al. (2016), Huang et al. (2014), Loh et al. (2016), Morstyn et al. (2015b), Chen et al. (2017)
Tertiary	MILP	Optimization algorithm in which both the objective function and the constraints are linear and some of the variables are restricted to be integers	Global method frequently used in economics and other sectors	Is centralized, can only optimize linear function and scales poorly	Qiu et al. (2019), Jabr (2021), Su et al. (2021), Trinh and Chung (2021)
	GD	Optimization algorithm for finding a local minimum of a differentiable function	Allows to tackle non linear functions and used frequently	Is a local method, centralized, stochastic and only works with smooth functions	Gheisarnejad et al. (2021), Mcree et al. (2019)
	EA	Meta-heuristic algorithms to solve optimization problems	Simple implementation, is embarrassingly parallel, could be used for multi objective problems and is a global optimization algorithm	Performance largely depends on hyper-parameters, stochastic, centralized and potentially need high computational resources	Qiu et al. (2019), Behjati et al. (2014), Jabr (2021), Su et al. (2021), Trinh and Chung (2021)
	CA	Coordinates several elements by sharing information	Decentralized, ensures data security and privacy and allows to easily use heterogeneous data	Sub-optimal error, requires a distributed communication network and complex implementation	Meng et al. (2015a, 2014)

7. Social impact

After having examined the technical aspects in Sections 4 to 6 we can analyze how each of them have an impact on different social factors that several authors have highlighted as essential in the planning of electrical networks. Such analysis can also help us determine the feasibility of the proposed renewable-based LVDC microgrids. To assist with this assessment, we have used the lists of 14 KPIs (Table 8) social impacts of microgrids and mini-grids from Castillo-Calzadilla et al. (2022).

One of the social impacts of the mentioned table is the "health and environment" key performance indicator (KPI), and the simple choice of DC over AC may have a positive influence on it. As aforementioned, mostly renewable systems produce DC power, and the preference for this type of green generation over others that emit greenhouse gases or pollutants has a positive impact that has been widely documented (Buonocore et al., 2016). A rising percentage of RES are connected presently to the utility grids with a significant compliance at both voltages (the onsite and the grid levels). This happens at the same time as the DSO cope with load demands that are constantly being changed and increased, and with an increasing urge to cut down the net carbon footprint (P. Marinakis, 2021).

The easiest way to build a reliable microgrid, especially in isolated areas, would be by including diesel engine generators (DEG), creating a controllable AC network. However, DEGs emit toxic contaminants that are harmful for humans, like PM (particulate matter) and NOx (Oxides of Nitrogen), that impact negatively the mentioned social factor. On the other side, there are DERs, since these type of systems which are mainly LVDC, have very low impact in terms of emissions (Rehman et al., 2020).

It is also worth pointing out that LVDC-MGs have an unavoidable commitment to safety. This system is focused on two aspects: firstly, providing electricity uninterruptedly to inhabitants to guarantee a high-quality service; and secondly, avoiding outages that entail a fire and put the safety of the system's operators at risk. Under no circumstance must the cost of the security systems be an excuse for reducing these protections because they must always protect people and the regular operation of the MG. As mentioned above, the security of users increases simply by choosing to implement protection schemes within a microgrid since they are designed to safeguard people and equipment against electrical hazards. This positively impacts the "health and environment" social KPIs.

Following with the discussion of those social consequences resulting from the mere electrification of a community, one of the technical purposes of installing protection systems within a grid is to guarantee the uninterrupted power supply to the system. A lack thereof would be detrimental to its users. According to Shayeghi and Younesi (2020), the three reliability index for a microgrid are the SAIDI, SAIFI, and energy not supplied (ENS). All of them are improved by using Protective Devices. Therefore, as in the case with interlinking converters, the implementation of protection schemes positively impacts the social KPIs linked to a community's access to electric power ("improved community facilities", "quality of life", "improvement in productivity and time savings", "access to electricity services for all households that want it".

At the same time and following the impacts shown in table 8 (Castillo-Calzadilla et al., 2022), once we have started the network design, the need to implement the AC-DC rectifiers and DC-DC converters is unavoidable. Without such devices, the impact on the social KPIs related to the electrification of a community ("improved community facilities", "quality of life", "improvement in productivity and time savings", "access to electricity services for all households that want it") would be negatively affected.

Another important social repercussion that we seek to achieve when implementing a novel electrical grid is more affordable electricity prices for consumers over the years. After analyzing the optimization of the compromise between electricity cost and its coverage in microgrids installed in isolated communities, it was concluded that the ideal design of any microgrid is the trade-off of two parameters: cost and quality (Bustos and Watts, 2017). Therefore, this certainty of using rectifiers and converters to guarantee the electricity supply will result in the consequent negative impact on the "affordability of electricity rates" social KPIs. Furthermore, the price-quality balance does not only directly affect such "Affordability of electricity rates" KPIs when we choose more expensive conversion devices with better performance. Using higher cost equipment would risk the economic viability of new grid projects and could lead to a situation where the use of renewable energy-based microgrids would be discouraged, and less expensive solutions (e.g., DEGs) would be chosen, which would damage, as we have analyzed, the "Health and environment" KPI Cuesta et al. (2020).

Other social KPIs should be analyzed when selecting and achieving the schemes and techniques to protect the microgrid. Some authors have produced surveys of these methods, adding features that can help evaluate the social factors. For example, Chandra et al. (2020) reviewed the existing DC microgrid protection techniques, and in their comparison, they include the cost as a factor to be considered when designing an appropriate scheme. The cost of voltage-based schemes or those using converter control actions were categorized as low, with the consequent positive impact on the "affordability of electricity rates" KPIs. Sarathkumar et al. (2021) provided a review of fault detection methods, including cost as a parameter to be considered, concluding that fuses are economical. Additionally, they incorporated the implementation ease as a factor, claiming that the protection method of Current Differential Protection and Rate of change in current is easy to implement, with the resulting improvement of the "Social acceptance" KPIs.

We have analyzed the technical aspects of the interlinking converters, protection schemes, and control strategies of the microgrids that may affect the different social KPIs. Based on this assessment, we have created table Table 5, which summarizes the type of impact (positive or negative) of each of the aspects considered.

8. Conclusions

In this final section of the paper, we offer an answer to our research question: Is a massive deployment of renewable-based LVDC microgrids feasible? We will provide a conclusion for every feature assessed through the survey. After analyzing most novel and updated research, the most remarkable findings have been achieved. As an added assessment on top of the analysis of the three technical aspects (Sections 4, 5 and 6), we have determined that the social impact of such technical traits help in achieving feasibility for the massive deployment of renewable-based LVDC microgrids. We have found that these specific elements have a positive effect on aspects such as health and environment or social acceptance. This undoubtedly improves the social criteria when making a feasibility decision, together with the analysis of other more usual, economical, technical or environmental criteria. This also helps decreasing energy poverty of societies of developing countries.

For starters, interlinking converters are examined. These systems are the cornerstone of renewable systems, since power-sharing is made through them. Some issues must be ruled out, such as droop control and low inertia due to renewable addition in the old power grid. There are results that point at the strategy of grid-following virtual synchronous converters (VSC) that are prone to sub/super synchronous oscillations. Its main advantage is that it responds quickly whereas the grid-forming VSCs are able to operate steadily in weak grids. It is also capable of sustaining the grid frequency and voltage operating on the set-point. Grid-forming converters seems to be the best alternative for renewable energy grids since these lack inertia to ensure transient steadiness.

Secondly, protection schemes are among the concerns that must be solved to promote the massive deployment of this kind of system. A massive deployment and facility integration with the old electricity generation model would not be possible unless it has been properly coped with problems like system control, stability issues, protection, and grounding of the LVDC systems. We have seen that there is a wide difference between the AC protection switches and the DC ones. The latter lack a wide variety of protection systems and the few are very costly. This industry is still being developed and is growing slowly since the AC networks dominate the global market. We strongly believe that new standards are needed for the protection of DC systems operating under the 1500 V. University and professional teaching has to focus more on the protection systems for this new generation of microgrids (LVDC) because there is evidence that there are not enough professionals that can deal with LVDC protection schemes.

Thirdly, an assessment of the facilities from a control point of view is carried out. The control architecture detailed here is hierarchical and consists of primary, secondary, and tertiary control. Primary control copes with the management of current and

Table 5
Social aspects related LVDC deployment.

Aspect of the micro and mini-grids	Impacted Social KPI	Impact
Lower emissions (GHG gases + other pollutants) Higher safety levels	Health and environment	Positive
Use of Protective Devices	Improved community facilities; Quality of life; Improvement in productivity and time savings; Access to electricity services for all households that want it	Positive
Need to implement the AC-DC rectifiers & DC-DC converters Use of rectifiers & converters to guarantee the electricity supply	Improved community facilities; Quality of life; Improvement in productivity and time savings; Access to electricity services for all households that want it Affordability of electricity rates	Positive Negative
Low cost of voltage-based schemes Easy deployment of the protection method of Current Differential Protection and Rate of change in current	Affordability of electricity rates Social acceptance	Positive Positive

voltage. Droop control is the most widely used method among the cases analyzed due to its simplicity and reliability, although other techniques such as fuzzy logic or DC-bus signaling are not uncommon. Secondary control addresses the compensation of voltage and the enhancement of the power sharing performance. It is also responsible for managing the flow of energy within the MG and in a group. Three different implementations have been analyzed: centralized, decentralized, and distributed. The latter is the one with the highest number of deployed applications. The fact that the system can still operate even if there is a communication failure between nodes contributes to this widespread adoption, even though the monitoring of the entire system is limited. Lastly, tertiary control extends its operational area beyond the MG. It provides optimal energy storage, scheduling, and management while minimizing the costs. This optimization is achieved using different strategies, mainly comprising genetic algorithms, particle swarm optimization, and consensus algorithms. None of these strategies seem to stand out above the others. Thus, one or the other is used depending on the intended application. We believe that it is precisely the tertiary control that will play a very relevant role in the massive deployment of LVDC-MGs. Due to its larger working timescale and its impact on resource optimization, the tertiary control of MGs will be essential for energy trading, both in the export of the surplus obtained from renewable generation to the utility grid and in the import of energy from the utility grid when there is insufficient renewable generation for internal consumption.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Cruz Enrique Borges reports financial support was provided by Fundación Iberdrola.

Data availability

Data will be made available on request.

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