Improving the Controllability of Microgrids through DC links

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***Abstract*—This work proposes the use of DC links between two supply points of a microgrid so that full advantage is taken from the capacity of each radial feeder. The demonstrated efficiency of these devices in smart grids allows to consider them as one of the drivers to deploy and manage the microgrids adding versatility and control capability. The two most important DC links topologies are presented and modelled in an optimization tool to determine their optimal power settings in order to maximize the use of dispersed generation or minimize the power losses subject to customary electrical constraints. Simulation and experimental results regarding a real network are presented to illustrate the advantages of the DC link in smart grids and microgrids.**

I. Introduction

The design and operation of the LV and MV distribution networks have been traditionally performed using a radial scheme composed by arborescent feeders where the power flows from the substation to loads. The low degree of reliability for these radial networks is usually improved by adding emergency ties that provide alternative routes for power supply in case of outages or scheduled interruptions. These links end with an open switch so that radial structure is maintained during normal conditions as shown Fig. 1. The improvements that would result by closing the normally open links are well known [1]: power lines would be less loaded, better voltage profile, reduction of power losses, etc. However, radial systems are easier to operate and more economic to protect, at least when all the customers connected to the network are passive loads where the power flows are unidirectional. This advantage has prevailed over the former limitations until now, but the increasing presence of distributed generators (DGs), fundamental for a transition from the traditional distribution networks to so-called smart grids [2], make it possible to question this radial operation topology.

If the system were operated in a meshed way, a higher DG penetration would result [3]. Unfortunately, actual radial systems are complicated to operate as a meshed network due to two reasons: first, a rise in the short-circuit current in each node that would imply the substitution of the existing circuit breakers [4], and secondly, important inversions in newly advanced protection schemes would have to be carried out. Moreover, the DG penetration could be limited due to reverse power flows, transformers and lines saturation and voltages increases in part of the network with a great DG presence [5]. A way to circumvent these problems consists of using DC links based on voltage source converters (VSC) [6]–[8]. These devices allow interconnecting adjacent feeders by replacing the traditional open switching center, as shown Fig. 1, and controlling the power flows between them. In this way, the energy throughout the network can be properly redirected to integrate as much DG as possible [9], increase the system loadability [7] or reduce the system power losses [10] maintaining the technical limits of currents and voltages. The most important benefits that VSC-based DC links can provide to the grids are summarized as follows:

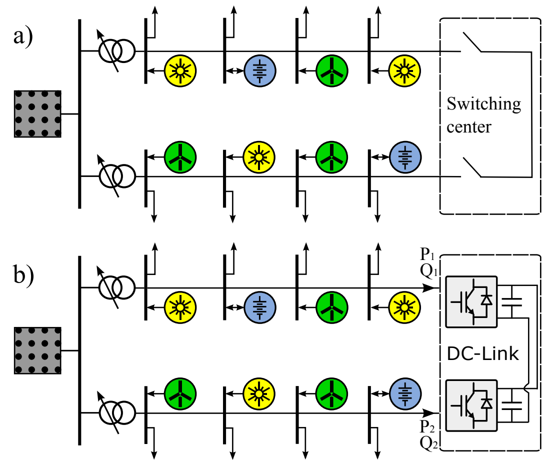

Fig. 1. a) Typical network connection; b) DC link interconnection.

- The VSC-based DC link can regulate the active power flow between the feeders continuously and the reactive power injection at both AC terminal nodes independently.
- If necessary, the VSC technology can be used to mitigate voltage imbalances, as well as low-order harmonics, improving the power quality of the distribution network.
- The DC link can be used to connect any group of feeders regardless of the angular difference between them (this may be a crucial factor when the feeders are supplied from different substations) or their rated voltage difference (which is not possible with mechanical switches).
- Existing short-circuit currents are not modified when adding multi-VSC links, owing to their almost instantaneous current control capability. Therefore their use does not involve any change of existing protecting devices.

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The good results achieved with the VSC-based DC links to integrate distributed energy resources efficiently in smart grids allow us to consider these devices for an adequate development of microgrids. These are characterized by having a similar topology to LV and MV distribution networks with high renewable energy generation, energy storage and loads such as the electric vehicle. Under these conditions, the interconnection between different microgrids using the flexibility provided by the VSC-based DC link could facilitate the deployment of these in electrical systems. Even, they would allow the expansion of hybrid microgrids where generators and loads could be connected either AC or DC grid.

The paper is organized as follows. First, a description of the microgrid operation and control is described. Second, the most important VSC-based DC links are introduced. Third, the mathematical optimization problem for the operation of VSC-based DC links in smart grids is presented. Then, some simulation and experimental results of applications of VSC-based DC links in smart grids are shown in section V . Finally, the paper closes summarizing the main conclusions.

II. Microgrid Operation and Control

According to the European projects *Microgrids* and *More microgrids* [11], [12], a microgrid is defined as follows:

Microgrids comprise LV distribution systems with distributed energy resources together with storage devices and flexible loads. Such systems can be operated in a non-autonomous way if interconnected to the grid, or in an independent way if disconnected from the main grid. The operation of microsources in the network can provide distinct benefits to the overall system performance, if managed and coordinated efficiently.

It is worth highlighting the following defining aspects of a microgrid:

- A microgrid is a platform for integrating resources of generation, storage and consumption of electrical energy, connected to the same electrical distribution network.
- A microgrid must be able to operate both connected to the electrical system in normal situations, and in isolation in emergency situations.
- The fundamental difference between a microgrid and a distribution network with distributed generation resources consists of the coordinated management of the different generation, storage and controllable loads.

Typically, a microgrid is limited to several MW regarding peak demand, although on a larger scale, it is easier to incorporate resources to improve controllability to reduce the intermittent nature of renewable generation and consumption [13].

A. Participation in Electricity Markets

Due to their relatively small size regarding peak power, microgrids generally do not participate in energy markets and channel their participation through aggregators or an Energy Service Company (ESCO).

Concerning microgrid consumption management, the following alternatives can be considered [14]:

- Price-based demand response implementations respond to time-based changes in the prices of the energy, including real-time pricing, critical-peak pricing and time-of-use rates.
- Incentive-based demand response programs facilitated by utilities, retail companies or DSOs to introduce load reduction incentives. Load reductions are coordinated by an operator and can include direct load control (i.e., the program operator remotely shuts down or connect a customers electrical equipment).

B. Provision of Ancillary Services

"Ancillary services are all services required by the transmission or distribution system operator to enable them to maintain the integrity and stability of the transmission or distribution system as well as the power quality" [15]. The services include both mandatory services and services subject to competition.

Ancillary services that can be provided by a microgrid are classified according to the operation modes [13]:

- Grid-connected operation: frequency control support, voltage control support, congestion management, reduction of grid losses, and improvement of power quality.
- Islanded operation: black start and grid-forming operation (frequency control and voltage control).

The provision of ancillary services in grid-connected mode is usually managed through long-term contracts with TSO (frequency control support) or DSO (voltage control support and congestion management), which may include real-time service requirements (voltage & reactive power support; congestion management through load curtailment).

C. Microgrid Control

Control is a fundamental issue in microgrids [12], [16], so that they appear to the upstream DSO as a coordinated unit. Such control can be implemented in a variety of ways, ranging from centralized control to fully decentralized control, depending on the degree of responsibility assumed centrally or locally by the different resources.

Although there is no generalizable structure to any microgrid, depending largely on the type of microgrid and its existing infrastructure, it is common for the microgrid control to be organized in a hierarchical structure at three levels [17]:

- A primary, local level, composed of several microsource controllers (MCs) which are responsible for controlling distributed energy resources.
- A secondary, centralized level, consisting of the Microgrid Central Controller (MGCC) responsible for the coordination and monitoring of the various local MCs.
- A centralized, tertiary level, in charge of providing the main interface between the MGCC and external actors such as DSO or ESCO. It is responsible for the maximization of the microgrid value and provides setpoints for the MCs and the MGCC. The tertiary level is equipped with

scheduling routines that provide optimal setpoints for the MCs, based on the overall optimization objectives [18].

The hierarchical structure of the microgrid can be operated in a centralized or decentralized way. In centralized control, secondary and tertiary levels are responsible for the optimization of the operation, and based on electricity prices and fuel costs, and taking into account grid security concerns and possible ancillary services requests by external agents, determines the power that the microgrid should import from the distribution grid, optimizing local generation or consumption resources. The operating scenarios are realized by regulating the MCs within the microgrid by sending set-point signals through the MGCC.

In a fully decentralized control, MCs compete or collaborate to optimize their production/consumption, to satisfy the demand and to provide the maximum return taking into account energy prices. This approach is more suitable in cases of different ownership of the microgrid resources, where several decisions must be made locally. In both centralized and decentralized approaches, some basic information is centrally available, such as local production/demand forecasting, and security monitoring (SCADA).

Centralized control is more appropriate when the resources of the microgrid have common objectives or a common operational structure (e.g., an industrial microgrid). The optimization problem has a definite objective (cost minimization) and a limited number of constraints, allowing to compute an accurate operational scheduling to avoid profit losses [13]. In a decentralized environment, the distributed resources require a certain degree of independence and local intelligence to achieve different objectives (e.g., minimizing their own energy cost, producing power & heat locally, controlling the local voltage, or providing backup power locally in case of system blackout), as is the case of residential microgrids.

The frequency control of a power system is implemented by a central controller, the Load-Frequency Control in Europe or Automatic Generation Control in the USA, based on a slow Proportional-Integral (PI) controller that restores the frequency of the grid when the error is over a specific value (e.g., 50 mHz) [19]. A similar control must be implemented by the MGCC to restore the frequency of an isolated microgrid, controlling the MCs.

For the local primary control in islanded mode, the MCs can be classified as grid-following or grid-forming [18], [20]. If the microgrid contains multiple dispatchable generation units, the power needs to be shared, and a P/f droop control must be implemented locally. Alternatively, a P/V droop control can be required in LV microgrids due to the high R/X ratio. Besides, the low inertia typical of isolated microgrids results in larger frequency deviations after an event, and virtual synchronous generators can be required to emulate rotating inertia [21].

Voltage control can be implemented by using a similar approach as the frequency control. When the voltage is outside a specific range, a slow PI control compensates the voltage error in the microgrid by sending orders to MCs to regulate their reactive power support.

The transition between on-grid mode and the islanded mode is also a crucial issue [22]. A microgrid can support a seamless transition to an islanded operation, or it may not. In the case of an unplanned and unexpected grid blackout, an intentional lack of requirement to support seamless transition is a good cost-benefit approach. Critical loads will certainly already have an uninterruptible power supply (UPS) to be relied upon during the transition to islanded mode. Otherwise, the microgrid would require having constantly running generation or significant energy storage, increasing capital costs.

III. DC link Topologies

In the specified literature, different DC link topologies have been proposed to interconnect independent radial feeders and controlling the power flows between them. However, from the flexibility in the power to be controlled and practical implementation point of view, two of them are considered the most relevant: B2B VSCs and Shunt-series VSCs.

The subsequent subsections analyse these topologies, describing their corresponding operational constraints and way of electrical connection to the network.

A. B2B VSCs

The BTB VSC topology shown in Fig. 2 consists of two VSCs sharing a common DC bus. The connection of the twin VSCs to the network depends on the rated voltage and usually a power transformer is necessary. This arrangement is capable of controlling the active power flow between the coupled feeders in addition to the reactive power injected at each point of common coupling (PCC). Note that, in order to maintain the DC voltage constant, this topology has three degrees of freedom because the active power at each PCC must verify: $P_m + P_n = 0$ (losses neglected). In this cascade-type arrangement both converters are rated to a voltage which is of the same order of magnitude as the PCC voltage, whereas the rated power is determined by the desired apparent power transfer in the interconnection.

B. Shunt-series VSCs

This configuration, also known as UPFC in transmission applications, is also shown in Fig. 2. It is composed of two VSCs with a common DC link but, unlike in the BTB configuration, one of them is in series with the interconnected feeders. In this manner, the rated voltage of the series VSC is only a fraction of the network voltage whereas the rated current should be enough to withstand the total line current. The rated voltage of the shunt converter, like in the BTB configuration, is approximately the network-rated voltage, whereas the rated current has to be selected considering the sum of the interconnected feeder currents. As a consequence, the rated power of the series VSC gets reduced, whereas the shunt VSC is usually dimensioned for full power. Like in the former case, three degrees of freedom are associated with the shuntseries VSCs (active power flow between the feeders and reactive power injections at each terminal node).

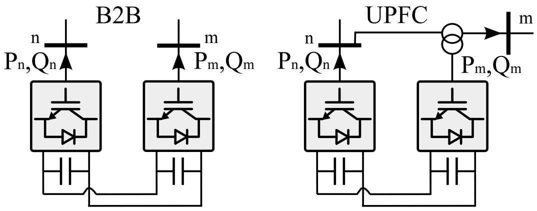

Fig. 2. Back-to-back and UPFC topologies.

IV. DC LINK INTEGRATION IN SMART GRIDS

The DC link operation is a task normally performed at the MGCC, where an overall sight of the network is available. The MGCC can be considered as an Energy Management System where several functions run to determine the state of the system (State Estimator) or to generate the set points to the different MCs. One of such functions is an Optimal Power Flow (OPF), which considering the system state computes the most suitable actions to improve the operation. The objective of the OPF could vary according to the interests of the microgrid owner. Some examples are costs reduction, security of supply improvement, maximization of the renewable penetration and active power losses reduction.

The rest of this section depicts the general formulation of an OPF used to compute the centralized control actions. The objective function is the reduction of the active power losses in the MV network. Examples of different objective functions can be seen in [7]. This option is selected because it allows the OPF to reduce the total system losses while avoiding current saturations and voltage levels outside safe limits.

The control variables ($\mathbf{x}$) are the active and reactive power references for the DC-link VSCs ($P_{1,2}^{opt}, Q_{1,2}^{opt}$). Eventually, other control actions could be considered, as the reactive power for DGs or the tap position for the substation transformer OLTC. The state vector $\mathbf{x}$ is composed of the voltage magnitudes and angles for every MV bus i.

This is expressed mathematically as follows:

$$\min_{\mathbf{u}} P_{\text{loss}}(\mathbf{x}). \tag{1}$$

The equality constraints are the active and reactive power balance for each bus:

$$P_i^{bal} = V_i \sum_j \left(V_j G_{ij} \cos\theta_{ij} + V_j B_{ij} \sin\theta_{ij} \right), \forall i \in \mathcal{N} \tag{2}$$

$$Q_i^{bal} = V_i \sum_j \left(V_j G_{ij} \sin\theta_{ij} - V_j B_{ij} \cos\theta_{ij} \right), \forall i \in \mathcal{N} \tag{3}$$

$$P_i^{bal} = P_{DGi} - P_{li}, \quad \forall i \in \mathcal{N} - \{1,2\} \tag{4}$$

$$Q_i^{bal} = Q_{DGi} - Q_{li}, \quad \forall i \in \mathcal{N} - \{1,2\} \tag{5}$$

$$P_{1,2}^{bal} = P_{DG1,2} - P_{l1,2} + P_{1,2}^{opt} \tag{6}$$

$$Q_{1,2}^{bal} = Q_{DG1,2} - Q_{l1,2} + Q_{1,2}^{opt} \tag{7}$$

$$P_{loss}^{link} = -(P_1^{opt} + P_2^{opt}) \tag{8}$$

where $\mathcal{N}$ is the set of buses, $P_{DGi} + jQ_{DGi}$, is the total complex power injected by dispersed generators connected at bus i, $P_{li} + jQ_{li}$ is the complex load demanded at bus i, $G_{ij} + jB_{ij}$ is the ij-element of the bus admittance matrix; 1 and 2 are the DC link connection buses, and P_{loss}^{link} are the DC link internal power losses.

On the other hand, inequality constraints are defined as follows:

$$0 \le I_{i,j} \le I_{i,j}^{max}, \quad \forall (i,j) \in \mathcal{B} \tag{9}$$

$$V_i^{min} \le V_i \le V_i^{max}, \quad \forall i \in \mathcal{N} \tag{10}$$

$$0 \le S_{link} \le S_{rat}. \tag{11}$$

where $\mathcal{B}$ is the set of branches, (9) is the conductor ampacity limit, (10) defines the bus voltage magnitude limits and (11) refers to the DC-link VSC rated power limit.

V. SIMULATION AND EXPERIMENTAL RESULTS IN SMART GRIDS

This section is devoted to showing simulation and experimental results of the DC link topologies presented in section III when these are used to interconnect the distribution network proposed by CIGRE Task Force C06.04.02 [23]. Fig. 3 shows the single phase diagram of the proposed benchmark which is composed of two sub-networks, i.e. sub-system 1 and sub-system 2, supplied through two HV/MV transformers from the main substation. The system contains 14 buses where several household and industrial loads and an intensive penetration of DG are connected. These are monitored every 5 minutes using measurement concentrators at each bus. The parameters of the electrical lines and the daily load profiles of the loads and generators are fully defined in [23]. Finally, the proposed DC links are connected between buses 8 and 9 to carry out the meshing of the network.

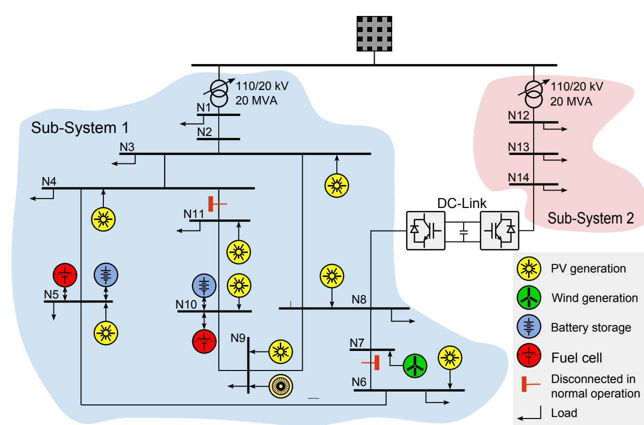

Fig. 3. Benchmark Network.

An OPF computes the control variables every 5 minutes to fulfil with the feasible operational margin of voltages and currents throughout the system. In Table I, the active power losses for the whole day are summarized for each DC link proposals when the objective function of the OPF is based on power losses reduction in the system. These are compared with the case base (BC) where no DC links are used to interconnect both sub-systems. It is remarkable the significant reduction, around 50% when the DC links are used. Especially when the UPFC topology is used since the power losses of the serial VSC are significantly lower than the shunt VSCs. This table also shows the results obtained when the objective function of the OPF is based on maximizing the DG penetration. The increasing of DG penetration (ΔDG) concerning the BC are 65% and 106% for B2B and UPFC topologies, respectively. This is because the high penetration of DGs in sub-system 1 produces lines saturations and overvoltages at certain buses. The DC link permits to evacuate part of the energy injected in sub-system 1 through subsystem 2, avoiding those problems.

Fig. 4 represents the daily evolution of the active and reactive powers injected by the DC link bus 8 when the objective is the reduction of power losses. This figure reveals that the DC link injects active power into bus 8, the same amount which withdraws from bus 14. In other words, part of the loads of subsystem 1 is fed by subsystem 2. Besides, the DC link also injects reactive power to bus 8. This increases the voltages helping in the reduction of power losses.

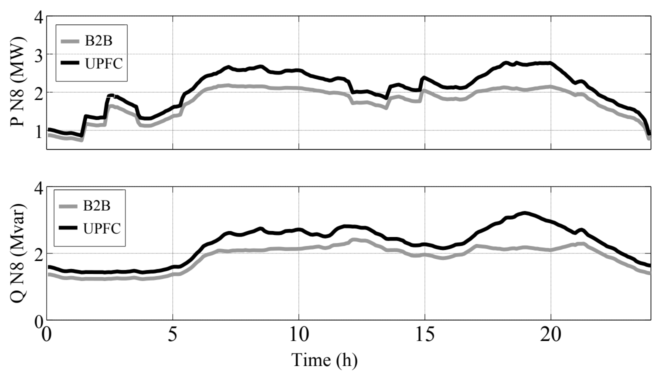

Fig. 4. Evolution of Active power flow at bus 8 (top) and Reactive power injection at Bus 8 (bottom).

The previous results are based on a Centralized Controller where the OPF is executed, and the calculated set-points are sent to the DC links local controller. This requires an extensive communication infrastructure that allows an adequate operation of the system, and that could hinder the implementation of these devices in smart grids. To facilitate their integration, exclusively local controls have been proposed to manage the DC links power flows. In [24], a multiterminal DC link (more than two shunt VSCs sharing a common DC bus) interconnecting two LV networks (with a similar topology to the system in Fig. 1) is proposed to integrate fast-charging electric vehicle stations (EVS) efficiently. A local controller is implemented to balance the active power supplied by the

TABLE I
ENERGY LOSSES, ENERGY LOSSES REDUCTION AND DG PENETRATION.

	E_{LOSS} [kWh]	ΔE_{LOSS} [%]	ΔDG [%]
BC	5027	–	–
B2B	2772	−44.9	65
UPFC	2401	−52.3	106

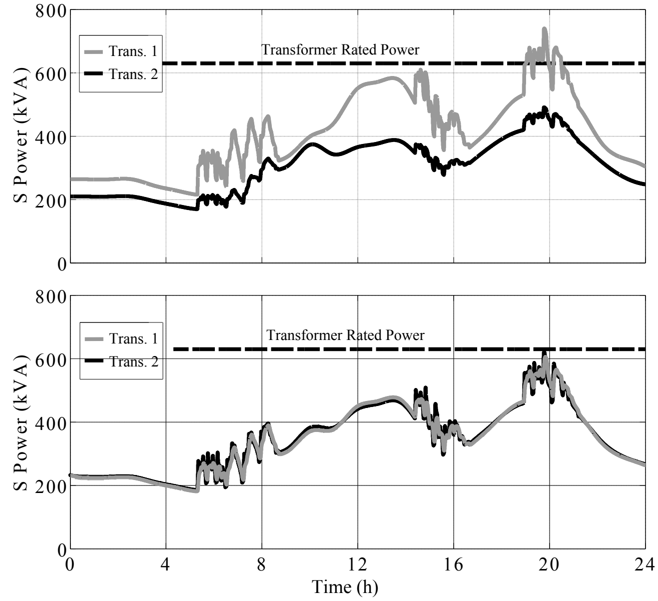

Fig. 5. Evolution of apparent powers at header transformer in BC (top) and evolution of apparent powers at header transformer with DC link (bottom)

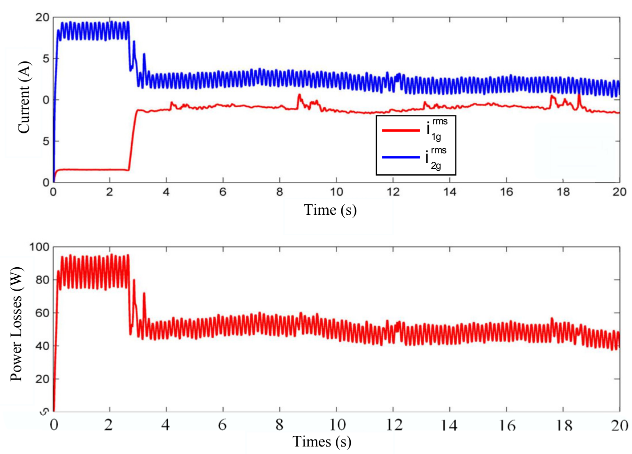

Fig. 6. Evolution of header current in the scaled-down distribution networks (top) and evolution of total power losses (bottom)

two header transformers. Fig. 5 compares the apparent power of the transformers in the BC and when the multiterminal DC link is used. The latter supply energy to typical domestic loads plus an EVS which is operative in three time slots (5:00-9:00, 15:00-17:00 and 19:00-21:00). This reflects that transformer 1 can suffer overloads in the BC around 20:00 whereas the DC link allow to balance both transformers controlling the power flows. Besides, applying the above strategy, the power losses were reduced by 50% and the voltages of the buses increased.

Finally, Fig. 6 shows experimental results with a B2B topology interconnecting two laboratory scaled-down distribution networks. The electrical parameters of the networks and VSCs are collected in [10]. A local strategy is implemented aiming to balance the header current of both scaled-down networks. This simple strategy allows equalizing the current on both feeders, which leads to a significant power losses reduction (up to 50% in the case shown in Fig. 6).

VI. Conclusions

This paper demonstrates the potential of incorporating VSC-based DC links among adjacent radial feeders in smart grids, and in particular microgrids. The objective could be to foster the integration of DG, improve feeder loadability by equalizing loads or maximize the efficiency by reducing the active power losses. Two VSC-based topologies are studied: BTB and shuntseries VSCs. Both provide three degrees of freedom, being it possible to control the active power flow and the reactive power injected at both terminal nodes independently.

Three use cases are shown in Section V: the first show the advantages of DC links to reduce losses and balance the load in a MV distribution system. It is also shown that the UPFC topology is more efficient than the B2B, mostly due to its smaller internal power losses. The second use case demonstrate the effectiveness of using multi-terminal DC links to balance the loads in LV feeders. In this case the control strategy is based only on local measurement, avoiding the need of a central controller. Finally, a similar approach is used to demonstrate the dynamic behavior of the control.

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