Description of scenarios for DC-AC/DC hybrid grid architectures and services provided to the main grid

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WP2. Boundary Conditions and Baseline for TIGON Development

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CERTH

Authors:

Maria Fotopoulou, Dimitrios Trigkas, Fotis Stergiopoulos, Dimitrios Rakopoulos, Nikos Nikolopoulos, Spyros Voutetakis (CERTH)

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Maria Fotopoulou, Dimitrios Trigkas, Fotis Stergiopoulos, Dimitrios Rakopoulos, Nikos Nikolopoulos, Spyros Voutetakis (CERTH)	Dimitrios Rakopoulos (CERTH)
	Jesus Muñoz, Breogan Sanchez (CIRCE)
	Dominique Roggo (TUAS)

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Executive Summary

Undoubtably, today we stand as witnesses of the major transformation occuring in the world of electrical power systems. Technological developments, the increased penetration of renewable energy systems, the shift towards electric propulsion both in land and at sea, have stirred the stagnant nature of power generation, tranmission and distribution, disputing the “unquestionable” dominance of AC over DC systems.

This report tries to shed light upon all aspects in the integration of DC into AC systems focusing – and not only! – on grid achitectures and services to the grid. By combining benefits of DC systems such as easier integration of renewable energy systems and energy storage systems, effective integration of DC loads, efficient transmission over long distances, enhanced power quality, reduced visual impact, with existing AC infrastructures, hybrid systems can be created to bring about the best of the two worlds. Acting as a catalyst in this “symbiosis”, power electronic converter technology ensures a smooth transition towards the hybridization of the AC grid.

There exist various options to interface DC into AC systems, generally divided into coupled and decoupled AC configurations, with complete or partial isolation. The selection of the appropriate interface needs to be made according to each application, considering the budget, the flexibility required, i.e. controllability, scalability, and modularity, the safety and the purpose of the designed grid.

DC power systems can take several forms and configurations such as radial (series or parallel), ring and interconnected (mesh or zonal type) configuration. Their control includes three basic levels, being primary, secondary and tertiary. Several techniques have been developed based on the purpose of each type of control.

Useful experience, know-how and best practices can be utilised from applications of DC power systems across various sectors that for example include sea vessels, urban transport, data centres, buildings, lighting, remote installations, transmission and distribution, electric vehicles and industrial applications. Started as “niche markets, these sectors pave the way towards the wider facilitation of DC systems.

The increased importance of supporting the grid and providing ancillary services is also a significant area for further development of DC systems. As “presented in detail, ancillary services can be classified based on the type of the equipment (AC or DC) and the grid provided (AC or DC). They mainly include support of active power/frequency, reactive power/voltage, oscillation damping, black start and restoration, transmission reserve and power flow control. Useful experience from the development of Network Codes for HVDC systems can also be utilised.

The future trend towards DC systems is for them to be used as integral parts in smart grids, renewable energy applciations, traction systems, ships and electric vehicles. However, action towards increased awareness, motivates R&D to address issues that lack behind their AC counterparts, such as safety and protection units. The lack of a comprehensive set of standards is also an obstacle that needs to be overcome, indicatively in areas such as railway systems, ships, buildings, circuit breakers and safety of operations, distributed resources, AC-DC connection, low voltage DC distribution, power quality and electromagnetic compatibility.

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Abreviations and acronyms

AC	Alternating Current
ACE	Area Control Error
BESS	Battery Energy Storage Systems
DAB	Dual Active Bridge
DC	Direct Current
DL	Deep Learning
DRL	Deep Reinforcement Learning
ESS	Energy Storage Systems
EU	European Union
EV	Electric Vehicle
FACTS	Flexible Alternating Current Transmission Systems
FCR	Frequency Containment Reserves
FID	Fault Identification Device
FRR	Frequency Restoration Reserves
HFT	High Frequency Transformer
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LED	Light Emitting Diode
LFC	Load Frequency Control
LV	Low Voltage
LVAC	Low Voltage Alternating Current
LVDC	Low Voltage Direct Current
MCS	Multi-Criterion Systems
MG	MicroGrid
MPPT	Maximum Power Point Tracking
MVAC	Medium Voltage Alternating Current
MVDC	Medium Voltage Direct Current
NN	Neural Networks

PET	Power Electronic Transformer
PPM	Power Park Modules
PSS	Power System Stabiliser
PV	PhotoVoltaic
RES	Renewable Energy Sources/Systems
RR	Replacement Reserves
SO	System Operator
SST	Solid State Transformer
STATCOM	STATic Synchrnous COMpensator
SVC	Static Var Compensator
TSO	Transmission System Operator
VSC	Voltage Source Converter

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1. Introduction

From the early times up until today, the energy infrastructure of electrical grids has been predominantly based on alternating current (AC) [1]. This is attributed to economic factors related to the power delivery capacity but also and most importantly to the ease of voltage levels adjustments using power transformers that allowed the efficient dispatch of electrical energy at distances far away from the production centres, with relatively low losses. The foundation of production has been mostly depended on fossil fuel based plants that produce AC power and the majority of loads have been AC devices and equipment. Large investments over the decades allowed also for the development of transmission and distribution grids, whereas a set of standards and international agreements helped to develop an operational framework of basic technical parameters such as voltage and frequency. Furthermore, a center-based approach has been applied for electrical power production, based on the ease of primary fuel (coal, natural gas, oil, etc.) accommodation. This status resulted to the development of a structure of the traditional unidirectional AC power flow grids, which dominate the wordwide transmission and distribution systems [2].

However, in modern times, socioeconomic indexes pave the way towards a more ecological, sustainable future, which influences all sectors of industry and economy, including electrical grids. It is true that electrical energy has been used as a moving force behind industrial development. As known the consumption of electrical energy at national or international level, expressed as an index e.g. per capita, is in many cases associated with economic growth. On the other hand, the continuous increase of demand has resulted in the emergence of severe environmental concerns and issues about security of supply, owing to the depletion of fossil fuels. By investigating possible solutions for these modern challenges from the aspect of the electrical grids, a variety of solutions has emerged, among which direct current (DC) solutions appear to be promising. As known, DC power has been known for years to be an effective solution for power transmission over large distances, due to stability issues that arise using AC systems. More importantly, over the course of time and especially in the last decades, significant improvements in DC technology such as cables, switchgear, etc. have taken place. Furthermore, the extensive proliferation of power electronics technology has led to the development of cost effective solutions in DC-based power converters (DC/AC and DC/DC), facilitating the adjustment of levels (transformation) of DC voltage, which was not possible earlier. Also, the increased application of electrical energy sources that primarily produce DC power such as photovoltaics and fuel cells, provide further incentives for the exploitation of DC technology. Inevitably, a new need emerges that refers to the provision of “interfaces” between DC and AC systems, be it sources or loads. This development highlights the need for further research regarding the integration of DC solutions in the existing AC infrastructures, thus creating hybrid AC/DC grids [3] [4], producing an overall seamless operational system, maintaining the standards of supply (security, quality etc) in a cost effective manner.

This report aims to showcase the high potential and the significant role that DC systems and grids have in the current framework of electrical energy systems by reviewing the main operational aspects, possible architectures and applications of DC-AC/DC hybrid grids as well as the ancillary services they may provide to the main AC grid. The rest of the report is organized as follows:

- Section 2 is focused on the main aspects and discusses the advantages and disadvantages of DC-AC/DC hybrid grids
- Section 3 reviews possible architectures and control schemes of DC-AC/DC hybrid grids
- Section 4 presents applications of DC-AC/DC hybrid grids
- Section 5 analyses the ancillary services that can be offered to the main (AC) grid

- Section 6 outlines future trends and possible challenges regarding DC-AC/DC hybrid grids

2. Main aspects of hybrid grids

2.1. Challenges of modern electrical energy grids

Sustainable development is a pillar of the European Union (EU) policy. According to the European Commission targets of 2020, following levels of more stringent approaches, the greenhouse gas emissions need to be reduced by at least 55% by 2030, compared to 1990 levels [5]. In order for these goals to be achieved, the utilization of Renewable Energy Sources (RES) is considered to be a milestone [6]. The growing need for RES has brought electrical energy producing technologies such as photovoltaic systems (PVs), wind generators, hydro generation and biomass/biogas-based systems to the spotlight. Today, photovoltaics (PV) seem to have the highest penetration level, owing to the ease of application and the reduced capital cost of typical installations [7]. PV systems can easily be distributed and mounted on any sun-exposed area, including both urban and rural areas. Therefore, there are limitless opportunities for power production. Furthermore, increased levels of production can be achieved by the application of solar tracking systems. It is estimated that the PV potential of urban areas can satisfy a high percentage of the electricity demand, depending on the latitude of the area and the technological evolution of the installed panels. In addition, PV systems produce their highest levels at times of increased insolation, which can be of benefit to the main grid, especially at times of high demand. [8]. Despite the advantages of the incorporation of PV systems or RES in general to the electrical grid, in most cases, the power produced by them is intermediate, which endangers the balance between generation and demand [9] that has to be met at any given instant. For example, PV systems cannot produce energy during the night or during times of low insolation. More importantly, wind speed, which is utilized by wind generators, is to a great extent a stochastic parameter. The sensitive balance of generation and demand can be therefore disturbed, i.e. having a low production when demand increases therefore creating a deficit which has to be covered or, vice versa having a high RES production in cases of low demand which can lead to curtailment and associated losses of useful energy. Adding more complexity to the problem, RES-based systems are distributed, scattered geographically and therefore connected to different points to the grid. This can impose more restrictions associated with the capacity of the electrical grid to manage energy, therefore creating further potential cases for the disruption of the balance.

In order to tackle this issue, much attention has been given to Energy Storage Systems (ESS) that act as a “buffers” of energy, able to handle the intermediate production of the RES, eliminating possible imbalances. There is a number of ESS technologies, including Battery Energy Storage Systems (BESS), flywheels, compressed air systems etc [10] [11], each one having specific characteristics in terms of energy, power, cycles of use, etc. Among them, BESS have drawn considerable attention due to their advantages, which include fast response, controllability and geographical independence [12]. Great experience acquired over the years regarding the operation of batteries combined with technological developments, which allow better performance at a reduced size, have been major drivers behind the development of BESS. Furthermore, the emergence of a new era as regards the electrification of transport, brings in new conditions that will allow for further investments in battery technology. In this way, the integration of RES and BESS in power systems is an effective method to decarbonize the electricity system, by enabling the increased proliferation of renewable energy, while also ensuring the stability of the grid.

Apart from the ability for a more eco-friendly future that is provided by the implementation of RES in combination with BESS, the main factor that differentiates them from traditional sources of energy is that, in most cases, they produce DC power. The DC voltage produced is converted to AC voltage through DC/AC converters, in order to be inserted in the AC grid. In the case of BESS, the converters being used are bidirectional allowing the BESS to be charged by the grid at suitable (e.g. with low cost or at periods of low loads) or necessary times. Furthermore, the conversion can be performed at a single stage (i.e. directly to AC) or through the intermediate production of a (usually higher) DC voltage in DC/DC converters.

In addition to the rise of DC technologies in the sector of electrical energy supply, similar phenomena occur on the side of demand. In fact, the profile of consumption, which is mostly based on AC loads has started to change over the past few years due to the accenting amalgamation of DC devices to the total load. Such devices include Electric Vehicles (EVs), computers, battery-based devices, LED lights, etc [13]. More particularly, the number of EV's is expected to keep increasing, since they provide an ecological solution to transportation, in contrast to the traditional vehicles. Additionally, LED lights have substituted the classic lighting system in many public areas, office buildings or even residences. Also, even though a great number of loads, such as electronic equipment, are considered to be AC loads, they are in fact DC loads including a power stage of AC/DC rectification and subsequent use of DC/DC converters to enable power up of the device. This is typically the case of many household appliances, elevators and modern air conditioning systems.

Facing the rise of both DC power supply and DC power consumption, questions are raised regarding the effectiveness of maintaining the same principle of AC distribution and there are cases where DC distribution is proposed as an alternative, as presented in Figure 2.1 [14]. The backbone of such an architecture is the creation of a DC bus, onto which all sources and loads are connected with suitable AC/DC and DC/DC power converters to accomodate supply levels. This structure consists of DC lines which distribute DC power from the local RES and BESS to the local demand. The AC power imported from the feeder is converted to DC through an AC/DC converter which can be bidirectional. Also the power feeding the AC loads is converted from DC to AC through a DC/AC converter. The proposed system is not only considered for large scale (in terms of power) grids but also for small scale applications, i.e. for buildings that are equipped with PVs and BESS, as presented in Figure 2.2 [15]. Furthermore, DC power is proposed for isolated grids such as ships, where there is AC and DC power on the side of both supply and demand, as presented in Figure 2.3 [14].

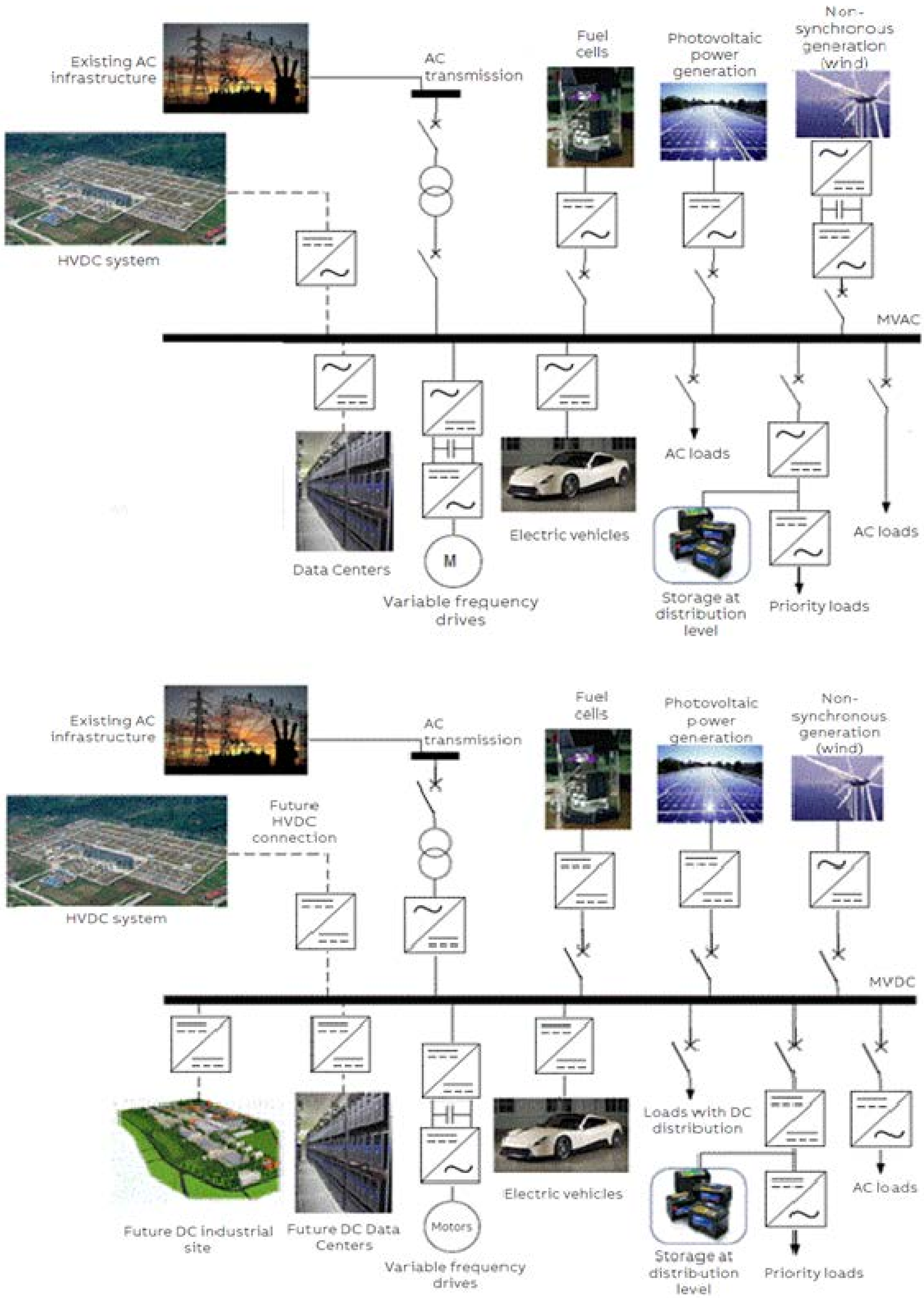

Figure 2.1: Main concept of traditional AC distribution (up) and DC-AC/DC hybrid grid approach (down) [14]

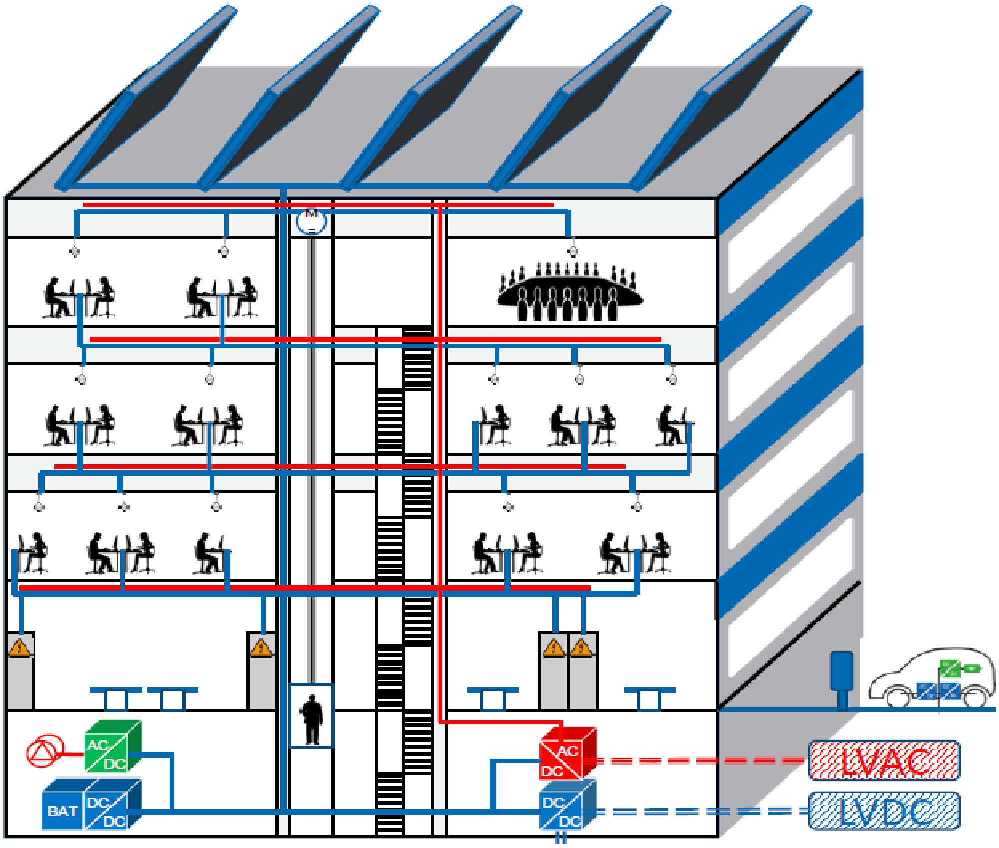

Figure 2.2: Main concept of DC-AC/DC hybrid distribution in buildings [15]

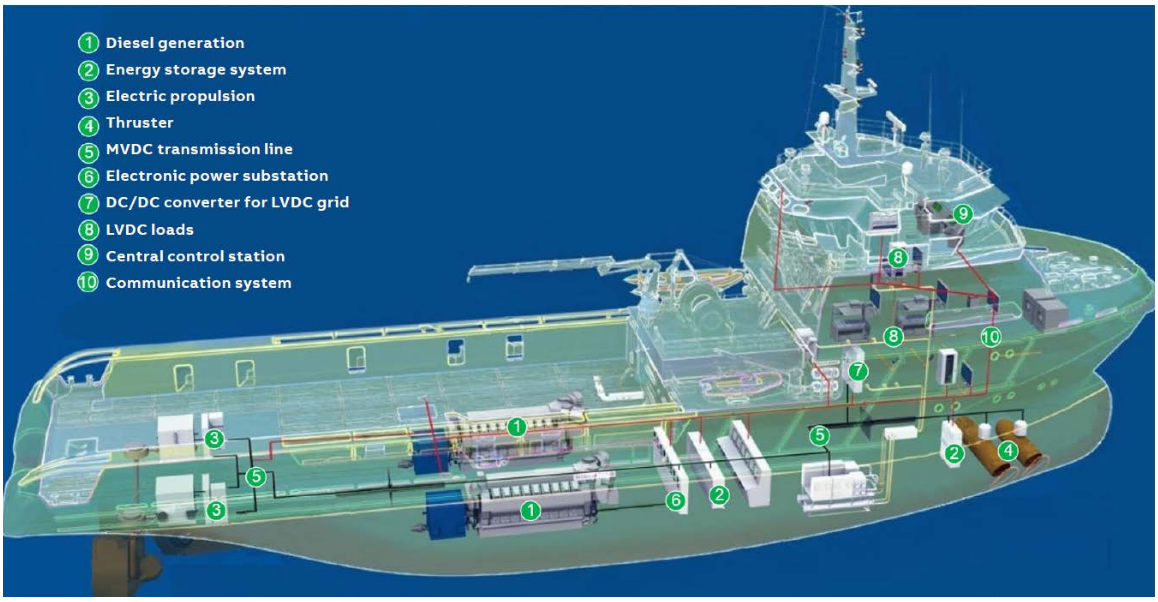

Figure 2.3: DC distribution system in ships [14]

Another challenge for modern grids is the effective management of operation in remote areas, areas with specific geographical characteristics (e.g. islands), or areas with weak grids, in terms of stability. The connection of such areas is of vital importance for two main reasons, apart from the socioeconomic fact that consumers should enjoy the same levels of services irrespectively of their location. The first reason is RES-related, based on the high-power production potential of such areas. For example, the wind energy potential of secluded islands has been on the spotlight over the past few years. High wind speed for many hours per year and large open space areas, are considered to be the main advantages for the production of “green” energy. For this reason, windfarms able to generate great amounts of power are installed in various islands. The full exploitation of the whole spectrum of (wind) energy potential necessitates the ability to transmit power to the mainland, as in most cases, the local power demand is relatively low, subject also to seasonal variation (e.g. winter/summer). However, some of these islands are located hundreds of kilometers away from the mainland. This poses a challenge to the expansion of the electrical grid [16]. In fact, underwater cables are required to transmit power over long distances. In these cases, it is essential that the distance is bridged in a cost-effective way, with low power losses. To tackle this issue, traditional AC solutions are proven to be less effective than DC solutions, as presented in Figure 2.4 [17]. As a result, DC transmission has gained the attention of grid developers, especially when it comes to the connection of offshore wind farms, as presented in Figure 2.5 [18] [19]. The second reason why modern grids need to expand is the connection of populated islands with weak grids. The challenge in this case is not only related to the physical distance that occurs between the islands but also to the power quality issues that the grid of an island can face. Islands typically have their own electrical power generation units and grid, which is in most cases weak and unstable compared to the grid of the mainland. Such grids typically include a growing number of decentralized and volatile sources with low system inertia [20]. This means that there may be imbalances between energy production and consumption, resulting to power quality issues and instability. The situation can worsen at certain periods of the year, when e.g. due to the large number of visitors-tourists, the stress on the network is greater. In order to reinforce the grid, the worldwide market is oriented towards the connection of islands with the mainland or even with other islands, utilizing underwater DC cables [21].This approach is not only related to the efficiency of DC links, but also to their inherent attributes [22] that contribute to the stability of the grid and improve its quality. It should be noted that in the case of DC links, not only the grid is reinforced but the connection of grids that have different frequency levels is feasible as well. The general concept of the topology of such hybrid grids is presented in Figure 2.6 [23].

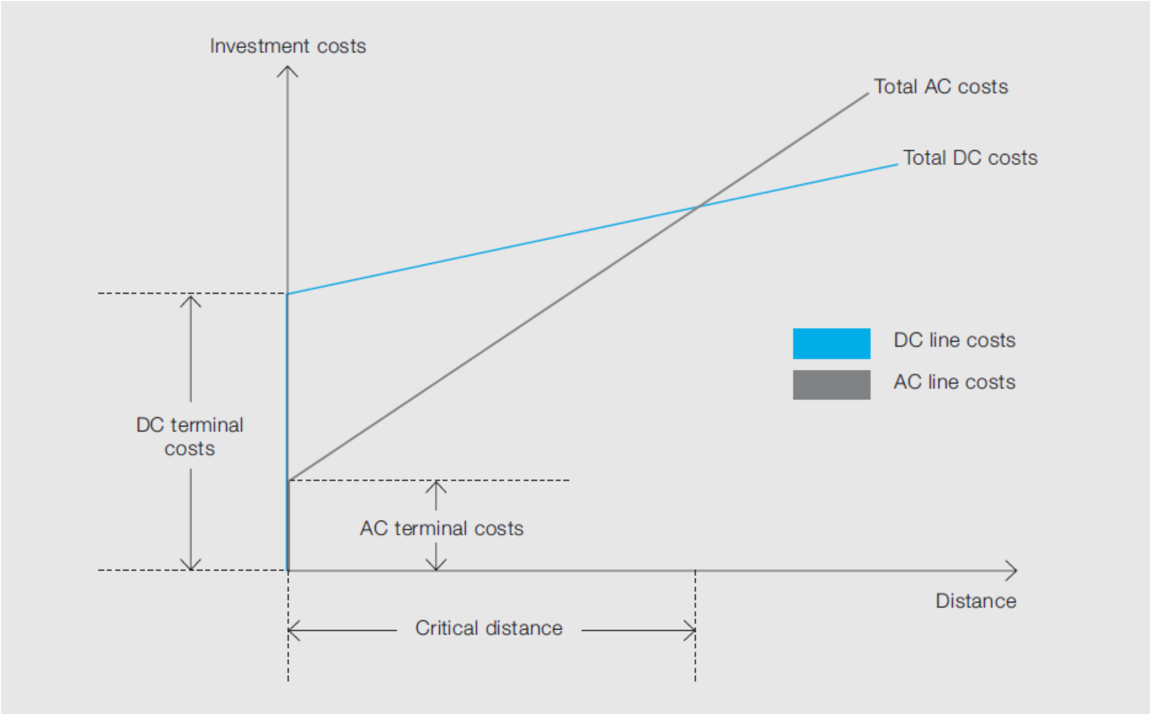

Figure 2.4: Cost effectiveness of DC lines over long distances [17]

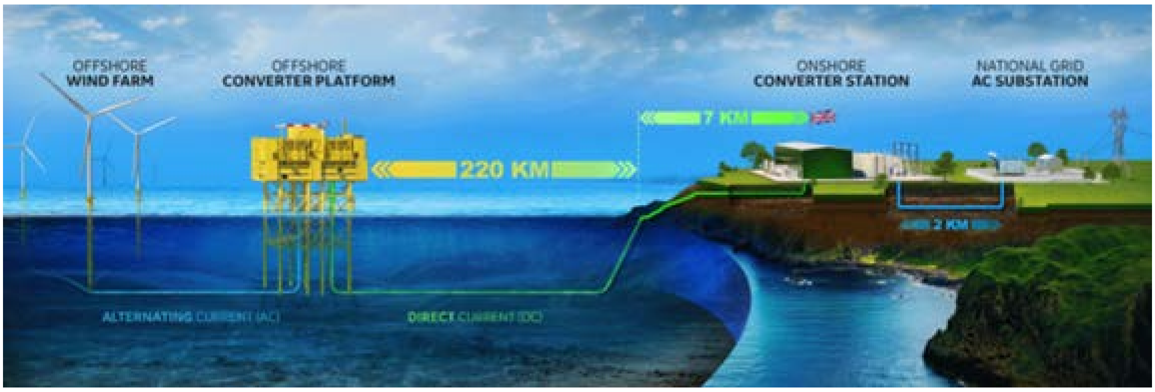

Figure 2.5: DC link between offshore wind farms and the main grid [19]

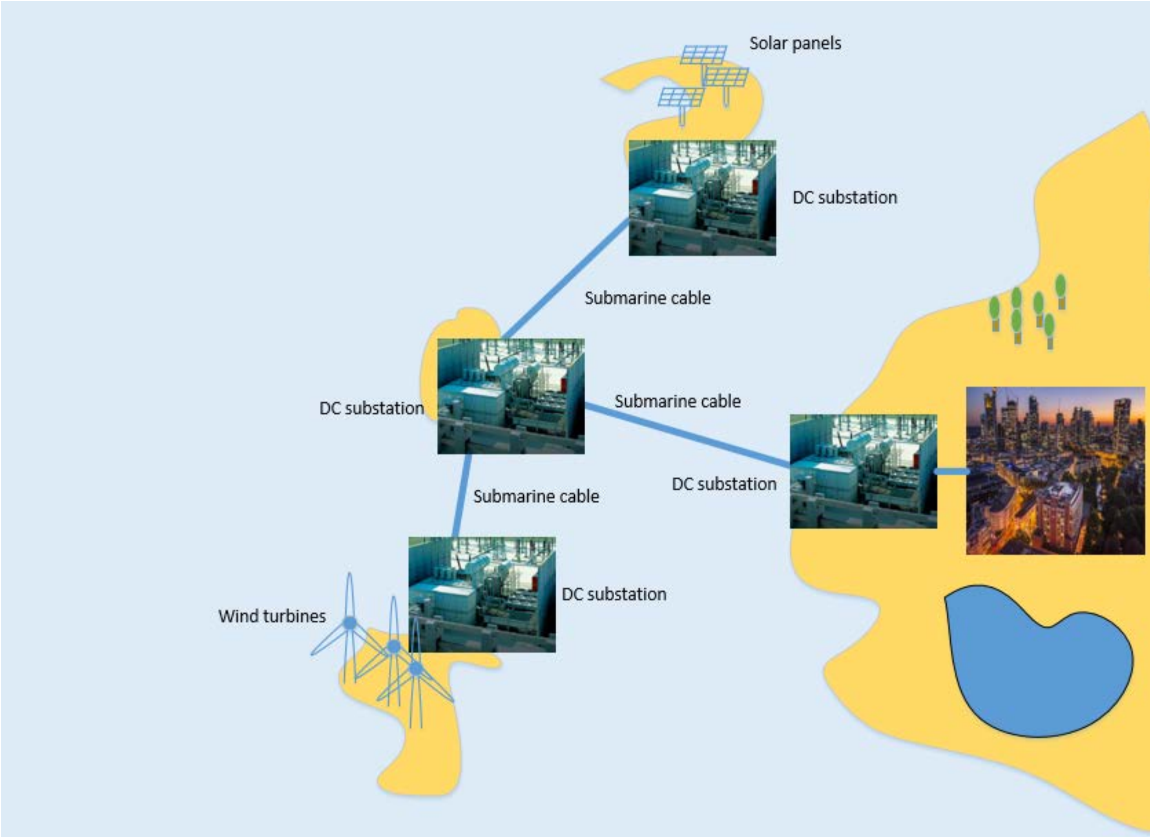

Figure 2.6: DC connection of islands with the mainland [23]

2.2. Advantages and disadvantages of DC-AC/DC hybrid grids

The utilization of DC for power transmission and distribution provides a new framework of grid operations. Developing new, from “scratch”, DC grid infrastructure could prove to be a task of gigantic proportions, necessitating huge investments over a long period of time. It is foreseen that DC will have to “harmonically co-exist” with available AC infrastructure, developing hybrid solutions in which the best result of both approaches can be achieved.

By these means, DC-AC/DC hybrid infrastructures indicate a new perspective into a variety of applications. In contrast to the traditional AC infrastructures, some of the main advantages of hybrid grids include [24]:

- **Easier integration of RES and ESS and reduction of primary consumption**: A high proportion of RES and ESS produce DC power that would be more efficiently integrated in a DC grid than in an AC grid. Examples include PVs, batteries, fuel cells or even EVs that act as power suppliers, in vehicle to grid (V2G) mode. In a DC grid, the conversion of these sources’ supply does not need to be converted from DC to AC. On the contrary, instead of DC/AC converters, DC/DC converters need to be implemented, which are more efficient and small, resulting in the reduction of primary energy consumption. Where necessary, bidirectional converters can be employed, e.g. in the case of battery systems.
- **Effective integration of DC loads:** Distributing DC power to DC loads, instead of converting it from AC to DC can lead to energy savings from the aspect of the consumer. By skipping

the conversion phase from AC power to DC power, there are reduced losses, resulting to lower costs of energy. This modification could lead to substantial savings considering DC loads such as EVs, LED lights, data centers, electronic equipment etc.

- **Power transmission over long distances**: Due to the effectiveness of High Voltage DC (HVDC) and Medium Voltage DC (MVDC) lines, more power can be transmitted over long distances, which makes DC integration into already existing AC grids extremely valuable for the expansion of the grid. Major technological developments have made possible the increase of DC voltage levels in the order of kV, allowing efficient power transfer even for distances in the order of several thousands of kilometers. This advantage of DC lines is considered to be of major importance when it comes to connection of remote generation or consumption.
- **Enhancement of the total grid power quality:** By facilitating DC connections, the power quality of weak grids can be enhanced. DC lines provide a “firewall” that prevents disturbances propagating from one network to another [21]. The use of DC can cope with undesirable resonances that can impose a threat in the stability of the grid over long distances. This includes the elimination of AC harmonic oscillations due to the existence of inductive and capacitive elements and the enhancement of the robustness of the system, by improving its frequency stability and inertia [25]. The reduction of the number of inverters interfacing renewable energy sources, energy storage systems and loads with the low voltage AC systems allows a better control of harmonincs and reduces the risk of instabilities. Hybrid DC-AC/DC infrastuctures represent a clear advantge in terms of power quality.
- **Lower visual impact:** Because DC systems transmit only active power, no line capacity is wasted on transmitting reactive power, therefore the total apparent power can be reduced resulting in less required current capacity, reducing the necessary distance between the conductors. This, combined with the fact that 2 lines instead of 3 are requires results in a smaller size. The smaller size of DC towers, compared to the size of AC equivalent structures, as presented in Figure 2.7 [26] [3], is considered to be an advantage of DC grids. This attribute, however minor may seem, is in fact quite beneficial considering overpopulated areas such as cities or places where the visual impact of the grids should be minimized, such as in tourist attractions, monument areas etc.

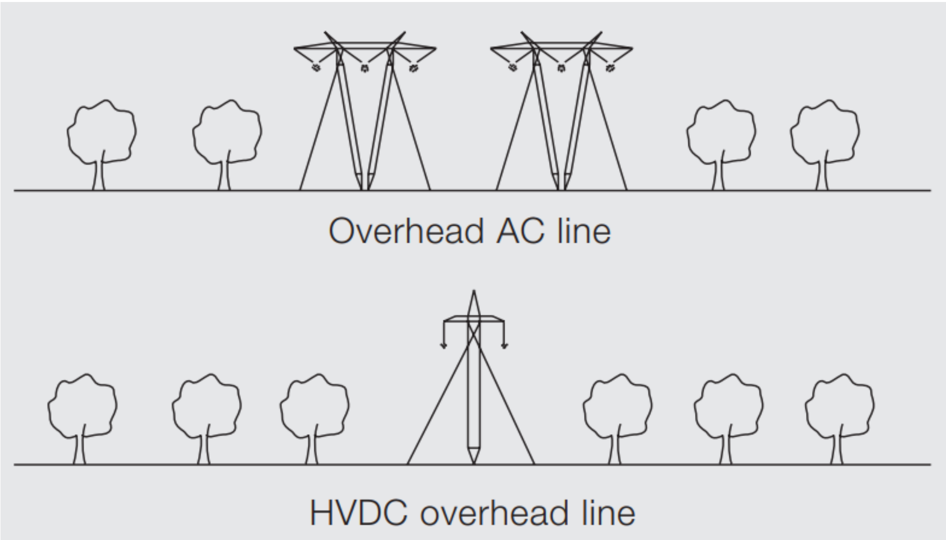

Figure 2.7: Visual impact of AC structures (up) versus visual impact of DC structures (down) [17]

On the other hand, the DC technologies have not been researched as much as their traditional AC counterparts. This is attributed to the fact that the entire concept of electrical energy production, transmission and distribution has been built on AC technology, which provided the means to progress and develop more efficient and cost effective equipment. This means that the implementation of DC solutions has certain drawbacks such as [27]:

- **Lack of specific standards:** In order for a system, such as the DC-AC/DC hybrid grid to be widely implemented, the definition of certain parameters, such as the voltage levels, needs to be specified. Due to the fact that DC applications are not as widespread as AC applications, there is a general lack of standardized values regarding their function. This issue needs to be addressed, in order for the DC-AC/DC hybrid grids to enter the worldwide market. As it will be described later, certain efforts are under way addressing this issue, which is quite important in order to enable the development of technologies based on common grounds and acceptable forms.
- **Difficulty in integration to existing grids in comparison with AC technologies:** The existing grids are most commonly AC-based. AC technologies have a simple design that has been studied and developed for many decades and is well known to grid developers and system operators. On the other hand, fewer specialists have studied DC technologies to that extent. This means that the application of DC solutions to the existing grid bears difficulties in comparison with the application of AC solutions. In simple words, AC and DC systems have different starting points. The AC technology is proven and mature, whereas DC technology is in a process to be established, considering that power electronics started becoming popular in the last quarter of the past century. Furthermore, voltage instability and electromagnetic compatibility issues present a risk for DC grids, pointing out the need for a smooth integration through the development of the necessary equipment. However, these drawbacks can be overcome if attention is given to specific aspects where DC technology can have a significant potential, in order to be firmly established, starting to build from that point forward. The increasing use and development of modern power electronics converters can significantly help for the diffusion of DC technology providing the necessary framework, backed up by the wider application of RES technologies.
- **Protection issues:** Once a new system is proposed, protection issues including switches and grounding schemes need to be studied. In the case of DC power, there are protection issues that are not only related to the lack of standards but also to the very nature of DC current. Specifically, breaking a functioning DC circuit is considered to be more difficult, compared to its AC counterpart, because there is no natural zero crossing of the current, to minimise the arc effect. Major research efforts are undertaken for the development of switchgear that can accommodate the secure disruption of DC voltages in the order of kVs, to enable the development of grid infrastructure.

Overall, the implementation of DC-AC/DC hybrid grids appears to be a key driver in paving the way towards sustainability, efficiency and mitigation of the anthropogenic climate change. For their proper incorporation in the traditional AC grid and their establishment in the worldwide market, further research needs to be conducted for their proper design and function. Particular areas to be investigated include DC cable technology, switchgear and more efficient power electronic converters.

2.3. Key features of DC-AC/DC hybrid grids

Before the further understanding of DC-AC/DC hybrid grids, the overall concept as well as some key features required for their implementation need to be determined. Perhaps the most interesting key feature of a DC-AC/DC hybrid grid is the Solid State Transformer (SST), which is practically the hybrid grid's interface with the AC grid. An SST is a multi-level power electronics device that enables the connection of grids with different voltage and frequency levels [28], as presented in Figure 2.8 [29]. Its special configuration has advantages which do not exist in typical transformers. In fact, the SST can provide DC ports that facilitate the integration of BESS, DC RES, DC loads and enables the implementation of power quality features, such as advanced control schemes. For this reason, the SST has been proposed by researchers to replace the traditional, passive AC/AC transformer in future grids [29].

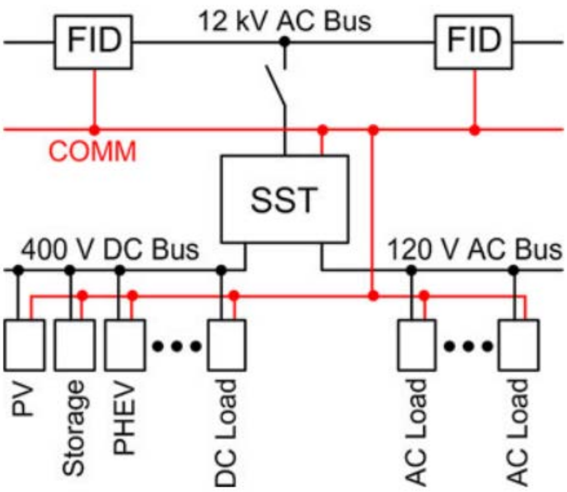

Figure 2.8: Implementation of SST in distribution grid with different voltage levels [29]

The application areas of SSTs are quite broad covering integration of renewable energy sources, smart grids and traction applications. Compared to low frequency transformers, the SST offers significant advantages such as reactive power compensation, voltage regulation, power flow control, voltage sag compensation, bi-directional flow, fault current limiting etc. Several topologies have been presented in the literature [30] which can be classified as presented in Figure 2.9:

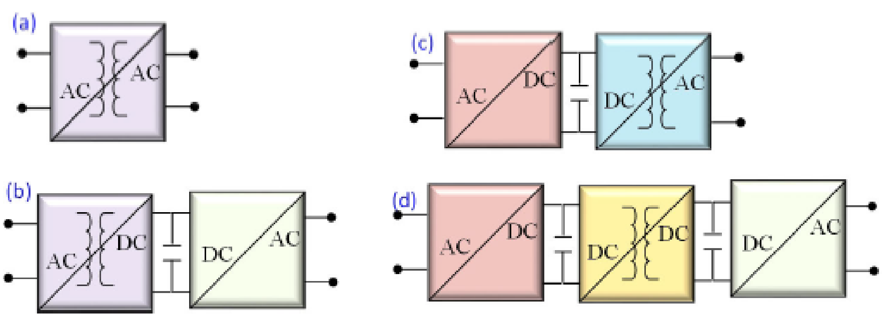

Figure 2.9: Topologies of SST [30]

The single stage topology (Figure 2.9a) is the simplest one that has a direct power conversion with transformer isolation to step down the voltage. This configuration is applied in direct AC/AC power conversion stages with higher reliability and better efficiency.

In the two-stage approach (Figure 2.9b,c), a DC link is inserted either in the high voltage or the low voltage side, giving the opportunity to have a bidirectional power flow at the expense of a more complex switching method as well as a large number of switching devices.

The three-stage SST topology (Figure 2.9d) presents the most interesting features as it is designed with two-DC links that are able to address issues of supply and utilization as well as provision of ancillary services (e.g power quality). In this respect they present a potential to optimize transmission and distribution, offering great opportunities for integration of DC and AC systems, as shown in Figure 2.10 [30].

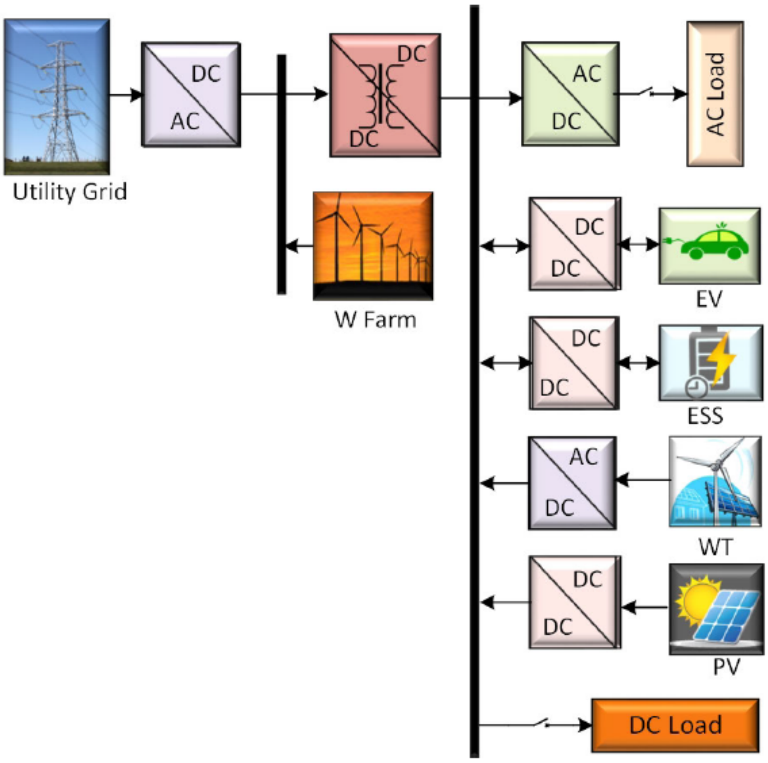

Figure 2.10: Opportunities for integration of AC and DC systems, provided by the SST [30]

Apart from the SST, which is apparently a component of major importance regarding future grids in general, there is a number of key components that constitute a hybrid DC-AC/DC grid, which can be determined through the display of the basic concept of such architectures. For this purpose, in Figure 2.11, a very generic topology of a grid is presented, before and after its hybridization [31]. It is noted that in the traditional AC grid, on the left hand side, a power transformer alters the voltage level of the grid from MV to LV, AC lines and DC/AC converters are employed on the side of DC production and demand, i.e. PVs, BESS, DC loads. It is understood that this topology would be fit for a grid that is mostly based on the AC feeder and consists of almost exclusively AC loads. However, since the aim is to maximize the input from the PV systems and other RES as well as ESS and incorporate more DC loads to the grid, the topology needs to be reformed. The topology of the DC-AC/DC hybrid counterpart of the original grid is presented on the right hand side of Figure 2.11. The proposed grid, constitutes of an SST, instead of a transformer, that provides the grid with DC power which flows through DC distribution lines. The DC power supply, derived from the PVs and the BESS, is injected into the grid through DC/DC converters in order to meet its voltage level. Finally, the DC power is converted into AC power through DC/AC converters in order to meet the AC demand.

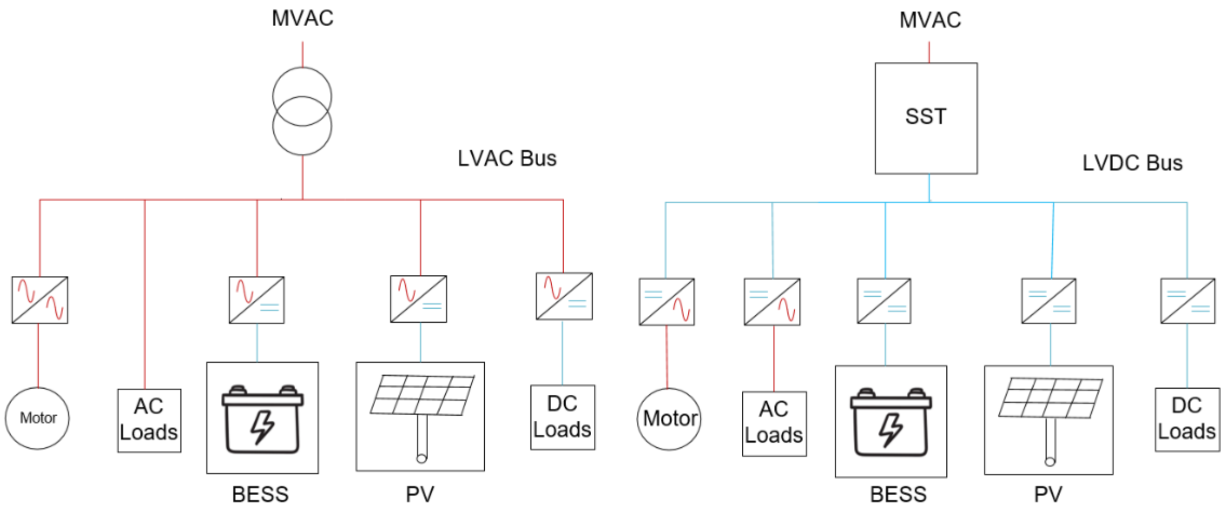

Figure 2.11: Conversion of a typical grid into DC-AC/DC hybrid grid

In conclusion, the key features/components of a DC-AC/DC hybrid grid are the following:

- **An SST,** that serves as interface between the AC grid and the DC-AC/DC hybrid grid. The SST is able to provide the distribution grid with different forms of power, i.e. AC, DC, AC power of different frequency etc, as well as with different voltage levels, i.e. MV, LV, etc.
- **DC/AC converters,** that convert AC power into DC power in order to cover the AC loads of the grid.
- **DC/DC converters,** that convert the voltage level in order to incorporate DC production or to feed loads of different DC voltage level.
- **DC lines,** that distribute the power from the SST to the entire grid.

These key features can be implemented and combined with each other in a variety of ways, depending on the application, producing different architectures. These architectures are to be described and evaluated in the following sections.

3. Architectures and control schemes of hybrid grids

The design of a hybrid grid has a number of key decisions that need to be made from the early stage of its conception. Such decisions include the determination of the interface between the main grid and the hybrid grid, the topology of the hybrid grid and the control system that will be implemented for its operation. This Section aims to present and discuss such issues, providing a range of solutions along with their advantages and disadvantages.

3.1. Interface architectures between the main and the hybrid grid

Hybrid grid topologies have the advantage of combining the features of AC and DC architectures, facilitating the direct integration of both AC and DC production, storage and demand. Although such grids are a great and innovative solution for the integration of mixed types of distributed production in future grids, little research has been made on hybrid topologies, as the greatest part of research focuses on AC or DC systems separately. Under this framework, it is useful to investigate topologies regarding the possible combinations of DC and AC systems.

When it comes to the architecture of hybrid grids, the interconnection of the hybrid grid with the conventional power network is an issue of interest that has lead to the emergence of a new research area over the past few years. In fact, several classifications have emerged regarding the interface stages of the conventional AC grid with the hybrid grid. To begin with, it is important to state two fundamental types of configurations, which are: a) the coupled AC configuration and b) the decoupled AC configuration [32]. Each of the two foundamental sorts of configurations is considered to be devided into categories, as presented in Figure 3.1, which will be analyzed in this Section.

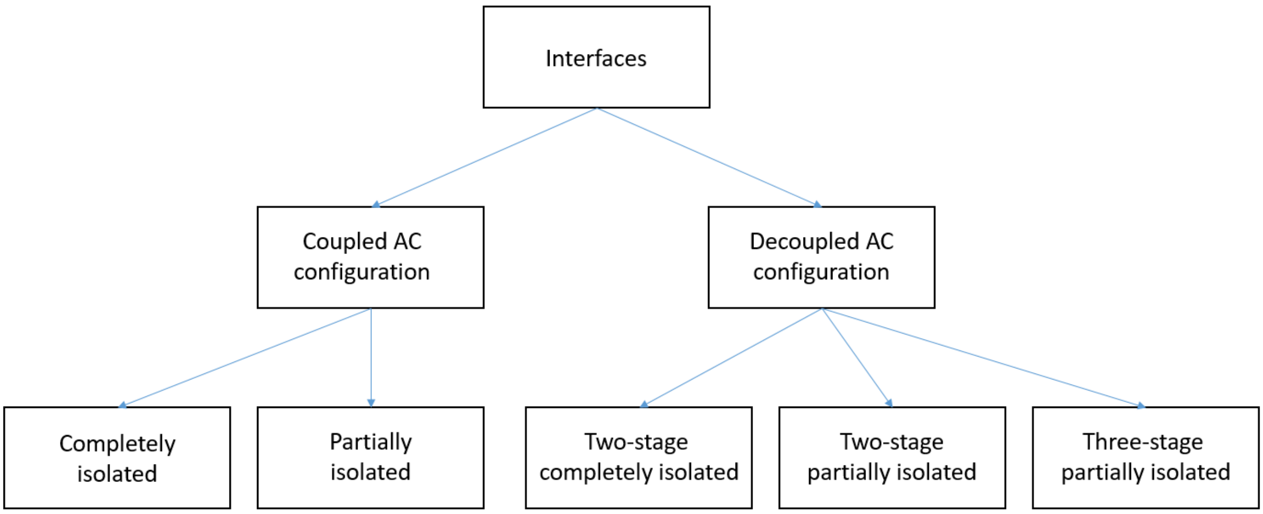

Figure 3.1: Types of interfaces between the main grid and the hybrid grid

As for the coupled AC configuration, there are two main ways of implementation: a) completely isolated and b) partially isolated. The first one, presented in Figure 3.2, consists of a typical transformer that alters the voltage level from MVAC to LVAC in order to supply the LVAC part of the grid with power. The LVDC grid is served through an AC/DC converter that converts the power from LVAC into LVDC. This topology is quite simple and close to the conventional form of a traditional grid. It is noted that the transformer, which is located in the beginning of the interface, provides the entire grid with galvanic isolation, which is considered to be an advantage of this configuration.

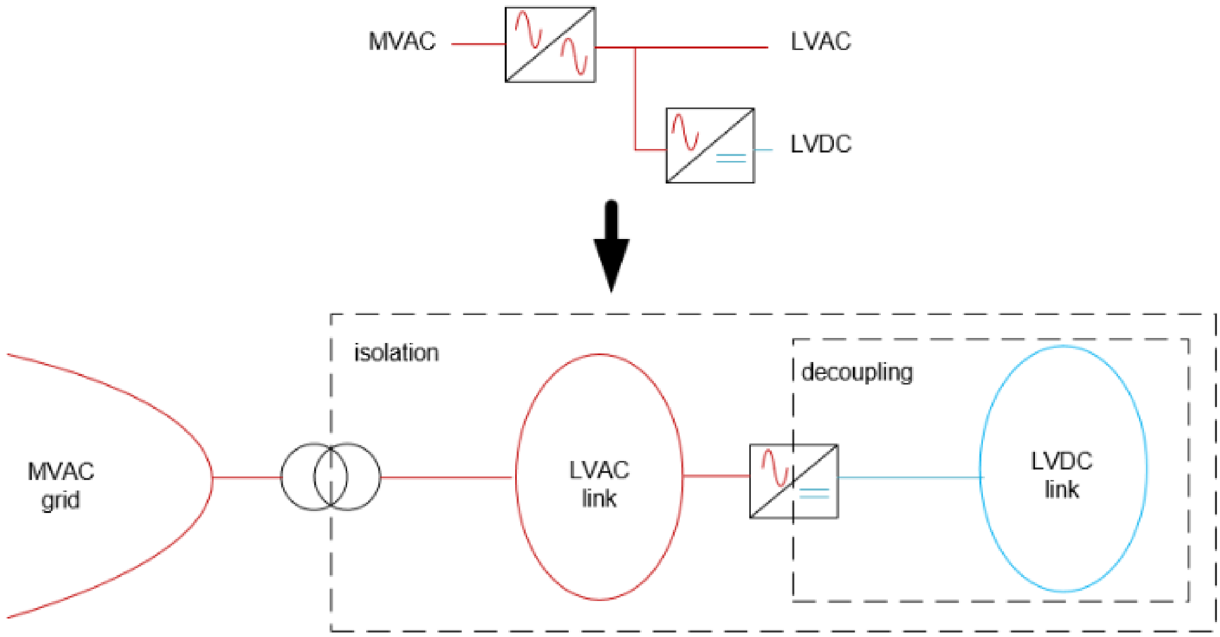

Figure 3.2: Completely isolated coupled AC configuration

On the other hand, the partially isolated AC coupled configuration can also be implemented, as presented in Figure 3.3 [33]. In this configuration there is a typical transformer that steps down the voltage level from medium to low, in order to serve the LVAC grid. Furthermore, an AC/DC converter is introduced, in order to directly convert the MVAC power from the distribution grid into MVDC power. This configuration is partially isolated, due to the fact that the transformer is not located between the AC distribution grid and the MVDC grid. However, this means that the transformer can be derated in both power and size as it only serves the LVAC part of the configuration, in contrast to Figure 3.2 where the transformer seves the complete load.

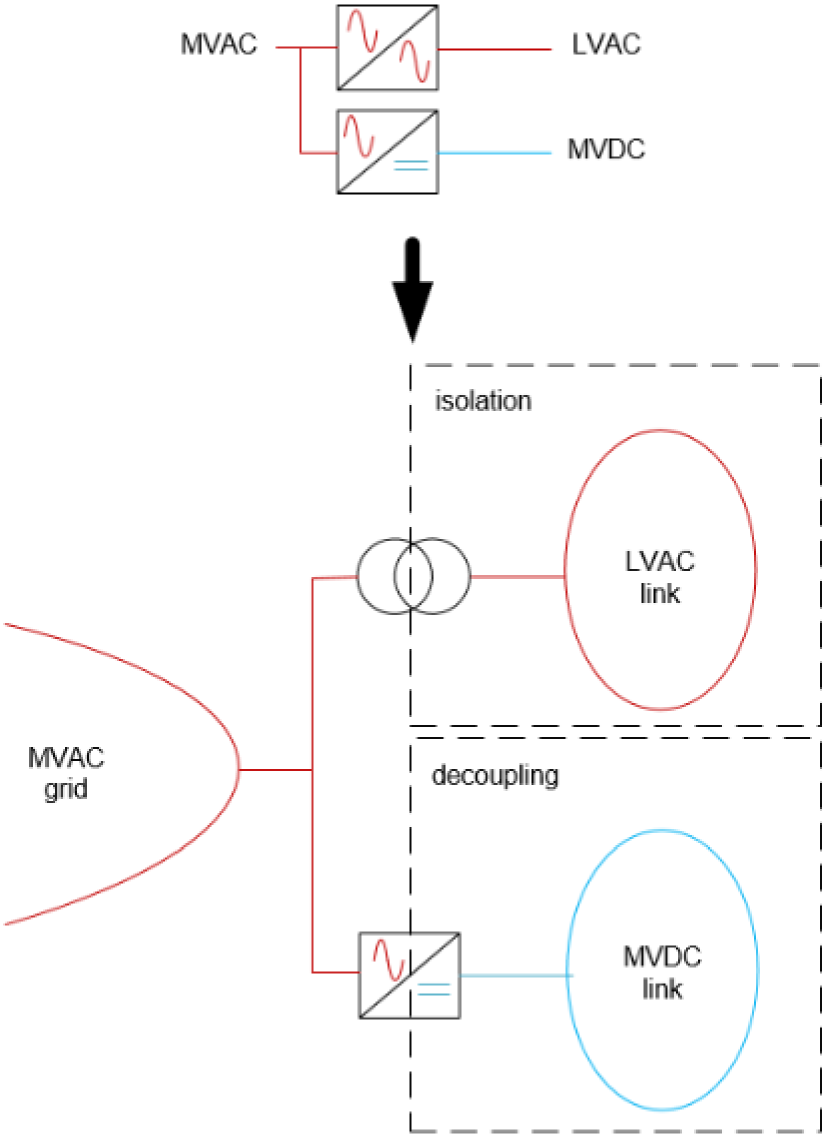

Figure 3.3: Partially isolated coupled AC configuration

Apart from the isolation and related power issues, the first approach is considered to be better that the second one when it comes to grids with high penetration of LVDC RES and BESS. For example, the authors of [34] consider the integration of DC distribution lines to the LV part of the grid, while the transformer isolates the entire grid from the distribution system. This configuration is proposed due to the fact that the PV, BESS and ultracapacitors are connected to the LV part of the hybrid grid. Several variations are investigated, utilizing different types of switches and connections between the loads and the units of power supply, highlighting the reliability of the proposed configuration. In [35] an optimization model is presented for the energy management of a distribution grid, in which the MVAC power imported by the grid is first converted to LVAC and then divided into two sections. The first section serves the LV part of the grid, including LVAC loads, LVAC and LVDC production. The second section is specially reserved for the DC storage system, which enhances the reliability of the proposed system and is connected to the grid through an AC/DC converter. The study highlights the cost effectiveness and low emissions of the grid, resulted by the implementation of the proposed energy management.

The second approach is considered to be a good solution in the case of high DC RES penetration at the level of MV but also in the case of interconnection of multiple asynchronous or weak AC grids. For example, the authors of [18] propose the conversion of MVAC into MVDC for the proper integration of wind generators that are installed at the MV distribution grid. The performance of the proposed architecture is tested in the cases of a) loss of one wind generator, b) loss of the grid's diesel generator and c) fault on the feeder of the grid, through simulations. The derived results showcase the efficiency and robustness of MVDC distribution. Simulations are also carried out for the AC respective architecture, the results of which are compared to the proposed DC architecture, in order to prove the advantages of MVDC distribution.

As stated previously, apart from the coupled AC configuration, there is also the decoupled AC configuration. Configurations of this type are considered to be superior, due to certain advantages they provide over the coupled ones [36]. Their highlight is that they decouple the LVAC part of the grid from the utility (MVAC) of the grid, through the interpolated DC stage. This modification provides better control, in terms of decentralization and independency for the hybrid grid. For the proper implementation of this sort of configurations, the incorporation of SST is considered to be essential. In fact, the SST is able to directly replace the traditional transformer, and facilitate both operation connected to the main grid and operation as microgrid (MG). The latter is a matter of major importance, considering that the trend of the market leads to the investigation and development of MGs in general and according to many researchers, to the establishment of DC MGs and AC/DC hybrid MGs in particular [37] [38] [39]. The key factor of the SSTs is that they consist of multiple transformers and converters, thus the fact that the can be arranged in many different configurations. The dominant configurations of SSTs in modern research and development are three: a) two-stage completely isolated, b) two-stage partially isolated and c) three-stage partially isolated. The two-stage completely isolated configuration is presented in Figure 3.4. The two-stage partially isolated configuration is presented in Figure 3.5.

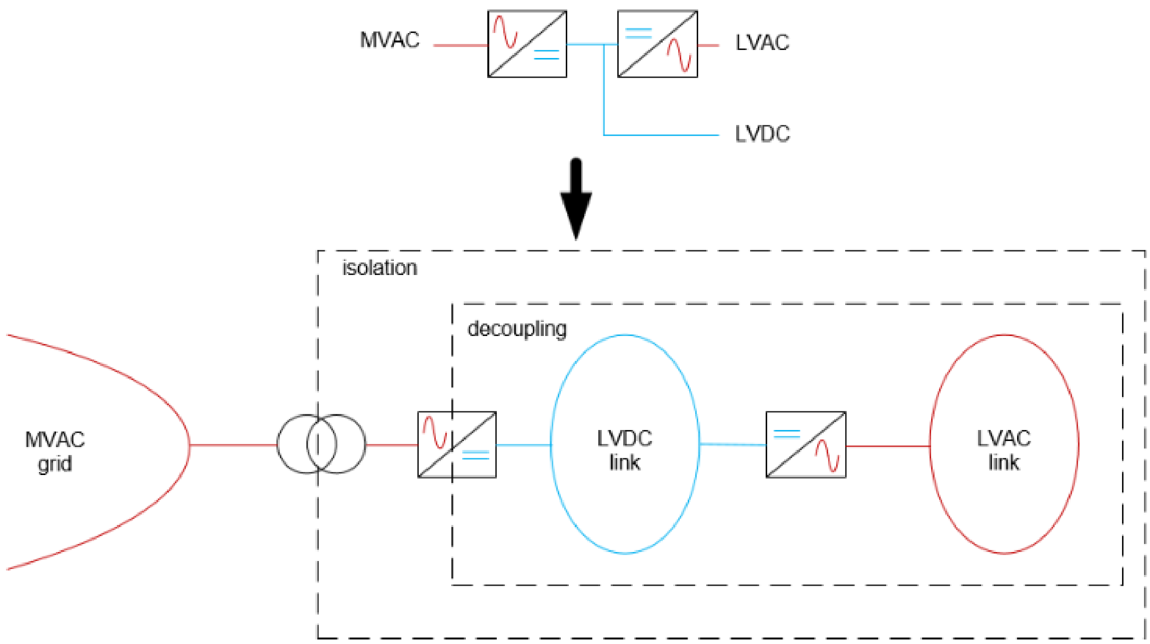

Figure 3.4: Two-stage completely isolated configuration

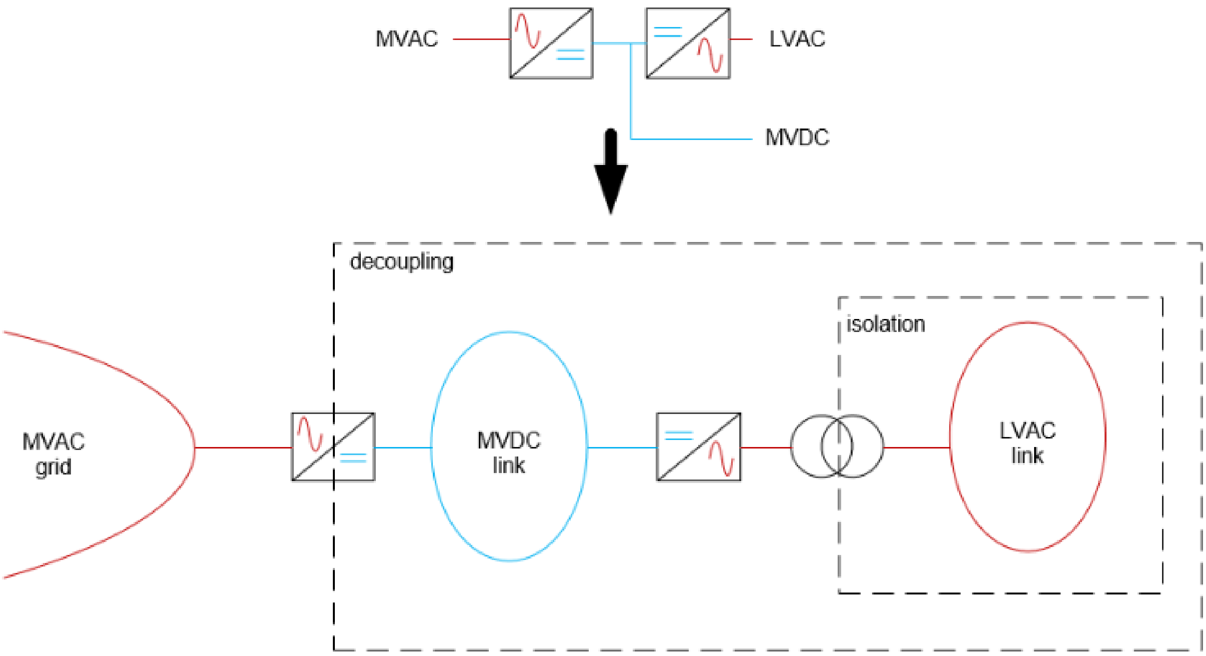

Figure 3.5: Two-stage partially isolated configuration

It is noted that the first two configurations take as input the MVAC from the grid and provide an LVAC link each. Also, the first configuration provides an LVDC link while the second one provides a MVDC link. Apart from this, a main difference is the location of the transformer. In fact, the first configuration includes the placement of the transformer in the beginning of the proposed set of converters. In this way, galvanic isolation is provided to the entire grid, which constitutes of a LVDC stage and a LVAC stage. This is the reason why this is called “two-stage completely isolated configuration”. On the other hand, the second configuration has two stages, i.e. MVDC and LVAC, yet the transformer is placed at the end of the proposed set of converters, which means that galvanic isolation is provided only to the LVAC part of the grid. For this reason, this is called “two-stage partially isolated configuration”.

Research been conducted on both configurations. More specifically, the authors of [40] approach the first configuration, through an energy conversion station which supplies an AC/DC hybrid MG with energy. The proposed system is based on the conversion of MVAC to LVAC, followed by a LVDC link for the integration of domestic distributed generation. The Energy conversion station also includes a DC/AC converter for the conversion of LVDC into LVAC, which is connected to the three-phase AC consumption lines of the hybrid grid. According to the simulation results, the proposed system is considered to enhance the performance of the hybrid AC/DC MG. The authors of [41] approach the two-stage partially isolated configuration with a novel Power Electronic Transformer (PET). The proposed PET directly converts MVAC to MVDC and on the second stage converts MVDC into LVAC. The novelty of the proposed solution lies in the implementation of a matrix converter in the architecture of the PET. The results provided by the simulations indicate the advantages of the proposed configuration, including power factor correction, voltage regulation and flicker reduction.

The above configurations have the advantage of simplicity regarding the generation of DC grids. However, the third configuration, i.e. the three-stage partially isolated configuration, presented in Figure 3.6, is considered to be more sophisticated and technologically advanced than all configurations that have been presented [42]. This configuration provides all three possible stages, i.e. MVDC, LVDC and LVAC. Its complex composition has the unique advantage of providing links for all types of inputs/outputs. Yet, since it provides an MVDC link, the transformer needs to be located after the MV AC/DC converter. This means that galvanic isolation is only provided for the LVAC and LVDC part of the grid. For the reasons described above, the proposed set of converters is called “three-stage partially isolated configuration”.

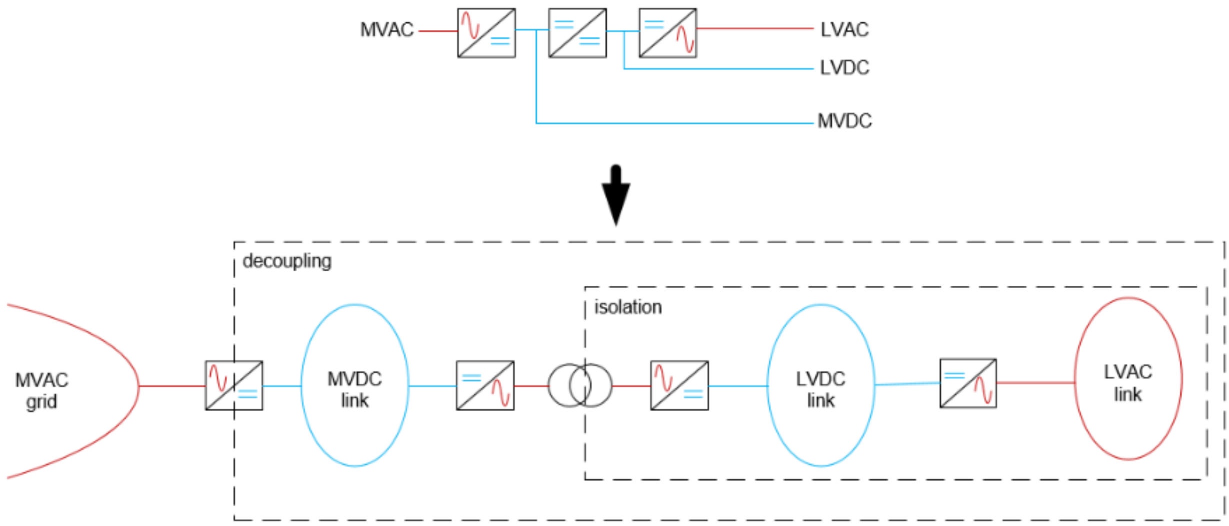

Figure 3.6: Three-stage partially isolated configuration

The design of a three-stage SST has gained a lot of attention over the past few years, due to the advantages they provides. Research and development is conducted regarding the optimization of their operation, the improvement of their efficiency, the enhancement of their reliability and of course the reduction of their cost and size. For example, in [43] a sensorless feedforward current controller is developed for the dual active bridge (DAB), i.e. the set of power electronics responsible for converting MVDC to LVDC, in a three-stage SST. The proposed control system uses only the information of terminal voltages, reducing the cost of the system. Simulations as well as experimental results highlight the proposed system’s fast response. The authors of [44] propose a multi-objective optimization model for the design of High Frequency Transformers (HFT) for SST applications. The model aims to the minimization of the core’s volume, the total losses and the overall cost of the HFT. According to the results, the designs derived by the optimization, which fulfil the objectives of the model, achieve efficiency higher than 97%. In [45] a smart building is presented. The smart building consists of a LVAC MG, including the AC appliances and lighting system of the building, as well as a LVDC MG, including RES generation, a storage system, a charging station for EVs, etc. The two parts of the grid interface with each other and with the MVAC grid through a three-stage SST. The research focuses on the investigation of both grid connected and off-grid mode for the building’s system and proves, through simulation results, the effectiveness of the proposed architecture. Furthermore, the authors of [46] have studied the combination of two three-stage SSTs into a dual-machine parallel optimal operation mode for the distribution system of an AC/DC hybrid system. The proposed methodology is compared to the case where the hybrid grid only includes one three-stage SST, through simulations. Results showcase the higher efficiency and lower system’s net present cost for the proposed combination of SSTs.

All configurations, coupled and decoupled, completely or partially isolated, provide the grid with DC and AC links. However, some of them have utilities that others lack and no configuration meets all evaluation criteria to the highest level. In this sense, the most important criteria are presented and discussed along with their potential of fulfillment by all presented configurations [33]:

- **Isolation**: Galvanic isolation between functional sections of the grid prevents the unwanted current flow in the sense that no direct conduction path is permitted. This feature is provided by transformers and its effect depends on the placement of the transformer, meaning that the earliest stage of implementation provides the grid with the highest possible isolation.
- **Controllability**: The control capability of hybrid grids varies according to the stages of conversion. Decoupled grids have high controllability, due to the DC conversion that they perform in the earliest stage of the interface with the feeder.
- **Scalability:** This feature examines the potential for voltage level variations. Systems with scalability are able to change the voltage level according to the load demand. Scalability is directly related to adaptability, efficiency and reduction of ageing of the components utilized. A major drawback of transformers is the lack of this feature and require additional devices, such as tap changers, in order to cope. On the other hand, power converters deal with scalability issues more effectively.
- **Modularity:** The term modularity refers to the ability of increasing the rated power of the system. This can be easily achieved in the case of power converters, by adding new branches to the existing converter. However, transformers do not have the same flexibility.
- **Fault management:** In the case of faults, the interface between the main grid and the hybrid grid can isolate the non-functional part. Depending on the stages of the interface, the fault can cause problems to the entire hybrid grid or to a part of it. Interfaces with many branches only need to isolate the branch on which the fault occurs.
- **Maintenance:** A drawback of interfaces including many stages is that they require more maintenance than simpler interfaces.
- **Reliability:** Interfaces that include many stages and devices are expected to have lower reliability than simpler ones.
- **Cost:** This parameter takes under consideration the total investment in the components of the interface. It should be noted that transformer-based interfaces are cheaper than converter-based interfaces, mostly due to the fact that they include less devices and older, less innovative technology.
- **Volume:** The space reserved for the interface between the main and hybrid grid depends on the components which it incorporates. For instance, transformers occupy more space than power converters.

Table 3.1 [33] summarizes the criteria and their potential of fulfillment for each configuration that has been reviewed. It is noted that the coupled AC configurations require lower maintenance, have lower cost and provide the grid with higher reliability than the decoupled AC configurations. The features on which they exceed make them a safe option with tested in time expectations. On the other hand, the decoupled AC configurations exceed in controllability, modularity, scalability, fault management and they, in most cases, have a lower volume. These attributes are the means required for achieving the goals of the future grids, i.e. smart grids, AC/DC hybrid MGs, etc.

Table 3.1: Evaluation of interfaces [33]

Feature	Coupled AC		Decoupled AC		
	Completely isolated	Partially isolated	Two-stage completely isolated	Two-stage partially isolated	Three-stage partially isolated
Galvanic isolation	Complete	LVAC network	Complete	LVAC network	LVAC & LVDC network (not MVDC network)
Controllability	Medium	Medium	High	High	High
Scalability	Low	Low	High	High	High
Modularity	Low	Low	High	High	High
Fault management	Medium	Medium	High	High	High
Maintenance	Low	Low	Medium	Medium	High
Reliability	High	High	Medium	Medium	Medium
Cost	Low	Medium	Medium	High	High
Volume	High	Medium	High	Medium	Low

According to the above, it can be perceived that there is no single interface that exceeds over all of the others in all criteria. The selection of the appropriate interface needs to be made according to each application, considering the budget, the flexibility required, i.e. controllability, scalability, and modularity, and the purpose of the designed grid.

3.2. Topologies of DC distribution systems in hybrid grids

A key decision regarding the design of a hybrid grid is its topology. Considering the ascending amalgamation of DC RES and ESS in future grids, the DC primary distribution dominates over the AC primary distribution. Consequently, the possibilities for DC distribution topologies need to be investigated, along with the advantages and disadvantages that they may provide.

There are three main types of DC distribution topologies including: a) radial configuration, b) ring configuration and c) interconnected configuration [47]. Each type is further divided into categories according to Figure 3.7.

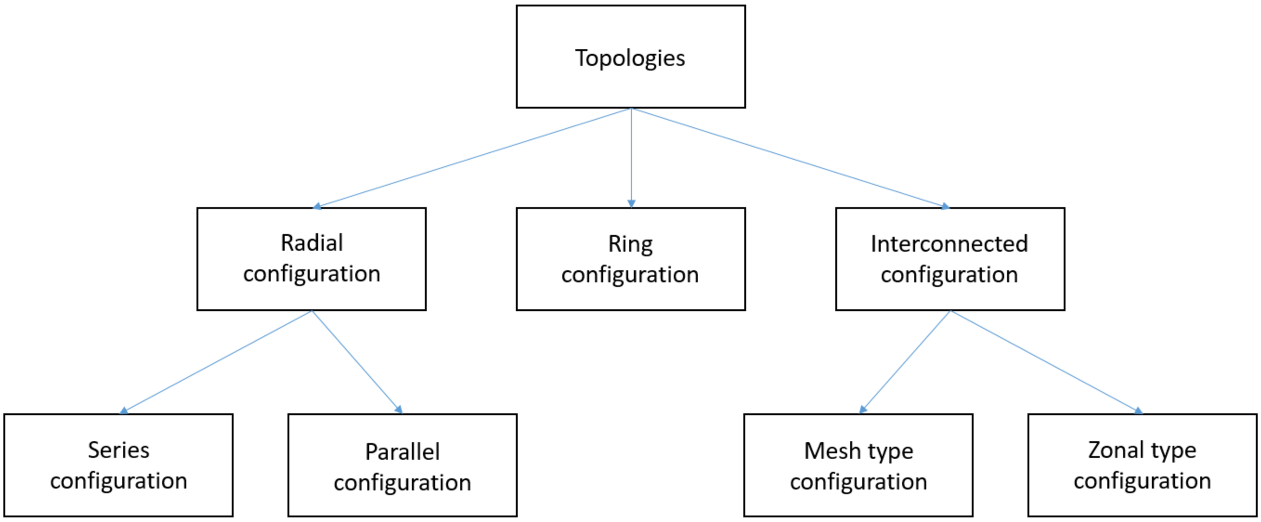

Figure 3.7: Types of topologies of a DC distribution system

The general topology of a radial configuration system is presented in Figure 3.8. In this type of topologies, the main characteristic is that there is only one point of connection between the components of the system, i.e. loads, generation units, storage units and the interface with the AC distribution network. This takes the form of a bus. Its main highlight is the simplicity of implementation and operation [48].

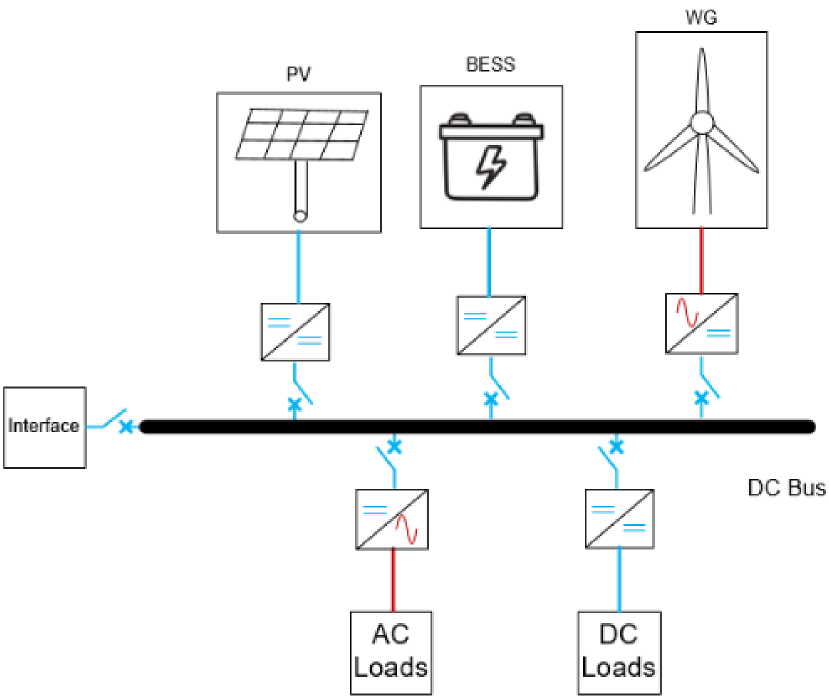

Figure 3.8: General topology of a radial configuration system

The general concept of a radial configuration system can be further divided in two main sub-categories, i.e. a series configuration and a parallel configuration. The general topology of a series configuration is presented in Figure 3.9. It is noted that there are two DC buses, each of which directly serves a combination of load, generation and supply units. The first DC bus is directly connected to the interface between the hybrid grid and the main grid. However, the second DC bus is only connected to the first DC bus, through a DC power cable, with the appropriate switching and safety devices. In this way, if a fault occurs to the hybrid grid, the faulty part can be isolated, giving to the rest of the grid the possibility to operate normally. Obviously, the proposed configuration can be extended to more than two buses, according to the system's requirements.

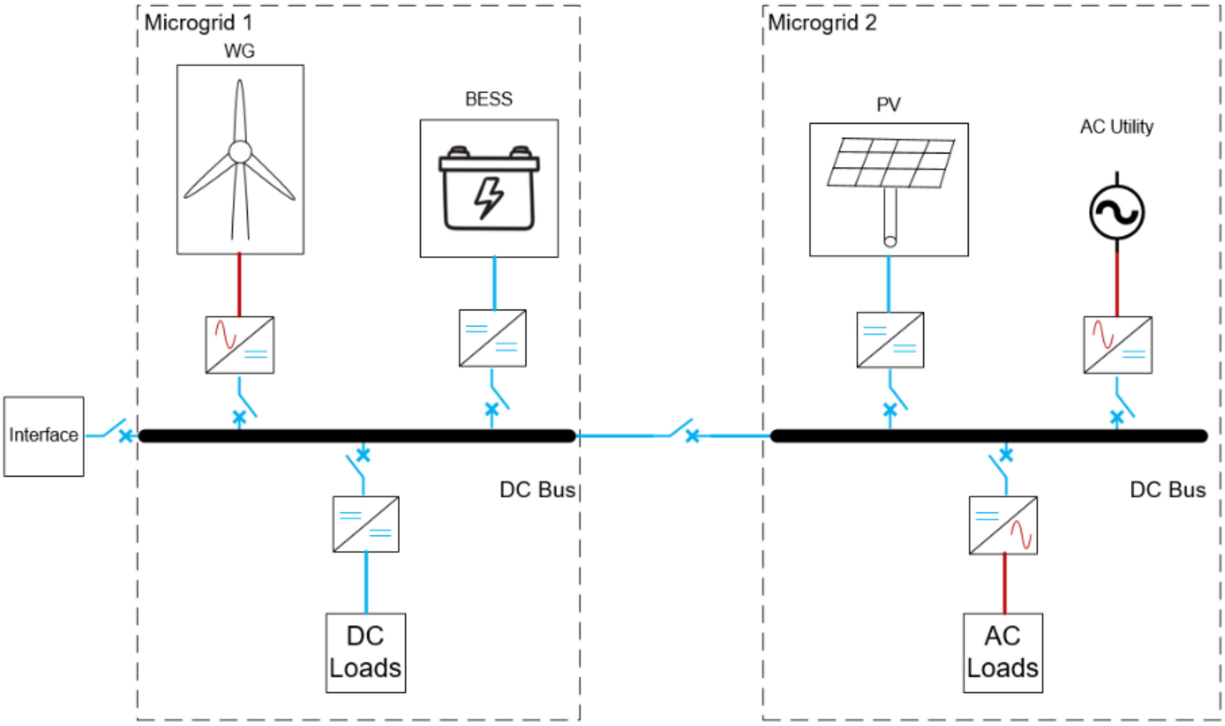

Figure 3.9: Series configuration in a radial system

The general topology of a parallel configuration system is presented in Figure 3.10. In this case the DC buses are not connected with each other. Instead, both of them are connected, through power cables, to the interface between the hybrid grid and the main grid. In this way, if a fault occurs on one bus of the hybrid grid, then the other bus of the grid will remain connected to the main grid, maintaining the ability of safe and normal operation. For this reason, this solution is considered to be more reliable than the series configuration. The parallel configuration can also be extended to a higher number of buses, depending on the system's requirements. When it comes to parallel configurations including more than two DC buses, an advantage over its series counterpart is the ability to share power between buses even in the instance of a fault that isolates one or more DC buses. This feature facilitates a power sharing capability of the parallel configuration.

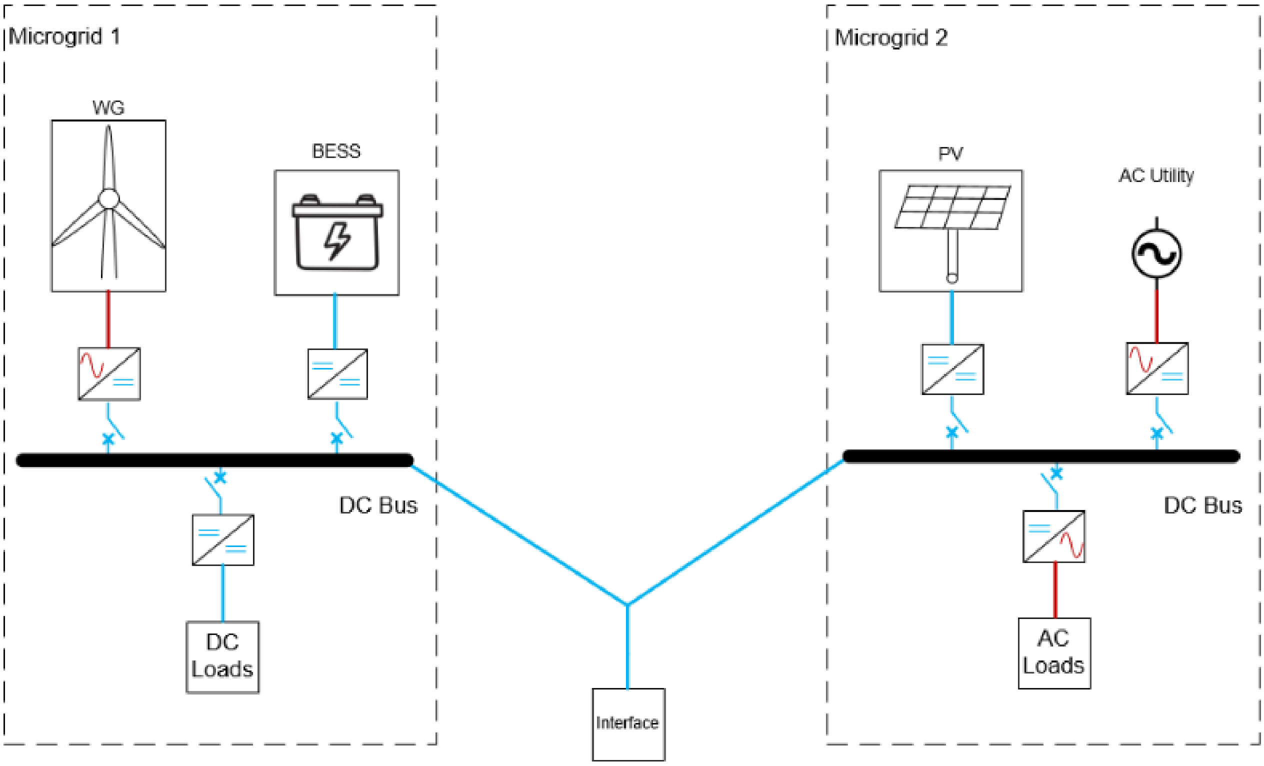

Figure 3.10: Parallel configuration

The above topologies have been extensively researched in many applications of distribution systems, varying from single smart buildings up to district scale, mostly due to their simplicity. For example, the authors of [49] present an AC/DC hybrid architecture for nearly/net-zero-energy buildings, following a radial topology for the AC and DC part respectively. The model consists of PV panels, a wind turbine, DC and AC equipment, a parking lot with AC and DC vehicle charging points, one BESS and a point of connection with the MVAC utility grid. The simulation results show that the proposed MG architecture, controlled by the appropriate strategy, can achieve a stabilized and flexible system operation under different scenarios. Additionally, the authors in [50] present a DC MG that is entirely based on generation by a combination of RES, i.e. one wind generator and one PV system. The production system is supported by a BESS, which is charged when surplus production occurs and discharged at times when the production is lower than the demand. The configuration is radial, containing only one bus which links the power supply with the demand. According to the results, the independency of the DC MG is feasible, considering the proper selection of nominal production and storage capacity. Also, the authors of [51] present a dynamic analysis of a radial DC MG. The study focuses on different types of loads, such as resistive loads, constant power loads and induction motor loads. Nyquist diagrams are provided regarding the stability of the system and the appropriate control strategies regarding the enhancement of the dynamic response and damping performance of the grid are proposed.

In spite of the advantages of radial distribution, there are certain limitations that pose a challenge in terms of flexibility and fault management. In order to overcome the limitations of the radial configuration, a more complex topology, i.e. the ring configuration, is introduced. The main concept of the ring configuration is presented in Figure 3.11. The proposed solution includes the placement of all loads, generation and storage units, interconnected in one single ring. For safety reasons, protection switches are located before and after the integration of each unit. This means that each component has two possible ways of connection with the interface between the hybrid grid and the main grid, i.e. through the line on its left and through the line on its right side. The ring configuration provides the hybrid grid with flexibility meaning that in case a fault occurs, the respective switches isolate it, converting the ring configuration into a parallel configuration. In this way all units are connected to the hybrid grid and maintain their functionality, except for the faulty component [52].

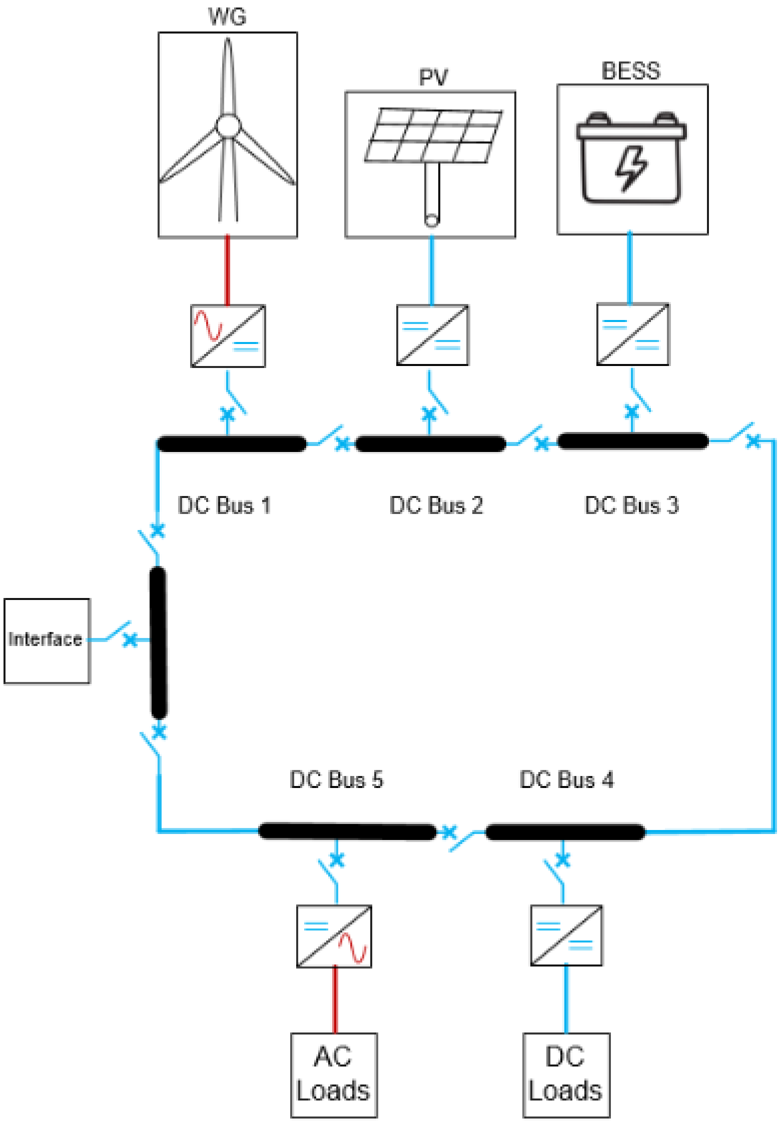

Figure 3.11: Ring configuration

The ring configuration appears in a number of studies over the past few years. For example, the authors of [53] have studied the structure of AC/DC hybrid MGs including distributed generation, storage devices and EVs. The purpose of the research is to attain the optimal configuration that minimizes the total system cost. In the test cases examined, according to the results of the methodology, rings are formulated between the buses of the MGs, indicating that there are cases where ring configurations contribute to the cost efficiency of the system. The ring configuration has also been studied in terms of fault protection. In fact, the authors of [54] present a new fault detection and location method for LVDC MGs in ring configuration. The proposed method is based on Multi-Criterion Systems (MCS) and Neural Networks (NN). Emphasize is given to the high speed of fault detection attained by the method, which is tested on a five bus test grid including RES and BESS, in order to prove its precision. Additionally, in [55], a novel protection scheme capable of detecting, classifying, and locating faults in DC MGs is presented, operating entirely based on the local measurements, avoiding the communication delay and vulnerability to the communication system failures. The protection scheme is applied on a five bus DC ring test system. Different sorts of faults that could occur to the DC ring MG are examined, such as pole-to-pole fault, monopole ground fault, etc. In all cases, the response of the proposed fault detection technique is highlighted, proving its efficiency.

Nevertheless, both sorts of topologies, i.e. radial configuration and ring configuration, have one common disadvantage. Due to their single connection to the main grid, if a fault occurs on the main grid, there is no possible way for the hybrid grid to abosorb power. In order to tackle this issue, the interconnected configurations are formed. These topologies include more than one interface between the hybrid grid and the main grid, which renders them by far more reliable in terms of fault management than all of the topologies previously described. Obviously, the increased flexibility they possess comes in the cost of increased complexity [37].

The interconnected configurations can be divided in two sub-categories, i.e. the mesh type and the zonal type configurations. A general mesh type configuration is presented in Figure 3.12. The proposed solution includes the placement of all loads, generation and storage units, in a mesh that is served by more than one interfaces with the utility grid. The switches between the components provide the operator of the grid with many possibilities for different architectures, containing one or more feeders. This attribute enhances the reliability of the proposed configuration.

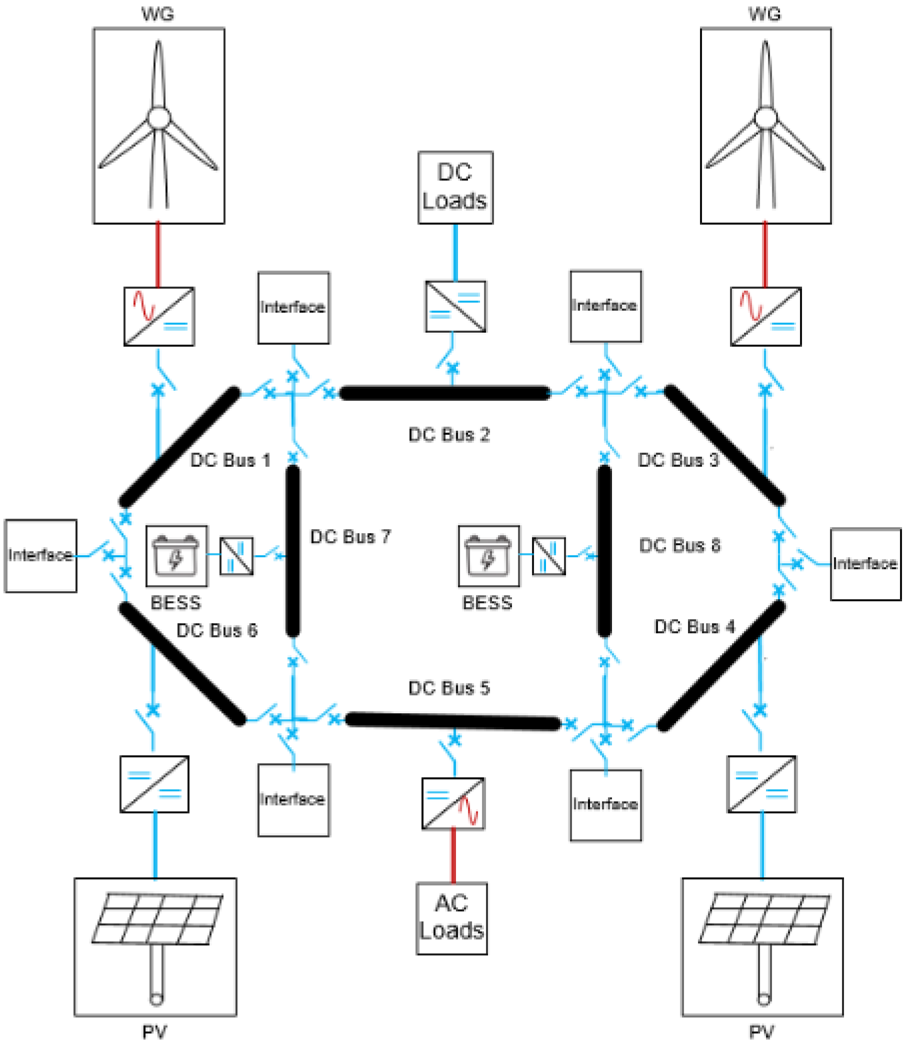

Figure 3.12: Mesh type configuration

The general topology of a zonal type configuration is presented in Figure 3.13. In this case, the distribution system is divided into a number of zones. Each zone interacts with the grid through two buses, one at each side. The buses that surround the zones formulate a ring which does also contain more than one interfaces with the utility grid. This configuration is completed by a number of switches that enable a variety of energy mixes as well as a number of solutions, in terms of reconfiguration, in case a fault occurs. This configuration is characterized by symmetry and reliability but also by complexity.

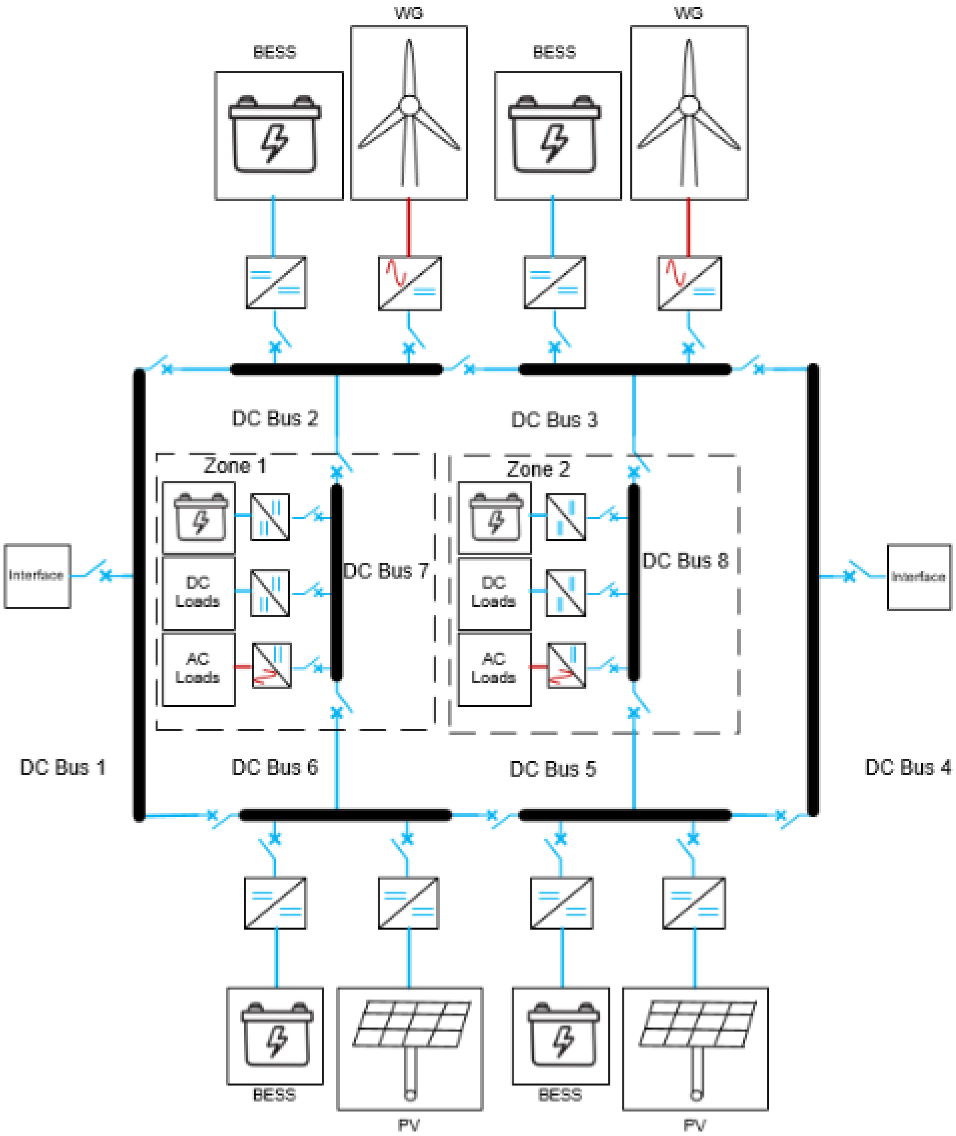

Figure 3.13: Zonal type configuration

Regarding interconnected configurations, research has been conducted mostly on navy applications. For example, the authors of [56], investigate possible configurations of distribution grids on navy shipboards. In fact, the traditional AC radial distribution system is proposed to be replaced by the respective DC zonal distribution system. According to the study, the proposed replacement is considered to have significant gains in terms of weight and cost. Furthermore, the authors of [57] propose an automatic reconfiguration scheme for DC zonal shipboard electrical systems for the instance of faults. The protection devices detect, locate and isolate the faults and collaborate for the reconfiguration of the system while maintaining the continuity of supply to the loads. Also, research has been conducted regarding the energy management of zonal configurations in ship power systems. For example, the authors of [58] have simulated an entirely electric ship power system consisting of two zones, including load dynamics, frequency oscillations, constraints of the power converters, etc. The developed method is based on a multi-agent system framework that achieves dynamic generation and load balancing while satisfying operational constraints. Simulations carried out showcase the efficiency of the proposed energy management, which fully exploits the advantages of the two-zonal distribution system, in terms of frequency behavior, supply availability and voltage stability.

Having examined the divisions of topologies of DC distribution in hybrid grids, it is essential to provide criteria for the comparison between them. Features of interest include:

- **Cost:** This parameter refers to the total investment cost for the implementation of the topology, including components such as DC distribution lines and DC switches.
- **Simplicity:** This parameter refers to the design of the grid, in terms of number of connections or number of buses required for the implementation of the topology.
- **Fault management:** This parameter refers to the capability of the topology to exclude as little as possible elements from the operation of the grid, in case a fault occurs. Also it refers to the capability of the grid to import power from more than one interfaces with the main grid, in case a fault occurs on one of the AC buses of the main grid.
- **Maintenance:** This parameter is related to the number of components utilized for the implementation of the topology that may ware out through use or need to be replaced, such as DC switches, etc.

Table 3.2: Evaluation of topologies

Features	Radial configuration	Ring configuration	Interconnected configuration
Cost	Low	Medium	High
Simplicity	High	Medium	Low
Fault management	Low	Medium	High
Maintenance	Low	Medium	High

Table 3.2 summarizes all described features along with the classification of each topology. It can be stated that the flexibility of a topology, in terms of fault management and acquisition of power supply is inversely proportional to its simplicity and cost effectiveness, as one could expect. Consequently, the selection of topology at the stage of design of a hybrid grid needs to be made according to its needs and available means of development.

3.3. Control systems of hybrid grids

Apart from the decisions regarding the interface with the main grid and the design of the topology for the connection of all the components included in the hybrid grid, it is essential to determine the control strategies according to which the total architecture will operate. The field of control strategies regarding these special structures, such as hybrid grids, has gained attention over the past few decades which has led to the rise of advanced control algorithms, creating a mixture of different approaches presented in the worldwide literature.

The key difference between a classical (traditional) AC grid and a hybrid grid lies in a combination of factors, most significant of which are: a) the introduction of a DC part of the grid, b) the increased integration of distributed generation, especially intermittent generation (RES) and c) the scope of the vast majority of hybrid distribution systems, which is the ability for autonomous operation, i.e. as MGs.

Therefore, control strategies of hybrid grids pose a challenge which renders them a major priority regarding hybrid grid architectures. Issues that need to be addressed include [59]:

- **Stability:** Regulation of the voltage and frequency of the hybrid grid for the avoidance of deviations during operation in different modes, i.e. connected to the main grid, isolated, in different configurations, with high RES penetration, etc.
- **Protection:** Monitoring of power flow, energy supplies and critical devices. This partincludes the design of actions regarding the fault management of the grid.
- **Power balance:** Coordination of load sharing among all power supply units included in the hybrid grid.
- **Transition:** Smooth transition between different operation modes is of major importance for hybrid grids as they are expected to switch modes occasionally, yet the power supply needs to remain intact.
- **Power exchange:** The exchange of power between the main grid and the hybrid grid, including possible ancillary services, needs to be defined by the control system.
- **Synchronization:** Synchronization of the hybrid grid with the main grid, if necessary, for the proper power exchange.
- **Optimization:** Depending on the objectives of the hybrid grid operators, decisions need to be made regarding the energy management system, taking under consideration constraints and uncertainties such as market prices, PV production, time of arrival and departure of EVs, etc.

According to the major criteria defined above, the control system of a hybrid grid needs to cover a wide area of functions. These functions concern different aspects of the grid and are divided by the worldwide literature in levels that are organized in a certain hierarchy. These levels are:

- **Primary control:** Primary, or otherwise, local control is the level of the control system with the fastest response. Its purpose includes, among other issues, the stabilization of voltage and frequency in the hybrid grid, power sharing, protection systems, etc [60].
- **Secondary control:** Secondary control is responsible for the regulation of voltage and frequency deviations (or only voltage deviations, in case of dc grids) of the hybrid grid. After a shift of the load or power supply in the grid, the secondary control eliminates the difference between the measured and the established operational values. It is also responsible for the active and reactive power control in the hybrid grid [61].
- **Tertiary control:** Tertiary control deals with the connection of the hybrid grid with the main grid, the power flow among MG clusters and the ways in which the hybrid grid participates in the market of the electrical network [62].

The hierarchy between the defined levels is presented in Figure 3.14. It is noted that the tertiary control is on the top of the hierarchy, including more general aspects of the hybrid grid, such as the market participation, cost optimization etc. Moving toward the bottom of hierarchy, issues of more technical nature are taken under consideration, including protection devices, voltage regulation, etc. It is noted that when operating in islanded mode, since there is no communication with the main grid or other MGs, there is no tertiary control level and the secondary control is the highest in the levels of hierarchy.

Each level of control is also divided into different tasks-categories, according to the purposes it serves. There is a variety of control strategies concerning different modes, such as centralized, decentralized, grid-connected and isolated operation.

The types of the primary control are presented in Figure 3.15.

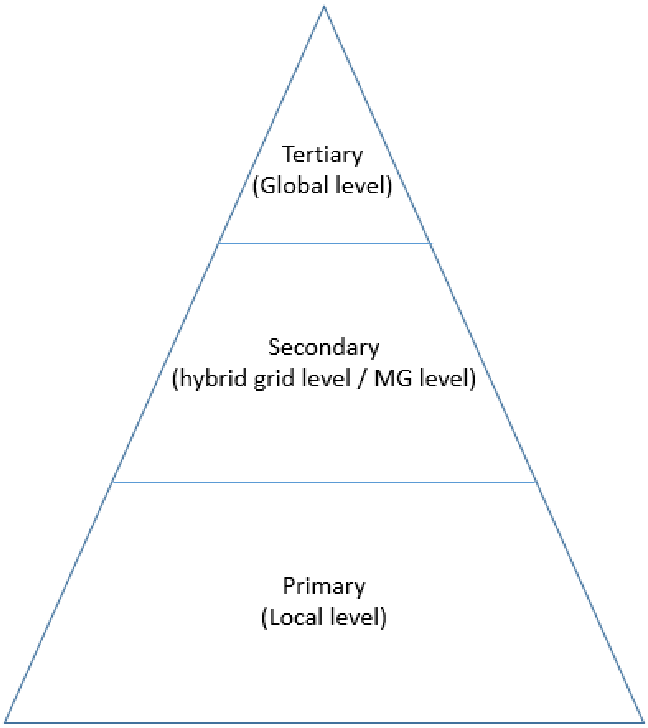

Figure 3.14: Hierarchy of control

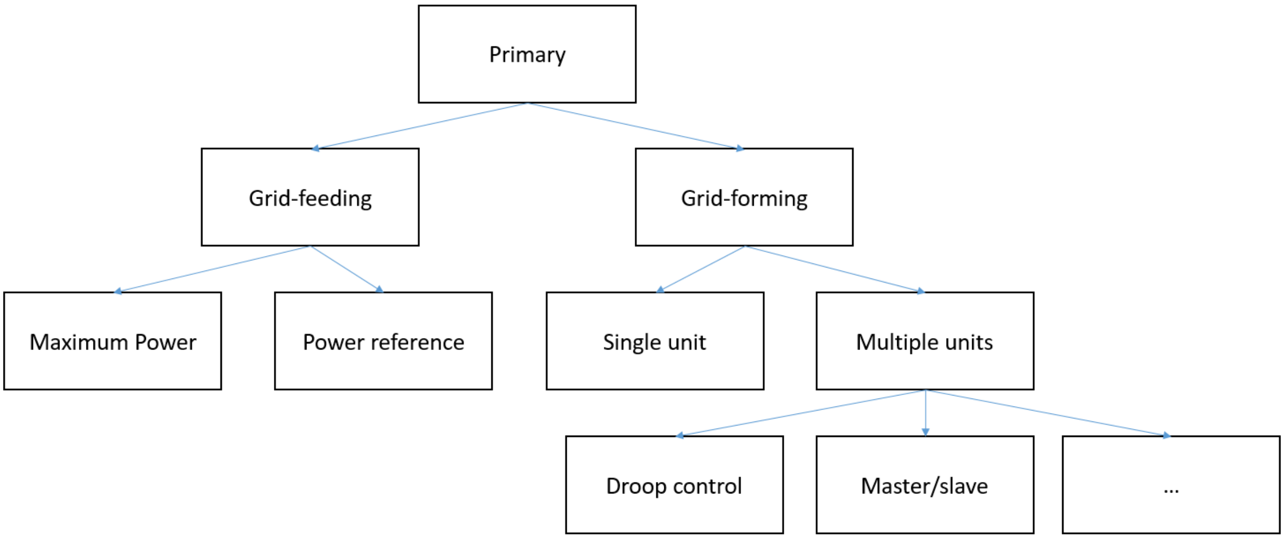

Figure 3.15: Types of primary control

The purpose of the local controller is to perform the current, voltage and frequency control of the power converters connected to the distributed generation and storage units. The control is divided in a) grid feeding and b) grid forming strategies. The grid feeding strategies relate to the operation of the hybrid grid when it is connected to the main grid, i.e. in grid-tied mode. In this case, the voltage and frequency of the hybrid grid are established by the utility grid. This means that the local controllers of the distributed generation and storage systems operate in current control mode or power output control mode. There are cases where the control's objective may be the extraction of maximum power provided by the sources. A common example is the maximum power point tracking (MPPT) mode, applied in wind turbine or PV systems. Another example is the rated power operation on diesel generators or biomass generators. Additionally, grid-feeding control is able to operate in a non-optimal point, as there are cases where the operation points are set by higher control levels, requiring a certain output as power reference.

Indicatively, related research regarding grid-feeding strategies has been conducted by the authors of [63], where a micro wind turbine is connected to a DC MG which operates connected to the AC main grid. An MPPT algorithm is implied, aiming to obtain maximum power output from the micro wind turbine. This is achieved by controlling the current according to variations of the DC link voltage. Simulation results highlight the success of the proposed algorithm in terms of maximum power point tracking with fast responding dynamics. Additionally, in [64] an MPPT-based model is presented for a DC MG, operating in grid-tied mode. The control regards the PV systems of the DC MG and aims to the extraction of maximum power. The effectiveness of the proposed method is demonstrated through simulations for different operating conditions.

On the other hand, the grid-forming control is applied when the hybrid grid is required to operate isolated, as a MG. In this case, the voltage and frequency of the MG need to be defined and stabilized by the distributed generation and storage systems. According to the requirements of the grid, one or more units shall operate to control the grid's voltage and frequency, hence the term "grid-forming mode", while the rest of the units continue to operate on grid-feeding mode. In the case that a single grid-forming unit is selected, the converter of the selected interface is responsible for the establishment and supply of a certain voltage and frequency level. The rest of the grid's components act accordingly, on grid-feeding mode. However, there is also the possibility of operation with multiple grid-forming units. This means that more than one converters are controlled in grid-forming mode. For example, a vastly used implementation of grid-forming operation with multiple units is the droop control. The aim of droop control is to vary the voltage, amplitude and frequency references depending on the active and reactive power demand in order to share the load between the available devices. This control strategy is mostly used for the power sharing of synchronous generators in conventional grids. However, storage systems often incorporate this control system in order to perform optimal power sharing [65] [66]. Another simple way to perform power sharing in hybrid grids is the master/slave control. This control strategy utilizes both voltage and current controllers in order to perform power sharing between the converters. The assigned master unit contains a voltage controller, for the regulation of the voltage level and is responsible for the specification of current reference of each slave unit. The slave units track the current reference given by the master unit and adapt to it through current controllers. In this way, the master-slave control performs current sharing with easy implementation, even with non-identical modules [67].

Several researchers have focused on grid forming control strategies. For example, the authors of [68] present a droop-based primary control strategy for the autonomous operation of AC/DC MGs. The proposed control is designed for the interlinking converter between the AC and DC part of the MG. Emphasis is given to the power sharing capability of the proposed controller as well as the stability it provides to the hybrid MG. Also, in [69], a novel droop-based control for multiple bi-directional distributed energy sources in DC MGs, based on voltage sensitivity analysis, is proposed. The control is applied on a five-node mesh type DC grid. According to experimental results, the developed controller improves the power sharing accuracy and voltage regulation performance of the DC grid. Furthermore, in [70], among other approaches for the proper operation of stand alone hybrid AC/DC grids, the benefits of the master/slave strategies are highlighted. The possibility for not only a single-master but also a multi-master approach, where more than one inverters operate on voltage-controlled mode is discussed.

As stated previously, above the primary control, in terms of hierarchy, there is the secondary control. Secondary level strategies can be distinguished in two types, namely: a) centralized and b) non-centralized, depending on their location. The main difference is that centralized techniques are located at a central point, whereas non-centralized techniques are located at the local controller of each device. These two types can be also divided in sub-categories, according to the specific purpose they serve, as presented in Figure 3.16.

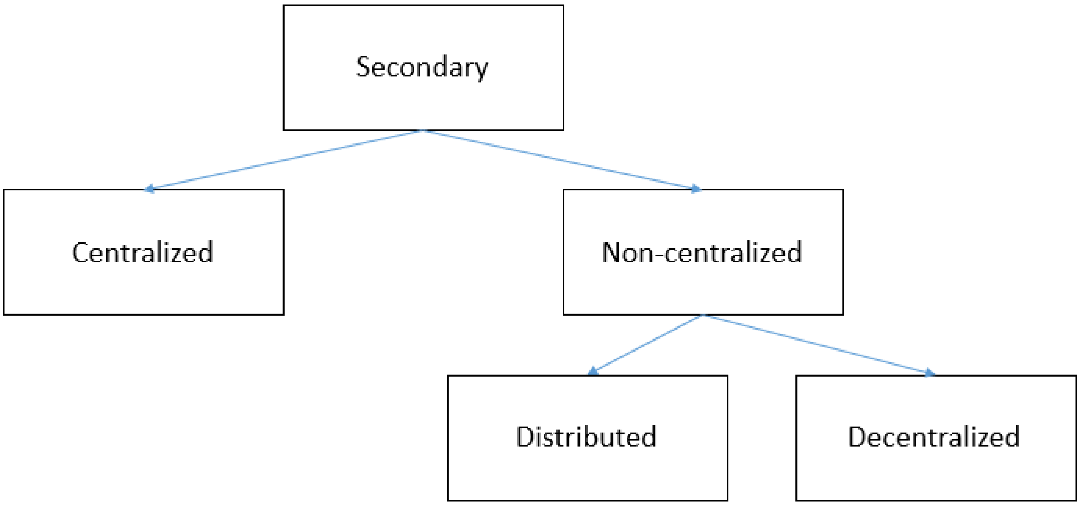

Figure 3.16: Types of secondary control

As regards to centralized approaches, the management is performed from a central controller. The central controller needs to be connected to a communication system. In this way, the controller gathers information about the distributed generation and storage systems of the hybrid grid, such as active and reactive power measurements, etc. Also, information regarding market conditions and requests from the upper control level are taken into account. Having processed the available data, the controller performs the necessary actions and provides references to the primary control level, as presented in Figure 3.17. This approach is suitable mostly for small scale hybrid grids, where there is a single owner of the distributed generation and storage units, providing the controller with clear, single tasks, thus avoiding conflicts of interest that would occur in the case of multiple owners [71].

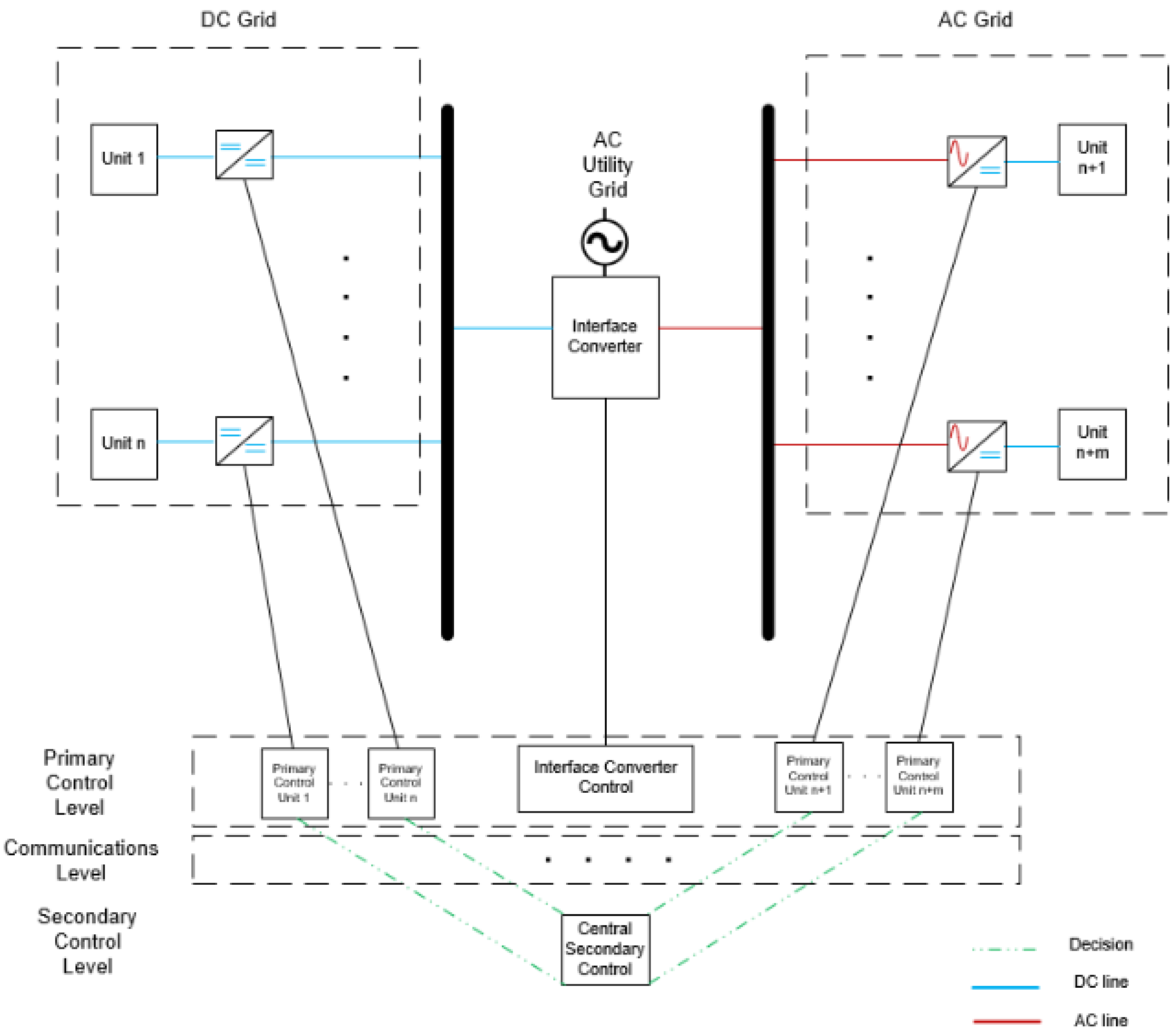

Figure 3.17: Centralized secondary control

Despite the efficiency of centralized control systems, the market is oriented towards hybrid grids of a larger scale, including more than one providers of power supply units. For this purpose, non-centralized control strategies are developed. This sort of strategies requires the implementation of secondary control in each unit separately/locally. Two main variations of this strategy are distinguished, i.e. distributed secondary control and decentralized secondary control. The distributed secondary control requires a communication network between the separate secondary control subsystems, as presented in Figure 3.18. The decentralized secondary control does not require a communication network between the secondary control subsystems, as presented in Figure 3.19. In general, the non-centralized control approach offers simple integration, meaning low communication requirements, facilitates the incorporation of multiple power supply producers and provides the ability for plug-and-play connection of devices. However, the operational pattern attained by this type of control is usually sub-optimal since there are sometimes conflicts of interest between the owners of the power supply units, meaning that some units may be competitive or have different kinds of goals with respect to others. Also, since there is no communication system with higher hierarchy control systems, the operation of the hybrid grid attached to the main grid is not possible. This means that this sort of control may be a great solution in MG operation but could not be implemented for grid-tied mode [71] [72].

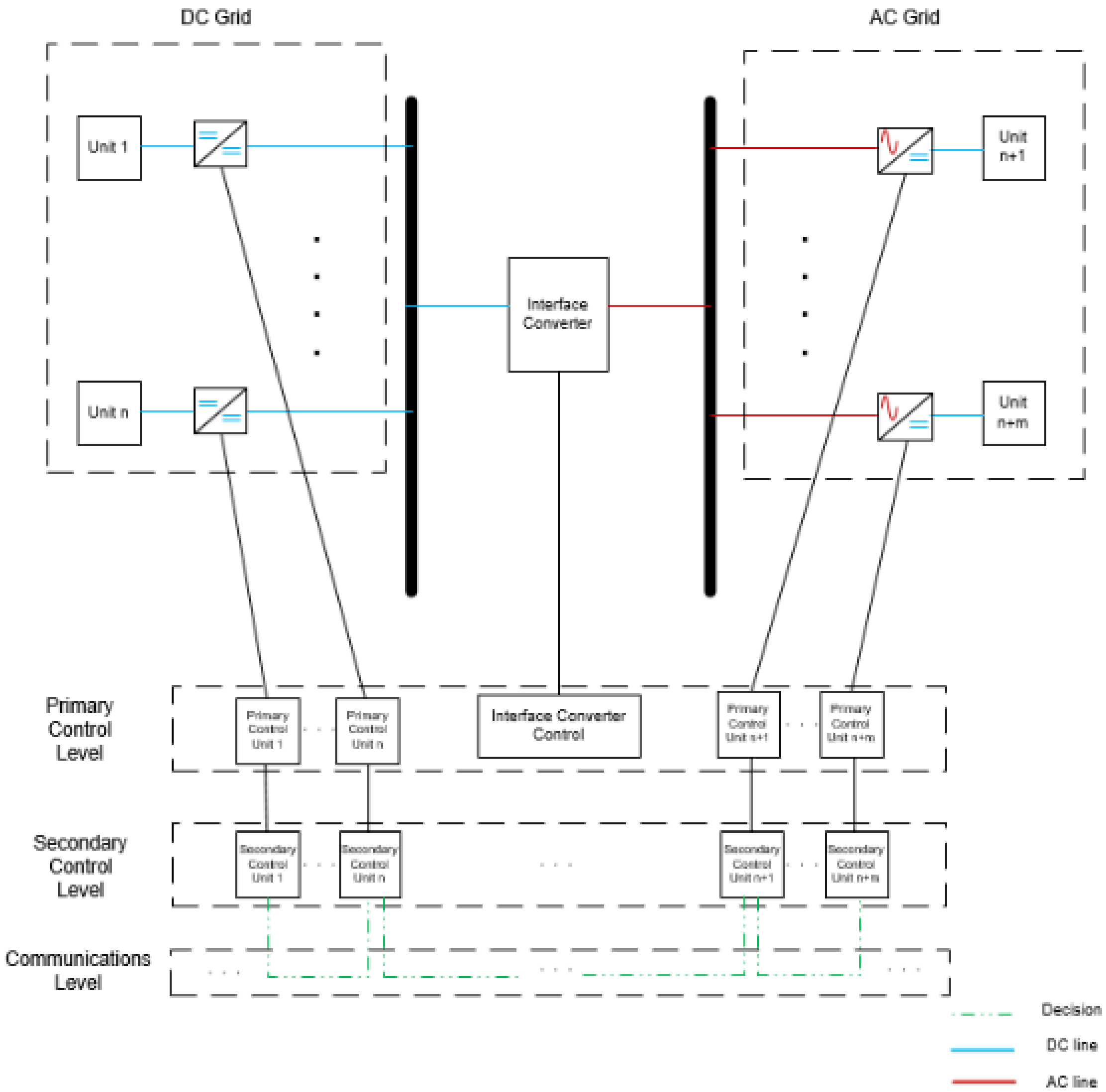

Figure 3.18: Distributed secondary control

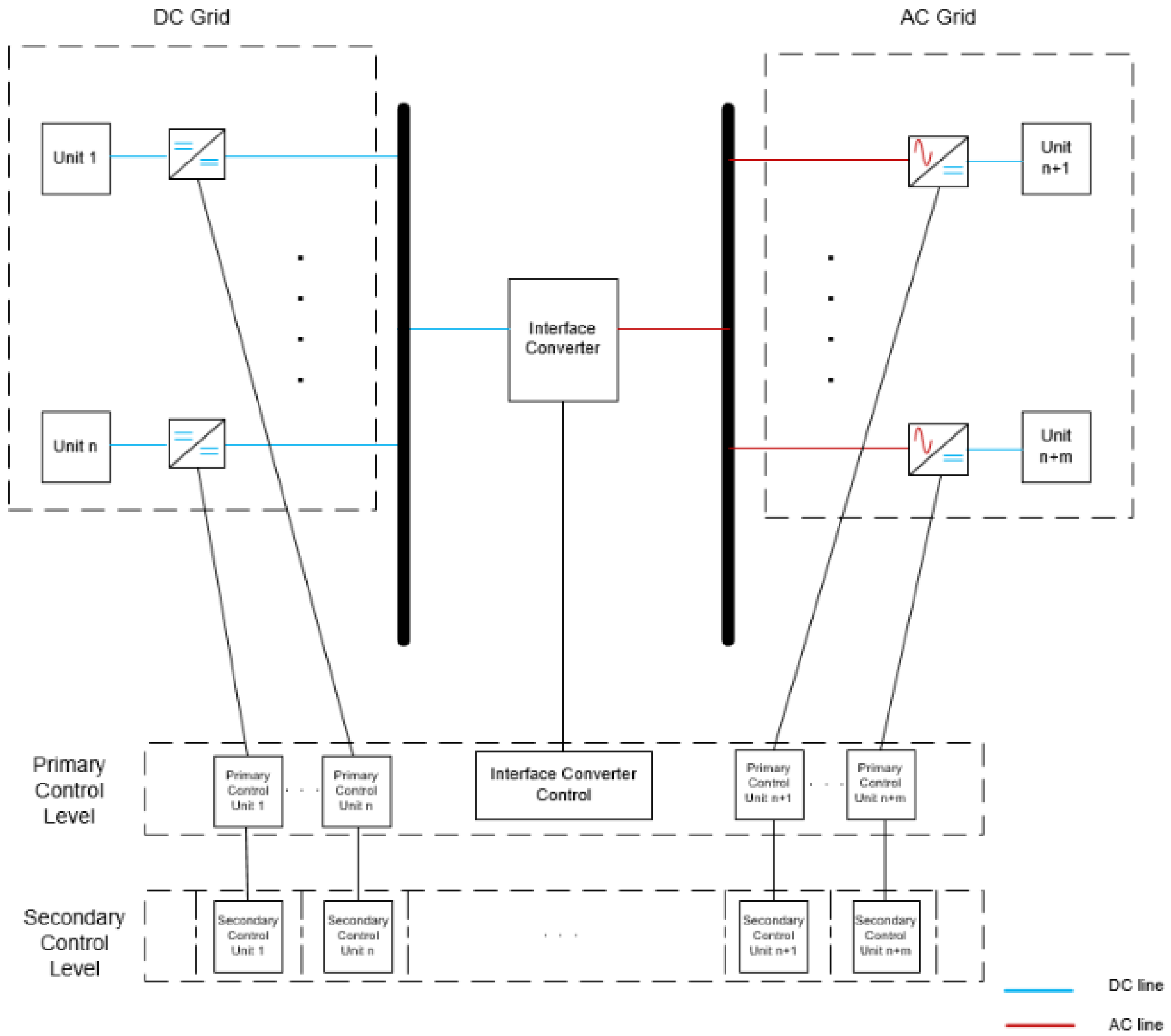

Figure 3.19: Decentralized secondary control

Secondary control strategies have been approached in a variety of ways by many researchers. For example, in [73], a centralized secondary control method is proposed to be applied on the bidirectional power converters of a grid-connected AC/DC hybrid grid. The secondary voltage-regulated controller is able to restore the DC bus voltage to the reference nominal value after power disturbances occur. Additionally, it ensures the economically optimal power distribution in the hybrid grid. The simulation results showcase the benefits of coordinated optimization, including energy cost minimization and voltage stability. The authors of [74] present a distributed control strategy for islanded hybrid MGs. The proposed control system relies on the communication system between the distributed generation units and manages to improve the frequency and power sharing of the grid. The algorithm is generic, meaning that it can be scalable for applications of different topologies. Also, in [75], a distributed control technique is developed for islanded MGs including RES and ESS. The proposed control is coupled with a droop-based primary control. Experimental results demonstrate the good performance of the proposed control system in terms of frequency and voltage stabilization as well as power sharing between the distributed generation units.

However, when the hybrid grid does not operate as MG, but in grid-tied mode, the highest level of hierarchy is the tertiary control. Tertiary control is responsible for the energy management between the hybrid grid and the main grid, regulating the active and reactive power exchanged between the two sides as well as the voltage and frequency of the hybrid grid. This level of hierarchy establishes the reference values of active and reactive power based on the requirements of the overall system, taking under consideration the status of the hybrid grid and the market. This includes the prices of energy, the state of charge of the storage systems, the forecasts of RES production, the energy demand and possible ancillary services that can be offered by the hybrid grid. The data obtained can be utilized for the optimal schedule of operation, taking under consideration objectives such as cost minimization, power quality maximization, etc [72].

The authors of [76] propose a hierarchical control architecture for hybrid AC/DC grid-connected MGs. The hierarchy constists of the upper level, i.e. tertiary control, the secondary level, i.e. centralized control and the lowest level, i.e. primary control. The tertiary controller includes a dynamic economic dispatch algorithm, aiming to minimize the MG's operating cost. The secondary control level deals with the frequency optimization of the MG and the primary control level tracks the optimal set points, received by the upper two control levels. The proposed hierarchical control has been tested experimentally, validating its effectiveness. Also, in [77] a hierarchical control scheme for connected MGs with RES production is presented. The tertiary control is responsible for the energy management between the MGs, the secondary control of each MG is responsible for the preservation of frequency and finally, the primary control is responsible for the application of the commands received by the higher levels. The results obtained by simulations showcase the cost minimization and stability achieved by the implementation of the proposed strategy. Moreover, in [78], the possible contribution of the incorporation of artificial intelligence in hierarchical control of hybrid grids is discussed. In fact, techniques such as deep learning (DL) and deep reinforcement learning (DRL) are considered to be efficient in tackling problems that occur in grids, providing possible solutions to overcome the challenges.

In conclusion, there is no standard way of control when it comes to hybrid grids, mostly due to the fact that they do not have a standard form. This leads to a number of possible control architectures, depending on the size, the number of owners and the connection to/isolation from the main grid. Nevertheless, there are three levels of hierarchy, i.e. primary, secondary and tertiary. The primary control is usually implemented with MPPT or droop-based techniques. The secondary control can be centralized or non-centralized, depending on the connection with the main grid or other hybrid grids and is the highest control level when the hybrid grid operates as isolated MG. However, when operating in grid-tied mode, the dominant control level is the tertiary. This level makes decisions regarding the interaction of the hybrid grid with the rest of the network and provides the lower levels of hierarchy with the appropriate set points. Considering that this is a field of innovation, no optimal solution is provided for the control scheme of hybrid grids in general. Each hybrid grid needs to have its control architecture designed individually, based on its assets and requirements.

4. Applications

As the needs of devices change over time so do the needs of the power systems supplying them with power. Due to the emergence of new technologies, the advantages of DC current have become extremely relevant. For example, the increased use of renewable energy sources and the emergence of electric vehicles lead to the establishment of DC power systems in academic research and they have even started to gather interest from many industries. What is more one of the main disadvantages of DC current was the cost of expensive voltage converters, which, aided by the advances in the field of power electronics, have much lower cost compared to years past.

In the previous section the various architectures available for DC grids were analysed. Each of those architectures has advantages and disadvantages [79]. It is the technical specifications subject to a series of restrictions that will determine which architecture best fits a particular need so that its advantages can be maximized and its disadvantages minimized.

The aim of this section is to present modern examples of applications of DC power systems, their aspects, operational results, technical knowledge and experience from real life installations across various sectors and best practices, where possible.

4.1. DC power systems in ships

Ships constitute a special applications environment, a microgrid that needs large amounts of power to operate properly. In reality, the ways to supply this power are limited due to the constraints imposed by the ship's needs like:

- **Constant power availability:** power must be always available to supply loads vital for the ship's operation. Constant power availability requires not only a reliable power system, but also energy storages in case of power system failures.
- **Space and weight concerns:** the installations responsible for ensuring the ship has available power must be as compact as possible due to the limited space available on ships.
- **Presence of pulsed loads:** ships increasingly require pulsed electric loads. The demand of pulse loads change periodically creating the need for power sources that can keep up with the fast changes in load demand.

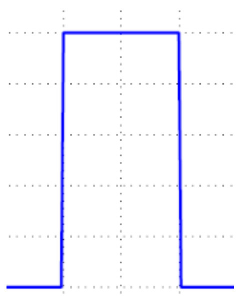

Figure 4.1: Waveform of the power demand of a pulse load in a window of time

When it comes to these constraints, AC power systems lack in comparison to their DC counterparts. AC power systems rely on complex converters to supply the ship's loads. This complexity causes the converters to be more prone to faults than simpler devices. For AC power systems to function, transformers of great volume are imperative which comes into conflict with the need for compact power systems that ships have. Last but not least, AC power systems are unable to support large pulsed loads as they have slower responses to a changing demand and face problems with power quality, harmonics and phase imbalances. On the other hand, medium voltage DC systems are lighter and smaller compared to AC systems of similar rating, due to the presence of converters instead of transformers. They allow the integration of energy storage systems easily, without the need for DC/AC converters, as most of them exchange DC power with the system resulting in fewer losses and increased reliability. Modern power electronics along with the presence of storage devices allow very quick responses to changes in load demand. Even the AC generators of the ship benefit from a DC power system as each generator can function at its optimal frequency instead of all of them forced to operate with a common frequency, resulting in fuel conservation. The resulting DC system can integrate effective controllers responsible for:

- handling faults and transient phenomena
- charge and discharge of storage systems
- ensuring voltage stability of all buses
- energy distribution among loads taking into account the energy stored in storage systems

Regarding potential architectures, the authors in [80] proposed a medium voltage DC power system with radial architecture connected with another DC system with the same architecture through a DC isolating switch. Each of the two DC power systems has two generators, one of which is auxiliary. Should the main generator fail, the auxiliary one will supply the loads of the ship assigned to that generator. Each power system has its own set of loads and storage systems comprised of batteries and supercapacitors, but in case of emergency, the loads of the power system in need can be supplied by the other power system through the DC isolating switch. Through the same isolating switch the generator and storage systems of one power system can supply the loads of the other power system. The system is shown in Figure 4.2 and achieves enhanced reliability. It even provides reconfiguration capabilities through the DC isolating switch. It also utilizes a controller that governs how the storage devices contribute to the energy needs of the ship, while maintaining the voltage on both sides of the isolating switch. It achieved equal load sharing among storage devices, prolonged their expected lifetime and kept the voltage of the buses between the desired limits.

In [81] a medium voltage architecture (Figure 4.3) is proposed. Two generators are connected to a common bus to ensure constant power availability. Loads are connected to the common bus using the properly sized intermediate converter. It is a multi-zone architecture whose main disadvantage lies to its vulnerability to faults of the common bus. A sparse-feedback, multi-rate LQR controller to regulate the bus voltage is utilised. Towards that end, energy storage system are used to provide power and help regulation when transient phenomena occur. Owing to the controller the energy storage capacity of the system is reduced.

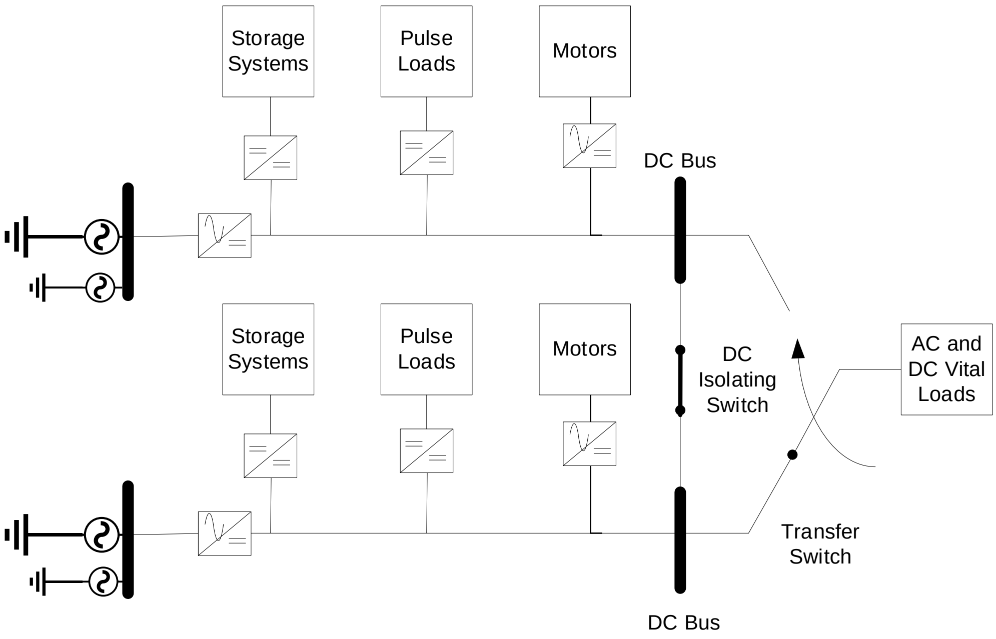

Figure 4.2: An example of a naval DC power system [80]

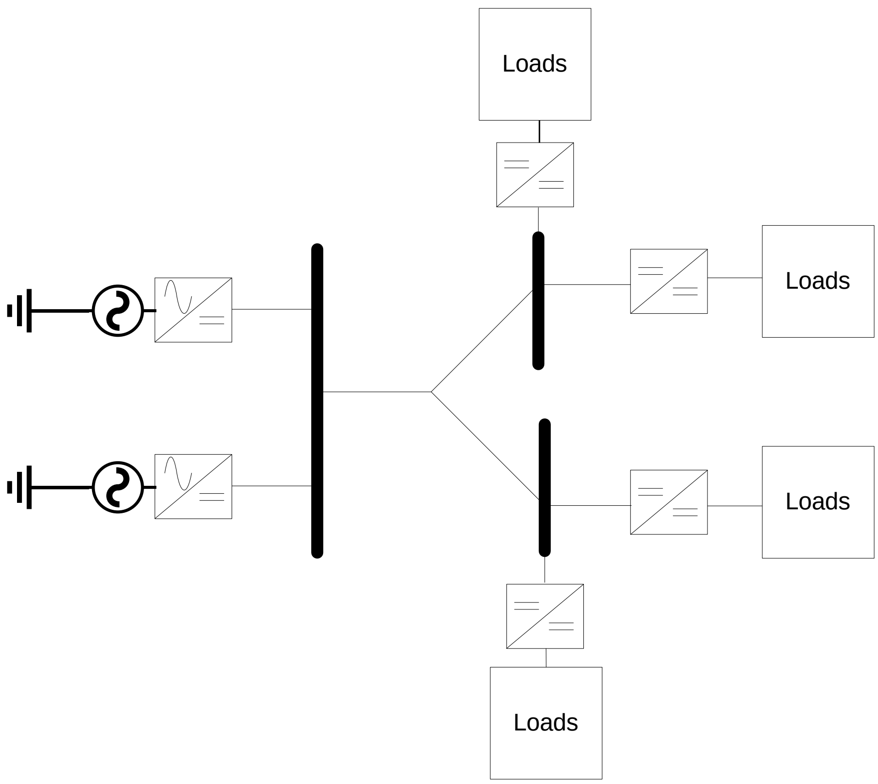

Figure 4.3: The DC power system presented in [81]

In [82] a zonal architecture similar to the one shown in Figure 4.4 is presented, but with more zones. Both the motors and the loads of the two zones are resilient to faults because they are connected with a generator with at least two paths. It also consists of multiple switches to quickly isolate faults making it a very advantageous configuration for ships, where safety and reliability are of paramount importance. The effects of distributed control algorithm were investigated and the algorithm managed to return the voltages of the system to their nominal values after one of the generators failed.

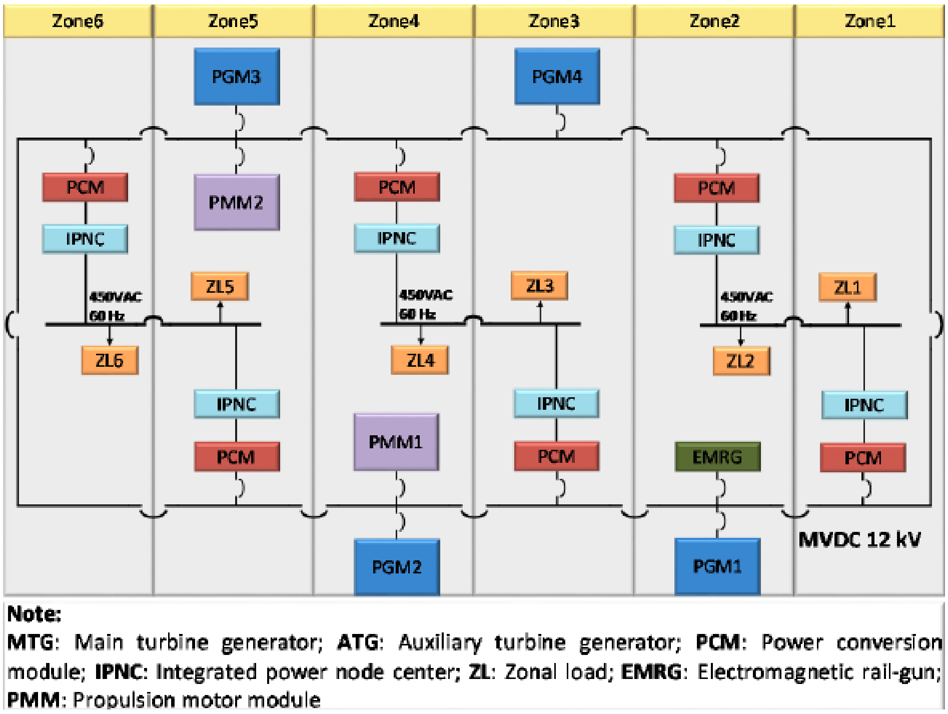

Figure 4.4: A mesh DC power distribution system for a ship [82].

The advantages of DC power systems have already lead to the construction of medium voltage all-electric ships [83]. Useful experience can be derived from such applications.

Figure 4.5: An all-electric ship [83]

4.2. Urban transport applications

Due to the high availability of DC motors and the ability they provided to easily control their speed, railways initially used DC current and continue to do so to this day. Even buses are moving towards DC current to power them for environmental reasons. One example of that is the purchase of a number of electric buses by the city of Geneva.

Both motors and auxiliary circuits inside urban transport vehicles use DC current. This results in the urban transport system itself being a DC power system drawing its power from the main city AC power system. Because current power systems of cities are mostly AC, AC/DC converters are needed to power urban transports resulting in losses. These losses can be avoided if the main grid is DC-based.

Another important application of DC power systems is the storage of the power produced by trains while braking (regenerative braking) [84]. The structure of modern AC/DC converters only allows unidirectional flow of power from the main AC power system to urban transport vehicles and does not allow them to return or efficiently store surplus energy to the AC power system. This surplus energy is mostly wasted but with a DC power system, incorporating batteries the energy can be stored for further use in other applications such as lighting.

The authors in [85] demonstrated that a medium voltage DC electrification system for the Paris-Strasbourg line is at least at par with the current AC one in terms of efficiency. It also allowed less installed power for substations, no phase shift between them, and required less power electronics and no autotransformer purchases.

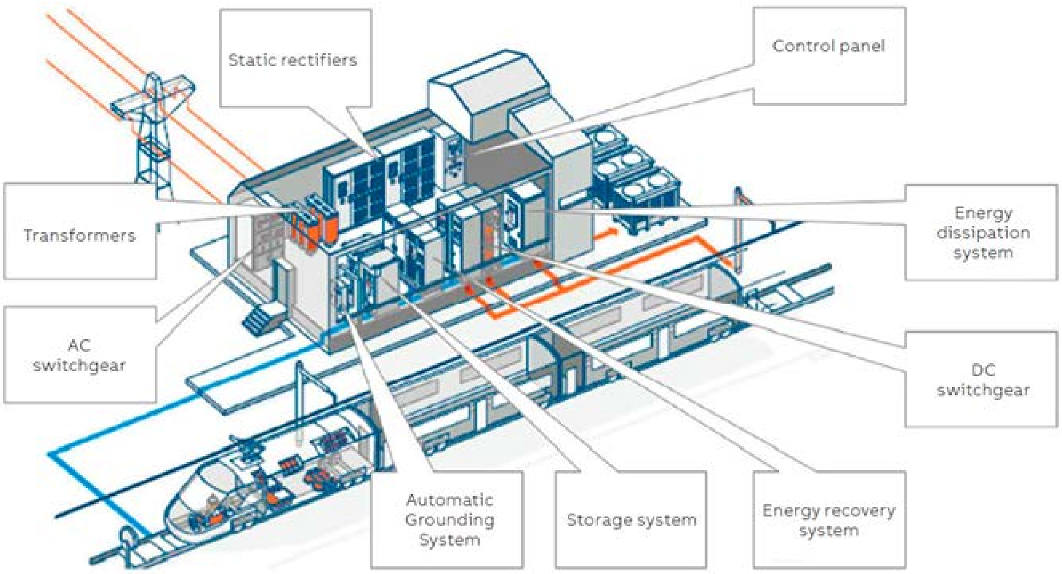

Figure 4.6: A DC railway station [86]

A possible architecture is shown in Figure 4.7 [86]. The railway is energized with medium voltage from the main AC grid through a transformer and a traction AC/DC converter (rectifier). If the main grid was DC instead of AC, the rectifier could of course be omitted. The power that is produced from braking is split into three categories. The one that is dissipated which is ideally very low, the one that is immediately returned to the main grid and the one stored into a storage system for future use.

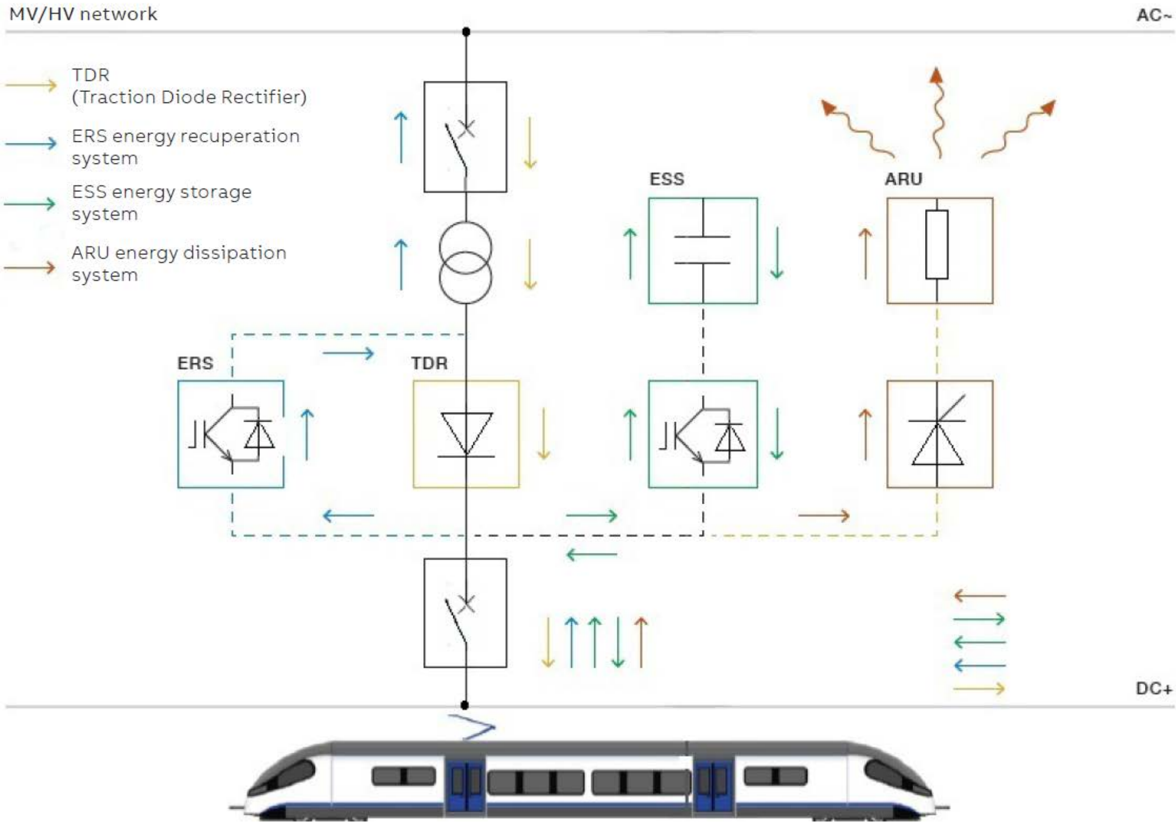

Figure 4.7: Architecture of a DC railway [86]

4.3. Data centres

Data centres are extremely important facilities. In fact, this importance will only increase as time passes and the need for high capacity of information storage increases as well. Future data centres could require power levels up to a few MWs to operate. Most loads in data centres are digital in nature and operate on DC current, so AC supply from the grid leads to losses due to AC/DC converters. AC/DC converters are more complex devices with greater failure rates than DC/DC converters, leading to reliability issues. These problems of AC power systems supplying data centres along with the trend of using renewable energy resources like solar panels and energy storage (both utilizing DC current) favour the adoption of a DC power system for data centres. According to [87], low voltage powered DC data centres require less 20 % copper, are 1000 % more reliable and have a 36 % lower lifetime cost than AC ones. The authors in [88] claimed the optimal level of DC voltage to be 400 V (considered low voltage) for many different load levels and ensured 7 % energy savings along with the other benefits of DC, like no harmonics.

Figure 4.8: A data centre benefits from a DC installation including batteries and solar panels [89]

Since data centres have an increased need for reliability they are usualle powered through multiple power sources as shown in Figure 4.9.

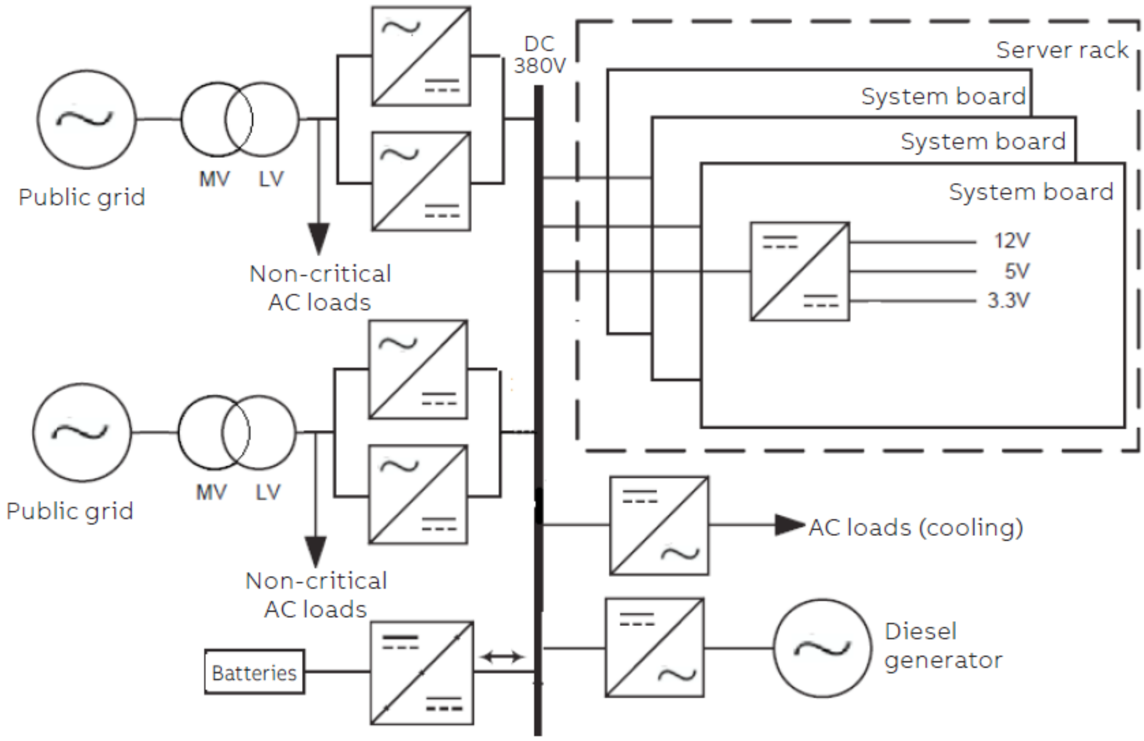

Figure 4.9: Possible architecture of a DC installation for data centres

4.4. Building applications

Due to environmental and economic concerns, PV installations are quite commonly installed at buildings. Excess energy produced can be diverted to energy storage systems that can supply power back if necessary. As PVs and energy storage systems are installed within the building they allow the minimization of transmission losses. Both these power sources provide DC power and usually help to supply a large number of loads inside the building. A type load of importance for exampie, are LEDs (Light Emitting Diodes) used for lighting with increased efficiency, operating on DC current. Furthermore, chargers and most other loads of the average building use DC current to operate. Due to the main grid being an AC one, these devices are forced to include AC/DC converters internally or, in the case of power sources such as PVs and batteries, they require an external DC-AC converter. By adopting a DC power system for powering the building, the converters and their associated losses are omitted.

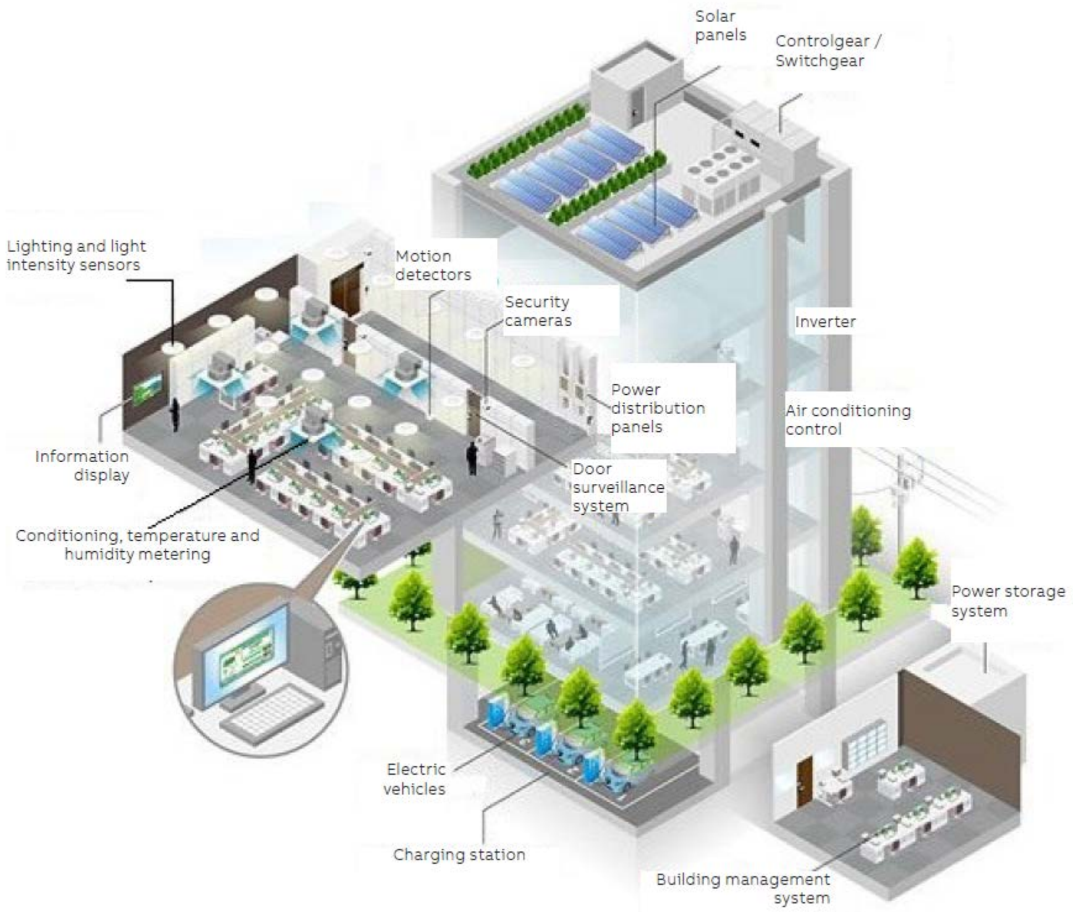

Figure 4.10: Concept of a smart building taking advantage of DC technology [86]

Installing solar panels on the roofs of homes along with batteries as power sources for a DC microgrid are presented in [90], [91], where energy savings in the order of 7% were achieved due to the DC installation. If such installations were adopted by a large number of homes, they could reduce energy costs in a sustainable manner. In [92], the authors demonstrate the possibility of having a connection to the AC main grid exclusive for high-power loads in case local generation is insufficient.

4.5. Lighting of public spaces and roads

As part of public works and services, older lighting equipment is replaced with LED technology lighting in most public spaces, roads and highways. DC grids power the LED technology allowing a very large financial gain, since public lighting is a significant public cost. These initiatives help reduce strain on the environment as LEDs are more efficient than the lighting equipment used in the past. In [93] the authors demonstrated that using a low voltage DC micro grid to power road lighting allows the integration of vacuum switches that achieved high reliability and low cost than switches used in AC grids.

A droop control technique for road lighting microgrids is presented in [94]. The method was successfully demonstrated in several grids and controlled their batteries effectively and safely.

4.6. Powering remote installations

Installations that are far from the main grid are troublesome to supply due to the large losses of lengthy transmission lines. An ideal solution for such installations are microgrids that draw energy from solar panels and store energy in batteries. The microgrids will be able to operate in island mode isolated from the public grid, but can also be connected in case additional energy is needed.

The IEEE Smart Village initiative and the Global Himalayan Expedition initiated projects [95], which resulted in providing entire off-grid communities in the mountains of India with lighting using microgrids. These communities are able to have access to lighting with low cost thanks to these DC microgrids using solar panels to power LEDs and store the excess energy in batteries. Their impact to the environment is minimal.

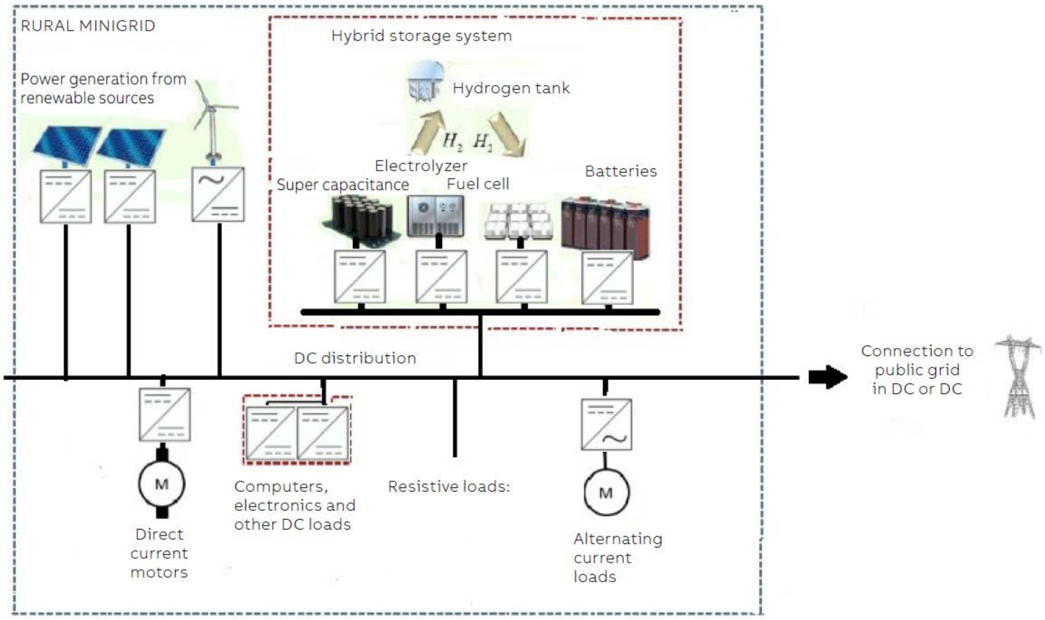

Figure 4.11: A remote rural DC installation [86]

4.7. Power transmission systems

Transmission lines are a vital part of every power system. DC transmission lines have a number of advantages compared to AC lines. These advantages led to the beginning of projects to harness high voltage DC transmission lines. In China, a 800 KV high voltage transmission system spanning 2172 km in Baihetan-Jiangsu, another of the same rated voltage in Wudongde-Yunnan spanning 1489 km are under construction. A 500 KV DC transmission system is already operating in Tian-Guang since 2000 delivering 1800 MW over 960 km [96]. Outside of China, a 500 KV transmission line connects Utah and California as part of the Intermountain Power Project [97] in the United States and a 350 KV underwater cable of 127 km connects the hydroelectric-based Norwegian grid and the wind and thermal power-based Danish grid. Advantages of DC transmission include:

a) Reduced number of conductors: Because DC power uses 2 conductors while AC power is three-phase, less conductors are required to construct a DC transmission line and the resulting transmission towers are smaller in size.

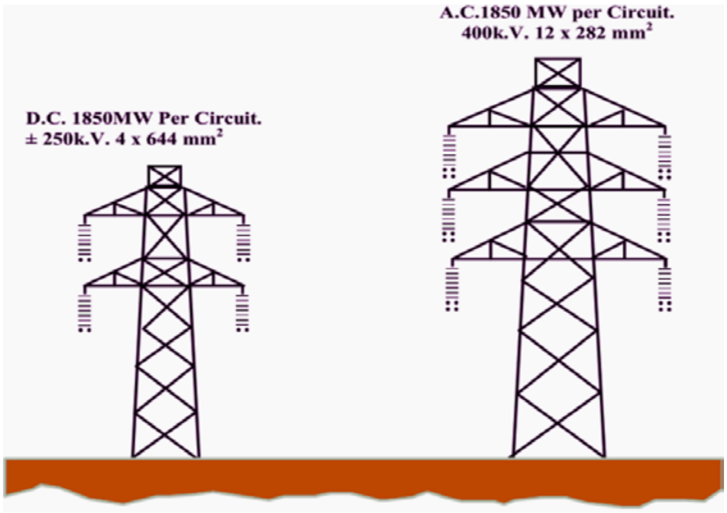

Figure 4.12: Comparison between towers required for DC and AC overhead lines [98]

b) Absence of reactive power, due to the freuqency being zero, allowing for more efficient power transmission.

c) Lower voltage drops, due to the absence of reactive impedance. The total voltage drop of a line is only caused by its resistance and is thus less than voltage drop of AC transmission lines.

d) Absence of skin effect: The phenomenon of AC current in a transmission line being unevenly distributed across its radius is called skin effect. It causes a larger amount of current to be concentrated away from the axis of the line and densely closer to its surface, increasing the effective resistance of the conductor. Making the AC cables thicker would have little effect as the current would still have more density at the surface and little density inside the conductor. This phenomenon is caused by the inherent time dependence of the AC current even if its amplitude is steady. DC current on the other hand is constant as long as its amplitude remains steady and because of that skin effect is not a concern.

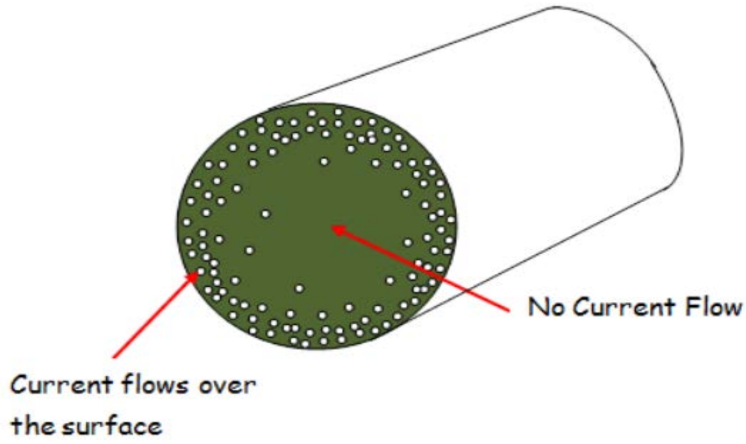

Figure 4.13: Cross-section view of conductor with AC current – skin effect [99]

e) Absence of the corona effect: The ionization of between conductors due to the high AC voltages present in AC transmission lines is called corona effect. It provides the current in the line an alternative path through the air and results in additional, unnecessary power losses. This effect is less severe in DC transmission lines because of the fewer and sparser conductors present.

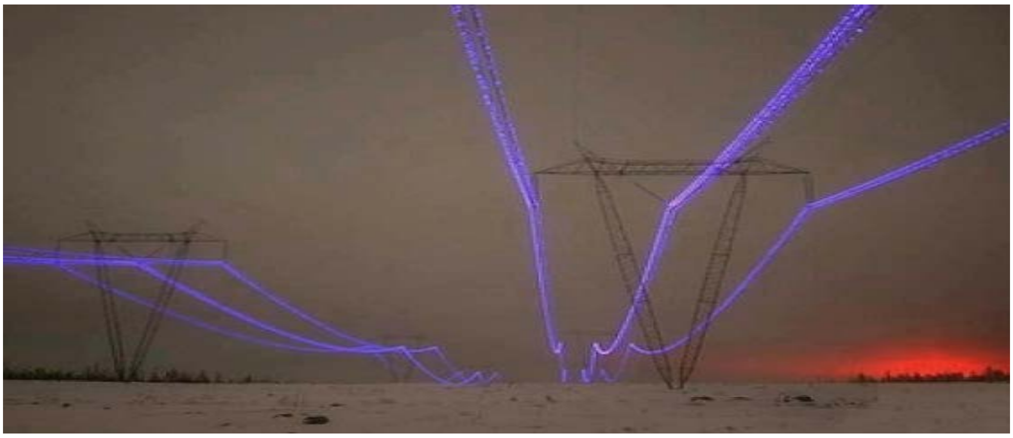

Figure 4.14: The Corona effect due to the presence of conductors and high voltages [100]

f) Fewer insulation materials required, because of fewer conductors and lessened impact of the corona effect the cost of insulating DC transmission lines is significantly lower.

g) Independecy to frequency concerns: in order for two AC systems to be connected with an AC transmission line their frequency must be exactly the same. However, by using a DC transmission line the two connected AC systems can have different frequencies. That is achieved by first converting the power with the frequency of one system to DC power and then transferring to the other end of the line where it is again converted to AC power through a DC/AC converter. DC/AC converters allow their operator to choose their output frequency and so the DC current is converted to AC current with a frequency equal to that of the second system. DC coupling of grids has been implemented for example in many of Japan’s regions, the Maritime Link project [101] connecting Newfoundland and Nova Scotia and the INELFE [102] project between France and Spain that has played a significant role in the integration of the Iberian Peninsula to the Larger European grid.

h) Replacement of transformers: originally, AC transmission systems had the advantage of easy conversion of voltage levels due to transformers. Nowadays, transformers are very expensive and bulky, which causes problems with the cost and easiness of their installation. DC transmission lines use DC-DC converters to change voltage levels and these converters are smaller in size and more efficient in comparison to transformers owing to advances in power electronics technology.

i) Increased transmission capability, also at greater distances: DC power cables effectively transmit more power than AC cables of the same size because of the absence of skin effect, corrona effect and reactive power. Also, AC cables cannot be too large since the reactive power flow due to the huge resulting capacitance will take up much of the cable's transmission capability. As capacitances don not affect DC current, DC cables are not limited in their length. Additionally, due to the transmission losses scaling with cable length and DC cables having fewer losses, they become the best alternative from an economic perspective as cable length increases.

j) Increased controllability: power electronics that can operate extremely fast are utilized in DC transmission systems. Combined with the fact that only active power needs to be controlled, DC transmission systems are easier and faster to control resulting in improved system stability.

k) Lower communications interference and environmental impact: DC power systems produce less noise and interfere less with radio signals [103]. They work well with renewable energy sources and encourage their use, which lowers their environmental impact

l) Easier acceptance by the general public: local populations often reject new power system installations for aesthetic reasons. The sheer volume of AC installations exacerbates this problem. DC installations are smaller, less intrusive from a visual perspective and can be integrated with the local environment making them more easily accepted by the residents [104].

m) Lower cost: Because of the fewer materials required in their construction and the smaller towers, DC transmission lines are cheaper when it comes to transferring power across long distances. While the AC cost is initially lower due to the cheaper terminal required, as line length increases a break-even point is reached [105]. After that point, a DC line always yields a lower cost. Of note, this break-even point is lower in submarine cables, making DC cables a common option for underwater transmission [107]. Another economic area where DC is advantaged is the lower cost of right of way for DC installations as they take up less space [104].

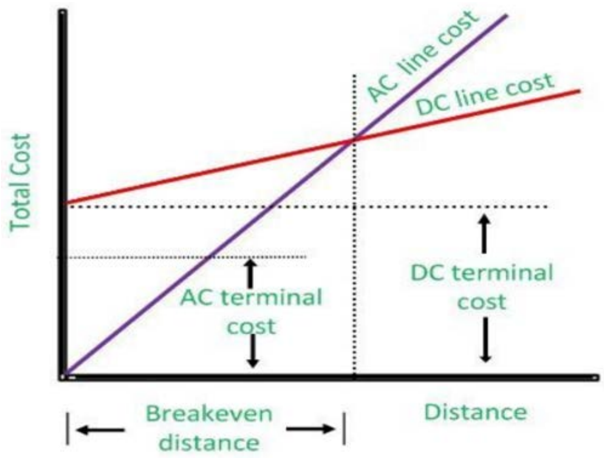

Figure 4.15: Comparison between the cost of an AC and DC transmission line including the terminal. [106]

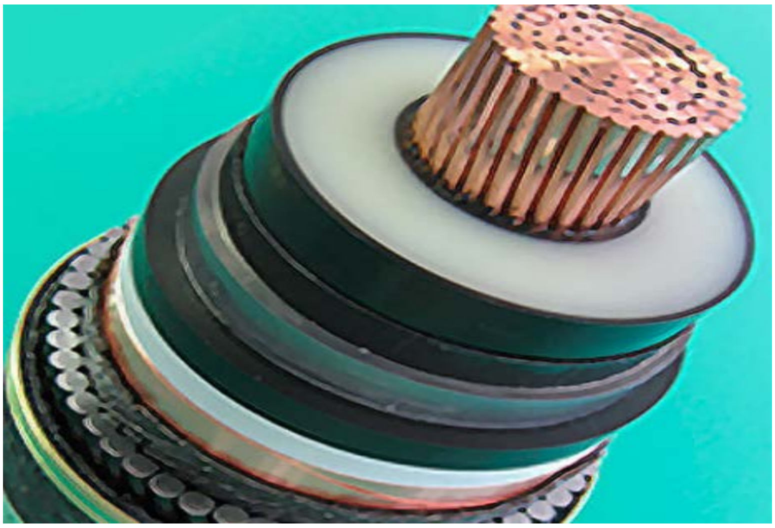

Figure 4.16: A DC transmission cable [108]

4.8. Power distribution systems

Distribution systems accommodate PV and energy storage systems much more efficiently since both supply DC power. Furthermore, sometimes distribution system sections need to be interconnected. Reasons for this may include:

- Avoidance of congestion of distribution lines
- Easier control of real and reactive power flows
- Ensuring voltage stability

Such interconnections are not always feasible by directly connecting the sections of interest because the frequencies or phases of the two sections may differ. Also, problems like distortion and harmonics only present in one section may negatively affect the other. It is even possible that protective measures that successfully secure the operating conditions of both power systems individually may fail once they are connected.

Medium voltage DC current can provide a solution to easily interconnect distribution system sections. This solution allows power to be shared between the sections, while blocking disturbances present in one section to be propagated to the other.

Indicatively, the authors in [109] analysed the ANGLE DC project, whose goal is the replacement of two AC distribution grids with medium voltage DC grids so as to avoid changing the already existing cables. The project achieved better power flow control and more effective power distribution along with its main innovation of retaining the old cables. In [110] a medium voltage distribution grid architecture is presentd, anticipating that higher voltages will be used in DC grids in the future. Such a development allows DC distribution systems to be connected to the AC main grid without the use of expensive transformers. For instance, a 10 KV medium voltage power distribution system is in operation since 2018 in Zhuhai, China [111]. The system does not use transformers, is efficient and combines power from the main grid with both storage systems and renewable energy sources as shown in Figure 4.17.

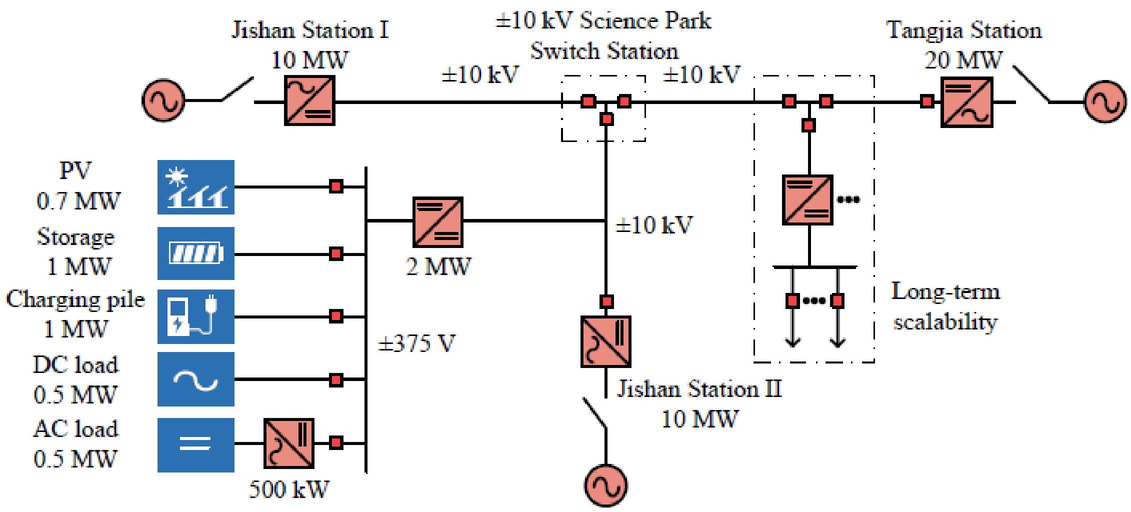

Figure 4.17: The distribution power system of Zhuhai, China [111]

4.9. Electric vehicles

Sales of electric vehicles are increasing day by day around the world due to the need to protect the environment from emissions of fossil fuels. This has caused car manufacturers to focus on producing electric vehicles, which in the near future will completely replace traditional fossil fuel powered vehicles.

Electric vehicles need charging at regular intervals to operate and their batteries are inherently DC powered. Powering batteries from an AC power system would require both a transformer, which is expensive and takes up a large volume not available in most areas and an AC/DC converter. Additionally, distortion and harmonic losses also affect efficiency when AC grids are involved. Even the speed and safety of charging the vehicle is affected by the type of the main grid. Drawing power from an AC grid, a 130 km battery can take more than 3 hours to charge. This time could be significantly shortened due to the higher current capacity of the plugs from low voltage DC chargers [112]. The University of South Florida has constructed a low voltage DC microgrid consisting of solar panels that feed power to a vehicle charger. Results showed that low voltage DC-DC charging was more efficient, reliable and safe than the AC-DC alternative [113].

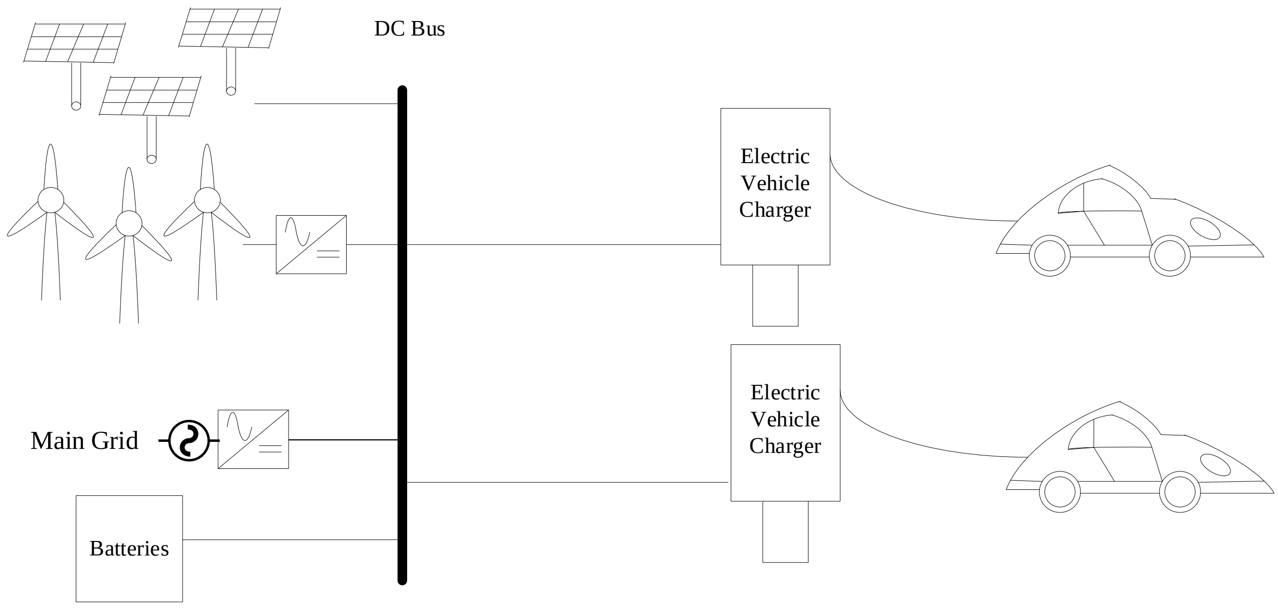

Figure 4.18: Powering electric vehicles through a plethora of power sources using DC current

4.10. Industrial applications

Medium voltage DC microgrids have applications in some industries, because their processes require DC power to operate [86]. Such industries include those that process steel or chemicals. The presence of DC disconnectors can ensure the safety of these processes for workers and equipment alike. In industry the economical advantages of DC installations are more pronounced as the DC microgrid has fewer losses allowing the industries that adopt it to gain an edge over their competitors. On the front of reliability, if a company invests in solar panels and batteries the ability to be more independent from power supplying corporations cannot be neglected. The company can operate on its own and consume its produced power unaffected by both faults in the public power system and fluctuating electricity prices.

DC microgrids can also be installed in power plants as shown in [114] where a measurement system was installed in a low voltage industrial microgrid containing robotic devices and proved the efficacy of the DC grid concept.

5. Grid services

Modern power grids need enhanced and flexible ways of controlling the flow of electricity within their networks, because it is a challenge to increase transmission capacity and flexibility with conventional AC expansion options, especially in meshed and heavily loaded networks.

The demand for reliable supplies of electricity is growing, increasing the need for more intelligent, high-level system control of power networks. Network congestion is increasing in many regions around the globe. Furthermore, the coupling of previously separated electricity markets and growing commercial interconnections require precise, controllable power flows in order to operate effectively.

In power transmission investments, features such as power quality improvement, stability enhancement, frequency and voltage regulation, emergency power support, bottleneck mitigation and controllability of power flow are often considered useful options, but otherwise are not usually given sufficient attention in the investment assessment unless they are deemed absolutely essential from a purely technical point of view.

Today, however, such features are becoming more and more important for network operators, especially with the integration of renewable energy, which has different characteristics compared to a traditional fossil fuel based energy matrix. These need to be addressed when considering the various alternatives of a power transmission investment.

The implementation of DC infrastructures in the architecture of existing AC grids, provides many benefits. Apart from the evident advantages of turning a traditional grid into a hybrid AC/DC grid, comes a number of possible functions that may improve the operation of the grid both in steady and transient state. These functions can be promoted to the grid operator as ancillary services.

Ancillary services are considered to be the specialty services and functions provided by the electric grid that facilitate and support the continuous flow of electricity so that the power supply does in all cases meet the demand. These services include a variety of operations that are required to maintain grid stability and security. Traditionally ancillary services have been provided by generators, however, the integration of intermittent generation and the development of smart grid technologies have prompted a shift in the equipment that can be used to provide ancillary services. In the literature, no single, general, definition for ancillary services is provided. That is because in every regulated zone, ancillary services can be defined independently, together with their own market rules. A collection of the most common ancillary services actually found in the literature are shown in Table 5.1. Almost none of the definitions by companies or organizations in Table 5.1 are identical to another but in the end, they have the same or similar meaning.

Table 5.1: Definition of ancillary services by various sources

Ancillary services: an overview [115]	▪ frequency and power regulation ▪ voltage control ▪ system restoration ▪ energy imbalance ▪ loss compensation ▪ miscellaneous
Eurelectric ancillary services [116]	▪ frequency control ▪ voltage control ▪ spinning reserve ▪ standing reserve ▪ black-start capability

	▪ remote automatic generation control ▪ loss compensation ▪ emergency control action
Elia [117]	▪ primary reserve ▪ secondary reserve ▪ tertiary reserve ▪ voltage control ▪ black start
Swissgrid [118]	▪ active power control ▪ voltage support ▪ loss compensation ▪ black-start capability ▪ system coordination ▪ operational measurement
Oak ridge national laboratory [119]	▪ scheduling and dispatch ▪ load following ▪ operating reserve ▪ energy imbalance ▪ real-power-loss replacement ▪ voltage control ▪ other services
[120]	▪ frequency control ▪ supplemental reserves ▪ spinning reserves ▪ backup reserves ▪ load following ▪ reactive power ▪ black start
[121]	▪ primary frequency control ▪ secondary control – regulation ▪ secondary control – reserves spinning ▪ secondary control – reserves non-spinning ▪ tertiary network control – replacement reserves ▪ voltage control service ▪ black-start service

5.1. Ancillary services overview

An increasing number of HVDC transmission systems embedded in the AC grid will result in a more controllable and precise power exchange. HVDC links may be used to control power flow in the AC network, thus optimizing and increasing the transmission capacity through the existing lines and at the same time reducing the overall losses. Reducing bottlenecks in heavily loaded AC networks is one of the effects achieved by installing a DC link inside an AC grid. HVDC Voltage Source Converter (VSC) technology can be used as a traditional HVDC link carrying power from one point to another. Because of its capability to inject reactive power into the adjacent AC network, it not only increases transmission power due to its own power ratings, it also increases the power transmission capability in the adjacent AC network. Examples exist where the total transmission capacity increases by 150% with the introduction of a VSC link at 100% transmission capacity.

An HVDC link inside an AC network can be used to strengthen a weak point in the power system. At the same time it increases power transmission capacity and gives the operator increased controllability and flexibility over the network and power flow.

Most common functions provided by these services and found in all references can be generalized as follows [17].

- ***HVDC as a firewall in the AC grid***

An HVDC system can be placed between AC grids as a "firewall" to prevent disturbances spreading from one AC grid to another. The HVDC system can be set up such that loop flows are avoided and market power exchange can be fulfilled. If a power imbalance occurs on the AC side, HVDC control can mitigate the imbalance and borrow spinning reserve from the neighboring AC systems in a controlled manner.

- ***Artificial inertia***

In very weak AC systems, frequency variations may be a problem due to the low ratio of rotating mass (inertia) related to synchronous machines. An HVDC link in such an AC system can be controlled to provide additional inertia in order to strengthen the local stability.

- ***Frequency stability***

An imbalance between the produced and consumed power will show up as a frequency deviation. Many HVDC systems can mitigate the frequency deviation if one of the converters is connected to a separate AC grid. Assuming that the separate AC grid has spinning reserve available, the stressed grid can be automatically supported through this reserve to restore frequency stability.

- ***Link grids of different frequency***

Grids with different frequency may be connected through an HVDC link. HVDC systems offer the desired frequency set points and thus connection of asynchronous grids is possible.

- ***Power oscillation dumping***

A stressed AC system is prone to electromechanical oscillations of the rotors in the synchronous machines. This is an unwanted situation since it wears down the governor systems of the turbines and indicates an operating working point close to the stability limit related to maximum power transfer. By modulating a control signal to the HVDC system, oscillations can be damped and a safe power transfer limit can be maintained in the AC system.

- ***Black start***

In some AC grids, black-start functionality is very valuable. The restoration process (black start) of an AC system following a contingency related to loss of crucial AC lines, islanding or blackout has some critical requirements, which, in certain cases, can be fulfilled with an HVDC link.

Voltage Source Converter (VSC) transmission technology is particularly suitable. The VSC link can follow the cold load pickup and the pickup of the power production with its smooth control of both active and reactive power. As the AC grid is rather weak and often has reduced short-circuit power during a black start, high requirements are implemented on reactive power control to maintain voltages.

- ***Maintaining synchronization***

To maintain synchronization, the HVDC system will support the AC system in several ways. For example, during a fault, the VSC technology will start to back up the AC system. When the fault is cleared, the reactive power output from the HVDC system will support the power transfer in the AC grid. This will reduce the risk of falling out of step and losing synchronization. Special schemes can be set up in the HVDC system to help quickly restore a viable power flow after a fault.

It is also possible to control the HVDC system in such a way that inadvertent power flow changes in the AC grid are automatically compensated for so that a safe power transfer can be maintained in the AC system. Alternatively, the active power control can alternatively be set up such that it resembles the phase-angle dependency of an AC line (possibly with reactive power support at each end).

- ***Merchant links***

The coupling of electricity markets and growing commercial interconnections requires precise, controllable power flows in order to operate effectively in line with the market-derived schedules. Power scheduling on an hour or minute basis is a common situation. The controllability of active power flow in the HVDC system guides the power flow in the AC system to fulfill prearranged commercial deals.

Table 5.2 summarizes the effect of the abovementioned function capabilities in embedded HVDC grids and separated grids.

Table 5.2: Summary of capabilities. Level of support possible from an embedded HVDC system during disturbances [17]

	Embedded HVDC grid		**Separated AC grids**	
	VSC	Classic	VSC	Classic
Operate as a firewall during contingencies	+	0	+++	++
Maintain frequency stability	N/A	N/A	+++	+++
Artificial inertia	N/A	N/A	+++	+
Maintain synchronism	++	+	+	+
Improve voltage stability	+++	+	++	+
Improve power oscillation damping	++	+	++	+
Merchant links	++	++	+++	+++
Black start	+	0	+++	0

In general, a HVDC system can alleviate power imbalances in an AC system and give operators full control over the power flow. With the introduction of VSC technology, HVDC is also able to operate as a FACTS device. The HVDC system can consist of a back-to-back converter, a point-to-point connection, a multi-terminal connection, or a meshed HVDC grid with parallel paths enhancing the availability of the HVDC system.

5.2. Ancillary Services details

Ancillary services are provided by the TSO or procured from other stakeholders, for carrying out the power transmission from generating units to the load centers while meeting power quality standards

[122][123]. The ancillary services are used to provide the stakeholders with the following capabilities [124]:

1. *Loss compensation*
2. *Frequency Control*
3. *Black start capability*
4. *Voltage or reactive power Control*
5. *Oscillation damping*
6. *Congestion management*

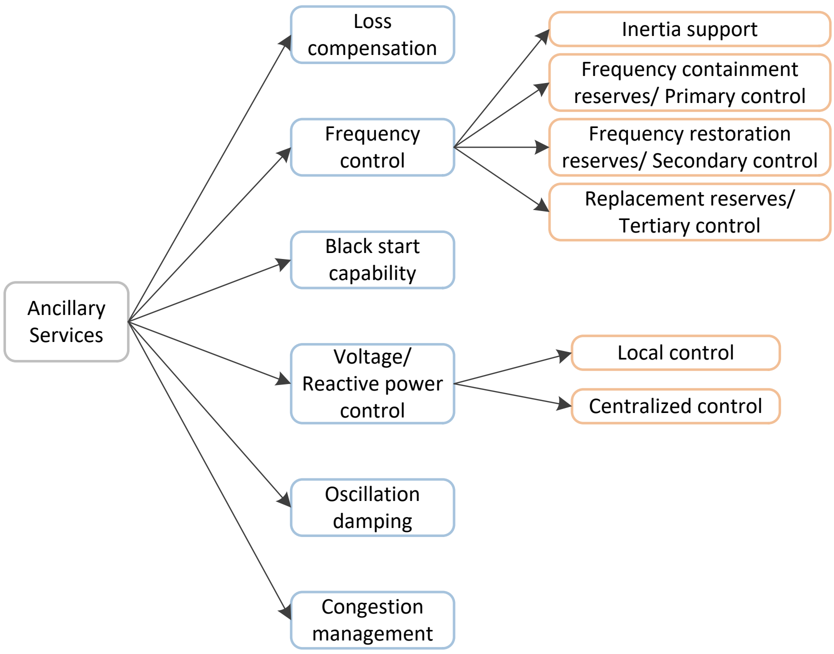

Figure 5.1: Ancillary services classification

The details of these services are discussed below:

5.2.1. Loss Compensation

The TSO must compensate for all the losses incurred in the process of power transmission from generation units to load centers. These losses correspond to transmission line losses and losses in various other equipment. The TSO must procure energy to make up for these losses. If the generation plant for this energy is not located in the TSO control area, the TSO must take into account the losses for the power transmission also in other zones [125].

5.2.2. Frequency Control

In conventional AC power systems, the system frequency is a universal characteristic for the synchronous system i.e., it remains same at every measurement point in the system. For reliable and secure power system operation, it is desirable that the frequency of the system shall remain constant at nominal system frequency value (50 Hz for ENTSO-E area). Any deviation in frequency can be attributed to a mismatch in power generation and power consumption (load). A set of parameters have been defined for the assessment of reliability and quality of frequency for ENSTO-

E area by the European Union Commission regulations guideline on electricity transmission system operation [126]. These parameters are defined as follows:

- **Time to recover frequency**: The maximum expected time (for the synchronous area of Continental Europe (CE), Great Britain (GB) and Ireland & Northern Ireland (IE/NI)) after the occurrence of an imbalance (smaller than or equal to the reference incident) in which the system frequency returns to the maximum steady-state frequency deviation. This time varies depending upon the time constants of equipment participating in the frequency control.

- **Frequency recovery range**: The range for the system frequency within which the system frequency is expected to be restored within the time of recover frequency in the event of an imbalance (equal to or smaller than the reference incident) in the synchronous area of CE, GB and IE/NI.

- **Frequency restoration range**: The system frequency range (for GB, IE/NI and Nordic synchronous areas) to which the system frequency is expected to return within the time to restore frequency, after the occurrence of an imbalance (equal to or smaller than the reference incident).

- **Standard frequency range**: Defined symmetrical interval around the nominal frequency within which the system frequency of a synchronous area is supposed to be operated.

- **Standard frequency deviation**: Absolute value of the frequency deviation limiting the standard frequency range.

- **Steady-state frequency deviation**: Absolute value of frequency deviation once the system frequency has stabilized after occurrence of an imbalance.

The frequency ranges (recovery, standard, steady state, and frequency deviation) vary from system to system depending upon the size of the system, typical generation mix, and the time required for activation of reserves. For a smaller islandic system such as GB or IE/NI, these frequency ranges are larger as compared to the larger CE power system. This is due to the fact that deviation in frequency has direct relation with deviation in active power and same power imbalance will result in large frequency deviation for the smaller systems as compared to the same for larger CE system [127] i.e.,$(\Delta P/\sum P_{large}) < (\Delta P/\sum P_{small})$. The range for these parameters as defined in the grid code for CE, GB, IE/NI and Nordic power system [OJEU] is shown in Table 5.3.

Table 5.3: Frequency quality parameters [126].

	CE	GB	IE/NI	Nordic System
Standard frequency range (mHz)	±50	±200	±200	±100
Maximum instantaneous deviation (mHz)	800	800	1000	1000
Maximum steady-state deviation (mHz)	200	500	500	500

Frequency control is a set of control actions aimed at maintaining the system frequency at its nominal value. Frequency control is implemented in different stages; the commonly defined services for frequency control in ENTSO-E area are categorized as follows:

- **Inertia Support:** Inertia support is the autonomous response of power system components to frequency deviations. When provided by synchronous machines, it represents the kinetic energy in rotating parts of the synchronous generators which is released on occurrence of system imbalance events [128]. Whenever there is any deviation in the frequency (from predefined nominal frequency value), the generators vary the power generation accordingly and makeup for the small deviations in frequency. For frequency decrease below the nominal frequency value, the power generation is increased by the synchronous generators which in turn brings the frequency back to its nominal value and the reverse happens in case of an increase in frequency [129]. The inertial response is the fastest response for any deviation in frequency (it starts as soon as any deviation in the system frequency is observed). Inertia of power system is an important parameter for frequency stability, and it influences the initial rate of change of frequency after a system imbalance. If a system has higher inertia the frequency deviation will be slower and hence TSO will have margin for activation of reserves [130].

- **Frequency Containment Reserve or Primary Control:** Active power reserves available to contain the deviation in the frequency whenever there is mismatch between load and generation (system imbalance) are termed as ‘frequency containment reserves’ or ‘FCR’ [126]. The FCR are activated within a few seconds of imbalance and remains active for a limited period of time. The active power injection set points of the generators remains unchanged during this time [131].

- **Frequency Restoration Reserve or Secondary Control:** ‘Frequency restoration reserves’ or ‘FRR’ are active power reserves which are available to recover the frequency back to nominal frequency value after any disturbance. FRR are also used for fine regulation of frequency. FRR reestablish the power balance to scheduled value for a control area with more than one Load frequency control (LFC) areas [126]. FRR brings the area control error (ACR) to zero by restoring the power exchanges between different zones to original values. The active power set points of various generators in the control area with imbalance are changed so that the committed FCR are again available [131]. FRR can be activated automatically and manually [132]

- **Replacement Reserve or Tertiary Control:** ‘Replacement reserves’ or ‘RR’ are the active power reserves available to restore and support the required level of FRR and to be prepared for further system imbalances, including generation reserves [126]. RR are activated manually as a result of system optimization by the system operator [131].

5.2.3. Black Start Capability

The ability of a power system to perform black start operation is known as ‘Black Start Capability’ [133]. Black start operation is the process of reviving a power system or a part of power system back to the operational mode from a partial or full shutdown (independent of another power system). Blackouts (situation of total or partial power loss in power system due to unexpected transmission system or generation failure) are the least desired scenarios for power systems and result in social and economic loss [134]. Restoration of power system after a blackout comprises a set of coordinated actions of many power system components and is very complex given the numerous generators, loads and transmission system constraints [135]. In present power systems, it is necessary to recognize the generating units capable of starting without external support and provide power locally. Because of electricity market de-regularization, black start service is treated as a separate ancillary service and is procured by the TSOs from the energy market [136]. As per the regulations, a TSO must identify the generators with black start capabilities in its control area and use these capabilities in a manner to minimize the system restoration time.

5.2.4. Voltage or Reactive Power Control

'Voltage or reactive power control' is a set of measures or control actions intended to maintain a constant voltage level or reactive power value at each node of the system [126]. These control actions are carried out at different nodes (generation nodes or transformers or AC transmission line ends or HVDC systems or other means) of the power systems. Contrary to frequency, which is a system wide variable, voltage is a local quantity varying for every node of the system. The voltage varies depending upon the system topology, generator, or load location and type of loads. Frequency in the power system is affected by active power balance while voltage is affected in the similar manner by the reactive power balance. Voltage control is implemented by controlling the injection of reactive power in the power system and for this purpose automatic voltage regulators, static VAR compensators, capacitor banks, and reactors are deployed. As it is difficult to transmit reactive power, it is important to control the voltage locally. In view of this limitation, it is very crucial that voltage control equipment is located at critical locations.

Depending on the connection point voltage, the operational voltage limits for steady-state power system operation have been defined for the ENTSO-E control area by the European Union Commission's regulation on electricity transmission system operation [126]. These limits are given in Table 5.4.

Table 5.4: Steady-state operational voltage range [126].

	CE	Nordic	GB	IE&NI	Baltic
	Connection point voltage 110kV-300kV				
Voltage range (pu)	0.9–1.118	0.9–1.05	0.9–1.10	0.9–1.118	0.9–1.118
	Connection point voltage 300 kV–400 kV				
Voltage range (pu)	0.9–1.05	0.9–1.05	0.9–1.05	0.9–1.05	0.9–1.097

Ensuring adequate volume and time response of remedial actions to keep voltage within the limits in its control area is one of the tasks of TSO [126]. Thus, a TSO must ensure that sufficient reactive power regulating capacity is available, and this capacity can be activated when needed. The regulating actions to control voltage level can be tap change of power transformer or switching of capacitors/reactors or control of HVDC systems or change in reactive power output of generators etc. The voltage or reactive control service can be split into two hierarchical levels i.e., local and centralized control.

- **Local Control:** An automatic control in which the participating devices adjust their reactive power to maintain a constant voltage value at a local measurement point. The local voltage control service is activated within a few seconds to voltage profile [137].
- **Centralized control:** 'Centralized voltage control' is a national/utility level manual voltage control that is activated on the request of the TSO by the control service provider. This control is aimed at optimizing the set points of pilot nodes based on centralized power flow studies. Centralized control manages the reactive power in the system so as to minimize system losses, increase dispatch control efficiency, reactive power resources co-ordination in real time in normal grid operation and recover the voltage level deviation [138].

In some countries for example France, voltage control is implemented in three hierarchical levels i.e., primary, secondary, and tertiary control. Primary control is activated locally and is activated automatically. Secondary control is an automatic control and controls the voltage at main transmission buses. Tertiary control is activated manually at utility level after power flow analysis to free reactive power reserves.

5.2.5. Oscillation Damping

In power system operation, it is desired that the frequency and voltage values shall remain within the stable operation range during or after internal (excitation loss, generator instability etc.) or external disturbances (transmission line fault, loss of generation or load etc.) [138]. As a consequence of these disturbances, low frequency oscillations occur in the power system. These oscillations can be local (to a single plant or generator or a region) or inter-area (geographically spread and involving several remote generators) [140]. Local oscillations (0.7–2 Hz) [141] occur due to presence of fast exciters in the power system whereas inter-area oscillations (0.1–0.7 Hz) [141] are a result of over loading of weak transmission links [142]. If not damped properly, these oscillations may cause partial or total power system blackouts. Automatic voltage regulators equipped with a power system stabilizer (PSS) [143] and flexible AC transmission system (FACTS) devices [140] such as static VAR compensator (SVC) and static synchronous compensator (STATCOM) are employed in the power system for damping these oscillations.

5.2.6. Congestion Management

Congestion in the power system is a situation in which the transmission system is not able to fulfill all the desired transactions due to power system's physical and operational limitations [144]. These physical and operational limitations can be thermal limits of transmission lines and transformers, voltage limitations, and transient or other stability limits [145].

In grid codes for capacity allocation and congestion management (CACM) [146], three types of congestion i.e., market, physical, and structural congestion have been defined. A situation when cross-zonal capacity or allocation constraints, limits the economic surplus for single day-ahead or intraday coupling is termed as 'Market congestion'. When the thermal limits of grid elements and voltage or angle stability limits of power system are breached during forecasted or realized power flows, it is defined as 'Physical congestion'. 'Structural congestion' has been defined as transmission system congestion that is predictable, geographically stable over time, and occurs frequently under normal power system conditions. In electricity markets power system congestion leads to price split between various regions. One such case was observed on 3rd October 2018 when the price difference for day-ahead wholesale price between Germany and Belgium was 105–152€ per MWh. This price difference was due to physical congestion between Belgium and Germany.

Congestion management is the process of making use of available power system infrastructure (economical and operational) while operating within system constraints [147]. Congestion management gives long-term investment signals to the TSO for strengthening local (to a single TSO) or cross-zonal (shared with other TSOs) transmission system infrastructure. A TSO responsible for a given control area or multiple TSOs responsible for the concerned control area must compensate the cost for remedial actions for congestion management [126]. A number of methods have been proposed for congestion management in [145]-[149]; these can be broadly categorized into two methods i.e., technical and non-technical methods. Technical methods of congestion management can be cost free and not cost free [150]. Use of FACTS devices, phase-shifters, and transformer tap change for congestion management comes under cost free congestion management methods. These methods are readily available with the TSO, have limited economic impact and do not involve other stakeholders such as generation or distribution companies. Load shedding and rescheduling of generating units for the purpose of congestion management comes under not cost-free methods. Technical methods are ordered by the TSO. Non-technical congestion management methods can be market-based (auctioning, counter trading, nodal, or zonal pricing etc.) and non-market-based (pro rata or first come first serve). There is no involvement of TSOs in non-technical congestion management methods and these are just observed by the TSO. Classification of various congestion management methods has been illustrated Figure 5.2.

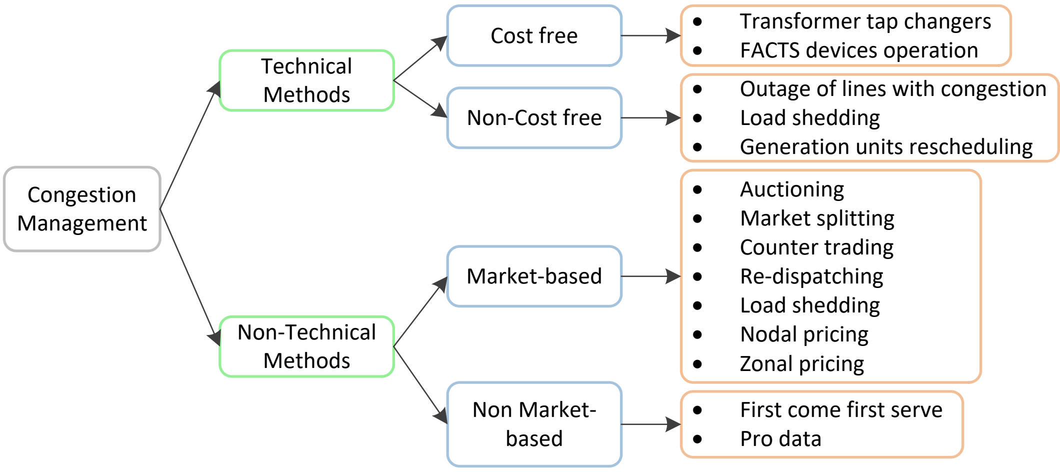

Figure 5.2: Congestion management classification [151].

A classification of the ancillary services depending on the service origin is given in [125]. As service origin is considered the equipment that provides the respective service. It shows that there are four possible origins in a transmission system with AC and DC grids as shown in Figure 5.3, namely:

- Ancillary services from AC equipment for AC grids
- Ancillary services from DC equipment for AC grids
- Ancillary services from AC equipment for DC grids
- Ancillary services from DC equipment for DC grids

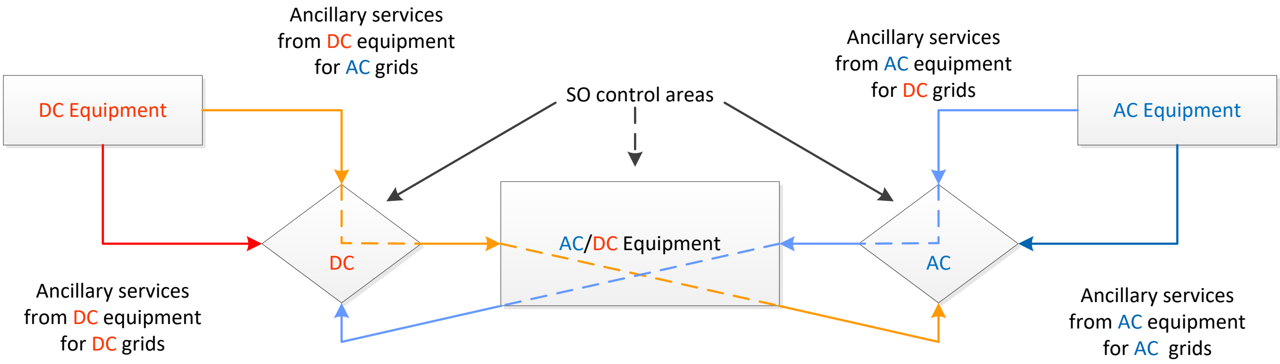

Figure 5.3: Origin of ancillary services

Each of the four categories inherits services described in the previous sections according to Figure 5.4

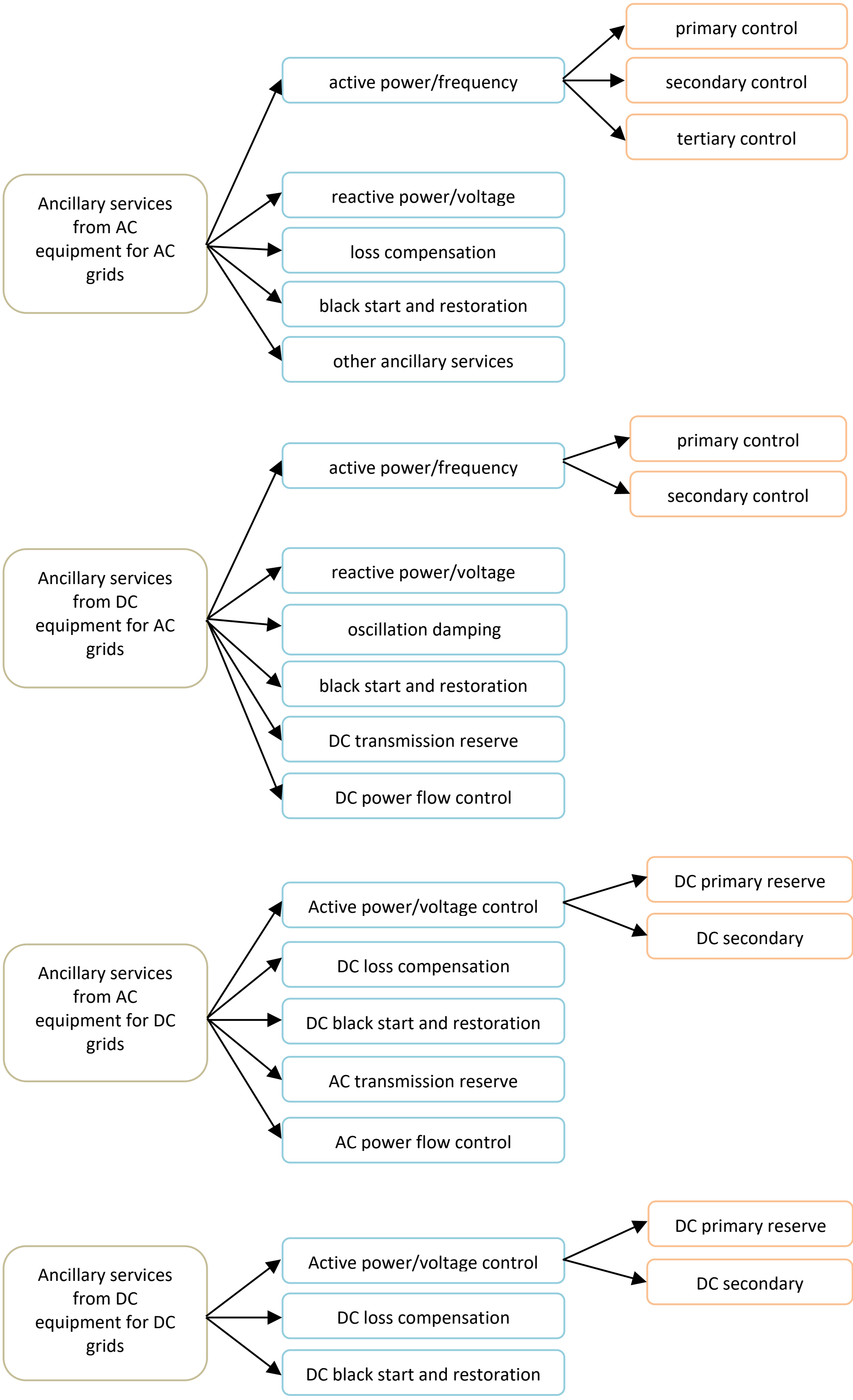

Figure 5.4: Classification of equipment providing ancillary services

5.3. ENTSO-e Specifications for HVDC

On 29 April 2013 ENTSO-E received a mandate letter from the EC to develop a network code on HVDC connection rules, within ACER’s framework guidelines on electricity grid connections. This code will be covered by ENTSO-E in a Network Code on ‘HVDC Connections and DC Connected Power Park Modules’ (NC HVDC).

5.3.1. Network Connection HVDC GENERAL PRINCIPLES

Besides HVAC transmission, HVDC technology is used as well for the connection between synchronous and asynchronous zones, within synchronous zones or for the connection to Power Park Modules (PPMs) as seen in Figure 5.5.

HVDC technology can enable interconnections between different TSOs, asynchronous zones or synchronous zones where AC technology is either not practical and/or is less beneficial in terms of cost, environment, or technical performance. It will bring new market and control options, allowing the development of cross border exchanges of energy and ancillary services and will lead to a better RES integration with the consequent increase in consumer benefits.

However, these technologies always need to interact with the HVAC systems. The HVDC systems are essential facilities and their compliance to code specifications is of great importance in order to ensure reliable operation of HVDC connections between synchronous zones, helping to maintain system security.

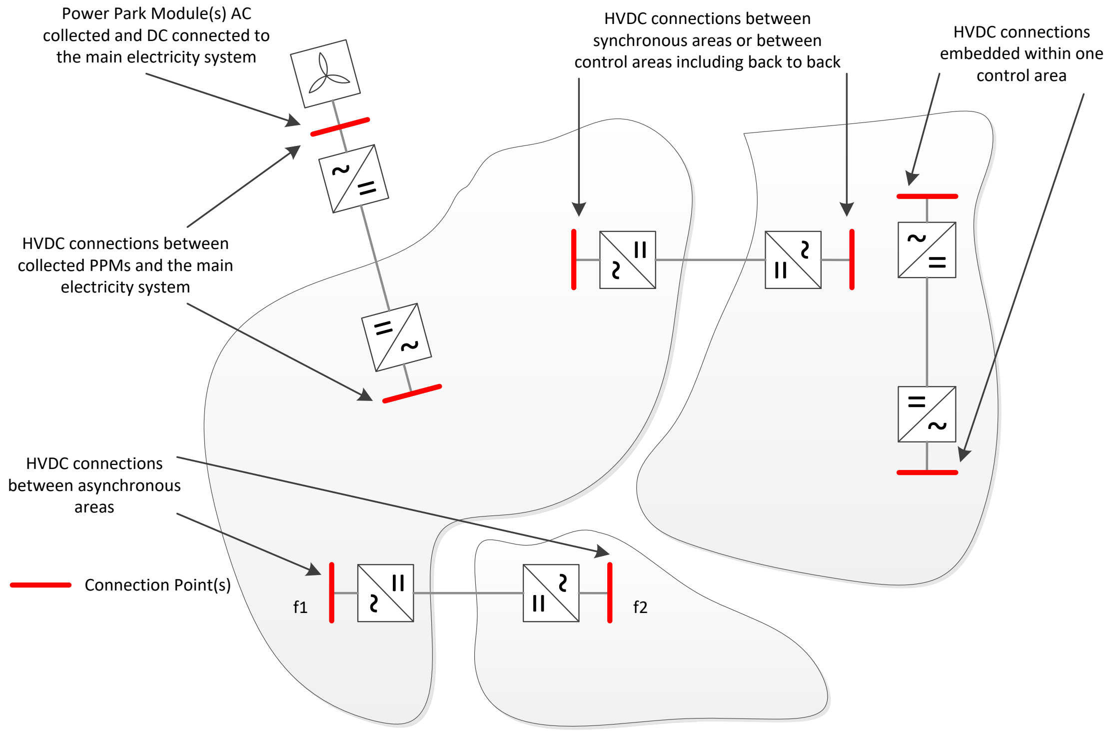

Figure 5.5: Implementation of HVDC technology

5.3.2. Network Code for HVDC GENERAL REQUIREMENTS

The requirements utilize the inherent capabilities of HVDC systems and DC connected PPMs to ensure or improve power system security and enhance market integration and renewable energy penetration.

For ensuring or improving power system security, HVDC systems and DC connected PPMs need to support frequency and voltage stability, robustness of transmission ways, system recovery after a black-out and harmonized protection.

In order to enhance market integration, they need to be capable of exchanging balancing and control energy. To that end, adequate power controllability is required, including frequency sensitivity and frequency control modes.

In order to enhance renewable energy sources penetration, they need to contribute to strengthen network operation conditions, in particular when conventional generation is far from the HVDC converter connection point or out of operation for economic reasons. Requirements such as synthetic inertia, priority to active or reactive contribution, post fault active power recovery enable HVDC converters to provide to the transmission system frequency and voltage stability.

Requirements for HVDC systems and DC connected PPMs have been distinguished in six categories/requirements:

- Active power control and frequency support
- Reactive power control and voltage support
- Fault-ride-through
- Control stability
- Protection devices and setting
- Power system restoration

This requirement classification is not exclusive. Some requirements related to fault-ride-through such as fault-ride-through capability, post-fault active recovery or auto-reclosure also contribute to frequency and voltage stability by maintaining or restoring rapidly pre-fault conditions for generation and load. These requirements shall apply when operating in either direction.

a) Requirements for Active Power Control and Frequency Support

The requirements for active power control and frequency support include:

- **Frequency ranges**: the HVDC converters shall be capable of staying connected to the AC network and operating normally when frequency changes in accordance with normal and contingency operation of the network.
- **Rate of change of frequency withstand capability:** the HVDC converters shall be capable of staying connected to the AC network and operating when frequency is varying within the rate of change defined by the TSO.
- **Active power controllability; control range and ramp rates**: the HVDC converters shall be capable of transmitting active power in both directions by manual and automatic control in accordance with the TSO’s operating and planning criteria.
- **Synthetic inertia capability:** the HVDC connection scheme shall be capable of providing synthetic inertia as a quantified response to frequency changes, activated both in low and high

frequency regimes by rapidly adjusting the active power injected to or withdrawn from the AC network.

- **Frequency sensitive mode**: is a mode in which HVDC converters shall be capable of responding to frequency deviations by adjusting the active power transmitted in a direction that assists in the recovery of target frequency.
- **Limited frequency sensitive mode (overfrequency)**: the HVDC converters shall be capable of operating in this mode that reduces active power output in response to a change in system frequency above a certain value.
- **Limited frequency sensitive mode (underfrequency)**: the HVDC converters shall be capable of operating in this mode that increases active power output in response to a change in system frequency below a certain value.
- **Frequency control:** is an HVDC operating mode that will be able to control the frequency by adjusting the active power output within normal operation.
- **Maximum loss of active power:** to maintain system stability, the maximum allowable loss of active power provided by an HVDC system to the wider system shall be specified at the connection point(s) by the TSO(s). This will ensure that loss of (an) HVDC system(s) at the connection point(s) does not lead to wide scale system instability.

b) Requirements for Reactive Power Control and Voltage Support

The requirements for reactive power control and voltage support include:

- **Voltage ranges:** A HVDC converter needs to be capable of staying connected to the AC network and operating within steady state and temporary operating voltage ranges for network security reasons, as defined by the TSO. The intention of this requirement is to specify voltage ranges in order to coordinate the performance of the overall system.
- **Short circuit contribution during faults**: An essential factor for the network performance, it ensures adequate system security and its contribution shall be settable according to the system needs.
- **Reactive power capability:** For HVDC converter stations, it is an essential requirement for safe operating conditions of the overall system. The intention of this requirement is to specify the reactive power capability as a function of the transferred active power and the AC operating voltage.
- **Reactive power exchange**: Uncontrollable exchange of reactive power between the HVDC converter station and the AC network may cause adverse operating conditions in the system. The intention of this requirement is that the HVDC connection installer will consider and design its installation to limit unexpected reactive exchanges to acceptable values.
- **Reactive power control mode**: The control of the reactive power of an HVDC converter station is of utmost importance for the steady state as well as the transient performance of the overall system. The intention of this requirement is to specify the control and utilization of the reactive capability (as specified in iii). The specification may address:
  - Control mode (e.g. voltage or reactive power control)
  - Maximum reactive power exchange with the network as a function of transmitted power
  - Control resolution
  - Control response, e.g. in steady state a slow control and a fast response to transients without exciting post-fault oscillations by providing maximum reactive power capability independently of the previous control state.
- **Priority to active or reactive power contribution**: The control of this balance can be of vital importance for the network security and voltage stability. The intention of this requirement is to ensure adequate balanced support from the HVDC converter station during AC network contingencies.

- **Power quality**: HVDC converters shall not introduce harmonics that would breach power quality rules compliance.

c) Fault-Ride-Through

"Fault-ride-through" denotes the ability of a HVDC converter to remain transiently stable and connected to the system for a close fault or voltage dip at the AC onshore and/or AC offshore connection point. This capability is needed for riding through faults located in AC onshore, AC offshore or DC systems. This capability is important to ensure that HVDC systems do not reduce the system integrity and performance of the transmission system, thereby affecting the secure and economic operation across borders.

The requirements related to fault-ride-through include:

- **Fault-ride-through capability**: The type of fault, fault duration, fault condition and voltage dip are dependent upon relevant TSO system security criteria. The capability to ride-through is to be determined by the relevant TSO who can specify system conditions that include minimum fault infeed at the connection point. In the event of an AC fault or opening of the main breaker on one side, the active power reduction seen on the remote end system should be determined by the TSO. In some cases, transient power reversal is not allowed. The reactive power capability of the interconnector on the 'healthy' side shall remain available according to performance defined by the TSO.
- **Post fault active power recovery**: The HVDC converter must be able to recover active power output following fault clearance for AC and DC faults or recovery from voltage dips. This ability shall help to restore frequency and voltage stability and shall reduce any consequential thermal overload. The speed and magnitude of recovery is to be determined by the relevant TSO.
- **Auto-reclosures**: Auto-reclosure of DC links post-fault improves the security of the transmission system by restoring system integrity quickly for transient faults. Where there is an overhead line connection, auto-reclosure capability shall apply.

d) Requirements for Control

The requirements for control include:

- **Converter synchronization to and disconnection from the AC or DC-network**: A control sequence shall be agreed between the relevant TSO and the converter operator for synchronizing the converters to and the disconnection from the AC or DC network.
- **Control interaction between converter stations**: The presence of other links in close proximity could lead to adverse interaction between converter controllers during transient or steady state. The intention of this requirement is to satisfy that undesirable interaction of the HVDC control system with a wind farm controller or between nearby HVDC controllers are avoided by proper and robust control design and control coordination.
- **Power oscillation damping capability**: An HVDC system may enhance power system damping and contribute to the overall system stability. The intention of this requirement is to specify the performance of HVDC system controllers with the purpose of damping electromechanical oscillations.
- **Sub-synchronous torsional interaction damping capability**: HVDC systems electrically close to power generating modules may contribute to instability in the sub-synchronous frequency range (5 – 50 Hz). The intention of this requirement is to ensure that no torsional modes of oscillation in the sub-synchronous frequency range on a mechanical shaft of nearby power generating module(s) are negatively damped or destabilized due to control interaction with the HVDC converter.

- **Short-circuit power**: The HVDC converter and associated link should operate within all operating characteristics at a minimum short-circuit power defined by the relevant TSO.
- **HVDC system robustness**: The converters within the HVDC system shall be capable of finding stable operation points after expected or unexpected changes in the configuration of the whole HVDC system. Changes in the system are (but are not limited to):
    - loss of communication
    - reconfiguration of the system
    - changes in load flow (scheduled or not)
    - changes in DC voltage (rise, fall)
    - trip of one converter
- **Control robustness in multi-terminal and in multi-terminal tapped HVDC systems**: A grid controller system has to be established, operated by the relevant TSO(s). The grid controller system shall include among others:
    - procedures to deal with scheduled power vs. real set points (losses or incompatible schedules)
    - data exchange with station controllers, dispatch center (communication in a non-discriminating way)
    - backup concepts for grid controller in terms of complete outage of controller;
    - The (N–1) criteria for a grid controller must be supported
    - basic control functions (e.g. load dispatch, voltage control)

e) Requirements for Protection Devices and Setting

The requirements for protection devices and settings include:

- **Re-connection**: The HVDC converter shall be able to reconnect after clearance of the transient fault or other disturbance causing the link to trip. The main goal is to again establish system integrity as fast as possible. Reconnection times shall be in line with the TSO's strategy. It is important to emphasize that the chosen protection strategy should be agreed in such a manner that there is minimum interruption of the HVDC system which will not jeopardize the system stability and that it can operate according to the agreed reconnection time.
- **Electrical protection schemes and settings**: This ensures that the HVDC systems are designed in a way that the protection devices are discriminative and stable to minimize malfunction operations.
- **Control schemes and settings**: The control schemes of the HVDC systems connected together have to be able to work together during operation. The control schemes and settings, both at AC and DC side, have to be compatible with other remaining requirements, because response times, tripping times, reconnection time etc. depend on the control settings.
- **Priority ranking of protection and control**: Because there are plenty of control and protection functions, a priority list has to be created by the TSOs operating a HVDC system. This requirement is necessary because the different control modes might interfere with each other and could lead to different control targets if not ranked with clear priorities. Hence, a clear list indicating what control modes are active and dominating together with the target values for the control protocols is essential. Moreover, all TSOs operating at the same HVDC system have to know all priority lists.
- **Changes to the protection schemes and settings**: Any changes to the protection schemes relevant for the HVDC converters and the network and to the setting relevant for the HVDC shall be agreed upon between the relevant TSO and the HVDC converter owner prior to the introduction of changes.

f) Requirements for Power System Restoration

The requirements for system recovery after a black-out include:

- **Black start**: The relevant TSOs decide if black start capability of a HVDC system is needed. Moreover, a procedure and a sequence for a black start of the system components have to be agreed upon, including those of HVDC systems.
- **Capability to take part in isolated network operation**: In the case where the HVDC system is connected to a weak grid, the HVDC system has to be designed to be able to take part in isolated network operations.

6. Future trends and challenges

Taking under consideration the possibilities of hybrid grids that have been reviewed in this report, it becomes apparent that they are an innovative approach that can have a great impact on future grids. Therefore, this Section reviews likely future trends, useful actions and challenges related to the evolution and market participation of hybrid grids.

6.1. Future trends in DC-AC/DC hybrid grids and useful actions

The modern needs of the worldwide market pave the way towards a more sustainable future including the integration of ecological solutions in both forthcoming and existing applications, the enhancement of efficiency and power quality as well as the cost reduction for the system operators and the end-users. Subsequently, as reviewed in the previous sections of this report, the utilization of DC technologies and the design of AC/DC hybrid power systems in all kinds of scales and applications may facilitate the fulfilment of the market's requirements. In fact, apart from HVDC structures, which constitute the beginning of DC incorporation in power systems, with a great number of applications throughout the past decades [17], many researchers support that the use and installation of DC technologies will increase, leading to the development of DC or AC/DC hybrid grids in the MV and LV levels in the near future in a variety of fields.

The DC power systems are expected to penetrate the market in applications related to a) high RES production, b) improvement of efficiency/cost minimization of distribution grids, c) connection of remote production or consumption as well as the enhancement of weak installations. More specifically, as analyzed in previous sections, theoretical as well as practical studies have been conducted in a variety of fields, acting as milestones for the wider adoption of DC-AC/DC hybrid grids in respective applications. In this way, as presented in Figure 6.1, it is forecasted that the market trend of power systems shall include further research and development in applications such as [47], [48], [152]:

a) renewable energy parks combined with storage systems

b) smart grids

c) high efficiency buildings

d) EV charging stations

e) data centers

f) ships

h) traction systems

i) connection of weak, remote or asynchronous installations

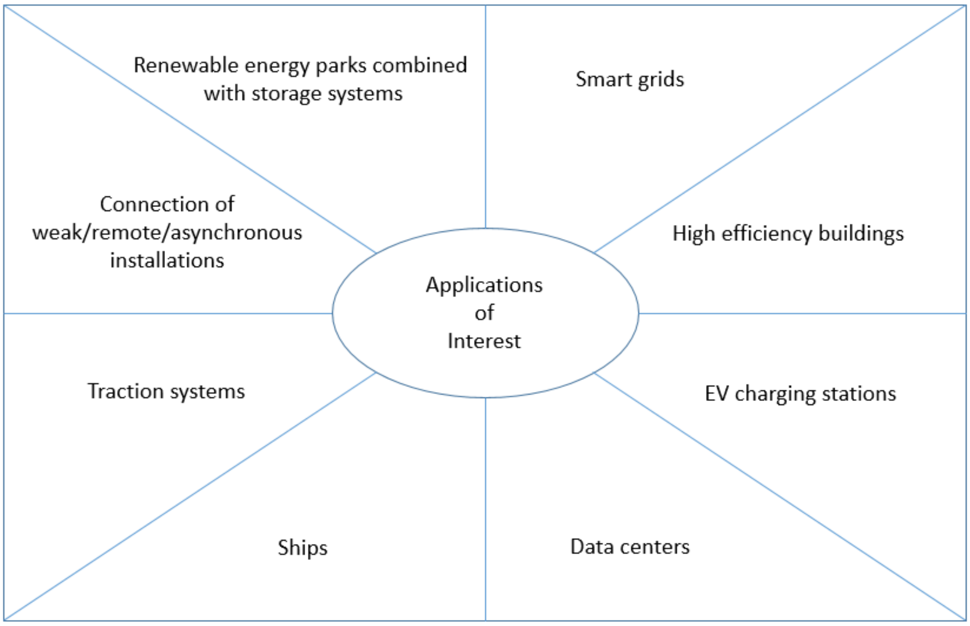

Figure 6.1: Market trend regarding DC-AC/DC hybrid grids.

Figure 6.2: Useful actions for the wider implementation of hybrid grids

Effort has been devoted the exploitation of the advantages of the combination of DC with AC systems. Yet, since the development of this sort of structures is at a relatively early stage, certain actions need to be taken prior to their wider implementation, as presented in Figure 6.2. In fact, as in with most cases of innovative ideas, such actions should include [1], [6]:

- **Increase of awareness:** It is possible that owners and operators of installations where AC/DC hybrid grids could be applied are not fully aware of the differences between AC and DC power or the benefits of switching from traditional AC to a combination of AC with DC. Indicative examples may be the designers/operators/owners of building complexes or even sole residences which aim to increase their autonomy by installing PV panels and BESSs and/or use EVs and other DC loads. Therefore, at this early stage of technology development proper dissemination is vital for future market success. Dissemination should initially target co-innovators and then the target market. Potential means for dissemination are:
  a) Participation in exhibitions and conferences (PV, battery storage, smart grids).
  b) Involvement of associations to reach a bigger audience (electrical installers, construction companies, suppliers, housing associations).
  c) Organization of workshops (with participants related to the DC innovation systems).

- **Investments on research and development:** Since the DC system components have not been researched as much as their AC counterparts, it is natural that they still have parameters, such as cost, that need to be further optimized. For this purpose, investments should be made in the sectors of research and development aiming at efficient and low-cost DC power components and systems. For example, according to [6], the field of power converters, i.e. the DC/DC converters, AC/DC converters and SSTs that are required in hybrid AC/DC grids, is a topic that requires further development. In fact, the following points should be addressed:
  a) Increase the efficiency and power density of these converters, with special focus on the devices with large voltage step, which is essential for the DC grid’s deployment.
  b) Reduce the cost of SSTs and relative converters.
  c) Investigate/develop new fault detection and avoidance/tolerance techniques.
  d) Ensure the same level of safety of equipment and people (workers, operators, etc.) as in respective current AC systems.
  e) Determine the most effective placement of converters in the hybrid grid topology.
  f) Develop or improve equipment for AC and DC grid interconnection.

  For example, in [15] innovative multiport DC/DC converters for MV and LV applications have been developed. The proposed device is considered to be effective in smart grid applications. Also, the authors in [153] propose an innovative DC/DC converter designed especially for shipboard MVDC system applications. Furthermore, another, less researched field of development is the DC conductors. For this purpose, the authors in [154] have developed a new technology of conductors which have already been implemented in a number of demo-sites, both in medium and high voltage.

Apart from the research and development regarding the optimization of the equipment utilized in hybrid grids, it is important to investigate different topologies and control systems for a variety of applications, in order to determine the optimal for each case.

- **Safety:** Regardless the optimization of already existing components, described above, the safety of hybrid grids is an issue of major importance that needs to be further researched. Safety and reliability issues include switches and protection schemes which are not as developed as their AC counterparts. Means to anticipate and overcome possible faults in the hybrid grid need to be thoroughly investigated before the large-scale deployment of such architectures.

- **Infrastructures:** There are cases where in order to efficiently convert a traditional AC grid into a hybrid grid there need to be certain infrastructures. An indicative example of such case is the building sector. For example, there are office buildings, complexes of commercial buildings or even residences which rely on RESs and ESSs power supply, hence the need for AC/DC hybrid grids, which provide a more efficient power distribution. In this sense, it is important to require the establishment of national and local building construction requirements that include DC power distribution in new homes and office buildings, as a way of achieving the ambitious energy efficiency targets in buildings.
- **Compatible equipment:** One of the main reasons why the DC power systems are researched and developed is the ascending amalgamation of DC devices in the total of loads that a distribution system feeds. Such devices include EVs, computers, power electronics, DC motors, etc. However, currently these devices are powered by AC sources and have incorporated converters that convert the AC input to DC power in order to be served. In hybrid grids this conversion is not required and reduces the efficiency of the grid. On the contrary, such DC loads are expected to be directly connected to DC lines. In order for these connections to be achieved, it highly important to establish mechanisms that promote and provide financial support to the cooperation between public and private entities, researchers and industry, allowing the development of DC-compatible equipment that is not yet available and suitable protection devices.
- **Experimentation and learning-by-doing:** When it comes to innovative architectures, for reasons related to safety, capital and expertise, it is not possible to proceed directly to large scale applications. Contrariwise, a certain hierarchy of steps needs to be followed, as presented in Figure 6.3. More specifically, sustainable innovation architectures usually start from the development of the required technological equipment. The technologically innovative components which are separately developed are later simulated combined with each other, forming a grid. The simulation tests provide the expected results prior to the actual implementation of the developed devices and are extremely important in terms of safety, energy management, efficiency, etc., giving feedback to the developers of the devices regarding their improvement. In the case of hybrid grids, the innovative technologies include the special converters, i.e. SSTs, AC/DC converters, DC/DC converters, the switches, the control systems, etc. Having developed the required technologies, the next step is the implementation of the proposed architectures, i.e. hybrid grids, in niche markets and demo-sites. These early adapters constitute small scale application fields or protected, controllable environments that can showcase the advantages of the proposed innovation but also provide valuable feedback in terms of flaws that need to be addressed. Market niches and demo-sites of hybrid grids can be MGs, buildings, traction systems, etc. This stage is the intermediate step between the technological innovation and the final full scale market implementation. Once the results obtained by the market niches and demo-sites prove the efficiency of the proposed architectures, the hybrid grids can penetrate the market causing a shift in the status quo of distribution grids, which traditionally are AC-based. In this sense, AC/DC hybrid systems can be adopted in many sorts of applications, including large scale distribution grids, ships, complexes of buildings, EV charging stations, installations based on RES and ESS systems, etc.

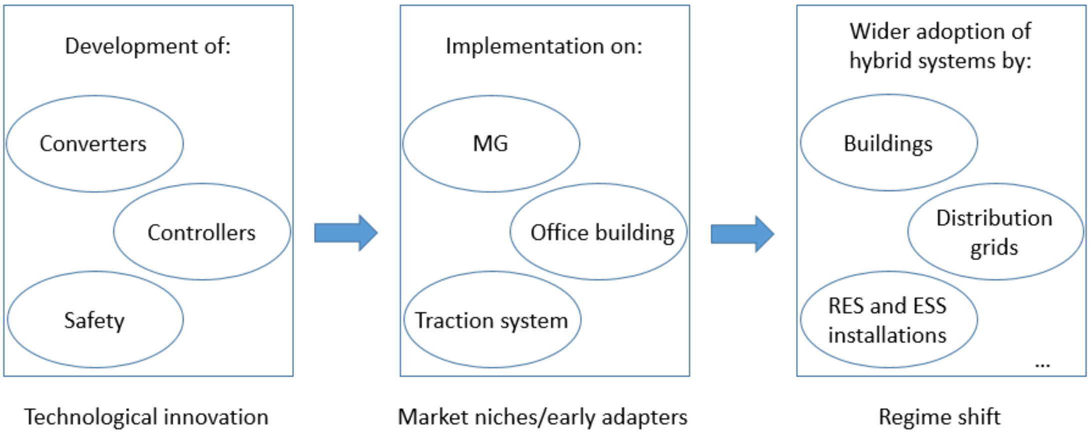

Figure 6.3: The way towards the shift from AC grids to hybrid grids

- **Monitoring:** The wider adoption of hybrid grids does also include the monitoring of their results. In this way, parameters regarding their design can be improved or optimized, more efficient algorithms can be developed and possible flaws can be corrected. Issues regarding maintenance due to the complexity of the system need to be addressed through monitoring. Furthermore, the comments of end-users need to be taken under consideration in terms of comfort loss, possible electricity bill rises or reductions, etc., in order for the hybrid grid operators to get valuable feedback and improve its sustainability.
- **Expertise:** A major factor that affects the promotion of hybrid grids in a negative way, is the lack of expertise from the side of technicians, installers, etc. Even if the appropriate devices are developed and the innovative architecture is designed, the implementation cannot be complete without technicians of the constructor sector capable of materializing the proposed plan. However, the vast majority of technicians and installers are only trained according to the needs of AC grids. For this reason, the training of the workforce is a necessity when it comes to the construction of hybrid grids for both early adapters and wider market applications. The desirable level of expertise can be achieved through special classes for the undergraduate technicians or seminars for graduate technicians.
- **Ancillary services:** As previously discussed, there is a wide range of ancillary services that can be offered by DC infrastructures. These ancillary services have proven their value in HVDC applications. Yet, their importance in MV and LV applications is not as well-known as they could be, mostly due to the fact that hybrid grids have just started to penetrate the MV and LV market. The promotion of ancillary services provided by MV and LV hybrid grids that can be utilized by system operators is vital for their wider adoption by more market sections, highlighting their advantages against their AC counterparts.

All of the actions described above can be quite beneficial for the facilitation of the establishment of the hybrid grids and are expected to be followed in the near future by various entities that want to promote the incorporation of DC power in the already existing or future applications. Nevertheless, there are still issues of legislative and technical nature that need to be addressed from the early stages of hybrid grid propagation, posing challenges that will be discussed below.

6.2. Main challenges

Several developments regarding hybrid grids have taken place over the past few years, in terms of research and implementation. Nevertheless, these developments have been conducted separately, taking under consideration the specific needs of each application, without having a more general and common framework. In order to challenge the wider dominance of traditional AC-based grids in the MV and LV distribution, a common legislative background for DC or AC/DC-based solutions is a necessity. It is important to have standards according to which the design of hybrid grids can be adjusted.

For example, there is a generalized requirement for the standardization of the voltage level on hybrid grid applications, new safety regulations and suitable protection mechanisms. More specifically, a major challenge for voltage standardization on the DC part of hybrid grids is the use of different voltage levels in distributed generation, residential, commercial and industrial consumption. So far, the research community has not agreed on one specific DC voltage level or even set clear limits between what is considered to be low, medium and high voltage, in terms of standardization. The preferred voltage levels for some vastly used applications are presented in Table 6.1 [47].

The lack of standards regarding DC voltage levels is a matter that needs to be addressed as soon as possible because without voltage standardization it is impossible to standardize appliances, equipment and devices that are directly connected to DC buses. In fact, it is inconvenient for manufacturers to design DC products capable of operating on different voltage levels. In order to speed up the incorporation of DC technologies in the distribution grid, voltage standardization is by far the highest priority. In this way, stakeholders, sellers, buyers and users can be attracted to hybrid grids, increasing their readiness level.

Table 6.1: Preffered voltage levels [47]

Applications	**DC Voltage (V)**
USB and other small electronic equipment	≤5
Cars, desktop computer	12
LED lights, trucks, fans	24
Future PV installation in LV	48
Telecommunications	48
Power of Ethernet	50
BESS	110/220 -> 380
Data center	380
EV charging	400
Future residential and commercial building distribution	350-450

Applications	**DC Voltage (V)**
Industry and transportation (metro, light and transit)	600-900
MPPT trackers for large and utility scale PV plants	800-1200
Traction system, marine and aircraft system	1000-1500

Apart from the voltage standardization, regulations need to be made regarding other aspects of hybrid grids. Such aspects include, for example, the connection between AC and DC grids and the standardization of circuit breakers that need to be activated in case a fault occurs in the hybrid grid. Over the past few decades, several standards have been developed regarding MV and LV grids with high DC power penetration, covering parts of different sectors, as presented in Figure 6.4, including railway systems, ships, buildings, circuit breakers, safety, distributed resources, connections between AC and DC grids, LVDC distribution grids, etc.

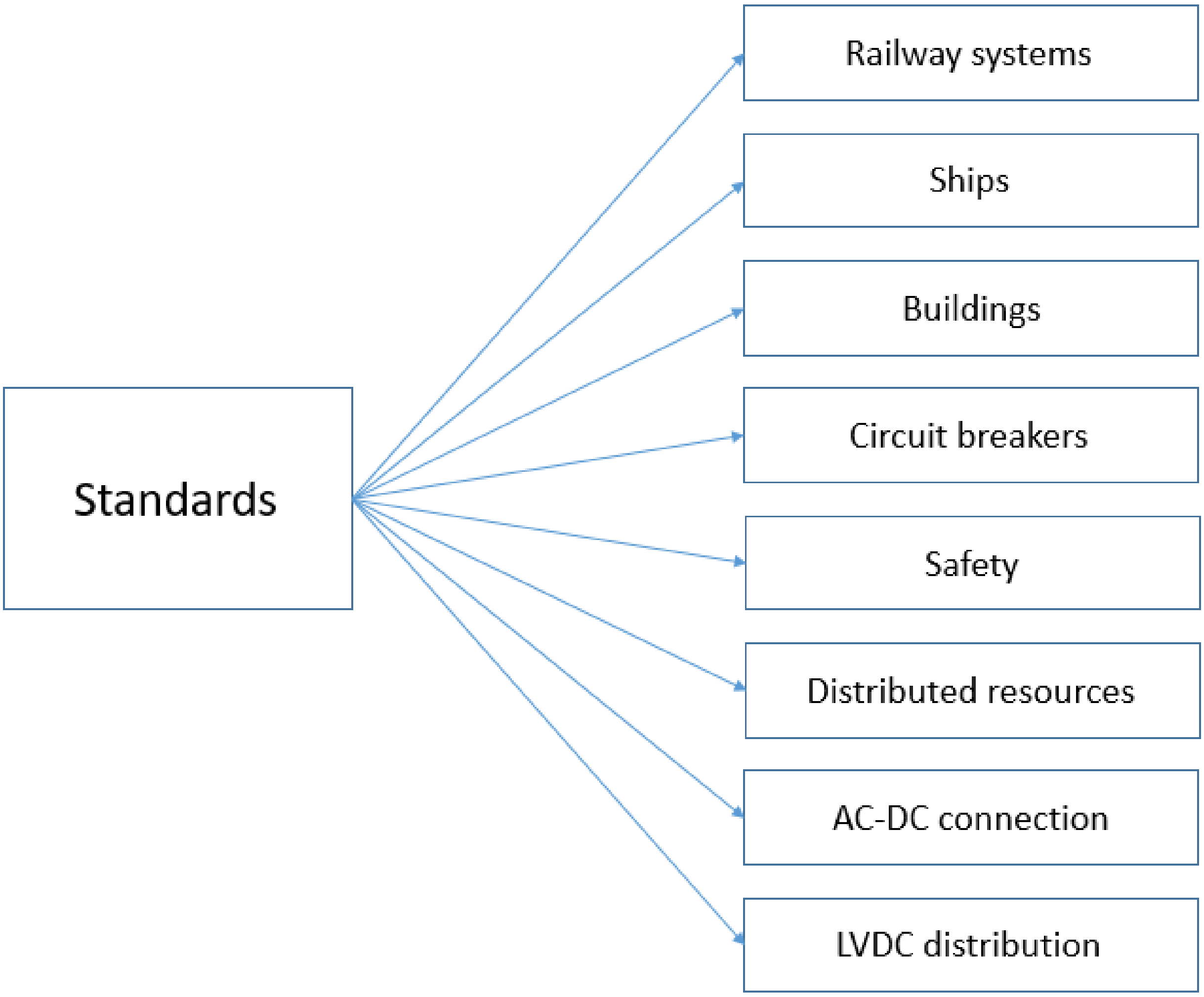

Figure 6.4: Standards for DC-AC/DC hybrid grid applications

Since there is already a plethora of standards covering the AC parts of hybrid grids, special attention is paid to DC grids and the connection between the AC and DC parts that form a hybrid grid. The existing standards have mostly been developed by the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE). A list of the contributions regarding standards and relative work that deal specifically or partly with DC applications, developed by different entities/organizations, is presented in Tables 6.2-6.9 [14].

Table 6.2: Contribution provided by IEC

Contribution	Description	Purpose
IEC 60850	Railway applications – Supply voltages of traction systems	➢ Specifies the main characteristics of the supply voltages of traction systems, as fixed installations for traction, including the auxiliary devices supplied by the contact line and the rolling stock, to use in: ▪ railway lines

Contribution	Description	Purpose
		▪ guided public transport systems such as trams, light rail, elevated and underground railways and trolley systems ▪ systems for transporting materials via rail ➢ This standard is also applicable to low speed MagLev trains or transport systems driven by linear motors.
IEC 60077-3	Railway applications – Electric equipment for rolling stock – Part 3: Electrotechnical components – Rules for DC circuit-breakers	➢ In addition to the general requirements of IEC 60077-2, this provides regulations for circuit-breakers, the main contacts of which must be connected to the DC supply and/or to the auxiliary circuits. ➢ In accordance with IEC 60850, the rated voltage of these circuits does not exceed 3000 V DC.
IEC 61995-1	Railway applications - Fixed installations - DC switchgear - Part 1: General	➢ The IEC 61992 series specifies the requirements for the DC of electrical switchgear and controlgear and is intended for use in fixed electrical systems with rated voltage up to 3000 V DC, which supply power to guided public transport vehicles, i.e. railway vehicles, vehicles for tramways, subways and trolleybuses. The general requirements are given in Part 1.
IEC 61992-3	Railway applications - Fixed installations - DC switchgear - Part 3: Indoor DC disconnectors, switch-disconnectors and earthing switches	➢ Contains the requirements for the DC of disconnectors, switch-disconnectors and earthing switches used in the fixed indoor installations of traction systems.
IEC 61660-1	Short-circuit currents in DC auxiliary installations in power plants and substations - Part 1: Calculation of short-circuit currents	➢ Describes the method for calculating DC short-circuit currents in the auxiliary systems of power stations and substations, which can be equipped with the following apparatuses, acting as sources of short-circuit current: ▪ three-phase AC rectifiers with bridge connection for 50 Hz ▪ fixed lead batteries ▪ voltage balancing capacitors ▪ direct current motors with independent energizing ➢ Provides a generally applicable calculation method, which produces

Contribution	Description	Purpose
		sufficiently accurate conservative results.
IEC 61975	High-voltage direct current (HVDC) installations - System tests	➢ The tests described in this standard are based on bidirectional and two-pole high-voltage direct current installations (HVDC) comprising a transmission terminal and a receiving terminal, each connected to an AC system. ➢ This standard only serves as a guide for the system tests of high-voltage direct current installations (HVDC). ➢ The standard provides potential users with information about how to plan the putting into service activities.
IEC TS 61936-2	Power installations exceeding 1 kV AC and 1.5 kV DC - Part 2: DC	➢ Provides in an appropriate form, common regulations governing the design and installation of electrical systems in installations with rated voltage values over 1.5 kV DC for the purpose of ensuring safety and correct operation for the required use.
IEC 60204-11	Safety of machinery - Electrical equipment of machines - Part 11: Requirements for HV equipment for voltages above 1000 V AC or 1500 V DC and not exceeding 36 kV	➢ Applies to the equipment and to the electrical and electronic systems of machines, including groups of machines that operate together in a coordinated way, excluding the aspects of higher-level systems (i.e. communication between systems).
IEC 60364-1	Low-voltage electrical installations – Part 1: Fundamental principles, assessment of general characteristics, definitions	➢ Defines the regulations for designing, assembling and checking electrical installations. These regulations intend to protect the safety of persons, animals and property against the dangers and damage that could occur during the proper use of electrical installations and to ensure that such installations function correctly. ➢ IEC 60364-1 covers circuits supplied at rated voltage up to 1000 V AC or 1500 V DC.
IEC 60947-2	Low-voltage switchgear and controlgear – Part 2: Circuit-breakers	➢ Applies to circuit-breakers with main contacts designed to be connected to circuits with rated voltage up to 1000 V AC or 1500 V DC. Also contains the additional requirements for integrally fused circuit-breakers.
SG4	LVDC distribution system up to 1500V	This deals with:

Contribution	Description	Purpose
		➢ Coordinating the standardization of different areas, e.g. data centers, office blocks and shopping centers, etc. ➢ Energy efficiency, EMC, reduction of natural resources. ➢ 100% DC installations or with AC and DC hybrid architecture. ➢ Life-cycle of protection and earthing equipment.

Table 6.3: Contribution provided by IEEE

Contribution	Description	Purpose
PC37.20.10/ D6	Approved Draft Standard for Definitions for AC (52 kV and Below) and DC (3.2 kV and Below) Switchgear Assemblies	➢ The terms and definitions in the standard are intended to encompass products within the scope of AC (38 kV and below for air-insulated equipment, 52 kV and below for gas-insulated equipment) and DC (3.2 kV and below) power switchgear assemblies, including components for switching, interrupting, metering, protection and regulating purposes as used primarily in connection with generation, transmission, distribution and conversion of electric power.
DC@Home	DC powered house	➢ Standards and roadmaps for LVDC Microgrid application in residential houses. ➢ The aim is to: ▪ Create a business case for DC by determining the effective losses and their value ▪ Identify the research work required to advance the state-of-the-art ▪ Establish the preliminary recommendations concerning the way in which DC would be delivered to houses ➢ Written for the AC system, but some of its contents could be used as a reference for establishing the standards governing DC systems.
IEEE 1547	Requirements for interconnecting distributed resources	➢ Operation in the islanded mode and with connection to the grid ➢ Normal and non-normal operation

Contribution	Description	Purpose
	with electric power systems	➢ Requirements and practices for distributed sources
IEEE 1709	Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power System on Ships	➢ Contains guidelines to specify, procure, design, manufacture and develop manuals, safety procedures, practices and procedures for effective maintenance of medium voltage direct current (MVDC) electrical power systems. ➢ Recommendations are made for analytical methods, preferred interconnection interfaces and performance characteristics for reliable integration of MVDC electrical components into ship MVDC electrical power systems. ➢ This guide contains indications about planning and designing DC connections which terminate at points of connection to AC systems, with low short-circuit values in the direct current supply.
IEEE 1204	Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities	➢ This guide is limited to the aspects of interactions between AC and DC systems that result from the fact that the AC system is "weak" compared to the power of the DC link (i.e. the AC system appears as a high impedance at the AC / DC interface bus). ➢ The guide contains two parts: Part I, AC / DC Interaction Phenomena, classifies the strength of the AC / DC system, provides information about interactions between AC and DC systems and their mitigation on economics and overall system performance, and discusses the studies that need to be performed.
IEEE Std 1653.6	Trial-Use Recommended Practice for Grounding of DC Equipment Enclosures in Traction Power Distribution Facilities	➢ Deals with the earthing of DC equipment enclosures installed in DC traction power distribution facilities as well as the related insulation treatments required for sound and resistant earthing methods. ➢ Guidelines are also given for the material, installation and testing of insulation used in DC traction facilities and further recommended criteria for acceptability are provided. Even though

Contribution	Description	Purpose
		related, the earthing system is not covered in this document.
IEEE 1227	Guide for the Measurement of DC Electric-Field Strength and Ion Related Quantities	➢ The purpose of this document is to provide guidance for the measurement of electric field strength, ion-current density, conductivity, monopolar space-charge density and net-space charge density in the vicinity of high voltage DC (HVDC) power lines in converter substations and in apparatus designed to simulate the HV/DC power line environment. ➢ The document defines the terms used, describes the interrelationship between electrical parameters, describes operating principles of measuring instruments, suggests methods of calibration where applicable, describes measurement procedures and identifies significant sources of measurement error.
IEEE 946	Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Systems	➢ Revision of IEEE Std. 946-1992. ➢ Guidance for the design of DC auxiliary systems for nuclear and non-nuclear power generating stations is provided by this recommended practice. ➢ The components of the DC auxiliary power system addressed by this recommended practice include lead-acid storage batteries, static battery chargers and distribution equipment. ➢ Guidance for selecting the quantity and types of equipment, the equipment ratings, interconnections, instrumentation, control and protection is also provided.
C37.14	Standard for DC (3200 V and below) Power Circuit Breakers Used in Enclosures	➢ This standard covers enclosed low-voltage DC power circuit-breakers of the stationary or draw-out type of one- or two-pole construction with one or more rated maximum voltages of 300 V, 325 V, 600 V, 800 V, 1000 V, 1200 V, 1600 V or 3200 V for applications in DC systems having rated voltages of 250 V, 275 V, 500 V, 750 V, 850 V, 1000 V, 1500 V or 3000 V; high-speed circuit-breakers and for rectifiers; manually or power-operated; with or without

Contribution	Description	Purpose
		electromechanical or electronic trip devices. ➢ It also deals with service conditions, ratings, functional components, temperature limitations and classification of insulating materials, dielectric withstand voltage requirements, test procedures and applications.
C37.16	Standard for Preferred Ratings, Related Requirements, and Application Recommendations for Low-Voltage AC (635 V and below) and DC (3200 V and below) Power Circuit Breakers	➢ This standard defines the preferred ratings for low-voltage AC (635 V and below) power circuit-breakers, general purpose DC (325 V and below) power circuit-breakers, heavy-duty low-voltage DC (3200 V and below) power circuit-breakers and fused (integrally or non-integrally) low voltage AC (600 V and below) power circuit-breakers.

Table 6.4: Contribution provided by NEC

Contribution	Description	Purpose
Article 393, 625, 690, 692	Legal codes including introduction of DC technology	➢ Presents DC technology

Table 6.5: Contribution provided by MIL

Contribution	Description	Purpose
STD-1399	Electrical interface characteristics for shipboard equipment	➢ Includes sections that define the requirements of DC equipment for shipboard supply systems.

Table 6.6: Contribution provided by ETSI

Standard	Description	Purpose
EN 300 132-3-1	Power supply interface at the input to data/telecom equipment	➢ About data / telecommunications equipment for voltage levels up to 400 V. ➢ Considers the voltage level during normal operation and the requirements for various types of non-normal operation, the fault current limits, earthing and EMC.

Table 6.7: Contribution provided by Emerge Alliance

Contribution	Description	Purpose
DC Microgrid	Standards for occupied spaces and data center	➢ Describes the architecture and control systems recommended in DC Microgrids.

Table 6.8: Contribution provided by REbus

Contribution	Description	Purpose
Open standard	Open standard for DC electricity distribution in homes, commercial buildings, campuses, and other settings	➢ Defines DC distribution for operation parallel to the existing AC system. ➢ Coordinates renewable energy generation on site, including solar modules and small wind turbines. ➢ Defines a common 380 V DC bus with acceptable variation depending on the state of power supply, load and storage.

Table 6.9: Contribution provided by The Green Grid

Contribution	Description	Purpose
White papers, calculation tools and industry glossary	Set of definitions and tools to determine and compare operational efficiency in data centers	➢ The Green Grid association is a nonprofit industry consortium of end users, policy makers, information and telecommunications technology (ICT) providers, facility architects and utility companies. Its purpose is to improve the efficiency of IT resources, including use of DC distribution.

As presented above, there is a variety of standards for different purposes that facilitate the integration of DC power systems into future grids. Nevertheless, this list is far from complete. There is a growing need for new standard developments, including all aspects of hybrid systems. This need poses a great challenge that should be properly addressed for the wider adoption of hybrid grids by the worldwide market.

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