

Toward the Universal DC Distribution System

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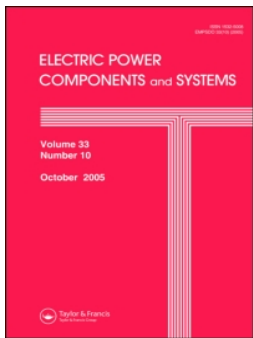
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Toward the Universal DC Distribution System

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Abstract—Due to an increasing number of power generation units and load devices operating with direct current (DC) at distribution level, there is a potential benefit of leading efforts toward building a DC distribution system. However, the implementation of DC distribution systems faces important challenges, including the market inertia of AC systems and standardization. Many of the benefits that are attributed to DC can only be realized if a complete DC system is developed, and not if only a few components are replaced. This paper presents the concept of a universal DC distribution system, as envisioned by the authors. The universal DC distribution system could be implemented in various use cases, but could also completely replace AC distribution grids. The paper covers the possibilities of having DC nanogrids inside buildings, DC microgrids in neighborhoods, and the connection to AC and DC medium voltage grids. Furthermore, considerations regarding flexibility, electricity market design, control, and protection are presented.

1. INTRODUCTION

The electrical power system is significantly changing in order to cope with the increasing participation of various distributed energy resources. These changes are required to ensure the reliability, efficiency, power quality, protection, and cost-effectiveness of the system. This presents a good opportunity to reflect about the overall system and reconsider certain design choices.

AC is nowadays the standard for transmission and distribution grids. The dominance of AC was facilitated by the ease of transforming AC electrical energy to different voltage levels through the AC transformer, needed for efficient transportation over long distances [1, 2]. However, the advances in power electronics nowadays allow for an equally simple transformation of DC voltages.

Currently, the employment of DC is growing at various voltage levels in the power system. The adoption of HVDC lines for the transport of electrical energy over long distances is one example. The advantages of HVDC over HVAC are reported to be low-cost, decreased losses, and the absence of restrictions on long distance cables [3].

At device level, DC is also having a comeback. The high switching frequencies of DC/DC converters result in

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smaller passive components and consequently a reduction in size, weight, and cost. In systems where previously an AC transformer was used to step down the voltage before it was rectified, rectification is now being immediately applied. Moreover, DC is being adopted for an ever increasing amount of applications including data centers, telecommunication, buildings, and ships. The benefits of adopting DC in, for example, data centers include improved efficiency, lower capital cost, increased reliability, and improved power quality [4].

Due to the increasing number of DC applications, it becomes potentially beneficial to build the distribution system on DC instead of AC. In literature, DC is seen to have several advantages over AC in terms of transmission, efficiency, converters, and control [5]. However, the broad application of DC distribution systems still faces challenges including the market inertia of AC systems and the lack of standardization. A comparison of AC and DC will not be covered in this paper, since the full benefits of DC over AC can only be quantified once a complete DC system is developed.

The lack of a general standard has led to diverse architectures and operations of DC distribution systems. Most literature focuses on local DC grids in buildings [6], e.g. for lighting applications and data centers [7]. Many of the design choices have been made for specific applications, without taking the potential advantages of having a complete low voltage DC distribution system into account. Furthermore, local generation and storage is often assumed [8], while sharing of resources and the location of renewable sources is neglected.

Most of the work on DC distribution grids assumes that converters are installed at each household, which connect the local DC or AC nanogrids [9–11]. These converters provide a convenient separation and could also be used for protection purposes [10]. However, since these converters need to be rated for peak power, they are generally expensive. By taking an integral view on the overall distribution system, these disadvantages could be avoided by removing the converters at each household. However, more complex interactions and interdependencies, e.g. in control and protection, have to be dealt with.

This paper contributes to the discussion toward a universal DC distribution system that could be generally applied to various use cases. An integral view is taken on the larger distribution system, and the challenges and opportunities, that can be found in system interdependencies are highlighted. For example, standardization, meshed distribution grids, modular voltage levels, flexibility, market design, control, and protection are discussed. It does not only consider near future applications of local DC nanogrids, but also aim at a universal system with the capability of completely replacing low voltage

AC distribution grids in a longer term. This includes tackling the challenges introduced by intermittent renewable energy sources. It is a continuation of two previous papers in which the opportunities and challenges of DC distribution systems were presented [12, 13].

The remainder of this paper is organized as follows: in Section 2, important elements of the future power system are discussed. The envisioned architecture of the universal DC distribution system is described in Section 3. Section 4 introduces the operational aspects of this system. Subsequently, possible steps toward the introduction of the universal DC distribution system are discussed in Section 5. Ultimately, conclusions are drawn in Section 6.

2. FUTURE POWER SYSTEM

To enable the broad adoption of DC distribution grids, economics of scale should be achieved. A universal DC distribution system that meets future requirements should be envisioned, so that economics of scale can be realized earlier. In this section, possible future use cases are discussed, to be later covered in the envisioned system. This is important in order to prevent over-optimization for specific near-future applications, which could lead to drawbacks for a more widespread adoption.

2.1. Centralized Generation

The share of renewable energy generation in the electrical energy production is rising in many countries. Therefore, the future power system should be able to cope with 100% renewable energy supply. It is often assumed that renewable energy is inherently decentralized; however, this is not necessarily true.

Traditionally distribution systems are built in a centralized fashion. Future distribution systems may still contain centralized power generation, for example in cases where conventional power plants are replaced by large-scale renewable generation plants. An important difference is that the location of the centralized generation sites will not likely be determined by the consumption centers anymore, but by the location of renewable resources.

For example, wind farms can be built at sea to exploit the higher average wind speeds. Large-scale solar thermal power plants can be located in deserts to exploit the higher solar radiation. Hydro power plants are likely placed in mountain regions where large-scale hydro-storage can also be realized. Just like in the case of conventional power plants, large-scale renewable generation plants also need appropriate transmission systems since consumption and generation are often far

apart. HVDC will play an important role in making this possible. Furthermore, an MV grid and an LV distribution grid are required in order to bring the power to the customers.

2.2. Distributed Energy Resources

In this paper, the term distributed energy resources is used to refer to distributed forms of generation, storage, and controllable loads. Distributed renewable sources introduce intermittency to the distribution grid due to varying availability of sun and wind. Distributed storage and controllable loads could provide flexibility to cope with this intermittency.

Currently many new small-scale (renewable) energy sources are distributed in the low voltage grid. Examples of these small-scale sources include rooftop photovoltaic systems, and small-scale wind and hydro plants, but could also include diesel generators. Moreover, many new applications such as electric vehicles have built-in storage capacity that could be utilized to benefit the grid. Likewise, the flexibility in loads such as heat-pumps can do indirect energy storage by shifting the load to a more convenient time.

It is important to note that most of these resources are owned by consumers. Therefore, a prosumer market model is required to model the role of consumers and producers of energy in a more abstract way. Consequently, this would enable a more economical utilization of these resources for both the prosumers and the overall distribution system.

2.3. Nano- and Microgrids

The reliability of a (centralized) power system is unlikely to increase when the system becomes more complex by the addition of distributed resources. However, distributed energy resources enable the isolated operation of parts of the grid in case of outages at a higher level. Therefore, it would be beneficial for the future distribution grid to consist of interconnected microgrids. In this case, the grid can sustain operation if parts of the grid fail.

In these isolated systems, demand response is likely to play an important role, as supply could be limited due to weather conditions. Storage and (conventional) backup supply could be installed in important locations; however, in many countries, this is financially not viable.

2.4. Off-Grid Systems

With the increasing participation of distributed energy resources, we can ask ourselves if the grid is actually needed. Independent distribution grids are often envisioned as an inevitable destination. Off-grid systems can be more economical for remote locations, where the cost of

interconnection exceeds the cost of additional storage and/or energy generation.

However, in more densely populated areas, the advantages of sharing resources outweigh the additional cost due to the low cost of interconnection and the high utilization factor. Moreover, it is unlikely that everyone will use high power loads at the same time. Additionally, weather conditions can make it expensive to cover 100% of the demand by local renewable energy and storage, as it is unlikely that load peaks will coincide with the peaks in supply.

2.5. Standardization

Economics of scale are very important in order to realize reduced cost and consequently to encourage a broad adoption of DC distribution grids. It is therefore important to arrive at a standardized system that can be used for various applications.

Standardization is most important in low voltage grids where a large variation of devices and components are connected. In medium voltage, the system has fewer nodes and connection to these nodes is often controlled by just a few entities. Consequently, individual optimization of voltage levels and components could be considered at medium voltage.

3. THE UNIVERSAL DC DISTRIBUTION SYSTEM

The envisioned standardized DC distribution system should be universal in a sense of being appropriate for various applications, conditions, and sizes as described in the previous section. In order to show the full potential and the affiliated considerations, a complete DC distribution grid architecture, that could be built in cities, is described in this section. However, for specific or initial applications, it is possible to implement only certain parts.

3.1. Modular DC Distribution Grid Architecture

The DC distribution grid architecture should consist of several subsystems that can be connected together. Moreover, it is not necessary that the complete grid is built on DC, any part on any level in the grid could be AC and connected to the DC grid via an AC/DC converter. Especially during a transition from an existing AC distribution grid to a full DC distribution grid.

3.1.1. DC Nanogrid. The grid inside buildings (or on private property) could be operated independently from the main grid in islanding mode if distributed energy resources exist. In order to enable the utilization of this energy supply potential in case of faults in the distribution grid, this part of the grid should be able to operate independently as a nanogrid.

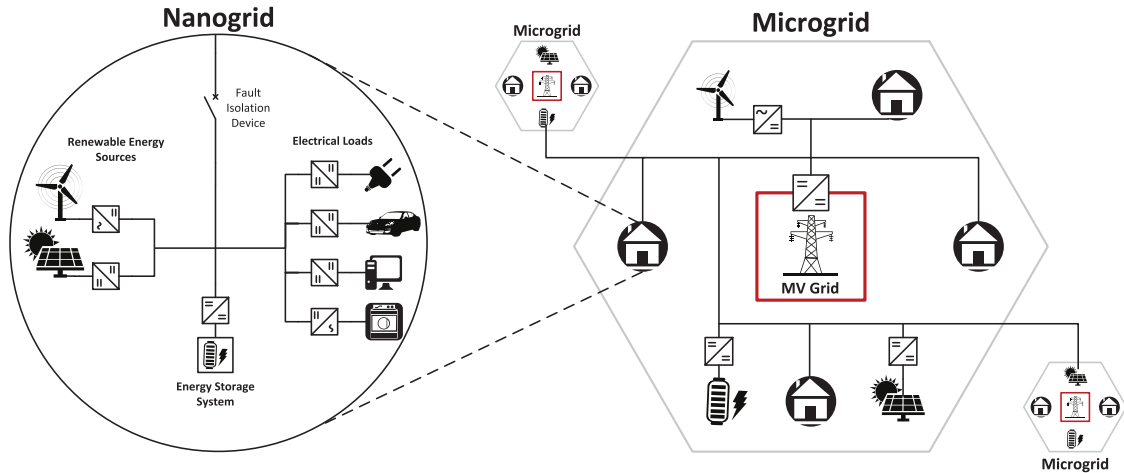


FIGURE 1. On the right: a DC microgrid connecting a neighborhood with multiple DC nanogrids inside buildings and some larger distributed energy resources. It can be connected to other DC microgrids on the same voltage levels and/or to the medium voltage grid at the substation depicted in the center. On the left: a DC nanogrid inside a building with various energy resources is shown in detail. A fault isolation device can separate it from the microgrid.

Nanogrids can be owned and controlled by independent entities. They can be connected to the DC distribution grid by a smart meter and a protection device, or to an AC distribution grid by an AC/DC converter. An example of such a nanogrid and its connection is shown in Figure 1 on the left. A typical power rating of a nanogrid could be 10 kW.

Inside the nanogrid, extra low voltage subsystems could be implemented. Typical voltages for these systems are 48, 24, or 12 V [14]. They could, for example, be used for low power LED lighting, or for connecting loads by USB Type-C connector and USB Power Delivery [15]. These are not in the scope of this paper as their design does not directly affect the distribution grid, because they always need to be galvanically isolated by a full power converter.

3.1.2. DC Microgrid. In order to allow the sharing of distributed energy resources between nanogrids (neighbors) in a resilient way, even if higher level grids fail, DC microgrids should be used to interconnect a neighborhood. The size of these microgrids could be, for example, one street block, one low-voltage feeder, or the low voltage distribution grid under one substation (e.g., 500 kVA) of today's 400 V AC grids.

Such a DC microgrid could have a connection to higher level grids but could also directly connect to neighboring DC microgrids as shown in Figure 1 on the right. As such, the low voltage grid is built out of interconnected microgrids [16] and could be extended to a large grid, connecting a whole city. These DC microgrids should be able to operate independently and therefore protection devices should separate them. In order to allow economic dispatch, even in islanded operation, local electricity markets could be implemented on

this level. Also the power flow and congestion should be controlled.

3.1.3. Medium Voltage Grid. Figure 2 shows an example of a medium voltage and a high voltage grid overlaying the connected DC microgrids. The medium voltage grid can be implemented in DC and could connect large-scale energy resources such as onshore windfarms. These grids could also be implemented in AC with a modular AC/DC converter at the substation connecting it to the low voltage DC grid, allowing for high partial load efficiency [17]. A connection to a medium voltage grid is optional and may not be implemented for remote locations. Microgrids could only connect to neighboring microgrids, which may or may not be connected to the medium voltage grid, or operate fully independently.

3.2. Meshed DC Distribution Grids

Nowadays AC distribution grids are often operated in a radial structure as this has advantages in protection and power flow control. Grids in densely populated areas are often constructed in a meshed architecture, but the meshes are not closed in order to keep the operation radial. This allows for more flexibility in, for example, maintenance and repair.

With the increased utilization of the grid infrastructure due to electrical vehicles, heat pumps and solar panels, it would be preferable to take advantage of available meshed connections [18]. In DC distribution grids, DC/DC or AC/DC converters take the role of traditional AC transformers. These power electronic converters cannot be overloaded for extended periods of time, like AC transformers can be. Meshing the low

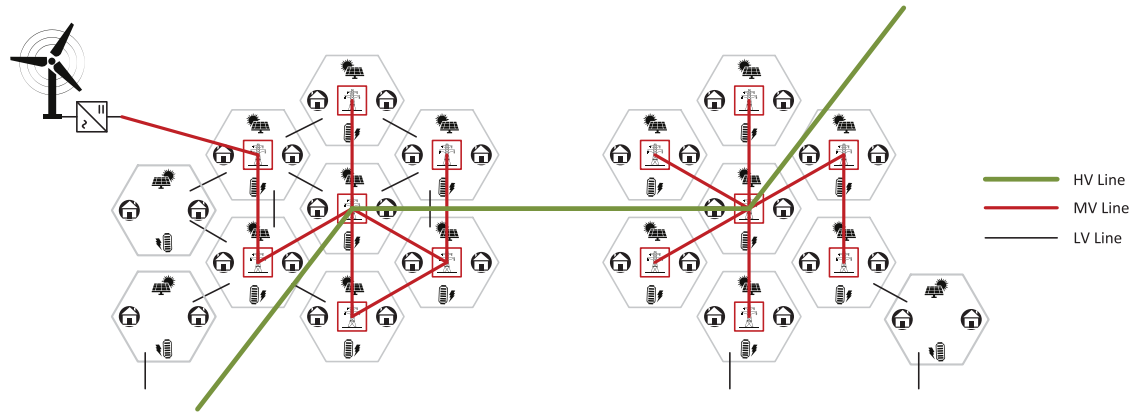


FIGURE 2. An overview of a distribution area with multiple DC microgrids that are directly connected (black) to each other forming some meshes. On top of that, a medium voltage DC grid (red) connecting most of these microgrids at substations. Furthermore, a high voltage transmission system is depicted in green.

voltage grid can allow for the utilization of a neighboring substation in case of congestion at one converter.

It has to be ensured that the power flow does not exceed the line limits for extended time periods. Power flow control converters, that impose voltages in series with lines, can be added to influence the power flow. In this way, the infrastructure can be better utilized if this is necessary. Power flow control converters are built using partial power converters to enhance efficiency and reduce cost. However, they do not provide galvanic isolation because a major part of the power is directly transferred from one side to the other. Large galvanically connected low voltage grids could emerge which have to be taken into account for power flow control and protection. Ensuring line limits can be done in a decentralized way without communication [18].

3.3. No Converters at the Nanogrid's Interface

Low voltage DC grids have emerged from applications such as lighting and data centers. From this perspective, it is normally assumed that DC nanogrids are interfaced with AC grids by a central AC/DC converter [19]. In literature, DC distribution grids are considered to have DC/AC inverters for each customer, allowing the usage of legacy AC devices [9, 20].

When combining these two approaches, one would naturally end up with a DC/DC converter at the entrance of every house [11]. The advantage of this system architecture is that the nano- and microgrid systems are electrically separated. Consequently, the control and protection of this system is easier as only well-defined parts of the subsystem have to be taken into consideration.

However, when considering a universal DC distribution grid, that can be used for all use cases, this solution is, in

general, suboptimal. This is best illustrated with an example of two neighboring buildings. The first building has solar panels while the other has storage facilities. During the day when little of the power is used, the solar power from the first building is stored in the second building's storage. Later, when demand is highest, the stored electrical energy is (partially) transferred back to the first building. Consequently, the two extra converters at the interfaces of the two nanogrids with the microgrid introduce four additional conversion steps, significantly decreasing efficiency.

Another problem with a converter at the nanogrids interface is that these converters would need to be designed for the peak demand of the nanogrid, which is expensive. Consequently, this converter will have a low utilization factor as the average demand is significantly lower. Most of the time these converters would operate at partial load condition with poor efficiency, as modular converters might not be economically feasible at these power levels due to the overhead of modularity. If the converters at the interface are replaced with a combined converter at a substation, it could be designed with a much lower rating than the sum of each nanogrid's peak demand. In AC grids, substation transformers are commonly designed for 10–20% of the total connected peak demand. Furthermore, since the power from distributed sources can take a direct path to the demand inside the microgrid, converter power capacity can further be reduced.

To summarize, removing the converters at the interface between nanogrids and the microgrid can reduce investment cost significantly. Nevertheless, in remote locations with long distances between nanogrids or for DC nanogrids connected to AC distribution grids, a converter at the interfaces could still be favorable.

3.4. Modular Bipolar Voltage Levels

One of the challenges in low voltage DC is to standardize the voltage levels. Extra low voltage levels are often seen in DC nanogrids, such as 24 V proposed by EMerge Alliance [7], 48 V in the telecommunication industry [21], or 20 V of the USB Power Delivery Standard [15]. They are, however, not suitable for a distribution grid with higher power and longer distances as they would result in high losses or thick and expensive cables.

It is expected that the standardization of input voltage levels for generic devices will converge to a value between 350 and 400 V. These voltage levels are also widely used in the DC links of AC power supplies today. Therefore, these voltage levels would allow easy implementation of DC ready devices [22].

Most of the low voltage DC literature focuses on these local DC grids and does not consider the expansion to a complete DC distribution grid. EMerge Alliance proposes to use midpoint grounding, effectively making ± 190 V out of the 380 V [7]. This can be applied to isolated local DC grids, such as today's data centers.

When it comes to transporting power over longer distances, higher voltages are necessary. Using true bipolar systems will reduce the line losses by 50% for balanced systems while copper can be reduced. Device interfaces should then be made such that they can be connected to a midpoint grounded system ground but also between a pole and the neutral. Bigger devices, that today are connected to three phase AC, could then be connected directly between a positive and a negative pole.

Figure 3 shows an example of a modular bipolar system of ± 350 V, as proposed by Direct Current B.V. [23]. A ± 700 V grid could then be made for applications where a lot of large loads are to be connected. With a margin for overvoltage droop regulation considered, this voltage stays under the

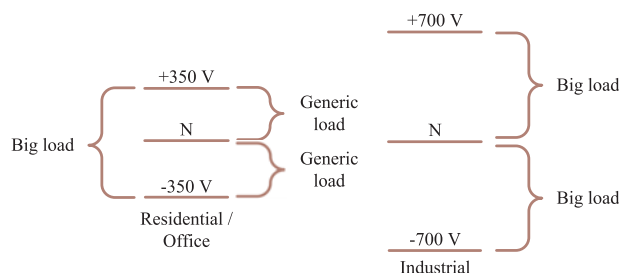


FIGURE 3. Modular bipolar voltage levels can be implemented for industrial applications with ± 700 V and for residential applications with ± 350 V. Small appliances connect to 350 V, while large appliances connect to 700 V by connecting to both poles.

1500 V low voltage limit imposed by the IEC. However, also ± 375 and ± 750 V have recently been discussed and might be a good compromise [14]. Regardless of the chosen nominal voltage levels, there is always an operation range around the chosen values that has to be specified. Modular voltage levels, if used from the beginning, would allow for the scaling of the system and increase compatibility with systems of different sizes.

In these bipolar systems it can be, in some cases, beneficial to remove the neutral conductor. This might be relevant when refurbishing four-cable three-phase AC cables where then two conductors could be used for each pole. However, if the neutral is removed, the currents flowing in both (independent) poles must be balanced. This can be done by means of a balancing converter shifting power between the two poles or by balancing local supply and demand on both poles (by using distributed energy resources or demand response).

4. OPERATIONAL ASPECTS

The standardization of a new system gives the unique opportunity to incorporate features that may be desirable in the future. Trade-offs will have to be made as optimal solutions for some applications may cause problems for other applications. This section highlights some of these aspects.

A key challenge in the operation of the universal DC distribution system is that the size and composition of different systems can vary. Moreover, the size and composition of a distribution grid could also vary over time due to grid extension, faults, or maintenance reasons. For example, microgrids and nanogrids should be able to island themselves and continue operation when other parts of the grid experience difficulties. After the problems have been resolved, the microgrids should reconnect (de-island) to reestablish the sharing of resources. Furthermore, the nanogrids should independently be able to black start to facilitate the usage of available energy sources as soon as they are available after a grid collapses.

4.1. Enable Flexibility

To facilitate operation when supply is scarce, enabling flexibility in demand and supply is crucial [24]. This will be more common as intermittent renewable sources are introduced.

Load shedding can be used as a last resort to prevent the collapse of the system. In DC grids load shedding can be done based on the local voltage, which is a direct indicator of the system's power balance [25]. The voltage thresholds, at which load shedding occurs, should be standardized and incorporated into all devices. Priority of loads can be realized by employing different voltage thresholds for different types

of loads. In order to increase system stability, loads should ramp down proportionally to the voltage if possible (e.g. lighting) [26]. It is important to note that this will prevent a grid outage in cases where nowadays AC grids would already be blacked out, increasing user satisfaction.

The increasing flexibility in appliances such as electric vehicles can, if enabled, reduce infrastructure investments significantly. While the overall system benefits can be high, individual benefits are often so small that this certainly has to be automated and no user interaction should be required. In case of demand response, the users should be able to actively increase the importance in order to override automatic action at any given time.

The smaller the devices get the worse the trade-off is in implementing these features. Therefore, a good balance has to be found. Local economical demand response could be achieved by combining a smart meter with a power flow control converter. In this case, the smart meter, which is connected to the market, could accomplish economical load shedding by reducing the voltage inside the nanogrid (triggering load shedding). Such a system could be interesting in, for example, developing countries when a cost limit should be achieved.

4.2. Electricity Market Design

Electricity market design is important for the adequate utilization of distributed resources. Until now, this has often been regarded as an independent topic on top of the technical aspects and independent of AC or DC. However, better utilization of the infrastructure could be realized if the market is seen as part of the (optimal) control system.

Prosumer market models in which each participant is equally able to consume and produce power seem to be the proper answer for emerging distributed resources as they do not penalize the storage of energy [26]. Furthermore, grid cost and electricity cost should be explicitly separated to allow for economic dispatch based on marginal cost. The grid cost can still depend on the rating of the connection to the grid.

Dynamic prices can enable the utilization of distributed demand and storage flexibility. The faster the dynamic prices are updated the less reserve power is needed. However, as a consequence, the cost of communication and clearing may rise, and thus a balance has to be found. The market model should incorporate price forecasts to allow adequate utilization of resources (such as load shifting and/or storage).

Increases in installed power by, for example, PV or electric vehicles are expected to lead to congestion in the low voltage grids. Also the stricter limit of AC/DC and DC/DC converters may lead more easily to congestion than AC transformers (which can be overloaded). The market model should manage

congestion by, for example, dynamic nodal pricing [24] using exact optimal power flow calculations [27]. Cost functions of demand need to be assumed in order to incorporate demand response. Exact optimal power flow in a bipolar DC grid can lead to nodal or locational marginal prices that depend on the pole of connection when only individual poles are congested due to unbalance. Losses of converters, lines, and power flow control converters (that modify the power flow) should also be included [27].

Market clearing should be implemented in a (partially) distributed way in order to allow independent operation of microgrids, but also to reduce complexity and communication needs [28]. Microgrids can act as an aggregator of the information that is shared with connected microgrids and higher level grids in order to converge toward a globally optimal operation. While centralized optimization can (in theory) always outperform distributed control, in practice the problem complexity, communication effort, and resilience speak in favor of suboptimal distributed solutions.

Preliminary work indicates that for DC, new solutions for distributed market clearing might be possible. This could include “physical market clearing,” where price information is broad casted and market participants act directly (only giving physical feedback). Moreover, local measurements might be taken into account for distributed real-time optimization iterations.

4.3. Control

A large amount of research has been done on the control of DC microgrids [29]. Often, full knowledge of the system components and parameters is assumed, which should not be a requirement for the universal DC distribution system. Rules for the control should be developed and standardized that allow reconfiguration of the system and enable economics of scale.

In normal operation, optimization could be done by the real-time market. The control should be implemented in a hierarchical way such that lower parts can continue operation even if communication is lost, increasing resilience of the system. Therefore, not only set points, but also the current-voltage (IV) characteristics should be defined for the full operation range of the converters. In Figure 4 an example of such an operation range is shown for a storage system. It can include current limits, power limits, droop control for the operation of parallel sources, and optionally a deadband where the converter is off. Ideally these parameters can be modified based on the market clearing or environment.

Moreover, the rules should consider the behavior and development of power electronics toward higher switching

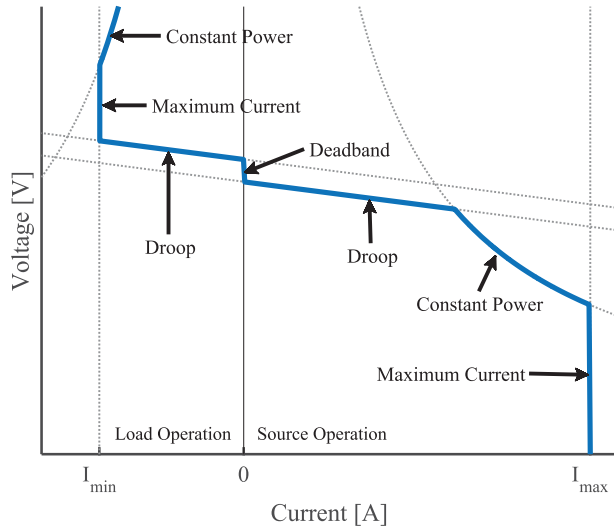


FIGURE 4. Possible current-voltage characteristic for the local control of a storage converter. In general, current limits, power limits, and droop rates should be defined.

frequencies and smaller passive components. The low inertia of DC distribution grids results in strict requirements on the control system [30]. It should be noted that low inertia grids are also a problem for future AC grids. Constant power loads complicate this challenge due to their negative incremental impedance. Possible solutions could be standardized control bandwidths and converter ramp rates to ensure system stability. Slower behavior of loads on the grid side results in better stability, but as a trade-off, intermediate storage is needed for devices that need fast power changes.

For long line lengths active damping could be necessary and limits may have to be defined. Disconnection and connection events of microgrids, especially in case of faults, should be given considerable attention in the design of the control guidelines.

4.4. Protection

The protection of DC grids is considered as one of the biggest challenges in the field, and it is getting more and more attention [31]. Unlike in AC systems, the current has no zero crossing that extinguishes arcs, resulting in high fault currents in DC systems. Moreover, series arcing can be an issue when high power loads are unplugged. Special plugs with leading pins is one of the possible solutions, but also selective load side arc detection could be implemented [32]. Furthermore, coordination with frequency-based backup protection would need to be standardized.

Traditional protection schemes in the low voltage grid rely on high short circuit currents, a radial system, and unidirectional power flow for selectivity. However, since these

three elements are not necessarily present in DC distribution systems, new short circuit protection strategies need to be developed.

Advances in power electronics have led to a reduction of capacitor size and consequently their contribution to short-circuit currents. Oversizing the converters is an expensive solution which is sometimes employed for AC systems [33]. Also, a small nanogrid in islanded operation might not be able to produce high enough short-circuit currents, even with oversized converters. Since high fault currents are not inherently desirable, a new low short-circuit current protection philosophy is favorable [34].

Low short-circuit currents allow for solid state breakers to be used, which enables fast fault clearing and avoids arcing. Fast selectivity in meshed grids with bidirectional power flow is therefore essential and an important research challenge. Current limiting inductors that limit the rate of change of the current need to be used. The significant impact of these limiting inductors on the control system needs to be taken into account. Inrush currents and ramp rates must be specified in order to allow fast fault discrimination. [34]

Grounding is another important topic to be taken into consideration since DC can cause corrosion if it flows through metallic structures in the environment for an extended period [31]. High impedance grounding schemes have often been used in DC microgrids (e.g. data centers), since it allows to sustain operation during a single ground fault. However, selectivity is not possible and therefore this is not feasible for DC distribution grids. Solid grounding in one point allows for selective protection for residual ground currents; however, if there are multiple grounding points, ground currents would flow. Multiple grounding points would be needed in order to be able to island individual nanogrids. The development of advanced grounding schemes is therefore fundamental. Preliminary research indicates that capacitive grounding could be an interesting alternative since it provides low impedance for fault transients and blocks DC currents.

5. HOW TO GET THERE?

This paper discusses many technological challenges of the universal DC distribution grid. However, the biggest challenge for the adoption of universal DC distribution grids is the market inertia of AC systems. Even if there are technological and economical benefits, it is challenging to select DC systems over the well-established AC systems. Therefore, this section discusses possible paths for the adoption of the universal DC distribution grid.

There are several technologies that are in development or already available that could benefit the adoption of DC

distribution grids. Firstly, a important development is the introduction of USB Type-C and USB Power Delivery, which allows up to 100 W (5 A at 20 V) to be transferred [15]. Therefore, USB Type-C could be used to provide power to most consumer electronic devices, even those that traditionally are connected to the AC grid. It is expected that in the near future, many types of low power devices will be available with USB Power Delivery. As a result, fewer devices would be directly connected to the AC power system. This means that all these devices could be connected to a DC distribution grid by means of a USB wall socket, thus simplifying a transition.

Secondly, DC ready devices that can work on both AC and DC, could allow for economics of scale for higher power appliances. DC ready devices are not significantly more expensive than AC only devices and enable the flexibility of choosing between AC and DC [22].

Currently, DC systems are mostly used for specific (industrial) applications such as telecommunication and data centers. In the near future, it is expected that the number of these industrial applications of DC systems further increases due to the scale of the applications. Some examples are LED street lighting, greenhouse lighting, motors with speed control, and shipboard power systems.

Upcoming is the application of DC distribution systems for commercial buildings. Commercial buildings adopt early as the benefits of DC outweigh the engineering effort at this larger scale. For example, LED lighting combined with USB Power Delivery and PV interconnected on DC can be an early business case for office buildings.

Once a market is established from industrial applications and commercial buildings, economics of scale are applied. As a result, more DC devices will become available and the cost of these devices will decrease. At this point residential DC houses could become feasible. Most of the higher power appliances (such as heat pumps, washing machines, cooking facilities and lighting) are fixed inside the building. Consequently, residential DC appliances could be installed during construction by the housing corporations (even if the supply is still limited).

A subsequent opportunity would present itself when in neighborhoods the majority of buildings operate on DC. In this case, using a DC distribution grid to connect these buildings would be beneficial. Moreover, in some cases parallel street lighting systems could be switched to DC and offer an alternative connection.

It is likely that AC and DC grids will co-exist at some locations for a transition period because of market development. However in long term, these hybrid systems will not produce a benefit, as virtually all appliances connected to the voltage

grid use a DC bus inside or could be designed with lower or comparable cost for DC.

When thinking about future DC distribution grids, one must realize that the transition is challenging. DC will only become a real alternative to AC once a market for DC devices is established. When working infrastructure exists, the benefits of DC are unlikely to outweigh the cost of replacing a working system. However, opportunities in these systems present themselves when line capacity has to be expanded or if changes have to be made anyway to the existing system. When new infrastructure is built, a true choice exists. This would be for example the case in not-electrified areas in developing countries, which could be built completely on DC, once a standard and market is established.

6. CONCLUSION

In this paper, the considerations for a universal DC distribution system that is capable of completely replacing nowadays AC distribution grids have been presented. Starting from the need for economics of scale, the various use cases of the power system in the future and desired system properties were discussed. The universal DC distribution system was described as a system that can come in many different forms. Starting from DC nanogrids inside buildings and DC microgrids in neighborhoods to the connection to AC and DC medium voltage grids, and with that to higher voltage systems. The advantages and challenges of meshed DC distribution grids were discussed.

One important aspect is that full power converters should not separate nano- and microgrids at building entrances. In this way, the voltage levels inside buildings and in the street will be equal. Furthermore, bipolar grids with modular voltage levels can satisfy the different power needs.

Operational aspects of the envisioned system were briefly discussed including flexibility, market design, control, and protection. Moreover, the challenging transition to the universal DC distribution system was discussed with USB Type-C connector and USB Power Delivery as important enablers for the millions of small devices.

In conclusion, this paper encourages to look at the big picture and longer term future applications of low voltage DC. Only considering near-future applications and business cases lead to (de-facto) standards that are suboptimal for a widespread adoption of DC. These standards would complicate the large-scale utilization and rollout of DC distribution systems. The ongoing standardization efforts pose a unique opportunity to do it right in the first place and create a system that can cope with most future challenges to come and the various use cases in the different regions of this planet.

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REFERENCES

- [1] Coltman, J. W., "The transformer [historical overview]," *IEEE Ind. Appl. Mag.*, Vol. 8, No. 1, pp. 8–15, January 2002.
- [2] McNichol, T. *AC/DC: The Savage Tale of the First Standards War*. Hoboken, NJ: Wiley, 2006.
- [3] Bahrman, M. P., "Hvdc transmission overview," *IEEE/PES Transmission and Distribution Conference and Exposition*, April 2008, pp. 1–7.
- [4] AlLee, G., and Tschudi, W., "Edison redux: 380 vdc brings reliability and efficiency to sustainable data centers," *IEEE Power Energy Mag.*, Vol. 10, No. 6, pp. 50–59, November 2012.
- [5] Larruskain, D. M., Zamora, I., Abarrategui, O., and Aginako, Z., "Conversion of AC distribution lines into DC lines to upgrade transmission capacity," *Electr. Power Syst. Res.*, Vol. 81, No. 7, pp. 1341–1348, 2011.
- [6] Weiss, R., Ott, L., and Boeke, U., "Energy efficient low-voltage DC-grids for commercial buildings," *IEEE First International Conference on DC Microgrids (ICDCM)*. IEEE, June 2015, pp. 154–158, available at <http://ieeexplore.ieee.org/document/7152030/>
- [7] EMerge Alliance, "Occupied Space Standard, Data/Telecom Center Standard," available at: <http://www.emergealliance.org/Standards/OccupiedSpace/Overview.aspx>
- [8] Singh, R., and Shenai, K., "DC microgrids and the virtues of local electricity," *IEEE Spectrum*, Vol. 6, 2014.
- [9] Salonen, P., Kaipia, T., Nuutinen, P., Peltoniemi, P., and Partanen, J., "An LVDC distribution system concept," *Nordic Workshop on Power and Industrial Electronics (NORPIE'08)*, 2008.
- [10] Boroyevich, D., Cvetkovic, I., Dong, D., Burgos, R., Wang, F., and Lee, F., "Future electronic power distribution systems - A contemplative view," *Proceedings of the International Conference on Optimisation of Electrical and Electronic Equipment (OPTIM'10)*, pp. 1369–1380.
- [11] Werth, A., Kitamura, N., and Tanaka, K., "Conceptual Study for Open Energy Systems: Distributed Energy Network Using Interconnected DC Nanogrids," *IEEE Trans. Smart Grid*, Vol. 6, No. 4, pp. 1, 2015. [Online].
- [12] Mackay, L., Hailu, T. G., Chandra Mouli, G. R., Ramirez-Elizondo, L., Ferreira, J. A., and Bauer, P., "From DC nano- and microgrids towards the universal DC distribution system—A Plea to think further into the future," *PES General Meeting*. IEEE, 2015.
- [13] Mackay, L., Hailu, T., Ramirez-Elizondo, L., and Bauer, P., "Towards a DC Distribution System Opportunities and Challenges," *IEEE First International Conference on DC Microgrids*, 2015.
- [14] Rodriguez-Diaz, E., Chen, F., Vasquez, J. C., Guerrero, J. M., Burgos, R., and Boroyevich, D., "Voltage-Level Selection of Future Two-Level LVdc Distribution Grids: A Compromise Between Grid Compatibility, Safety, and Efficiency," *IEEE Electr. Mag.*, Vol. 4, No. 2, pp. 20–28, June 2016.
- [15] USB Promoter Group, "Universal Serial Bus Revision 3.1 Specification," 2014, available at <http://www.usb.org/developers/docs/>
- [16] Guerrero, J. M., Chandorkar, M., Lee, T.-L., and Loh, P. C., "Advanced Control Architectures for Intelligent Microgrids Part I: Decentralized and Hierarchical Control," *IEEE Trans. Ind. Electron.*, Vol. 60, No. 4, pp. 1254–1262, April 2013.
- [17] She, X., Huang, A. Q., Lukic, S., and Baran, M. E., "On Integration of Solid-State Transformer With Zonal DC Microgrid," *IEEE Trans. Smart Grid*, Vol. 3, No. 2, pp. 975–985, June 2012.
- [18] Mackay, L., Hailu, T., Ramirez-Elizondo, L., and Bauer, P., "Decentralized Current Limiting in Meshed DC Distribution Grids," *IEEE 1st International Conference on DC microgrids*, 2015.
- [19] Rodriguez-Diaz, E., Savaghebi, M., Vasquez, J. C., and Guerrero, J. M., "An overview of low voltage DC distribution systems for residential applications," *IEEE 5th International Conference on Consumer Electronics - Berlin (ICCE-Berlin)*. IEEE, September 2015, pp. 318–322.
- [20] Nuutinen, P., Kaipia, T., Peltoniemi, P., Lana, A., Pinomaa, A., Mattsson, A., Silventoinen, P., Partanen, J., Lohjala, J., and Matikainen, M., "Research site for low-voltage direct current distribution in a utility network - structure, functions, and operation," *IEEE Trans. on Smart Grid*, Vol. 5, No. 5, p. 2574–2582, 2014.
- [21] Dragicevic, T., Vasquez, J. C., Guerrero, J. M., and Skrlec, D., "Advanced LVDC electrical power architectures and microgrids: A step toward a new generation of power distribution networks," *IEEE Electr. Mag.*, Vol. 2, No. 1, pp. 54–65, March 2014.
- [22] Mackay, L., Ramirez-Elizondo, L., and Bauer, P., "DC ready devices is redimensioning of the rectification components necessary?" *16th International Conference on Mechatronics Mechatronika*. IEEE, 2014.
- [23] Stokman, H., "Direct Current B.V.," available at <http://www.directcurrent.eu>
- [24] Lund, P. D., Lindgren, J., Mikkola, J., and Salpakari, J., "Review of energy system flexibility measures to enable high levels of variable renewable electricity," *Renew. Sustain. Energy Rev.*, Vol. 45, pp. 785–807, 2015.
- [25] Mackay, L., Kolios, P., Ramirez-Elizondo, L., and Bauer, P., "Voltage dependent demand response with dynamic hysteresis thresholds in DC microgrids," *IEEE PowerTech Conference Eindhoven*, 2015.
- [26] Mackay, L., Imhof, M., Wiget, R., and Andersson, G., "Voltage dependent pricing in DC distribution grids," *IEEE PowerTech Conference Grenoble*. IEEE, June 2013.
- [27] Mackay, L., Dimou, A., Guarnotta, R., Morales-Espania, G., Ramirez-Elizondo, L., and Bauer, P., "Optimal power flow in bipolar DC distribution grids with asymmetric loading," *IEEE Energycon Leuven*, 2016.
- [28] Mohammadi, J., Zhang, J., Kar, S., Hug, G., and Moura, J. M. F., "Multilevel distributed approach for DC Optimal Power Flow," *IEEE Global Conference on Signal and Information Processing (GlobalSIP)*. IEEE, December 2015, pp. 1121–1125.
- [29] Dragicevic, T., Lu, X., Vasquez, J. C., and Guerrero, J. M., "DC microgrids - part I: A review of control strategies and stabilization techniques," *IEEE Trans. Power Electron.*, Vol. 31, No. 7, pp. 4876–4891, July 2016.
- [30] Hailu, T., Mackay, L., Ramirez-Elizondo, L., Gu, J., and Ferreira, J. A., "Voltage Weak DC Microgrids," *IEEE 1st International Conference on DC microgrids*, 2015.

- [31] Dragicevic, T., Lu, X., Vasquez, J. C., and Guerrero, J. M., "DC microgrids - part II: A review of power architectures, applications, and standardization issues," *IEEE Trans. Power Electron.*, Vol. 31, No. 5, pp. 3528–3549, May 2016.
- [32] Mackay, L., Shekhar, A., Roodenburg, B., Ramirez-Elizondo, L., and Bauer, P., "Series arc extinction in DC microgrids using load side voltage drop detection," *IEEE 1st International Conference on DC Microgrids*. IEEE, 2015.
- [33] Vandoorn, T. L., Vasquez, J. C., De Kooning, J., Guerrero, J. M., and Vandevelde, L., "Microgrids: Hierarchical control and an overview of the control and reserve management strategies," *IEEE Ind. Electron. Mag.*, Vol. 7, No. 4, pp. 42–55, December 2013.
- [34] Mackay, L., Gouvalas, N., Hailu, T., Stokman, H., Ramirez-Elizondo, L., and Bauer, P., "Low short circuit current protection philosophy for DC distribution grids," *IEEE J. Emerg. Sel. Topics Power Electron.*, 2017, in review.

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