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From DC Nano- and Microgrids Towards the Universal DC Distribution System – A Plea to Think Further Into the Future

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***Abstract*—The traditional ac power system is challenged by the increased amount of distributed energy resources. Enormous changes and investments are necessary in order to achieve an ac smart grid capable of coping with the challenges introduced. In dc, solutions seem to be more straightforward since most of the distributed energy sources and most of the loads connected to the low voltage grid operate with dc. For this reason, dc distribution systems should be considered as an alternative with significant potential. Nevertheless, nowadays research is mainly focused on local dc nano- and microgrids. This paper introduces relevant aspects related to dc distribution networks. A wide field of opportunities and challenges are briefly exposed.**

I. Challenges in the AC Power System

The increasing participation of intermittent renewable energy generation and the rising adoption of distributed generation technologies pose new challenges both to transmission and distribution grid operators. Major changes are needed to ensure the reliability of the electricity supply. Future power systems should be able to cope with the higher uncertainties introduced to the network by the intermittent sources, but also with the bidirectional power flows introduced by the small generation units installed at the distribution or even at the household level.

Smart-grid applications can provide higher flexibility by allowing the controlled injection of locally generated electrical energy and by enabling the optimization of energy storage, leading to a better deployment of resources and a better match between energy production and energy consumption. Furthermore, nano and microgrids will play a crucial role in the energy infrastructure of the future. In ac this can be quite complex and expensive. For example solid state transformers are proposed to decouple the ac frequency of microgrids by implementing four ac/dc conversion steps [1].

The electric energy demand is growing worldwide. On one hand there is still a significant lack of infrastructure in developing countries and on the other hand the networks are close to reach their maximum capacity in crowded cities of developed countries. Therefore we currently have the opportunity to rethink the whole system and to determine if indeed dc is the most suitable option both for the new energy distribution infrastructures to come, but also for existing systems requiring a refurbishment.

II. Comeback of Direct Current

The war of currents lead by Edison with dc and by Westinghouse and Tesla with ac was won by the latter a century ago for good reasons. However as time passed and new developments were made, the arguments of this victory started to become weaker. Nowadays, power electronics can carry out dc/dc conversion and in this way, enable what hundred years ago only ac transformers could do properly: to change voltage levels. DC is already having a comeback in HVdc power transmission systems as line losses are much for dc lines than for ac. In addition to that, the prevention of skin effects and the fewer problems with cable capacitance, especially for sea cables, are two other strong arguments supporting HVdc systems.

At low voltage, dc is having a come back too, particularly inside the devices. Previously ac transformers were used to bring down the voltage to usual application levels, e.g. 20 V, and rectification was done thereafter. Today ac transformers in devices are more and more being replaced with dc/dc converters. Thanks to their higher switching frequencies, typically 100 kHz instead of $50/60$ Hz with ac, much smaller passive components are required, which reduces size, weight and material costs. Today even ac motors are more and more driven by motor controllers using ac/dc followed by dc/ac conversion, which allows variable speed control.

Due to the growing environmental concerns, we are encouraged to shift towards a more sustainable energy scenario by the use of more renewable energy sources. Distributed renewable energy technologies are either dc inherently, e.g. photovoltaics, or use a dc link to decouple rotation speed from the ac grid such as in the case of wind power. Batteries operate in dc and their application is evolving in electric vehicles and other devices. As a consequence, it seems reasonable to bring dc one step higher, namely, to the distribution level and in this way connect the generation units and the loads directly to dc, eliminating dc/ac and ac/dc conversions.

Nowadays off-grid dc microgrids are used to power remote telecommunication infrastructures. Traditionally -48 V has been used as the voltage level for this kind of infrastructure. In the past, backup batteries were directly connected to the grid for these systems, however lately batteries have been connected with dc/dc converters in order to allow better control [2].

The adoption of LVdc systems in data centers, over the conventional ac backbone systems, can provide several benefits namely, improved efficiency, lower capital cost, lower use of copper in cables, higher reliability, lower amount of floor space, and lower harmonics [3]. The dc data center built by Lawrence Berkeley National Laboratory exhibited 28% improved efficiency compared to 208 V ac supply, 7% better efficiency compared to 415 V ac supply, 15% lower capital costs, 20-100 times lower use of copper, 33% less floor space and 100% increase in reliability.

EMerge Alliance proposed a dc microgrid for commercial interiors and data/telcom centers that can be used along with ac [4]. In terms of standards, the Occupied Space Standard proposed the use of a 24 V dc grid for commercial interiors whereas the Data/Telecom Center Standard proposed the use of a 380 V dc grid. In the first case, the voltage is set to a low value of 24 V as it is safe and does not require metal jacketing, metal junction boxes, ground wires and expensive protection means. In the second case, a 380 V dc grid is used in order to support high power loads, longer and thinner cables and to remain within the Class 1 voltage limits set for NEC. It is important to note that these systems are mid-point grounded, so effectively of only $\pm$190 V. This is reasonable as long as only local dc nano- and microgrids are considered.

A recent implementation of a LVdc system was carried out in the Netherlands for the provision of public street light [5]. The system contains smart lamps, in which the intensity and the on/off switching are individually controlled from a central controller using power line communication. The system does not use electrolytic capacitors, which increases the lifetime of the drivers, and the system capacitance is very small as the rate of change of loads during turning on and off of each device is controlled. Grounding and safety is also systematically and practically implemented.

Another representative implementation is a field test of a LVdc distribution network that was carried out in Finland [6] using $\pm$750 V dc. It was observed that LVdc distribution becomes economically attractive for Finnish rural areas compared to 20 / 0.4 kV ac distribution when distance is over 1 km. The LVdc network was designed considering the LV standards HD 60364, IEC 60364, IEC 60664, EN 50160. In this project the dc power is still converted to ac at every house.

III. Viable Future Path for LVDC

The implementation of large scale distributed generation in the form of PV and the adoption of electric cars will pose a new demand for the use of dc grids at the customer end. Charging electric vehicles (EV) directly from PV via a dc connection will reduce the conversion stages and this will result in improved efficiency [7]. Vehicle-to-grid operation of EV will be simplified with a dc microgrid. The next step will be to connect other dc loads like LED lighting, heat pumps, variable-frequency drive machines like washing machines and refrigerators where currently ac/dc rectifiers are required to power the appliances. All this is interesting for partially new investments and for the deployment of hybrid ac/dc systems.

A. Transition to a DC System

The transition to a true dc distribution grid is a big challenge, even if dc outperforms ac. The high initial investment cost prevents the replacement of the whole ac distribution grid at one time. This results in a chicken-and-egg problem: the lack of available dc devices hinders the implementation of small dc grids while the lack of dc grids prevents manufactures from building dc devices. A way to tackle this problem is to introduce dc ready devices that work on both ac and dc. Large volumes of ac consumers would also let play economics of scale for the early adopting dc consumers. Moreover, the costs of dc ready devices are not significantly higher than for ac only devices, as shown in [8].

B. Fewer Pluggable AC Devices

It should be noted that in the future fewer devices will be connected directly to the ac grid. Already today, small devices like mobile phones are powered by USB cables. The USB Type-C connector with the new USB Power Delivery 2.0 Standard increases the power up to 100 W (20 V and 5 A) and allows bidirectional power flow [9]. The first devices to be sold with these characteristics are expected in early 2015 and should be widely available around the time of publication of this paper. Regulations may increase the speed of adoption.

It can be expected that over time the complete range of low power devices will be available with this type of connector. As a result, only few appliances will be left to be connected directly to the ac or dc grid. Most of them are devices that are fixed in the building like heat pumps, washing machines, cooking facilities and lighting. This will simplify the shift to dc in the future.

C. New Infrastructure & Developing Countries

Replacing a working ac distribution infrastructure by a dc equivalent at one time will probably not be a viable solution as the investment costs would be tremendous. However when infrastructure needs to be replaced anyway, it may be a good option to go for dc. In developed countries, it is mainly interesting for newly built quarters to choose dc instead of ac. Nevertheless, increasing the power of existing cables by choosing dc is also an interesting business case in these regions.

In developing countries with unreliable electrical ac infrastructure however, the barrier to move to dc is lower. The overall cost for traditional ac power systems is often high, as backup diesel generators are often installed. A dc distribution system that includes demand response would allow to use the available power. In rural areas that are not connected to an electricity grid it would be very interesting to directly invest in a dc distribution grid instead of an ac one since no infrastructure needs to be replaced. This could turn out as it occurred in the case of the telecommunication infrastructure:

in many developing countries land lines where skipped in favor of a cellular network. However a standardized universal dc distribution system would still be needed.

IV. Opportunities and Challenges

To enable the extended use of dc, it is important to think big from the start. While dc nano- and microgrids can be used to connect for example PV, storage and LED lighting in otherwise ac houses, it is important to already start thinking about the necessary steps to implement a dc distribution network. It is crucial to take the unique chance of defining a new power system and explore all opportunities for the future dc smart grid at this moment, particularly when the electricity infrastructure in developing countries is emerging and the existing networks in developed countries are reaching their maximum capacity. In addition to that, devices should be ready to be connected to a dc grid in the future, even if used first in isolated systems.

A. Grid Architectures

One of the interesting opportunities provided by dc is the possibility of operating meshed distribution grids. This cannot be done in ac due to the fact that power flow is based on phase angle difference. A meshed dc distribution grid built out of interconnected microgrids potentially increases the reliability. The advantage is that power from distributed generators could take the direct path without conversion to higher voltage levels up and down. In case of local failures, other paths would still allow a limited amount of power flow. Of course the prevention of over currents has to be considered.

A LVdc distribution grid can be connected to a MVac grid at multiple points or a MVdc grid could be used. This aspect however is not as critical to be standardized as this part of the system can be fully controlled by the grid owner.

Further, it is important to considered that until now it is often assumed that there will be ac/dc or dc/dc converters at the meter located at each house entrance respectively. While this has the convenience of decoupling the systems it is probably not an optimal solution. Converters would need to be sized for the peak power and there is an additional conversion step required. However disconnection in case of faults should be provided to increase reliability by use of decentralized energy resources. The lowest voltage level covering all devices has to be considered simultaneously as one system.

B. Voltage Levels

One of the challenges in LVdc is to standardize the voltage levels. Ultra low voltage level as currently often seen in dc nano- and microgrids like 24 V proposed by EMerge Alliance [4], 48 V in the telecommunication industry [2] or the 20 V of USB PD Standard [9] suitable to connect small devices are not high enough for a distribution grid with longer distances.

It is expected that the standardization of input voltage levels for generic devices will converge to a value between 350 V and 400 V. These voltage levels are also widely used in the dc links of ac power supplies today. Emerge Alliance proposes to use midpoint ground, therefore effectively making $\pm$190 V out of the 380 V. This can be suitable for isolated local dc grids, like today's data centers.

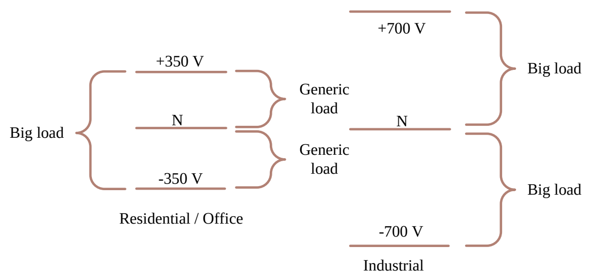

Fig. 1. Bipolar LVdc voltage levels and how devices could be connected [5].

When it comes to longer distances as in a distribution grid, higher voltages are necessary. Using true bipolar systems will half the line losses for balanced systems while copper can be reduced. Generic devices should then be made such that they can be connected to a midpoint grounded system ground but also between a positive and a neutral or a neutral and a negative pole. Bigger devices – that are today connected to three phase ac – could be connected directly between a positive and a negative pole. Fig. 1 illustrates this as proposed with $\pm$350 V by Direct Current B.V. [5]. A $\pm$700 V grid could then be made for applications where a lot of big loads have to be connected. With some room for over voltage droop regulation considered, this is still the under 1500 V limit imposed by the IEC low voltage regulation.

C. Market Integration

Increased amount of distributed energy resources suggest new market models. Prosumer market models will encourage market participation. Real-time pricing has the potential to encourage the use of energy when it is available. Moreover, nodal pricing allows to represent grid congestion through market prices: prices will defer at both ends of the congested infrastructure. Connecting the market closer to the physics should be investigated and losses in the grid could be included in the market price [10].

A hierarchical distributed market model would allow the local usage of energy even when there is a failure at a higher voltage level in the network. Demand response should be incorporated into all devices at least based on undervoltage in order to allow the use of available energy even if the demand exceeds the supply [11]. A good market model and real-time pricing could reduce the necessary rated converter power and the need of additional storage to shift energy from times with high supply to those with high demand. Local storage can be used to allow lower peak power in converters and parts of the grid are thereby weakly coupled.

D. Control and Communication

Microgrids should have intelligent decision-making capabilities for the security, reliability, efficiency and sustainability of the system. As the bulk grid is becoming more of an ”internet of energy”, there should be a way of communication between different terminals in order to enable control strategies. Generally, control strategies can be categorized into centralized, decentralized, distributed and hybrid [12]. Communication is used in centralized and distributed control, whereas no communication is generally used in decentralized and hybrid control. Distributed control has the potential to be the most practical way of control in LVdc because of the fact that it can provide optimal load sharing, high expandability and intermediate reliability. However, there needs further investigation on how much communication is needed for different application.

The use of different kinds of communication methods at different levels of dc has become an interest of research for grid control and data communication. At multi-terminal HVdc and MVdc, communication is mainly used to enable optimized power flow [13]. In LVdc, different communication methods are used for different applications. In [14], wireless communication is implemented for dc grid control. Moreover, wireless communication is a common practice in stand-alone PV [15], dc LED lighting [16] and parallel dc/dc converters for current sharing [17]. The use of Control Area Network (CAN) bus is demonstrated in [12] for dc grid control.

In the case of household applications, optimal energy extraction from renewable sources, smart human interface and the possible future market participation, makes the need for more communication bandwidth and infrastructure. Advances in power line communication technologies have made the use of existing cable infrastructure more economically viable. The use of narrow band power line communication (10 to 500 KHz) for low voltage dc grid control should be investigated. There has been some research done on channel modeling of dc grid [18] and on the effect of noises on communication and the possible remedial actions. However, the effect of power line communication filters on control strategies needs further investigation. The use of broad band power line communication (2 to 30 MHz) for internet and home automation should be researched and it has to be clarified if communication in buildings should only use this band.

E. Constant Power Loads

The dynamics of LVdc systems differ from a traditional ac systems due to the inertia of the system. At the consumer side, most electronics having power electronics interface (PEI) act as constant power loads. Constant power loads have negative resistance during a microgrid disturbance [19]. The inertia of the system is dependent either on the stored energy in the passive component, mostly capacitors, or on how fast the converters respond to the system disturbance. The negative impedance characteristics of PEI with the passive components in a LVdc network introduces instability. LVdc microgrid stability in connections with constant power loads at different levels of network complexities has been addressed with small-signal analysis by linearizing the nominal operation for specific types of power converters. The solution for stability problems can be grouped into two strategies: hardware-based and controller-based. In the case of hardware-based, the solution is based on adding capacitors [20], adding storage [21], and carrying out load shedding [22]. In the case of controller-based solutions, linear PID and passivity control [23] and non-linear boundary controller are used [24].

Small-signal control-based solutions have limitations in terms of their practical implementation, particularly in big systems. In the case of linear controller-based, the PID control works only for local system characteristics, which limits the control to a local equilibrium point. Moreover, the passivity controller-based control applies for single direction of current, which makes it inapplicable for bi-directional power transfer. In the case of non-linear controller-based, the boundary controller-based works with state space switching surface boundary. This method requires the identification of state space boundaries mathematically for each converter, which makes it complex for big systems having a wide range of power levels and for networks having a variation in time with the number of power electronics loads.

Large-signal based LVdc control strategies, which address the inertia of the system, have not been independently studied. With a hardware-based strategy, the inertia of the system will increase, however this will negatively affect the cost of the system, reliability, complexity and will increase fault currents. A step change in load in the LVdc could create a system collapse if the inertia of the system is low or the rate of change of the load is not controlled [25]. There has not been a systematic approach to address the problem of low inertia of the LVdc and constant power loads. Decreasing the system capacitance decreases the fault current of LVdc and allows the use of breakers with considerably less peak currents. Directly coupling batteries into a LVdc grid, solves the problem of the inertia. Nevertheless, sizing and paralleling of the batteries and also faulting issues have to be addressed.

F. Protection Strategy

Conventional LVdc protection categories are utility, converter, distributed generation unit, feeder and bus-bar [26]. In a conventional LVdc, where the system capacitor is large, bus-bar protection is the main concern as the other protection categories can be easily incorporated with in the PEI. For conventional LVdc, commercially available dc protection devices can be used like molded-case circuit breakers, fast static switches [27]. Fuse is possible but it needs an overrated design of source PEI [26] to have high current for generating enough heat. A smart solution with fast detection and isolation mechanism for high impedance faults can be designed and easily achieved for conventional LVdc. Protection coordination needs to be looked further at application level of LVdc.

However, in non-conventional LVdc systems, batteries are decoupled from the system using PEI and terminal capacitors of loads are decoupled using diodes. Detection and isolation can be tricky, therefore a smart way of fault identification should be achieved due to the small value of fault current. One of the simplest approaches is the use of breakers based on voltage levels on the system. However, a thorough study on low inertia LVdc or other optimized architectures is necessary. Decoupling batteries and terminal capacitors decreases the system inertia (stored energy in the bus) and leads to complicated control strategies.

Grounding is a complex aspect. Ungrounded, high, and low impedance grounding connected either to the positive, neutral or negative bus-bars are the common approaches. Ground faults, safety and corrosion are concerns of the different methods. Plug-related arching for consumer electronics needs to be investigated as there is not an inherent zero voltage crossing in the dc bus to minimize it. With constant power loads dominating any microgrid, arching current increases when plugging out a load from the dc bus [28]. The influence of constant power loads in arching during plugging in and out has not been addressed.

Some of the practical challenges that need further investigation in LVdc are lightning and electromagnetic compatibility. Preventing high voltage spikes, for example by the use of varistors at strategic locations, would allow the use of MOSFETs in LVdc.

V. Conclusion

Using dc instead of ac for the smart grids could be an interesting option for the future. The main challenge is that most research topics mentioned in Section IV are heavily interdependent and in order to accomplish a universal dc distribution system, all these aspects have to be considered.

Standardization is essential at the voltage levels where most devices will be connected. However it is important not to only consider local dc nano- and microgrids but to consider their connection to a full universal dc distribution system. Standardization will allow developing countries to choose dc when electrifying rural areas or when investing in new infrastructure in large scale. However, also in developed countries dc could be an attractive option as an alternative to ac smart grids. More research is required to support this.

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