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Review

Analyses of efficiency/energy-savings of DC power distribution systems/microgrids: Past, present and future

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ABSTRACT

DC is reappearing in the power system – it can be seen on the generation side as solar photovoltaics and wind farms with AC/DC/AC conversion; on the transmission side as HVDC lines and on the consumer side as a variety of modern electronic loads. Power distribution is an area where DC has not yet made any practically extensive appearance, this area is still in research phase. Related to DC distribution, the concept of DC microgrids is also witnessing a significant research contribution in the recent times. One of the research areas besides system control, protection etc., is the energy efficiency of the system. This paper gives an overview of the recent and relatively old research efforts in the field of efficiency/energy-savings analysis for the DC power distribution system. Furthermore, critical analysis of the previous research efforts has been provided and gap in the present body of knowledge related to this field has been identified. The requirements of a comprehensive analysis, mathematical modelling and system designing from a future study in this direction have been mentioned. The findings of this paper can serve as guidance for further investigation and research for the energy savings potential of DC power distribution networks.

1. Introduction

While the concept of using DC power for electrical distribution may seem odd to some, this is how the electric power system began its journey [1,2]. However, the concept of DC power was replaced by AC because, apparently, DC did not have any means of varying its voltage level in the early days of power system. AC, on the other hand, could do so by virtue of its electro-magnetic transformer and therefore the voltage level could be stepped up for long distance power transfer and then stepped down for utilization. So the power system became AC and DC was left for some niche applications [3].

However, today we can see that DC has re-appeared in different parts of the electric power system. The power generation side, which has traditionally been the territory of AC three-phase synchronous machines, is now witnessing a strong push towards renewable energy sources (RES). Among these, Solar Photovoltaics (PV) naturally produce DC power, and different windfarms [4,5] also produce DC power as an intermediate stage before converting it to line frequency AC. Furthermore, the concept of DC collector grids, both for solar PV and off-shore wind farms has been proposed [6–9].

Moving on towards power transmission, the HVDC lines have proven a successful option and various installations for these may be found around the globe. Significant amount of research efforts such as [10,11] have been directed towards this field in recent times as well, and HVDC may be regarded as a mature technology at this time with Siemens [12] and ABB [13] providing solutions for it.

On the residential and commercial energy utilization side, the modern electronic loads are hungry for DC power. Personal computers, laptops, LCD displays etc. use DC power and resort to an AC/DC conversion for being plugged into the current power system. Lighting, which is another big consumer of energy is also evolving as a consumer of DC energy with the Light Emitting Diodes (LED) [14,15] based lighting for homes and offices. Table 1 shows US electrical energy consumption data [16] (variations in such category-wise load division may be found from case to case, e.g. [17] places electronics at 14% for residential and commercial sectors and it also mentions “other”

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Table 1
US residential electrical energy end-use splits.

Serial No.	Category	Energy used (Quad. Btu)	Energy usage converted to %
1	Space Heating	0.42	8.8
2	Water Heating	0.48	10
3	Space Cooling	1.02	21.3
4	Lighting	0.53	11.1
5	Refrigeration	0.45	9.4
6	Electronics	0.33	6.9
7	Wet Cleaning	0.33	6.9
8	Cooking	0.11	2.3
9	Computers	0.19	4
10	Other	0.94	19.6

consumption (which includes lighting and appliances, hence this is not exactly the same as that in Table 1) to be 60% for low energy homes). Taking the Lighting, Computers and Electronics categories to be DC makes the demand for this energy to be about 22%.

Furthermore, with the advent of Variable Speed Drives (VSD) that use an AC/DC/AC conversion, the categories of Space Heating and Space Cooling may also be taken as DC loads [16]. Thus, the total demand for DC energy by the residential customer sums up to be 52.1%. This is an astonishing figure; the demand for DC energy is even more than that for AC. So, DC energy is already present in three of the four parts of the electrical power system, leaving distribution as the only area where it has not set a firm foot yet. Fig. 1 gives a summary for this state of DC in the power system. Power distribution is the area which may be regarded as in the phase of research at the current time; different aspects of this new field need to be researched upon; some of these are the system efficiency, control of the constituent converters and protection of the system. In the recent past, the concept of Microgrids has been presented and this has also been extended for DC distribution systems [18–26].

The current work is an attempt that presents an overview of the different research efforts related to the efficiency of DC distribution networks. Furthermore, we present a critique on various earlier efforts and bring to light the gap in the current body of knowledge related to this field. The directions for future work related to the efficiency/

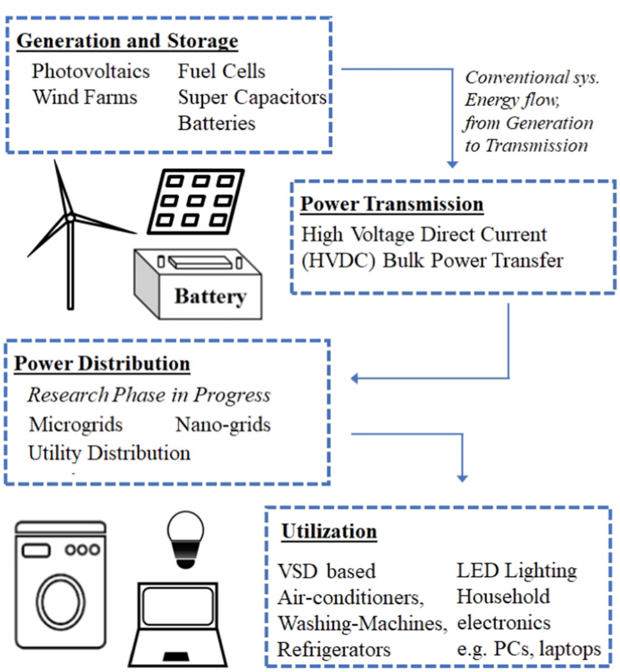

Fig. 1. DC in the electric power system.

energy-savings of DC power distribution may be adjusted based upon the findings presented in the current paper. Moreover, the significance of this effort is that while a number of review/magazine articles related to DC power distribution exist in literature [3,21,27,28]; the current work may be first paper focused towards reviewing the publications related to efficiency/energy-savings potential of DC distribution. The distribution part of the power system may further be divided into three portions – Primary, Secondary and Tertiary distribution systems; which are, respectively, the relatively high voltage power transfer network from substation to SSTs/Transformers – also referred to as medium voltage (MV) system, the relatively low voltage (LV) power transfer network from SSTs to building blocks and lastly the low voltage power distribution portion inside the building.

2. Applications of DC distribution and microgrid

2.1. DC distributed power system

The traditional DC distributed power system (DPS) may be regarded as the forerunner of the current DC microgrids and distribution systems. A significant amount of publications has been dedicated towards it such as [29–34]. The modern DC microgrids may be regarded as an up-scaled version of the DC DPS [34].

2.2. DC power for residential and commercial buildings

As the loads become DC, it is natural to think about DC as the medium for in-building power distribution. Then again it is natural to consider DC for the integration of distributed generation (DG) via Solar PV and also for the integration of different energy storage media such as batteries and super-capacitors. Thus microgrids, which can be thought of as a concept that can bring together alternative energy based DG, hybrid storage and residential and/or commercial loads while allowing connected or independent (islanded) operation from the utility grid (wherein the latter i.e. islanded mode may be regarded as a defining characteristic for microgrids), have shown an inclination towards research and development with DC power [18–26].

Fig. 2 shows the concept of a DC microgrid, with loads, storage media and generation sources connected to it via/without appropriate power electronic converters (PEC). Single voltage and dual voltage topologies for in-building utilization are shown and efficiency values of different components are mentioned. Various topologies such as bipolar single regulated bus and multiple DC microgrid cluster as well as different voltage levels such as 24, 48, 380 and ± 170 V have been proposed for the DC microgrid concept. Nanogrids is another word that is being used for power transfer at small level and DC may be found here as well [35–37].

2.3. Charging stations for hybrid electric vehicles

In the recent past, the Hybrid Electric Vehicles (HEV) have been introduced in the market and research is going on for different options related to their charging stations. One of the options is the use DC bus for these charging stations [38–41].

2.4. Solar and wind collector parks

The concept of DC collector grids has been proposed both for Solar PV farms and for off-shore Wind farms [6–9]. For the latter case, using AC submarine cables for carrying power from the farm to the on-shore grid naturally leads to power losses due to charging current. This can be avoided by the use of a pure DC off-shore grid and coupled with an HVDC energy transfer. For the Solar farms, a DC collector grid will serve to gather DC energy from all the individual panels of the farm and finally convert the combined DC power to AC for connecting to the grid. Such a solution has been mentioned to increase the overall energy yield