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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.**

Keywords: Applications of DC power, DC power distribution, DC versus AC, Energy savings, Efficiency.

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 I 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" consumption (which includes lighting and appliances, hence this is not exactly the same as that in Table I) 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%.

TABLE I. 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

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/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.

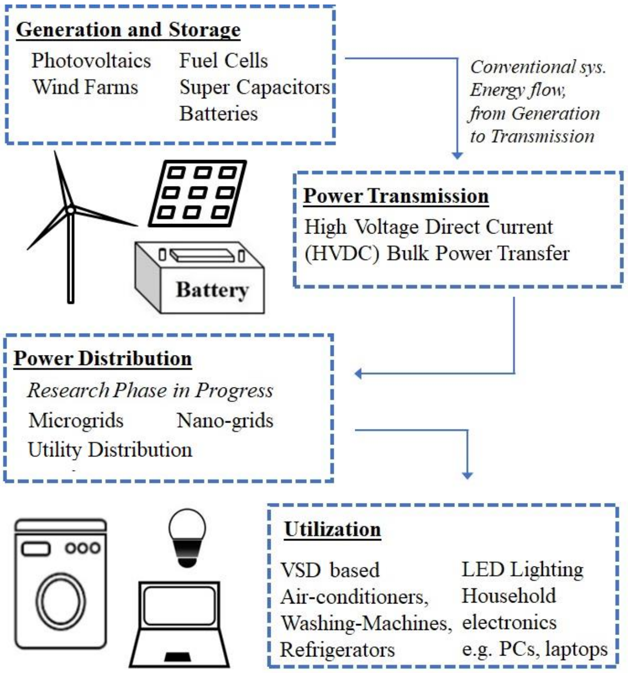


Figure 1. DC in the Electric Power System

2. Applications of DC Distribution and Microgrid

A. *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].

B. *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 ±170V 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].

C. *Charging Stations for Hybrid Electric Vehicles*

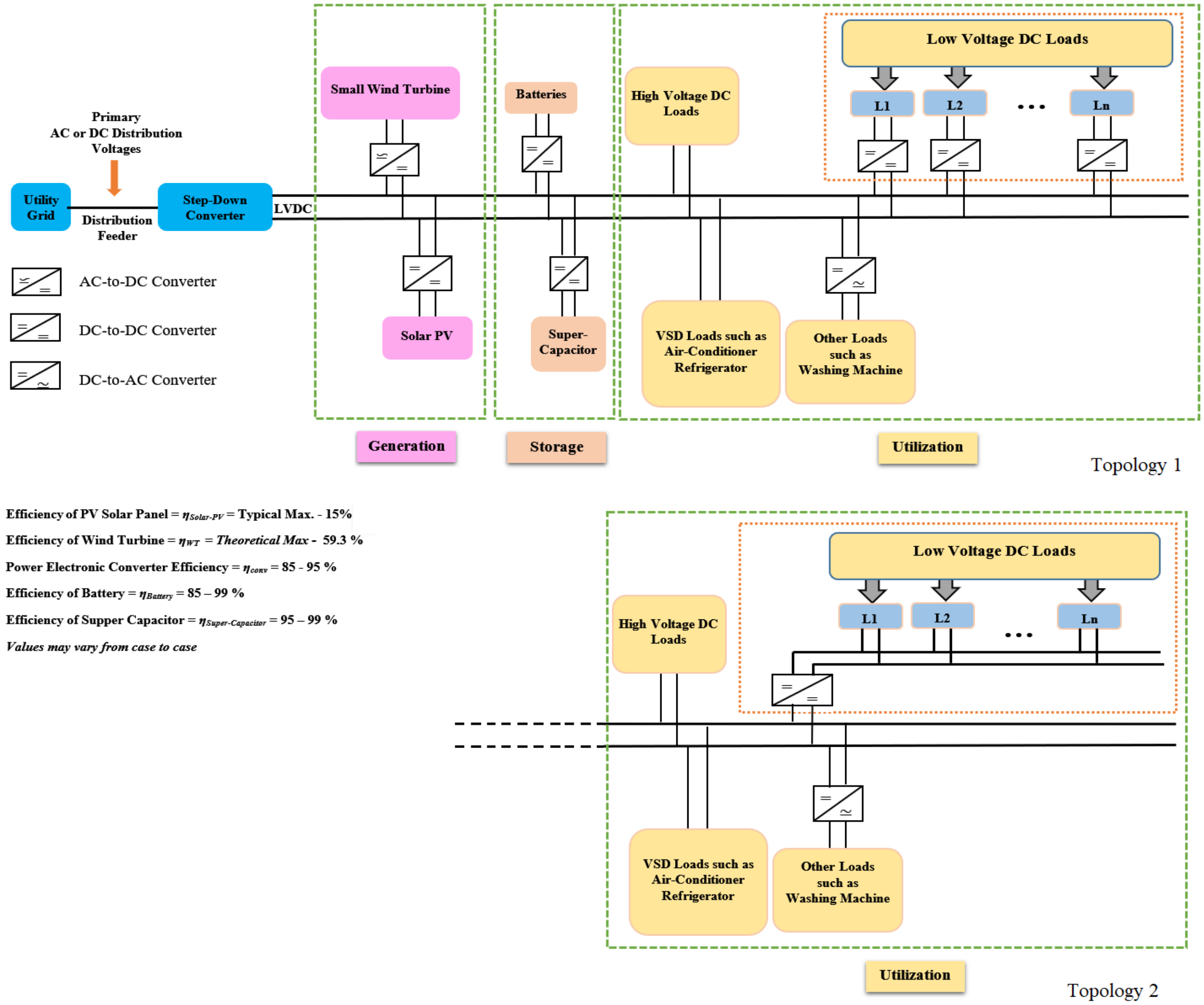
In the recent past, the Hybrid Electric Vehicles (HEV) have been introduced in the market and research is going on for different options related to their charging stations. One of the options is the use DC bus for these charging stations [38]–[41].

D. *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 of the plant [9].

E. *Power Supplies for Telecom and Data Centers*

DC power distribution has long been an option for telecom power supplies [42]. The voltage level has been 48V DC. Also, for Data Centers, the DC power has seen a number of



Efficiency of PV Solar Panel = $\eta_{Solar\text{-}PV}$ = Typical Max. - 15%

Efficiency of Wind Turbine = η_{WT} = *Theoretical Max* - 59.3 %

Power Electronic Converter Efficiency = η_{conv} = 85 - 95 %

Efficiency of Battery = $\eta_{Battery}$ = 85 – 99 %

Efficiency of Supper Capacitor = $\eta_{Super\text{-}Capacitor}$ = 95 – 99 %

Values may vary from case to case

Figure 2. DC Microgrid Schematic

research efforts [43], [44] and [45] was a practical high-power DC datacenter in Zurich, Switzerland.

F. USB and Power over Ethernet Systems

Among the applications of DC power distribution, USB and PoE may also be mentioned although these are limited to relatively small power. The USB port can supply DC power to connected devices and the power level is generally rising with the newer specifications. Power over Ethernet (PoE) appears more suitable for powering residential loads e.g. smart loads where both communication and power are required [46].

3. EFFICIENCY STUDIES OF DC DISTRIBUTION: THE PAST

This section discusses various studies related to the efficiency of DC power distribution made relatively in the relative past (around/before 2012). The authors of [44] discuss the use of DC power for data centers. They mention that high efficiency is offered by the use of facility-level DC distribution as it eliminates a number of components in a conventional AC distribution system for the data centers. These components are a DC/AC inverter, an AC/DC rectifier as well as a transformer. The authors present an efficiency comparison of different cases for data center power architecture based upon calculation and show that the facility-level DC distribution has the highest efficiency of. all. The paper further goes on to present a small-scale demonstration for comparison of AC and DC distribution for system efficiency and the authors mention an input power savings of about 7% for their test scenario when 400V DC distribution was used instead of their AC architecture

Reference [28] is another article that mentions the efficiency advantage of DC distribution for data centers. The authors say that in 2004, an investigation for the efficiency of power distribution in data centers was initiated by Lawrence Berkeley National Laboratory (LBNL). Their result was a potential 28% increase in system efficiency if the 208V AC system was replaced by 380V DC system. The article further mentions that compared to 415V AC system, the 380V DC system gives an efficiency advantage of 7%. Furthermore, GE and Validus DC Systems have estimated a 36% lower life time cost for DC. Although not being an efficiency study, [47] mentions that the current found in a 380V DC grid is only 61% of the real current in a 230V single phase grid. Consequently, conduction losses in DC are 37% of AC network and an efficiency gain of 1 – 2 % may be obtained for the DC system. However, it raises a question that is the DC grid demanding more power (*380*0.61 > 230*1*). In the current paper, section 5A mentions the presence of differences in results of research.

Reference [48] was an effort related to the efficiency comparison of DC and AC distribution systems by two of the current authors. We used US Energy Information Administration data for load modeling and categorized the loads as inherently DC, inherently AC and independent loads (which can work with both AC and DC). The DC loads were used with AC/DC and DC/DC conversions in AC and DC distribution systems respectively and our study included both the MV and LVDC network. Our result showed a 2.5% efficiency advantage of the DC system over AC. Furthermore, we worked towards a mathematical equation, presented here as (1), for determining the minimum required efficiency η_{PEC} of the system power electronic converter to make the DC system efficiency equal to that of a given AC system.

$$a.\eta_{PEC}^{-2} + b.\eta_{PEC}^{-1} + c = 0 \tag{1}$$

Where,

$$a = \frac{r_1.l_1*(P_A+P_D)^2}{V_b^2} * \frac{\alpha}{\eta_{DX}} \tag{2}$$

$$b = \left[(P_A + P_D) + \frac{2P_I(P_A+P_D)}{V_b^2}\right] * \frac{\alpha}{\eta_{DX}} \tag{3}$$

$$c = \left[P_I + \frac{P_I^2}{V_b^2} * r_1 * l_1\right] * \frac{\alpha}{\eta_{DX}} - P_{IDX} \tag{4}$$

The various parameters include P_A, P_D & P_I which are the power demands of AC, DC and independent load categories, α is the number of residential buildings served by one DC/DC transformer whose efficiency is η_{DX} and whose input power is P_{IDX}. However, this work did not include the variation in load and the corresponding variation in converter efficiencies. Also, the results were only presented for a single case, a variety of scenarios was not considered. Furthermore, we did not include the modern concept of VSD based loads in this study.

Reference [49] analyzes the feasibility for supply of DC to commercial facilities. A case study analysis is presented for supply of power to a department in a university. The authors give voltage drop and power loss calculations for DC power supplied at 326, 120, 230 and 48V, besides performing an economic evaluation of DC system. The conclusion drawn by authors is that DC can lead to big advantages and technically and economically 326V is the most suitable voltage level. The major limitation of this work is that it only includes the conduction losses occurring in the system for the loss comparison results; the power losses in the PEC have not been mentioned explicitly in this study.

The authors of [50] determine the losses occurring in a DC and AC power distribution system including both MV and LV portions. Results have been given for different voltage levels and efficiencies of DC/DC converter. The authors conclude that AC and DC distribution have same merit when half of the loads are AC and half DC. They further mention that DC/DC converter is the defining device for DC distribution system. However, this study does not mention the efficiency values of the other two PECs i.e. DC/AC inverter and AC/DC rectifier. Furthermore, a 50-50 division of DC and AC loads cannot always be realized. Also, the authors use fixed values for the efficiency of DC/DC converters in this study.

Reference [51] is another efficiency comparison of DC and AC for in-building power distribution including the distribution transformer. Comparative results are based on the number of energy conversion stages; conduction losses are not included. The results showed that if DC power had to be supplied via a rectifier to a building, then DC does not have an advantage. However, if local DC generation is present, DC will show better efficiency. Variation of load, variable efficiencies of PEC and partial generation via local DC source have not been included in this study. Reference [52] presents topological design, safety measures and efficiency analysis of DC distribution. The authors assume that loads are suitable for use with DC system. The results only show a difference in conduction losses of the two systems.

Amin et al [53] compared low voltage (24V and 48V) DC distribution with a 230V AC system for home. The authors have concluded that losses are lowest for the 48V DC case. They assumed that DC loads can directly work with the distribution DC voltage and load variation was not included in this study. Reference [54] is another efficiency comparison of DC and AC systems that includes MV and LV levels. The authors present results for AC, DC and mixed AC-DC (MV is AC and LV is DC) systems. They conclude that losses for the DC and the mixed system are about 0.5% and 1% higher than that of AC system. The authors have used a fixed value (300W) for the loads and the difference of internally-DC and internally-AC loads has not been mentioned. The loads are assumed to be directly compatible with DC voltage and there is no mention of PEC inside a building. In short, the intricate details of the system inside a building have not been included in this study.

This section presented a number of efforts related to the efficiency of DC distribution networks carried out in the past (around/before 2012). The idea of efficiency analysis for DC systems has been there for a substantial time – the earliest paper cited by us was published in 2003. However, the area witnessed a relatively less amount of research focus. Furthermore, the basic question of superiority of DC over AC, remained un-answered as some authors were inclined towards DC while others were not-so-inclined towards it. In our view, this difference of author opinions was due to the lack of comprehensive studies (as mentioned in section 5) which could bring out a definite verdict for the DC versus AC comparison for power distribution networks.

4. EFFICIENCY STUDIES OF DC DISTRIBUTION: THE PRESENT

This section discusses relatively recent studies related to the efficiency of DC power distribution. The authors of [18] discuss a DC microgrid where energy generated via Solar PV is connected to their load (LED lights) via only one power electronic conversion which is the driver for LEDs. Fig. 3 shows this configuration.

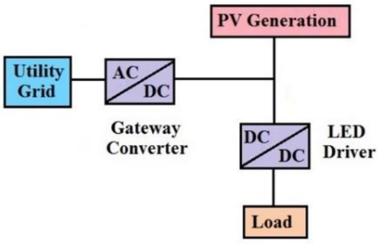


Figure 3. DC microgrid of [18]

The authors mention that in the patented configuration, the maximum power point tracking (MPPT) is performed by the voltage regulation of the AC/DC gateway converter. This configuration enables higher efficiency as compared to the case where MPPT is performed by the converter through which all of the PV generated power passes. The authors mention an installation in North Carolina where an AC system was installed next to the DC for efficiency comparison. They mention that the DC system used PV energy 8% more efficiently as compared to the AC system. In our view, the work of [18] needs to be extended for the general residential and/or commercial loads which include induction motor based loads that necessitate a DC/AC inverter stage. Furthermore, the work may be extended to multiple voltage levels and varying load profile for its applicability to residential microgrid scenario.

The authors of [19] mention that DC distribution system can give higher efficiency due to reduction in stages of power conversion. They give an efficiency comparison of DC and AC microgrid and choose 48V as the voltage level for DC. Their work is based upon the assumption that DC loads (even high-power loads such as electric iron) are compatible with this voltage level. However, this assumption reduces the significance of the results as it is quite infeasible to operate an electric iron at such a low voltage level because of the huge copper losses or the corresponding large investment in higher diameter wiring. The authors mention that their analysis shows higher efficiency of the DC distribution system as compared to the AC system.

Reference [20] is another comparative analysis of efficiency for AC and DC microgrids. The authors mention that they have used a stochastic technique for estimation of household load profile for a small community microgrid. The authors make the assumption that the total residential load is equally divided as DC and AC loads. Furthermore, although the authors have included load variation in their study, they have still used fixed values of PEC efficiencies which may be regarded as another assumption of this effort. The work of these authors shows higher efficiency for the AC microgrid system.

Reference [55] was another research effort towards the efficiency of DC distribution by two of the current authors. We included both the medium voltage (MV) and the low voltage (LV) distribution in the study. The primary aim was to investigate the DC system efficiency for the case of variation in system load while taking into consideration the corresponding variation in the efficiencies of the constituent PEC. We divided one complete day into three portions Night (00:00 to 06:00), Day-1 (06:00 to 15:00) and Day-2 (15:00 to 00:00) and evaluated the system efficiencies to be 82.8%, 85.6% and 85.7% respectively. The Night mode, with the least load showed the least efficiency. Followed by this, a sensitivity analysis of system efficiency was also performed to bring to light the effect of variation in individual converter loss coefficient on the overall DC distribution system efficiency. In terms of loss coefficients, the efficiency of a converter may be written as

$$\eta = \frac{p_o}{p_{in}} = \frac{p_o}{p_o + k_o + k_1 p_o + k_2 p_o^2} \tag{5}$$

where η is the converter efficiency, P_o and P_{in} are output and input powers, k_0, k_1 and k_2 are constant, linear and quadratic loss coefficients. The system was found to be highly sensitive to the coefficient k_0 in the Night mode. Furthermore, the highest loss was found to be occurring in the DC/DC converter transformer, and a distribution of losses in the Night mode presented in Fig. 4, showed a high proportion of constant PEC (DC/DC SST) losses. However, we did not make a comparison of the system performance with a corresponding AC system in this work. Furthermore, this work neither included on-site renewable generation nor VSD based loads.

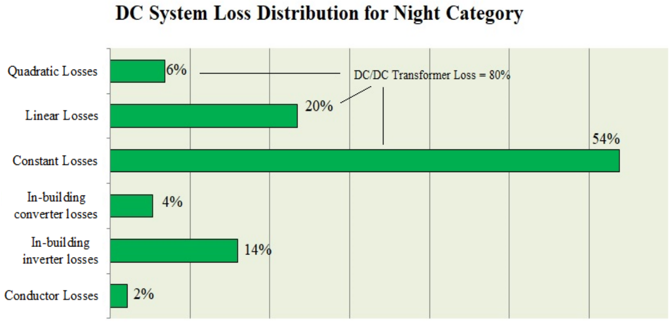


Figure 4. DC distribution System Losses presented in [55]

Reference [16] is a relatively recent work related to DC distribution system efficiency by two of the current authors. We have given a comparative analysis for residential (MV and LV) AC and DC distribution. We included the load categories of space heating and space cooling as loads demanding DC power based upon the assumption of VSD air-conditioning. For a fair comparison, we used the same voltage level (230V) for both systems although higher voltage levels of 326 and 380 had been suggested in literature. Moreover, the converter efficiencies for both systems and the primary distribution conductor were kept the same. The utility grid was assumed AC for AC distribution and DC for the DC distribution. The DC system showed slightly higher (about 1%) efficiency as compared to AC. In the concluding remarks, we mentioned that although DC has shown comparable efficiency value to AC distribution, however to give up AC and take up DC, the performance of DC should exceed that of AC. Since our result, showed a minor benefit of DC, so we could not recommend it for general adoption. The limitations of this work include not taking into consideration on-site DC generation, variation of system loads and corresponding PEC efficiency variation.

Reference [21] is a magazine article that discusses LVDC power architectures and microgrids. The authors say that a DC subsystem connected to an AC distribution system via DC/AC converter gives independence from the utility mains quality. Moreover, it gives natural interface for modern electronic loads and for most RES and energy storage systems.

Furthermore, with proper selection of nominal voltage, the system efficiency will generally be higher than its AC counterpart. The authors go on to mention that DC power demanding loads such as LEDs, consumer electronics and VSD based loads (such as air-conditioners and refrigerators) can contribute to the improvement of DC system efficiency by omitting one or more DC/AC conversion stages.

Vossos et al [56] estimate the potential energy savings by the use of direct-DC in net-metered residences in the US. The authors conclude that while accounting for variable loads, direct-DC can save about 5% of total electricity for non-storage case and about 14% for storage case. A couple of assumptions made by the authors are that all residential loads are internally DC and that the in-building distribution losses for AC and DC are comparable. Reference [57] is another comparative efficiency study for DC and AC distribution aimed at the commercial buildings. The authors conclude that if a local DC source is not present then DC distribution does not bring any significant advantage. The DC distribution for an islanded building with PV and storage can give an advantage of 3.4%, and for a general case of having AC and DC sources along with battery consumption, the efficiency improvement due to DC is only 1.3%. The authors are of the view that efficiency alone is not a significant driver for adopting DC power distribution in buildings.

The authors of [58] present efficiency advantage of DC over AC distribution for an office test bed. LED lighting is the only load considered. Equation (6) has been used for the calculation of relative energy consumption savings of DC versus AC in different time intervals.

$$\Delta p = \frac{\Delta E_{AC} - \Delta E_{DC}}{\Delta E_{AC}} \cdot \frac{1}{\Delta t} \qquad (6)$$

The authors conclude that for their test set-up, a 2% energy savings has been measured for the DC system as compared to AC. They further mention that the efficiency advantage of DC can go upto 5% at twice the power level.

In [59], Weiss et al present comparative efficiency results for DC and AC power distribution for commercial sector using a DC distribution hardware test bed. The authors mention that the European ENIAC R and D project consortium DC components and Grid (DCC+G) is developing high efficiency components and sub-systems for 380V DC grid. This is to show the advantage of DC grid concept on test site in office environment. The components used for the hardware based proto-type include central rectifier, integrated solar MPPT converter, micro-CHP unit, programmable electronic DC load and others. The authors conclude that for a usual day of operation, the 380V DC system was found to give 2.7% efficiency advantage as compared to 400/230 V AC system.

Reference [60] is a simulation based comparison of system efficiency for DC and AC power distribution in commercial buildings. Comparative system efficiency results are presented for different sizes of office buildings. Furthermore, the results are presented for three main experimental studies, solar experiment, battery experiment and converter experiment. In these experiments, the comparative results are presented against varying solar capacity (kW), battery capacity (kWh) and converter oversize ratio. In the conclusion section, the authors mention that their research found that the baseline efficiency savings in case of small and medium office building while using DC distribution are 9.9% and 11.9%; the best case scenario gives savings of 17.9% and 18.5% respectively.

In [61], Glasgo et al give energy savings as well as levelized annual cost (LAC) of various scenarios of in-building DC power as compared to traditional AC home for residential buildings. The scenarios include all-DC home with DC distribution as well as DC loads and partly-AC, partly-DC cases such as DC for lighting only or for HVAC condensing only. The option of including battery storage has been considered. Certain assumptions have been made such as assuming high efficiencies of niche DC appliances to be maintained in residential products, and assuming line losses in DC home to be comparable to those of a traditional AC home.

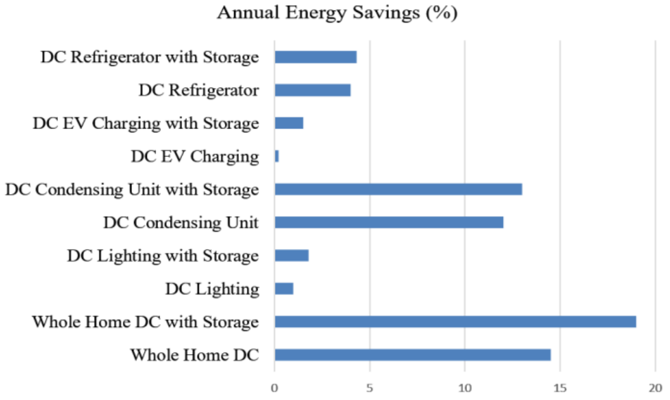


Figure 5. Energy savings of DC as percentage of baseline consumption of traditional AC homes presented by [61]

Fig. 5 shows energy savings results of the authors for different cases of their study. The authors mention that despite energy and emission savings, the extra cost for DC is higher as compared to implementing AC distributed solar PV alone in all cases except the case of solar arrays with direct-DC distribution to condensing unit only.

As a summary of the review, it may be said that sections 3 and 4 depict that the studies related to the efficiency of DC power distribution are in progress for more than a decade. However, despite the long research, the topic still seems to require more work in order to reach a definite conclusive verdict. One major issue with the research efforts in this field is the lack of comprehensive studies; the majority of publications are papers presented in conferences while in-depth and detailed journal publications have a much smaller number. The concept of efficiency/energy-savings of DC distribution networks has not been investigated thoroughly by a single group of scientists, rather various researchers have investigated this field for their own set of parameters/circumstances/assumptions. Based upon the variety of assumptions/test-scenarios, conflicting results exist in literature. The next section mentions further directions of research in this area.

5. EFFICIENCY STUDIES OF DC DISTRIBUTION: THE REQUIREMENT IN FUTURE

This section begins by giving an idea of the differences in the parameters included in DC distribution studies by some of the researchers– this is presented in Table II.

TABLE II. VARIOUS PARAMETERS FOR DC DISTRIBUTION EFFICIENCY STUDIES INCLUDED BY VARIOUS RESEARCH EFFORTS

Research Work	Load-side PEC losses included	Load side PEC efficiency variation included	DC/DC SST losses included	DC/DC SST efficiency variation included	Comparison with AC sys.	Distribution AC transformer losses included	Distribution AC transformer loss variation included	Applicable for current loads	Conductor losses included	MVDC	Renewable Energy	Energy Storage	Multiple voltage levels (MV/LV)	Variety in residential/commercial loads	Load variation based upon time of day	Results – Briefly
Gerber et al [60]	✓	✓	_	_	✓	_	_	_*1	✓	_	✓	✓	✓*2	✓	✓	DC is better than AC for the small and medium office buildings. However, a batteryless ZNE building rarely benefits from DC.
Glasgo et al [61]	✓	✓	_	_	✓	_	_	_*3	_*4	_	✓	✓	_	✓	✓*5	Average energy savings in whole-home DC are between 9%-20% as compared to a traditional AC home. Energy storage increases savings.
Dastgeer &Gelani [16]	✓	✓	✓	✓	✓	✓	✓	_*6	✓	✓	_	_	_	✓	_	AC is better than DC for case of non-VSD air-conditioning; for the opposite case, DC gets slightly better than AC.
Vossos et al [56]	✓	✓*8	_	_	✓	_	_	_	_*4	_	✓	✓	✓*7	✓*9	✓*8	DC could give significant savings for U.S. net-metered houses. The DC system gives 5% & 14% savings for non-storage and storage cases respectively.
Dastgeer &Kalam [48]	✓	_	✓	_	✓	✓	_	✓*10	✓	✓	_	_	_	✓	_	DC can be the preferred choice for distribution systems.
Hammerstrom [51]	✓	_	_	_	✓	✓	_	✓	_	_	_*11	_	_	✓	_	DC is unsuitable except with a local DC power source.
Ujjal et al [19]	✓	_	_	_	✓	_	_	_	_	_	_	_	_	✓	_	LVDC shows higher efficiency vs LVAC.
Jérôme et al [57]	✓	_*12	_	_	✓	_	_	_	✓	_	✓	✓	_	✓	✓	Applications with AC and DC sources along with self-consumption and battery usage improve efficiency only by 1.3% with DC distribution. Efficiency alone cannot be a strong motivation for DC.
Boeke & Wendt [58]	✓	_	_	_	✓	_	_	✓	✓	_	✓	_	_	_	_	2% energy savings has been measured for DC as compared to AC. It can rise to 5% at twice the power level.
Weiss et al [59]	✓	_*13	_	_	✓	_	_	✓	✓	_	✓	_	_	✓	✓	For a usual day of operation, efficiency advantage of DC over AC is 2.7%.

*1 - Applicable for current load refers to the idea that the research does not require modified loads (as compared to those available) for its applicability. The work of Gerber et al assumes all loads are internally DC and future VFD loads designed for direct DC will required no input DC/DC converter. Hence it is not given a check mark.

*2 - Two levels, at LVDC; 48V and 380V.

*3 - The work assumes refrigeration is BLDC motor based. However, the extra investment for DC systems is included in the economic comparison.

*4 - Line losses of AC and DC are assumed comparable.

*5 - Load variation is not present explicitly. However, the work is apparently based upon dataset including recording for approx. 693 houses with data available for upto 28 circuits per home at one-minute interval.

*6 - Assumes all lighting is DC. Also, assumes DC loads are directly compatible with distribution DC voltage.

*7 - Two levels, 380V and 480V DC.

*8 - Two steps only (Full load & Part Load) for load variation and corresponding converter efficiency variation.

*9 - Three types only – Low power, cooling and non-cooling loads.

*10 - Assumes lighting and heating loads can directly use supplied DC level.

*11 - The study includes one case where fuel-cell is assumed to produce DC energy for the home.

*12 - Efficiency values have been averaged for different scenarios.

*13 - Efficiency variation for PEC has not been mentioned explicitly.

A. *The Need for a Comprehensive Analysis*

It may be seen from Table II that different earlier research efforts have worked with different sets of system parameters. Differences in the results of DC distribution efficiency studies exist as well. For instance, where [16] and [57] mention little or no advantage of DC over AC; [61] and [56] give good results in favor of DC. Moreover, [58] and [59] mention around 2% energy savings for DC in the commercial sector, while [60] mentions that the baseline efficiency savings for small and medium office buildings with DC power are 9.9% and 11.9% and the best-case scenarios raise these values to 17.9% and 18.5%. A comprehensive research effort to obtain a definite verdict for efficiency of DC distribution/microgrids compared to an equivalent AC system for commercial and residential buildings is missing in the present body of knowledge. Is DC really better than AC? If yes, by how much? Under what conditions? For which scenarios? A single comprehensive study needs to be performed to answer such questions. It is really important what assumptions are made for the efficiency of PECs (which include rectifiers, DC/DC converters and inverters), and a comprehensive study should take this into account. Since efficiency may also be related with the load type and position, henceforth, a comprehensive analysis should include all feasible combinations of type and position for the system loading. Furthermore, instead of giving just a few efficiency answers, the study should be able to give system efficiency for a variety of feasible combinations (states) of the system parameters.

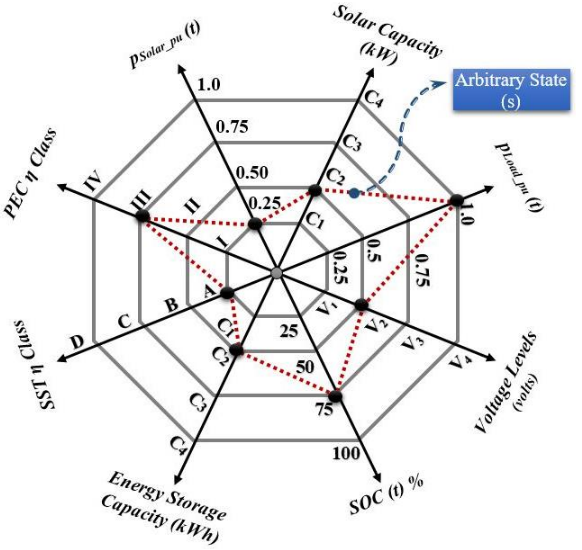


Figure 6. Concept of a multi-dimentional state space for a multi-parameter, muti-valued efficiency analysis

Fig. 6 is presented here to pictorially deliver the concept of various states for a comprehensive analysis comprising multiple system parameters each having multiple values – the figure is limited to eight parameters only, an actual analysis may have more parameters. The state variables shown in Fig. 6 are capacity of solar PV installed in kW, actual power delivered by the solar PV at a time *'t'* in per-unit (pu), efficiency class of the load side PECs, SST efficiency class, installed energy storage capacity in kWh, its state of charge (SOC) at time '*t*', the voltage level in volts of the system and load power demand in pu. The idea is to include the various significant system parameters for a DC system efficiency analysis as well as for a DC-AC comparative study, in order to cover the various scenarios/conditions. At a given time *t*, assume a generic system having multiple state variables to be in state s_1. This state may be expressed as a set of state equations shown in (7).

$$\left.\begin{cases} p_{Solar} = f_1(t) = \rho\, Watts & f_1 \rightarrow \; solar\ insolation\ curve \\ p_{Load} = f_2(t) = \sigma\, Watts & f_2 \rightarrow daily\ load\ curve \\ \eta_{Load\ side\ PEC} = g_1(load) = \varphi\% & \\ \eta_{SST} = g_2(load) = \omega\% & \\ & g_1, g_2 \rightarrow PEC\ and\ SST \\ & Efficiency\ vs. Load\ curves \\ SST\ \eta\ Class = X & X \rightarrow Arbitrary\ \eta\ Class \\ SOC_{Battery} = h_1(t) = \epsilon\% & h_1 \rightarrow Battery\ SOC \\ \quad . & \quad vs. time\ curve \\ \quad . & \\ \quad . & \end{cases}\right\} \rightarrow s_1 \quad (7)$$

The comprehensive analysis needs to proceed to find the system efficiency and the comparative energy savings of DC over AC

$$\eta_{DC}\,(s_1) = \gamma\%,\ \eta_{savings}\,(s_1) = \delta\%, \qquad (8)$$

where, $\eta_{savings}$ is the efficiency advantage of DC over AC. Subsequently, the analysis may be carried out for all of the state space theoretically; practically the analyses will be run over and over for a variety of feasible/possible states of the system. A concept state flow diagram is shown in Fig. 7 where only two state variables p_{Solar} and p_{Load} have been chosen to give the notion. α and β mention the state-to-state change in values of the variables p_{Solar} and p_{Load} respectively. For an actual system, with, say *n* state variables, the change in any variable will lead to a new state. The results of (8) i.e. the analysis for system efficiency/energy-savings may be performed for a large number of the feasible states in the wider state space of the system, in order to finally answer if DC is really superior to AC overall or is the superiority largely conditional and limited.

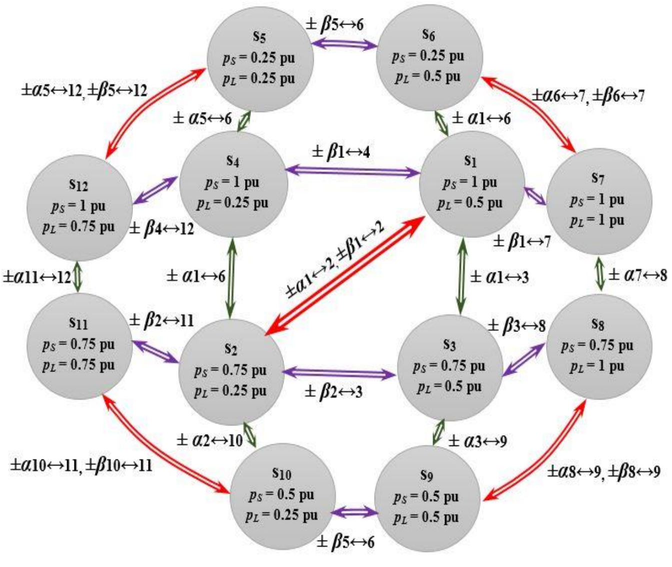


Figure 7. A state flow diagram for a distribution network (Only two state variables p_{Solar} and p_{Load} chosen to depict the concept)

B. *Sensitivity Analyses of System Efficiency*

Subsequent to the comprehensive efficiency comparison, a sensitivity analysis may also be carried out to precisely determine the effect of variation in individual system parameter upon the comparative energy savings of the DC and AC systems. The sensitivity study may be able to break down the analyses in terms of individual parameter variations, and present a scenario similar to the classical comparison of HVAC transmission vs HVDC transmission. Fig. 8 shows this concept in pictorial form, where the traditional HVAC vs HVDC comparison is shown besides multiple parametric comparisons for AC vs DC distribution. DC and AC need to be mutually compared for the variation in different parameters to give the break-even values similar to the traditional break-even distance of HVAC and HVDC. Such break-even values may be there for each parameter e.g. a break-even value of installed solar capacity will yield equal system efficiency for DC and AC distribution; higher installed solar capacity will lead to higher energy savings via DC.

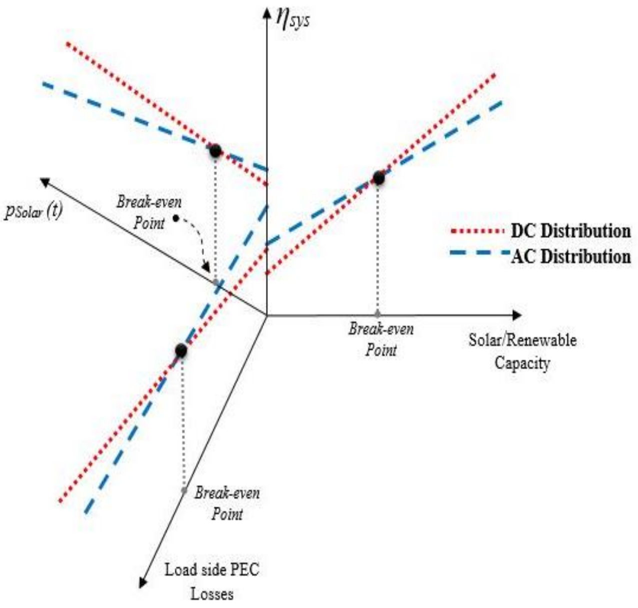


Figure 8. Sensitivity analysis of DC vs AC systems

C. *Mathematical Modeling*

Mathematical modeling of DC (& AC) distribution systems for the specific purpose of efficiency analysis is also a missing feature in this body of knowledge. Different papers such as [16], [55], [56], [61] and [62] are not only simulation based but also do not present detailed mathematical models of the DC (and if present, the AC) systems. Briefly, here we attempt to present an initial stage mathematical model of a DC network for efficiency analysis. Fig. 8(a) presents schematic diagram of a residential building block, with loads divided into four categories as in [16];

A category Loads: Natively AC loads such as induction motor based washing machine.

D Category Loads: Natively DC loads such as LED Lightning.

I Category Loads: Independent loads that can fundamentally work with both AC and DC such as electric iron.

VSD category Loads: Variable Speed Drives loads such as air-conditioner.

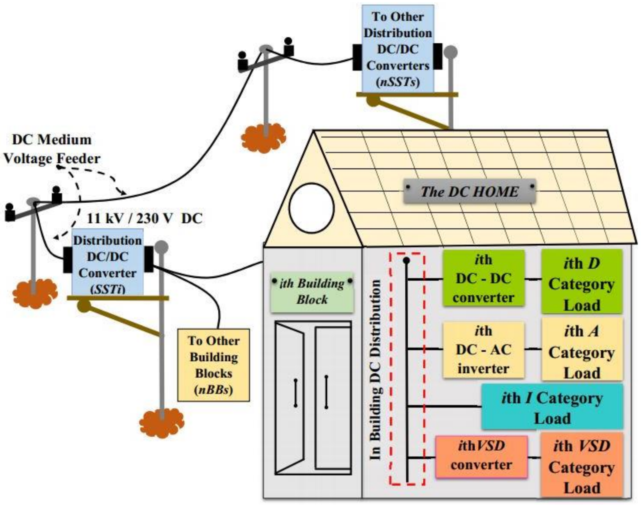


Figure 9. Conceptual Diagram of DC distribution

The aim of the model is to calculate the total input power of the system at a given time '*t*'. Following a bottom-up approach and starting with a single building block *BB1*, which has 'n_1' number of DC loads; total DC input power for *BB1* becomes

$$p_{DC\_BB1}(t)=\sum_{i=1}^{n_1}\left(\frac{p_{D_i}(t)}{\eta_{conv-i}}\right) \tag{9}$$

where $p_{Di}(t)$ is the power consumed by the *i*th load from *D* category in *BB1*, dividing this by the associated converter efficiency η_{conv-i} gives the power demand of the *i*th DC load. Here it has been assumed that the DC loads are fixed power loads and follow an ON/OFF portion only – for variable loads with a varying profile of associated converter efficiency, we may require to use η_{conv-i} as a function of the load i.e. $\eta_{conv-i}(p_{Di}(t))$. Continuing for the other load categories of *BB1*

$$p_{AC\_BB1}(t)=\sum_{i=1}^{n_2}\left(\frac{p_{A_i}(t)}{\eta_{inv-i}}\right) \tag{10}$$

$$p_{I\_BB1}(t)=\sum_{i=1}^{n_3}\left(p_{I_i}(t)\right) \tag{11}$$

$$p_{VSD\_BB1}(t)=\sum_{i=1}^{n_4}\left(\frac{p_{VSD_i}(t)}{\eta_{VSD_i}(p_{VSD_i}(t))}\right) \tag{12}$$

Here $p_{Ai}(t)$, $p_{Ii}(t)$ and $p_{VSDi}(t)$ are powers consumed by the *i*th loads from *A*, *I* and *VSD* categories at time '*t*' respectively, n_2, n_3 and n_4 are their total number respectively in *BB1*; while $p_{AC\_BB1}(t)$, $p_{I\_BB1}(t)$ and $p_{VSD\_BB1}(t)$ are the corresponding power demands of these categories for *BB1*. Hence, total input power for *BB1* becomes

$$\begin{aligned} p_{in\_BB1}(t) = {} & p_{DC\_BB1}(t)+p_{AC\_BB1}(t)+p_{I\_BB1}(t) \\ & +p_{VSD\_BB1}(t) \end{aligned} \tag{13}$$

$$\begin{aligned} p_{in\_(BB1)}(t) = {} & \sum_{i=1}^{n_1}\left(\frac{p_{D_i}(t)}{\eta_{conv-i}}\right)+\sum_{i=1}^{n_2}\left(\frac{p_{A_i}(t)}{\eta_{inv-i}}\right) \\ & +\sum_{i=1}^{n_3}\left(p_{I_i}(t)\right)+\sum_{i=1}^{n_4}\left(\frac{p_{VSD_i}(t)}{\eta_{VSD_i}(p_{VSD_i}(t))}\right) \end{aligned} \tag{14}$$

and the total input power for '*n*' number of building blocks (*nBBs*) being served by one SST in the system under consideration becomes

$$p_{DC\_nBBs}(t)=\sum_{j=1}^{m_1}\left(\sum_{i=1}^{n_1}\frac{p_{D_i}(t)}{\eta_{conv-i}}\right)_j \tag{15}$$

$$p_{AC\_nBBs}(t)=\sum_{j=1}^{m_2}\left(\sum_{i=1}^{n_2}\frac{p_{A_i}(t)}{\eta_{conv-i}}\right)_j \tag{16}$$

$$p_{I\_nBBs}(t)=\sum_{j=1}^{m_3}\left(\sum_{i=1}^{n_3}p_{I_i}(t)\right)_j \tag{17}$$

$$p_{VSD\_nBBs}(t)=\sum_{j=1}^{m_4}\left(\sum_{i=1}^{n_4}\frac{p_{VSD_i}(t)}{\eta_{VSD_i}(p_{VSDi}(t))}\right)_j \tag{18}$$

$$p_{in\_nBBs}(t)=p_{DC\_nBBs}(t)+p_{AC\_nBBs}(t)+p_{I\_nBBs}(t)+p_{VSD\_nBBs}(t) \tag{19}$$

Here m_1, m_2, m_3, and m_4, are the total number of building blocks in which *i*th *D*, *A*, *I* or *VSD* category load present in *j*th building block are consuming power. Thus $p_{in\_nBBs}(t)$ is the sum of all kind of load demands in ‘n’ building blocks which are under consideration in ‘*t*’ time interval, is the output of the SST. Subsequently including secondary distribution losses $p_{SDL}(t)$, the $p_{sst\_out}(t)$ would be

$$p_{SST\_out}(t)=p_{in\_nBBs}(t)+p_{SDL}(t) \tag{20}$$

$$p_{SST\_in}(t)=\frac{p_{SST\_out}}{\eta_{SST}(p_{SST\_out})} \tag{21}$$

The grid output can be calculated from $p_{SST\_in}(t)$ of ‘*x*’ solid state transformers (SST) as;

$$p_{grid\_out}(t)=\sum_{k=1}^{x}\left(p_{SST\_in_k}(t)\right)+p_{PDL}(t) \tag{22}$$

Here $p_{PDL}(t)$ represents primary distribution losses. Finally, the total system efficiency can be calculated as;

$$\eta_{sys}(t)=\frac{p_{Load\_total}(t)}{p_{grid\_out}(t)} \tag{23}$$

Here $p_{Load\_total}(t)$ is the total power consumed by the loads present in *nBBs* (excluding the losses in PEC, SST and lines). Thus from (19) $p_{Load\_total}(t)$ can be evaluated as;

$$p_{Load\_total}(t)=\sum_{j=1}^{m_1}\left(\sum_{i=1}^{n_1}p_{D_i}(t)\right)_j+\sum_{j=1}^{m_2}\left(\sum_{i=1}^{n_2}p_{A_i}(t)\right)_j+\sum_{j=1}^{m_3}\left(\sum_{i=1}^{n_3}p_{I_i}(t)\right)_j+\sum_{j=1}^{m_4}\left(\sum_{i=1}^{n_4}p_{VSD_i}(t)\right)_j \tag{24}$$

The basic efficiency analysis model can be extended by including various other system elements. For example, solar PV may be included; where a daily insolation graph is modeled via polynomials or via piece-wise polynomial functions.

$$p_{Solar}=\left\{\begin{array}{cc} f_1(t)=a+bt+ct^2+\cdots & T_1<t<T_2 \\ f_1(t)=d+bt^2+ct^3+\cdots & T_3<t<T_4 \\ \vdots & \vdots \\ f_n(t)=v+wt^1+\cdots+yt^{n-1}+zt^n & T_{m-1}<t<T_m \end{array}\right\} \tag{25}$$

D. *Designing of Parameters for a Desired Efficiency*

Subsequent to the comprehensive system analysis and mathematical modelling, the study may be carried on further towards designing of a system for achieving a given efficiency/energy-savings target. In other words, the flow of work may be reversed and instead of finding efficiency for a given system, a system may be found i.e. designed for a given efficiency goal.

$$Desired\ Net\ \eta_{savings}\,(d_1)=\ \delta\% \tag{26}$$

$$d_1\rightarrow\left\{\begin{array}{l} Solar\ Capacity=\ \alpha\,Watts \quad given\ the\ yearly \\ \qquad\qquad\qquad\qquad\qquad solar\ insolation\ profile \\ Voltage\ Levels=\left\{\begin{array}{c} \beta\ Volts\rightarrow primary\ ditribution \\ \gamma\ Volts\ \rightarrow secondary\ distribution \\ or \\ \gamma_1,\gamma_2\ldots Volts\ \rightarrow multiple\ levels \end{array}\right\} \\ Native\ DC\ Loads\ = \\ \quad\left\{\begin{array}{l} Not\ requiring\ voltage\ conversion\ \rightarrow\ \varphi\,\% \\ \quad requiring\ a\ voltage\ conversion\ \rightarrow\ \varphi'\% \end{array}\right\} \\ . \\ . \\ . \end{array}\right\} \tag{27}$$

Thus, the loop may be closed and the fundamental questions regarding feasibility of DC may be answered as well as a DC system providing required energy-savings may be designed (if possible) and implemented (if feasible). Such a system designing which may fulfill an efficiency target while providing reasonable feasibility may be a study area in itself with multiple directions for research.

Briefly summarizing this section, we have mentioned the further areas of research that can be taken up by researchers in the field of efficiency analyses of DC power distribution networks. These are performing comprehensive analysis of the system, performing sensitivity analysis, developing mathematical models and finally designing a DC system to meet a given efficiency target. The next section provides an additional discussion related to efficiency of DC systems.

6. FUTURE EFFICIENCY STUDIES OF DC DISTRIBUTION: A FURTHER DISCUSSION

In a comparative study of AC and DC, the factor of fairness is also important; [57] mentions that the efficiency gap claimed by different papers is not fair and can lead to misunderstanding. For example, if a 230V AC system is compared with a 380V DC system, the efficiency advantage of the latter is not just because of conversion to DC but also due to the use of higher system voltage. In order to show the benefit of DC only, it needs to be compared with an equivalent AC of the same voltage. Moreover, voltage is just one parameter; to have a clear picture of the advantage of DC over AC, a fair comparison should use the same conductor, the same insulation and realistic efficiencies of PEC in both systems. To this end, a need for an economic cost estimation of DC over AC naturally arises, because for example if a DC system naturally requires less copper for conduction, this should add to its advantage.

Besides the efficiency comparisons, a variety of scenarios for efficiency enhancement of DC also need to be researched upon. One of these is the use of multiple voltage levels, e.g. a residential DC microgrid can offer 380V for high power loads, and at the same time deliver 24 and/or 48 V for smaller electronic loads. Another scenario is the use of modular approach for the distribution level DC/DC converter. Via this approach, the large sized distribution converter may be integrated from smaller powered bricks with only the necessary amount of bricks be turning on at a time thereby attempting to operate the modular converter near optimum efficiency.

From the side of the authors of this paper, the potential of energy-savings via DC distribution networks, as compared to the AC counterpart, may be regarded as conditional i.e. it depends – on certain factors such as system configuration, load type etc. Furthermore, summarizing our view point in this regard, it may be said that an important aspect to make DC advantageous would be to reduce the power electronic conversions as much as possible – this may be achieved by multi-voltage power distribution inside a building and/or by standardizing DC input voltages of various equipment in order to reduce the disparity in requirements and consequently use lesser converters. Despite the fact that we are having DC showing-up more and more in the system in the form of LED lighting, house-hold electronics, solar PV etc., yet if the voltage levels do not match and we have to resort to power electronic voltage conversions for interfacing the equipment – then it may not make much of a difference if the system is AC or DC. Adding to this the fact that AC systems are the prevalent option with household loads readily available in the market, DC may have to provide a substantial justification for a paradigm change in its favor. In any case, the clash between AC and DC for higher efficiency has been re-ignited and the answer is yet to come.

The author(s) of the current paper have an intention of working towards the question, ‘How much power can we save via DC’. To this end, firstly distribution system models can be selected for AC and DC paradigms – both powering the same loads. Then, for the set of system parameters (e.g. system voltage, SST efficiency, load side converters efficiency, solar capacity etc.), nominal values may be selected. Finally, for both systems, the power demands may be observed via simulation/calculation while varying one parameter at a time.

7. CONCLUSION

DC power distribution has gained a significant interest especially with the concept of microgrids. Various parameters of the DC networks need research and/or development for a widespread practical implementation. These include suitable protection schemes for the system, reliability and stability of the system, the integration with RES and modern energy storage equipment and the investigation of efficiency as well economic advantage of using DC as compared to AC. This paper presented a summary of different publications mentioning the efficiency of DC power distribution systems. It went on to give a critical review of the past research efforts and mentioned about the details of a comprehensive study required in the future. Such a comprehensive study may be able to fill the gap in the present body of knowledge and provide us with a definite verdict: Is DC better than AC? If yes, then under what conditions and scenarios?

The mathematical models of the comprehensive study that we envision should be able to determine the efficiency/energy-savings advantage of DC over AC for a given system design. At the same time, they should be able to help in designing a system for a given target of efficiency/energy-savings. DC has already set foot in generation, transmission and utilization; and the time may be near when it enters the distribution portion of the power system as well.

8. LIST OF ABBREVIATIONS

BB	Building Block
DG	Distributed Generation
DPS	Distributed Power System
HEV	Hybrid Electric Vehicle
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
LAC	Levelized Annual Cost
LED	Light Emitting Diode
LVAC	Low Voltage Alternating Current
LVDC	Low Voltage Direct Current
PEC	Power Electronic Converter
PDN	Power Distribution Network
PDV	Primary Distribution Voltages
PoE	Power over Ethernet
PV	Photo Voltaic
MPPT	Maximum Power Point Tracking
RES	Renewable Energy Sources
SOC	State of Charge
SST	Solid State Transformer
USB	Universal Serial Bus
VSD	Variable Speed Drive

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