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POWER SYSTEMS AND POWER ELECTRONICS

# System efficiency for AC vs. DC distribution paradigms: a comparative evaluation

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**Abstract.** The birth of electricity witnessed "the battle of currents" between AC and DC as a medium of power transfer. AC won the battle in the first place because of its ability to transform voltage levels. However, with the development of power electronic converters (PECs), DC is striking back. Most of the electronic loads in our conventional AC-based homes are DC by nature. Moreover, the modern concept of energy-efficient variable speed drive (VSD) based loads, i.e. DC-inverter based air-conditioners and refrigerators, require a DC link for their operation. The driving component of all such loads is the PEC. The operational efficiency of PECs depends on the loading which varies throughout the day. This paper presents a mathematical model based on a bottom-up approach to the comparative efficiency analysis of AC and DC distribution systems considering daily load variation. Two topologies are presented where AC and DC distribution systems are compared in terms of efficiency. The first topology (T1) defines a separate/independent converter for each load, whereas in the second topology (T2) loads of a particular class are lumped and driven by a single converter. The results present DC distribution better than AC distribution with an efficiency advantage of 2.28% and 1.57% for T1 and T2, respectively.

**Key words:** AC vs. DC; DC distribution; efficiency analysis; residential loads.

## 1. INTRODUCTION

The excursion of electrical power system began with DC as the medium of power transfer, soon after that DC and AC epitomes conflicted with each other and the conflict was termed as "the battle of currents" [1, 2]. The conflict arose as a result of the efficiency of power transferring medium at long distances. DC lacked the ability of power transformation at that time whereas AC possessed the ability due to the invention of electromagnetic transformers. The battle became news embellishment as technological rivalry between Tesla and Edison, with Tesla supporting AC and Edison supporting DC [3, 4]. AC was then able to adore its rules over the major components of the power system, i.e. generation, transmission, distribution, and utilization [5–7]. AC enjoyed its supremacy for decades whereas DC was left with niche applications in the power system [8]. However, this supremacy of AC was not everlasting; with engineering approaches redefined and the development in the field of power electronics, DC stroke back. The transmission sector was the first one to witness the importance of DC in the power system. High voltage direct current (HVDC) transmission system proved better as compared to high voltage alternating current (HVAC) for long distances [9, 10]. This opened the doors of a power system for DC and "the battle of currents" reignited. Soon after that DC made its way to the generation side in the form of solar photovoltaic (PV). At utilization scale, DC entered our homes in the form of mobile phones and laptop chargers, light-emitting diode (LED) lights, and computers, etc. The distribution phase is still under research. A handsome number of research efforts have been presented specifically in the field of the efficiency analysis of DC distribution systems; still, certain aspects need to be researched upon. A comparison of the present body of knowledge with the current research shall be established in the last part of this section.

Indeed the revival of DC can be attributed to the expeditious development in the field of power electronics, which formed the basis of the emergence of efficient power electronic converters (PECs). The electronic loads in our conventional AC homes are all DC by nature, driven via suitable PEC. Another notable factor that is gaining fame nowadays is the use of variable speed drive (VSD) based energy-saving technology with motor-based loads [11]. A PEC stage can be eliminated if the VSD based loads are operated in a DC system (with a suitable distribution voltage level), thereby providing better efficiency of the DC system. Although PECs are efficient, still a drawback associated with the functioning of PECs is their low efficiency during light loads. Since the load keeps on varying throughout the day, the efficiency of the installed PEC varies accordingly. This paper investigates the effect of the variation in the efficiencies of PECs on the comparative analysis of AC and DC distri-

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bution systems considering the modern concept of VSD based loads in addition to other loads in the residence. The analysis is performed on mathematical grounds. A bottom-up approach is employed to find the efficiency of the distribution systems. Two topologies are presented for analysis, in the first topology T1, separate converters are installed for each load, whereas in the second topology T2, a single converter is employed lumping the loads belonging to a particular category.

Remarkable research was presented in the past considering the viability of DC as compared to the AC paradigm and vice versa. The authors of [12] presented a comparative analysis of AC and DC distribution systems and concluded that DC was a better choice. However, the authors considered fixed efficiencies of the installed PECs that rule out the fact that the true effect of load variation is not included in the analysis. Similar to [12], fixed values of PEC efficiencies are considered in the DC efficiency analyses presented in [13–17]. The work of [18] assumed direct DC loads in the DC system and neglected PECs in the AC system. The work presented in [19] considers two values of PEC efficiency with respect to load (full load and part load-part load at 20% of full load). In contrast, this research takes into account the effect of daily load variation and in turn the effect of PEC efficiency variation. Moreover, this research effort takes into account actual loads of a US home with actual variation throughout the day, in comparison to the studies presented in [14, 16, 17, 20–22]. The authors of [20] present an average load interface i-e combining all loads into a single load entity. Papers [21, 22] present the comparative analysis of AC and DC systems based on single load i-e lighting. The work presented in [16, 17] considers two loads i-e lamp and motor. The authors of [14] have considered a fixed proportion of loads in the analysis i-e half AC and half DC. The research efforts of [23–28] are some of the publications belonging to the lead authors of the current paper related to the efficiency of DC distribution systems. [23] is a simulation-based analysis of the feasibility of DC distribution systems. The paper does not present a comparative analysis of AC and DC distribution systems. [24] presents a comparative analysis; however, the overall residential consumption is distributed arbitrarily among the residential loads based on assumptions. The research presented in [25] was an attempt to encompass modern household trends in the comparative analysis; however, the research was based on the efficiency of PECs within a fixed defined range. In [26], the comparative analysis is performed only at the utilization level. The research of [27] presented a comparative analysis ignoring the modern trend of VSD based loads and [28] included AC loads in addition to VSD loads in the analysis, creating redundancy in load classification.

The current effort is unique in the sense that it addresses various weak aspects of the past research and encompasses the modern trend of VSD-based energy efficient loads. The comparative analysis is performed on actual data of a US-based home. Moreover, the effect of a load variation on PEC efficiency is employed in the true sense. Furthermore, the research highlights the importance of the topological architecture regarding the PEC/load installation within the premise. Besides a comparative efficiency analysis, future recommendations are also stated considering the inclusion of solar PV in the presented model with respect to the energy savings scenario.

## 2. SYSTEM MODELING

Data taken from Building Energy Data Book (BED) [29] for a US-based home has been utilized in the modeling of AC and DC distribution systems. The data provides an insight into the energy usage for heating, cooling and other appliances. The energy splits for residential loads are presented in Table 1.

The residential loads are classified into the following categories:

### 2.1. ‘V’ Class

With the advancement of technology and engineering approaches towards energy-saving scenarios, traditional fixed-speed motor-based loads conventionally operating on AC are now employing variable speed drives which facilitate higher efficiencies [30–33] with reduced losses as compared to their standard technology. In the AC distribution system, two conversion stages are required prior to ‘V’ class loads, i.e. input AC power is first converted to DC followed by a DC to AC inversion stage to obtain variable frequency operation. In the DC distribution system, ‘V’ loads shall require a single DC to AC conversion stage assuming the residential DC voltage level matches the DC input demand of ‘V’ class loads.

### 2.2. ‘D’ Class

The loads which are internally DC fall under this category. The DC-internal loads refer to the loads that are inherently DC and require an AC to DC conversion in the conventional AC system. Mainly electronic loads, computers, and LED lights fall under this category. Since the voltage demand of these loads is quite low, therefore they require a DC to DC converter for stepping down the residential voltage level to the load level in the DC distribution system.

### 2.3. ‘I’ Class

Loads which can successfully operate on both AC and DC power without any prior conversion stage are referred to as independent loads and therefore fall under the ‘I’ category. Examples of the ‘I’ category include water heating and cooking appliances.

The average monthly energy consumption of a US home provided by Energy Information Administration (EIA) residential data is utilized for analysis [34]; the average daily consumption of a US home is computed to be around 30 kWh. Energy in kWh is calculated by combining daily consumption with energy usage data of BED. For example, cooking consumes 0.11/4.795 of the total energy consumption. This fraction treated with daily consumption of 30 kWh gives per day energy consumption of 0.71 kWh. Similar calculations are performed for all types of loads and per day consumption of all the loads is presented in Table 1. It is important here that the “others” load present in EIA data is given an equal share in all three classes. Since the daily load curve of a residential facility presents three

**Table 1**
Energy splits for residential loads

| Category | Energy % | Energy used (quad. Btu) | Load categorization | Energy kWh | 'D' Class kWh | 'V' Class kWh | 'I' Class kWh |
|---|---|---|---|---|---|---|---|
| Water heating | 9.93 | 0.48 | I | 2.98 | – | – | 2.98 |
| Lighting | 11.04 | 0.53 | D | 3.31 | 3.31 | – | – |
| Electronics | 6.86 | 0.33 | D | 2.06 | 2.06 | – | – |
| Space cooling | 21.24 | 1.02 | V | 6.37 | – | 6.37 | – |
| Space heating | 8.78 | 0.42 | V | 2.64 | – | 2.64 | – |
| Cooking | 2.36 | 0.11 | I | 0.71 | – | – | 0.71 |
| Refrigeration | 9.45 | 0.45 | V | 2.84 | – | 2.84 | – |
| Computer | 3.95 | 0.19 | D | 1.19 | 1.19 | – | – |
| Wet cleaning | 6.80 | 0.33 | V | 2.04 | – | 2.04 | – |
| Others | 19.69 | 0.94 | | 5.91 | 1.97 | 1.97 | 1.97 |
| Total | | 0.94 | | 30.05 | 8.53 | 15.86 | 5.66 |
| Power demand in kW | | 4.795 | | | 0.36 | 0.66 | 0.24 |

steps as demonstrated in Fig. 1; therefore, a day is divided into three portions as presented in Table 2. Further utilizing the EIA data, the power consumption of each load in each portion of the day is evaluated and presented in Table 3.

**Table 2**
Portions of a day

| Sr. No. | Portion name | Duration | Period |
|---|---|---|---|
| 1 | P1 | 00:00–08:00 | 8 hours |
| 2 | P2 | 08:00–17:00 | 9 hours |
| 3 | P3 | 17:00–24:00 | 1 hours |

**Table 3**
Power consumption for three portions of a day

| Category | P1 (00:00–08:00) | P2 (08:00–17:00) | P3 (17:00–23:00) |
|---|---|---|---|
| 'V' Class loads (W) | | | |
| Space cooling | 68.96 | 122.5 | 604.84 |
| Space heating | 88.53 | 150.15 | 133.82 |
| Refrigeration | 36.76 | 109.35 | 108.88 |
| Wet cleaning | 109.81 | 118.65 | 126.54 |
| Others | 81.80 | 81.80 | 81.80 |
| 'D' Class loads (W) | | | |
| Lighting | 47.66 | 51.57 | 49.51 |
| Computer | 144.06 | 124.94 | 144.74 |
| Electronics | 83.02 | 90.59 | 83.88 |
| Others | 81.80 | 81.80 | 81.80 |
| 'I' Class loads (W) | | | |
| Cooking | 12.42 | 45.26 | 31.06 |
| Water heating | 87.75 | 101.5 | 140.75 |
| Others | 81.80 | 81.80 | 81.80 |
| Total | 924.37 | 1159.91 | 1669.42 |

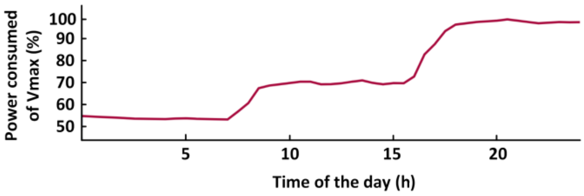

**Fig. 1.** Residential daily load variation curve [35]

## 3. MATHEMATICAL MODELING

The data in Table 3 can be treated as entries of a $12 \times 3$ matrix. The rows present the power consumption of the loads in a residence and columns present the three portions of the day. The entries of this matrix represent the load consumption in each portion of the day

$$X_{a,b} = \begin{bmatrix} x_{1,1} & x_{1,2} & x_{1,3} \\ x_{2,1} & x_{2,2} & x_{2,3} \\ x_{n1,1} & x_{n1,2} & x_{n1,3} \\ \vdots & \vdots & \vdots \\ x_{n3,1} & x_{n3,2} & x_{n3,3} \end{bmatrix} \in \mathbb{R}^{a \times b}. \tag{1}$$

Power consumption per portion of the day for loads of 'V' class is taken from $x_1$ to $x_{n1}$. Similarly, in for 'D' category loads, the power consumption is taken from $x_{n1+1}$ to $x_{n2}$. And for 'I' category loads, the power consumption is taken from $x_{n2+1}$ to $x_{n3}$.

Both topologies, T1 and T2, are presented in Figs. 2 and 3, respectively, considering the DC distribution system of topology (T1), presented in Fig. 2. In order to find the appropriate rating of the converter, it is important to know the maximum load that the converter must supply from three portions of the day as mentioned in (2)

$$Y(a,1) = \max_{of}\left(x_{a,b}\right), \tag{2}$$

where $(x_{a,b})$ represents the entries of $X$.

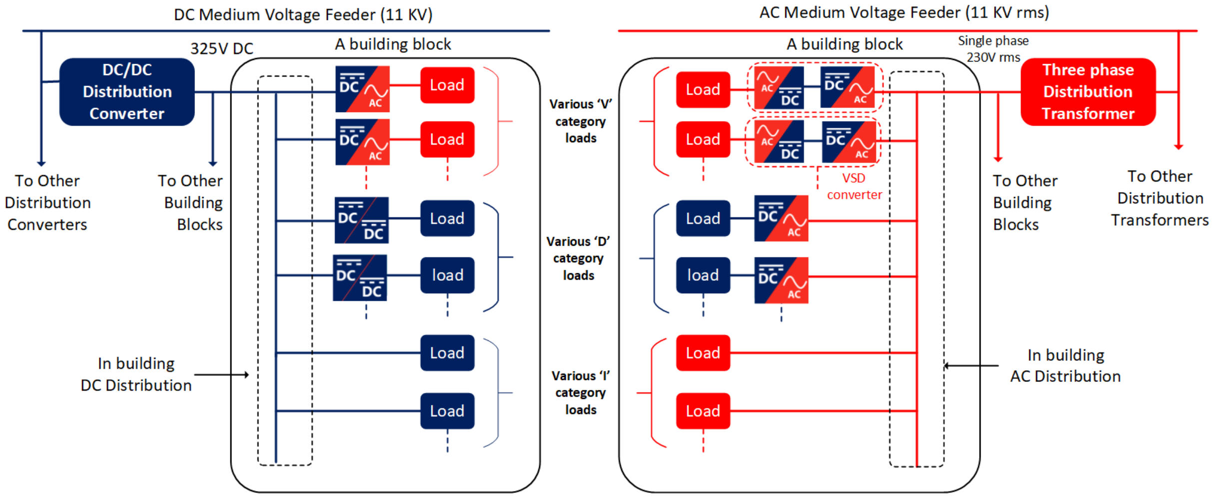

**Fig. 2.** System diagram for topology (T1)

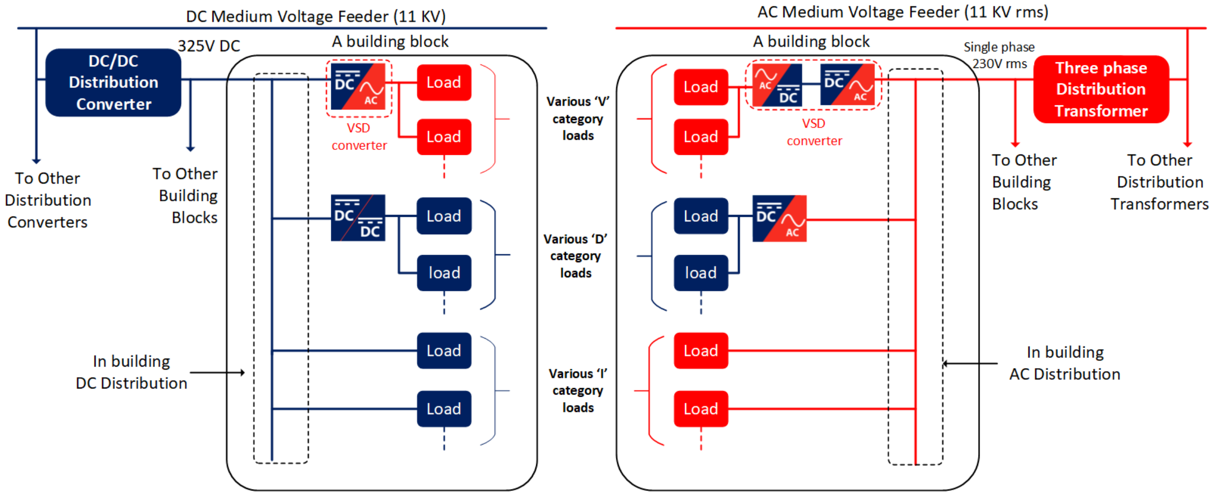

**Fig. 3.** System diagram for topology (T2)

The matrix $Y(a,1)$ gives the maximum load from each portion of the day. An oversize ratio of 30% is allocated for practical reasons, drawing support from [36, 37]. Moreover, for the ease of calculations transpose of $Y$ is taken as presented in (3)

$$R(a) = 1.3 \times Y^T. \tag{3}$$

The next step in the mathematical modeling is to calculate percentage loading, which can be acquired by making use of (4)

$$P_{a,b} = \frac{100 \times x_{a,b}}{R(a)}. \tag{4}$$

$P$ has the dimensions of power consumption matrix $X_{a,b}$ and presents the percentage loading of each converter.

### 3.1. 'V' loads

In a DC distribution system, 'V' class loads shall require a single DC–AC conversion stage, therefore utilizing the characteristic equation of the percentage loading vs. efficiency curve of the DC–AC converter from Fig. 4. The characteristic equation is determined using the curve-fitting toolbox of MATLAB software. The loading $u$ input to the MATLAB generated function $f(u)$ gives the operating efficiency for the particular loading $u$. Mathematically presented in (5)

$$\eta_{a,b} = f(u)_{\text{DC–DC}}, \qquad a = x_1 \ \text{to} \ x_{n1}. \tag{5}$$

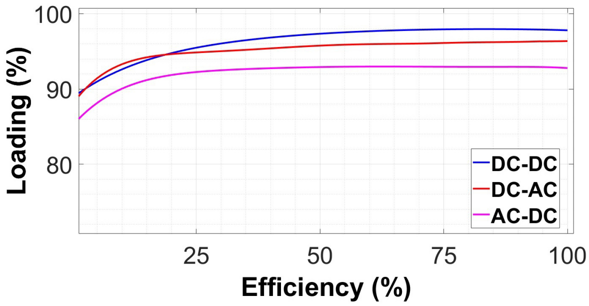

**Fig. 4.** PEC efficiency curves [38–40]

### 3.2. ‘D’ loads

A similar approach is employed for ‘D’ class loads, the only difference is in the converter, i.e. DC–DC converter in this case; and operating efficiency can be computed from (6)

$$\eta_{a,b} = f(u)_{\mathrm{DC–DC}}\,, \qquad a = x_{n1+1} \ \text{ to } \ x_{n2}\,. \tag{6}$$

### 3.3. ‘I’ loads

Since no conversion is required for this category of loads, efficiency can be given by (7)

$$\eta_{a,b} = 100\%, \qquad a = x_{n2+1} \ \text{ to } \ x_{n3}\,. \tag{7}$$

The value of $b$ is taken from 1 to 3 in all the cases since we have three loads in each category. The values of $a$ represent the power consumption entries of the ‘VDI’ loads.

The output of a residential system is the load power consumption, whereas the input power of the system can be computed by using the bottom-up approach in this case. The elements between the input and output of the residence are PECs. Using their operational efficiency matrix formed from the combination of (5) to (7), the input of the residence can be computed from (8)

$$Xin_{a,b} = \frac{X_{a,b}}{\eta_{a,b}} \times 100\%\,. \tag{8}$$

All the entries of the input matrix are then summed up to give the total power input to the building per portion of the day as depicted in (9)

$$Xin_b = \sum_{a=1}^{n1} Xin_{a,b} + \sum_{a=n1+1}^{n2} Xin_{a,b} + \sum_{a=n2+1}^{n3} Xin_{a,b}\,. \tag{9}$$

And total loading for each portion of the day can be calculated from (10)

$$X_b = \sum_{a=1}^{n1} X_{a,b} + \sum_{a=n1+1}^{n2} X_{a,b} + \sum_{a=n2+1}^{n3} X_{a,b}\,. \tag{10}$$

Finally, the overall efficiency of the building per portion of the day can be calculated from (11)

$$\eta_m = \frac{X_b}{Xin_b} \times 100\%\,. \tag{11}$$

A similar mathematical approach can be devised for the AC distribution network for comparative analysis.

Considering the second topology (T2), where a single converter is employed for a load class as depicted in Fig. 3, the mathematical model is modified for the comparative efficiency analysis of AC and DC systems in the following fashion.

The only difference lies in computing the percentage loading of the converters. For this purpose, the rating of the converters needs to be recomputed as now a single converter has to supply multiple loads of the respective category. The maximum loading against each conversion stage of the ‘V’ and ‘D’ category can be computed from (12) to (13); whereas the ‘I’ category does not require a conversion stage therefore neglected.

$$A(1,b) = \max_{of}\left(x_1 \ \text{ to } \ x_{n1}\right), \tag{12}$$

where the power consumption of ‘V’ category loads is taken from 1 to $n1$.

$$A(2,b) = \max_{of}\left(x_{n1+1} \ \text{ to } \ x_{n2}\right), \tag{13}$$

where the power consumption of ‘D’ category loads is taken from $n1+1$ to $n2$.

The value of $b$ is taken from 1 to 3 because there are three ‘V’ and ‘D’ category loads. A matrix of dimension $3 \times 3$ is created and percentage loading is found by using (14) and (15); again ‘I’ category conversion efficiency is taken as 100%

$$P_{1,b} = \frac{100 \times A_{1,b}}{R(1)}\,, \tag{14}$$

$$P_{2,b} = \frac{100 \times A_{2,b}}{R(2)}\,. \tag{15}$$

The same procedure, i.e. the bottom-up approach stated above, is tailored to determine the efficiency of the system. The analysis of the AC system is also performed using the lumped PEC model of topology T2 with appropriate PECs.

### 3.4. Line losses

The DC and AC distribution system is evaluated for line losses by using the modified Newton–Raphson method. Percentage line losses for both topologies are shown in the following section. Equation (16) is used for the calculation of line losses

$$L_L = \frac{1}{2} G_{nm} \sum_{n=1}^{k} \sum_{m=1}^{k} \left(V_n\left(V_n - V_m\right) + V_m\left(V_m - V_n\right)\right), \tag{16}$$

where $G_{nm}$ denotes the conductance matrix of a power system in which bus $n$ is connected to bus $m$ varying from 1 to $k$. Equation (17) shows power in terms of voltage and conductance. The expression obtained after the expansion of (17) is iterated and a converged value of voltage is obtained which is used to find the line losses by using (16)

$$P_n = \sum_{m=1}^{k} V_n V_m G_{nm}\,. \tag{17}$$

## 4. ANALYSES, RESULTS AND DISCUSSION

The topologies T1 and T2 for DC and AC distribution systems are compared by making use of the mathematical model devised in the previous section. MATLAB software is used for computations. In order to provide the analysis of a “system”; we connected 20 buildings per primary distribution converter/transformer as depicted in Figs. 2 and 3. The total number of primary distribution converter/transformer are chosen to be 5, making a system of 100 residential buildings. The voltage level of the primary distribution is taken to be the standard

11 kV. The secondary distribution voltage level is taken to be 230 V for the AC system and 325 V for the DC system. These voltage levels draw their support from [27]. The voltage levels are utilized to compute the line loss for both systems. Practical resistance values of a "dog" type conductor are employed for the analysis [41]. The distance between two adjacent primary distribution converter/transformers is taken to be 250 m. During computations, it was revealed that there is a minute difference between the line loss of AC and DC distribution systems. The line loss was computed to be less than 1% for both topologies. Hence, it can be stated here that line loss for AC and DC distribution systems is comparable and the overall efficiency of both systems is more prone to the loss occurring in the PECs. The system efficiency results are tabulated in Tables 4 and 5. The results are presented pictorially in Fig. 5 to demonstrate the comparison of the topological grounds of AC and DC distribution networks.

**Table 4**

System efficiencies for T1 for portions of a day

| Portion | AC distribution | DC distribution |
|---|---|---|
| P1 | 90.11% | 93.22% |
| P2 | 92.39% | 94.91% |
| P3 | 95.52% | 96.73% |
| Average | 92.67% | 94.95% |

**Table 5**

System efficiencies for T2 for portions of a day

| Portion | AC distribution | DC distribution |
|---|---|---|
| P1 | 87.41% | 89.13% |
| P2 | 91.26% | 93.33% |
| P3 | 93.47% | 94.40% |
| Average | 90.71% | 92.28% |

The results present an efficiency advantage of DC over AC at the distribution scale. The efficiency values are lower for P1 since converters are lightly loaded and operate at lower efficiency. The efficiency values are almost comparable for P3 for AC and DC systems. During P3, the 'V' loads (space cooling, etc.) predominantly operate at higher demand, because of which the attached PEC operates at better efficiency. Furthermore, T2 presents lower efficiency values as compared to T1. In T1, the converters supply a single load and operate at an efficiency defined by the loading of that particular load. The variation in the range of efficiency of a particular load in T1 is small as compared to the range of variation of lumped loads as a result of which the converter in T2 operates at relatively lower efficiency values. An interesting figure is the relatively lower efficiency advantage of T2 over T1 when DC and AC distribution networks are compared. This is because 'V' loads offering an AC output operate at higher demand; and in the lumped architecture of T2, the PECs operate at better efficiencies for the case of the AC system causing the overall difference between AC and DC distribution systems to reduce.

## 5. CONCLUSIONS AND FUTURE RECOMMENDATIONS

The AC and DC distribution networks are compared for two different architectures considering the modern concept of VSD loads. The analysis is performed using practical data from EIA and BED. The variation in PEC efficiency as regards to daily load variation is studied. During periods of lower power consumption, the attached PECs present lower efficiency values, thereby affecting the overall system efficiency values. Line losses are also computed for both systems but they do not present a significant effect on system efficiencies as compared to the PEC efficiency values. The line loss is accommodated. The results present DC distribution better than AC distribution with an efficiency advantage of 2.28% and 1.57% for T1 and T2, respectively.

### 5.1. Critical assessment of the results

The results of this paper may be regarded as an impetus to the electrical industry for re-considering the choice of using AC paradigm in the distribution systems. In Tables 4 and 5 of the paper, one can roughly see that the advantage gained via DC systems is a meager 2% or so – and this might not be enough to validate a widespread system re-invigoration to replace the traditional AC with DC power. However, studies like this can incentivize the electrical industry to consider this re-invigoration from their point-of-view that may include feasibility, long term benefits and even profitability. Studies like this may also push the policymakers to make suitable policies. This single study is definitely not enough to persuade a practicing engineer into preferring DC systems over AC. However, it is one of the many

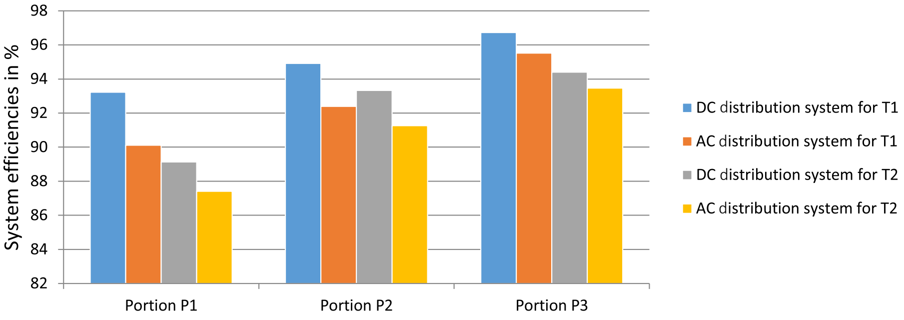

**Fig. 5.** Comparison of AC and DC distribution systems for T1 and T2

studies pushing for DC distribution – mentioning it is more beneficial, or at the least equally beneficial to AC systems. Moreover, the results can contribute to further research directions, as mentioned in the subsequent subsection.

### 5.2. Assumptions in the current research effort

This section mentions some of the assumptions used in the current work – thus a critical reader can quickly realize the significance of the results and prospective future research scientists realize the improvements which can be made to the current study.

- The analysis is based on average household load profile for the US.
- A 24-hour day is divided into three portions – wherein, within a portion, the load is assumed constant.
- All 'D' category loads are assumed to require a DC/DC preconverter in the DC system – this is a worst-case assumption; if a 'D' category load can work with the in-building DC voltage and therefore does not require a DC/DC preconverter, then this would be adding to the efficiency of the DC system.

### 5.3. Future recommendations

The 21st century has witnessed the trend of rooftop installation of solar PV systems. Solar PVs generate power in the DC and require a PEC for connection to in-house AC or DC system. Further analysis can be carried out considering the inclusion of solar PV in the system. A generic concept is presented in Fig. 6.

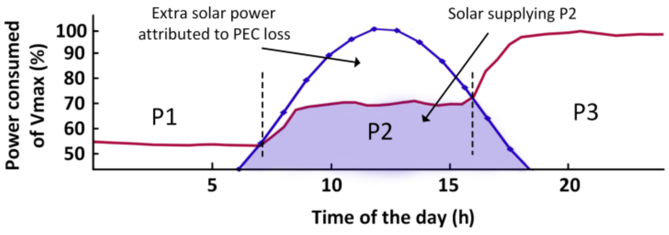

**Fig. 6.** Section P2 supplied by solar

The generic curve of solar PV output power is drawn against the residential power consumption curve. It can be seen that solar PV output is available during P2, thus the whole P2 section can be supplied by solar PV depicted as a shaded section. The extra power of solar PV can be attributed to the PEC loss. A comprehensive future study can be performed in this regard, encompassing the following points:

- The discussion presented above takes into account generic solar PV curve; however, the future study should be able to incorporate actual solar insolation data with actual solar insolation variation throughout the day/year even in an averaged analysis.
- Proper choice of solar PV capacity to minimize the difference between generation and utilization during P2; hence, etting the maximum benefit from solar PV at minimal loss.
- Analysis with a storage system to make use of the difference between generation and utilization during P2.
- Load shifting/management-to drive maximum loads via solar PV.

The current effort may form the base for another future research as regards to efficiency enhancement of DC distribution system. The loss distribution of AC and DC distribution networks is presented in Fig. 7.

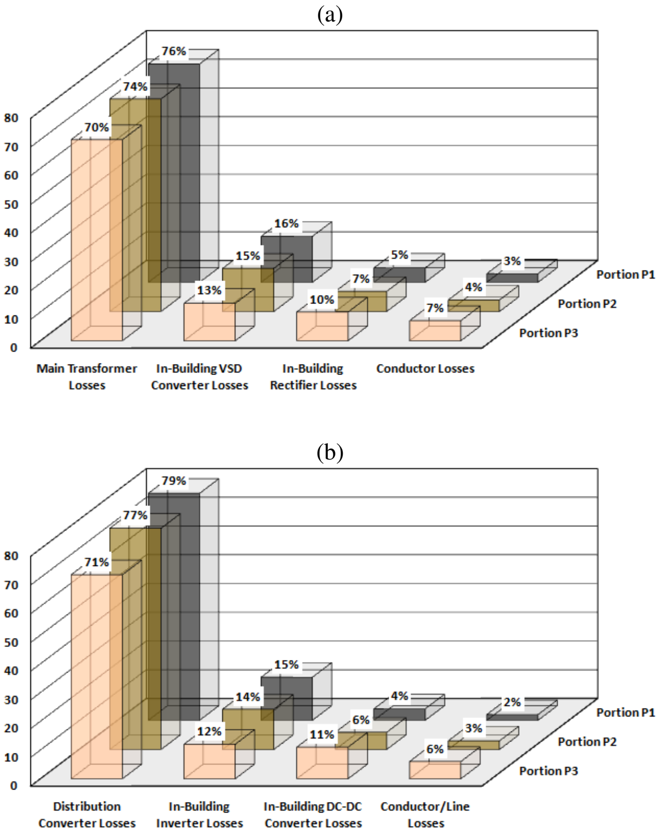

**Fig. 7.** Loss distribution for distribution systems (a) AC and (b) DC

It is evident that the main transformer converters are responsible for major contribution in the overall loss of the system. The contribution is more pronounced for the case of DC distribution system. A scheme for efficiency improvement can be established using the modern technique of modular architecture for distribution converters [42]. An enhancement in the efficiency of distribution converters shall lead to enhancement of the overall efficiency of the DC distribution network. Hence, a future study aimed at improving its efficiency via a technological/topological change can be incentivized.

## ACKNOWLEDGEMENTS

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