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Review Paper

AC vs DC Distribution Efficiency: Are we on the right path?

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Abstract: The concept of DC power distribution has gained interest within the research community in the past years; especially due to rapid prevalence of solar PVs as a tool for distributed generation in DC microgrids. Various efficiency analyses have been presented for the DC distribution paradigm, in comparison to the AC counterpart, considering a variety of scenarios. However, even after a number of such comparative efficiency studies, there seems to be a disparity in the results of research efforts - wherein a definite verdict is still unavailable: 'Is DC distribution a more efficient choice as compared to the conventional AC system?' A final verdict is absent primarily due to conflicting results. In this regard, system modeling and the assumptions made in different studies play a significant role in affecting the results of the study. The current paper is an attempt to critically observe the modeling and assumptions used in the efficiency studies related to the DC distribution system. Several research efforts will be analyzed for their approach towards the system upon which they have performed efficiency studies. Subsequently, the paper aims to propose a model that may alleviate the shortcomings in earlier research efforts and be able to give a definite verdict regarding the comparative efficiency of DC and AC networks for residential power distribution.

Keywords: DC vs. AC; DC distribution networks; energy efficiency in buildings; energy savings; microgrids

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1. Introduction

The first power system designed and operated ever since the history of electricity was DC in nature. Soon after AC replaced the DC as a result of the invention of transformers whereas DC had no means of transforming voltage levels at the time. It was then that "battle of currents" initiated. AC enjoyed supremacy over DC and ruled in all areas of power; generation, transmission, distribution, and utilization. The era of AC's rule remained for a long time but with the advancement in the field of power electronics; the only variable, "voltage transformation"; that kept AC's equation stronger than DC, originated in DC's equation also. This was the time when DC started to strike back and the "battle of currents" reignited. DC started proving itself in the fields of generation through solar and fuel cells; transmission through the construction of HVDC transmission over long distances; utilization through the adoption of DC loads e.g., computers, laptops, LED lights, etc. Distribution is the field that is still under the research phase and demands a definite verdict "whether DC is better than AC or not, if YES, is the model forming the base of comparison authentic enough to provide this definite verdict?"

Several studies have been presented in the past regarding the feasibility of the DC at the distribution level as well as the efficiency comparison of AC and DC distribution systems. The localities targeted by researchers were mainly residential, commercial, and data centers. The main focus of most of the studies was however residential and commercial sectors. The authors of [1] presented the feasibility of DC at the distribution level for a residential colony considering daily load variation and concluded with reduced

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efficiency of the system during the night as a result of lower converter efficiencies. The authors of [2] compared conversion efficiencies of residential loads when powered with AC and DC. He found 3% less electricity consumption when appliances are powered with DC. The authors of [3] showed that AC and DC distribution networks can be equally beneficial when equal AC and DC loads are present in a building. In [4], the authors claimed that making direct use of DC by assuming all DC loads can yield 5% energy savings of total home electricity usage. [5] showed comparable efficiencies, differing by a factor of 1%, of AC and DC distribution systems even when variable speed drive (VSD) loads are considered as DC loads in a modern home. The studies presented so far have primarily focused on establishing the feasibility of DC systems and comparing the proposed DC systems with conventional AC system on energy savings grounds. For the purpose, the authors have:

- Proposed various network schemes e.g., AC/DC system with/without distributed generation.
- Assumed different load models e.g., actual or averaged loads, single or multiple category loads.
- Considered multiple technical parameters like fixed or varying converter efficiencies, direct DC appliances or DC internal appliances, 48V DC or 326V DC etc.

In the end, all the authors present a quantitative comparison i.e., by this percentage or value, AC distribution is better than DC distribution or vice versa. A question arises here, whether the proposed model in a specific study is valid enough to give the conclusive verdict that "DC is better than AC" or "AC is better than DC"? This question forms the base of the current study.

The current research effort critically reviews the research efforts presenting the efficiency analysis of DC distribution system alone, or in comparison of AC distribution systems. The paper highlights the loopholes in the present body of knowledge by considering the employment of various parameters that affect distribution systems efficiency. The paper then presents the employment of these parameters in a fashion that can present the comparative efficiency analysis of AC and DC distribution systems in true sense.

The research presented in this paper has two parts; first, a critical analysis of the models shown in the previous studies on the basis of the employment of significant parameters affecting the efficiency analysis, and second, highlights the true employment of parameters in a model that has the ability to produce realistic and definite comparison of AC and DC distribution.

2. Critique of Various Parameters of AC-DC Distribution System Efficiency

The significant parameters that affect the comparative efficiency analysis of AC and DC distribution systems include load modeling, power electronic converter (PEC) efficiency, storage, line losses, voltage level, and distributed generation. This section provides a critical review of the employment of the stated parameters in the research efforts *specifically* related to the efficiency of AC-DC distribution systems.

2.1. Critical Review Of Load Models Presented In The Past

Load models are important to discuss as they form the base of the analyses of DC distribution efficiency as well as the comparison of AC and DC distribution systems. The targeted localities are mostly residential and commercial; however a few data centre facilities are also analyzed on the basis of load modeling. The models are discussed on the basis of load types i.e., either AC or DC; consideration of the effect of load variations; a variety of loads/appliances considered, the proportion of load type in a model e.g., half AC and half DC loads.

The authors of [1] presented a residential model comprising of averaged loads. The term "averaged loads" refer to the power consumption of loads averaged over a specific period of time. The authors claimed that the load variation effect is considered, but the load profile considered in the study is for only three periods of the day rather than a continuous load profile. The author of [2] presents a comparative analysis of AC and DC distribution systems for the residential locality. The residential data taken under consideration is again an averaged one as of [1], but does not consider load variation effect. A strong major assumption is made that each AC load in a residence has a DC counterpart making the model under consideration completely DC.

The work presented in [3] is another attempt at the evaluation of efficiency comparison of residential distribution systems. Unlike the research efforts [1] and [2], where appliances installed in a residence are considered; [3] assumes buildings as individual loads; therefore the study does not present any idea of proper appliance distribution among AC or DC. The research work of [4] is another study that makes the same strong assumption as [2] regarding load modeling i.e., all loads in the system are DC. Even in the case of the AC system; the loads are internally DC. The effect of load variation is considered but only for two levels i.e., part load and full load; where the part load is 20% of full load.

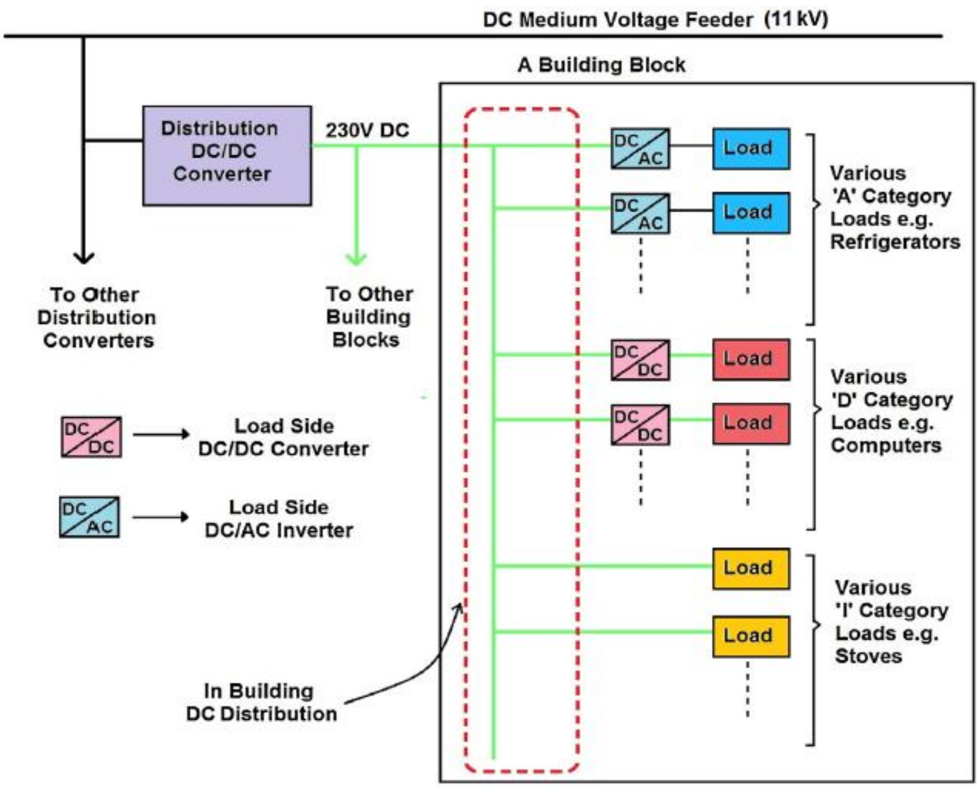

Figure 1. Load Model of a typical community distribution system [5]

Similar to [1]–[4], the average load model is presented in [5]. The authors adopt the same mechanism of load division among AC, DC, and Independent categories as presented in [1]. However, a slight difference is, certain AC loads employing variable speed drives are considered internally DC. The model of [5] for the AC distribution case is presented in Fig. 1. The authors did not present the effect of load variation as compared to [1].

The model of [6] is similar to [1] with assumptions based on load categorization. Likewise [2] and [5] the effect of load variation is not considered in the study and the

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average load model is considered. The work of [7] has further reduced the model of home to kitchen appliances. The scope of the work is quite limited because only kitchen appliances with an assumption of all DC internal loads, cannot describe a valid comparison of AC or DC distribution system.

The work presented in [8] is somewhat unique as it considers a data centre facility for modeling. The comparison of AC and DC distribution systems is established assuming highly efficient DC loads whose commercial availability is indeed an issue. The work presented in [9] is another case of partial uniqueness; the loads are arbitrarily distributed among different voltage levels i.e., 48% loads are assumed to operate on 325V, another set of 48% loads on 230V DC and the rest 4% operate on 20V. In contrast to this uniqueness, there is a similarity with [2] and [4] that all loads are assumingly DC.

The authors of [10] have proposed an office model with equal 300W loads in all; the AC, the DC and the mix AC-DC networks. Although this study presents a comparison of three scenarios, the load model assumption has weakened the overall worth of the study. The work is not a reflection of a realistic model of a locality because of the constant power consumption of all the loads. [11] is another research effort concerning the data centre. As compared to [8]; it presents a generalized DC microgrid model; with no significant explanation of load modeling.

The model presented in [12] considers selective office loads. The load division among AC and DC is also arbitrary; quite similar to [1] and [5]. The scheme employed for lighting is almost similar to [10]; where lights are assumed as AC in nature in the AC system and DC nature in the DC system. The study is a straightforward comparison of two systems considering five loads and does not present a variety of scenarios. The work presented in [13] presents an averaged load interface, where all the loads are averaged to produce a single interface which is DC in nature for both AC and DC distribution networks. Furthermore, the study is based on a futuristic approach as the loads are taken from a reference that is considering forecasted data of the year 2020.

[14] is comparing AC and DC distribution networks on the basis of lighting load only. Furthermore, lights are assumed to be DC in both AC and DC distribution networks. Selection of a single load; and further assuming it purely DC, weakens the model for comparative analysis of AC and DC distribution systems. The model presented in [14] driving LED loads is presented in Fig. 2.

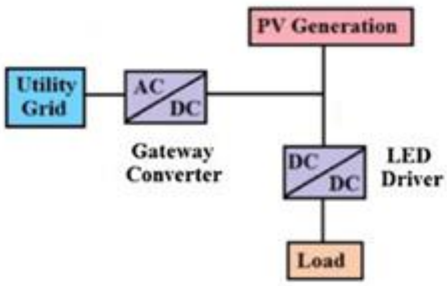

Figure 2. Load Model for LED Loads [14]

The work of [15] is somewhat related to the work presented [3] as regards a fixed ratio of AC and DC loads. [16] focuses on the model of a commercial facility. Office loads are considered but the selection of loads seems inclined towards kitchen appliances. This makes it an office analog of the work presented in [7]; where kitchen loads are considered in a residence.

The load division presented in [17] is quite similar to [1], [5], and [6] where loads are arbitrarily distributed among AC-DC categories. All lights were assumed DC in [1], [5], and [7] whereas in [17], all lights are considered AC. Furthermore, constant loads are considered in the study, the effect of load variation is not considered. [18] and [19] present similar load models; the scope of the work is limited similar to [7] as only two loads (lamp and motor); are considered in the model. The authors of [20] make the same assumption as [14] regarding load and its type i.e., only lighting load is considered in the study assuming the whole lighting system as DC-based. It is further assumed that all the lights are switched ON at 6 am and OFF at 8 pm. Hence, the actual effect of load variation is not considered. The paper lacks a comprehensive comparative analysis between AC and DC distribution systems as a single model is divided into two subsets i.e., AC and DC.

In [21], selective office loads are considered in quite a similar fashion as presented in [12] and [16]. The complete analysis is performed on four load types i.e., electric hybrid vehicle (EHV), information technology (I.T), lighting and heating, ventilation, and air-conditioning (HVAC). [22] presents a variety of scenarios and the study can be considered futuristically concrete regarding efficiency analysis of AC and DC distribution systems. The study aims at office models and assumes all loads to be DC as assumed by the authors of [13] and [20]. The loads are classified as 'native DC' (loads which require a rectifier in the AC system) and 'direct DC' (loads which are directly, or via DC-DC converter, connected to DC system).

The model does not present the effect of a variety of loads i.e., the targeted loads are HVAC (which is assumed as a 24 Ampere packaged unit), lights (assumed to be operating at constant, 75% of rated power), computers, laptops and power over Ethernet (PoE).

The importance of [23] is equivalent to [22] as the study of [23] presents various scenarios and discusses the comparison of AC and DC distribution systems considering seven different topologies and five load classes (refrigeration, AC motor, electric vehicle, resistance heating and other). Certain assumptions within the topologies, however, make the study unrealistic or futuristic. For instance, in five architectures, AC motors are considered to be replaced by brushless DC motors. Moreover, for each appliance class assumed to be served by DC, a new profile is established as a function of the "proposed" power supply and new end-use efficiencies. In some topologies, a load class is further divided on an unknown criterion into AC operated and DC operated e.g., refrigeration is divided into "BLDC based" and "other refrigeration".

Similarly, [24] assumes all the loads as internally DC similar to the assumption made in [4],[7], and [22]. Similar to [7] and [12], the work does not provide a comprehensive study as only a specific set of loads are considered in a residential model. In comparison to [24], [25] considers an even lesser number of loads for the study. Only lighting, elevator, and "other" loads are considered in the study.

Summarizing the above discussion regarding the assumptions and gaps in the consideration of load model for a definite efficiency comparison of AC and DC distribution networks, it is concluded that each and every research has made unrealistic or futuristic assumptions in the model considered.

The common assumptions include models comprising of DC loads only [2], [4], [8], [9], [13], [14], [18]–[23]; fixed proportion of AC and DC loads [3], [15]; consideration of a single or small set of loads for analysis [7], [12], [18]–[21]; uneven or arbitrary distribution of loads among various classes [1], [5], [6], [23] and neglecting the actual effect of load variation [2], [5], [6], [17]–[19], [24], [25].In contrast, a realistic load model considering a variety of loads with actual load profile and appliances divided into AC and DC classes without assumptions of being internally DC or direct DC; can be the best fit for definite comparative analysis of AC and DC distribution system efficiency. Fig. 3 presents a summary of the gaps/loopholes in the load models presented in various studies.

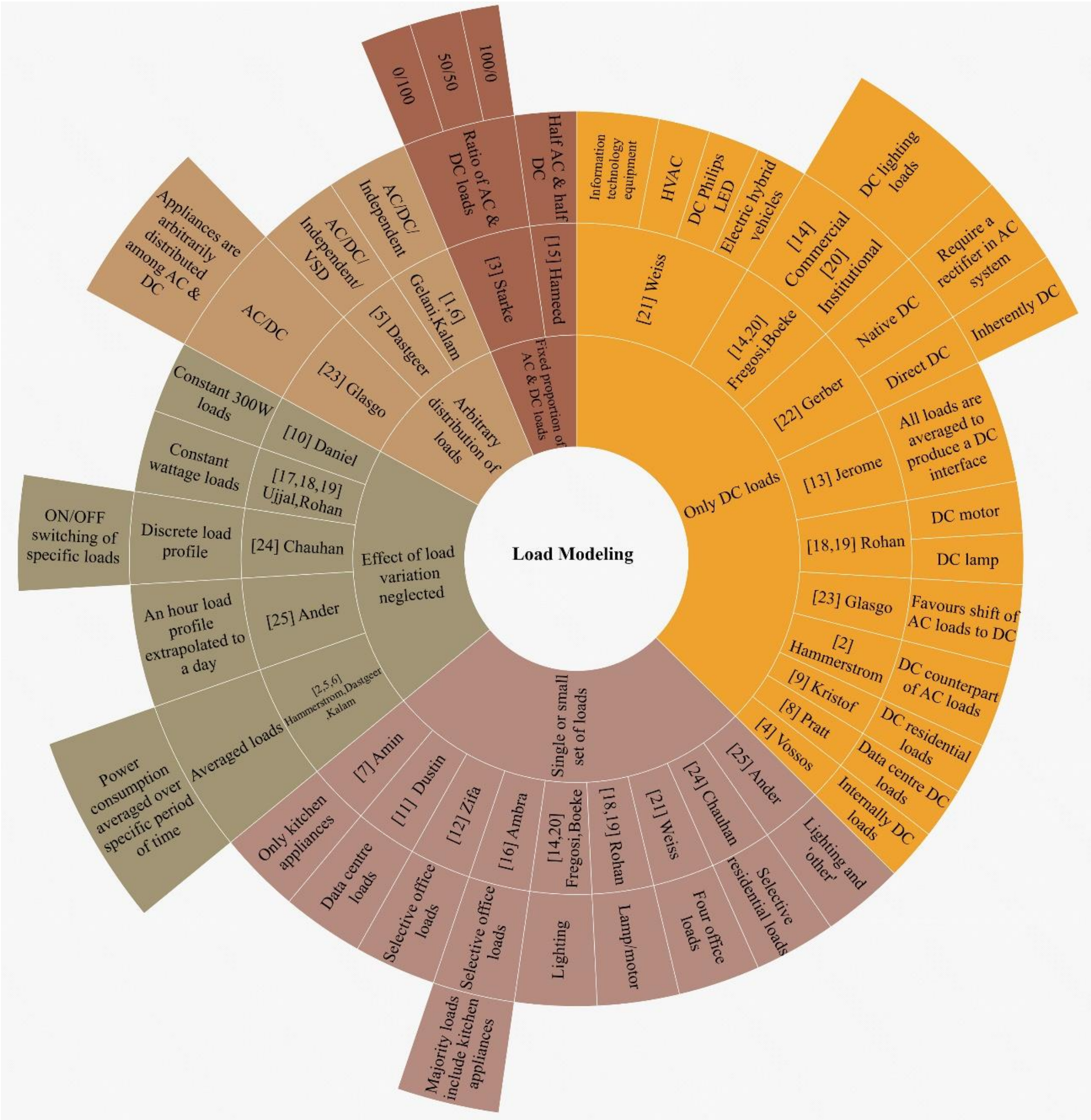

Figure 3. Load Modeling Presented In Various Studies

2.2. Critical Review of the Consideration Of PEC Efficiency

Converters are employed for power conversion, from AC to DC and vice versa, as well as voltage transformation in distribution systems. The revival of DC in the power system is linked with the development of PEC capable of replacing conventional transformers. The losses exhibited by converters contribute the most to the overall facility's electrical loss. Therefore, converters hold a strong position in defining the efficiency of AC and DC distribution systems. Generally, the efficiency of the converters varies with the loading. Since the operation of appliances or loads in a facility is a randomly varying process; the efficiency of the associated converters changes accordingly. A few authors have tried to accommodate the effect of varying efficiency of the converters against loading such as [1], [4], [13] and [22]. The authors of [1] divided the whole day into three arbitrary periods; 'Night (00:00-06:00)', 'Day1 (06:00-15:00)' and 'Day2 (15:00-00:00)'. The effect of instantaneous load variation throughout the day is not taken into account; weakening the overall consideration of the effect of variation in converters efficiencies.

The work presented in [4] considers two values: full load and part load (part load is taken 20% of full load) for defining converter efficiency variation with respect to load. The efficiency of converters operating between 20% loading up to 100% loading is assigned full load efficiency value, and the efficiency of converters operating at less than 20% loading is assigned part load efficiency value. The selection of 20% loading as a boundary of part load and full load raises a question i.e., a small value of load above 20% is equivalent to full load? In contrast to two values presented in [4]; the work presented in [13] accounts converter efficiencies at four loading levels i.e., 25%, 50%, 75%, and full load. A formula is presented in the study assuming three sources of PEC losses; constant losses ($\boldsymbol{K_{e1}}$), switching losses ($\boldsymbol{K_{e2}}$) and conduction losses ($\boldsymbol{K_{e3}}$). Switching and conduction losses are in linear and quadratic relation to the output power of the PEC respectively. In order to compute the three coefficients; (1) is utilized.

$$K_e(\alpha 1, \eta 1, \alpha 2, \eta 2, \alpha 3, \eta 3) = \begin{bmatrix} 1 & \alpha 1 & \alpha 1^2 \\ 1 & \alpha 2 & \alpha 2^2 \\ 1 & \alpha 3 & \alpha 3^2 \end{bmatrix}^{-1} \begin{bmatrix} \alpha 1\left(\frac{1}{\eta 1} - 1\right) \\ \alpha 2\left(\frac{1}{\eta 2} - 1\right) \\ \alpha 3\left(\frac{1}{\eta 3} - 1\right) \end{bmatrix} \quad (1)$$

Where, $(\boldsymbol{\alpha 1}, \boldsymbol{\eta 1})$; $(\boldsymbol{\alpha 2}, \boldsymbol{\eta 2})$; $(\boldsymbol{\alpha 3}, \boldsymbol{\eta 3})$ are three arbitrary points taken on loading versus efficiency curve of PEC; '$\boldsymbol{\alpha}$' and '$\boldsymbol{\eta}$' denote loading and efficiency respectively. The efficiency of the PEC is given by (2)

$$\eta(\alpha) = \frac{\alpha}{K_{e1} + (1 + K_{e2})\alpha + K_{e3}\alpha^2} \quad (2)$$

The study of [22] can be regarded as better than [1], [4], and [13] in the sense that the efficiency curves of the converters are devised on the basis of data from commercially available converters.

As compared to the aforementioned research efforts; which tried to account for the effect of variation in PEC efficiency with respect to load variation; the authors of [5] and [23] have defined a fixed range of values representing converter efficiencies. In [5], the converters are divided into two categories i.e., distribution side (at primary distribution voltage level) and load side (at residential voltage level). While the efficiency of one set is kept fixed, the other is varied in discrete steps within a fixed range and vice versa. Whereas in [23]; the range of converters efficiency is not discrete as compared to [5]. However, both studies; [5] and [23] show an unrealistic selection of ranges because of the reason that none of the converter range accommodates the efficiency of any converter below 80%. Whereas in reality; converters may operate below 50% efficiency when the load(s) driven through them are operated at lesser power with respect to rating.

Descending from the consideration of PEC efficiency with respect to load variation to considering PEC efficiency within fixed range; there are certain studies which have considered fixed efficiency of PEC e.g., the authors of [2], [3], [12], [15], [17], [18], [19] and [21] have assumed fixed efficiency of the converters in the efficiency analysis of distribution systems. The study in [2] assumes fixed loss associated with each conversion stage i.e., 2.5% and does not consider the effect of converters efficiency variation. In [3],the efficiency analysis of the distribution systems is again performed on different fixed conversion efficiencies such as 95%, 97%, and 99.5% for DC-DC converters. The authors themselves claimed that a PEC with 99.5% efficiency is rare as regards to availability. Lastly, there is a set of research efforts that do not consider the role of converters in their model. Examples include, the studies of [7], [9], [11], [16] and [24].

These studies base the comparison of AC and DC distribution systems on parameters other than converters efficiencies e.g., line losses, voltage drops, etc. The authors of [7] and [16] present a comparative analysis of AC and DC distribution systems based on power losses and voltage drops; without considering the efficiency of the converters. The authors of [9] highlight the requirement of efficient converters particularly at partial loading but do not actually account for the efficiency of the converters in any of the topologies presented in their study.

Besides the categories of studies presented above as regards the consideration of PEC efficiency; it is important to point out the basic reason for the installation for converters i.e., power conversion or voltage transformation. The selection of loads in a model is highly related to converters e.g., a load model with only AC loads eliminates DC-DC and AC-DC converters in the DC distribution system. As pointed out earlier for the case presented in [21] and [22]; there are a few similar cases where converters are neglected as a result of unrealistic/futuristic load assumptions e.g., the models of [2], [4] and [20] as mentioned in load modeling section.

Fig. 4 demonstrates the consideration of converters' efficiency in various studies. Critically summarizing the discussion presented in this section, there is no doubt that converters have a strong influence on the efficiency of distribution systems. Considering fixed converters efficiencies is better than neglecting the effect of converters; similarly considering a variation of the converters with loading is far better than employing fixed converter efficiencies in the analysis. Moreover, there are constraints associated with the consideration of an actual role of converters e.g., in certain cases a statement is established that devices which require an internal rectifier stage can directly operate on DC-based distribution; or VSD based loads (which require two conversions i.e., AC-DC and DC-AC in AC distribution systems) can be operated on DC via single conversion i.e., DC-AC. Both these statements are true but bounded by a constraint. The constraint is the matching of DC input voltage demand of the loads and available DC supply voltage level.

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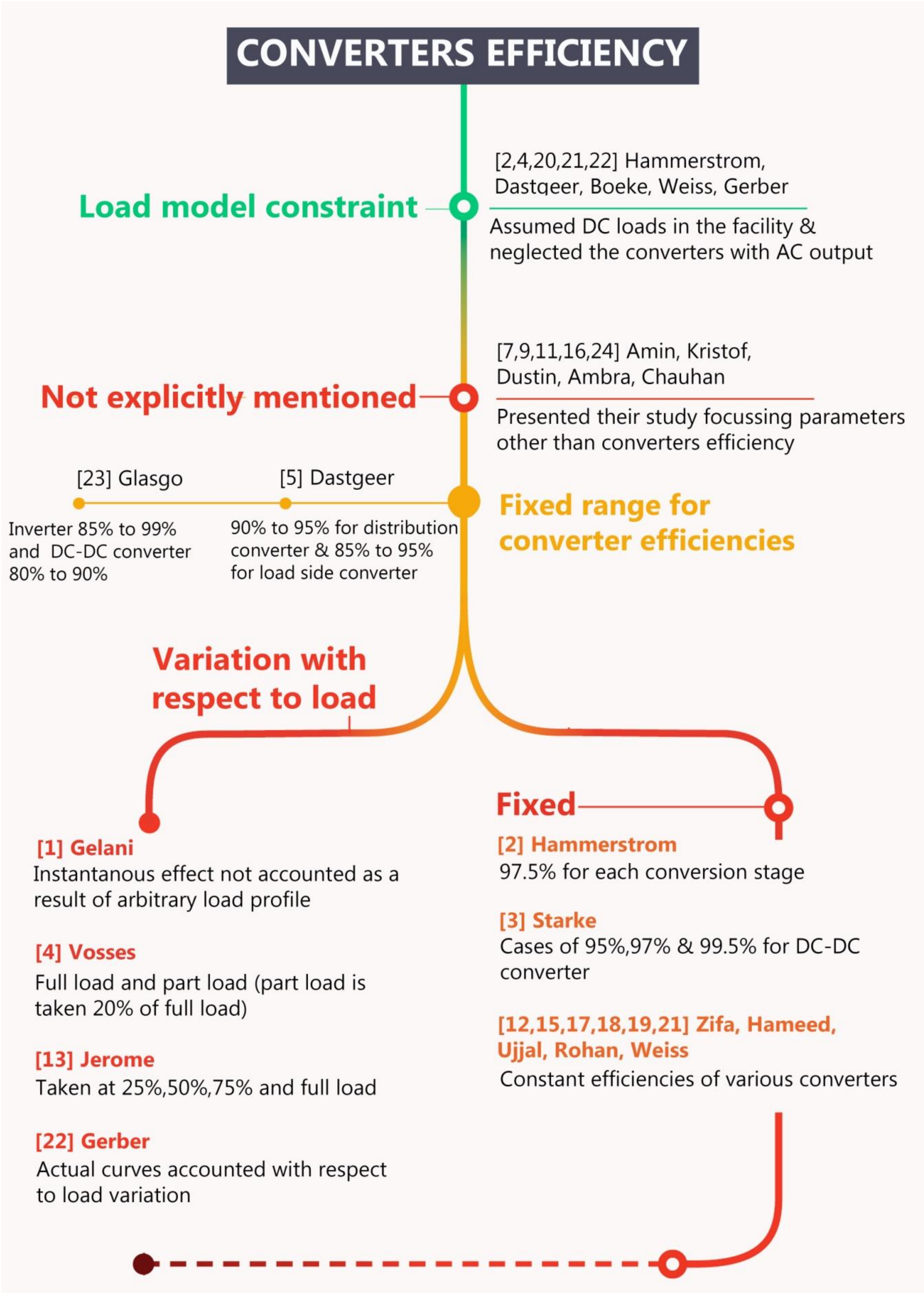

Figure 4. PEC Efficiency presented in Various Studies

2.3. Review of the consideration of Storage elements in AC And DC Distribution Studies

The basic aim of storage items in the conventional AC system was to provide an uninterruptible supply of power for sensitive loads. However, with the advancement in the field of distributed generation, storage has gained a notable position in distribution systems.

Generally, the parameters associated with battery are state of charge (SOC), rating/size and efficiency. Installing a battery in a distribution network without considering any of these parameters would not be a recommended practice from an engineering point of view. The study of the effect of battery on the efficiency analysis of AC and DC distribution systems cannot be regarded as a complete study without incorporating the stated battery parameters. Various authors considered battery in different fashion in their respective studies such as the author of [2], although states the presence of battery in the system but neither considers the associated losses nor the rating of battery and the authors of [7] considered battery for sensitive loads only, without providing any associated value for losses or rating. In contrast, neglecting the battery completely in the system would lead to an even more incomplete study of AC and DC distribution systems such as the authors of [1], [3], [5] and [20] etc.; did not install a battery or any storage item in the distribution system models.

A few authors, [4], [22] and [25]; considered the parameters associated with the battery. The study presented in [4] provides criteria for battery sizing and then employs a 10kWh battery in the system. The losses associated with the battery are also taken into account by assuming a 90% (one way) efficiency of the battery. The authors of [22] considered battery losses by accounting for 90% (one way) and 81% (round-trip) efficiencies. They also defined a battery charging algorithm as a function of excess solar power available given by (3).

$$P_{solar}^{excess} = P_{solar} - P_{load} \tag{3}$$

where'$\boldsymbol{P_{solar}^{excess}}$' is the hourly excess solar power, '$\boldsymbol{P_{solar}}$'is the total solar generation and '$\boldsymbol{P_{load}}$' is the total load demand. The controller charges the battery when $\boldsymbol{P_{solar}^{excess}} > 0$and discharges when $\boldsymbol{P_{solar}^{excess}} < 0$. The authors of [25] employed a 500Ampere-hour battery assuming that utility power is only available during the night (for a few hours).

To summarizing, apart from certain studies that do not incorporate battery in their power distribution models; a variety of studies installed a battery. However, installing a battery in a system does not make a system capable enough to define the effect of storage in the efficiency analysis of AC and DC distribution systems. The state of charge (SOC) of the battery varies throughout the day while the battery is charging or discharging as well as while it is in an idle state. The appropriate sizing of the battery holds concrete importance from a realistic point of view. Performing an efficiency analysis of AC and DC distribution systems by installing a battery without considering its losses and SOC variation or making an assumption for battery sizing like utility power is available for a few hours during night; these gaps and assumptions raise a question whether such an efficiency analysis of AC and DC distribution systems is valid enough to give a definite verdict that AC is better than DC or vice versa at distribution level? Hence, appropriate sizing and consideration of losses associated with the battery are necessary for defining a realistic efficiency analysis of AC and DC distribution systems.

2.4. The choice of Voltage Level in DC Distribution Efficiency Analyses

In order to compare the AC distribution network against the DC distribution network, the choice of appropriate voltage level is very important because line losses, voltage drops, appropriate converter selection; all depend on voltage level considered. AC distribution networks, being conventional have almost fixed operating voltage levels in various studies e.g., 230V (RMS) is excessively used in most of the studies in AC distribution system modeling. However, the case of DC distribution is complex as well as confusing. Complex in the sense that some studies use various voltage levels within a single facility whereas confusing in the sense that which voltage level should actually be employed that is authentic enough to compare AC and DC distribution networks.

The availability of a particular voltage level depends on the load demand. Electronics and other small loads usually operate in the range of 12V to 48V. In order to drive such loads, authors of various studies have provided the respective voltage level according to load demand such as the authors of [7], [17] and [24]. However, such a small voltage cannot be employed to drive high power loads which contribute to a major portion of overall power consumption in a facility. In order to fulfill the voltage requirement of high power loads, authors from various studies proposed 230V, 325V, or 326V, 380V, and 400V in their distribution system models. An important study in this regard is presented by the authors of [16]; in which different voltage levels (326V, 230V, 120V, and 48V) are compared and then 326V is declared most suited from a technical and economic standpoint.

The authors employing a particular voltage level in their respective model claims in favor of that voltage level and utilize the particular voltage in the efficiency analysis of AC and DC distribution systems. The authors of [5] use 230V in their model. The reason presented by [5] is the fairness of the comparison of AC and DC distribution systems since the AC voltage level is 230V. The authors of [1], [6], and [10] employed 325V in their study for the reason that 325V is the peak value of 230V. With 325V; the same conductor as AC can be employed for power flow in the DC distribution system and loads that require a rectifier stage in the AC distribution network can be operated on 325V directly in the DC distribution network.

380V is the choice of a variety of authors such as [4], [11], [13], [20], [21] and [22]. The basic reason for employing 380V in the DC distribution system is that the losses in the system are highly dependent upon the chosen voltage level. While considering 380V in the system, the losses in the DC distribution system get minimized as compared to the DC distribution system operated with lesser voltage levels.

The claims that a particular level is chosen to drive DC internal loads or to add a factor of fairness in the comparative analysis are not strong enough to standardize the particular voltage level for the analysis of AC and DC distribution systems. Physical factors such as conductor size and converter size are associated with the voltage level. The commercial availability of loads rated on a particular voltage level is a strong factor. Employing a specific voltage level does not mean that the load demand of the appliances matches that voltage level. Fig. 5 presents different voltage levels utilized by authors of various studies for the DC system.

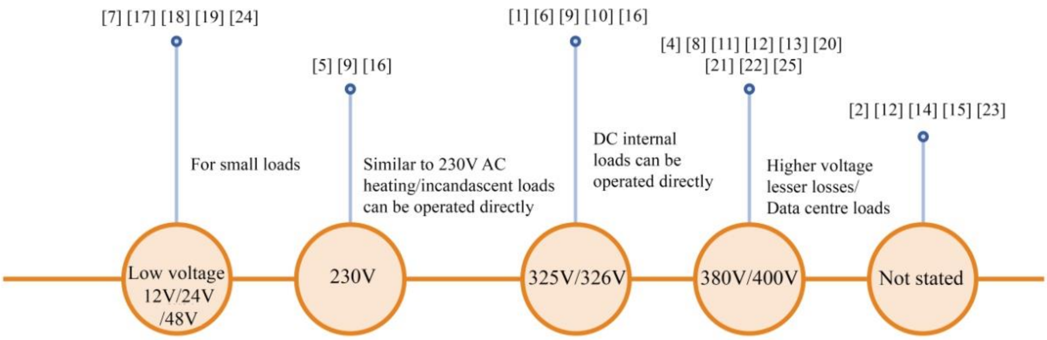

Figure 5. Consideration of Voltage Levels by Various Authors

2.5. Consideration of Line Losses in the Past AC DC Distribution Efficiency Studies

Predominantly, it was the factor of line losses that supported DC in the sector of power transmission; and HVDC transmission gained importance over HVAC transmission. A variety of authors have not considered line losses while performing the efficiency comparison of the AC and DC distribution systems such as [4], [6] and [25], etc. They assumed that line losses in both, AC and DC, systems are comparable; therefore, they did not account for the conductor losses in the study. On the contrary, some authors included line losses in the study such as [1], [5] and [10]. However, the line lengths are arbitrarily taken. In this context, [16] can be regarded as a better study as authors calculated voltage drop and power loss occurring in each conductor of an actual office network.

The authors of [17] have derived an expression comparing AC and DC distribution line losses given by (4)

$$\frac{P_{dc}}{P_{ac}} = cos^2\theta \tag{4}$$

Where' $\boldsymbol{P_{dc}}$ ' represents DC distribution system line losses, '$\boldsymbol{P_{ac}}$'represent AC distribution system line losses and '$\boldsymbol{cos^2\theta}$' is the square of the power factor.

The consideration of line losses is important. Although there is not much difference in the line losses of AC and DC distribution systems, ignoring smaller factors like line losses may affect the overall results. The authors of [13] have concluded the power loss in the conductors equal to 1.08% and 0.32% for AC and DC distribution systems respectively. Similarly, the authors of [20] also presented the power loss occurring in the conductors equal to 0.43% and 1.2% for DC and AC distribution systems respectively. The difference in the losses for AC and DC systems is not enough but it can be a decisive factor while the efficiency of AC and DC distribution systems is equal considering factors other than line losses.

2.6. Employment of Distributed Generation in AC DC Distribution Efficiency Studies

Distributed Generation (DG) is an important factor that has helped DC, against AC, to form its influence on the power system at the distribution level. As presented in the introductory section of the paper, renewable energy resources, particularly solar, produce DC at their output. However, at residential and commercial facilities, solar PV has gained enough importance because of easy installation and negligible maintenance [26]-[29]. This is the reason that studies focusing on the feasibility of DC or the comparison of AC and DC at the distribution level; employ solar PV in their model. This section explores the studies regarding the distributed generation i.e., whether the distributed generation is presented in the study; if yes then how distributed generation is modeled in the network so as to consider its effect on the overall system.

A variety of authors have utilized solar as a source of DG in their studies. There are certain factors that are linked to solar based DG which are incorporated by a few authors to some extent whereas some authors neglected those factors while performing the efficiency analysis of AC and DC distribution systems. The output of solar based DG varies throughout the day. Furthermore, the efficiency of the converters employed with solar, for voltage transformation to DC or power conversion to AC; varies with the output power of the converter. Another important factor associated with solar based DG is the size/capacity of the system.

The variation of solar output with respect to time has been considered by the authors of [4] and [13]; however, the authors did not account for the variation in the efficiency of the converters with output power. The authors of [14] presented a PV energy efficiency metric called PV utilization fraction (PVUF); which defines the usefulness of PV energy i.e., the fraction of PV energy that is either delivered to the load or grid.

$$PVUF = \frac{\sum_{t\in T|E_{ft}\leq 0}(E_{dt} - E_{ct}) + \sum_{t\in T|E_{ft}>0}(\frac{E_{dt}}{E_{ct}})E_{bt}}{\sum_{t\in T} E_{at}} \tag{5}$$

The numerator of (5) contains useful PV energy i.e., energy delivered to the load '$\boldsymbol{E_d}$'and energy exported to the grid '$-\boldsymbol{E_c}$'when PV generation exceeds the load, plus the portion of PV energy supplied to the load when loads exceed the PV generation. The PVUF is an annual metric in which '$\boldsymbol{t}$' is an arbitrary time period in a set of time periods

$\boldsymbol{T} = \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{T}\}$ that span the entire year. The time periods are separated by duration 'Δt' and within each time period 't', the system is assumed to operate at steady state energy 'E_{at}', 'E_{bt}' and so forth. The denominator sums the overall PV generation.

The authors of [22] performed an efficiency comparison of AC and DC distribution systems for various solar capacities.

A proper efficiency analysis AC and DC distribution systems demand the consideration of all the factors associated with DG that directly or indirectly affect the efficiency of distribution systems. It is important to note that several studies did not consider DG in their studies like [1], [2], [3], [5], [7], [8]–[12], [17] etc. In comparison to these, the authors who considered DG in their study did not account for all the factors linked with DG. Ignoring DG completely or neglecting some factors associated with DG that may affect the overall efficiency of the distribution systems cannot present a definite or complete study of the efficiency of distribution systems. Considering one or two factors of DG and employing those in the study can definitely produce an efficiency comparison of the AC and DC distribution systems but cannot produce a definite comparison of the AC and DC distribution systems. Hence, there is a need to consider all the significant factors associated with DG that may affect the efficiency of AC and DC distribution systems.

3. An Approach to a Definite AC DC Distribution System

Since we are interested in presenting a load model that can give a definite verdict of whether AC is better than DC at the distribution level; we need to consider advancement in load models as a result of advancement in technology. Considering the load model, the major loads that consume most of the percentage of total power in a facility are based on motors e.g., cooling, refrigeration, cleaning, etc. [30]–[33] Incorporating the current scenario; the shift of trend towards VSD and the futuristic replacement of induction motor based appliances by BLDC motors; the load model is broadly classified into three portions:

- Conventional/classical
- Shifting trend
- Futuristic

In the conventional load model; the loads are classified into AC and DC according to their existence in current systems. The loads that are inherently AC and those inherently DC fall in AC and DC category respectively.

The computers, laptop/mobile phone chargers, LED lights, electronics; all are classified as DC loads. This and the next paragraphs should be joined. Induction motor based compressors i.e., cooling, refrigeration and wet cleaning; incandescent lights, etc. are classified as AC loads. With the advancement in the field of power electronics; the trend is shifting towards VSD based induction motor appliances for cooling, heating and refrigeration [30], [34], [35]. As compared to the conventionally employed fixed speed induction appliances; the VSD based appliances operate at with reduced losses, thereby provide better operating efficiency [35]–[41]. The world has witnessed this shift in trend from classical fixed speed systems to VSD based systems; and most of the countries have installed VSD based cooling, heating, and refrigeration at residential as well as commercial facilities. In the classical load model; the VSD based loads operate via the double conversion stage. The incoming AC is converted to DC which is then converted to variable frequency AC in order to provide variable speed control of the motor [41], [42]. It is important to note that in a DC system, this may be achieved via a single conversion stage provided the incoming DC voltage level matches the DC voltage rating of the appliance.

Another shift in the load model is observed in the case of LED-based lighting and LED-based television sets. The reason is the same as VSD; the power consumption of LED lights and LED television sets is lesser as compared to classical incandescent lights and television sets. Both require a driver (AC–DC converter) when operated in an AC distribution system.

The futuristic load model is based on the complete replacement of major loads i.e., cooling, heating, cleaning, and refrigeration; by their DC counterparts. The purpose or function performed by all the major loads in the futuristic load model would be the same but their most significant part i.e., induction motor shall be replaced by BLDC permanent motor. BLDC motors are capable of providing energy savings as compared to standard induction motors as shown in Fig. 6.

Loads keep on switching on and off according to their requirement throughout the day [43]–[46]. Furthermore, while the loads are on; their power consumption may vary e.g., automatic lights dimming. The power consumption of loads with respect to time is expressed as a load profile. Most of the loads are used on a daily basis e.g., lights, computers, refrigerators, cleaning, etc. However, some loads are utilized on a seasonal basis e.g., heating loads during winters and air-conditioning loads during summers. Moreover, the load profile is somewhat different at weekends than it is during weekdays. Therefore, a complete model necessitates the consideration of the instantaneous as well as the seasonal power consumption of all the loads taken during weekdays and weekends. Hence, it is proposed to consider the instantaneous power consumption of the loads on a bimonthly basis (one during the weekday and other during the weekend). The same strategy holds for the load models representing a shifting trend and futuristic modeling.

Since the basic requirement of the load model is the consideration of real-time power consumption of loads. A bottom-up approach can be employed to determine the efficiency of the system. In the case the of DC system, the loads can be divided according to voltage level and power demand (AC or DC). However, in the case of the AC system, the loads may be categorized according to their power demand; since the voltage level is constant throughout the building i.e., 230V.

Suppose the loads are divided as AC and DC within the building as shown in Fig. 7; the DC loads are further divided into high voltage and low voltage categories. The mathematical model of the DC system can be performed as:

$$P(t)_{DC} = \sum_{i=1}^{n1} P(t)_{DC(i),h} + \sum_{i=1}^{n2} \frac{P(t)_{DC(i),l}}{\eta(P)_{DC-DC(i)}} \tag{6}$$

where'$P(t)$' and '$\eta(P)$' represent the power consumed by various loads with respect to time and efficiency of the converter at that consumed power respectively. The number of high voltage and low voltage loads is assumed to be $n1$and $n2$ respectively with high voltage loads connected to the mains voltage directly.

$$P(t)_{AC} = \sum_{i=1}^{n3} \frac{P(t)_{AC(i)}}{\eta(P)_{DC-AC(i)}} \tag{7}$$

where $n3$ is the number of AC loads within the house.

The total input power to the house can be derived using:

$$P(t)_{in-H} = P(t)_{DC} + P(t)_{AC} \tag{8}$$

$$P(t)_{in-H} = \sum_{i=1}^{n1} P(t)_{DC(i),h} + \sum_{i=1}^{n2} \frac{P(t)_{DC(i),l}}{\eta(P)_{DC-DC(i)}} + \sum_{i=1}^{n3} \frac{P(t)_{AC(i)}}{\eta(P)_{DC-AC(i)}} \tag{9}$$

For j number of houses connected to secondary distribution-solid state transformer (SD-SST), the power output at SD-SST can be derived from:

$$P(t)_{out-SD} = \sum_{j=1}^{m} \{P(t)_{DC} + P(t)_{AC}\}_j \tag{10}$$

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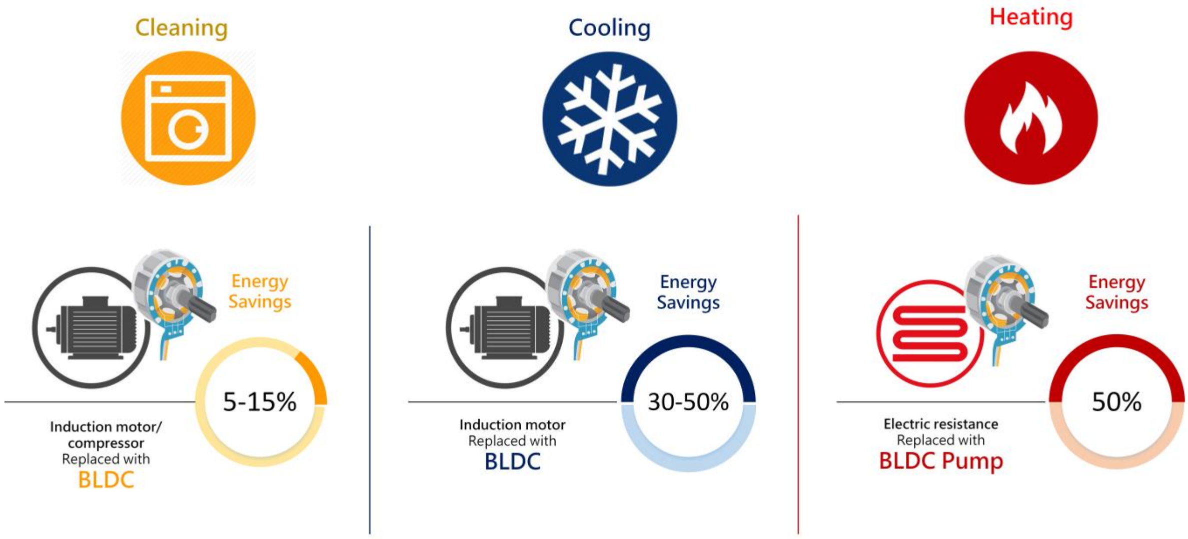

Figure 6. Replacement of conventional induction motor with DC motor

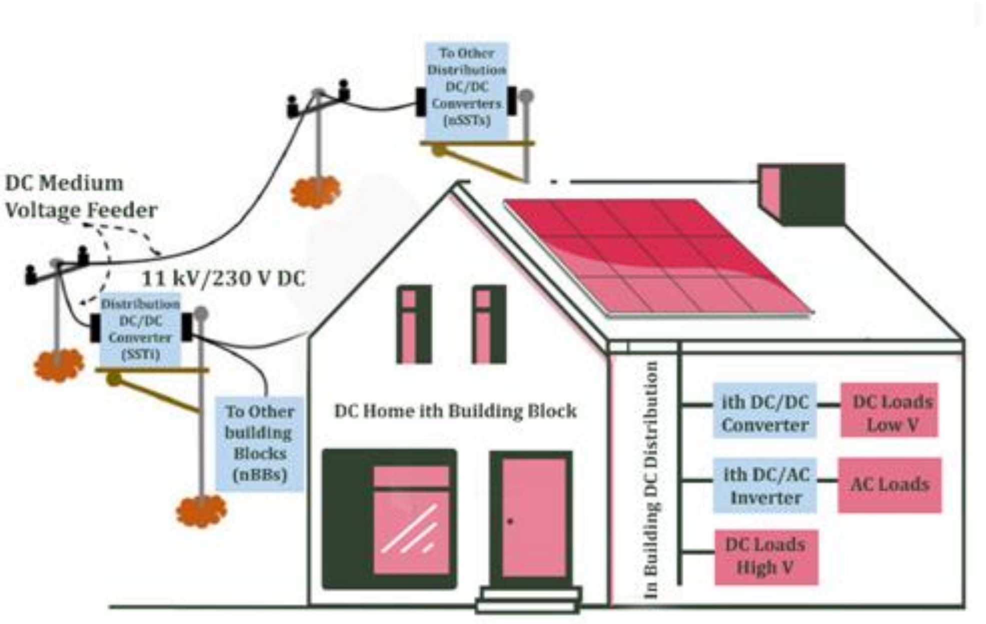

Figure 6. Overall system model for mathematical analysis

The input power of the SD-SST can be computed by dividing output power by the operating efficiency of the transformer.

$$P(t)_{in-SD} = \frac{P(t)_{out-SD}}{\eta(P)_{SD}} \tag{11}$$

Suppose there are x SD-SSTs in the system; the power taken from the grid can be found by summing the power of all the SST-SSTs using:

$$P(t)_{out-G} = \sum_{k=1}^{x} \{P(t)_{in-SD}\}_k \tag{12}$$

In the end, the efficiency of the system can be computed by dividing the overall power consumed by the loads to the power taken from the grid.

$$\eta(t)_{sys-DC} = \frac{P(t)_{load}}{P(t)_{out-G}} \tag{13}$$

The above mathematical model can be extended or modified for any load model. The categorization in this model is done on the basis of the voltage level; however, this can be modified on the basis of loading category of [1], [5] and [6]. Furthermore, solar power can be added to the model by employing real time solar insolation data to the model.

3.1. Inclusion of PEC Efficiency in System Model

Since it is proposed in the previous section that the instantaneous load profile should be considered; this dictates the consideration of the instantaneous efficiency of power converters. Furthermore, it is emphasized to consider the characteristics of commercially available converters. Although highly efficient converters have been designed and implemented in research there are constraints associated with their availability.

- Regarding the modeling of converters; three approaches are observed in the research:
- Separate/independent converter for each load [5]–[6]
- Loads with a similar rating are lumped and driven via a single converter
- Paralleling of converters/ Modular architecture [47]–[49]

The use of a separate converter for each load and paralleling of converters demands the installation of numerous converters in the model. Although the schemes may be fruitful from a technical point of view; but seem unrealistic from a structural point of view. Such installations may be found at grid stations whereas, in residential or commercial facilities, the installations are kept as limited as possible in order to reduce wiring complexities. In contrast, the approach of lumping of loads with a similar rating and driving them through a single converter seems realistic as it requires lesser installations.

Another important parameter associated with the converters is to assign a practical oversize ratio. Oversize ratio defines the operating region of the converter on its efficiency curve. From a realistic and practical point of view, a converter seldom operates on its maximum allowable power, there is always room between full load rating and the maximum load that the converter can practically drive [22], [45], [50]–[52]. The real time efficiency of the converters can be added to the model by considering the practical characteristics of the converter efficiency against loading. The polynomial function governing the efficiency of the converter against loading can be of the form:

$$\eta(P)_{conv} = a + bP + cP^2 \ldots \tag{14}$$

Or in the form of piecewise function:

$$\eta(P)_{conv} = \begin{cases} a_1 + b_1P + c_1P^2 \ldots & P_1 < P < P_2 \\ a_2 + b_2P + c_2P^2 \ldots & P_2 < P < P_3 \\ a_3 + b_3P + c_3P^2 \ldots & P_3 < P < P_4 \end{cases} \tag{15}$$

3.2. Inclusion of Storage Elements in System Model

One of the key factors in the revival of DC in the power system is the DC nature of storage items i.e., batteries. Batteries are considered to be an integral part of the distribution system for ensuring continuous delivery of power to sensitive loads as well as providing required power when utility and distributed generation are not enough to meet the demands [53]–[59].

Quite similar to load model; the selection of batteries in the distribution network raises the consideration of current scenario, shifting trend and futuristic scenario. The classical system employs battery for fulfilling the basic requirements of uninterruptible supply while utility power and distributed generation are exhausted. However, nowadays a shift in trend is observed often termed as net-metering. Net-metering is the reverse flow of power from the facility to the utility while the requirements of the facility are fulfilled by the combination of distributed generation and battery units. Regarding the future; the new era is witnessing an advanced technology called as zero net energy (ZNE) [60-63]. ZNE is one step ahead of net-metering; ZNE based system is optimally efficient by locally generating as much of power that is required to drive the loads; over the course of a year. The right choice of storage becomes an easy task when 'target' is defined and in the case of ZNE; 'zero target' is available i.e., the generation and consumption sum up to zero over a specific course of time.

In all the three scenarios stated above, the charge/discharge power ratings and losses associated with battery are necessary to be considered in AC and DC distribution system analysis. The datasheet that comes with battery contains values of maximum rated charge and discharge powers. Furthermore, the losses exhibited by battery are:

- Loss during charging and discharging of the battery [64], [65]
- Idle loss- decrease in SOC with time [66], [67]

A realistic model that is capable of providing a definite verdict between AC and DC at distribution level demands the consideration of losses stated above.

The proper selection of the capacity of the battery is another objective besides consideration of losses. A quick discharge and an extremely late discharge to a minimum are indications of low and high capacity of the battery respectively. If the SOC of the battery never decays to a minimum; it means that the battery is larger than the requirement. Similarly, if the SOC of a battery falls quickly, it means that the battery is smaller than needed. Another important feature in the consideration of the battery is the proper utilization of the battery. For example, if a battery stays for ample time at its maximum SOC, it means that the battery is not utilized in driving the loads; or if a battery spends enough time in a fully discharged state, it means that the battery is not getting its charge properly. The variation of SOC with time is, therefore, an important variable in deciding the functionality of the battery. The study of battery losses along with the variation of battery SOC with time is highly recommended in the analysis of AC and DC distribution systems.

Battery charges when:

$$SOC < C_{max} \tag{16}$$

Battery supply cuts off when:

$$SOC = C_{min} \tag{17}$$

Battery charges till:

$$SOC = C_{max} \tag{18}$$

The battery can be charged via solar panels as well as the grid. However, considering economic constraints; it is better to charge the battery through solar panels because charging the battery via grid adds to the utility bills.

For the purpose, there is a requirement of real time tracking of the solar power output as well as load power consumption.

Battery charges via solar when:

$$P(t)_{solar} > P(t)_{load} \tag{19}$$

As stated earlier, the SOC should also be monitored with respect to time; because SOC rises as a result of charging and falls as a result of charging. Solar power is not available throughout the day; battery power can be employed to supply the loads. Since batteries are costly; a realistic approach demands that the battery sizing should be bounded within previously stated technical as well as economic constraints. For the case of a moderately sized battery, battery power can be utilized to supply evening loads. And during the night the load demand decreases and power can be taken from the grid. For net-metering cases; again SOC variation with respect to time is demanded. Power is delivered to the grid while

$$P(t)_{solar} + P(t)_{battery} > P(t)_{load} \tag{20}$$

Whereas power is taken from the grid when:

$$P(t)_{solar} + P(t)_{battery} < P(t)_{load} \tag{21}$$

In the case of ZNE, since the target is defined in the form of net-zero; battery sizing can be achieved considering the load profile and solar output curve for the defined course of time.

3.3.Selection of Voltage Level in System Model

The classical AC system has been operating since the first battle of currents between Thomas Edison and Nicola Tesla. Therefore, the standard voltage levels of the AC distribution system are defined. However, there was no specific standard defined for the DC distribution system regarding the voltage level. Different voltage levels were opted in various studies without genuine reasoning. Recently, a comprehensive comparative analysis of AC and DC distribution systems is presented considering various voltage levels in [68]; however, the analysis did not consider the variation of PECs efficiency with loading and results were furnished that supported 48V DC. Not too long ago, with the efforts of [69]; 380V has been standardized as the voltage level for the DC distribution systems for commercial buildings; this has partially solved the confusion regarding the choice of voltage level.

380V is the voltage level available at the service mains. The loads rated at different voltage shall require an appropriate converter e.g., a 24V load shall be operated via 380/24 DC-DC converter.

3.4.Line Loss Consideration

The basic requirement of a model that can present a definite efficiency comparison of AC and DC distribution systems is that it should take into account every aspect responsible for affecting the efficiency of the systems. As depicted earlier, various authors have not considered line losses in efficiency studies assuming the line losses equivalent in AC and DC distribution systems. However, there may be a chance when line losses can be the defining factor e.g., the study presented in [5]; the authors accounted for the line losses and showed a 1% difference in the efficiency of AC and DC distribution systems. Therefore, due consideration must be paid to the factor of line losses.

3.5.Inclusion of DG in System Model

The output energy from solar PV changes throughout the day as well as with the seasonal climatic changes [70]–[74]. This demands instantaneous analysis of the output of the solar PV over a day as well as a year. A technique similar to the load model is proposed to be employed for the case of solar PV i.e., daily as well as yearly variation in the output of solar PV should be accounted for. The geographical location of the model is also an important factor in regards to the solar PV system [75], [76]. A moderate location should be considered that can accommodate daily as well as seasonal variations in solar energy at a wider scale so that a comprehensive analysis can be established.

The data of loads coincident with solar PV can be quite fruitful in evaluating the independent effect of solar PV on the efficiency of AC and DC distribution systems. Moreover, it is important to state that the capacity of solar PV must be chosen taking into account the fraction of loads coincident with solar PV. Although wind can be better optimized with DC systems, there is a negligible trend of considering wind plants as rooftop generators for the case of residences. However, it is important to point out the studies that take wind into account for example [77-78].

A classical realistic model does not allow high capacity solar PV that is coincident with all or a high fraction of the loads. However, the case with net-metering and ZNE based buildings may be different. Furthermore, the solar PV panels are installed on rooftops. This defines the limit of the size of the panels. The size/ capacity of the panels is required to be selected keeping in view the rooftop dimensions.

Since the trend is shifting towards net-metering; the only boundary is the dimension of the roof; as net-metering offers payments to the consumers against the energy, they sell to the grid. However, there are many states around the developed countries that do not offer net-metering currently; the case of developing and underdeveloped countries is quite behind. Regarding the futuristic ZNE; the baseline is defined i.e., the net of consumption and production is zero. This helps in deciding the capacity of solar PV bounded with the rooftop dimensions.

Although converters have been discussed in the previous section; there is a need to discuss converters linked with solar PV electric power as well. In case of AC distribution, converters are installed to convert solar DC output into building compatible AC and in the case of DC distribution; converters are employed to convert solar DC output into building compatible DC [79]. In both the cases i.e., AC and DC distribution systems, two parameters associated with the solar converters are:

- Efficiency
- Clipping

The converters employed with solar PV follow an efficiency pattern [80]–[84]. The efficiency of the converters is low at a lower percentage of rated power whereas the converters operate at better efficiency at a moderate and higher percentage of rated power. Clipping is related to the proper selection of the converter. A converter with lower power rating as compared to the maximum deliverable power of solar PV may not be fruitful at times when solar PV is producing maximum power; the difference of the power produced by solar PV and converted by the converter goes wasted because the converter is capable of converting power up to its rating. Therefore, it is important to pay due consideration to the variation in converters efficiency against output power as well as the proper selection of the converters. The power output from the solar panels can be evaluated from the product of solar power and connected converter.

$$P(t)_{solar-out} = P(t)_{insolation} \times \eta(P)_{Solar-conv} \quad (22)$$

Whereas $P(t)_{insolation}$ can be derived from the solar characteristics and $\eta(P)$ corresponds to the efficiency of the solar converter at that power; both can be represented in the form of single or piecewise polynomial, similar to converters discussed previously.

$$P(t)_{insolation} = a + bt + ct^2 \ldots \quad (23)$$

Or in the form of piecewise function:

$$P(t)_{insolation} = \begin{cases} a_1 + b_1 t + c_1 t^2 \ldots & T_1 < t < T_2 \\ a_2 + b_2 t + c_2 t^2 \ldots & T_2 < t < T_3 \\ a_3 + b_3 t + c_3 t^2 \ldots & T_3 < t < T_4 \end{cases} \quad (24)$$

4. The Future of AC-DC Efficiency Comparison

The study presented so far can be extended to include the effect of the highlighted parameters at a broader scale. The system can be classified into a number of operating states for different values of parameters. Fig. 8 presents the concept of multi-parameter and multi-value efficiency analysis. The efficiency of a particular system changes its state from one to another as the value of these parameters changes. An arbitrary state representing a particular scenario for specific values of parameters is also presented. The values in any specific state, at a given time *t*, are presented in (25)

$$\left\{\begin{matrix} p_{Solar}(t) = P_s Watt \\ p_{Load}(t) = P_L Watt \\ C_{solarPV} = C_s Watt \\ \eta_{PECs}(load(t)) = \eta\,\% \\ Voltagelevel = vVolts \\ . \\ . \\ . \end{matrix}\right\} - state1 \tag{25}$$

Where $p_{Solar}(t)$ and $p_{Load}(t)$ are solar PV generation and system load demand at any time t, η is the efficiency of the PECs against loading, $C_{solarPV}$ is the solar PV capacity; besides other system parameter values, together they form an operating state - state1. For this state

$$\eta_{savings}(state1) = x\% \tag{26}$$

Where $\eta_{savings}$ is the efficiency advantage of DC over AC for state 1.

Theoretically, the analysis may be carried out for any state of the system. The state modeling and analysis can provide a detailed analysis when AC is better than DC at the distribution scale and vice versa. An actual system can have a large number of operating states due to varying parametric values; the analyses need to be carried out over and over again for different states. In this way, the efficiency advantage of DC distribution systems can be evaluated for a wide number of states. Combining the results of all the states forms a composite analysis which can comprehensively present the comparison of AC and DC distribution systems. A conceptual state flow diagram is presented in Fig. 9. The values of all the parameters of fig. 8 form one state of the system at a particular time. As the value of one or more parameters changes with time, the system moves to another state. In fig. 9, only three state variables are shown i-e solar power 'Ps', load power 'P_L' and solar capacity 'C'. Suppose the values of these variables are 0.1pu each, forming state S1. The variables 'α', 'β' and 'γ' represent the increment and decrement in the values of 'Ps', 'P_L' and 'C' respectively. With an increment of 'α' and 'β' in the values of 'Ps' and 'P_L', the system shifts to new state S6 and vice versa. Similarly, while the system is at S_1, an increment in Ps alone shall move the system to S_2. Fig 9 is an illustration of how the system shifts states with the variation in the values of system parameters; and the energy savings at all the states is required to be performed in the future for a comprehensive analysis of comparative AC and DC systems.

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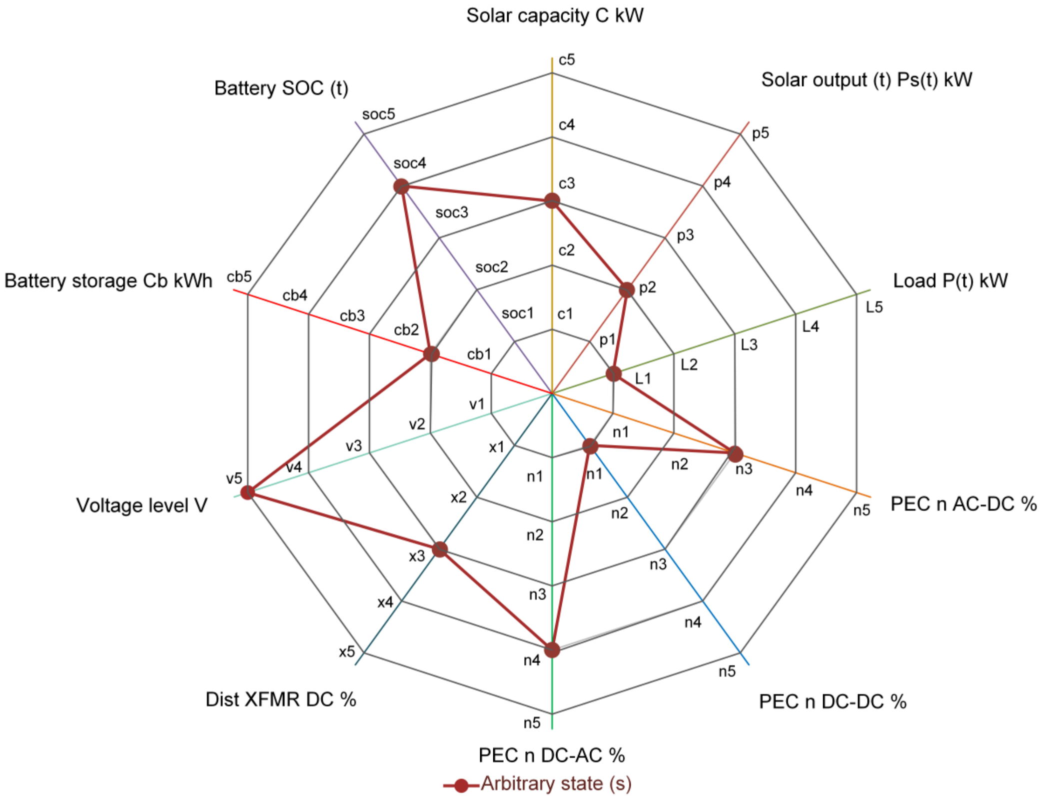

Figure 8: Concept for a multi-parameter multi-valued efficiency/energy savings analysis

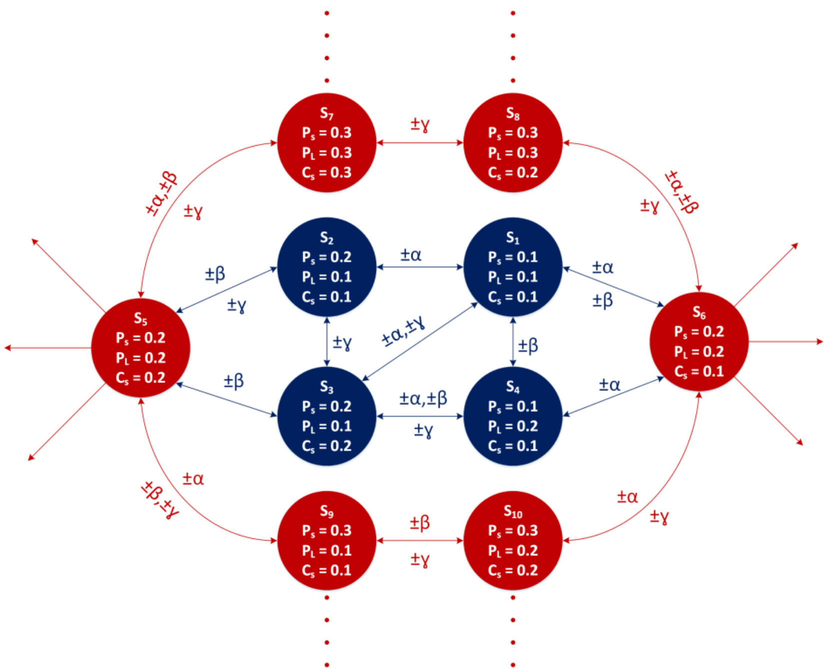

Figure 9: Conceptual state flow diagram (only three states shown).

5. Conclusion

DC, given up a long time ago is witnessing a revival. The advancement in technology has enabled DC to strike back. Efficiency was the factor that once wiped DC out of the scene at the birth of electricity and this may now be the factor to bring DC back to the power system. Hence, the efficiency analysis or more precisely the comparative efficiency analysis AC and DC distribution systems prime importance. Various authors have presented efficiency analysis but based on their own test scenarios, conflicting results exist. The efficiency depends on various factors, an approach encompassing the true employment of these factors in the efficiency analysis is the need of time so that one can be able to answer the questions like *DC better than AC? Under what scenarios? By how many factors of efficiency?* This paper presents a critical analysis of the studies presented in the past as regards the employment of the factors of efficiency and using constructive criticism a model is presented that accounts for the factors of efficiency to provide a definite verdict whether DC is better than AC or not. The future of comparative AC and DC distribution efficiency analysis is also presented as multi-valued multi-parameter efficiency analysis with the concept of state flow. The findings of this research effort may form a concrete base from research standpoint that humankind may be able to realize if the time has/is-going-to come for making a big change in the power system; make it DC instead of AC, because of better system efficiency.

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