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Article

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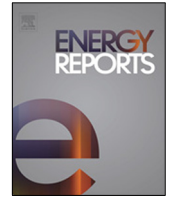
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Research paper

DC distribution for residential power networks—A framework to analyze the impact of voltage levels on energy efficiency



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ABSTRACT

DC networks for residential consumers have gained attraction in recent years, primarily due to building-integrated photovoltaics and increasing electronic loads coupled with the decreasing prices of DC appliances. Unlike AC (110V, 60Hz, or 220 V, 50Hz), the existing standards for DC distribution are disjoint, ranging from 48V to 380V with distribution voltage selection affecting the system efficiency. In this work, we formulate a framework to analyze the impact of various voltages on residential system losses incorporating both distribution losses and power electronic conversion losses. Subsequently, we evaluate the system efficiency for a typical DC home at 48 V, 220 V, and 380 V DC and compare it with the 220 V AC using the developed analytical framework as well as through simulation. Results show that for a medium scale solar integrated house, the DC system at 220 V and 380 V is 4% and 10% more efficient than the AC 220 V system, respectively. Further, for 48 V DC, the system efficiency is higher than 380 V DC for wire size AWG-6 and beyond. While the efficiency depends on several factors such as conductor size, voltage selection, loads connected, and the solar capacity, the framework presented is the key in the quantification of losses and selection of suitable system components for DC home.

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1. Introduction

The war of currents in the late 19th century concluded with the implementation of the AC as a medium for electricity transmission and distribution (McNichol, 2011). The single-phase AC distribution (110V, 60 Hz or 220 V, 50 Hz) has now been a standard for over a century primarily due to (a) the practicality of voltage conversion using transformers and (b) invention of machines based on poly-phase AC system favoring the adoption of AC distribution (Elsayed et al., 2015). However, DC has found its way back in generation transmission as well as distribution systems of our modern electricity networks. While DC output based solar cells, state of the art wind farms, biogas, and fuel cells are changing the dimensions of today's electricity generation. DC transmission has also established its significance in the present era as high voltage DC (HVDC) using kV-range voltages (in turn, small currents), to minimize line losses and using the total cross-sectional area of the conductor due to the absence of skin effects (due to better conductor utilization) thus transferring more power than HVAC (Arrillaga and Arrillaga, 1998; Lin and Xiao, 2019). Beyond the break-even distance, the HVDC system is, therefore, becoming more economically viable than HVAC systems.

While HVDC is now a viable option for long-distance transmission (and is being readily adopted for specific installations such as large-scale offshore wind farms which generally require long lengths cable to transmit power from the generation site to the AC mains Andreasson et al., 2017), the low voltage DC (LVDC) distribution at utility distribution scale is not readily viable due to a large infrastructural investment requirement (Patrao et al., 2015). Alternatively, DC distribution beyond a utility meter (residential house level), is now becoming increasingly viable due to (a) increasing adoption of distributed generation for example solar photovoltaic (PV) generation integration at a household level making every home a Nano-grid in itself (Vossos et al., 2017b; Dastgeer et al., 2019; Nasir et al., 2019, 2018) (b) changing load dynamics where a vast majority of loads are DC, for instance, lighting is now primarily DC LED.

The integration of decentralized residential PV systems has increased due to the decreasing costs of PV modules (Adefarati and Bansal, 2016) and advancements in inverter technologies (O'Shaughnessy et al., 2018). With regards to changing load dynamics, an increasing digital load, LED lighting, efficient DC fans, electronic appliances and variable frequency drive (VFD) based cooling and heating systems are a ready fit for DC distribution for home systems as these appliances require a DC rail for their operation (Kamran et al., 2017). However, due to the conventional AC distribution in the current residential settings, these modern appliances are supplied with AC power resulting in the additional

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Nomenclature

| | |
|-----------------------|--|
| A. | <i>Indexes</i> |
| H | Model house |
| K | Total no. of floors in house (H) |
| i | No. of appliances at any floor k |
| B. | <i>Variables used in the spreadsheet model</i> |
| N_1^k | DC appliances (category 1 loads) |
| N_2^k | AC appliances (category 2 loads) |
| $P_{i,AC}^k$ | Rated power of load (AC) |
| $P_{i,DC}^k$ | Rated power of load (DC) |
| P_r^k | Total rated power of all loads at k |
| P_s^k | Total power input to k th floor H |
| L_{conv-l}^k | Total power loss through all the converter at k th floor |
| L_{dist}^k | Total distribution losses at k th floor |
| η^H | Efficiency of overall house H |
| P_u | Total power drawn from the grid |
| $P_{sol-mppt}$ | Total power available through MPPT Converter |
| $P_{sol-inv}$ | Total power available at solar inverter |
| $L_{conv}^{sol-mppt}$ | Power loss due to solar MPPT converter in DC house |
| L_{conv-s}^H | Total conversion losses of all the resources of house H |
| L_{conv}^u | Power loss due to rectification of utility power in DC house |
| L_{conv-s}^H | Total conversion losses of all the resources of house H |
| $L_{conv}^{sol-inv}$ | Power loss due to inversion of solar power in AC house |
| V_{dist} | Voltage level for distribution |
| C. | <i>Parameters</i> |
| ρ | Resistivity of the conducting wire |
| l | Length of the wire |
| A | Area of the wire |
| l_1 | Conductor length from the distribution box to 1st floor. |
| l_2 | Conductor length from the distribution box to the ground floor |
| l_3 | Conductor length from the distribution to the basement floor. |
| $\eta_{A/D}$ | Efficiency of AC to DC converter |
| $\eta_{D/D}$ | Efficiency of DC to DC converter |
| $\eta_{D/A}$ | Efficiency of DC to AC converter |

conversion losses in the overall operation. On the other hand, a DC distribution system can eliminate the AC/DC rectification stage making overall operation relatively more uncomplicated, more reliable, and more efficient (Vossos et al., 2017). Other advantages of DC distribution like the omission of reactive power issues and skin effect, positively impact the distribution losses (Whaite et al., 2015). In sum, DC distribution at a residential level can offer certain advantages compared to the AC distribution, mainly if distributed generation and storage are in place (Vossos et al., 2014).

LVDC has already been adopted as a medium of distribution in many applications such as data centers (Kim et al., 2011), and telecommunication power systems are using 380 V DC and 48 V

DC, respectively (Dulout et al., 2017; Usui et al., 2016). Uninterrupted power supply (UPS) systems being a requirement for data centers use 380 V DC to keep the system less complicated, eliminating the need for extra conversion stages, making the system more efficient and reliable (AlLee and Tschudi, 2012). Some other high-end applications such as spacecraft, The National Aeronautics and Space Administration (NASA) International Space Station, and shipboards also use the DC distribution system (Grassi et al., 2011; Mourra et al., 2012; Sulligoi et al., 2010). Other significant applications of DC systems are the traction power system with DC motors (Jefimowski and Nikitenko, 2018; Jabr and Džafić, 2018; Arboleya et al., 2018).

While DC is becoming commonplace in many high-end applications, the utility of DC distribution in mass-markets such as residential settings has not been able to significantly replace AC distribution despite many inherent advantages (Ghadiri et al., 2017). Historically, a significant reason for this was the ever-evolving LVDC standards without consensus on one distribution voltage for residential DC (Arzhannikov et al., 2016; Wang et al., 2013). At present different researches and organizations of many countries have not been agreed on a single DC voltage level to be implemented as residential voltage level (Sheng et al., 2016). Importantly, the standardization of a single voltage as DC residential voltage is essential because it will reduce the number of power electronic conversions to reduce cost and improve reliability.

In 2004 Lawrence Berkley national laboratory (LBNL) started to explore the impact of DC distribution over AC distribution in data centers. The results showed that using DC instead of AC saves up to 28% of the energy (Prabhala et al., 2018). In the same year (2004), the Institute of Electronics and Electrical Engineering (IEEE) published a revised version of IEEE Standards 946-1992, which provided the system design of the DC auxiliary power system. The guidance is provided on how to select the equipment of a DC system, such as lead-acid batteries, chargers, and other essential instrumentation and control devices, including grounding guidelines on the DC auxiliary power systems. They specified a range of voltages of 100 V 250 V DC for auxiliary DC system without recommendations mainstream power distribution (Papadimitriou et al., 2015; West, 1979). Later in 2004, IEEE 1547-2004 standards regulated the technical aspects of the DC systems such as allowable harmonics, islanding due to faults (Jovic and Ooi, 2011), and acting time of the re-closers (Salomonsson et al., 2009; IEEE, 2004). The recommended practices according to this standard for LVDC based electrical power systems are 1000 V or less.

Many other standards, such as NEC national electrical code issued by the National Fire Protection Association, USA, standardizes the utilization and installation of DC technologies (Tagare, 0000). Emerge Alliance, together with the partnership between Japan and South Korea's governments, with academic institutes, and industrial groups, have also made a significant development on the standardization and technological development of DC-powered buildings and microgrids (Earley and Sargent, 2011; Glasgow et al., 2018). So far, the standards for using DC with AC in hybrid settings in commercial buildings are established by the Emerge Alliance, which uses 48 V DC for low-power applications and 380 V DC for high power applications (Rodriguez-Diaz et al., 2015a; Weiss et al., 2015). Apart from these organizations, several researchers have also evaluated the viability of DC distribution for home systems. For instance, Hammerstrom (2007) showed that the DC distribution, for residential distribution, encounters lower converter losses, and uses 3% less electricity when employed with renewables. Rodriguez-Diaz et al. (2015b) found similar results with the DC system being more efficient than the AC system due to lower power electronic conversion losses. This work also highlights the market challenges for DC systems to

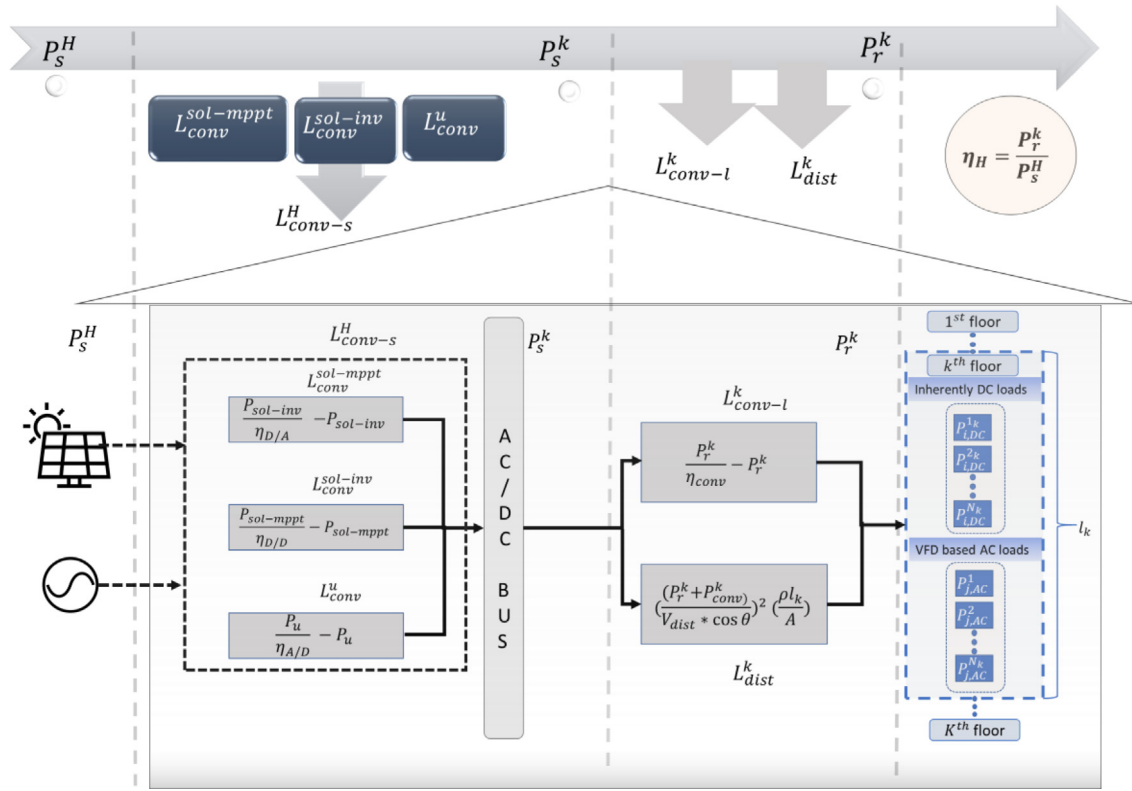


Fig. 1. The general layout of the modeled house having K floors and N^k loads. The overall flow from the source (P_s^H) to the useful delivered power (P_r^k) is shown along with conversion losses ($L_{conv-l}^k, L_{conv-s}^H$) and distribution losses (L_{dist}^k).

dominate this sector. Further, [Savage et al. \(2010\)](#) estimated that approximately 25% of energy savings from a DC distribution could be attained with central rectifiers at an appropriate percentage loading. [Gerber et al. \(2018\)](#) provided a detailed model for the efficiency distribution comparison of AC and DC with net metering, suggesting the direct use of DC to achieve maximum benefits. [Sannino et al. \(2002\)](#) calculated the losses in the DC distribution system for a commercial building at different voltage levels and suggest the highest voltage of DC, i.e., 325 V, to be the best choice among LVDC systems. Based on the efficiency, reliability and cost comparison reference [Prabhala et al. \(2018\)](#) propose different voltage levels of DC bus for residential applications.

While the above mentioned (and other) papers addressed the feasibility of DC distribution through the analysis of either conversion losses ([Gelani et al., 2019](#)) or distribution losses ([Nasir et al., 2016](#)), none of them considered conversion and distribution losses simultaneously at various possible distribution voltages and conductor sizes. Further, we develop a framework to quantify the performance of DC voltage on the basis of loads, wire sizes, and size of the building on which the DC network is to be implemented. The selection of voltage levels can significantly affect the system efficiency ([Vossos et al., 2017](#)), and therefore in this work, we formulate a framework to analyze the impact of voltage levels on system losses, including conversion and distribution losses along with system efficiency at different mass-produced distribution conductors. The framework is then applied for the realistic efficiency comparison in DC home systems with different voltage levels and a conventional AC (legacy) system. Because of the conversion efficiencies, the impact of various wire gauges, quantity, and spatial distribution of loads in a typical residential setting are considered as variables in the framework. We, therefore, believe that this work would be highly beneficial for researchers and developers working in this area along with

useful insights towards the advancements of standards in DC distribution to maximize the system efficiency.

The rest of the paper is organized into sections as follows: Section 2 presents the power distribution model of the household in terms of connected load, power electronics converters, and the distribution conductor. The house is divided into floors, and every floor has an associated conductor length with it. Section 3 presents a case study based on a typical residential house. Section 4 compares the results of AC and DC distribution at different voltage levels; the comparison is between the typical candidates for DC distribution in a residential setup, i.e., 48 V, 220 V, and 380 V DC with the conventionally used AC 220 V. This section also provides the result through simulations on ETAP. Section 5 concludes the discussion is citing efficiencies of various systems under investigation.

2. System model (layout of the model house)

For the overall efficiency comparison, we consider the layout of a house H in a typical residential setting, as shown in [Fig. 1](#). The house has a power distribution network that interconnects the two sources (utility grid and PV) with the household loads through distribution conductors. The primary source of electrical energy is utility power, with solar as a supplementary resource (a prevalent setting in residential homes). The household load is classified into two categories, (1) inherently DC loads, (2) variable frequency drive (VFD) based AC loads. House H is composed of total K floors with a specific k th floor having spatially distributed N_1^k DC appliances (category 1 loads) and N_2^k AC appliances (category 2 loads), where the power rating of the i th appliance at the k th floor is represented by P_i^k . The overall power required by the loads on the k th floor (P_r^k) is given by (1) while the overall

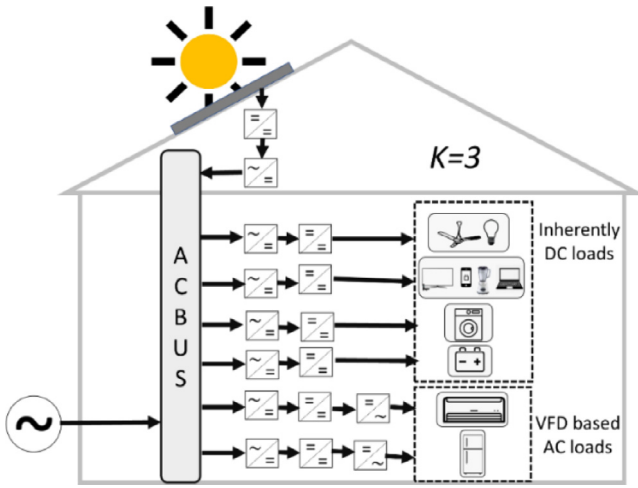


Fig. 2. The layout of an AC distribution-based home catering modern VFD based appliances.

household loads (P_r^H) are calculated through (2),

$$P_r^k = \sum_{i=1}^{N_1^k} P_{i,DC}^k + \sum_{j=1}^{N_2^k} P_{j,AC}^k \quad (1)$$

$$P_r^H = \sum_{k=1}^K \sum_{i=1}^{N_1^k} P_{i,DC}^k + \sum_{k=1}^K \sum_{j=1}^{N_2^k} P_{j,AC}^k \quad (2)$$

where $P_{i,DC}^k$ is the power rating of the DC load, and $P_{j,AC}^k$ is the power rating of the VFD based AC loads at k th floor. In both cases, the power distribution from the source point to the consumption point experiences two types of losses i.e., conversion losses and distribution losses. Therefore, the total power supplied (including losses) at the k th floor and the complete household load is given by (3) and (4), respectively. In this case L_{conv-l}^k is the total power loss of the total conversion stages required by all the appliances at floor k , and L_{dist}^k is the total distribution loss of floor k . Consequently, the overall power delivery efficiency of the house (η^H) is given by (5).

$$P_s^k = P_r^k + L_{conv-l}^k + L_{dist}^k \quad (3)$$

$$P_s^H = \sum_{k=1}^K P_s^k + L_{conv-s}^H \quad (4)$$

$$\eta^H = \frac{P_r^H}{P_s^H} * 100\% \quad (5)$$

Both the conversion and the distribution losses are a function of the distribution system (AC or DC), voltage level and depend upon the number of AC/DC interconversions involved in the path of the power flow along with the total power supplied from the source to load point. Therefore, both distribution systems are considered separately for the assessment of distribution and conversion losses.

2.1. AC distribution system

AC based distribution is the conventional distribution system commonly seen in residential settings for which a typical layout is shown in Fig. 2. The two types of losses, i.e., power electronic

conversion losses and distribution losses, are tackled separately as given in this section.

2.1.1. Power electronic conversion losses

For the evaluation of power electronic conversion losses, we have two categories of loads, i.e., category 1 (inherently DC loads) with two conversion stages i.e., a rectifying stage with efficiency, $\eta_{A/D}$ and a DC to DC conversion stage with efficiency, $\eta_{D/D}$. Category 2 (VFD loads) has three conversion stages with an additional inversion stage having efficiency ($\eta_{D/A}$). The overall efficiency of these conversion stages depends on the voltage levels of conversion, which is discussed later in Section 3 (Table 3). The power loss in these conversion stages for category 1 (N_1^k) and category 2 (N_2^k) loads at a floor k can be calculated using (6).

$$L_{conv-l}^k = \sum_{i=1}^{N_1^k} \left(\frac{P_{i,DC}^k}{\eta_{A/D}^i \cdot \eta_{D/D}^i} - P_{i,DC}^k \right) + \sum_{j=1}^{N_2^k} \left(\frac{P_{j,AC}^k}{\eta_{A/D}^i \cdot \eta_{D/D}^i \cdot \eta_{D/A}^i} - P_{j,AC}^k \right) \quad (6)$$

Besides, the conversion losses from the sources (L_{conv-s}^H) must also be considered and are given in (7).

$$L_{conv-s}^H = L_{conv}^{sol-mppt} + L_{conv}^{sol-inv} \quad (7)$$

Where, $L_{conv}^{sol-mppt}$ is the power loss due to the MPPT operation and $L_{conv}^{sol-inv}$ is the power loss due to inversion operation in an AC distribution-based system. These are quantified in (8) and (9).

$$L_{conv}^{sol-mppt} = \frac{P_{sol-mppt}}{\eta_{D/D}} - P_{sol-mppt} \quad (8)$$

$$L_{conv}^{sol-inv} = \frac{P_{sol-inv}}{\eta_{D/A}} - P_{sol-inv} \quad (9)$$

The overall conversion loss of house H can be found using (10).

$$L_{conv}^H = \sum_{k=1}^K L_{conv-l}^k + L_{conv-s}^H \quad (10)$$

2.1.2. Distribution losses

In addition to conversion losses, distribution losses are also evaluated for overall efficiency calculation. The distribution losses depend on the conductor lengths l_k , resistivity (ρ), and area (A). The power factor ($\cos \theta$) is also considered, and the overall distribution losses of the floor k and the total house H are given in (11) and (12), respectively.

$$L_{dist}^k = \left(\frac{P_r^k + L_{conv-l}^k}{V_{dist} * \cos \theta} \right)^2 \left(\frac{\rho l_k}{A} \right) \quad (11)$$

$$L_{dist}^H = \sum_{k=1}^K (L_{dist}^k) \quad (12)$$

2.2. DC distribution system

2.2.1. Power electronic conversion losses

The typical layout of a DC home with DC distribution system is shown in Fig. 3. Compared to the AC house in Fig. 2, the additional stage of rectification is eliminated in DC distribution. To evaluate the converter losses for floor k and the entire house H , in this case, (6) and (7) have been modified to (13) and (14), respectively,

$$L_{conv-l}^k = \sum_{i=1}^{N_1^k} \left(\frac{P_{i,DC}^k}{\eta_{D/D}^i} - P_{i,DC}^k \right) + \sum_{j=1}^{N_2^k} \left(\frac{P_{j,AC}^k}{\eta_{D/D}^i \cdot \eta_{D/A}^i} - P_{j,AC}^k \right) \quad (13)$$

$$L_{conv-s}^H = L_{conv}^{sol-mppt} + L_{conv}^{sol-inv} \quad (14)$$

where $L_{conv}^{sol-mppt}$ is the conversion loss from the source side rectifier converting grid power from AC to DC for DC distribution.

$$L_{conv}^H = \frac{P_u}{\eta_{A/D}} - P_u \quad (15)$$

Table 1
Features of some mature battery technologies for residential PV systems.

| Battery type | Energy density (Wh/kg) | Capital cost (\$/kWh) | Cycle life (100% DOD) | Self-discharge | Round trip efficiency |
|--------------|------------------------|-----------------------|-----------------------|----------------|-----------------------|
| Lead-Acid | 35–50 | 100–300 | 200–1000 | Low | 75–85% |
| NiCd | 50–60 | 300–600 | 1500–2000 | High | 70–75% |
| Li-ion | 75–200 | 300–2500 | 1000–10000 | Medium | 85–97% |

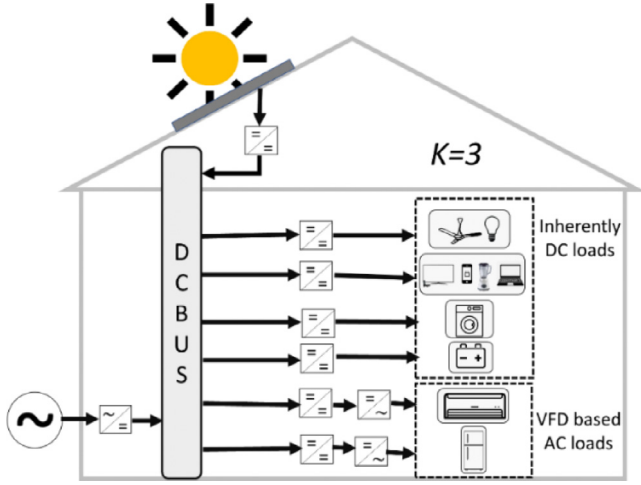


Fig. 3. The layout of a DC distribution-based home catering modern VFD based appliances.

2.2.2. Distribution losses

For distribution loss evaluation in the DC network, the power factor is not required, and hence distribution losses of floor k and house H are given through (16) and (17), respectively.

$$L_{dist}^k = \left(\frac{P_r^k + L_{conv-l}^k}{V_{dist}} \right)^2 \left(\frac{\rho l_k}{A} \right) \quad (16)$$

$$L_{dist}^H = \sum_{k=1}^K (L_{dist}^k) \quad (17)$$

3. System parameters

To evaluate the losses for both types of distributions, we consider a typical case of a residential house with parameters summarized in Table 2 (taken from Chauhan et al., 2015; Shivakumar et al., 2015). The home network has a primary input from the utility grid with supplemental solar power (2.2 kWp). While this work does not include storage as part of the power system due to the high costs associated, many regions with intermittent grids can have storage as part of the solution. Different batteries technologies such as lead-acid, nickel-cadmium, lithium-ion, vanadium redox etc. are available in the market (Prabhala et al., 2018). The selection of battery for a residential system is based on many vital factors like energy density, cycle life, capital cost, self-discharge and round trip efficiency (Zhang et al., 2018). Among all the battery mentioned above chemistries, Lead-Acid (LA) batteries are commonly used due to their low upfront cost but at the same time, they have a short cycle life. Various other technologies are also summarized in Table 1 (Curry, 2017; Vega-Garita et al., 2019).

For a fair comparison between the performances of AC or DC house, the loads are kept identical for both setups. We consider two forms of loads, i.e., DC loads (electronic loads) and VFD based AC loads are referred to as category 1 and category 2 loads, respectively, in Section 2. Modern loads such as air-conditioners,

Table 2
Floorwise placement of loads in the case study.

| Loads (n_i) | Quantity | | | Power rating (P_i) (W) |
|-----------------|-----------|--------------|----------|----------------------------|
| | $k = 1$ | $k = 2$ | $k = 3$ | |
| | 1st floor | Ground floor | Basement | |
| LED lighting | 30 | 30 | 15 | 18 |
| Air conditioner | 1 | 2 | – | 1000 |
| Refrigerator | – | 1 | – | 400 |
| Laptop | 1 | 1 | – | 90 |
| Cell charger | 1 | 2 | – | 3 |
| LED TV | 1 | 1 | – | 60 |
| Ceiling fan | 4 | 5 | – | 70 |
| Blender | – | 1 | – | 300 |
| Vacuum cleaner | – | 1 | – | 700 |
| Washing machine | – | – | 1 | 500 |
| UPS | – | – | 1 | 500 |

Table 3
The efficiency of various converters used Vossos et al. (2017a).

| Conversion stage (S) | Efficiency | Loss |
|--------------------------------|------------|-------|
| AC/DC (high wattage) > 5 kW | 93.7% | 6.3% |
| AC/DC (low wattages) 1 kW–5 kW | 87.60% | 12.4% |
| DC/DC | 98.30% | 1.7% |
| DC/AC | 96.90% | 3.1% |

refrigerators, and washing machines, etc. are generally VFD based to reduce losses and reduce inrush currents (Kamran et al., 2017).

With conventional AC systems, the interface of VFD based appliances is typically composed of a rectifier, a DC to DC chopper, and an inverter (Kakigano et al., 2010).

The floorwise placing of all the loads and their power requirement is based on a typical residential house and is shown in Table 2 (IEEE, 2004). The loads are connected at each floor at lengths $l_1 = 35$ m, $l_2 = 55$ m and $l_3 = 30$ m. These values are set for this typical case study; however, the framework allows consumers to modify the model to evaluate variable lengths. Conversion losses (L_{conv-l}^k) for each floor vary with power processing capability and loading levels of that floor.

For this analysis, we take rated loading and various conversion efficiencies, i.e., rectifiers ($\eta_{A/D}$), DC/DC converters ($\eta_{D/D}$) and inverters ($\eta_{D/A}$) are taken constant based on the Berkley report 2018 (Vossos et al., 2017), summarized in Table 3. Distribution losses (L_{dist}^H) are evaluated on 6 different conductor gauge size (AWG) given in Table 4. For both types of houses, the overall distribution losses L_{dist}^H depend on the physical parameters of the conductors which, are kept the same for both cases, taken from Vossos et al. (2017), Chaidez (2011) and Dastgeer and Gelani (2017).

The results are computed using both analytical models using (1)–(17) and a simulation-based model in Power Management System software, ETAP. The loads are simulated, incorporating the power ratings of loads and overall efficiencies.

A sample simulation setup for DC house is shown in Fig. 4, which shows all the required components such as static loads, DC and AC motors, rectifiers, DC to DC converters, and wire cables.

4. Results and discussion

Analytical and simulated results, shown in this section, are based on three use cases where DC distribution at 220 V, 48 V,

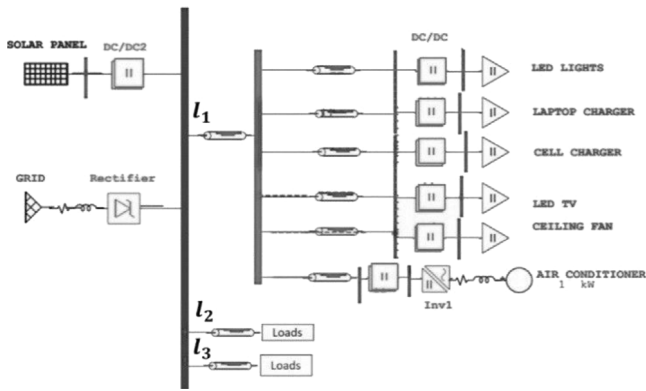


Fig. 4. ETAP Simulation of the DC house.

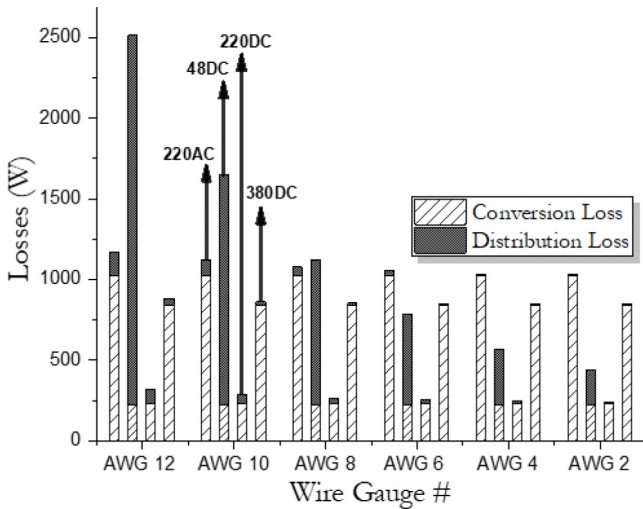


Fig. 5. Losses encountered by AC 220 and DC (48, 220, 380 V) through an analytical model for overall useful power delivery of 7.6 kW.

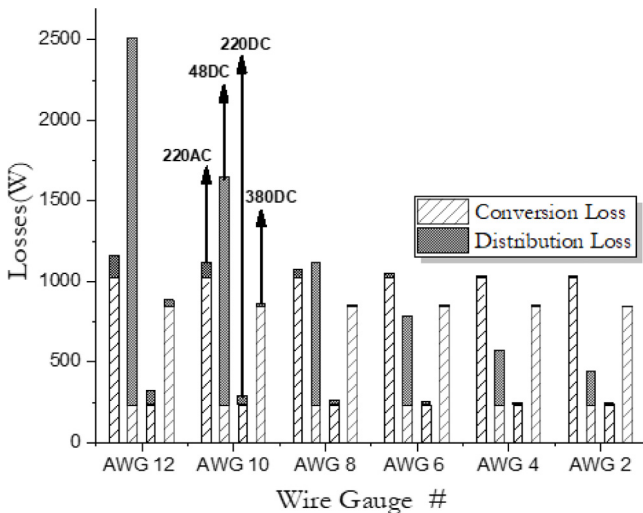


Fig. 6. Simulated losses evaluation in AC 220 and DC (48, 220, 380 V) house through ETAP for overall useful power delivery of 7.6 kW.

and 380 V is compared with standard AC distribution at 220 V, 50 Hz. The analysis is performed for all the connected loads of approximately 7.6 kW with utility catering for 67% of the load with solar supplementing the rest. The analytical and simulated

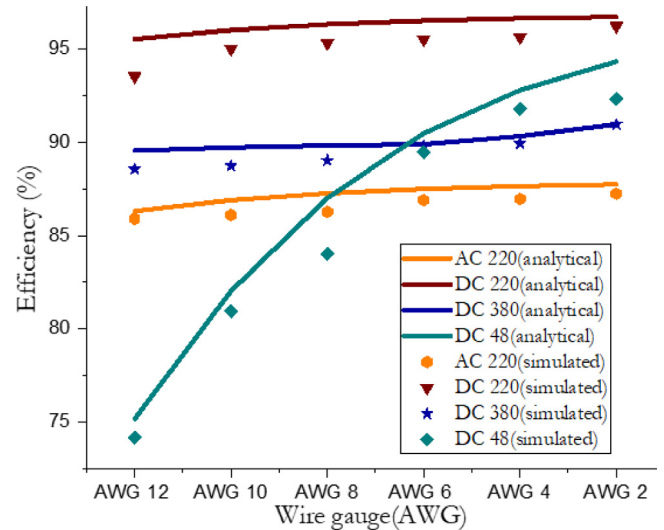


Fig. 7. Efficiency comparison of AC 220 V and DC (48, 220 and 380 V) at various wire gauge.

Table 4

American wire gauge to the area (mm²) and diameter (m) conversion.

| American wire gauge (AWG) | Diameter (mm) | Area (mm ²) |
|---------------------------|---------------|-------------------------|
| 12 | 2.0525 | 3.3088 |
| 10 | 2.5882 | 5.2612 |
| 8 | 3.2636 | 8.3656 |
| 6 | 4.1154 | 13.3018 |
| 4 | 5.1894 | 21.1506 |
| 2 | 6.5437 | 33.6308 |

results are shown in Figs. 5 and 6, respectively, which represent the distribution and conversion losses separately. The variation of the overall loss with varying gauge sizes, as well as distribution levels, is also shown in the plots. The results show that the distribution losses decrease as the voltage level increase for a fixed conductor size. Similarly, low voltage level 48 V DC has the highest distribution loss for thinner conductors (AWG 12 and AWG 10), and due to this loss, the overall power required by the DC house is much higher than the AC house.

From Figs. 5 and 6, the distribution losses are less than 5% for all distribution levels except 48 V DC, where this loss is over 2250 W, i.e., more than 30% of the total useful power consumed (7.6 kW). As the distribution losses depend on the wire gauge size, as we move towards lower AWG number (larger cross-sectional area of the conductor), the distribution losses decrease, e.g., AWG 6 –AWG 2 is better suited to minimize the distribution losses. It should also be noted that, among DC systems, the conversion losses for 380 V are higher due to low efficiencies related to larger voltage transformations. The overall efficiency of the systems is also compared for both analytical and simulation-based results in Fig. 7. Both the analytical and simulation-based result follows a similar pattern. The result also shows that the 220 V DC house is approximately 10% more efficient than the AC house for all AWG sizes. DC 220 V has the highest efficiencies as distribution at this voltage has lower conversion losses compared to 380 V while the negligible gain in the distribution efficiency is seen at 380 V DC.

At AWG 12 (highest resistance conductor), the efficiencies of 48 V DC distribution are as low as 75% because of the high distribution losses. However, at AWG 8, the efficiency of DC 48 V becomes approximately equal to AC 220 V which points out that, from an efficiency perspective, the DC 48 V can be comparable to conventional AC with AWG 8 onwards. Further, for lower resistance wire gauges (AWG 6/4/2), the DC distribution at 48

shows a significant increase in its efficiencies. Overall, DC 220 V shows the highest efficiency for the typical loads taken in this work.

Although this work quantifies the efficiency gains of using a DC system and establishes a baseline for efficiency, the cost element should also be investigated. A detailed techno-economic analysis of DC distribution including the cost of conductors and market prices of different converters would thoroughly measure the savings of a DC system. Another concern is the protection in DC which is more problematic compared to AC systems due to the lack of zero-crossing in DC. This requires more sophisticated and costly protection devices (Hernandez et al., 2016) However, there is major movement in this regard with major companies like Siemens, ASEA Brown Boveri (ABB), Schneider Carling Technologies etc. are making dedicated fuses and circuit breakers for different voltage level to be used in residential DC distribution system (Carling, 2015; ABB, 0000).

It is important to note that the efficiencies of a system will change with conductor lengths, loads connected and their types, solar PV system size, and converter efficiencies but this work provides an essential framework for efficiency modeling residential systems for future deployment. For the existing AC systems, this work provides significant insights into conductor selection and the impact of efficiencies on the system with various types and ratings of loads for system optimization. For prospective new DC-based systems, the analytical model and framework established will allow better planning for new systems for loss minimization and, in turn, efficiency maximization for new architectures.

5. Conclusion

This work presents a mathematical framework for the performance comparison of AC and DC power distribution schemes in residential settings. Significant factors that affect the performance of power distribution architecture are evaluated, and the efficiency analysis is performed at various available voltage levels of LVDC along with conventionally used 220 V AC distribution. The comparative efficiency study of 220 V AC with 380 V, 220 V, and 48 V DC for a medium-size residential household show an apparent advantage of DC distribution in buildings with onsite renewable resources such as PV. This is due to lower losses due to lower power conversions stages. Simulation results using ETAP also back the analytical framework (developed in this work), which is crucial in the assessment of suitable system selection for residential consumers. For a typical wire size of AWG 4 used in residential systems, 48 V LVDC distribution system shows a 4% higher efficiency than 380 V DC and around 9% improvement on AC 220 V.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Kiran Siraj: Formal analysis, Investigation, Methodology, Software, Writing - original draft. **Hassan Abbas Khan:** Conceptualization, Investigation, Funding acquisition, Supervision, Writing - review & editing.

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