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# A Case Study of Optimal Voltage Levels for DC Home in Appliances point of View

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## ABSTRACT

Owing to the depletion of fossil fuels, increased energy demand from the grid, global warming etc. the concept of designing energy efficient home is being widely researched upon. Since the present load and renewable energy sources are mainly DC in nature, the alternative system called "DC Home" is becoming more prominent for remote areas where main grid is not easily accessible and also may be for future home. In this proposed system, a 1BHK building is considered to match with houses living in rural or remote areas and the optimal voltage level of DC system is defined so that the appliances and sources voltage level are matched to simplify the appliances driver and system designed.

**Keywords:** *DC home, AC-DC comparison, Energy consumption and Losses in AC system.*

## 1. INTRODUCTION

DC distribution system is being used in ships, traction systems and communication system for a long time [1]; however, in recent times a DC system is being introduced into a home as the appliances end load with sources mostly becoming DC in nature [2]. Using DC distribution only, the unwanted losses can be eliminated while converting from DC to AC supply by an inverter and back to DC for the appliances. Also a DC powered home can eliminate the requirement of transformer/rectifier stages and standby losses in appliances. With no inductance effect, there are no reactive power losses in the DC distribution system, which improved the system efficiencies [3]. The optimal voltage level for DC home is an important parameter that affects efficiency and safety of the system. Various studies on possible voltage level for residence and commercial building has been performed in [4]. EPRI has set 380V DC as the standard voltage for Data centers, along with the Lawrence Berkeley National Laboratory [5]. However, for residential purpose where load demand is less, 380V DC may not be suitable for DC home powered by PV panel source and safety related issues. Since most of home appliances work on 12V or 24V DC, Emerge Alliance developed a standard for 24V for low power appliances [6]. Suitability of voltages level for DC home also depends on desired appliances ratings. For low voltage level, power appliances demand high current which result in huge losses on the line conductor whereas at high voltage level, switching spark and arc are dominant, brings corrosion effects and safety issues on appliances operation. In this research work, performance of DC systems are analyzed and compared with that of the present AC system using a case study. Performance analysis are carried out based on power consumption, losses on the feeder, standby losses, rectifier losses and safety factors by home appliances. Optimum voltage levels for DC home are determined by comparing with various system voltage levels.

In section II, home appliances are selected and classified into lighting and power loads. The ratings of appliances, loads for 1BHK building, appliances operating time and standby mode are estimated. For evaluation of losses and power consumption of voltage level are done for a year in Section III. Section IV compares the performance of different systems and the standard voltage is determined

## 2. HOME APPLIANCES

Consider a 1BHK building [7] which is more feasible for a small house in rural or remote area. For performance analysis of DC system in a building, it depends on home appliances load and the feeder length. Home appliances are chosen based on the loading requirement of a building in a remote area. Household appliances which are used in daily life for 1BHK building has been given in [8] with their ratings. For a small household in remote area, lighting appliances and ceiling fans are commonly used in each room. Power appliances such as a small refrigerator and air conditioning are used for storing and preserving of items in hot areas whereas in cold places, they are not dominant in household. Electric oven and mixer grinder are mostly used as kitchen appliances due to cheap and affordable. Home electronics such as modem, TV and computer run on DC supply internally. Their ratings are considered to be the same since it can work both in DC and AC with/ without modification. The feeder length of cable in a house depends on power rating of appliances as well as the size of the building. The feeder length for household loads usually varies between 12 m and 80m [9]. In these studies, the average feeder length is assumed for the appliances whose power rating less than 200W, at 50 m (phase and neutral) and 20 m (phase and neutral) for rating greater than 200W. The numbers of electrical loads and appliances wattages both in AC and DC system are estimated as given in Table 1.

In Table 2 shows the standby losses, rectifier losses and on-time per day of the investigated appliances. The standby losses for different home appliances are considered based on [10] but which may also vary depending on different manufacturers. For AC system, there are always some losses associated while converting AC to DC rectification and also no-load losses in a small transformer though it is not performing the basic function

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while in standby mode. But these losses can be eliminated if DC appliances are supplied from DC sources only and moreover, can simplify the internal power circuit of the appliances.

**Table 1:** Selected appliances and Its Power Rating for AC and DC supply in W (Watts).

| Type of Load | Items | Quantity | Appliances AC (W) | Appliances DC (W) | Total Power AC (W) | Total power DC (W) |
|---|---|---|---|---|---|---|
| Lighting Load | Bulb | 6 | 40 | 5 | 240 | 30 |
| | Tube-light | 2 | 36 | 18 | 72 | 36 |
| | Ceiling fan | 2 | 67 | 24 | 134 | 48 |
| | Modem | 1 | 7.2 | | 7.2 | 7.2 |
| | TV | 1 | 83 | | 83 | 83 |
| Power load | Computer | 1 | 108 | | 108 | 108 |
| | Refrigera-tor | 1 | 125 | | 125 | 125 |
| | AC | 2 | 900 | | 1800 | 1800 |
| | Elec. Oven | 1 | 800 | | 800 | 800 |
| | Mixer | 1 | 350 | 266 | 350 | 266 |
| Total | | | | | 3720.1 | 3304.1 |

**Table 2**. Power Rating of Various Loads

| Appliances | | Feeder length (m) | Standby Power (W) | Rectifiers (W) | On time /day (hrs) | Standby /day (hrs) |
|---|---|---|---|---|---|---|
| Lighting Load | Bulb | 50 | 0 | 0 | 12 | - |
| | Tube-light | | 0 | 0 | 10 | - |
| | Ceiling Fan | | 0 | 0 | 6 | - |
| | Modem | | 1 | 00 | 21 | 3 |
| | TV | | 2.2 | 1.224 | 7 | 17 |
| Power Loads | Computer | 20 | 1.5 | 2.116 | 1 | 23 |
| | Refrigerator | | 10 | 0.979 | 12 | 12 |
| | AC | | 6 | 7.07 | 7 | 12 |
| | Elec. Oven | | 2.8 | 6.283 | 1 | 23 |
| | Mixer | | 00 | 00 | 0.5 | 12 |

## 3. LOSSES AND CONSUMPTION CALCULATION

In figure 1. shows a system of 230V AC distribution system with generation sources and AC-DC loads. The DC power source such as solar panel can be connected to AC distribution system through a DC to AC converter and converted it back to DC source for DC appliances. For solar panel and battery source, a DC to AC inverter is required. To utilize solar or battery energy involves two stages of energy conversion i.e DC-AC and AC-DC. For calculating the voltage drop and losses on the feeder of appliances, a single phase circuit is considered as in figure 2.

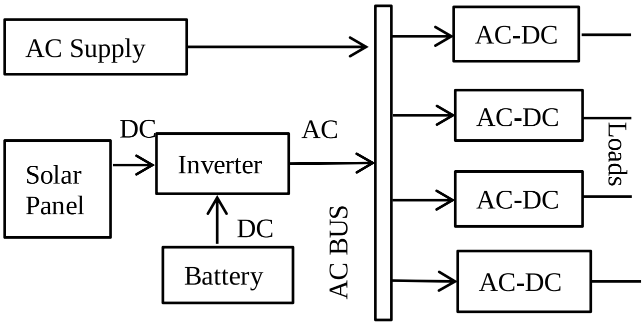


**Figure 1.** AC System

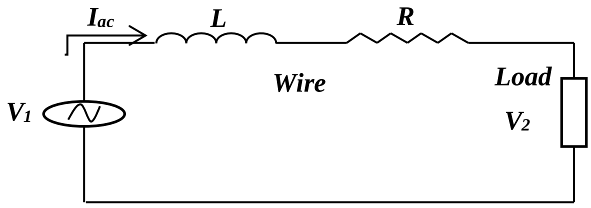


**Figure 2.** A Simple DC Circuit**.**

By applying phasor diagram method, the input voltages equation in the circuit is calculated as

$$V_1 = V_2 + (R + jX)I_{ac} = V_2 + ZI_{ac} \quad (1)$$

where, $V_1$ is the rms value of supply voltage of the house. $I_{ac}$ is the AC supply current in the circuit and $R$ is the resistance of the feeder cable, $X = 2\pi f L$ is the reactance of the feeder cable . where $L$ and f are the inductance and frequency of the cable. If the load voltage $V_2$ is selected as reference phasor, the supply current can be expressed as

$$I_{ac} = |I_{ac}|cos\varphi - j|I_{ac}|sin\varphi \quad (2)$$

where, $\varphi$ is the phase angle between the voltage and current of the load .

The load voltage can be expressed as

$$V_1 = V_2 + (R + jX)(|I_{ac}|cos\varphi - jX|I_{ac}|sin\varphi) \quad (3)$$

$$V_1 = V_2 + (R|I_{ac}|cos\varphi + X|I_{ac}|sin\varphi) + j(R|I_{ac}|sin\varphi - X|I_{ac}|cos\varphi) \quad (4)$$

Since active power is expressed as

$$P_2 = |V_2||I_{ac}|cos\varphi \quad (5)$$

Reactive power, $Q = |V_2||I_{ac}|sin\varphi$ (6)

Therefore, $V_1 = V_2 + \frac{RP_2 + XQ_2}{|V_2|} + j\frac{XP_2 - RQ_2}{|V_2|}$ (7)

Since most of the investigated appliances are operating almost equal to unity power factor. The unity power factor is considered for all appliance loads in this study, therefore, the reactive power, $Q_2 = 0$, and the load voltage are calculated as

$$V_1 = V_2 + \frac{RP_2 + XQ_2}{|V_2|} = V_2 + \frac{ZP_2}{|V_2|} \quad (8)$$

$$|V_1||V_2| = |V_2|^2 + ZP_2$$

$$|V_2|^2 - |V_1||V_2| = +ZP_2$$

$$|V_2| = \frac{|V_1|}{2} \pm \sqrt{\frac{|V_1|^2}{4} - |Z|P_2} \quad (9)$$

Voltage drop, $\Delta V = \frac{V_1 - V_2}{V_1} X\ 100\ \%$ (10)

Current, $|I_{ac}| = \frac{P_2}{|V_2|}$ (11)

The feeder losses on the cable can be calculated as

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$$P_{loss} = R|I_{ac}|^2 \quad (12)$$

The feeder resistance of the cable can be calculated as

$$R = \rho \frac{l}{A} \quad (13)$$

where, $\rho = 1.7 \times 10^{-8}\ \Omega m^{-1}$ is the resistivity for copper, $l$ is the feeder length and $A$ is the area of the feeder cable. The inductance of the cable can be calculated by assuming that the phase and neutral wires in two parallel lines as in [14].

$$L = 0.05 + 0.2\, ln \frac{d}{r}\ [\mu H/m] \quad (14)$$

where, $r$ is the radius of the cable and $d$ is the distance between phase and neutral wire . From eq.14, the inductance varies with the distance between the two wires. Considering PVC pipes which are normally used in house wiring, the distance between the two wires (phase and neutral) inside the PVC pipe varies at different positions. The variation of inductance is considered for a PVC pipe with an inside inner and outer diameters are of 13mm and 16mm respectively [14]. The value of resistance and inductance for different cross sectional areas of the wire has been presented in Table 3 [12].

**Table 3.** Inductance and Resistance in different Core Size.

| Core size, [$mm^2$] | Inductance, L [$\mu H/m$] | Resistance, R [$\Omega$/m] |
|---|---|---|
| 1.0 | 0.622 | 0.017 |
| 1.5 | 0.576 | 0.011 |
| 2.5 | 0.517 | 0.006 |
| 4.0 | 0.459 | 0.004 |
| 6.0 | 0.407 | 0.002 |
| 10 | 0.335 | 0.0017 |
| 13.3 | 0.291 | 0.0013 |

The total energy consumption in a house for a complete year can be calculated by summing up the energy consumption of all appliances. The total amount of energy consumption in a year by an appliance can be calculated as

$$Energy\ Consump. = On\ energy\ consump + Standby\ Energy\ Consump. \quad (15)$$

where $On\ energy\ consump. = \frac{On\ power\ X\ On\ time/\ day\ X\ 365\ day}{1000}\ kWhr/_{Yr} \quad (16)$

$$Standby\ energy\ consump. = \frac{Standby\ Power\ X\ Standby\ time\ /\ day\ X\ 365\ day}{1000} kWh/yr \quad (17)$$

The losses on the rectifiers depend on the forward voltage drop, $V_F$ and load current which has also been considered in AC system. The forward voltage drop for diode 1N4007 is 0.8 to 1.1 ***V***. For calculation, $V_F = 0.9\ V$ is accounted for losses in the diode. Assuming zero switching losses, the Losses in a diode are computed as,

$$P_{diode\_loss} = V_F I_{rms} \quad (18)$$

Full wave bridge rectifier having four diodes in which two diodes are always in forward bias and two are in reverse biased. The rectifier loss of diodes can be calculated by,

$$P_{rectifier_{loss}} = 2V_F I_{rms} \quad (19)$$

**Table 4.** The Voltage Drops and Energy Losses across the Cable for 230V AC System

| Loads | Items | Power (W) | Wire area $mm^2$ | Impedance (Ohm) | Voltage drop (Volt) | Feeder Loss (kWh/yr) | Rectifier Loss (kWh/yr) | Total Loss (kW/yr) | Standby loss (Watt /yr) | Total Energy (On + standby) (kWh/yr) |
|---|---|---|---|---|---|---|---|---|---|---|
| Lighting | Bulb | 40 | 1.5 | 0.566 | 0.04 | 0.42 | 0 | 0.42 | 0 | 1051.2 |
| | Tubelight | 36 | 1.5 | 0.566 | 0.03 | 0.1 | 0 | 0.1 | 0 | 315.36 |
| | Ceiling. Fan | 67 | 1.5 | 0.566 | 0.07 | 0.208 | 0 | 0.208 | 0 | 293.46 |
| | MODEM | 7.2 | 2.5 | 0.226 | 0.003 | 0.0004 | 0 | 0.001 | 7.66 | 15.54 |
| | TV | 83 | 2.5 | 0.226 | 0.03 | 0.074 | 3.12 | 3.194 | 13.6 | 225.71 |
| | Mixer | 350 | 2.5 | 0.226 | 0.149 | 0.095 | 0 | 0.095 | 0 | 63.875 |
| | | | | | **Total** | | | **4.017** | | |
| Power | PC | 108 | 2.5 | 0.226 | 0.04 | 0.017 | 0.772 | 0.789 | 12.5 | 52.33 |
| | Fridge | 125 | 2.5 | 0.226 | 0.05 | 0.2628 | 4.28 | 0.263 | 43.8 | 591.3 |
| | AC | 900 | 2.5 | 0.226 | 0.385 | 17.37 | 36.12 | 53.47 | 74.4 | 4599 |
| | Elec.Oven | 800 | 2.5 | 0.226 | 0.342 | 0.992 | 2.3 | 3.292 | 23.5 | 315.5 |
| | | | | | **Total** | **19.53** | **46.59** | **66.03** | **175** | **7533.9** |

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Therefore in an AC system, total energy losses can be calculated as the sum of the feeder cable losses and rectifier losses for the appliances having internal rectifiers.

$$Energy\ losses\ = \frac{(Feeder\ losses + rectifier\ losses)X\ On\ time\ X\ 365\ day}{1000}\ kWhr/_{yr} \qquad (20)$$

here the feeder losses are computed using Eq.12 and rectifier losses by Eq.19. The voltage drop, total power losses, standby losses and total energy consumption for the distribution system have been calculated and analyzed as discussed in Table 4. Here, the rectifier losses for the home appliances have also been considered.

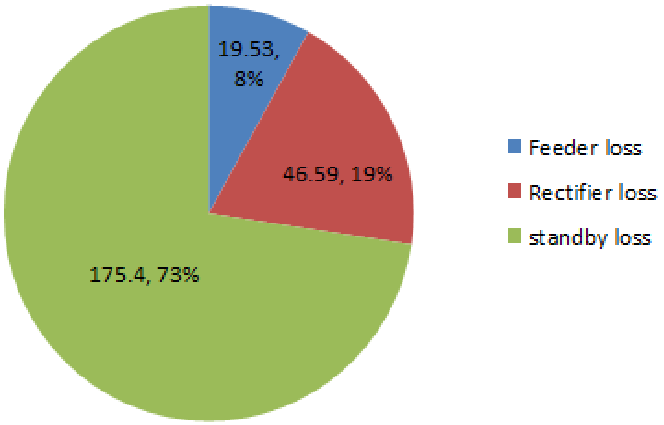


**Figure 3. Loss Components of 230V System**

In AC system, the total energy losses are classified into three parts: losses due to standby mode, feeder losses on the line and losses due to the rectification from AC to DC. By observing the calculation of losses in table 4 for all appliances, the resistive losses are 19.53 kWh per year, rectification losses is 46.59 kWh and standby losses of 175 kWh. The losses component of the AC system in Figure. 3, for standby losses, rectifier losses and feeder losses are at 73%, 19% and 8% respectively.

## 4. DISTRIBUTION SYSTEM FOR DC HOME

Mostly appliances used at home operate internally on DC supply where an AC of 230V, 50Hz is converted into a low DC supply. In this research work, the scheme of the proposed DC system is as presented in Figure 4. The AC supply is converted into DC system before being fed to the DC bus. The solar panel and battery source are connected to the DC bus through a simple and low cost solar charge It has been considered that appliances can be connected directly to DC bus with or without converters. The different levels of DC voltage have been evaluated and compared with AC system. Due to the absent of inductance effect in DC system the voltage drop can be calculated by using a simple circuit as shown in Figure.5.

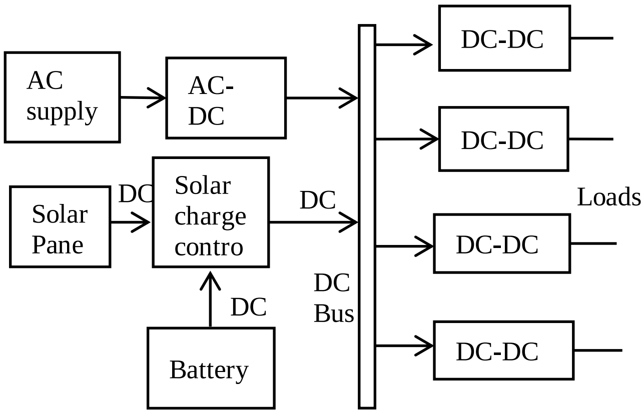


**Figure 4**: The Proposed Of DC Distribution System

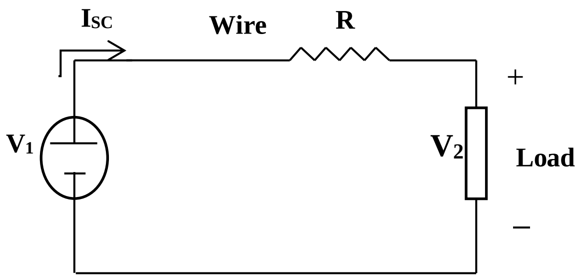


**Figure 5.** A Simple DC Circuit**.**

By applying the voltage equation, $V_2$ can be calculated as,

$$V_2 = V_{dc} - I_{dc}R \qquad (21)$$
$$V_2{}^2 = V_{dc}V_2 - V_2 I_{dc}R$$
$$V_2{}^2 = V_{dc}V_2 - PR$$
$$\left(V_2 - \frac{V_{dc}}{2}\right)^2 = \frac{V_{dc}{}^2}{4} - PR$$
$$V_2 = \frac{V_{dc}}{2} \pm \sqrt{\frac{V_{dc}{}^2}{4} - PR} \qquad (22)$$
$$\text{Voltage drop} = \frac{V_1 - V_2}{V_1}\ X\ 100\ \% \qquad (23)$$

Here $R$ is the resistance on the feeder line whereas $P$ is the load power.

Therefore, for DC system the energy loss can be calculated using Eq.25. The rectifier's losses are set to zero since no converter is required. The energy consumption for on-time is evaluated similar as in AC system. In DC system, the standby losses is considered to be negligible and the rectifier loss are also neglected if appliances are directly connected to DC bus. The voltage drop across the feeder's line depends on the cross sectional area, length of the feeder cable and the power rating of the appliances. The power losses on the feeder can be minimized by increasing the cross section of the cable, since the resistance of a cable is inversely proportional to the cross-sectional area of the wire. For appliances loads in DC system below 100W, 1.5mm$^2$ cable is used, below 200W, 2.5mm$^2$ and above 200W, 4mm$^2$ cable is used to match with the power losses on the feeder.

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**Table 5**. Losses and Voltage Drops and Total Energy Consumption for DC system

| Loads | Items | Power (W) | 12V DC | | 24V DC | | 48V DC | | 120V DC | | On Energy (kWh/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Voltage drop (Volt) | Feeder loss (kWh/yr) | Voltage drop (Volt) | Feeder loss (kWh/yr) | Voltage drop (Volt) | Feeder loss (kWh/yr) | Voltage drop (Volt) | Feeder loss (kWh/yr) | |
| Lighting | Bulb | 5 | 2 | 2.36 | 0.5 | 0.644 | 0.12 | 0.12 | 0.02 | 0.026 | 131.4 |
| | Tube-light | 18 | 7.66 | 9.19 | 1.8 | 2.48 | 0.44 | 0.58 | 0.07 | 0.087 | 105.1 |
| | C. Fan | 24 | 10.54 | 9.89 | 2.4 | 2.326 | 0.59 | 0.62 | 0.09 | 0.1 | 131.4 |
| | MODEM | 7.2 | 0.68 | 0.052 | 0.17 | 0.013 | 0.04 | 0.01 | 0.01 | 0.005 | 7.88 |
| | TV | 83 | 8.57 | 16.53 | 1.99 | 4.1 | 0.49 | 1.03 | 0.07 | 0.163 | 212.1 |
| | Mixer | 266 | 19.5 | 5.48 | 4.09 | 1.87 | 0.99 | 0.47 | 0.16 | 0.078 | 48.54 |
| | | | **Total** | **43.5** | | **11.43** | | **2.82** | | **0.459** | **635** |
| Power | PC | 108 | 11.56 | 20.05 | 2.64 | 5.02 | 0.64 | 0.25 | 0.10 | 0.04 | 39.74 |
| | Fridge | 125 | 13.67 | 64.36 | 3.04 | 16.07 | 0.74 | 4.03 | 0.12 | 0.643 | 547.5 |
| | AC | 900 | - | 2443 | 15.76 | 610.7 | 3.43 | 152 | 0.53 | 24.42 | 4599 |
| | Elec.Oven | 800 | - | 137.6 | 13.67 | 34.46 | 3.04 | 8.61 | 0.47 | 1.37 | 292 |
| **Total** | | | | **2708.5** | | **677.6** | | **169.5** | | **27.12** | **6114.6** |

The sizes of the cables are being maintained constant for comparison of different voltage level systems. The feeder losses in 12V DC system are very high in power appliances due to demand of high current. The voltage drop for Air conditioner (AC) and Electric Oven are practically not feasible at this voltage level for the recommended feeder length. For 24V DC system with the same size of the conductors, the power losses has improved a lot but still higher than 230V AC system. For 48V DC system, the voltage drop for this voltage level decrease due to lower current demand as compared to 24V DC system and the feeder losses are also improved. In 120V DC system, the voltage drop is comparable to AC system and power losses on the feeder are less than 230V AC system. Table 5. shows the losses on the feeder line, voltage drop and energy consumption for different voltage levels in DC distribution system.

## 5. RESULT

The summary of the power consumption of both AC and DC systems is as shown in Figure 6. The power consumption of 230V AC is higher than DC system, since AC appliances are being replaced by efficient DC appliances and also standby losses have been eliminated.

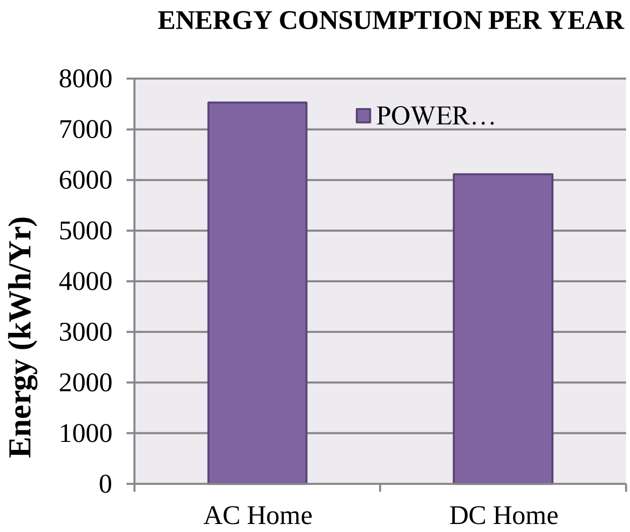


**Figure 6**. Power Consumption in AC and DC System

The total feeder losses of AC system and different voltage levels for DC systems have been determined as in Figure 7. The feeder loss is high for 12V and 24V DC system due to high current in power appliances whereas 48V and 120V system have low losses. However, for 48V and 120V DC

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system, the conventional AC switchgears have to redesign for switching surge and safety issues. But considering only the lighting appliances which is more feasible with 1 BHK buildings load, the 24V DC system would be more economical since the feeder loss of DC system are not much different from 230V AC system as shown in Figure 8.

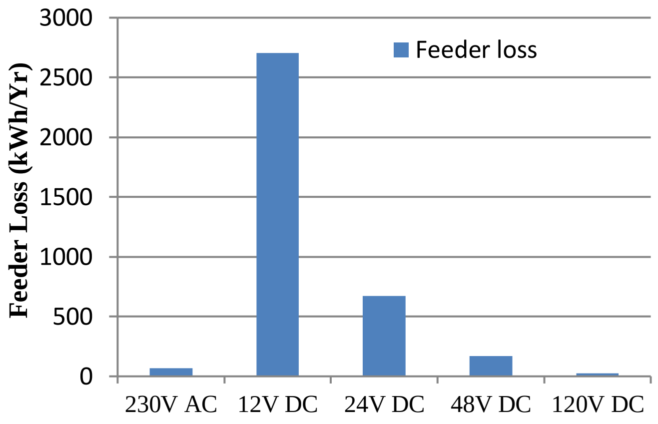


**Figure 7.** Feeder Loss with Power Load Per Year

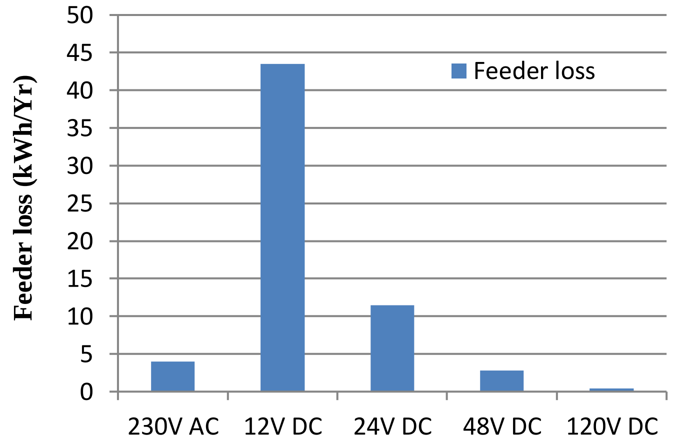


**Figure 8**. Feeder Loss without Power Load Per Year

## CONCLUSION

Energy consumption and losses for a 1BHK building have been evaluated for comparison of 230V AC system with low voltage DC distribution system of varying voltages viz. 12V, 24V 48V and 120V. The energy consumption in DC system is lower than the AC system by using efficient appliances. The losses on the feeders are high in the case of 12V DC systems and least in 120V DC with power loads. Neglecting the power loads from the system, the losses in 24V DC voltage has found to be comparable with 230V AC system. Choosing the 24V DC as the standard voltage level of a DC home, the conventional AC power plugs, switches, and sockets can be used for it's low arcs and sparks which also result easy in transition from AC home to DC home. It does not require the costly DC to AC inverter for connection to the solar energy. The standby consumption is eliminated as it does not need any transformer; and it is also safe to use for low DC voltage.

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