An exploration of the technical and economic feasibility of a low powered DC voltage mains power supply in the domestic arena

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Abstract

This paper explores the feasibility of supplying electrical power to modern homes using a DC voltage mains within the house. A bottom-up approach is adopted in the design of the DC supply, starting with known domestic loads to build a power usage profile based on assumed lifestyle for the occupants of the house. The load profile is then used to work out cable sizes for the mains distribution network. It looks at the type of electrical cables to be employed and the calculations involved in working out voltage drops, and therefore power loss along the cables. The voltage used in the calculations, was 24 V, as this is the voltage rating of DC appliances and devices. The methodology is then employed with a range of powers and voltages to work out different possible load and cable scenarios. The constraints to the analysis and further work are discussed. Economic analysis is carried out on energy losses, and the advantage of using DC appliances, as against using AC appliances is discussed. The goal is to build a framework that will provide the necessary tools that will help in identifying an optimal voltage for the low powered DC home. Previous work is looked at.

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1. Introduction

The main barrier to using DC power at very low voltage is the high current needed to supply the power to correctly operate many appliances. Any length of copper cable has a resistance, which causes energy to be lost as the electrons move along the cable, as Ohms' Law applies, this increase in resistance causes a voltage drop along the cable. The voltage drop along a cable is also affected by its cross-sectional area, the larger its gauge the lower the voltage drop per meter. Tables of the tabulated values for the voltage drop per amp per meter (V_{tab}) are given in Appendix 4[1], with each gauge cable having a different value. Appendix 12[1] gives a value to the maximum allowed voltage drop along the cable as 5% of the load voltage.

2. Voltage drop equations

The total voltage drop over a given length of cable with a given current is given in Equation 1below

Equation 1 $$V_{TotDrop} = V_{tab} * I * L$$

Where:

$V_{TotDrop}$	Is the total voltage drop over a given length of cable (V)
V_{tab}	Is the tabulated voltage drop in millivolts per amp per meter (mV/A/m)
L	Is the length of the cable in meters (m)
I	Is the current (capacity) in Amperes (A)

Therefore for any given cable when 1 Amp flows through 1 meter of cable, $V_{TotDrop}$ is equal to V_{tab}. For an electrical system to operate within the permitted Standard at full load, $V_{TotDrop}$ at the load must not exceed 5% of the required operating voltage for the load. Therefore $V_{TotDrop}$ will depend on whatever voltage is chosen for the system. Table 1 shows the maximum, allowed voltage drop at the load.

Voltage rating for system	24 V	120 V	220 V

Total voltage drop allowed (5%)	1.2 V	6V	11V

Table 1 Maximum allowed voltage drop as measured at load with 100% load factor

At domestic AC voltage, the voltage drop in the cables is not usually an issue. However in the all DC voltage house, the voltage will be below 50 Volts and perhaps as low as 24 Volts. At these low levels the voltage drop in the cables will have a dramatic affect and impose severe constraints to its electrical design. What is therefore very important and most useful to work out, is the maximum length of cable that can be used, given the power ratings of the known loads. Therefore rearranging equation 1 above, we get equation 2 below.

Equation 2 $$L_{\max} = \frac{V_{TotDrop}}{V_{tab} * I}$$

The values for the tabulated voltage drop along, a cable are given in appendix 4[1]. However, these values are given for the specific scenario, of a 100% load factor at maximum current rating and operating at maximum temperature for each cable of specific cross-sectional area. In reality for most of the time in the domestic arena the loads connected to the electrical supply cable will be below the maximum rating for that cable. This can easily be seen in the ups and downs of the nonlinear shape of a usual domestic daily load profile.

When the load current is below the maximum current rating of the mains cable, two things will be affected. One, the maximum temperature that the cable will reach will be below, the maximum rated temperature for that cable. Usually for domestic application the maximum operating temperature is given as 70˚C. Two, as temperature affects the resistance of the cable, the lower the temperature, the smaller the resistance, and the actual voltage drop along the cable would be less than the tabulated voltage drop given in the Tables of appendix 4. Therefore, in reality, equation 2 is only a rough guide to work out maximum length of cable.

To calculate the maximum operating temperature when a load of known current rating is connected to a cable Equation 3[2] is used.

$$t_{op} = t_a + \left(\frac{I_b^2}{I_{ta}^2}\right)(t_p - t_{amb})$$

Equation 3

Key

- t_{op} Operating temperature for the cable
- t_a Actual ambient temperature
- I_b Current rating of appliance
- I_{ta} Tabulated maximum current for cable
- t_p Maximum equilibrium conductor temperature
- t_{amb} Rated ambient temperature

To calculate the actual voltage drop per amp per metre when the loads connected to the cable are below the cable's maximum current rating, a correction factor will have to be worked out. The equation to work out this correction factor is found in section 6.1[1] and is given as Equation 4 below.

Equation 4 $$C_t = \frac{230 + t_p - \left(C_a^2 * C_g^2 - \frac{I_b^2}{I_t^2}\right)(t_p - 30)}{230 + t_p}$$

- C_t Correction factor
- t_p Maximum equilibrium conductor temperature
- I_b Operating current of load and cable run
- I_t Tabulated maximum current carrying capacity of cable
- C_a Rating factor for an ambient temperature
- C_g Group weighting factor

The actual voltage drop along the cable, designated V_{cal} (calculated voltage drop per amp per metre), is worked out using Equation 5 below

Equation 5 $V_{cal} = V_{tab} * C_t$

In keeping to the design strategy of starting from the loads to work out the design for the electrical mains cables, we will start by looking at the appliances.

3. The appliances

For many years, the leisure industry has used DC power, provided from (car) batteries, to power 12 and 24 V DC appliances. These appliances are mostly used in the mobile-home/camping industry, and on different types of boats.

Most home AC powered appliances use electronics that require DC voltage to operate. In a conventional AC powered system using renewable energy generators, the electrical energy will have to go through a DC to AC conversion, followed by an AC to DC conversion to power the appliances. Therefore herein lays the advantage of the DC voltage powered home, where only low power DC to DC conversion is required. For an all DC system supplied from PV's, the removal of the inverter stage saves up to 15% of the array's energy, followed by a further saving of between 20% and 50% from the energy lost in the AC to DC power supply in the load, (Section 1[3]). Another advantage of DC motors over AC motors is their robustness and the lower currents drawn[4]. Vent-Axia's LoWatt range[5] of fans are claimed to have an 80% efficiency and last five times longer than conventional AC motors.

Most of the twenty four DC appliances chosen for our DC home were from www.roadpro.co.uk and show a good cross-section of appliances which together should provide an adequate level of convenience. The computer is an Inveneo 12V DC powered computer.

For very good technical reasons, an appliance will have a specific voltage-current combination, however for any given fixed value of power an appliance can be designed such that many values of voltage-current combination can successfully be used in its operation. Many of the chosen appliances operate on 12 V, which is too low for our home, as the power losses along the cables are intolerable. For some of the appliances we have therefore improvised by doubling the voltage and halving the current, while keeping the power the same. All therefore operate at 24 V. Lighting is not considered in this paper, as LED or low powered halogen lights, which operate at a very low power, can effectively operate without the necessity for large gauge cables.

4. Calculations

We started with the premise that a reasonable length of cable in a family house is 30 meters. The equations were inputted into Excel spread sheets and for all 24 appliances the calculations for the maximum length of cable were worked out for all the five possible cable gauges.

For our example calculations, we chose a 24 V 3.5 Amp DC slow cooker. What we are trying to ascertain is whether this slow cooker can operate on a reasonable length of cable without the voltage drop being too large, and what will be the smallest cable gauge on which this appliance can function? As can be seen from Table 2 using $4mm^2$ cable, a reasonable cable length is achievable, therefore in our example calculations we are using this size cable.

The total voltage drop allowed is 5% of 24 V, which is 1.2 V. Therefore we will use Equation 2 above, with a 4 mm^2 cable to work out L_{max}. V_{tab} for $4mm^2$ cable is given in table 4D2B[1] as 11mV/A/m

$$L_{max} = (1.2)/ (0.011*3.5) = 31.17 \text{ meters}$$

This length gives us a general indication that for this particular appliance a $4mm^2$ cable can be used if its length is less than 31.17 meters. At longer than this the voltage drop at the appliance would be greater than 5% of its rated voltage and a $6mm^2$ cable would be needed. The same calculations were carried out for different cable gauges and are shown in Table 2.

Cable Cross-section area (mm^2)	Rated current (A)	(V_{tab}) voltage drop per Amp per meter at 70°C (mV/A/m)	Maximum Length (m)
1.5	3.5	29.0	11.82
2.5	3.5	18.0	19.05
4.0	3.5	11.0	31.17
6.0	3.5	7.3	46.97
10.0	3.5	4.4	77.92

Table 2 Maximum cable lengths for a 24V 3.5Amp DC slow cooker

This calculation is strictly true only if this particular appliance is the only load attached to this cable. Other loads attached to this cable will increase the current drawn, and therefore reduce the maximum length of cable at which the 5% voltage drop occurs. The current carrying capacity of this 4 mm^2 cable is given as 25 amps in table 4D2A. As we know that temperature affects resistance. We will use Equation 3 to work out the equilibrium temperature for the cable with only this appliance attached to it.

t_{op}	This value is what we have to work out
t_a	Same as rated ambient temperature, 30°C
I_b	3.5 amps (this is given by the Manufacturer)
I_{ta}	25 Amps (this is given in table 4D2A)
t_p	70°C (given in heading of table 4D2A)
t_{amb}	at 30°C this is 1(from 4B1 page 267)

$$t_{op} = t_a + (I_b^2/I_{ta}^2)(t_p - t_{amb})$$

$$t_{op} = 30+(3.5^2/25^2)(70\text{-}30) = 30.78°C$$

This result indicates that when a 3.5 amp load is attached to a 4 mm^2 cable that has a 25 amp current carrying capacity, the tabulated value for the voltage drop per amp per metre is not that given in table 4D2A, which is only true with a maximum load factor at 70°C. We will therefore have to work out a correction factor C_t using Equation 4 above, which will be inputted into equation 5 to work out the calculated voltage drop per amp per metre (V_{cal}).

C_t	This is what we need to work out
T_p	70°C (given in heading of table 4D2A)
I_b	3.5 amps (this is given by the Manufacturer)
I_t	25 V (this is given in table 4D2A)
C_a	At 30°C this is 1(this is given in table 4B1)
C_g	Is 1 for one cable (this is given in table 4C1)

From Equation 4

$$C_t = \frac{230 + 70 - \left(1 * 1 - \frac{3.5^2}{25^2}\right)(70 - 30)}{230 + 70}$$

$$C_t = 0.86928$$

This value is then multiplied by the tabulated voltage drop per amp per metre, to give us a calculated voltage drop per amp per metre.

Equation 5 $\quad V_{cal} = V_{tab} * c_t$

$$V_{cal} = 11 * 0.86928 = 9.56\text{mV/A/m}$$

Using Equation 2 we can calculate a more accurate value for the maximum length of 4 mm² cable at which a 5% drop will occur, when our appliance is attached to it.

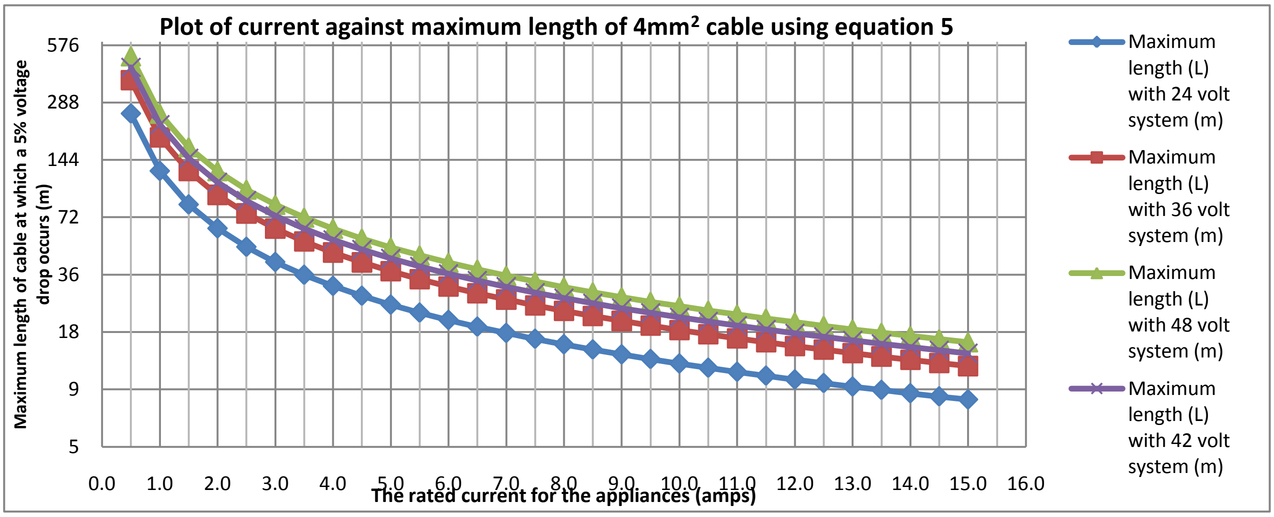
$$L_{max} = \frac{1.2}{0.00956 * 3.5} = 35.8 \text{ meters}$$

This is an increase in the length of approximately 15% from 31.17 m to 35.8 m or in real terms the distance between a power source and our load has increased by 4.8 m. This length could be very significant when working at very low voltage.

5. Optimum voltage and cable size

This analysis was carried out with a range of load currents at different voltages and using Equations 3, 4 and 5, for each cable size a plot was produced. Plot 1 is for a 4mm² cable.

In this analysis there are four parameters, all of which are variables. They are; (1) cable size, (2) maximum length of the cable run, (3) the current ratings of the appliances and (4) the voltage of the appliances. In trying to determine an optimum DC voltage for the house we will have to fix some parameters. If (2) is fixed by the size of the house, and cable size is 4mm² then using plots like Plot 1 we could determine the maximum load current for any given cable length at any fixed voltage. This however still leaves us with a possible range of voltage and current and does not determine an optimum value. The best choice for the DC mains voltage will have to be determined by further research into the operability of a full range of home appliances connected to a given cable gauge, with consideration given to the voltage drops at different cable lengths.



Plot 1 Shows different currents and maximum length of cable for different voltages.

6. The house

The average size of a future living space has been designated to have a floor area of 184 m^2 [6] and has a height of 3 meters. This is far larger than the average mobile home and will have a much larger power consumption. From the analysis it becomes obvious that a conventional ring-main design will lead to larger voltage drops and a smaller maximum length of cable. The best configuration for the mains power cable in the DC house is therefore a star shape (See Appendix 2.3[3] and section 4.1.1[7]) with spurs coming out from a centralised multiplex power board, which is the black box above the kitchen ceiling in Figure 1. The maximum length of cable needed in this house is only 15 meters. Our design has two bedrooms, a bathroom/toilet, with the kitchen and living area in open plan. Distributed around the house are 20 power sockets connected to the power board via cable spurs.

The appliances were then put into three groups one each for the sleeping, recreational, and catering zones of the house. Each zone was designated a few power sockets and the total power for each zone worked out.

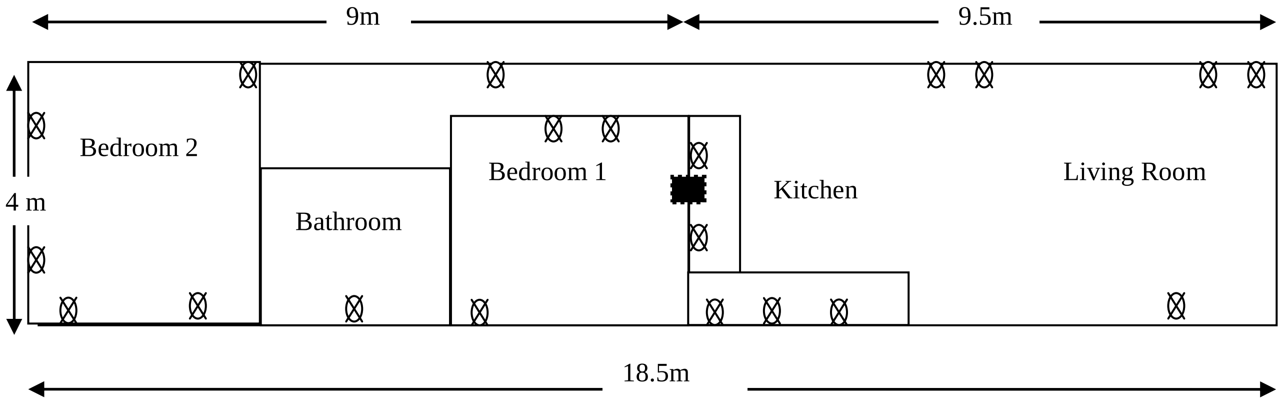


Figure 1 Schematic of the DC House

7. Testing the electrical integrity of the mains

Usually knowing the input power to a cable and the voltage and current ratings of the load, it will be possible to work out what the power, voltage and current will be at any given point along the length of any cable. However, we are working backwards from the load, with a known voltage and current rating. By presuming a worst case scenario that all the loads were lumped together at the end of a 15 meter cable spur, calculations were carried out to determine an input voltage that would adequately supply our 24 volt lumped appliance. For this particular set of appliances connected each to its designated power socket a 25 Volt as the input mains voltage was found to keep the integrity of the voltage at the loads for all the loads. By choosing a homogenous supply voltage for all appliances some sort of voltage regulation, using DC to DC power converters will have to be used with each appliance.

By an iterative process a set of power sockets were assigned to each cable spur such that the whole house was connected up with nine $4mm^2$ cable spurs and one $10mm^2$ cable.

8. Economics

One goal was to work out a monetary value for the energy lost in the cable due to voltage drop. For each appliance, a designated average time of usage per day was given (See Appendix 2[3]). Then for each group of appliances the total kilowatt-hours per day was worked out. To simplify our calculation, as above, each cable spur was lumped together and represented by one appliance operating with the fall power of that spur normalised to operate for one hour per day.

Another goal was to look at the effect on the capital outlay for the electrical installation. The capital cost of installing 4mm^2 cables as against conventional 2.5mm^2 cables should be the same whereas the increase in the cost for the larger 4mm^2 cables is approximately £50. The energy losses in the cable were calculated at approximately 55.5 kWh per year. At £0.1226 per kWh[8] this is a monetary value of £6.80 per year.

The losses due to poorly designed conventional AC to DC converters are not known and therefore a direct economic comparison cannot be made. It is expected that the total energy used by an all DC house will be smaller than that of the conventional AC home making the all DC home more economic. Also as an inverter on a PV installation will not be needed, then not only will its cost of between £800 and £1800 be eliminated but the area of the PV array will be smaller and thus cheaper than a PV system supplying an AC voltage house.

The extra cost to manufacture DC only appliances should be minimal and perhaps even cheaper without the AC power stage.

9. Constraints and further work

This model is constrained by the lack of available DC appliances and their power electronic interface with the mains. More work is needed to show; (1), how their power consumption will be affected by redesigning them to work on low-power DC, (2), how a multiplicity of appliances that require different operating voltages can be interfaced to a fixed voltage mains and (3), how much energy can be saved by exchanging, low voltage DC to DC power converters for the conventional AC/DC converters. Also needed is a mechanism that will limit the total current drawn such that the integrity of the system will not be compromised.

10. Previous work

The first known paper on this subject is entitled "The DC low-voltage house"[9] this study is well appraised in Appendix 1[3] of the second study. In section 7.4 this second study concludes erroneously that 10mm^2 cables must be used, which doubles the cost of installation. However no details are given about the energy saved by using DC appliances as against using AC appliances and no value is given to the savings achieved through the elimination of the inverter. Both agree that the all dc house is not feasible, something which this paper disagrees with. Both agree that more research is needed.

11. Conclusions

1. It is concluded that contrary to opinion a full DC voltage powered home is feasible within the constraints given.
2. At this stage the mathematics work and for most applications 4mm^2 cable is sufficient. But further work will have to be done to bring the practical solution closer.
3. The economics will improve as manufacture of DC appliances takes advantage of economies of scale.
4. There are many advantages for the decentralisation of electrical energy distribution, some are economic others are, Energy Security and Energy Independence. The all DC house will help towards fulfilling these goals.

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[1] BS 7671:2008 Requirements for Electrical Installations – IEE Wiring regulations 17th edition

[2] Electrical Installation Calculations by B.D. Jenkins

[3] The Use of direct current output from PV systems in buildings. By Building Research Establishment for the DTI/Pub URN 02/961. 2002

[4] http://www.vent-axia.com/new/news.asp?a=131

[5] http://www.vent-axia.com/products/domestic/lowatt-wcbathroom.asp

[6]40% House page 31 By Environmental Change Institute Oxford UK

[7] Concept for a DC low voltage house; Sustainable Building 2000 Conference by Maaike M Friedman et al

[8] Average price for UK in 2008, from file Berr file Average annual domestic electricity bills for selected towns and cities in the UK and average unit costs (QEP 2.2.3) found at http://www.berr.gov.uk/energy/statistics/publications/prices/tables/page18125.html

[9] MSc thesis by J Pellis Technische Universiteit Eindhoven 1997 .