Direct current for low-power households: a DC-DC converter analysis

June 15th, 2015, Published in Uncategorised articles

by Christo Venter, Atanda Raji and Dr. Marco Adonis, CPUT

A design framework for the implementation of a DC powered house and the design and simulation of a household DC-DC converter.

Over the last century, AC power has been the main type of power generated and used for residential purposes. This resulted in household appliances using AC power [1, 2]. Modern electronics use DC power as the main source of power and the AC power must therefore be converted to DC before it can be used. This makes using DC as the standard voltage in homes much more efficient.

With this in mind, the solution to powering rural areas could be low-voltage DC as most renewable sources supply DC output.

This article will review DC power systems that may be suitable for small off-grid households and then evaluate a DC-DC converter system using a circuit simulator to evaluate its performance using the typical load profile of a small home.

<table>
<thead>
<tr>
<th>Load</th>
<th>Power per unit (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large appliances</td>
<td>1400</td>
</tr>
<tr>
<td>Small appliances</td>
<td>600</td>
</tr>
<tr>
<td>Lighting (LED)</td>
<td>30</td>
</tr>
<tr>
<td>Personal electronics</td>
<td>100</td>
</tr>
<tr>
<td>Total power</td>
<td>2130</td>
</tr>
</tbody>
</table>

Power budget of a small house

Using only renewable DC sources simplifies the solution. This solution applies only to a single stand-alone installation. The load not included in the calculation is water heating, which could be supplied with solar heating.
Only a limited number of household appliances are currently DC powered. However, this number is growing.

### Table 2: DC voltage determination.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
<th>Cable size</th>
<th>Cable price</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 V</td>
<td>145.83 A</td>
<td>50 mm²</td>
<td>R57.50 p/m</td>
</tr>
<tr>
<td>48 V</td>
<td>72.92 A</td>
<td>25 mm²</td>
<td>R38.78 p/m</td>
</tr>
</tbody>
</table>

Table 1 shows the total power budget of a small DC house. The total power that will be needed is 2130 W for all the essential DC loads. An additional 15% will be added to the converter as a reserve capacity so that, when the full load is required, the converter will only use 85% of its full capacity. This practice should prolong the life of the converter.

Also, if the load experiences a spike in power demand, the converter will use this 15% reserve capacity to handle the spike in power so that the components in the converter are not damaged. The required DC-DC converter will therefore need to supply a load with a peak instantaneous power demand of approximately 2500 W.

**Fig. 1: Boost converter test circuit**

**DC house standard voltage**

DC distribution has been widely used in ships, traction systems and communication. It has recently attracted more attention as a suitable solution for small households. The reason for this is that conventional AC power in most household applications is converted to DC voltage for many appliances.

Establishing a reasonable voltage standard is essential for the expansion of DC distribution. An overview of some work done on DC voltage standards reveals that the Electric Power Research Institute (EPRI) developed a standard DC voltage of 380 V for data centres. This, however, will not be suitable for residences because of the safety risk posed by DC voltage of that magnitude. The International Electrotechnical Commission (IEC) defines 120 V DC as the “upper boundary” of extra low voltages. This 120 V DC would also have to be modified since most DC applications work at much lower DC voltage levels. This would be more efficient for higher power applications [1, 2].
The Emerge Alliance developed a standard for a safe, low voltage of 24 V DC for DC power distribution in commercial building interiors [3]. This alliance is interested in creating a family of area-specific DC microgrids that, when interconnected, create a resilient and versatile building or campus-wide energy network.

The restriction on 24 V as a standard household voltage is that it is only really suitable for extra-low power appliances in a small house or room due to its large power losses over long cable lengths [1]. A network using 48 V DC would have much lower power losses in comparison. As shown in Table 2, smaller diameter cable for the rated current suggests a more cost-effective solution if 48 V rather than 24 V is implemented. Table 2 lists the differences in cost and cable size for the 48 and 24 V systems. It indicates that, from an economic perspective, a 48 V standard may be a more suitable option.

**DC-DC converter evaluations**

The two most common converters applicable to this type of application are the boost converter and the buck-boost converter [4, 5]. The boost converter produces an output DC voltage greater than the input, while the output DC voltage of a buck-boost converter can be either smaller or larger than the input voltage.
The main limitation on the use of the buck-boost converter is that the polarity of the output DC voltage is reversed, i.e. the input voltage and output voltage have no common ground. In addition, the power switch needs a floating drive [9]. This results in further complexities in circuit wiring and control. For these reasons, the boost DC-DC converter was chosen for further evaluation for the low-power house implementation.

The evaluation tool used is Simulink circuit simulation software [10]. A boost DC-DC converter is simulated under a range of scenarios, in which loads are switched in and out, and the transient responses recorded.

Output current and voltage values are evaluated against standard criteria to ensure that transient fluctuations are within accepted industry standards.

**The boost DC-DC converter**

Fig. 1 shows the boost converter circuit configuration. The following parameters were used to calculate the values of the boost converter circuit components:

- Input voltage 24 V.
- Output voltage 48 V.
- Switching frequency 100 kHz.
- Load resistance 0.685 Ω.
- Output ripple current must be <1%.
- Output ripple voltage 0.1 V.

The circuit components were determined from the standard design calculations shown here:

\[
D = 1 \left( \frac{V_o}{V_i} \right)
\]

\[
1 = \frac{V_o}{(1 - D)(1 - D) R}
\]

\[
L = \frac{V_o D}{2 \Delta i \ell f}
\]
\[ C' = \frac{VD}{2\Delta v_c RF} \]

where

\( D \) = Duty cycle  
\( V_i \) = Input voltage  
\( V \) = Output voltage  
\( I \) = Inductor current  
\( R \) = Load resistance  
\( L \) = Inductor  
\( \Delta i_l \) = Inductor ripple current  
\( F \) = Switching frequency  
\( C \) = Capacitor  
\( \Delta v_c \) = Output ripple voltage

The inductor and capacitor values were determined:

\( L = 41.4 \) uH  
\( C = 1824 \) uF

The results obtained from the simulation of this boost converter using Simulink are shown in Fig. 2. The output waveforms on Fig. 2 show the output voltage of the converter, output current and the inductor current.

**Load testing**

The following scenarios were considered to ensure that the DC-DC converter can handle changes in the load and that fluctuations in the output voltages remain within predetermined limits:

- Load was increased in intervals of 25%.
- Load was increased in one step from 25% to 100%.
- Load was decreased in intervals of 25%.
- Load was decreased in one step from 100% to 25%.

![Fig. 4: Simulink results for scenario 1.](image-url)
Fig. 3 shows the Simulink diagram used to perform these load tests. Switches were added to simulate the load changes. These switches were set up to close at preset times so that the response of the converter could be monitored.

The circuit in Fig. 3 will be used to create the boost converter that can accept three inputs and supply one load [6]. To develop a boost converter that can accept three inputs, three boost converters will be connected in parallel and in series with the load [7]. This connection of converters creates a multiple input boost converter [7]. The load represents the equivalent power usage of a low-power household using DC power. This power has been determined in Table 1 and the current which the converter must deliver was calculated and is presented in Table 2.

Load test scenarios

Scenario 1: Load current increased in intervals of 25%

To test how the controller would respond to increasing load current, the load current was increased in intervals of 25%. This will simulate people switching on appliances in the house at various times during the day. Fig. 4 shows output voltage and current results from scenario 1.

![Fig. 5: Simulink results for scenario 2.](image)

Scenario 2: Load current increased from 25% to 100%

This is a sudden load change. It will simulate a big change as if all loads in the house were switched on at the same time. Fig. 5 shows the output results from this test.

Scenario 3: Load current decreased in intervals of 25%

The load was decreased in intervals of 25% to test how the controller would respond to decreasing loads. This will simulate people switching off appliances at various times during the day. Fig. 6 shows the output results from scenario 3.

Scenario 4: Load current decreased from 100% to 25%

Scenario 4 is a sudden load change. This will simulate all loads in the house being switched off at the same time. Fig. 7 shows the results from the test of scenario 4.
These results indicate that the controller is adequately able to mitigate an increase or a decrease in the load capacity. When a change in load capacity occurs, the controller reacts within 3 ms to achieve steady state.

In the South African context, there currently exists no applicable standard for power quality for low-voltage DC power systems. The national power quality standard (NRS048-1/SABS0480-1) applicable to AC power systems does offer some direction on this issue. The standard describes voltage limits for power supply connections to customers. For voltage supplies less than 500 V, the maximum deviation should not be more than 15%.

The gradual load variations as depicted in scenarios 1 and 3 produce the smallest transients. These voltage spikes are in the order of 3 V peak-to-peak. The transients produced for the abrupt load variations depicted in scenarios 2 and 4 are larger. However, these are not prolonged and the load voltage level is restored quickly. The voltage spikes are of the order of 7 V peak-to-peak.

The analysis of the voltage deviations derived from the load switching simulations in Figs. 4, 5, 6 and 7 reveals a minimum variation of 6.3% and a maximum variation of 14.6%. These values fall within the acceptable limits of the NRS power quality standard.
Conclusion

It is imperative for the voltage supply in a residence to remain stable and free from excessive spikes and prolonged transients as loads are connected and disconnected. These voltage variations can cause damage to household appliances. The various load tests performed show that, through many switching scenarios, the load voltage level remains relatively stable since the voltage deviations obtained from the converter switching action stay within the power quality standard’s recommended 15 % allowance.

The simple DC-DC converter control mechanism can compensate adequately for load variations. The results show that the boost DC-DC converter is a good candidate for implementation in a DC house.

Acknowledgement

This article is based on a paper presented at the 2015 Domestic Use of Energy Conference and is published here with permission.

References

The references to this article appear online at www.vector.co.za

Contact Dr. Marco Adonis, CPUT, Tel 021 959-6488, adonism@cput.ac.za