MULTI-CONVERTER TOPOLOGY EVALUATION FOR CONNECTION OF LOW VOLTAGE DC SOURCES

P. Sernia and G.Walker

School of Computer Science and Electrical Engineering
University of Queensland

Abstract

A design for a cascaded multilevel DC-DC converter is proposed. The applications of a multilevel converter and the design issues involved in changing from a single converter to multiple converters are discussed. Implementation of the multilevel system using multiple Cuk converters is suggested and explanations of design decisions are given. The merits of the proposed design are discussed.

1. INTRODUCTION

There are a number of proposed multilevel inverter topologies that produce a high voltage AC signal from separate DC sources [1]. The intent of these designs is to reduce component stresses in high voltage systems. The designs and techniques used in these inverters can also be applied to lower voltage systems that are supplied from separate, low voltage DC sources.

Common examples of these low voltage energy sources are fuel cells, solar cells, batteries and ultracapacitors (ultracaps). Individual “cells” of these components operate at low voltages of between 0.5V and 4V, but they are useful in applications that require a DC bus voltage of hundreds of volts.

This paper proposes a cascaded multilevel arrangement of DC-DC converters and investigates the advantages and disadvantages of such a system. An implementation of the DC-DC converters is also suggested.

2. MULTILEVEL DESIGN CONCEPT

The proposed design is shown in Figure 1. The multilevel converter is specifically aimed at modular energy sources that would typically be placed in *series*. Where previously the energy sources (shown as batteries in the figure) would have been connected in series before connecting to a single DC-DC converter, they are now broken up into smaller sized ‘modules’, where each module has a dedicated DC-DC converter. The modules are then connected in series giving an output voltage that is equivalent in magnitude to the original output bus.

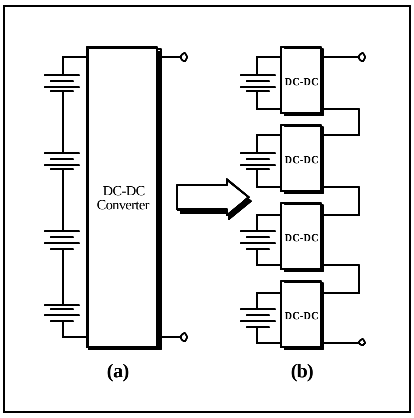


Figure 1. Moving from (a) a single converter to (b) smaller modules and more converters.

2.1. Isolated DC Sources

The intent of the multilevel design is that it should accommodate a variety of different modular DC power sources. In general, the final output voltage level is not expected to exceed $400V_{DC}$ and the power to the load will be in the order of kilowatts. There are a number of energy source technologies that would be suitable for this converter design, the most notable of these being batteries, fuel cells, solar cells and ultracapacitors.

2.2. Converter Design Issues

There are a number of considerations that must be addressed when changing a converter design from single to multilevel. The most important of which is ascertaining whether modularising the power sources is a worthwhile exercise and if so, under what conditions.

2.2.1. Why Change to Multilevel?

An obvious concern with moving to a multilevel architecture is that increasing the number of converters will result in a similar increase in losses and signal disturbances. The immediate benefits would be a greater capability for power management of the low voltage sources.

When placed directly in series, the DC power sources can experience the following detrimental effects:

- Inefficiency
- Reduced cell utilisation
- Weak cells and individual cell damage
- A single cell failure results in total system failure
- Over/under charging/discharging
- Lack of monitoring and management at individual cell level.

Moving to a multilevel architecture can alleviate these problems to a certain degree, and can also cater more specifically to the management and operation of each particular 'module'.

2.2.2. Modularity

Modularity of the multilevel design is of particular importance considering the different energy sources that it will be designed to accommodate. A DC-DC module can be added to the converter stack with minimum effort, and faulty modules can be removed just as easily.

The modules will also be operating on a smaller scale, making power management of the DC sources, such as battery balancing, more accurate, and hence increasing lifetime.

The modularity also allows DC sources to be physically located at a distance from each other, such as in a solar array application. The DC sources can be of different technologies or types, as long as the output characteristics of all modules are matched.

2.2.3. Minimising Ripple

It is desirable that input and output ripple of the modules should be kept to a minimum. Many of the DC sources considered, such as batteries and ultracaps, can be adversely effected by large ripple currents. The modules should be designed to draw current as smoothly as possible from the source.

By using multiple converters, the combined ripple at the output will have a smaller magnitude but will be of a higher frequency. Switch synchronisation can be used to smooth the output ripple without requiring any additional filter components. By synchronising and staggering the modules such that no two ever switch simultaneously, the ripple voltages of the modules will partially interfere with each other to reduce the overall ripple frequency.

3. DESIGN SOLUTION

3.1. System Criteria

The theory of the proposed multilevel design can be applied for a variety of DC sources. In this paper, the particular application chosen for demonstrating design viability was that of a solar array.

For simplification, the array will consist of 4 solar panels connected in series through converter modules. The solar panels will have a maximum output voltage of 15V and a power rating of 60W. The purpose of the converters is to operate the panels at their peak power point (15V@4A) while maintaining, for example, a constant output voltage.

Considering the V-I curve of a solar panel as shown in Figure 2, the peak power operating points at different insolation levels are marked as black squares. If the current drawn is increased from this point, then the voltage output decreases rapidly and similarly the current will decrease as the output voltage rises.

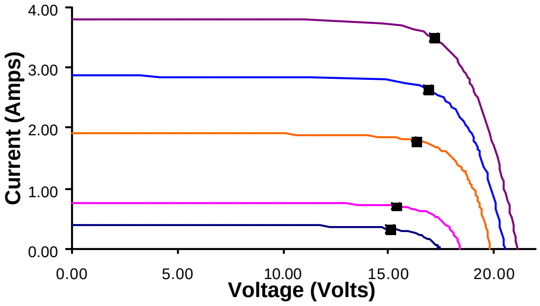


Figure 2. Solar panel V-I curve for varying insolation. Peak power points are shown in black.

Considering the series stack of converter modules as a single multilevel converter, it is also desired that the output voltage from the multilevel converter be kept at 60V (= 4 x 15V). The restrictions and behaviours imposed by this criteria are examined further in Section 3.3.

3.2. Switch Synchronisation

As discussed in Section 2.2.3, output ripple can be reduced by interleaved switching of the modules. Due to waveform irregularities and timing jitter between modules, the noise can not be completely cancelled.

A reduction in noise can be achieved by simply switching the modules randomly, however in order to achieve the best possible output some form of communication is required between modules for synchronisation. This increases the complexity of the converter modules, but is desired as it maintains the modularity of the design.

3.3. DC-DC Converter Selection

Before performing a numerical analysis, a suitable converter topology must be selected. Existing multilevel designs, such as cascaded full-bridge inverters, offer possible solutions, but are mainly used as DC-AC converters [1].

The purpose of this paper is to select a design that offers a simple topology that provides DC-DC conversion, but also addresses the problems of input and output ripple. Hence other basic DC-DC converter topologies will be considered.

3.3.1. Module Behaviour

The most desirable solution for module topology is to use a simple buck or boost derived DC-DC switchmode converter. However, not all of these will operate as desired when placed in series with each other.

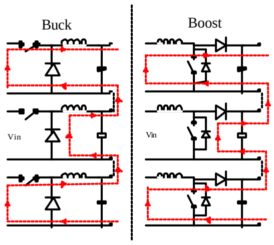


Figure 3. Passive current path through series connected Buck and Boost converters.

During operation, the output voltages of each module will add and the total output current will circulate through every module. The passive (ie zero power contribution) current path of two types of converters is shown in Figure 3.

In the case of the Buck modules, the DC source will be isolated from the output by the silicon switch and the multilevel converter output will experience a diode voltage drop. For the Boost converter, the DC source will be shorted and the current path will flow through two silicon components.

In both cases, the total voltage will drop by a single converter output, which will be 15V in the case of the solar array. To counter this loss, remaining modules can boost their voltage to compensate. For the series connected buck converters this would mean that all modules initially operated with an output voltage much smaller than the input voltage in anticipation of a voltage rise. For the boost converters, the output would be almost equal to the input voltage initially, but would then be boosted as required.

In comparison, the buck converter has a lower conduction loss and automatically isolates the DC source. However, as a precaution against failure of other modules, it can not operate close to peak input voltage. In contrast, the boost converter can operate at peak voltage and then boost the output further as required. However it will have a higher conduction loss and will short-circuit the source.

The conclusion reached is that while the buck current path is preferable because of its lower silicon losses and DC source isolation, it will rarely be operating at maximum voltage. Because many DC sources have a low peak voltage, it is preferable to use a boost converter to operate at maximum voltage for the majority of the time and include some form of source isolation.

3.3.2. DC Source Characteristics

An additional problem arises for a boost converter. In the situation where the output power from a single DC source decreases, the output current from the connecting module must remain constant, causing the output voltage to drop.

For a boost converter $V_{in}<V_{out}$. As the output power of a module drops, as would be the case for a solar panel that is in the shade, maintaining a constant output current would force the output voltage to drop. For each drop in V_{out} there will be a similar drop in V_{in}. As V_{out} approaches zero, the inequality approaches $V_{in}< 0$, which is not a possible operating state for the boost converter.

In addition, large deviations in V_{in} would prevent operation at peak power points in the case of solar arrays, or would not be practical in cases where the source voltage varies little, such as for batteries. A clear solution to this would be to use a converter that will allow $V_{in}<V_{out}$ as well as $V_{in}>V_{out}$, such as a buck-boost topology.

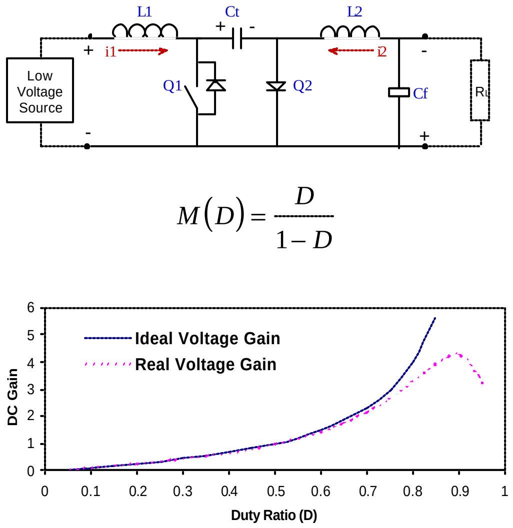
3.3.3. Converter Selection

The chosen converter was selected based in part on the following criteria:

- Buck/boost capabilities
- High efficiency
- Minimal components
- Individual control of power to each module
- Low ripple
- Bidirectional power flow

The converter deemed most suitable for this role was the Cuk converter, shown in Figure 4. The Cuk converter can be described as a boost-buck combination and has a transfer function M(D) identical to that of a buck-boost converter. The primary advantage of a Cuk is that, unlike other single inductor converters, both the input and the output currents are non-pulsating, reducing the ripple seen at both the input and output [3].

When cascaded in series, Cuk converters have a constant conduction path through the output inductor and diode. As shown by the graph in Figure 4, the converter will have a unity gain at 50% duty, although it deviates from the ideal values at high duty ratios due to parasitic losses [3].



$$M(D) = \frac{D}{1-D}$$

Figure 4. A Cuk converter (top) and its transfer function characteristics. Note the decrease in actual gain at high values of D due to parasitic losses in non-ideal components.

3.3.4. Cuk Operation

In contrast to many other basic converters, energy transfer in a Cuk occurs capacitively instead of inductively. Referring to the diagram in Figure 5 during the interval when switch Q1 is off, diode Q2 conducts both currents i1 and i2, and transfer capacitor Ct is charged in the positive direction through L1.

When switch Q1 is closed, capacitor Ct is connected across the diode, reverse biasing it. Hence switch Q1 now conducts currents i1 and i2, and capacitor Ct discharges through the load RL and inductor L2. The resulting output polarity is the inverse of the input.

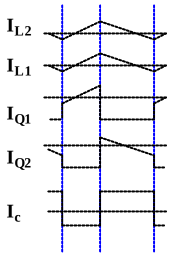


Figure 5. Current waveforms during a switching cycle

It can easily be observed that the ripple current waveforms of both inductors L1 and L2 will have the same shape in a single switching period, with different magnitudes. More detailed explanations of Cuk operations can be found in [2][3][5].

3.3.5. Component Selection

The next step in the design process is to verify that a Cuk converter is suitable under realistic operating conditions. The following values and equations were used:

$f_s = 150kHz$ $\quad V_s = 15V$ $\quad I_s = 4A$

$I_{ripple} = 0.5A = 12.5\%$ $\quad V_{ripple} = 1V$ $\quad DutyRatio(D) = 0.5$

	Peak-peak Ripple	Component	Value
Inductors	$\Delta i_{L_1} = \frac{V_S D}{f_s L_1}$	L_1	$100mH$
	$\Delta i_{L_2} = \frac{V_S D}{f_s L_2}$	L_2	$100mH$
Capacitors	$\Delta v_{c_t} = \frac{I_S D'}{f_s C_t}$	C_t	$13mF$
	$\Delta v_{c_f} = \frac{DV_S}{8C_f L_2 f_s^2}$	C_f	$420nF$

Both inductors need to be rated continuously at 4 Amps with a current ripple of 0.5 Amps and the average voltage across the transfer capacitor C_t will be 30V. As the energy transfer from input to output occurs through C_t, the ripple current through this capacitor will be the same as the ripple current through each of the inductors. Through discriminate selection of a capacitor technology that offers a low equivalent series resistance (ESR), the power loss in the capacitor can be minimised to an acceptable level. The inductor values and ratings are also well within achieveable limits.

3.4. Additional Improvements

Figure 5 shows the similarity of the inductor current waveforms. For the values used in Section 3.3.5, the inductor values are the same, implying that the current waveforms will also be exactly the same. Having noted this, it is then possible to show that by coupling the inductors on a common core with a turns ratio close to 1:1, the AC current in one or the other, but not both, of the inductors can be steered towards zero [2][6].

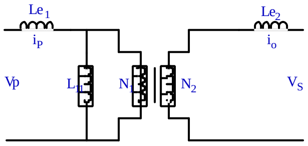


Figure 6. Equivalent model of coupled inductors.

Figure 6 shows the coupled inductors modelled as a transformer. Analysis of this arrangement leads to the result that for zero input current ripple, the following condition is to be met:

$$L_{e_2} = L_{11}\left(\frac{N_2}{N_1}\right)^2\left[\frac{N_1}{N_2} - 1\right]$$

where
L_{11} is the self-inductance of L_1
L_{e1} is the leakage inductance of L_1
N_1 is the number of turns on L_1
N_2 is the number of turns on L_2
Le2 is the leakage inductance of L_2

Typically, it would be more desirable that the output from the converter be as close to a DC value as possible. However, for the purpose of this multilevel design, a reduced input current ripple is preferable for two reasons:

1) better line regulation at the power source will ensure a longer lifetime and higher efficiency of that power module, and
2) moving to a multilevel architecture already addresses the problem of reducing output ripple by implementing interleaved switching.

3.4.1. Bidirectional Power Flow

Bidirectionality of the converter is required for charge balancing and recharging of power sources such as batteries and ultracaps, removing the need for separate charging or balancing circuits. The Cuk converter presented in Figure 4 only allows power flow in a single direction.

However, after observing that the converter is symmetrical, bi-directional power flow can be achieved by replacing diode Q2 with a MOSFET - essentially placing a switch in parallel with the diode[4]. This new arrangement is shown in Figure 7.

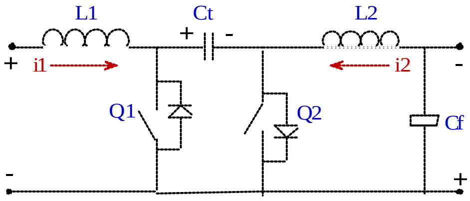


Figure 7. Bidirectional Cuk Converter

Switching the two MOSFETs alternately reduces the conduction losses while still maintaining a passive conduction path through the reverse diode if required.

4. DISCUSSION

The design presented incorporates switching techniques of multilevel converters with cascaded Cuk converters as shown in Figure 8. The properties of the Cuk converter that have been discussed make it appear to be an attractive solution. It offers very low ripple values at both the inputs and outputs of the converters and is capable of bi-directional power flow.

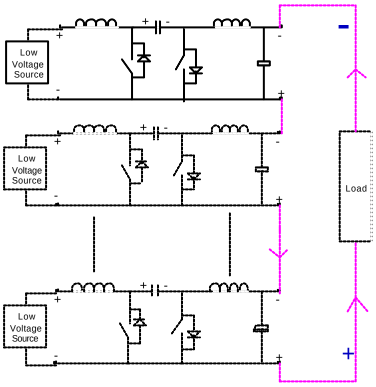


Figure 8. Final Cascade Cuk Multilevel Converter

There are however a number of other characteristics of Cuk converters that should be noted. In general, they offer a higher efficiency than other basic converters, however conducting large currents is potentially a problem as the switches conduct both the input and the output current simultaneously ($I_{L_1} + I_{L_2}$). Hence they are better suited for lower power applications to keep conduction losses small.

Similarly, the switches also see a high voltage $(V_{in} + V_{out})$ that is generated across the transfer capacitor (C_t). Since the Cuk converter uses a capacitor as the energy transfer device, it requires a high ripple current, which in turn produces EMI. With careful arrangement of components the EMI can be contained within the 'inner' switching loop of the converter [3].

5. CONCLUSION

Although it might be preferable to operate low voltage power sources on an individual basis rather than in a large series string, this is not always possible or practical. However, there are valid reasons for using a multilevel design in place of a single, larger converter. These reasons include modularity of different power sources and converters, ripple reduction and increased operating lifetime.

By cascading Cuk converters in series, a multilevel converter design has been proposed that appears to exhibit the desired properties for the low power sources involved. The concept was verified using a test case of series-connected solar panels and converters.

The Cuk converter has many characteristics that make it well-suited to this application. It has low ripple as a result of continuous input and output currents and inductor coupling, has a high efficiency and a minimum number of switching components.

The transfer function operates over a wide range, although the power output is limited for large gains. The switching components also experience high voltage and current stresses, as does the transfer capacitance which experiences a large current ripple.

Although promising, the success of the Cuk converter in a cascaded multilevel design requires further investigation and analysis in order to produce the best system that caters to low voltage DC power sources such as batteries, fuel cells, solar cells and ultracapacitors.

6. REFERENCES

[1] J. Lai, F.Z.Peng, “Multilevel Converters – A New Breed of Power Converters,” *IEEE Transactions on Industry Applications*, Vol. 32, No. 3, May/June 1996, pp 509-517.

[2] T.S.Finnegan, “Cuk: the best SMPS?” *Electronics World + Wireless World*, January 1991, pp 69-72.

[3] S.Cuk, R.D.Middlebrook, “A New Optimum Topology Switching DC-To-DC Converter,” *IEEE Power Electronics Specialists Conference,* 1977, pp 160-179.

[4] R.D.Middlebrook, S.Cuk, W.Behen, “A New Battery Charger/Discharger Converter,” *Proceedings IEEE PESC Conference*, 1978 pp 251-255.

[5] W.Erickson, *Fundamentals of Power Electronics*, Kluwer Academic Publishers, Massachusetts, 1997.

[6] S.Cuk, “Switching DC-To-DC Converter with Zero Input or Output Current Ripple,” *IEEE Industry Applications Sociery Annual Meeting*, 1978 pp.1131-1146.