Deriving New Topologies of DC-DC Converters Featuring Basic Switching Cells

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***Abstract*- This paper will introduce the two basic switching cells, P-cell and N-cell, and their applications in different power electronic circuits. These basic cells have one switching element and one diode. The P-cell is the mirror circuit of the N-cell and vice-versa, and this paper suggests that any power electronic circuit can be analyzed and re-constructed using these basic switching cells. The present paper will describe the construction and operation of the basic switching cells, and it will also show a sequential method to construct several dc-dc converters from these basic switching cells. Moreover, considering the potential of combining these cells in multiple fashions, new kinds of power electronic circuits can be designed.**

***Keywords* – dc-dc converter, modular, P-cell, N-cell, Cúk converter, buck converter.**

I. Introduction

Different power electronic circuits such as dc-dc, ac-dc, dc-ac, and ac-ac converters use switching devices, diodes, inductors, and capacitors as the basic elements. Many circuits have been invented, proposed, and demonstrated to perform various power conversion uses. Classical dc-dc converters such as buck, boost, buck-boost, and Cúk converters are used in various applications. However, these circuits have rarely been examined and investigated in terms of their relationships, topological characteristics, or what are their basic building blocks [1-7].

The modularity in power electronic circuits has been shown in several papers [2-8]. Several methods have been presented to construct basic power electronic circuits using small modular blocks consisting of very few elements [2,5,9,15,17]. When a power electronic circuit is represented with some modular blocks, it becomes easier to analyze the circuit [18]. Unlike digital circuits, most power electronic circuits do not have a uniform pattern so that they can be expressed using some modular blocks. However, the main intention of this paper will be introducing some modular structures and show how existing power electronic circuits can be synthesized from these structures. Existing well-known circuits can easily be represented using some modular blocks configured from the basic switching cells. Moreover, some new circuits will be addressed that are of great interest in understanding the basics of power electronic circuits and their control.

II. The Canonical Switching Cell

The concept of switching cells in power electronic circuits started in the late 1970's [9]. It started with the canonical cell

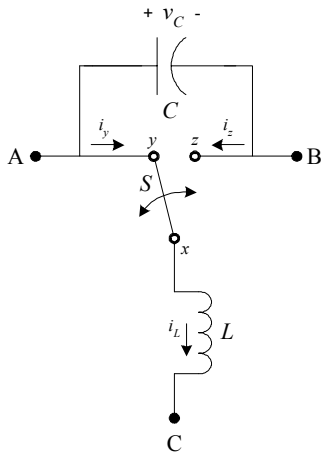


Fig. 1. The basic canonical cell.

[9,17,19] where an inductor, a capacitor, and a single-pole double throw switch form a basic canonical switching cell shown in Fig. 1. The cell has three terminals A, B, and C and each of them can be used as an input/output/common terminal. If terminal A is used as an input, B as an output and C is used as the common terminal, the canonical circuit forms one kind of dc-dc converter. Six different combinations can be formed by changing the function of the three terminals in different combinations [15]. Among these six combinations, only three distinct effective circuits are found, whereas the others are functionally the same. Thus, using these three combinations, the buck, boost, and buck-boost converter can be formed.

III. Two Basic Switching Cells

Fig. 2 shows the two basic switching cells defined in this paper. Unlike the canonical cell, each basic cell consists of one switching device and one diode connected to three terminals: (+), (-), and (→) /or (←). Each cell has a common terminal which is shown as (→) /or (←) on the schematic. For the P-cell, this common terminal is connected to the positive terminal of a current source or an inductor. For an N-cell, this common terminal is connected to the negative of a current-source or an inductor. The active switching device in a P-cell is connected between the (+) and common terminal, whereas in an N-cell, the switching device is connected between the (-) terminal and the common terminal. Thus, the P-cell is the mirror circuit of the N-cell and vice-versa.

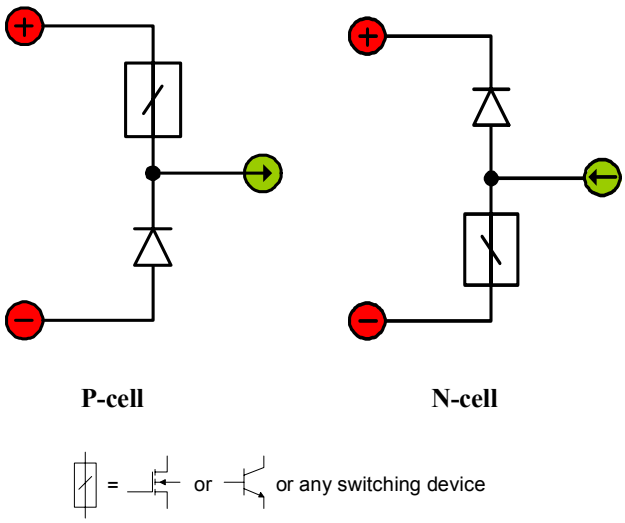


Fig. 2. Two basic switching cells: P-cell and N-cell.

The basic switching cells proposed in this paper are the practical implementation of the canonical switching cell found in [9]. Although the switching cells presented in this paper have only two components, they can be connected in different combinations to create various power electronic circuits.

IV. DC-DC Converters Composed from the Basic Switching Cells

Fig. 3 summarizes the four classical converters and their cell structures. In Fig. 3, there are three columns and each column has 4 figures. The figures in the leftmost column show the four major classical converters. These converters are made from inductors, capacitors, diodes and controlled switches. As stated previously, each of these converters can be expressed using the basic switching cells and the corresponding circuits are summarized in the middle column. The converters in this column are made from either N-cell or P-cell. Thus except for the boost converter, all of the conventional converters have an inherent P-cell structure where the active switching element is connected to the positive power supply terminal. The conventional boost converter is inherently an N-cell boost converter.

All of these classical converters also have a mirror circuit representation. When the P-cell in a buck converter is replaced with an N-cell, the circuit takes a different configuration. In this way, the classical boost converter can be re-constructed using a P-cell, rather than an N-cell. The buck and boost converters can be easily decomposed into a P-cell and N-cell based circuit, respectively. However, this procedure is not so obvious for the buck-boost and Cúk (boost-buck) converters; they inherently take the P-cell structure. The mirror circuit

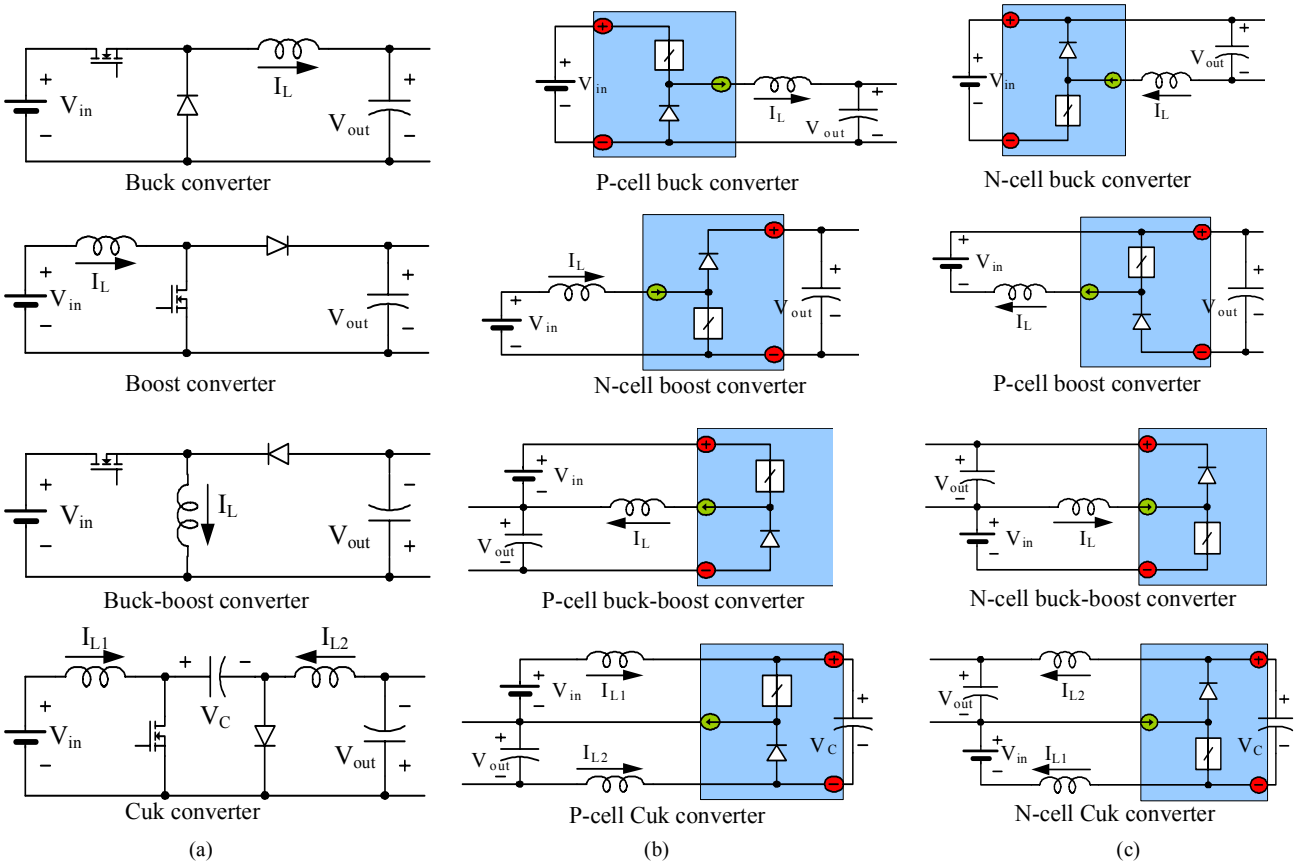


Fig. 3. (a) Classical dc-dc converters, (b) formation by the basic cells, (c) their mirror circuits.

representation of each dc-dc converter is shown in the rightmost column of Fig. 3. These circuits are new and will find some interesting applications.

The construction of a P-cell circuit differs from an N-cell circuit by the relative position of the active switch. The introduction of an N-cell module simplifies the gate drive circuit because of the ground referenced gate signal. When the gate drive circuit is ground referenced, the converter circuit is more immune to supply noise and gate drive noise. To compare the performance of P-cell and N-cell structure, two different buck converters were simulated and tested experimentally, and the corresponding results are shown in section VI.

V. Insights of the Basic Cells and New DC-DC Converters

The conventional Cúk converter has an especially unique structure [8]. However, after simplification using P-cells, the two inductors can be equivalently moved to the center rail and consolidated into one inductor as shown in Fig. 4. This new configuration of the Cúk converter will be advantageous over the conventional Cúk converter because of lesser part count. From Fig. 4, it is obvious that the new Cúk converter is very similar to the P-cell buck-boost converter, except the capacitor across the positive and negative terminals of the P-cell. In practical use, it is necessary to place a decoupling capacitor in the buck-boost converter, which makes the buck-boost converter identical to the Cúk converter. Thereby, introducing the P-cell and N-cell structures it is possible to create a link between these two converters. Moreover, new converter topologies can be developed using these basic switching cells. The new Cúk converter presented in this paper is an example of many potential findings.

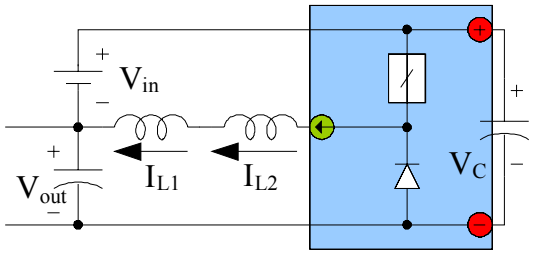


Fig. 4. Moving the two inductors of the Cúk converter to the center rail and combining them into one.

VI. Simulation and Experimental Results

A. Buck Converter

To validate the concept of P-cell and N-cell mirror relationship, a P-cell buck converter and an N-cell buck converter were simulated under continuous and discontinuous conduction mode. The simulations were done in PSIM and no difference was found between the two configurations, which lead to the conclusion that there is a mirror relationship between the N-cell and P-cell structures.

Then for further verification, a pair of buck converters (one P-cell and one N-cell) were constructed from discrete components and tested in the lab in continuous conduction mode. The operating and loading conditions of the N-cell buck converter and the P-cell circuit were the same, but some slight differences were observed in their output voltage. The test results are shown in Fig. 5.

The test setup was as follows:

V_{in} = 20 V, d = 0.4, f_c = 10 kHz, C_1 = 100 µF, L_1 = 1 mH, D_1 = MURB1020CT-1, S_1 = IRG4BC30U, R_L = 20 Ω.

For an input voltage of 20 V and duty cycle 0.4, the dc output voltage for the N-cell structure was 6.82 V and for the P-cell buck converter, it was 7.07 V. Fig. 5(a) and (b) show the output ripple components of the P-cell and N-cell structure respectively. The fundamental frequency component present in the ripple was the same for both topologies. However, the overall ripple component in a P-cell circuit is more than what was found in an N-cell circuit, and this feature of N-cell circuit can be used in [19] to reduce output voltage ripple.

These experimental results mentioned above explain the difference between a P-cell and N-cell structure. When a circuit is constructed from N-cell, the circuit uses a ground-referenced gate drive circuit, and the output is referenced to the + of the input power supply. On the other hand, a P-cell circuit produces ground-referenced output with a gate drive circuit referenced to the source of the transistor. When the output does not require to be referenced with the ground node, an N-cell circuit is advantageous over the P-cell circuit because an N-cell circuit with a ground referenced gate drive produces better output compared to the P-cell structure, and this effect is shown in Fig. 5.

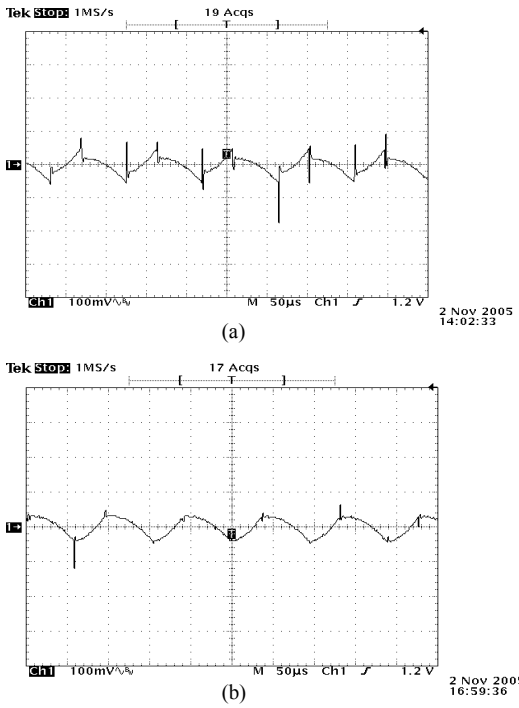
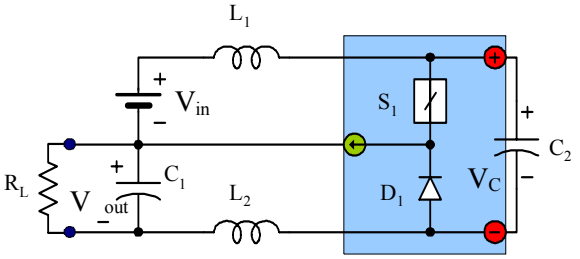
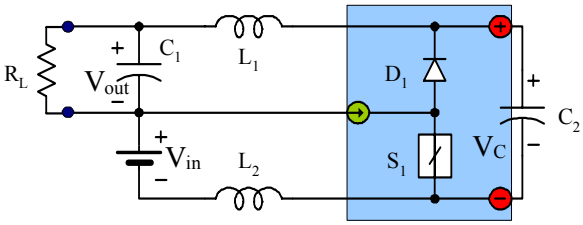


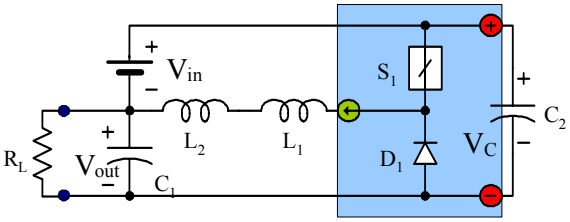
Fig. 5. Experimental output voltage ripple (100mV/div) of buck converter, a) P-cell, b) N-cell.



P-cell Cuk converter



N-cell Cuk converter



New Cuk converter

R_L = 20 ohm $C_1 = C_2$ = 47 uF

$L_1 = L_2$ = 1 mH

D_1 = MURB1020CT-1

S_1 = IRG4BC30U

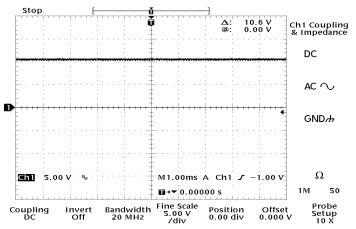
V_{in} = 20 V d =0.333 f_s = 10 kHz

Fig. 6. Schematic of the experimental circuits for a Cúk converter.

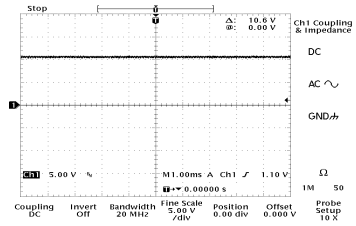
B. Cúk Converter

The previous section reveals the fact that the classical Cúk converter is inherently a P-cell structure. Thereby, there exists a mirror circuit of it, which is the N-cell Cúk converter. When the two inductors are transferred to one branch while using only one inductor, the third version of the Cúk converter is found. To introduce the advantages of basic switching cells, three different kinds of Cúk converters were constructed and tested. Fig. 6 shows the schematic designs of the three topologies that were constructed and experimentally tested. Fig. 7(a) shows the output voltages of these converters for a 20 Ω resistive load with a supply voltage of 20 V. The duty cycle of the gate drive was kept at approximately 0.33, and for this duty cycle, the output voltage of a Cúk converter should be around 10 V. In Fig. 7(b), the output ripple is shown by zooming the dc output voltage.

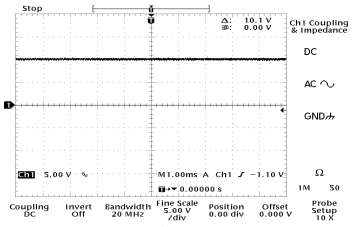
Fig. 7 clearly shows the evidence that these three converters are fairly equivalent. For the same duty cycle, the P-cell and the N-cell structures produce a 10.6 Vdc output, while the new combined inductor topology produces 10.1 Vdc output. The



P-cell Cuk Converter

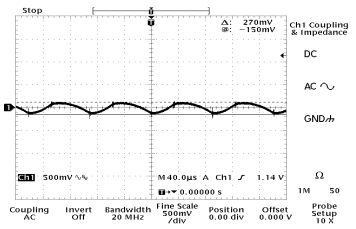


N- cell Cuk Converter

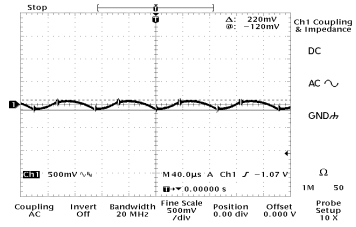


New Cuk Converter

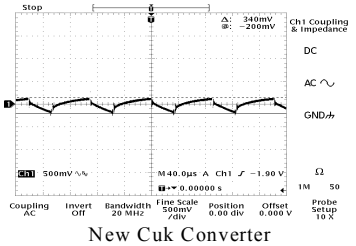
(a)



P- cell Cuk Converter



N- cell Cuk Converter



New Cuk Converter

(b)

Fig. 7 (a) Experimental output voltage of the converters (5V/div) (b) output ripple for different configurations (500 mV/div).

ripple component in the N-cell circuit has the lowest amplitude of 220 mVp-p compared to the original Cúk converter with P-cell structure producing 270 mVp-p. However, the new

topology with the two combined inductors produces a ripple of 340 mVp-p, which is slightly higher than the other two topologies. Whenever lesser part count is more important, the new topology can be used in place of the conventional Cúk converter by tolerating some additional ripple at the output.

VII. CONCLUSIONS

This paper has defined the two basic switching cells: P-cell and N-cell. It has been shown that the traditional buck, boost, buck-boost, and Cúk dc-dc converters are composed of these basic cells. These two cells are the foundation and basic building blocks of all power electronic circuits. They also have a mirror relationship that helps in the analysis and synthesis of circuits as well as the derivation of new circuit topologies.

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