

GENERALIZED TOPOLOGIES FOR CONVERTERS WITH REACTIVE ENERGY STORAGE

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Abstract

A generalized model for resonant and non-resonant converters is proposed which allows the systematic exploration of circuits using a given number ($n=0$ to infinity) of AC (reactive) energy storage elements. The method is simple, intuitive and is particularly useful for resonant converters. By way of illustration, the process is applied to the family of two AC element resonant converters to determine if any undiscovered circuits exist. Examples are also given for the important 3 element family of resonant converters.

I. Introduction

The need to increase power density has driven DC-DC converter switching frequencies well into the MHz. At these frequencies resonant circuits provide many advantages. Despite the wide use of resonant circuits, no generalized means for determining the possible topological variations for resonant converters has been presented. Converters using two AC energy storage elements may be explored piecemeal and indeed this has been done, with many of the useful circuits already seen in practice. However, when more than 2 AC storage elements are used, a systematic process is mandatory. The following work, which appears to have a broader application, was done to solve this particular problem.

The primary purpose of the paper is to propose a generalized technique for exploring the topological variations of resonant DC-DC converters. A secondary purpose is to suggest that the technique may be extended to quasi- and non-resonant circuits. Section II introduces the basic concept that converters can usefully be partitioned into a set of cascaded blocks, which may be combined in various ways, subject to a set of rules, to derive different circuits. Section III gives examples for $n=0$ and 1, where n is the number of AC energy storage elements. In section IV an exposition of the possibilities for 2 element converters is presented and in section V, a brief discussion of 3 element circuits is presented. In section VI quasi-resonant circuits are briefly examined and in VII a number of unresolved issues are addressed.

II. Converter Partitioning

A block diagram for a general DC-DC converter is shown in figure 1. Note that the partitioning adopted is not unique, other schemes could be used. The partitioning shown was selected because it was suitable for a particular problem: the exploration of resonant converter topologies. Other applications might well use different partitioning schemes. The dashed lines indicate the possibility of polyphase AC conversion. For power levels above 1 kW polyphase conversion can be advantageous. This discussion will be limited to single phase but can be readily generalized.

The blocks in figure 1 can be grouped into a source (voltage or current), AC energy storage and a load (voltage controlled current load or a current controlled voltage load). For this discussion the transformer will be omitted because it is not needed to determine the topology variations. The transformer can be reintegrated into the circuit as necessary. The resulting simplified block diagram is shown in figure 2. N represents the general AC energy storage network and n is the number of network elements in N .

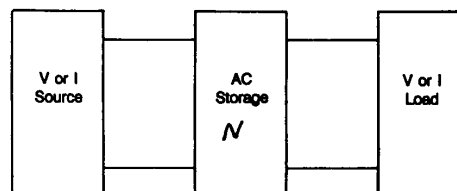


Figure 2, Simplified converter block diagram.

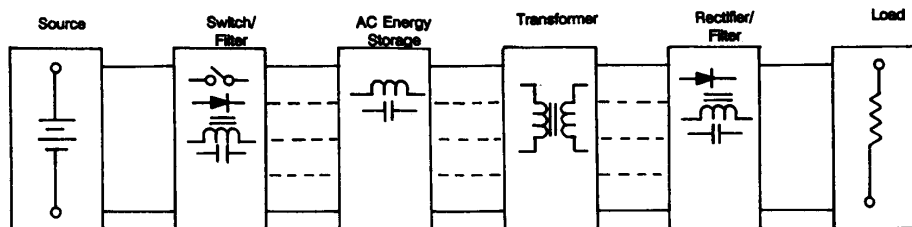


Figure 1, Converter partitioning scheme.

There are many possible realizations of each of the blocks in figure 2. Figure 3 shows typical halfwave and fullwave loads. Obviously there are many other examples of both categories [1]. These loads can be reduced to a voltage controlled current load or a current controlled current load as shown in figure 4.

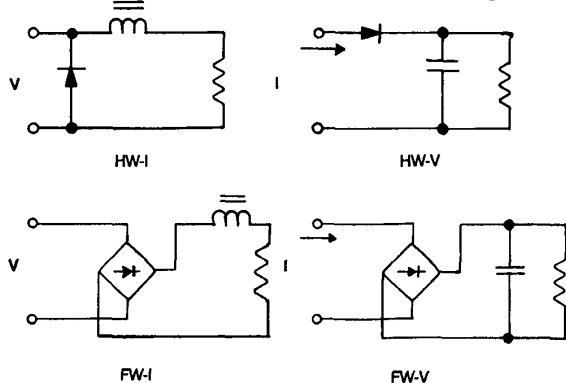


Figure 3, Typical halfwave and fullwave loads.

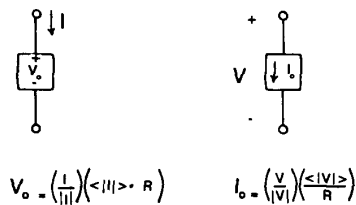


Figure 4, Load equivalent generators.

If the controlling I or V is sinusoidal with low harmonic content then the load reduces to an equivalent resistor as indicated in figure 4 [2]. Note that these examples use only diodes which are halfwave for both voltage and current. It is equally possible to use halfwave-voltage/fullwave-current, halfwave-current/fullwave-voltage and fullwave voltage/current switches.

Figure 5 shows equivalent halfwave or single ended sources. Again a variety of 1, 2 or 4 quadrant switches may be used. For

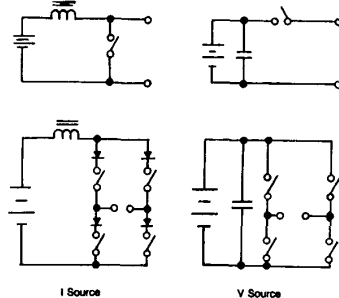


Figure 5, Typical halfwave and fullwave sources.

control purposes these sources may be PWM, FM or some combination of both. These sources can be represented by the equivalent sources given in figure 6.

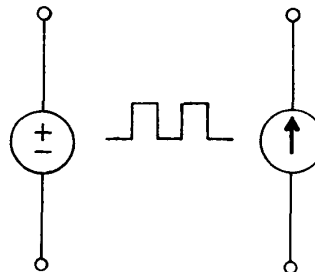


Figure 6, Source equivalent generators.

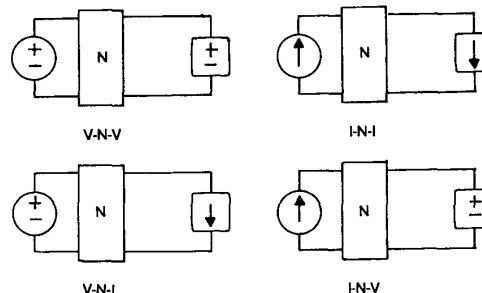


Figure 7, Load, source and network combinations.

III. 0 and 1 element topologies

There are four possible combinations of sources and loads as shown in figure 7. Before proceeding with the combinations it is necessary to derive some basic rules that limit the interconnection. In general we will be using squarewave or quasi-squarewave sources having only switches (no linear elements) for reasons of efficiency. If a squarewave voltage source is connected directly to a shunt capacitor there will be large current spikes in the source during switch state transitions. Similarly a current source connected to a series inductor will have voltage spikes. It should be noted that in some quasi and multiresonant [3] topologies shunt capacitors and series inductors are directly connected to the switches but the circuit operation is so arranged that either the inductor current or the capacitor voltage is zero at the moment of switching. The network operates with $n'=n-1$ during part of the operating cycle. Operation with two different values of n during the switching cycle accounts for the "multi" resonant operation where the natural resonant frequency of the network assumes two values during one switching sequence. This action is not restricted to resonant converters. In a switchmode converter the sequence $n=1, n'=0$ is possible. Some quasi-resonant converters operate with $n=2$ and $n'=1$. The class E converter has $n=3$ and $n'=2$.

The following interconnection rules will be observed

- 1) Cut sets of inductors and/or current sources are not allowed.

2) Loops of capacitors and/or voltage sources are not allowed.

An $n=0$ example is given in figure 8. This is nothing more than the common boost converter. If we had chosen to use a voltage source and a current load the buck converter would have appeared. For $n=0$, I-N-I and V-N-V combinations are not allowed by the above

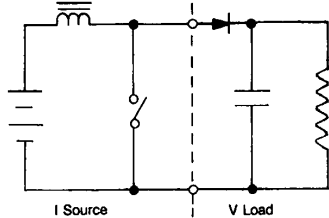


Figure 8, Boost converter shown as an $n=0$, I-N-V topology.

rules so that only two families of topologies appear: boost and buck derived [4].

For $n=1$, there are six circuit combinations as shown in figure 9.

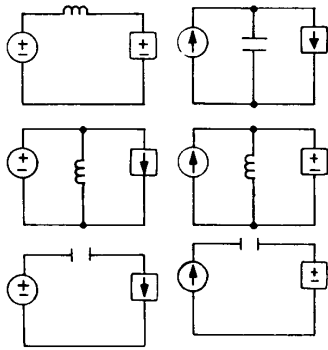


Figure 9, Load, source and network combinations for $n=1$.

I-N-I combinations have the interesting property that the input and output currents are nonpulsating. This class of circuit requires $n>0$. The Cuk converter is an $n=1$, halfwave example (see figure 10). The buck-boost converter would be another $n=1$, halfwave example.

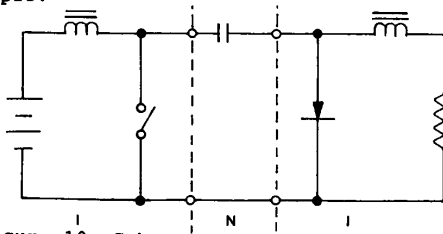


Figure 10, Cuk converter shown as an $n=1$, I-N-I topology.

A large number of fullwave $n=1$, I-N-I circuits are possible, one example is given in figure 11. In the following sections examples of $n=2$ and $n=3$ I-N-I circuits will be given. It is clear that the Cuk converter is only one member of a much larger class of converters that display non-pulsating input and output currents.

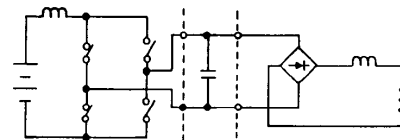


Figure 11, Fullwave, $n=1$, I-N-I example.

Networks ($n>0$) that incorporate a series capacitor or a shunt inductor allow an AC only transformer to be easily inserted as shown in figure 12, even if they are only halfwave in nature. It has been previously presumed that only the Buck-boost and Cuk converters were suitable but the principle can be applied in any converter meeting the requirement.

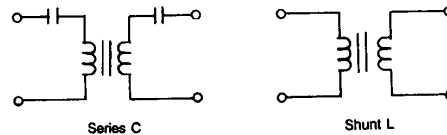


Figure 12, AC transformer insertion.

IV. $n=2$ topologies

Networks made up of two reactive elements may have two inductors, two capacitors or one capacitor and one inductor. Because the focus of this discussion is resonant topologies we will restrict the circuits to those networks with 1 L and 1 C. Before looking at the possible topologies it is necessary to define what is meant by a "resonant converter". Referring to figure 2, we can define resonant converters as those circuits in which the response of N (either the voltage or current) to the sources and loads takes the form of piecewise sinusoids. This assumption implies that N acts like a filter so that the input to output power transfer occurs primarily at the fundamental switching frequency with only small contributions from the harmonics. This allows an important simplification: the sinewave approximation. The load can be approximated by a resistor (see figure 4) and the source by a sinusoidal generator. The analysis is then totally linear and therefor greatly simplified.

Figure 13 shows the eight possible combinations of 1 L and 1 C for N . Applying

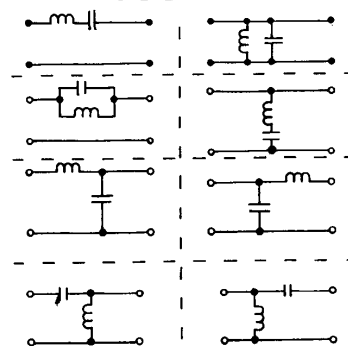


Figure 13, Network topologies for $n=2$ using 1L and 1C.

the combinational rules and the above definition for resonant converters, the four topologies shown in figure 14 appear.

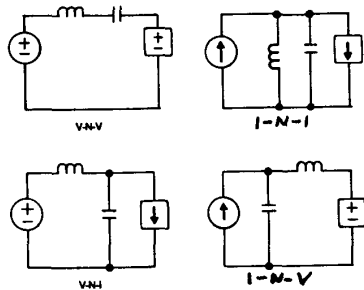


Figure 14, 2 element resonant converter topologies.

At least three of the four resonant topologies have appeared in the literature and are in present use. The V-N-V topology is the series resonant converter. The V-N-I topology is usually called the parallel resonant converter. The I-N-I topology is also a parallel resonant converter. The I-N-V topology is possibly a new one. This author at least has not seen it in the literature although it may well be there.

Eight other usable converters generated by this process which do not fit the resonant definition are shown in figure 15.

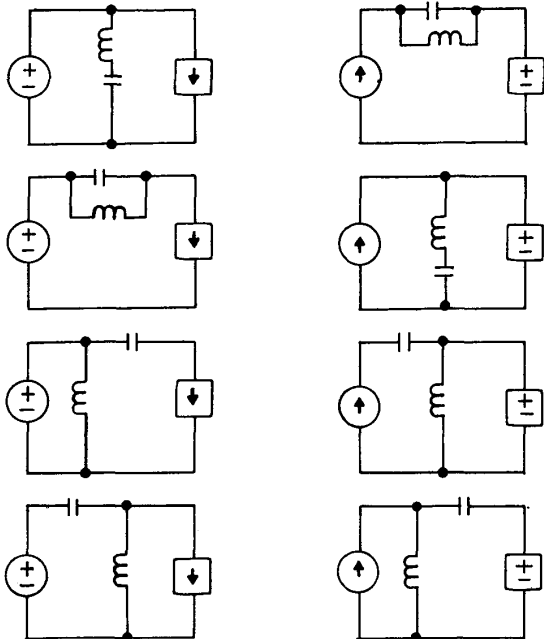


Figure 15, Non-resonant 2 element converter topologies.

One or two of the eight nonresonant topologies have been used for commutation in thyristor converters. The others appear to be new and some may be useful. There is a nomenclature problem here. In these eight circuits the power transfer includes the harmonics so they do not fit the above stated definition of "resonant". There are however sinusoidal currents flowing which in some cases have been used for commutation. Calling them "non-resonant" is deceptive. Perhaps "pseudo-resonant" would be better. This is a question that needs to be resolved.

V. $n=3$ topologies

This procedure can be repeated for $n=3$ and higher order networks. A complete discussion of the possibilities is not possible due to the limited length of this paper but a few points can be made. A full discussion of $n=3$ topologies will be presented in a future paper.

The three element family of topologies are of particular interest because some members of the family display properties that are intermediate between the 2 element series (V-N-V) and parallel (V-N-I) converters. The degree to which a particular converter mimics one or the other can be controlled by the ratio of the third reactive element to the original elements. This can be used for example to create a converter that has the general behavior of a series resonant circuit but which is load independent and which can easily be operated open circuit.

Both the series and parallel converters have serious drawback that prevent their use in many applications. $N=3,4,\dots$ topologies offer the possibility of eliminating the drawbacks while retaining the advantages.

Using this procedure 40 or more usable topologies appear. Of these at least 15 are resonant and 9 are I-N-I in character. Figure 16 shows typical examples. Of the many possible topologies only a few [5,6,7] have previously appeared in the literature.

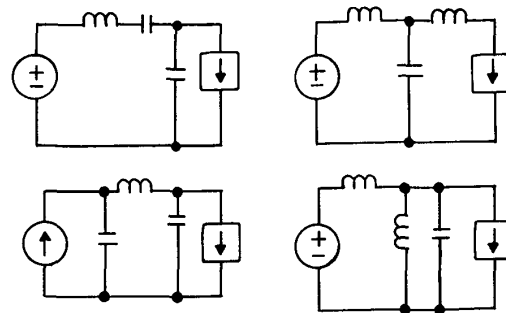


Figure 16, Typical 3 element converter topologies.

VI. Quasi-resonant circuits

This discussion has emphasized resonant converters but the process is equally applicable to quasi-resonant topologies. Figure 17 gives an example using a halfwave-current/fullwave-voltage switch in the source and a halfwave-voltage/current switch (diode) in the load combined with a two element network. The result is the halfwave, zero-current-switching, quasi-resonant converter. A fullwave current/halfwave voltage switch can be used in the source along with a three element resonator to produce the class E converter [8] as shown in figure 18. Both of these families of circuits can be generalized by selecting different types of switches and combining them with $n=2,3,4,\dots$ networks.

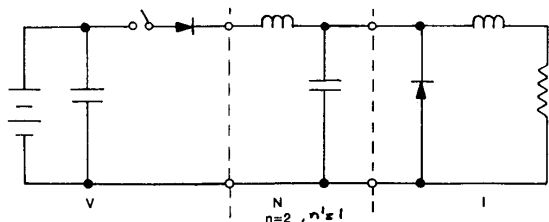


Figure 17, Halfwave, quasi-resonant, zero current switching converter shown as a 2 element V-N-I topology.

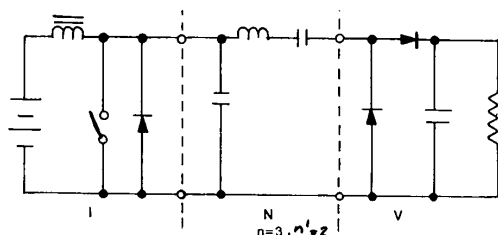


Figure 18, Class E converter shown as a 3 element I-N-V topology.

VII. Loose ends

Only a few of the issues raised by this proposed model have been addressed in this paper. Among the issues that should be addressed in the future are:

1) The sources need to be generalized. The work of Wood [9] and Tymersky and Vorperian [10] would seem to be applicable. An extension of this work to other types of switching cells would be very helpful.

2) In converters such as the boost, buck-boost and Cuk there is a right halfplane zero due to the switching action when PWM control is used. Is it a general rule that a PWM modulated current source inherently introduces a nonminimum phase transfer function into the control loop regardless of the form of N ? If this is true then the right halfplane zero becomes a property of the source and it would be no surprise when it appears with certain types of sources.

3) The work by Maksimovic [11] should be generalized to include any converter, including the resonant circuits. From the model it would appear that the differences between converter classes are a matter of degree not fundamental. The powerful, systematic topology search introduced by Maksimovic should be generally applicable.

4) A general investigation of 3 and 4 element converters, seeking in particular those circuits with useful and unusual properties has yet to be done.

VIII. Conclusion

A procedure has been introduced that allows the synthesis of a wide variety of resonant, quasi-resonant and nonresonant or switchmode converters. It is not claimed that this procedure by itself generates all possible circuits but in combination with rigorous topological procedures it may very well do so. At the least it is a very handy way to generate new multielement resonant topologies. The procedure is not limited to DC-DC converters. It appears to be generally applicable to all switching power converters whether AC-AC, AC-DC, DC-AC or DC-DC. It will also accommodate multiple input and output ports, polyphase or single phase operation and the incorporation of transformers with relative ease. Symmetry and topological rotation procedures [12,13] also appear to be compatible.

Bibliography

- [1] Sequier, "Power electronic converters-AC/DC conversion", McGraw-Hill inc, 1986
- [2] Steigerwald, R., "A comparison of half bridge resonant converter topologies", IEEE PESC conference record, 1987
- [3] Tabisz and Lee, "Zero Voltage switching multi-resonant technique-a novel approach", IEEE PESC conf. record, April 1988, pgs 9-17
- [4] Bloom and Severns, "Modern DC-DC switchmode power converter circuits", Van Nostrand - Reinhold, 1985
- [5] Chen and Bonert, "Load independent AC/DC power supply for higher frequencies with sine-wave output", IEEE IAS transactions, Vol IA-19, No. 2, Mar/Apr 1983, Pgs 223-227
- [6] Seidel, "A high power factor tuned class D converter", IEEE PESC conference record, April 1988
- [7] Liu, Batarseh and Lee, "The LLC-type and class E resonant converters", High Frequency Power Conversion conference record, May 1989
- [8] Redl, Mohnar and Sokal, "Class E resonant regulated DC/DC power converter", IEEE PESC conference record, 1983
- [9] Wood, P., "Switching power converters", Robert Krieger Publishing, 1984
- [10] Tymersky et al, "nonlinear modeling of the PWM switch", IEEE PESC conference record, 1988
- [11] Maksimovic, "Synthesis of PWM and quasi-resonant DC-to-DC power converters", California Institute of Technology, Department of Electrical Engineering, Ph.D. thesis, January 1989
- [12] Erickson, "Synthesis of switched-mode converters", IEEE PESC conf. rec., 1983
- [13] Tymersky and Vorperian, "Generation, classification and analysis of switched-mode DC-DC converters by the use of converter cells", International Telecommunications Energy conference record, October 1986, pgs 181-195