AVERAGE MODELING AND SIMULATION OF SERIES-PARALLEL RESONANT CONVERTERS BY PSPICE COMPATIBLE BEHAVIORAL DEPENDENT SOURCES

abstract

A new methodology for developing average models of resonant converters is presented and verified against cycle by cycle simulation, showing excellent agreement. The proposed modeling approach applies the concept of $R_{ac}(t)$ which represent the instantenous effective load of the resonant network. The model can be used as is to run steady state (DC), large signal (transient) and small signal (AC) simulations.

Indexing terms

- modeling
- Simulation
- Resonant converters

Introduction

A prerequisite for a solid engineering design of resonant converters [1-3] is a good model that describes their operation in the time as well as in the frequency domain. Two basic approaches have been used hitherto, to develop such models. One approach applies analytical relationships to derive the expressions that describe the behavior of a given converter in the various domains [4]. A second approach developed by Steigerwald [5] uses the first harmonics approximation and the R_{ac} concept. By this, the converter is described as a simple resonant network with a load dependent damping (or quality) factor which can then be examined by basic (steady state) network equations. The limitation of the second approach is the difficultly of applying it to more than just the steady state (DC) voltage ratio relationships. In this study we overcome this deficiency of the R_{ac} approach by extending the behavioral modeling methodology [6] to resonant converters. The advantage of the average models derived by the proposed high level presentation, is their ability to emulate the DC, large signal and small signal responses of the corresponding switch mode or resonant system. Once derived, the models can be run as-is on practically any modern circuit simulation package to obtain open or closed loops responses in the time and/or frequency domain. The fundamental ideas of the proposed approach are exemplified by developing the behavioral model of a series-parallel resonant converter and verifying the validity of the model against cycle by cycle simulation.

Model Derivation

Following Steigerwald [5], the basic operation of a resonant converter, such as a series-parallel converter (Fig. 1), can be represented by a damped resonant network (Fig. 2). In this representation the virtual AC resistor (R_{ac}) expresses the effect of the dissipative nature of the load (R_{out}, Figs. 1, 2) on the resonant circuit. In general the value of (R_{ac}), is time dependent. Yet, the average 'load' seen by the resonant network at any given moment is resistive. This stems from the fact that the current through L_{out} (Figs. 1, 2) can be considered constant over one switching cycle and the fact that the current drawn by the output section is always in phase with the voltage across C_p (Figs. 1,2) [5]. Consequently, R_{ac} can be considered as a time dependent resistor. The value of $R_{ac}(t)$ at any given time can be derived dynamically by dividing the average of the absolute value of the voltage across C_p ($\overline{|V_{cp}(t)|}$) by the average current of L_{out} ($\overline{I_{L_{out}}(t)}$) (Fig. 2). Namely:

$$R_{ac}(t) = \frac{\pi^2}{8}\frac{\overline{|V_{cp}(t)|}}{\overline{I_{L_{out}}(t)}} \tag{1}$$

A basic assumption of the present modeling approach is that quasi steady state conditions prevail during any given switching cycle. That is, we assume that rate of change of the disturbances is sufficiently low such that steady state solutions of the resonant network equations are a good approximation of the instant input to output relationships. Under this assumption, the average voltage across C_p can be obtained by simple steady state transfer function e.g.:

$$\overline{|V_{cp}(t)|} = V_{dc}\frac{8}{\pi^2}|H(j\omega)| \tag{2}$$

where:

$$|H(j\omega)| = \frac{\omega C_s R_{ac}(t)}{\left[\left(1-\omega^2 L_r C_s\right)^2+\left(\omega R_{ac}(t)\left(C_s+C_p-\omega^2 C_s C_p L_r\right)\right)^2\right]^{\frac{1}{2}}} \tag{3}$$

and V_{dc} is the DC input voltage.

Equations (2) and (3) can now be solved for $\overline{|V_{cp}(t)|}$ and $R_{ac}(t)$ assuming that all other variables are known. In the present approach, the chores of deriving the solution are left to circuit simulators such as PSPICE [7] that have a build-in capabilities to handle behavioral dependent sources. To accomplish this, we first transform the problem to an equivalent circuit representation . In this portrayal, all time dependent variables are coded into voltages or currents (Table 1). Next, we present the relevant equations by dependent sources that are a function of the coded variables and constants. Finally we add the excitation and the output section to complete the picture. The final result for the series-parallel converter is the equivalent circuit of Fig. 3. It should be pointed out that the average model of Fig. 3 is transparent to the switching frequency. Namely, at steady state, all the voltages and current in the model (Fig. 3) are DC. During a transient state, the voltages and currents are time dependent. For a constant switching frequency, the excitation Vf (Fig. 3) is a DC voltage source. For FM modulated switching frequency, Vf will comprise a DC component plus an AC component that represents the frequency deviation. In transient analysis Vf is time dependent.

Results and discussion:

The proposed model methodology was verified by comparing the model behavior against a full, cycle by cycle, PSPICE simulation.

The parameters of the resonant converter studied were as follows (Fig. 1):

V_{dc} = 100V

L_r = 78μH C_s = 43nF C_p = 43nF

L_{out} = 1mH C_{out} = 1μF R_{out} = 120Ω

The comparison was made for steady state (DC), large signal (transient) and small signal analyses (AC). The agreement between the model behavior and the cycle by cycle simulation (Figs. 4, 5) was found to be excellent. The main advantages of the model are the ease of its derivation and the fact that the basic average and high level model is directly applicable to DC, transient and small signal analysis. The derivation of the model is carried out for large signal, leaving the task of linearization to the simulator. Following the same reasoning, similar models can be developed for other resonant topologies.

S. BEN-YAAKOV

G. RAHAV

Department of Electrical and Computer Engineering

Ben Gurion University of the Negev

PO Box 653 Beer-Sheva, Israel.

References

1 STEIGERWALD, R. L.: 'High-Frequency Resonant Transistor DC-DC Converters', *IEEE Transaction on Industrial Electronics*, Vol. IE-31, No. 2, pp. 182-90, May 1984.

2 SCHUTTEN, M. J., and STEIGERWALD, R. L.: 'Characteristics of Load Resonant Converters Operated in High-Power Factor Mode', *IEEE Transaction on Power Electronics*, Vol. 7, No. 2, pp. 304-14, April 1992.

3 POLLAND, B.C., and NELMS, R. M.: 'Using The Series Parallel Resonant Converter in Capacitor charging applications', *APEC-92*, pp. 731-37.

4 VORPERIAN, V.: 'Approximate Small-Signal Analysis of the Series and the Parallel Resonant Converters', *IEEE Transaction on Power Electronics*, Vol. 4, No. 1, pp. 15-24, January 1989.

5 STEIGERWALD, R. L.: 'A Comparison of Half-Bridge Resonant Converter Topologies', *IEEE Transaction on Power Electronics*, Vol. 3, No. 2, pp. 174-82, April 1988.

6 BEN-YAAKOV, S.: 'Average Simulation of PWM Converters By Direct Implementation of Behavioural Relationships', *Int. J. Electronics*, Vol. 77, No. 5, pp. 731-46, 1994.

7 PSPICE: Micro Sim Co., Irvine, California.

Variable	Reference Figure	Coded	Model Notation (Fig. 3)
$R_{ac}(t)$ [Ω]	2	Yes	v(Rac) [Volt]
$\overline{\lvert V_{cp}(t) \rvert}$ [Volt]	2,3	No	v(cp) [Volt]
$\overline{I_{L_{out}}(t)}$ [Amp]	2	No	-i(Ecp) [Amp]
V_{dc} [Volt]	1	No	v(in) [Volt]
f [Hz]		Yes	v(f) [Volt]
ω [1/Sec]		Yes	v(w) [Volt]

Table 1 Time dependent variables representation.

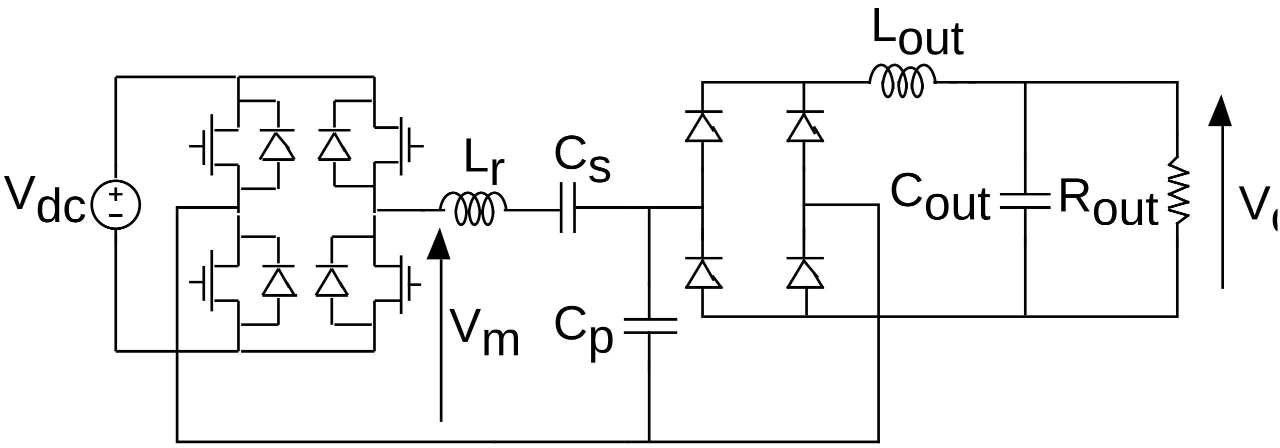

Fig. 1 Basis configuration of the series-parallel resonant converter topology.

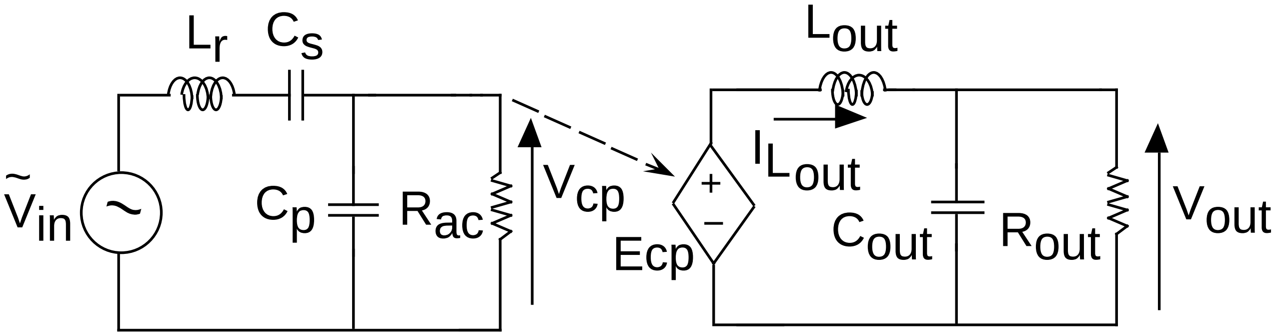

Fig. 2 First-harmonic approximation of the series-parallel resonant converter.

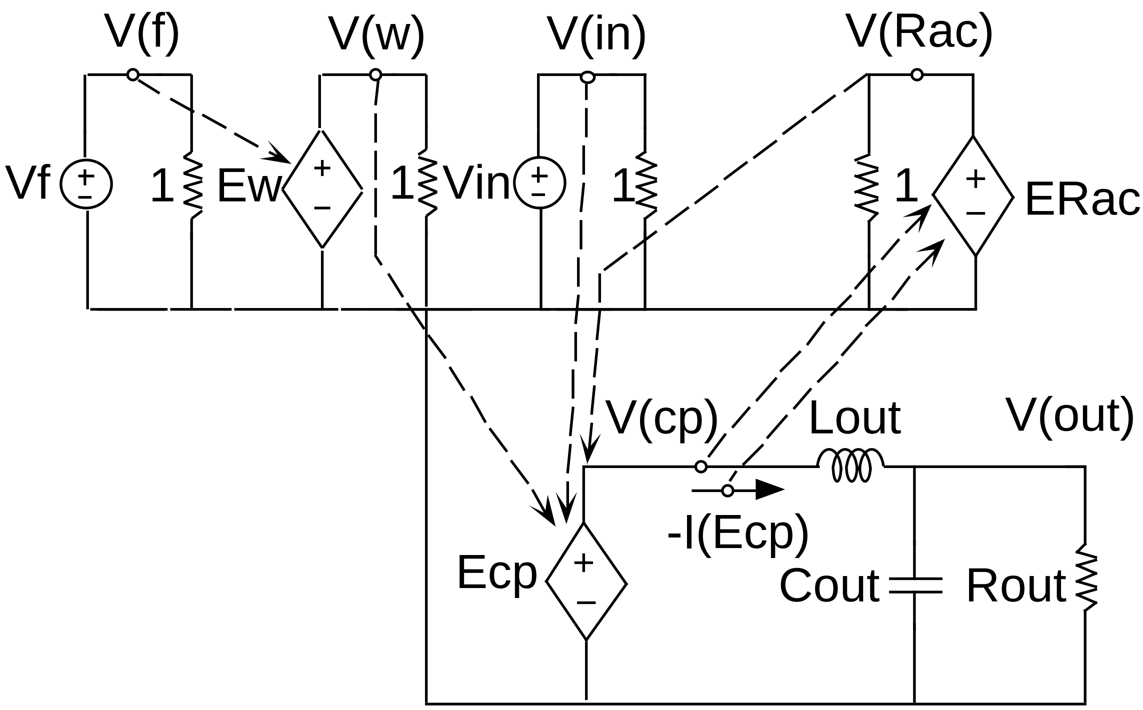

Fig. 3 Average model of the series-parallel resonant converter by applying PSPICE behavioral dependent sources.

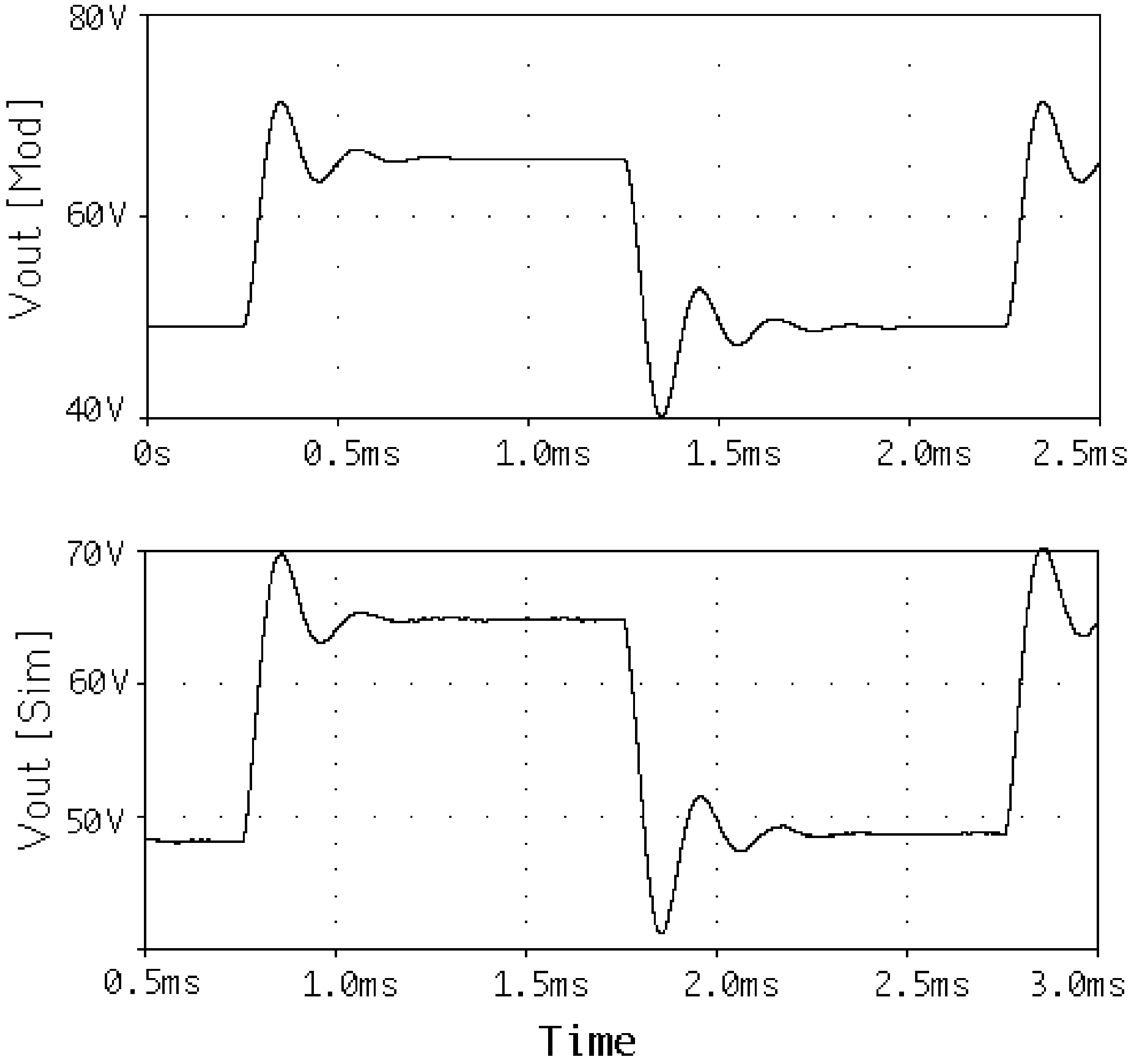

Fig. 4. Comparisons between Vout response to a step in frequency, Upper trace, model simulation (Mod); Lower trace, cycle by cycle simulation (Sim).

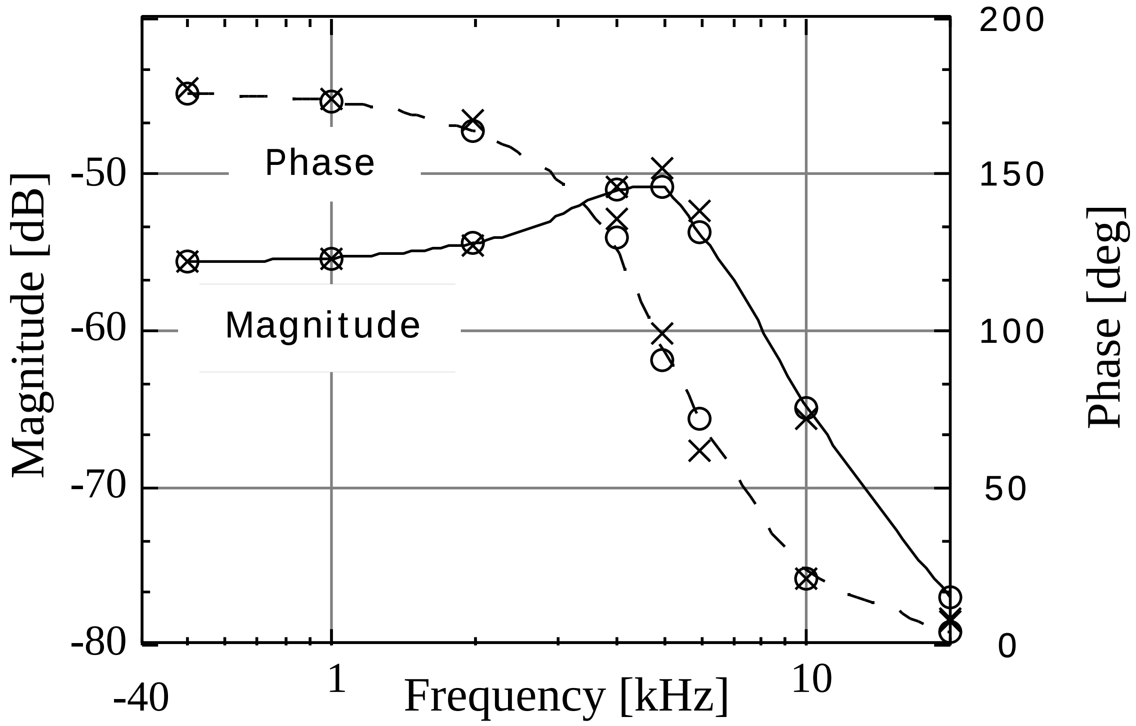

Fig. 5 Comparisons between small signal, frequency to output response in the model simulation (Mod) and the cycle by cycle simulation (Sim).

Table 1 Time dependent variables representation.

Fig. 1 Basis configuration of the series-parallel resonant converter topology.

Fig. 2 First-harmonic approximation of the series-parallel resonant converter.

Fig. 3 Average model of the series-parallel resonant converter by applying PSPICE behavioral dependent sources.

Fig. 4. Comparisons between Vout response to a step in frequency, Upper trace, model simulation (Mod); Lower trace, cycle by cycle simulation (Sim).

Fig. 5 Comparisons between small signal, frequency to output response in the model simulation (Mod) and the cycle by cycle simulation (Sim).