

A parallel resonant constant current power supply

MANGESH BORAGE*, SUNIL TIWARI AND SWARNA KOTAIAH

Power Supplies Division, Centre for Advanced Technology, Indore 452 013, India.
email: mbb@cat.ernet.in; Phone: +91-731-2488024; Fax: +91-731-2488000.

Received on October 20, 2003; Revised on December 10, 2003.

Abstract

In the past, resonant converters have generally been analyzed and characterized for constant output voltage power supplies. When applied to power supplies, in which output current is regulated, the topological requirements of a resonant converter differ. This means, a resonant converter topology not suitable for constant voltage power supplies may become attractive for constant current power supplies. This fact is illustrated here. The operation of a parallel resonant converter (PRC) as a constant current power supply is presented. A PRC operating at resonant frequency gives constant output current. If designed properly, the output current can become nearly independent of load over a wide range of switching frequency. Repeated simulations and laboratory experiments on prototype converter verify the analysis.

Keywords: Power supply, resonant converter, DC-DC converter, CC power supply.

1. Introduction

Resonant converters offer low switching losses due to zero voltage switching (ZVS) and/or zero current switching (ZCS) making them popular for high-frequency applications such as DC and AC power supplies, power factor correction and discharge lamp ballast. Many simple and higher-order resonant converters have been explored and studied in the literature [1–3]. The emphasis, however, has mostly been on the analysis, design and optimization of resonant converters for constant output voltage power supplies. The efforts were focused on a topology that would give load-independent output voltage, no load regulation, better part-load efficiency and less circulating currents. This results in circuits, such as LCL resonant converter [3, 4], which are suitable for a constant voltage (CV) power supply.

A constant current (CC) power supply is required in many applications such as electromagnets, industrial heaters, capacitor charging and welding. Although resonant converters for CV power supply have been analyzed in detail, the generalized analysis of characteristics of resonant converters for a CC power supply is not explored in the literature. Topological requirements of a resonant converter for a CC power supply are different from those of a CV power supply. Output current, not the output voltage, is now the control variable. For a CC power supply, the DC gain or the control characteristic is the relationship between output current and switching frequency. Thus, for a topology to be attractive for CC power supply, the output current should be independent of load. This would mean that some reso-

*Author for correspondence.

nant converter topologies which do not exhibit load-independent output voltage and are therefore not considered beneficial for a CV power supply may become suitable for a CC power supply if they exhibit load-independent output current. This fact is signified in this paper with a parallel resonant converter (PRC) as an illustration. A PRC is basic two-element resonant converter topology used with inductive output filter. Analysis of PRC for voltage regulator type of applications is presented in Swami and Bhat [5]. Apart from its other limitations, the output voltage is highly dependent on load resistance due to which a wide variation in switching frequency is required for output voltage regulation. Therefore, it is not considered an attractive topology for a CV power supply; instead, a series-parallel resonant converter is proposed [6].

We show in this paper that the PRC behaves as a current source under certain operating conditions. Output current is constant, independent of variation in load resistance. Thus, PRC can be used advantageously in a CC power supply. Analysis of PRC for application as CC power supply is presented and performance of converter as CC power supply is discussed. A prototype PRC was built and tested to experimentally verify its suitability as a CC power supply.

2. Conventional constant current power supplies

Traditionally, a passive way of realizing practical current source is to place a large inductance in series with the load. The obvious drawback of this method is large size, weight and cost associated with the choke.

A bipolar junction transistor (BJT) or a metal oxide semiconductor field effect transistor (MOSFET) operating in active region behaves as a constant current source. In this operating region, collector current of BJT is proportional to its base current and the drain current of a MOSFET is proportional to the gate-to-source voltage. A large power dissipation across the regulating transistor is a serious limitation of this technique which worsens the conversion efficiency particularly under part-load conditions or for low voltage-high current applications.

The series resonant converter (SRC) operating in discontinuous conduction mode (DCM) with switching frequency, which is less than one half of the resonant frequency, behaves as the constant current source [7]. High peak current stresses and associated increase in the conduction loss is a major limitation of these techniques. Also a large output filter capacitor is required due to lower switching frequency of operation.

3. PRC as a constant current source

A full-bridge PRC circuit is shown in Fig. 1. Inductor L and capacitor C form the parallel resonant circuit. A MOSFET bridge inverter excites the resonant circuit with a square wave voltage. Voltage across C is rectified and filtered using an LC filter to get the required DC output voltage. The subsequent analysis of PRC uses AC analysis method in which output rectifier and filter are replaced by the equivalent AC resistance and the squarewave input voltage source is replaced by its fundamental sinusoidal equivalent [6]. The AC equivalent circuit of PRC is shown in Fig. 2. In the subsequent analysis, turns ratio of isolation transformer is assumed to be unity without losing generality.

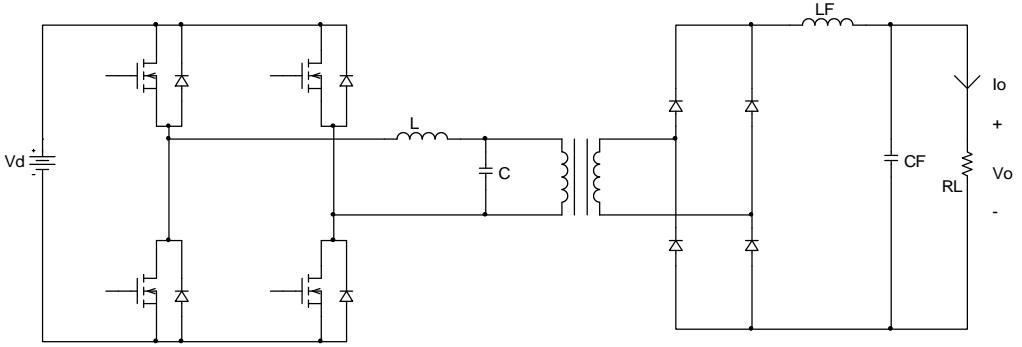


FIG. 1. Circuit diagram of a full-bridge parallel resonant converter. In the analysis, the turns ratio of isolation transformer is assumed to be unity without losing generality.

The equivalent AC resistance, RMS value input source and resonant frequency of resonant network are given, respectively, by

$$R_{ac} = \frac{p^2}{8} R_L, \quad V_s = \frac{2\sqrt{2}}{p} V_d \quad \text{and} \quad \omega_o = \frac{1}{\sqrt{LC}}, \quad (1)$$

where V_d is the input DC voltage, and R_L , the load resistance. $\omega = 2pF$, where F is the switching frequency. Next, normalized switching frequency, circuit Q and characteristic impedance (Z_n) are defined as,

$$\omega_n = \frac{\omega}{\omega_o}, \quad Q = \frac{R_L}{\omega_o L} \quad \text{and} \quad Z_n = \sqrt{\frac{L}{C}}. \quad (2)$$

The voltage and current gains of the converter are defined as,

$$M = \frac{V_o}{V_d} \quad \text{and} \quad H = \frac{I_o}{\left(\frac{V_d}{Z_n}\right)} = \frac{M}{Q}, \quad (3)$$

where V_o is the output voltage and I_o , the output current of the converter. The voltage and current gain of PRC can be derived as,

$$M = \frac{8}{p^2} \frac{1}{(1 - \omega_n^2) + j \frac{8}{p^2} \frac{1}{Q} \omega_n}; \quad (4)$$

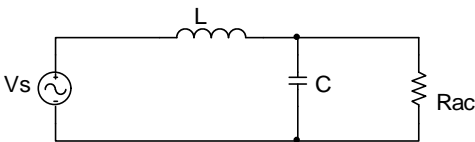


FIG. 2. AC-equivalent circuit of PRC.

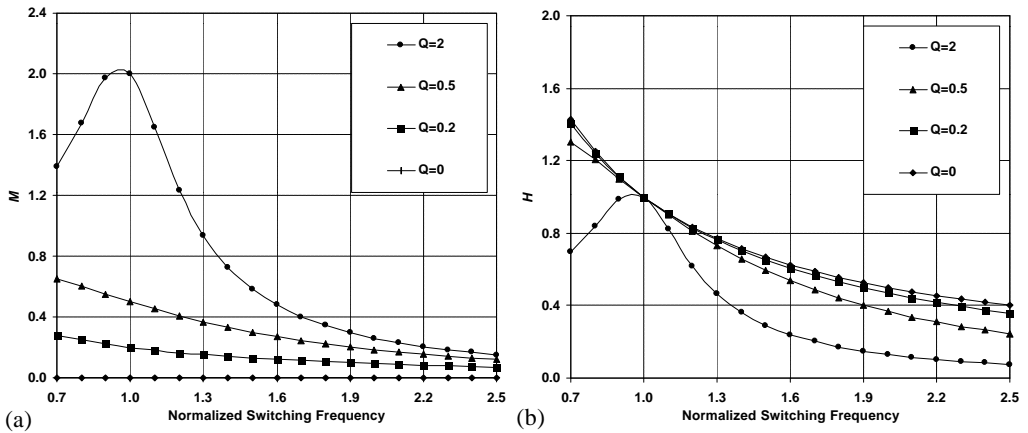


FIG. 3. Control characteristics of PRC. (a) Voltage gain; for application as CV power supply. (b) Current gain; for application as CC power supply.

$$H = \frac{8}{P^2} \frac{1}{Q(1-w_n^2) + j \frac{8}{P^2} w_n}. \quad (5)$$

Equation (5) gives the current gain of a PRC. At $w_n = w_i = 1$, H is independent of load and,

$$H|_{w_n=w_i=1}, \quad \text{and} \quad M|_{w_n=w_i=1} = Q, \quad (6)$$

where w_i is defined as the normalized switching frequency in which the output current is independent of load resistance.

Figure 3 shows the normalized load current and voltage gain as a function of switching frequency for different values of Q . The following observations can be made:

1. Figure 3(a) shows the converter control characteristics for application as a CV power supply. This control characteristic is a relationship between the output voltage and switching frequency. Output voltage is a strong function of load resistance over almost entire range of operating frequency. Therefore, a large variation of switching frequency is required to regulate the output voltage against specified input and load changes. This is a limitation of PRC when used as a CV power supply.
2. The control characteristic for application of PRC as a CC power supply is shown in Fig. 3(b), which shows the dependence of output current on switching frequency. The load current is seen to be independent of load resistance when PRC is operated at the switching frequency equal to the resonant frequency, that is, at $w = w_0$. Thus, a PRC behaves as a constant current source.
3. As seen from Fig. 3(b), the control characteristics are closely spaced for lower values of Q . Thus, additionally, the output current is nearly independent of load resistance over a wide range of switching frequency if a low value of circuit Q is chosen.

When a low value of circuit Q is chosen, the resonant network is essentially overdamped presenting inductive input impedance. The current response to input squarewave excitation will thus not be sinusoidal. However, according to the definition of resonant converters [1] the circuit response needs only to be piece-wise sinusoidal. Therefore, the circuit with chosen parameters can still be classified as the resonant converter. Another concern is the need for capacitor C when the resonant network is overdamped. As shown in Fig. 1, the output stage of PRC is a rectifier with LC filter; the latter makes the load seen by the resonant network as a current sink. The waveform of the output current of the resonant network (or the transformer primary) is squarewave. For this type of load, Severns [1] imposes additional constraint on the output impedance of resonant network. For current sources and loads the impedance seen by the source or load harmonics must be low. If an inductor is connected in series with the squarewave current load, large voltage spikes will be generated. Therefore, to absorb the fast current transitions, capacitor C is required for proper functioning of PRC even if the LC resonant circuit is overdamped. While the output current can remain nearly independent of load over wide switching frequency range with suitable choice of Q , there are other factors which govern the choice of Q while designing the converter. The effect of Q on converter performance is described in the next section.

The analysis of PRC for a CV power supply is presented in Swami and Bhat [5]. Subsequently, we examine only the properties of PRC for application as a CC power supply.

At $w = w_0$, phase angle of bridge inverter output current (that is current through L) is,

$$f = \tan^{-1} \left(\frac{p^2}{8} Q \right) - \frac{p}{2}. \tag{7}$$

From eqn (7), it can be seen that for $Q > 0$ the phase is negative which means that the inverter output current lags the voltage. Advantages of operation in this lagging power-factor mode are well known [8].

Normalized RMS voltage and current ratings of inductor L are

$$\frac{V_{L,rms}}{V_d} \Big|_{w_n = w_i = 1} = \frac{I_{L,rms}}{(V_d/Z_n)} \Big|_{w_n = w_i = 1} = \frac{2\sqrt{2}}{p} \sqrt{1 + \left(\frac{p^2}{8} Q \right)^2}. \tag{8}$$

Similarly, normalized voltage and current ratings of capacitor C are given by

$$\frac{V_{C,rms}}{V_d} \Big|_{w_n = w_i = 1} = \frac{I_{C,rms}}{(V_d/Z_n)} \Big|_{w_n = w_i = 1} = \frac{2\sqrt{2}}{p} \frac{p^2}{8} Q. \tag{9}$$

Under no load condition (i.e. when the load terminals are short-circuited), $Q = 0$. From (8), the no-load inductor current (also the inverter output current) is $(2\sqrt{2}/p)$. Ratio of no-load to full-load current can then be expressed as,

$$R = \frac{1}{\sqrt{1 + \left(\frac{p^2}{8} \right)^2 Q^2}}. \tag{10}$$

Resonant inductor is normally the most bulky and heavy component of a resonant network. The physical size of an inductor is indicated by the area product, which is directly proportional to the energy to be handled by the inductor. Normalized inductor energy can be derived as,

$$E_n |_{w_n = w_i = 1} = \frac{\frac{1}{2} L I_{L, \text{rms}}^2}{\frac{V_d^2}{w_o R_L}} = \frac{4}{p^2} \left(Q + \frac{p^4}{64} Q^3 \right). \quad (11)$$

4. Converter performance

To evaluate the performance of a resonant converter the following factors should be studied:

1. The size of resonant inductor should be minimized as it is the bulkiest component of a resonant network. As explained above, normalized stored energy can be used as the index for the size of resonant inductor.
2. In resonant converters, soft-switching in the switches is achieved with the help of additional resonant network which increases size, weight and cost. To keep the additional increase in size to minimum, the (kVA/kW) rating of the resonant network should be minimized [5].
3. Sinusoidal reactive current is drawn from the bridge inverter, increasing conduction losses. A ratio of inverter output current to the load current (or equivalently, current in R_{ac}), $I(L)/I(R_{ac})$, should be minimized to reduce conduction losses.
4. The resonant network preloads the bridge circuit. Therefore, even if the converter is not loaded, a significant circulating current is still drawn from the bridge inverter. The ratio of no-load to full-load inverter output current (R) should be low.

Figure 4 shows the variation of the above listed parameters as a function of Q at $w_n = w_i = 1$, i.e. for operation of PRC as a CC power supply. The following observations can be made:

1. The normalized inductor energy increases rapidly with increase in Q . Therefore, for converter design with high Q , the inductor size will be more.
2. The (kVA/kW) rating of resonant network first decreases with increase in Q , reaches a minimum value at $Q = 0.57$ and then again increases with further increase in Q . The value of Q for which the (kVA/kW) rating of resonant network is minimum is defined as the optimum value, Q_{opt} . Thus, $Q_{opt} = 0.57$.
3. The ratio $I(L)/I(R_{ac})$ is also seen to be monotonically increasing with increasing Q . A high Q design will thus have lower efficiency due to increased conduction losses.
4. The ratio R is seen to decrease with increase in Q meaning that a converter design with low Q will suffer from poor part load efficiency.

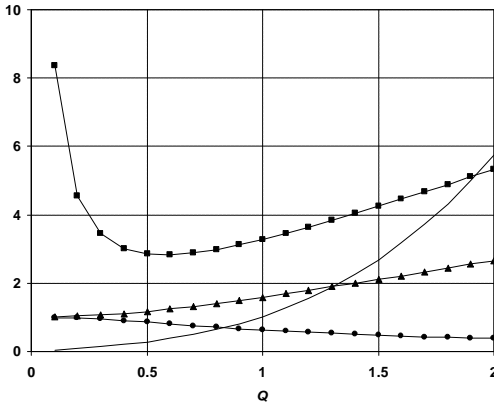


FIG. 4. Performance curves. Variation of key parameters as a function of Q for operation at $w_n = w_i = 1$. —: E_n , —■—: (kVA/kW), —▲—: $I(L)/I(R_{ac})$, —●—: R .

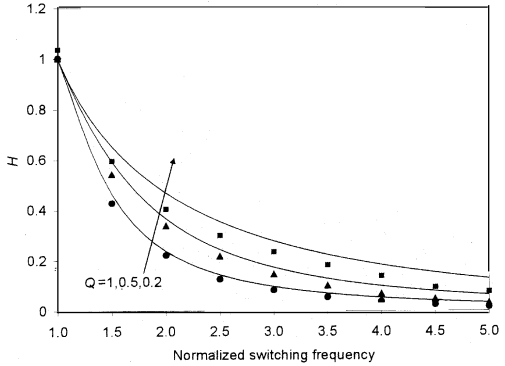


FIG. 5. Current gain of PRC: Comparison of results of AC analysis with the results of simulation. Curves shown with continuous line represent the results of AC analysis and the solid markers show the result obtained from simulations.

A design of resonant network for $Q < 0.57$ thus results in smaller size of resonant inductor and better full-load efficiency. Such a design however results in overall high installed (kVA/kW) rating and poor part-load efficiency. Recall from the plots of current gain (H) as shown in Fig. 3(b) that the load current, besides being load independent at $w = w_0$, is also not greatly affected by load resistance over a wide range of operating frequency if full-load Q is low. However, this can be achieved at the cost of relatively bigger resonant network.

5. Converter control

Although the output current of PRC-CC is seen to be constant irrespective of changes in the load, for practical application of a current-source power supply, it should be able to regulate the output current against specified line changes. Also, in some applications it should be possible to set and regulate the output current over wide range. The output of resonant converter is normally controlled by varying switching frequency. The other methods of regulation are clamped mode control and integral cycle control.

The variation of switching frequency complicates the design of magnetic components and EMI filters. Nevertheless, as shown in the previous section, the output current of PRC is nearly independent of load over a wide range of switching frequency if low Q is chosen. Therefore, it is possible to retain the current source behaviour of resonant converter even with switching frequency variation used for output control. Even though clamped mode control uses fixed frequency phase shift PWM for control, it suffers from loss of ZVS transitions under some operating conditions. Thus, if clamped mode control is to be used, an additional constraint over the choice of Q is imposed. The critical value of Q to ensure ZVS operation of all switches is derived in Gonzalez *et al.* [9]. At times, this constraint may contradict the choice of Q governed by other performance parameters described above. In the integral cycle control [10], output variation is possible only in discrete steps. Each method of control thus has pros and cons; the choice of control methodology is therefore governed by the demands of the particular application.

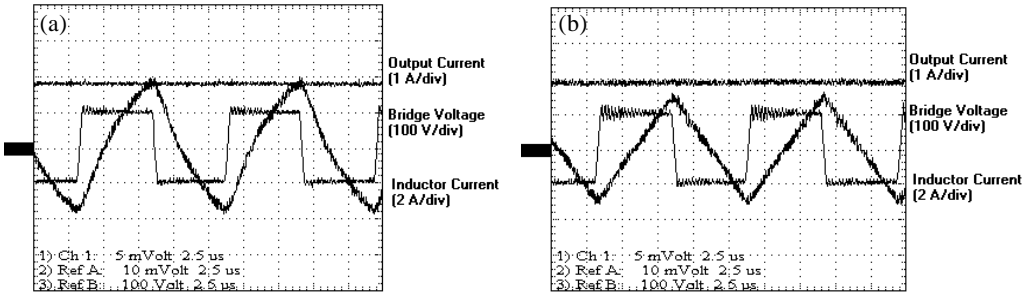


FIG. 6. Experimental results. The waveforms of bridge output voltage, resonant inductor current and output load current (a) at full load and (b) under load short-circuit condition. (X-scale: 2.5 ns/div).

6. Simulation and experimental verification

Individual transient or time-domain simulations were performed with PSpice for a large number of combinations of normalized operation frequency and circuit Q . Steady-state results were noted to derive the DC current gain of PRC. Figure 5 shows the comparison of results of PSpice simulations with the results obtained with AC analysis. The simulation results match with analysis results with reasonable closeness. The AC analysis itself is an approximate method since it assumes only the fundamental component of input squarewave excitation; therefore, a slight disagreement is expected.

A laboratory prototype of PRC-CC power supply rated for 100 W, 2 A operating from a DC supply of 110 V and running at 94 kHz was built to validate the results. Parallel resonant network uses 95 μH inductor and 30 nF capacitor giving $Q = 0.44$. Figure 6 shows the bridge voltage, inductor current and load current at full load and under output short-circuit (or no-load) condition. The load current is observed to remain constant at approximately 2 A under these extreme operating conditions.

7. Conclusion

Although analysis of resonant converter has been performed in great detail for voltage regulator type of applications, a study of their suitability for CC power supply is not reported. A resonant converter topology not considered beneficial for a CV power supply may become suitable for a CC power supply if it exhibits load-independent output current. In this paper, PRC is shown to exhibit current source behavior under variable load condition. The load current is independent of load resistance, completely at resonant frequency and partially over a wide range of operating frequency, if circuit is suitably designed with low value of Q . Most importantly, the current source characteristics are exhibited in lagging power factor mode of operation. This makes PRC an attractive topology for a CC power supply with simpler control. Experimental results on a laboratory prototype confirm the application of PRC in CC power supply.

However, like a PRC-CV power supply, the PRC-CC application also suffers from higher circulating currents and poor part-load efficiency. Also, being a second-order resonant converter, a large variation of switching frequency is required if wider conversion range is desired. These drawbacks can be removed using higher-order resonant converters.

References

1. R. P. Severns, Topologies for three-element resonant converters, *IEEE Trans. Power Electron.*, **7**, 89–98 (1992).
2. I. Bataresh, Resonant converter topologies with three and four energy storage elements, *IEEE Trans. Power Electron.*, **9**, 64–73 (1994).
3. M. Borage, S. Tiwari and S. Kotaiah, Comparison of three-element V-N-V resonant converters, *Proc. India Int. Conf. on Power Electronics (IICPE)*, Mumbai, India (2002).
4. A. Bhat, Analysis and design of LCL-type series resonant converter, *IEEE Trans. Ind. Electron.*, **41**, 118–124 (1994).
5. M. Swami and A. Bhat, Analysis of a parallel resonant converter with secondary side resonance, *IEEE Trans. Aero. Electr. Sys.*, **28**, 1042–1055 (1992).
6. R. Steigerwald, Comparison of half-bridge resonant converter topologies, *IEEE Trans. Power Electron.*, **3**, 174–182 (1988).
7. N. Mohan, T. Undeland and W. Robbins, *Power electronics: Converters, applications and design*, Wiley (1989).
8. R. Steigerwald, High frequency resonant transistor DC–DC converters, *IEEE Trans. Ind. Electron.*, **31**, 181–191 (1984).
9. S. Gonzalez, M. Valla and C. Muravchik, Analysis and design of clamped-mode resonant converters with variable load, *IEEE Trans. Ind. Electron.*, **48**, 812–819 (2001).
10. J. Ko, S. Hong, M. Kim and M. Youn, Modeling and improved current control of series resonant converter with non-periodic integral cycle control, *Proc. IEEE PESC'91*, pp. 745–751 (1991).