Design of an LCC current-output resonant converter for use as a constant current source

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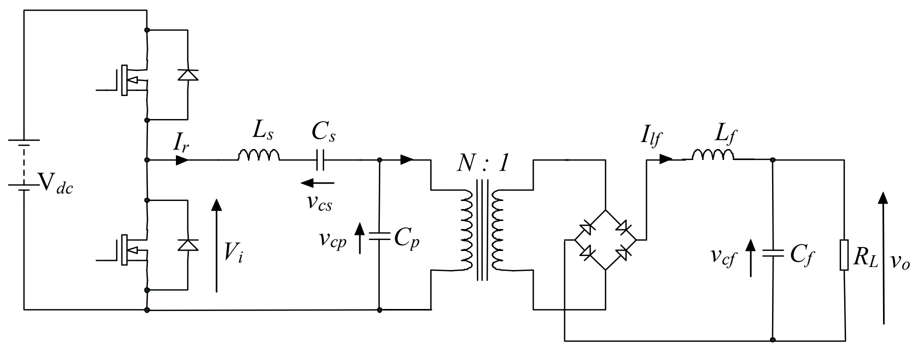
Abstract

A methodology for the design of LCC resonant current-source converters, is presented. Unlike previous techniques, the resulting converter provides near constant steady-state output current over an extended load range when excited at the resonant frequency, through use of a self-oscillating controller.

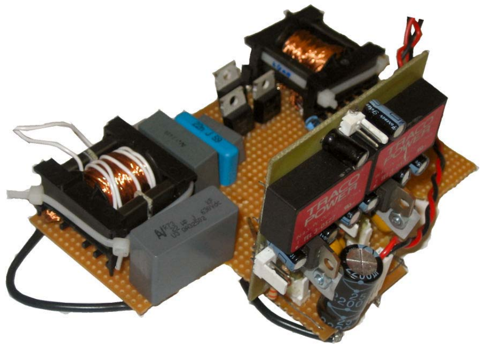
Introduction

It is well established that resonant converters are advantageous in-terms of size and efficiency. This paper first establishes that an LCC current-output converter can be made to perform as a constant current-source at the resonant frequency and then provides a simple design process.

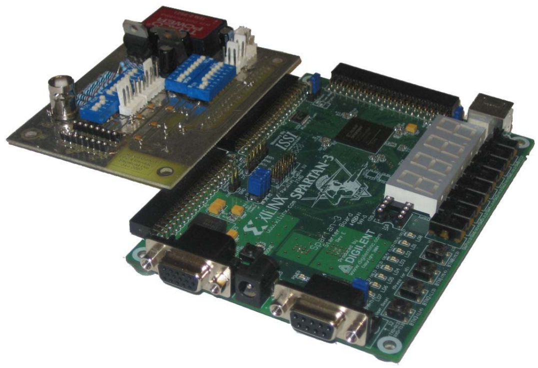
Many of the underlying equations used in the proposed methodology have been previously reported [1-3]. The design process utilises the accuracy of Fundamental Mode Approximation (FMA), at the resonant frequency, and the potential for rapid analysis that it provides. The analysis is based on the LCC current-output resonant converter shown in Figure.1.



(a)



(b)



(c)

Fig. 1: LCC current-output resonant converter (a) schematic (b) prototype converter (c) self-oscillating phase lock controller

Design Methodology

In [3] it is shown that the tank components are related to the tank gain at resonance G_{tr}, the transformer turns ratio N , the resonant switching frequency f_r, the parallel to series capacitor ratio ($A=C_p/C_s$) and load resistance R_L as follows:

$$C_p = \frac{\sqrt{G_{tr}^{\,2}\pi^4 - 16}}{\pi^3 N^2 R_L f_r} \tag{1}$$

$$L_s = \frac{N^2 R_L\left((A+1)G_{tr}^{\,2}\pi^4 - 16\right)}{4\pi^3 f_r G_{tr}^{\,2}\sqrt{G_{tr}^{\,2}\pi^4 - 16}} \tag{2}$$

where $A=C_p/C_s$, G_{tr} is the tank gain at resonance i.e $V_o=V_{in}\,G_{tr}/N$ at resonance, f_r is the resonant frequency and R_L is the load resistance.

It is now shown that as the load resistance is increased, the converter output current tends to a constant value. Solving both (1) and (2) for f_r equating the results and further solving for G_{tr} gives:

$$G_{tr} = \frac{\sqrt{2}}{4\pi^2\sqrt{L_s}}\sqrt{64L_s + N^4 R_L^{\,2} C_p \pi^4 (A+1) + X} \tag{3}$$

where $X = \sqrt{4096L_s^{\,2} + 128L_s N^4 R_L^{\,2} C_p \pi^4 (A-1) + N^8 R_L^{\,4} C_p^{\,2} \pi^8 (A+1)^2}$

Now, for a given output current, the tank gain at resonance can be calculated as follows:

$$I_o = \frac{V_{in} G_{tr}}{R_L N} \tag{4}$$

substituting (3) into (4) gives an expression for the output current as load is varied and the converter switched at resonance.

The output current ideally tends to a constant minimum value as the load resistance is increased and the converter switched at resonance. This can be shown by taking the limit of (4) as $R_L \rightarrow \infty$ (open-circuit) after G_{tr} is eliminated through the use of (3) giving:

$$I_{o\_min} = \frac{V_{in} N \sqrt{C_p} \sqrt{A+1}}{2\sqrt{L_s}} \qquad (5)$$

This is the minimum output current the converter will produce when excited about the resonant frequency. When the load resistance is lowered, the output current will be larger. Given that the maximum current (at minimum load resistance) is K times larger than the minimum current ($I_{o\_max}=K.I_{o\_min}$) allows the required value of A to be calculated. Solving (5) for C_p/L_s then yields:

$$\frac{C_p}{L_s} = \frac{4 I_{o\_min}^{\ 2}}{N^2 (A+1) V_{in}^{\ 2}} \qquad (6)$$

Dividing (1) by (2) , eliminating G_{tr} through the use of (4), replacing I_o with $K.I_{o\_min}$ and R_L with R_{L_min}, equating the result with (6) and finally solving for A gives:

$$A = -\frac{I_{o\_min}^{\ 2} N^2 R_{L\_min}^{\ 2} \pi^4 K^2 \left(K^2 - 1\right) + 16 V_{in}^{\ 2} (1 - K^2)}{K^2 \left(I_{o\_min}^{\ 2} N^2 R_{L\_min}^{\ 2} \pi^4 \left(K^2 - 1\right) - 16 V_{in}^{\ 2}\right)} \qquad (7)$$

It is now possible to generate a constraint on the minimum and maximum allowed values of N for a given design specification. To generate the minimum, the value of A must never be *-ve*, hence, solving for N in (7) at $A=0$ gives:

$$\frac{4 V_{in}}{I_{o\_min} R_{L\_min} K \pi^2} < N \qquad (8)$$

To generate the maximum value, solving (7) for the limit of N as $A \rightarrow \infty$ gives the following constraint:

$$N < \frac{4 V_{in}}{\pi^2 R_{L\_min} I_{o\_min} \sqrt{K^2 - 1}} \qquad (9)$$

Hence, for a given specification, the range of N must first be calculated, the transformer turns ratio N specified, the capacitor ratio A calculated from (7), the G_{tr} calculated at the minimum load by assuming $I_o=K.I_{o\_min}$ and solving (4), and finally computing the required components from (1) and (2). The minimum resonant frequency corresponds to f_r. The peak resonant frequency will correspond to the resonant frequency of the converter with the rectifier disconnected.

The methodology is now applied to the design of a constant current converter. The specifications for the supply are provided in Table 1.

Table 1 – DC-DC Converter Specifications

DC Input Voltage	Current source Range	Output voltage Range
18V	0→1A	10→20V

The theoretical open circuit output current, at resonance, is selected to be 10% larger than the required peak current, thereby ensuring that parasitic effects (such as diode voltage drops) will not reduce the current so as to make the design ineffective and will ensure above-resonance operation at the peak required output current,. Therefore $I_{o\_min}=1.1A$. Now, selecting $K = 1.1$ ensures that at the minimum specified load resistance, the output current at resonance will not exceed 1.21A. Equations (8) and (9) provide a constraint on the range of N. At 1A output, the minimum load resistance is 10Ω, hence 0.60<N<1.45. Selecting an N of 1 for simplicity and reduction in converter cost, gives a G_{tr}=0.672 and from (7) the value of A is therefore found to be 0.582. Assuming a minimum switching resonant frequency of 133kHz, the required tank components from (1) and (2) are C_p=128nF C_s=220nF and L_s=13.6uH.

For the component values selected above, Fig. 2 provides the steady-state output current when switched at resonance, as the load is varied. The data is obtained from a prototype converter, ideal simulation, and design process (see equations (3) & (4)).

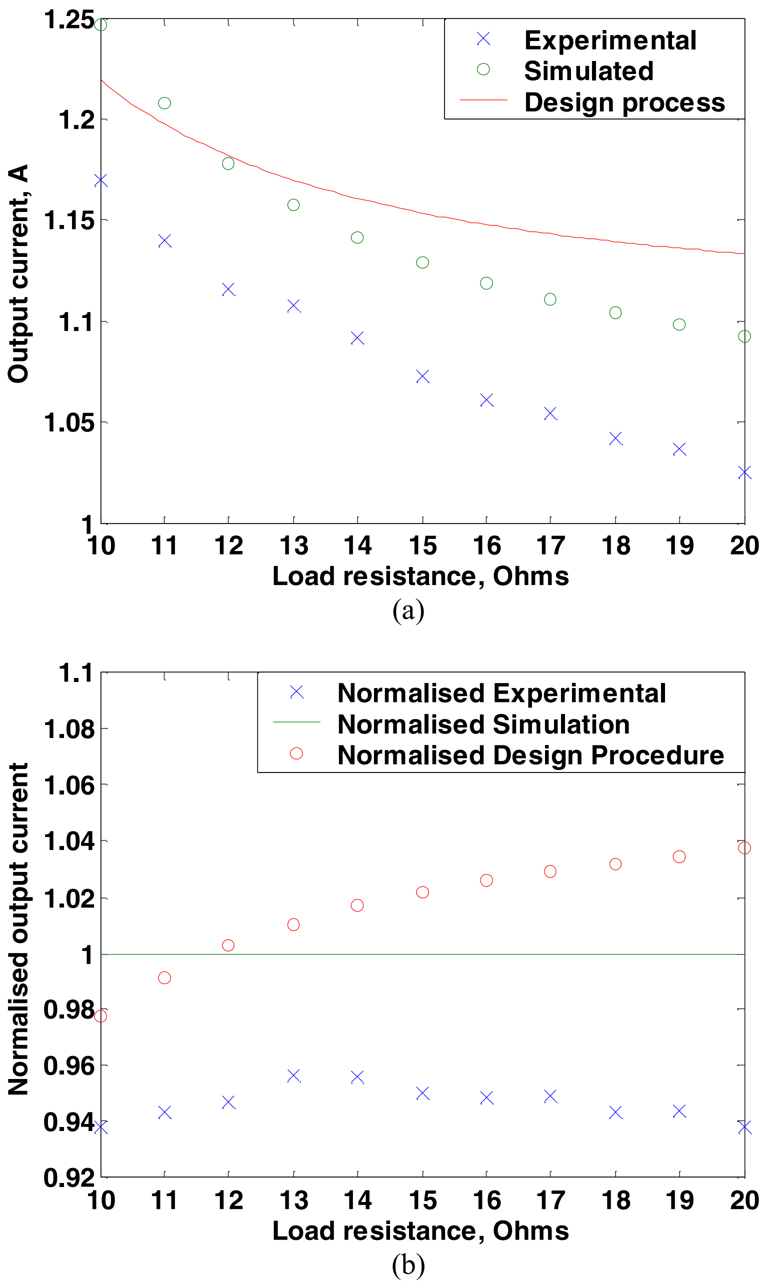


Fig. 2: (a) Output current (b) normalised output current w.r.t ideal converter simulation as load is varied from 5Ω to 10Ω when switched at resonance

From Fig. 2(a) it can be seen that the prototypes' steady-state output current varies little as the load is changed and the converter switched at resonance. Since a series-inductor resistance of 0.15Ω is present in the converter, it is expected that the experimental output-current data will be slightly lower than that of the ideal simulated converter. Note that from an ideal perspective the presence of a forward voltage drop should not reduce the output current below the theoretical open-circuit current since the diodes effectively make the load resistance appear larger, thus forcing the converter to naturally compensate by increasing the resonant tank current. Figure 2(b) provides a measure of error in the proposed analysis. In the presented data, the largest error between the analysis and simulated ideal converter is approximately 4%. The maximum error between experimental output-current and the analysis occurs at the highest output power, and is approximately 10%. This makes the design process ideal for prototype component selection especially when one considers the simplicity of the equations.

A benefit of the proposed design procedure, when a constant load current is desired, is the ability to operate near resonance across the full load range. This maximises the converter efficiency since less reactive power is present in the resonant tank. Figure 3, provides the efficiency of the prototype converter for the load range specified in Table 1, when switched at resonance.

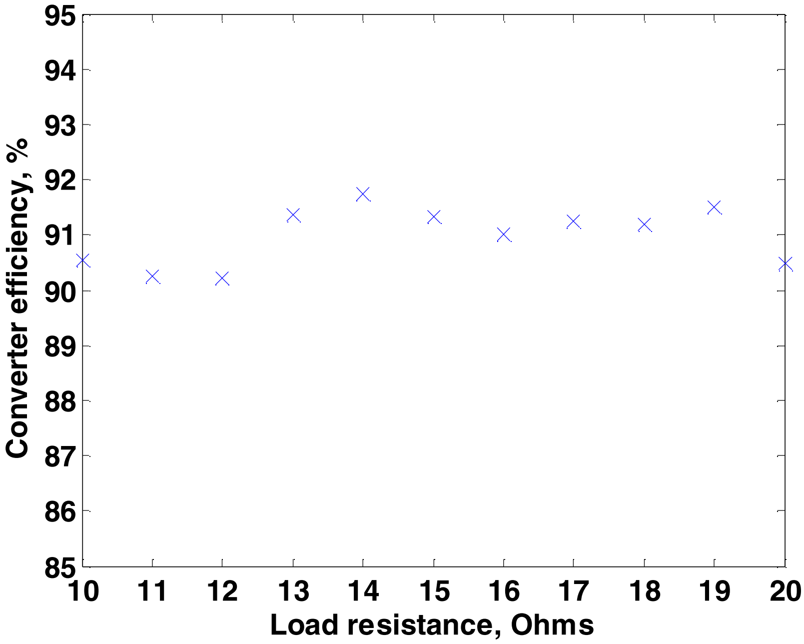


Fig. 3: Prototypes efficiency when operated at resonance over the specified load range

Conclusion

An LCC resonant converter current-source design methodology, based on the FMA analysis technique, has been presented. The steady-state output current has been shown to remain near constant over an extended load range when switched at the resonant frequency. If supplied by a constant voltage, the converter is capable of virtually constant output-current regulation in open-loop via a self-oscillating at resonance switching mechanism. Results from a prototype converter have validated the proposed methodology.

References

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