Design of Resonant LLC Converters by Cloning

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Introduction
Resonant LLC converters (RLLCC) are currently very popular and are a preferred design approach due to their multitude advantages such as zero voltage switching (ZVS) and low electromagnetic interference (EMI) as compared to PWM converters. The efficiency of well-designed RLLCC could reach 95% and beyond, and they normally include transformer isolation. Consequently, RLLCC are now being implemented widely and they are very popular in server farms.

The design of RLLCC is complex, since it includes many degrees of freedom and requires extensive engineering experience considering the fact that it is guided by many rules of thumb. The objective of the design is to reduce losses on one hand, and on the other hand to enable a wide load range, without losing regulation. In reality, the ability of the RLLCC to maintain the output voltage at light load is limited and burst operation needs to be invoked. This leads to lower efficiency and extensive noise. In the light of the above, RLLCC design required many simulations runs and a trial and error approach.

In many instances, the RLLCC designer has at its disposal a 'good' design of an RLLCC, either his own, or one of those found in application notes and reference designs offered by practically all pertinent vendors. However, in most cases, the available design does not meet the required design objective in terms of input voltage, output voltage, power level or switching frequency.

This article described a simple method by which a 'good' RLLCC designed can be cloned to meet different requirements without losing the original 'good' featured of the design such as frequency span, load range and high efficiency.

A short video on the subject can be found at:
https://www.youtube.com/watch?v=YGt6p5zr3mg

RLLCC small signal model
Resonant converters, including RLLCC, are based on a resonant network, square wave driver, transformer and rectifier. The driver could be of a full bridge configuration (Figure 1a) or a half bridge form (Figure 1b). Analysis and design of RLLCC are normally done by applying the small signal equivalent circuit (Figure 2) which is based on the first harmonics approximation.

The small signal equivalent circuit of the RLLCC has been used here to develop the transformation rules listed below. The theoretical foundation of the transformation rules is based on the following principles that ensure not only proper operation but the same features as the reference 'good' design. For example, one of the transformation criterium is keeping the quality factor equal to that in the reference design. This implies an identical value for the ratio between the equivalent resistance Rac and the impedances of the inductors. Another criterium is to maintain the inductance ratio constant. This will maintain the voltage gain about constant over a wide load range. Hence, these conversion rules keep the 'good' properties of the original RLLCC even if there is a change in the nominal switching frequency, power level, output voltage or input voltage.

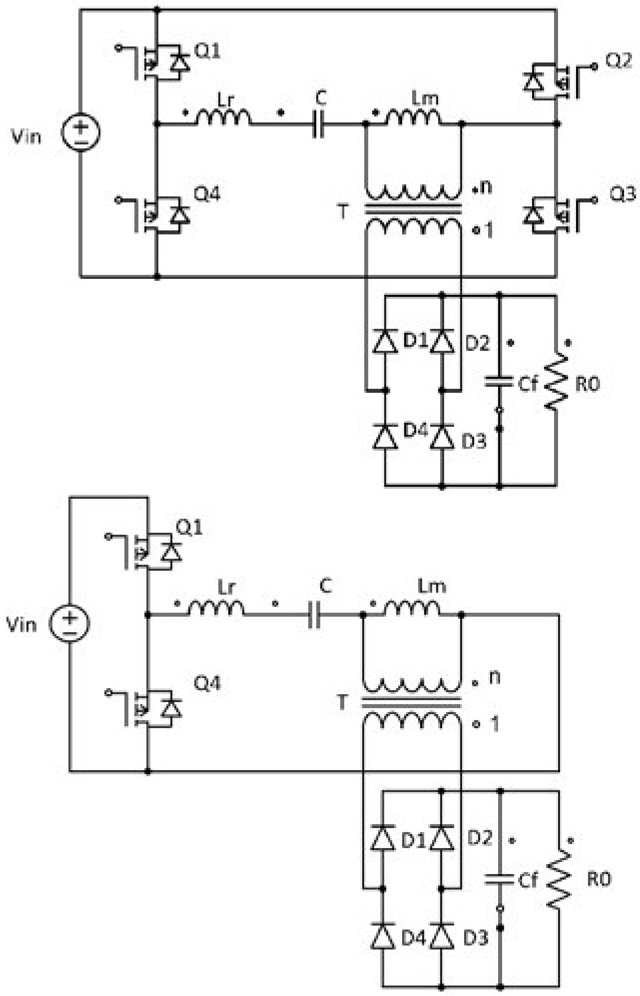

Figure 1: Resonant LLC converter. a. Full bridge configuration. b. Half bridge configuration.

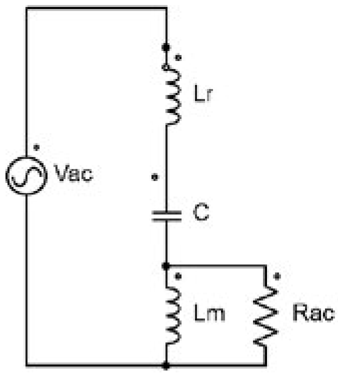

Figure 2: Small signal equivalent circuit of the RLLCC

Rule for cloning when a 'good' RLLCC design is given
The followings are the parameter definitions used below:
Vin = input DC voltage
V_o = output DC voltage
R_o = nominal output (DC)
f = nominal switching frequency
p = nominal output power
Lr = series inductor (see Figure 2)
Lm = parallel inductor (to output)
C = resonant capacitor
n = transformer turns ratio
Index 1 = designates original design (e.g. Vo1)
Index 2 = designates a parameter of desired RLLCC

Change of output DC voltage from Vo1 to Vo2 – power, input voltage and switching frequency are maintained
Since the power is kept the same, nominal output (DC) resistor must be changed from Ro1 to Ro2 and the transformer's turns ratio needs to be altered from n1 to n2

$$R_{02} = R_{01}(\frac{V_{02}}{V_{01}})^2 \qquad n_2 = n_1\frac{V_{01}}{V_{02}}$$

In this case, there is no need to change the value of the resonant network elements. The change in Ro and n is such that the reflected Rac (Figure 2) is kept the same. So, from the point of view of the small signal equivalent circuit, there is no change.

Change of nominal switching frequency from f1 to f2 – all other parameters are kept the same.
In this case there is a need to change the values of the inductors and capacitor.

$$C_2 = C_1\frac{f_1}{f_2} \qquad Lm_2 = Lm_1\frac{f_1}{f_2} \qquad Lr_2 = Lr_1\frac{f_1}{f_2}$$

The change of the reactive elements keeps the values of the impedances and quality factor as in the reference RLLCC. The inductors ratio also does not change to keep the same behavior as in reference unit.

Change of output power from p1 to p2 - all other parameters are kept constant

$$R_{02} = R_{01}\frac{p_1}{p_2} \qquad C_2 = C_1\frac{P_2}{P_1} \qquad L_{r_2} = L_{r_1}\frac{p_1}{p_2} \qquad L_{m_2} = L_{m_1}\frac{p_1}{p_2}$$

The power change requires a modification of the equivalent Rac resistor. This dictates a change in reactive elements to keep the quality factor constant.

Change of input voltage from Vin1 to Vin2 – all other parameters are kept constant

$$n_2 = n_1\frac{V_{in2}}{V_{in1}} \quad L_2 = L_1(\frac{V_{in_2}}{V_{in_1}})^2 \quad C_2 = C_1(\frac{V_{in_1}}{V_{in_2}})^2 \quad L_{m_2} = L_{m_1}(\frac{V_{in_2}}{V_{in_1}})^2 \quad L_{r_2} = L_{r_1}(\frac{V_{in_2}}{V_{in_1}})^2$$

This conversion rule keeps the same input to output voltage ratio (despite the change in input voltage) and the value of the quality factor.

A change from full bridge to half bridge configuration – all other parameters are kept the same
A change from a full to half bridge is equivalent to a change in input voltage by ½. The rules for a change in input voltage are given above.

Conclusion
A method is presented for changing the components' values of a 'good' RLLCC design such that the cloned RLLCC will meet another set of specifications. This without altering the 'good' behavior of the design. For example, operation from 40V rather than from 400V. It should be pointed out that the cloned RLLCC has the potential of keeping same efficiency as the reference if the components will be chosen to meet the new operating conditions. For example, if the cloned RLLCC is to be operated from a lower input voltage, the current will be higher than in original circuit, and to maintain the efficiency, the inductors resistances should be lower.

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www.youtube.com/user/sambenyaakov/videos