Analysis of Multi-resonant Circuitin Overloading States

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Abstract— The paper deals with the analysis of behavior of multi-resonant circuit in state of overload. Investigated topology is multi-resonant LCL2C2 resonant circuit. The main focus is given on its transient properties and its ability withstands the short circuit. The two simulation models are analyzed and compared with the experiments and results are given on the end of the paper.

1. INTRODUCTION

Standard categorization of resonant circuits is into series or parallel combinations, as well as into hybrid combinations of the serial and parallel connections. The proposed LCL2C2 belongs to the category of multi-resonant tank converters. Resonant circuit is composed of two serial LC branches between which, two parallel LC filters are connected [1]. The principal schematic is shown on Fig. 1.

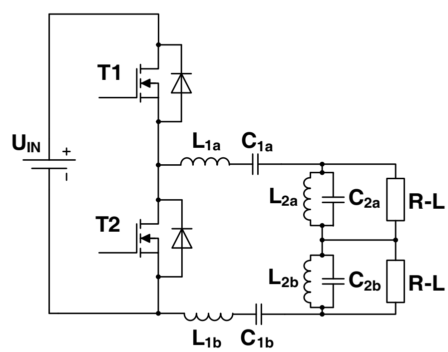

Figure 1: Principle schematic of LC2L2C2 resonant converter [2].

The schematic shows that proposed solution represents non-isolated version of the resonant converter. The load is composed by serial connection of R-L. The shape of voltage waveform at the outputs has to be pure sinusoidal waveform, due to fact, that L-C filters at the output are tuned for the switching frequency. The regulation of the magnitudes can be done using the pulse frequency modulation (PFM) or with the asymmetric pulse width modulation control (APWM). By simple modification of main circuit with the implementation of high frequency transformer, the isolated version of LCL2C2 converter can be done. In this way, due to transformer ratio, a higher regulation range of output voltage can be achieved [3].

Nevertheless for the determination of proper operation it is necessary to investigate the suitable operation regions. The approach of the operation regions analysis will be shown in next chapters together with derivation of the basic equations for LCL2C2 network design [2, 4].

2. OPERATIONAL SWITCHING FREQUENCY OF LCL2C2 RESONANT CONVERTER

The resonant components are computed in order to be tuned for basic harmonic. The resonant filter can be supplied by either single-phase voltage inverter in full- or half- bridge connection. Base on Thomson relation, the resonant frequency of accumulation components should be the equal to fundamental switching frequency of the converter. In order to not exceed nominal voltages or currents of the storage elements was use value of internal impedance of the storage element equal to the nominal load $|Z_N|$.

The *nominal quality factor* q_N for *LC* components, where its value refers to the nominal value of the load [3]

$$q_N = \frac{L\omega_{res}}{|Z_N|} = \frac{1}{\omega_{res}C\,|Z_N|} \tag{1}$$

The above equation is similar to quality factor defined as $q = L_{load}\omega_{res}/R_{load}$, however q_N does not depend on actual value of the load (R_{load}) just on nominal load ($|Z_N|$).

Based on the input impedance frequency characteristic is possible to choose two load-invariant input impedance "izo-impedace" operational points for switching frequency. In this case (point) input impedance is not depending on the load of the inverter, two mirror trajectories with minimal input impedance of the LCL2C2 circuit depending on the load. First point is when impedance is proportional depended on the load (Fig. 2) [5]. Then the module of input impedance will be:

$$\frac{|Z_{in}(\omega)|}{|Z_N(\omega)|} = \sqrt{\left[r_1 + \frac{\left(\frac{1}{r_2}+\frac{1}{r}\right)}{DEN}\right]^2 + \left[\left(f_{rel} - \frac{1}{f_{rel}}\right)\left(q_{N1} - \frac{q_{N2}}{DEN}\right)\right]^2} \tag{2}$$

And the voltage transfer $\frac{|U_{out}(\omega)|}{|U_{in}(\omega)|} = \frac{|Z_2(\omega)|}{|Z_{in}(\omega)|}$ will be

$$F(\omega) = \frac{|Z_2(\omega)|}{|Z_{in}(\omega)|} = \sqrt{\frac{1}{DEN\left\{\left[r_1 + \left(\frac{1}{r_2}+\frac{1}{r}\right)\frac{1}{DEN}\right]^2 + \left[\left(f_{rel} - \frac{1}{f_{rel}}\right)\left(q_{N1} - \frac{q_{N2}}{DEN}\right)\right]^2\right\}}} \tag{3}$$

where denominator (DEN) is described as

$$DEN = \left(\frac{1}{r_2}+\frac{1}{r}\right)^2 + \left[q_{N2}\left(f_{rel} - \frac{1}{f_{rel}}\right)\right]^2 \tag{4}$$

The graphical presentation of impedance and voltage transfer can be seen below.

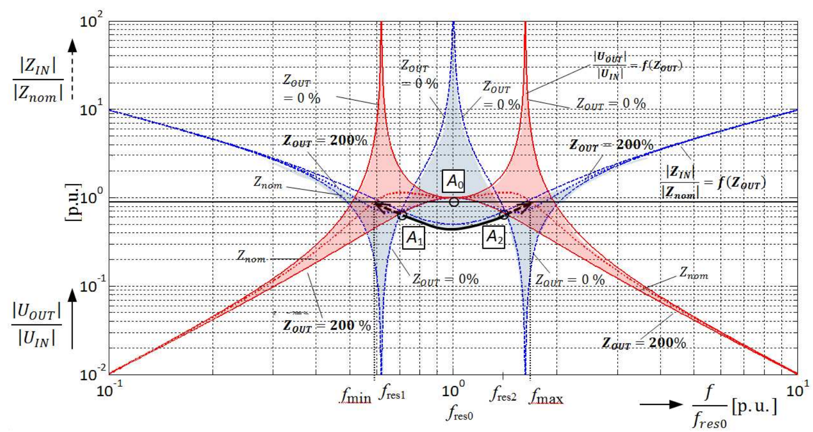

Figure 2: Input impedance and voltage transfer frequency log-characteristics [5].

Similarly, voltage transfer frequency characteristic of the LCL2C2 resonant circuit offers two mirror trajectories with maximal output voltage of the circuit depending on the load, and also one point (A0) when the output voltage of the inverter does not depend on the inverter's load. Also, is possible to determine the optimal operation frequencies for other value of overloading and functional relation is

$$|f_{\min}|_{overload} = f(Z_{overload}) \text{ or } |f_{\max}|_{overload} = f(Z_{overload}) \tag{5}$$

to input current was be the same as nominal one [5, 7].

3. SELF-REGULATION OF ITS OWN INTERNAL FEEDBACK

Based on the computed values of LCL2C2 elements, the gain characteristic of proposed converter was made through the use Matlab simulation tool. Fig. 3 shows gain curves in dependency on the load change. Based on this characteristic, the proper operation regions of LCL2C2 converter is possible to determinate. It is generally know, the optimal switching frequency is equal resonant frequency of LC element at nominal condition. Anyway, it is more suitable set the switching frequency in the range from $f_{\min}$ up to $f_{\max}$ (Fig. 2) under overloading (e.g., 200–800% in the Fig. 3), short-circuit operation to be not overcoming the nominal value of input current and/or output voltage, respectively. That one, of course, can be combined with the asymmetrical control of input voltage of the inverter [6, 7].

The curves in Fig. 2 represents the voltage transfer of proposed converter depend on the load. The simulation focuses on the load states from the nominal value of the load (100%) till the short circuit (state of overload). The overload state was considered as a minimum wire resistance (at the output), but not zeroload. In ideal state, the ratio between the switching and resonant frequency is equal 1 and voltage gain is for different load values always the same and equal 1 (in p.u.) [7, 8].

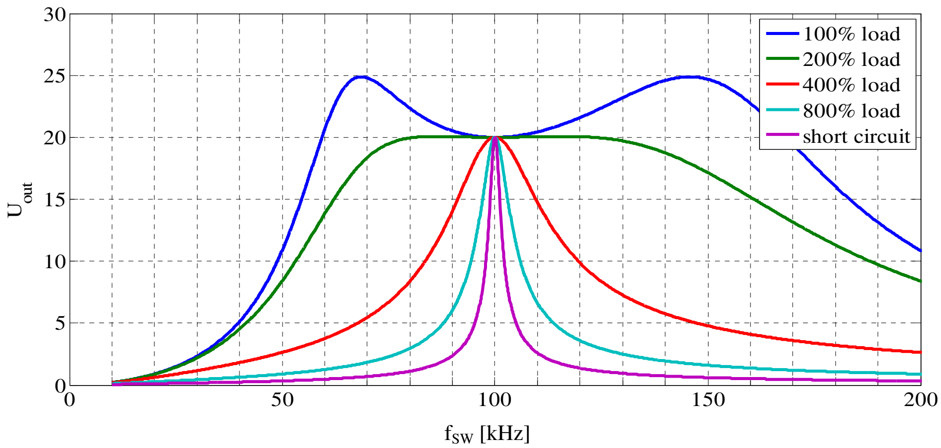

Figure 3: Voltage transfer of the LCL2C2 converter (idealizated theoretical example).

The figure above presents tansfer curves of the converter where the nonlinearities and parasticis elements are no take in the consiederation into the model.It is an idealized theoretical example because during the short-circuit the output voltage can not be equal to the input one. Analysisng the physical sample (Chapter 4.) and recognizing major parasitic elements in circuit was modificated the final model of multi-resonant converter.Without parasitic elements, the series resonant circuit voltage would increase to the high values while the output current would be infinitely large.Since, theoretically zero (output) current is divided by zero (output) impedance, what is indefinite expressions, the mathematical (analysis) solution would need use limits. In this case, the output current with different values of frequency would infinitely rise up.

Applyng the nonlinear inductance model [9] and determined (possible) parasitic elements into the Matlab converter model results in to the change of voltage transfer curves shape.

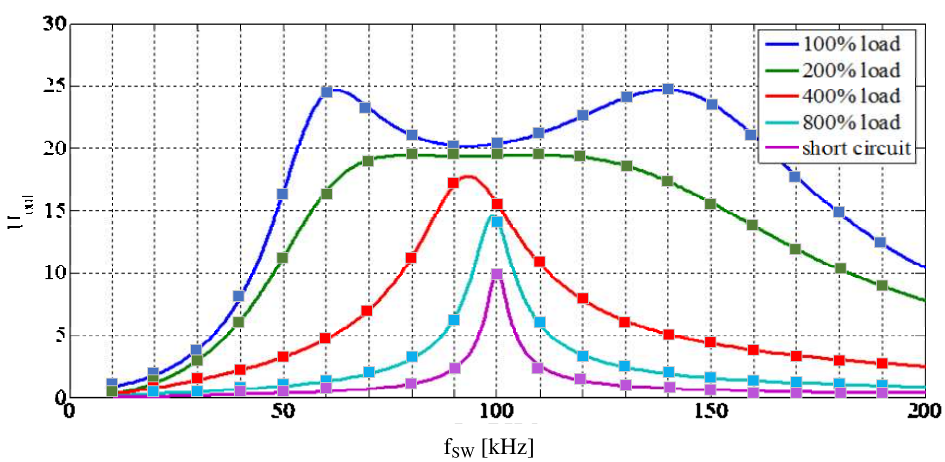

Figure 4: Voltage transfer of LCL2C2 converter (parasitic and nonlinearities are considered).

Due to modifications the curves of voltage transfer has changed in two ways. First, the final gain value at all stages of the loading is different. What is caused by the parasitic elements witch have great affect to the final value of gain. Second, the ratio of $f_{\rm sw}$ and $f_{\rm res}$ is changing with the load increase. In state of nominal load is about $f_{\rm res} = 95\,\rm kHz$, while in state of short circuit is 100 kHz (or more). The frequency difference between the nominal load and short circuit is about 5–10% compere to ideal model. With the increase of the load, increases the impact of the parasites elements. Best match between the simulation models is at the nominal state of the load. The difference is less than 3% [10].

4. EXPERIMENTAL VERIFICATION OF SELF-REGULATION DUE TO OWN INTERNAL FEEDBACK

The experimental measurements have been done on the physical sample. The parameters of experimental set-up were: $L_{1\rm a} = L_{1\rm b} = 59\,\rm uH$, $L_{2\rm a} = L_{2\rm b} = 59\,\rm uH$, $C_{1\rm a} = C_{1\rm b} = 43\,\rm nF$, $C_{2\rm a} = C_{2\rm b} = 43\,\rm nF$, load nominal: R-36 ohm, MOSFETs = IRF5N50C.

The test stand consisted of the impulse generator, half-bridge converter, primary laboratory source; LCL2C2 resonant network and the load.Change the frequency in range of 10 till 200 kHz was measured the output value of the voltage in different levels of the load (range 100–800% of load). State of short circuit was measured as well. The experimental results are given in the Fig. 5.

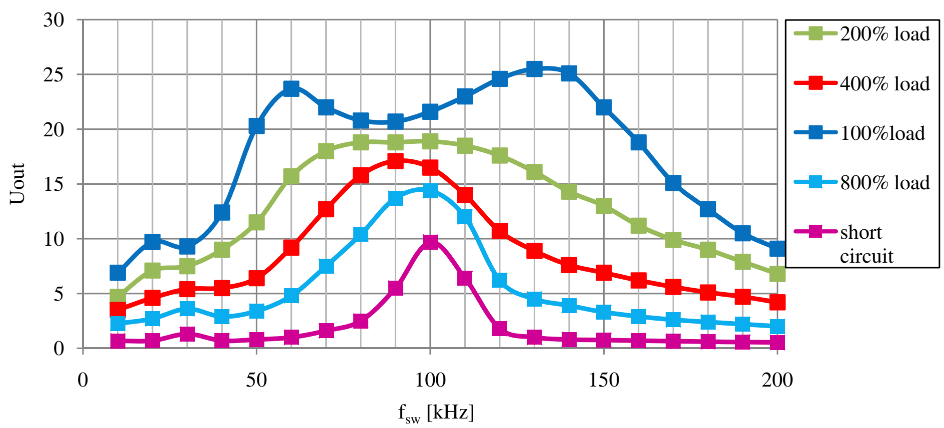

Figure 5: Voltage transfer of LCL2C2 converter (experimental verification).

As it can be seen, the theoretical assumptions match with experimental measurements. The shape of transfer waveforms is similar to the simulation results (Fig. 4). Output voltage values compared to simulation oneis similar too. The perceptual difference between the simulation (Fig. 4) and experiments are from 3 till 15%. The biggest difference is observed in the case of the short circuit in frequency area between 80–90 kHz and 110–120 kHz. On other hand, best match is observed at nominal load. The frequency ratio is changing as it was in the simulation experiments where the nonlinearity and parasitic elements was considered [7, 10].

The short circuit causes the output current increase. It causes saturation of the magnetic elements and it results in to the change of the inductors values. Therefore, the ratio between switching and resonant frequency is changing. The ratio change affects the point of the maximal gain value. These phenomena can be considered as a method of the "self-regulation" due to own internal feedback. I case of short circuit is output current limited by the converter self-regulation. Also, the regulation causes the current shape distortion and its THD increases about 3–5%. The final THD values may be about 6–9%. All these "negatives" are the tax to pay on self-regulating feedback. Under these conditions, the regulation by asymmetric changes in duty-cycle or changing the ratio of the $f_{\rm sw}$ and $f_{\rm res}$ it is necessary to consider. Other way, the accumulation elements design for the higher values of the load is possible to take in consideration.

5. CONCLUSION

Base on the theoretical assumption was created the mathematical model of the multi-resonant circuit. Simulation results are given in two levels. First,idealized mathematical model and second modified model where parasitic elements and nonlinearities in circuit were taken into consideration. Comparing this two models been held that with increasing load (from nominal to short circuit) increase the difference between simulation results.Without parasitic elements, the series resonant circuit voltage would increase to the high values while the output current would be infinitely large.

Validation of proposed models was provided on built physical sample. Analyzing built sample was modified the second simulation model. The results are given in 4th chapter. The experimental results comparable and fully match with theoretical assumptions. The method of self-regulation due to own internal feedback was confirmed by experimental verification. I case of short circuit is output current limited, current shape distortion and its THD increases about 3–5%. The THD values of output current and voltage increase up to 6–12%. Under these conditions, the asymmetric regulation change of the frequency ratio orover-dimensioned the accumulation elements can be considered.Also, oversizing of the accumulation elements is possible to consider.

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