Analysis of the resonant LCL circuit operation: the case of discontinuous current

Abstract. The article is focused on the analysis of the LCL resonant circuit, which operates under discontinuous input current condition. This condition leads to the LCL topology variability phenomenon what drastically changes Inverter-LCL system properties. The LCL topology variability phenomenon is precisely described. The analytical analysis presents formulae that express VSI-LCL converter features. The theoretical results are compared with laboratory tests. The concept of Controlled Variable Frequency Resonant Converter is presented and illustrated by simulation tests. The principle of CVFRC operation is based on the LCL topology variability phenomenon.

Introduction. Very good application characteristics of voltage inverters with LCL (series-parallel) resonant load determine their increasingly wider use in industrial induction heating systems [1]. The LCL circuits present the high impedance conformability with the outputs of voltage inverters and the VSI-LCL converters can be connected in parallel easily [2,3]. The control methods and the converters design are continually developed [4,5,6]. The inverter topology and the applied control process may result in the phenomena that can change vitally the system operation principles and properties. The LCL topology variability [7], the VSI-LCL inherent control and power range limitation for high factor Q [8] are the phenomena that should be considered during analyzing and designing of VSI-LCL converters. This paper is focused on the LCL topology variability phenomenon only. The article includes, specifies and expands the variability description, its analysis and implications [9]. Research and description of the variability phenomenon lead to new power electronics converters solutions.

Discontinuous current in the VSI-LCL converter. The considered induction heating converter consists of one phase full-bridge voltage inverter and the LCL resonant load. Figure 1 presents the commonly used inverter schematic and the invariant topology, equivalent scheme of LCL circuit. The L and R elements of equivalent scheme correspond to the induction furnace/batch parameters. The control method is based on synchronous modulation, which is adequate for the single and multi-inverter systems.

The real current and voltage waveforms are shown on Fig.2. It illustrates system controlling method and indicates current conducting phases (I,II,III) durations. The signals defining conducting time $t_m$ of diagonal transistors are generated synchronously to zero-crossings of voltage $u_C$, assuring IGBTs soft ON commutation. The control system guaranties fully synchronous operation in whole resonant load parameter changes.

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The figure 3 presents the changes of LCL equivalent scheme in successive (I,II,III) inverter current $i_l$ conducting phases. The two schemes are created – the first one without any topological change (phase I,II) and the second one (phase III), which is reduced to C-L-R elements. The obvious reason of LCL topology changes is the discontinuous nature of the input current.

The conditions of topology changes are functions of the reference signal $t_{m}$. The two schemes are created – the first one without any topological change (phase I,II), while the right side guaranties existence of the LCL circuit parallel resonant pulsation.

The consequence of topology changing is fluctuation of all the resonant circuit parameters - resonance pulsation $\omega_0$, impedance $Z$, quality factor $Q$ etc - at invariant values of the circuit elements $L_S$-C-L-R. The new resulting parameters are functions of the reference signal $t_{m}$, since it defines the instants of topology changes.

The changes range of acting resonant angular frequency of VSI-LCL variable system topology can be depict analytically:

$$\omega_{act} = \omega_{act}/\omega_{(III)} = \omega_{act}/(t/\sqrt{LC}) = f(m)$$

where: $m=2t_{m}/T_{act}$

The numerical calculations allow obtaining the graphical representation of relation (2). The figure 4a illustrates changes of acting resonant pulsation $\omega_{act}$ for different values of resistance $R$ and constant $L_S$-C-L-R. The figure 4b shows chosen comparison results of laboratory test and analytical calculations for two different LCL circuits:

LCL1: $L=2.5\,mH$, $C=30\,\mu F$, $\rho=0.581$, $k=0.488 \Rightarrow f_{0(III)}=524.2\,Hz$, $f_{0(III)}=581.2\,Hz$

LCL2: $L=2.2\,mH$, $C=30\,\mu F$, $\rho=0.537$, $k=0.555 \Rightarrow f_{0(III)}=574.2\,Hz$, $f_{0(III)}=619.5\,Hz$

The comparisons show good convergence of analytical and laboratory results. The absolute value of relative error $\delta=|f_{act}-f_{lab}|/f_{act}$ is lower than 8% in the whole range of variability of control ($m$) and the resonant circuit elements value.

The angular resonant frequency of LCL circuit, before and after topology change takes the values appropriately:

$$\omega_{0(I,II)} = \sqrt{1+2k-\rho^2k-\sqrt{\rho^2k^2-4k+2}} + 1/2kLC$$

where: $\rho = R/\sqrt{L/C}; \; k = L_S/L$

Taking $\omega_{0(III)}$ as the unit value and denoting the real acting pulsation as $\omega_{act}$ one can express the relative value of acting resonant angular frequency:

$$\omega_{act} = \omega_{act}/\omega_{0(III)} = \omega_{act}/(t/\sqrt{LC}) = f(m)$$

where: $m=2t_{m}/T_{act}$

The expression (4) states preconditions that must be met to ensure a physical sense of formula (3).

The left side of inequality (4) defines resonant nature of the LCL circuit, while the right side guaranties existence of the LCL circuit parallel resonant pulsation.

The figure 5 illustrates the border value of formula (3). The dashed lines represent conditions (4). The relation (3) shows that the changes of acting pulsation can be very large. They may have a significant impact on the effectiveness of the induction heating process by modifying the depth of magnetic field penetration.
The topology variability phenomenon enables creation of real variable frequency, induction heating converter with LCL load. Typically the modulation depth factor \( m \) defines the output power \( P \) of VSI-LCL converter while the acting frequency \( f_{act} \) variation is the side effect. But one can use the \( m \) factor for frequency regulation only. In this case the DC-link voltage \( u_I \) should be used for power regulation. The proposed Controlled Variable Frequency Resonant Converter (CVFRC) block scheme is shown on Fig. 6.

\[ f_{act} = f(t_m, u_L, L_S, ...) \]
\[ P = f(t_m, u_L, L_S, ...) \]

The obtained results of the analysis are sufficient for any technical computing and perfectly present the LCL topology variability properties.

The Controlled Variable Frequency Resonant Converter proposal

In many cases the induction heating process is divided on stages requiring different frequencies. Such sub-processes are realized by separate heating systems because the conventional resonant converters are not suitable for variable frequency operation. The attempts to solve this problem have been continuously made [10,11,12,13,14].
They present the inverter and the LCL circuit waveforms acting frequency Rys.10. The CVFRC waveforms for output power (operating with discontinuous input current is presented. The Conclusions frequency regulation range covers the entire analytically regulation as it shown on Fig.6.

All the simulations have been made for open loop system phenomenon arising is the discontinuous current of any described. The necessary condition for the variability phenomenon enables the resonant circuit parameters alteration, without changing its elements. This in turn opens up new application areas of power electronics.

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