Maciej A. DZIENIAKOWSKI
Warsaw University of Technology, Institute of Control and Industrial Electronics

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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.*

Streszczenie. *Artykuł omawia pracę rezonansowego układu LCL przy nieciągłym prądzie wejściowym, prowadzącym do zmienności topologii obwodu. Przedstawiono wyrażenia analityczne obrazujące działanie przekształtnika z obciążeniem LCL. Porównano wyniki badań teoretycznych z testami laboratoryjnymi. Przedstawiono koncepcję rezonansowego przekształtnika FN-LCL o regulowanej częstotliwości w oparciu o zjawisko zmienności topologii. (**Analiza pracy rezonansowego układu LCL pracującego w warunkach nieciągłości prądu**).*

Keywords: resonant circuit LCL, resonant converter, topology variability, induction heating, voltage inverter control.
Słowa kluczowe: przekształtnik rezonansowy LCL, zmienność topologii, grzejnictwo indukcyjne, falownik napięcia, sterowanie.

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.

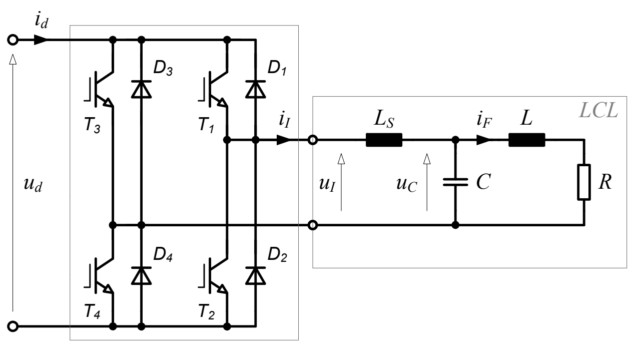


Fig.1. The voltage-fed inverter schematic and the equivalent scheme of LCL resonant load

The real current and voltage waveforms are shown on Fig.2. It illustrates system controlling method and indicates current conducting phases (I,II,II) 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.

a) t_m=160μs ⇨ f_{act}=585Hz

b) t_m=810μs ⇨ f_{act}=518Hz

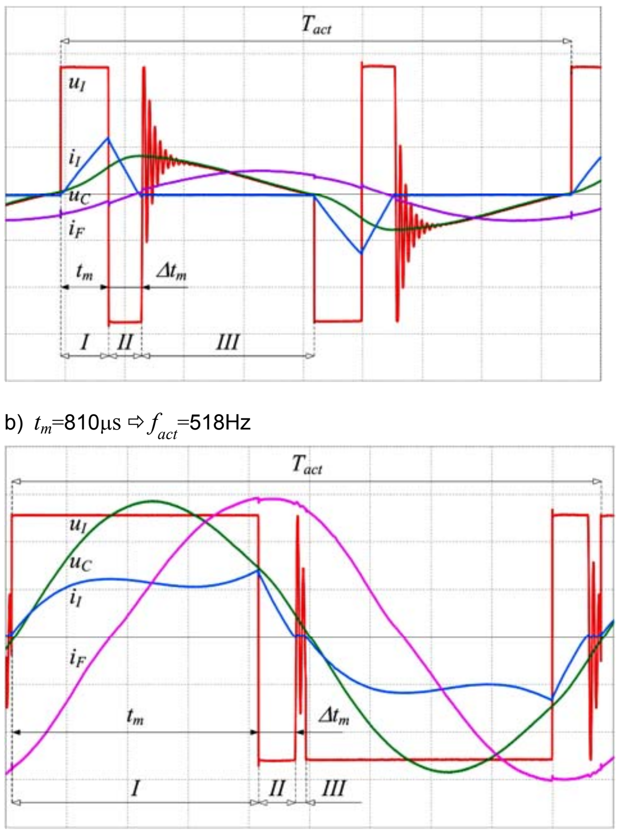


Fig.2. The oscillograms of current and voltage waveforms for two different control signals t_m in the case of constant LCL circuit and VSI parameters – L_S, C, L, R, u_d; u_C,u_I - 200V/div; i_F, i_I - 20A/div; t - 200μs/div

The figure 3 presents the changes of LCL equivalent scheme in successive (I,II,III) inverter current i_I 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 i_I:

phase $I+II$ - $i_I \neq 0;\ 0 \le t < (t_m+\Delta t_m)$

phase III - $i_I = 0;\ (t_m+\Delta t_m) \le t < T/2$

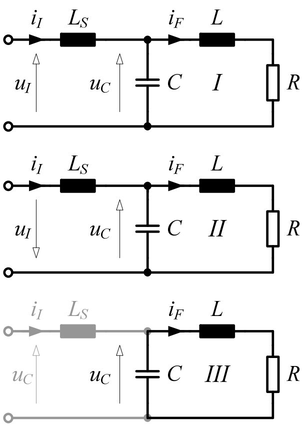


Fig.3. The successive LCL topology changes

The consequence of topology changing is fluctuation of all the resonant circuit parameters - resonance pulsation ω_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 clear examples of the described phenomenon are the oscillograms in Fig.2. They show the voltage and current waveforms of the VSI-LCL system under the same LCL elements values, for two different values of reference signal t_m. The resulting, acting resonant frequency f_{act} depends on the control signal t_m only.

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

$$(1)\quad \begin{cases} \omega_{0(I,II)} = \sqrt{\dfrac{1+2k-\rho^2 k-\sqrt{\rho^2 k(\rho^2 k-4k+2)+1}}{2kLC}} \\ \omega_{0(III)} = 1/\sqrt{LC} \end{cases}$$

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

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

$$(2)\qquad \omega_{act}^{rel} = \omega_{act}/\omega_{0(III)} = \omega_{act}\big/\left(1/\sqrt{LC}\right) = f(m)$$

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 $\omega_{act}{}^{rel}$ for different values of resistance R and constant L_s-C-L.

The figure 4b shows chosen comparison results of laboratory test and analytical calculations for two different LCL circuits:

LCL$_1$: L-2,5mH, C-30μF, ρ-0,581, k-0,488 ⇨ $f_{0(I,II)}$=524,2Hz, $f_{0(III)}$=581,2Hz

LCL$_2$: L-2,2mH, C-30μF, ρ-0,537, k-0,555 ⇨ $f_{0(I,II)}$=574,2Hz, $f_{0(III)}$=619,5Hz

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

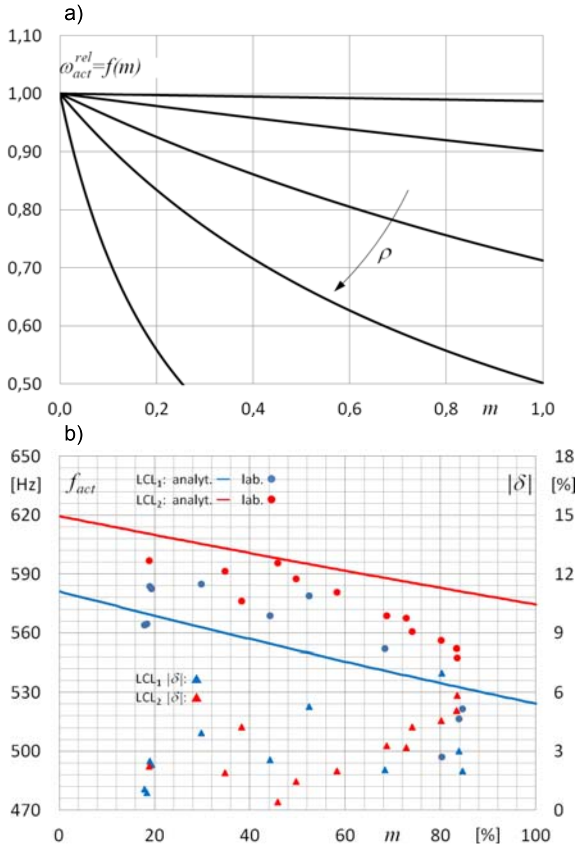


Fig.4. The theoretical relative value of acting resonant pulsation (a) and the laboratory test results (b) vs. modulation factor m

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

$$(3)\quad \begin{cases} \omega_{act}^{rel}\Big|_{m=0} = 1 \\ \omega_{act}^{rel}\Big|_{m=1} = \dfrac{\sqrt{1+2k-\rho^2 k-\sqrt{\rho^2 k(\rho^2 k-4k+2)+1}}}{\sqrt{2k}} \end{cases}$$

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

$$(4)\qquad (\rho^2-1) \le k \le 1/(2\rho-\rho^2)$$

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 effectivity of the induction heating process by modifying the depth of magnetic field penetration.

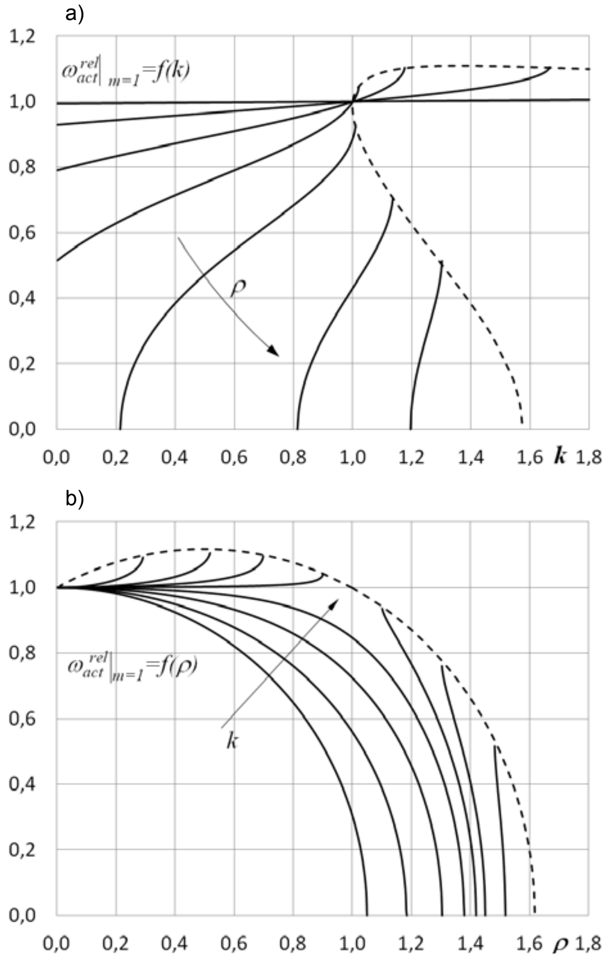


Fig.5. The acting resonant pulsation range limits as the function of factor $\boldsymbol{k}$ (a) and factor $\boldsymbol{\rho}$ (b)

The other parameters (Q, Z etc) describing the LCL circuit are also t_m depended. They take two different, constant values according to the actual phase. This fact allows calculating the consequent, average parameters values for variable topology:

(5) $$\overline{Pr}_{act} = m' \cdot (Pr_{I,II} - Pr_{III}) + Pr_{III}$$

where: $m' = 2(t_m+\Delta t_m)/T_{act}$, $Pr_{I,II}$ -the basic LCL circuit parameter value (phase I and II), Pr_{III} - the reduced LCL circuit parameter value (phase III)

The presented analysis describes the variability phenomenon which exists in the case of discontinuous input current. Not all physical conditions were taken into account as having negligible effect on the calculation accuracy - the damping factor for phase III and the higher harmonics of LCL waveforms.

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].

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_d should be used for power regulation. The proposed Controlled Variable Frequency Resonant Converter (CVFRC) block scheme is shown on Fig.6.

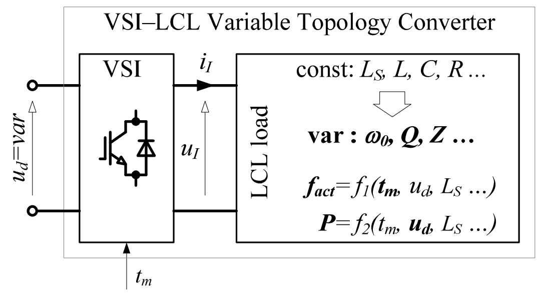
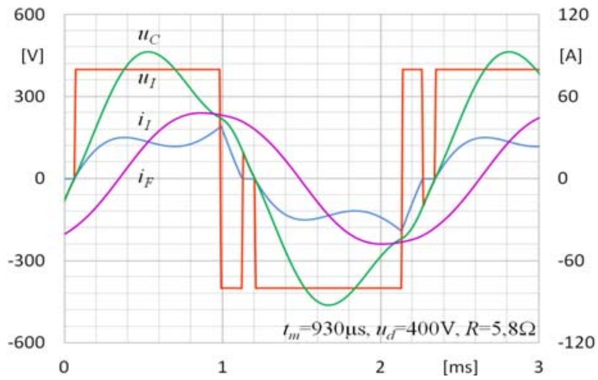
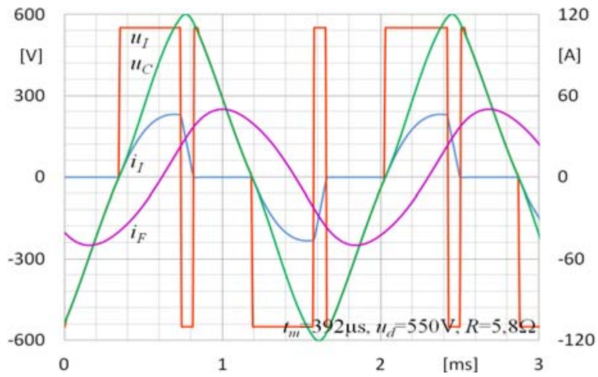


Fig.6. The principal CVFRC block scheme

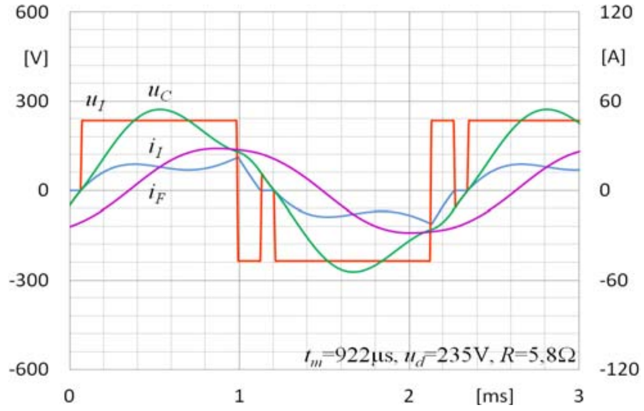
The acting frequency f_{act} and the converter output power P are the functions $f_1;f_2$ of the same independent variables t_m,u_d. The $f_1;f_2$ are coupled what results in mutually depended regulation of P and f_{act}. Furthermore the DC-link voltage u_d influences on f_{act} by modifying indirectly Δt_m – the phase II duration and the acting frequency consequently. In the closed loop control system the decoupling procedure should be applied. The obtained simulation results show that both functions $f_1;f_2$ are monotonic and the DC voltage u_d impact on acting frequency f_{act} is weak. It makes simple decoupling and control system structure.



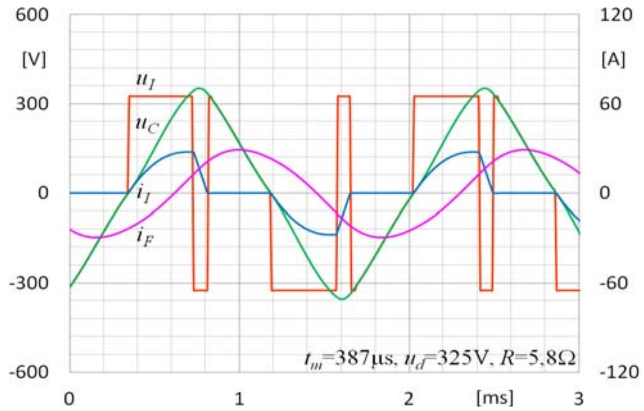
Rys.7. The CVFRC waveforms for output power P=7,3kW and acting frequency f_{act}=440Hz



Rys.8. The CVFRC waveforms for output power P=7,3kW and acting frequency f_{act}=600Hz



Rys.9. The CVFRC waveforms for output power P=2,5kW and acting frequency f_{act}=440Hz



Rys.10. The CVFRC waveforms for output power P=2,5kW and acting frequency f_{act}=600Hz

The figures 7-10 depict the chosen simulation results. They present the inverter and the LCL circuit waveforms u_I; u_C; i_I; i_F for different values of regulated parameters P; f_{act} with constant values of the resonant circuit elements (L_S=2000µH, L=2400µH, C=30µF).
All the simulations have been made for open loop system regulation as it shown on Fig.6.

The numerical research showed that the CVFRC frequency regulation range covers the entire analytically defined area. The output power range depends on the converter technical limitations only.

Conclusions

The overall analysis of converter with LCL load, operating with discontinuous input current is presented. The notion of the resonant topology variability is introduced and described. The necessary condition for the variability phenomenon arising is the discontinuous current of any resonant circuit branch. The analytical expressions determine selected parameters of LCL variable topology circuit. The parameters values of the variable topology depend on the inverter control signals. The numerical and the experimental investigations have been made. The obtained results illustrate the LCL variability phenomenon and its properties.

The new Controlled Variable Frequency Resonant Converter idea, based on topology variability phenomenon is described. The operation principles are discussed. The simulation tests have been made and presented. They indicate large application potential of proposed converter.

The variability phenomenon enables the resonant circuit parameters alteration, without changing its elements. This in turn opens up new application areas of power electronics.

Author: *Ph.D. Maciej A. Dzieniakowski, Politechnika Warszawska, Instytut Sterowania i Elektroniki Przemysłowej, ul. Koszykowa 75, 00-662 Warszwa, E-mail: mad@isep.pw.edu.pl*

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