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Design Analysis of LCTLC Resonant Inverter for Two-Stage 2-Phase Supply System

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Original scientific paper

This paper deals with the design analysis and synthesis of power resonant inverter with sinusoidal output voltage for sensitive loads. The proposed filter must be capable of removing higher harmonic components from the supplying voltage to reach a harmonic distortion of roughly 5% in the whole range of the load $(0 - 100\%)$. The inverter can be supplied from either single-phase voltage inverter in full- or half- bridge connection, or from simple DC/DC buck converter. Non-symmetrical control causes higher harmonic content, both odd and even. Simulation and experimental results based on designed parameters and subsequently obtained from Matlab and OrCad models confirm good quality of output quantities, voltage and current.

Key words: DC/AC converters, LCLC resonant filter, resonant-mode power supplies, Bode diagram, Fourier analysis, transfer function

Analiza dizajna LCLC rezonantnog invertera za dvostupanjsko dvofazno napajanje. Tema je ovog članka analiza dizajna i sinteza učinskog rezonantnog invertera sa sinisuidalnim izlaznim naponom za osjetljve terete. Predloženi filtar mora moći filtrirati više harmonike ulaznog napona kako bi distorzija harmonika bila oko 5% u čitavom radnom području $(0 - 100\%)$. Inverter se može napajati ili iz jednofaznog naponskog invertera u mosnom ili polumosnom spoju ili iz jednostavog DC/DC buck pretvarača. Nesimetrično upravljanje uzrokuje pojavu viših harmonika u signalu, kako parnih tako i neparnih. Simulacijski i eksperimentalni rezultati temeljeni na sintetiziranim parametrima dobivenim od modela napravljenih u programskim paketima Matlab i OrCad potvrđuju dobru kvalitetu izlaznih veličina napona i struje.

Ključne riječi: DC/AC pretvarači, LCLC rezonantni filtri, rezonantno napajanje, Bodeov dijagram, Fourierova analiza, prijenosna funkcija

1 INTRODUCTION

There are many electrical applications requiring the load to be supplied by HF transformer with solid harmonic voltage due to synchronization, constant frequency and precise phase control demands. One of them is the cyclo- or matrix converter fed motor drive application. The required input can be provided by different converter types [1-3].

Resonant pole converters - or phase shift converters, offer lossless switching capabilities and their operation, in many respects, mimics that of switch mode converters. The one feature they do not share is the low conduction loss of switch mode converters. This undesirable property stems from the freewheeling idle current required to flow in the primary side circuit during the dead-time between conduction intervals.

Resonant LLC converters - the undesirable switching losses of switch mode converters led to the design of resonant class of converters that eliminate switching losses, enabling higher frequencies and physically smaller converters. However, these converters have high conduction loss and large peak currents and voltages.

Asymmetric duty cycle LLC converters – these converters offer an optimal feature-set of both aforementioned converter types. Their conduction losses are comparable to those of switch mode circuits and they switch lossless like resonant circuits. Various timing difficulties can limit their maximum frequency to a value lower than that of true resonant circuits, and the boundary condition requirements for lossless switching are somewhat more restrictive than those for resonant pole converters. In many cases, however, these drawbacks are acceptable because of the benefit of low conduction loss and the elimination of switching loss [2].

One of the novel types of converters are LCLCL con-

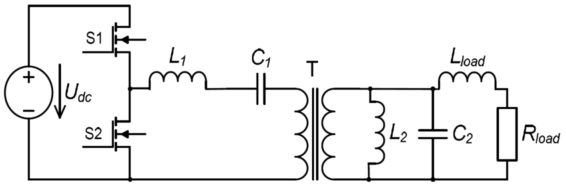


Fig. 1. Basic scheme of LCTLC inverter

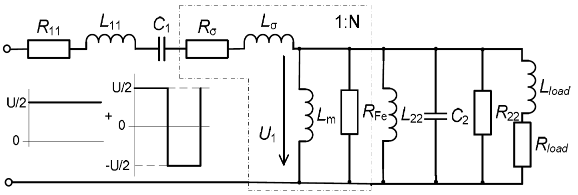


Fig. 2. Equivalent detailed scheme of LCTLC circuit

verters [4] based on LLC resonant scheme, and LCTLC inverter [5, 6] consisting of DC/DC buck converter [12, 15] LCLC resonant filter and HF transformer. The HF transformer can also be connected after the LCLC filter, if necessary, and can also be used to boost converter types [13, 14, 16]. The inverter (LCTLC) is usually used as power supply for either HV rectifiers [6, 7] or HF cycloconverters or matrix converters for 2-phase motor applications [8, 9], respectively.

2 LCTLC INVERTER ANALYSIS

2.1 State-space analysis

The basic scheme of LCTLC inverter is shown in Fig. 1.

Based on [5-7] we can create an equivalent scheme of the LCTLC circuit, as per Fig. 2 and Fig. 3.

Let us consider the following equations for the equivalent circuit

$$R_1 = R_{11} + R_\sigma, \frac{1}{R_2} = \frac{1}{R_{Fe}} + \frac{1}{R_{22}} \tag{1}$$

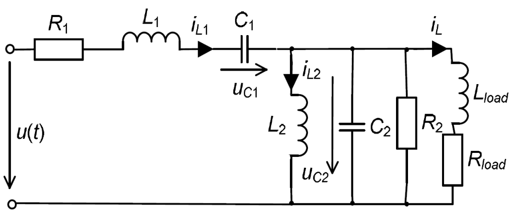


Fig. 3. Equivalent simplified scheme of LCTLC circuit

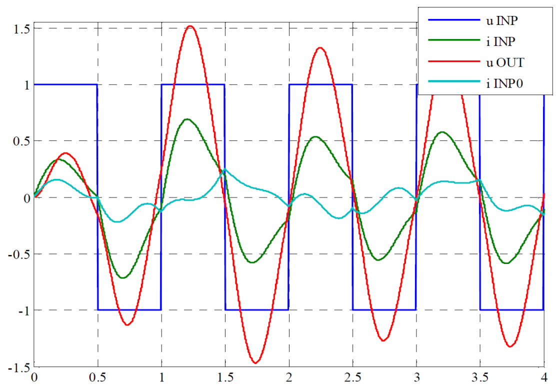


Fig. 4. Simulated waveforms of the LCTLC inverter

$$L_1 = L_{11} + L_\sigma, \frac{1}{L_2} = \frac{1}{L_m} + \frac{1}{L_{22}} \tag{2}$$

where R_σ, L_σ, R_{Fe}, L_m are equivalent parameters of the transformer [11], R_{11}, R_{22} are resistances of LCLC filter elements. The state-space equations will then be

$$\frac{di_{L1}}{dt} = \frac{1}{L_1}u(t) - \frac{R_1}{L_1}i_{L1} - \frac{1}{L_1}u_{C1} - \frac{1}{L_1}u_{C2} \tag{3}$$

$$\frac{di_{L2}}{dt} = \frac{1}{L_2}u_C \tag{4}$$

$$\frac{du_{C1}}{dt} = \frac{1}{C_1}i_{L1} \tag{5}$$

$$\frac{du_{C2}}{dt} = \frac{1}{C_1}i_{L1} - \frac{1}{C_2}i_{L2} - \frac{1}{C_2R_2}u_{C2} - \frac{1}{C_2}i_L \tag{6}$$

$$\frac{di_L}{dt} = \frac{1}{L_{load}}u_{C2} - \frac{R_{load}}{L_{load}}i_L \tag{7}$$

where i_{L1}, i_{L2} are currents through the inductors L_1 and L_2, respectively; i_L is current through the load R_{load}, L_{load}, u_{C1},u_{C2} are capacitor voltages of C_1 and C_2, respectively, $u(t)$ is the output voltage of the converter (filter input voltage).

2.2 THD of Output voltage determination

Impedance of series and parallel part of the LCLC filter is defined by the following equations

$$\begin{aligned} Z_1(j\omega) &= R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \\ &= 0.01Z_N + jZ_N\left(k - \frac{1}{k}\right) \end{aligned} \tag{8}$$

$$\begin{aligned} Y_2(j\omega) &= \frac{1}{R_2} + j\cdot\left(\omega C_2 - \frac{1}{\omega L_2}\right) \\ &= \frac{1}{Z_Z} + j\cdot Z_N^{-1}\cdot\left(k - \frac{1}{k}\right) \end{aligned} \tag{9}$$

$$\begin{aligned} Z_2(j\omega) &= \frac{1}{Y_2} = \frac{1}{\frac{1}{Z_L} + j\frac{1}{Z_N}\left(k-\frac{1}{k}\right)} \\ &= \frac{\frac{1}{Z_L} - j\frac{1}{Z_N}\left(k-\frac{1}{k}\right)}{M} \end{aligned} \tag{10}$$

where Z_L is the load impedance, Z_N is the nominal impedance of the LCLC filter parameters, and M is defined as

$$M = \left(\frac{1}{Z_L}\right)^2 + \frac{1}{Z_N^2}\cdot\left(k-\frac{1}{k}\right)^2 \tag{11}$$

Thus:

$$Z(j\omega) = R_1 Z_N + jZ_N\left(k-\frac{1}{k}\right) + \frac{\frac{1}{Z_Z} - j\cdot Z_N^{-1}\cdot\left(k-\frac{1}{k}\right)}{M} \tag{12}$$

$$Z(j\omega) = \frac{R_1|Z_N|Z_L M + 1}{Z_L M} + j\cdot\left(k-\frac{1}{k}\right)\cdot\frac{|Z_N|^2 M - 1}{|Z_N|M} \tag{13}$$

And the module of the filter impedance is

$$|Z(\omega)| = \sqrt{\left(\frac{R_1|Z_N|Z_L M+1}{Z_L M}\right)^2 + \left[\left(k-\frac{1}{k}\right)^2\frac{|Z_N|^2 M - 1}{|Z_N|M}\right]^2} \tag{14}$$

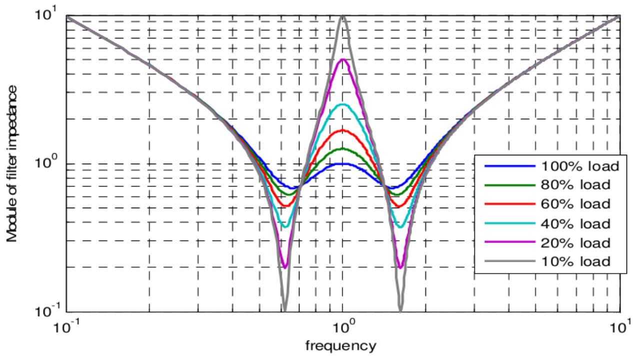
Dependency of filter impedance on frequency is presented in Fig. 5.

The voltage transfer function of LCLC filter $U2/U1$ is

$$F = \frac{U_2}{U_1} = \frac{|Z_2|}{|Z|} = \frac{\sqrt{\left[\frac{1}{Z_L}\right]^2 + \left[\frac{1}{Z_N}\left(k-\frac{1}{k}\right)\right]^2}}{\sqrt{\left(\frac{R_1|Z_N|Z_L M+1}{Z_L}\right)^2 + \left[\left(k-\frac{1}{k}\right)^2\frac{|Z_N|^2 M-1}{|Z_N|}\right]^2}} \tag{15}$$

Dependency of voltage transfer of LCLC filter $U2/U1$ (Bode diagram) is shown in Fig. 6.

From the above characteristics it is possible to determine the total harmonic distortion (THD) of output voltage of the LCLC filter.



x: $\log(\omega/\omega_{res})$; y: Z/Z_N

Fig. 5. Filter impedance vs. frequency for full range of load

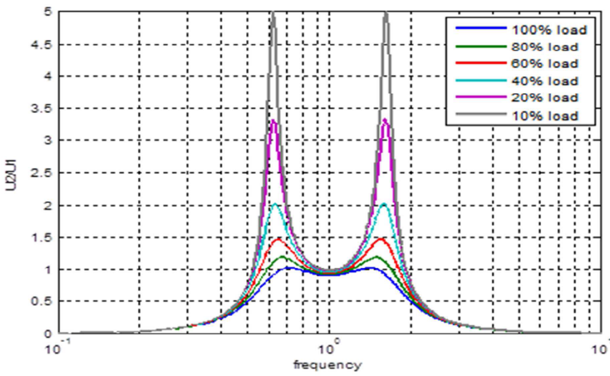


Fig. 6. Voltage transfer function U_2/U_1 of LCLC filter (Bode diagram)

3 DESIGN OF LCLC COMPONENTS

The resonant frequency of L_1C_1 and L_2C_2 should be the same as basic fundamental frequency of the converter and is governed by load requirements. Thus, based on the Thomson relation

$$\omega_{res} = \sqrt{\frac{1}{L_1C_1}} = \sqrt{\frac{1}{L_2C_2}} \tag{16}$$

or, respectively

$$L_1\omega_{res} = \frac{1}{\omega_{res}C_1} = L_2\omega_{res} = \frac{1}{\omega_{res}C_2} \tag{17}$$

where ω_{res} is equal $2\pi\times$ fundamental frequency of the converter. Values of storage LC components and their parameters are important for properties of LCLC filter and/or LCTLC inverter, respectively. Theoretically, ω_{res}, L_1 and other values of Eq. 17 can be chosen from a wide range. For our first design approximation we suppose a simple resonant circuit (Fig. 3) with a resonant frequency equal to the switching input frequency ($\omega_{res} = \omega_{sw}$).

The LC design process can be considered from 3 different points of view or criteria:

1. nominal voltage and current stresses at steady-states
2. minimum voltage and current stresses during transients
3. required value of total harmonic distortion of the output voltage.

In order to not exceed nominal voltages of the storage elements, we used value of internal impedance of the storage element equal to the nominal load $|Z_N|$.

$$L_{res} = \frac{1}{\omega_{res}C} = |Z_N| = \frac{U_1^2}{P_1} \tag{18}$$

where U_1, P_1 are nominal output voltage or power, respectively (fundamental harmonic).

Let's define the nominal design factor q_N for LC components as

$$q_N = \frac{L\omega_{res}}{|Z_N|} = \frac{1}{\omega_{res}C\,|Z_N|} \tag{19}$$

The above equation is similar to quality factor defined by $q = \frac{L_{load}\omega_{res}}{R_{load}}$, however q_N does not depend on the load R_{load}.

From and one can obtain the design formulas for LC storage elements

$$L = \frac{U_1^2}{\omega_1 P_1}q_N \qquad C = \frac{P_1}{\omega_1 U_1^2}\frac{1}{q_N} \tag{20}$$

The voltage on storage elements at nominal steady-state is defined as

$$U_L = L\omega_{res}I_N q_N = L\omega_{res}\frac{P_1}{U_1}q_N \tag{21}$$

$$U_C = \frac{1}{\omega_{res}C}I_N q_N = \frac{1}{\omega_{res}C}\frac{P_1}{U_1}q_N \tag{22}$$

That means that for q_N equal to one, the voltages on storage elements will be nominal values, and are proportionally depend on q_N factor.

Going back to LCLC filter, then

$$L_1 = \frac{U_1^2}{\omega_1 P_1}q_N \qquad C_1 = \frac{P_1}{\omega_1 U_1^2}\frac{1}{q_N} \tag{23}$$

$$L_2 = \frac{U_1^2}{\omega_1 P_1}\frac{1}{q_N} \qquad C_2 = \frac{P_1}{\omega_1 U_1^2}q_N, \tag{24}$$

where U_1, P_1, ω_1 are nominal output voltage, power and frequency, respectively (fundamental harmonic).

Dependence of *THD* on quality factor q is shown in Tab. 1.

Table 1. *THD* of output voltage of LCTLC inverter

Quality factor q	1	1.5	2	2.5
THD [%]	16.6	11.0	8.2	6.6
Quality factor q	3.5	4	4.5	5
THD [%]	4.7	4.1	3.6	3.3

3.1 Calculation of fundamental harmonic of filter output voltage

When considering the equivalence of resonant frequency ω_{res} of LCLC components and the switching frequency of the inverter, the fundamental harmonic of output voltage of LCTLC inverter is defined as

$$U_{2rms} = \frac{2\sqrt{2}}{\pi}U_1\left(1 - \frac{R_1}{R_2}\right) \tag{25}$$

4 PRELIMINARY EXPERIMENTAL RESULTS

4.1 Parameters of the LCTLC circuit

Following parameters have been used for experimental verification: $L_1 = L_2 = 14.61\,\mu$ H,
$C_1 = C_2 = 99$ nF.

Transformer type used:

Type Flyback transformer

P_{out} 2 W

f_T 132 kHz

L_σ $0.6\mu H$

$U_{1,2}$ $5 - 15$ Vrms

Signal generator type: Agilent 33521A

Power linear amplifier type: Krohn-Hite 7500

Settings: $U_1 = 6$ V, $fSW = 132$ kHz, $RL = 12.25$ Ohms.

4.2 Experimental results

Select preliminary experimental results are shown in Figs. 7-10.

Input voltage of the LCTLC filter with full width of pulse is depicted in Fig. 7. It is clear that the waveform is not an ideal square wave. We also investigated an input voltage with 120 deg. width of pulse. Quality-wise, the output voltage was the same, only with varying magnitude. Fig. 8 confirms good quality of the output voltage

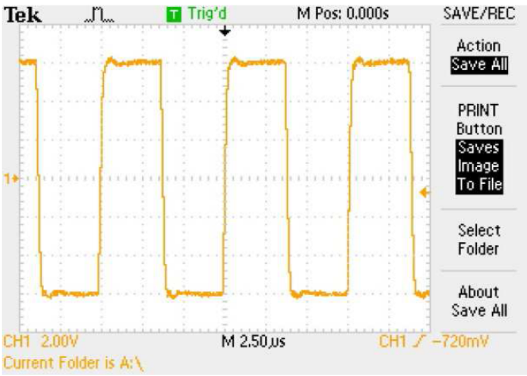


Fig. 7. Input voltage of the LCTLC filter (full width of pulse), no load operation

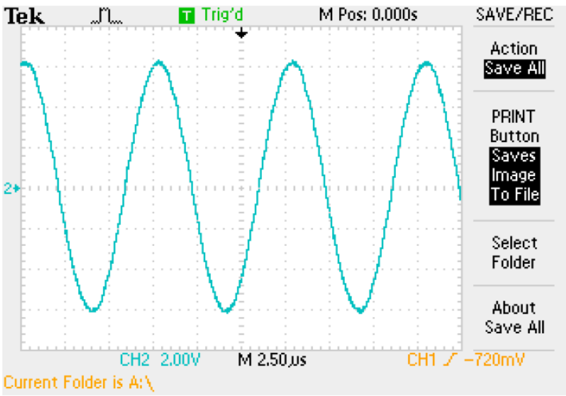


Fig. 8. Output voltage of the LCTLC filter (full width of pulse)

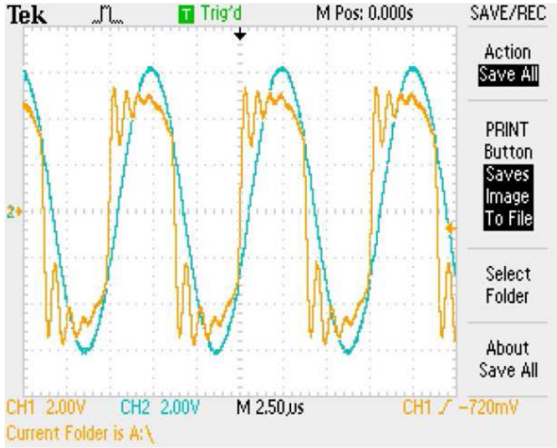


Fig. 9. Input and output voltages of the LCTLC filter (full load)

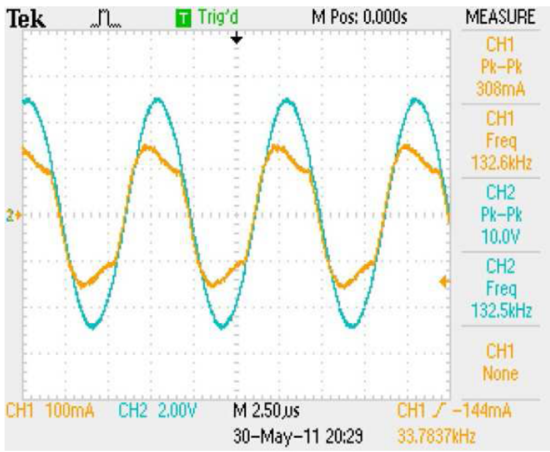


Fig. 10. Input current and output voltages of the LCTLC filter (full load)

shape. Loading caused distortion of the input voltage, as can be seen on Fig. 9., in comparison to no-load operation, Fig. 7. It is also evident that the magnitude (average value) of input voltage in this case, Fig. 9., is only about 4.4 Volts instead of 6 Volts in comparison to Fig. 7. This phenomenon arises due to non-zero impedance of the DC source.

4.3 Comparison of Simulation and Experimental Results

Simulations have been performed using settings identical to those defined in chapter 4.1 of this article: 6 V, full width of pulses, 132 kHz, nominal and no load operation. The results are presented in Fig. 11 and 12.

Based on obtained simulation and experimental results we can conclude that the:

1. output voltage of LCTLC inverter is of high quality ($THD \sim 5\%$)
2. output voltage is nearly constant in the whole range of the load
3. frequency of the voltage is constant.

5 THE SECOND STAGE OF 2-PHASE POWER ELECTRONICS SUPPLY SYSTEM

5.1 Configuration of 2-Stage 2-Phase Power Electronic Supply System

The system consists of high frequency LCTLC inverter and 2-phase high frequency cycloconverter or matrix converter, depending on the control type and commutation required. For ordinary phase control, the cycloconverter is connected to the output of the LCTLC inverter using T/4-symmetric control [10]. The matrix converter has to be

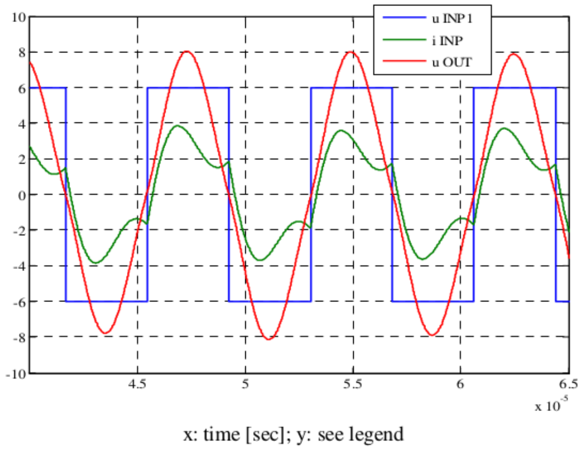


Fig. 11. Input and output quantities of the LCTLC filter (full load)

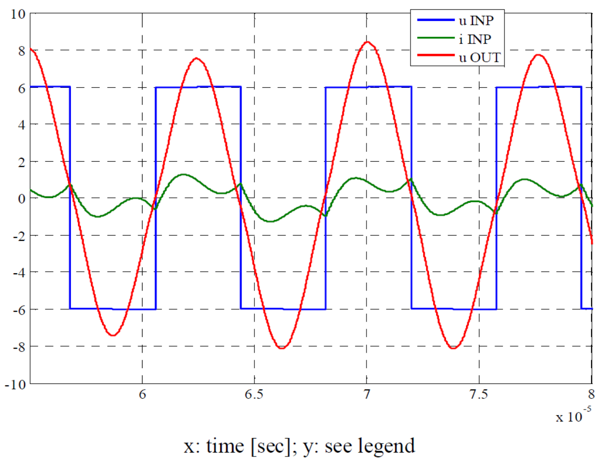


Fig. 12. Input and output quantities of the LCTLC filter (no load)

connected in Figs. 13 and 14 due to the need of forced commutation.

5.2 Calculation of the fundamental harmonic of the cycloconverter output voltage

The fundamental harmonic can be calculated for the output voltage of two-pulse cycloconverter connected to the output of the LCTLC inverter, Fig. 15.

First, we need to know the term

$$\sin(2\omega t)\sin(\omega t) = \frac{1}{2}\left[\cos(2\omega t - \omega t) \; - \cos(2\omega t + \omega t)\right] \tag{26}$$

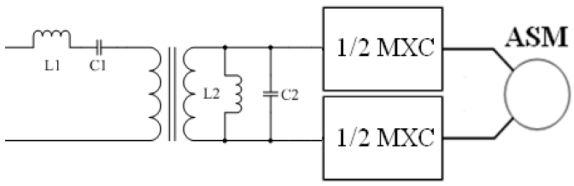


Fig. 13. Connecting of matrix converter to output of LCTLC inverter

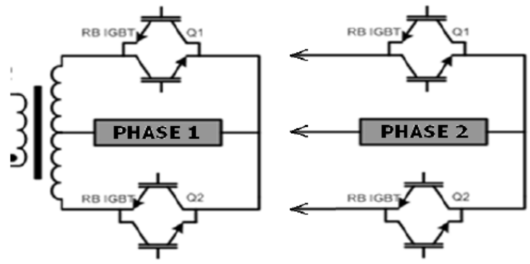


Fig. 14. Circuit scheme of half-bridge matrix converters

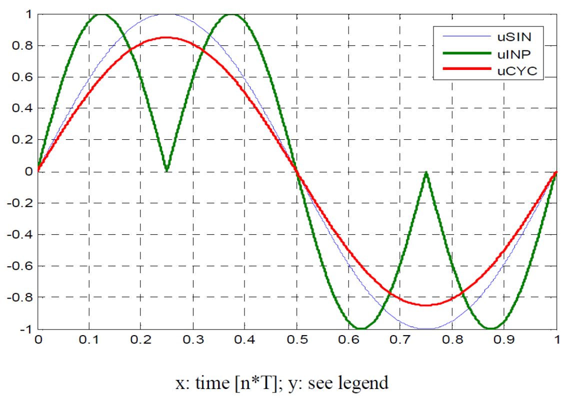


Fig. 15. The output voltage of two-pulse cycloconverter and its fundamental harmonic

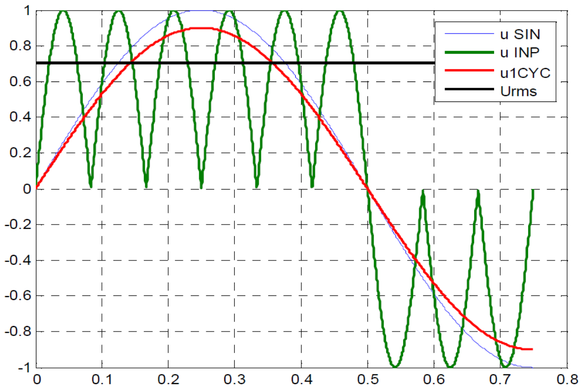


Fig. 16. The output voltage of six-pulse cycloconverter and its fundamental harmonic

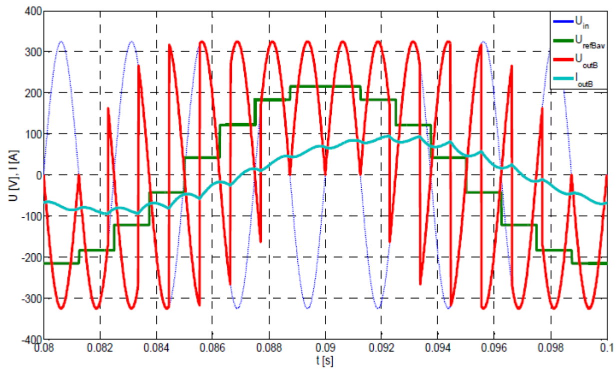


Fig. 17. Output quantities of matrix converter under RL load

Then, continuing the integration

$$U_{2max(1.HARM)} = \frac{8}{T}\int_0^{T/4}\frac{1}{2}[\cos(2\omega t-\omega t)-\cos(2\omega t+\omega t) = \frac{4}{T}\left\{\frac{1}{\omega}[\sin(\omega t)]_0^{T/4}-\frac{1}{3\omega}[\sin(3\omega t)]_0^{T/4}\right\} = \frac{4}{T\omega}\left\{\left[\sin(\omega\frac{T}{4})-\sin(0)\right]-\frac{1}{3}\left[\sin(3\omega\frac{T}{4})-\sin(0)\right]\right\} = \frac{2}{\pi}\left[(1-0)-\frac{1}{3}(-1-0)\right] = \frac{2}{\pi}\left(1+\frac{1}{3}\right) = \frac{2}{\pi}\frac{4}{3} = 0.85 \Rightarrow 0.85\% \tag{27}$$

Thus, the RMS value of the output voltage of the LCTLC inverter should be 1.15-times greater than the requested voltage of the cycloconverter.

THD of the output voltage of cycloconverter for the above determined fundamental harmonic (without phase-control) is

$$THD_{cykl} = \frac{\sqrt{\sum_{k=3}^{\infty}U_{2k}^2}}{U_2} = \frac{\sqrt{U_{EF}^2-U_{1EF}^2}}{U_{EF}} = \sqrt{1-\left(\frac{U_{1EF}}{U_{EF}}\right)^2} = \sqrt{1-\left[\frac{\left(\frac{8}{3\pi}\frac{1}{\sqrt{2}}\right)}{\frac{\sqrt{2}}{2}}\right]^2} = 0,52 = 52\% \tag{28}$$

The maximum theoretical value of cycloconverter fundamental harmonic is shown in Fig. 16.

Since the RMS value of the output voltage of cycloconverter is known $(1/v2)$, the maximum value of the fundamental harmonic magnitude is defined as

$$U_{maxCYC(1.HARM)} = \frac{4}{\pi}\frac{1}{\sqrt{2}} = 0.9006 \tag{29}$$

The controlled output voltage (with $T/4$ symmetry) of matrix converter is shown in Fig. 17.

Harmonic distortion of output voltage and current is possible to decrease using output LC or LCL filter [17].

6 CONCLUSION

Design analysis of high frequency LCTLC inverter has been discussed and presented in this contribution. As was mentioned in the chapter 4, the LCTLC inverter has the following features

1. output voltage of LCTLC inverter is of high quality ($THD \sim 5\%$),
2. the output voltage is nearly constant in whole range of the load,
3. frequency of the voltage is constant.

The output of this type of inverter can be used for second stage presented by two half-bridge inverters or matrix converters, respectively.

In comparison with other types of resonant converters [1-4], the above properties of the LCTLC inverter are very good, and the circulating energy is higher due to four storage elements.

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