ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2011. No. 5(111)
ELEKTRONIKA IR ELEKTROTECHNIKA

AUTOMATION, ROBOTICS
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AUTOMATIZAVIMAS, ROBOTECHNIKA

Transient Analysis and Modelling of 2nd- and 4th-Order LCLC Filter under Non-Symmetrical Control

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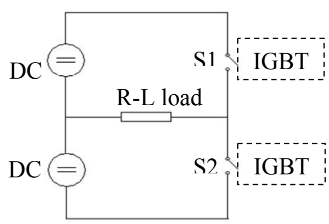
Introduction

The problem how it is possible to obtain sinusoidal voltage at load side under non-harmonic periodical supply from the converters is very important in technical practices. The paper shows possibilities to use either *LCLC* resonant filter for frequency of fundamental harmonic component, or *LC* filter tuned for switching frequency. Both filters have to remove higher harmonic components from the supplying voltage to reach the harmonic distortion roughly 5 %. Using non-symmetrical control the output voltage of inverter comprises all harmonic components, both odd and even ones. The paper deals mainly with analysis and modelling of 4th order *LCLC* filter (of the first type) under non-symmetrical supply and with comparing to the other types of filtering. Simulation results as well as experimental verification confirm good quality of output filter quantities, voltage and current.

Basic connection of single-phase inverter with output resonant filter

The single-phase voltage inverter can be realised in principle as full-bridge [1], [2] or half-bridge connection [3] with DC sources, Fig. 1a. For alternative sources there are either single-phase AC-AC converter – type of cyclo-converter (if it is a natural commutation and $f_1 > f_2$) or single-phase matrix converter (with a forced commutation and $f_1 > f_2$ or $f_1 < f_2$), Fig. 1b, [4], [5]. In case of the harmonic sinusoidal voltage of load demand, it is possible to use resonant AC filter tuned to base harmonic, or filter tuned to switching frequency on converter output, Fig. 2a,b.



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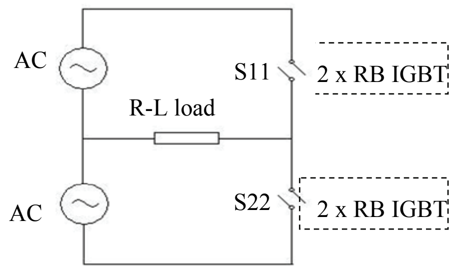
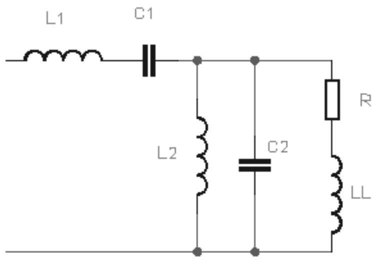
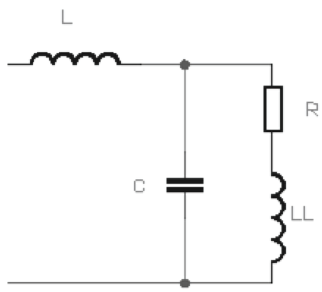


b)

Fig. 1. Principle schematic connections of the single-phase half-bridge voltage inverter: a – the single-phase DC-AC inverter supplied from DC sources; b – the single-phase AC-AC inverter supplied from AC sources



a)

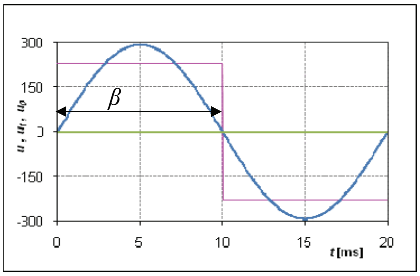


b)

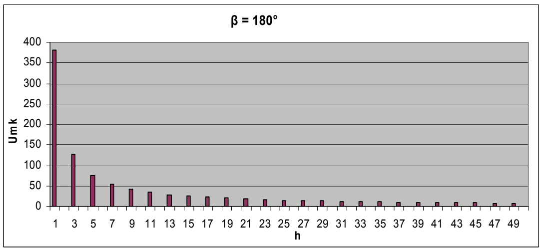
Fig. 2. Principle schematic connections of the single-phase voltage inverter and the output filter: a – the output resonant filter with basic resonance frequency; b – the output resonant filter with switching resonance frequency

Transient analysis and modelling of 4th-order *LCLC* filter under symmetrical control

Output voltage of the inverter contains by wide spectrum of higher harmonic components. Full-width waveform is depicted in Fig. 3a. Harmonic content (odd harmonics, THD = 43.5 %) is shown in Fig. 3b, [6, 7].



a)



b)

Fig. 3. Full-width output voltage (β = 180°el.) of the inverter (a) and its harmonic content without filtering (b) [6, 7]

Using Fourier theory one can derive relation (1) for basic harmonic amplitude of output voltage of inverter

$$\frac{U_{1M}(\beta)}{U} = \frac{4}{\pi}\sin(\beta/2), \qquad (1)$$

where $U_{1M}(\beta)$ is amplitude of fundamental harmonic depending on voltage pulse width β; U is maximum value of inverter input *DC* voltage; β is voltage pulse width under the range of 0-180 °el. deg., whereby

$$\beta = \pi - \alpha, \qquad (2)$$

where α is control angle oriented from end of half-period to the end of positive voltage pulse.

Considering converter scheme in Fig. 1a and *LCLC* filter in Fig. 2a with inductor resistance r_L and capacitor resistance r_C then the state-space equations can be [8]:

$$\begin{cases} \dfrac{di_{L1}}{dt} = \dfrac{1}{L_1}u(t) - \dfrac{r_{L1}}{L_1}i_{L1} - \dfrac{1}{L_1}u_{C1} - \dfrac{1}{L_1}u_{C2}, \\ \dfrac{di_{L2}}{dt} = \dfrac{1}{L_2}u_{C2}, \\ \dfrac{du_{C1}}{dt} = \dfrac{1}{C_1}i_{L1}, \\ \dfrac{du_{C2}}{dt} = \dfrac{1}{C_1}i_{L1} - \dfrac{1}{C_2}i_{L2} - \dfrac{1}{C_2 \cdot r_{C2}}u_{C2} - \dfrac{1}{C_2}i_{LL}, \\ \dfrac{di_{LL}}{dt} = \dfrac{1}{L_L}u_{C2} - \dfrac{R}{L_L}i_{LL}, \end{cases} \qquad (3)$$

where $L_1 = L_2 \rightarrow r_{L1} = r_{L2}$; $C_1 = C_2 \rightarrow r_{C1} = r_{C2}$.

After time discretization of system equations using implicit Euler's methods

$$\overline{x}_{n+1} = h\left(\mathbf{A}\overline{x}_{n+1} + \mathbf{B}\overline{u}_n\right) + \overline{x}_n, \qquad (4)$$

it yields

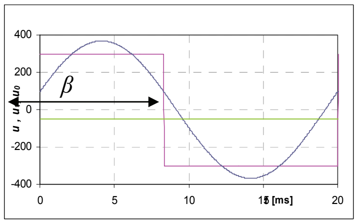
$$\begin{bmatrix} i_{L1}(i+1) \\ i_{L2}(i+1) \\ u_{C1}(i+1) \\ u_{C2}(i+1) \\ i_{LL}(i+1) \end{bmatrix} = [\mathbf{J} - h\mathbf{A}]^{-1} \begin{bmatrix} i_{L1}(i) \\ i_{L2}(i) \\ u_{C1}(i) \\ u_{C2}(i) \\ i_{LL}(i) \end{bmatrix} + [\mathbf{J} - h\mathbf{A}]^{-1} u(t)\, h \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \qquad (5)$$

where
$$\mathbf{A} = \begin{pmatrix} \frac{-r_L}{L} & 0 & \frac{-1}{L} & \frac{-1}{L} & 0 \\ 0 & 0 & 0 & \frac{1}{L} & 0 \\ \frac{1}{C} & 0 & 0 & 0 & 0 \\ \frac{1}{C} & \frac{-1}{C} & 0 & \frac{-1}{C r_C} & \frac{-1}{C} \\ 0 & 0 & 0 & \frac{1}{L_L} & \frac{-R}{L_L} \end{pmatrix}; \qquad (6)$$

i_{L1}, i_{L2} are currents through the inductors L_1 and L_2; i_{LL} is current through the load R, L_L; u_{C1}, u_{C2} are voltages of the capacitors C_1 and C_2; **J** is unit matrix; **A** is system matrix; h is step size and $u(t)$ is output voltage of the inverter.

Transient analysis and modelling of 4th-order *LCLC* filter under non-symmetrical control

The real output voltage of inverter waveform has a wide spectrum of harmonic components. Using non-symmetrical control the output voltage of inverter (Fig. 4a) comprises all harmonic components, both odd and even ones of Fourier series as it is shown in Fig. 4b, [6, 7].



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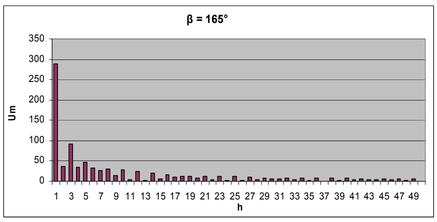


b)

Fig. 4. The output voltage of the 1-phase inverter under non-symmetrical control 165/180°el (a) and its harmonic content without filtering (b), [6, 7]

The distortion is quite large, e.g. for 2/3-non-symmetrical it is 62.5 %.

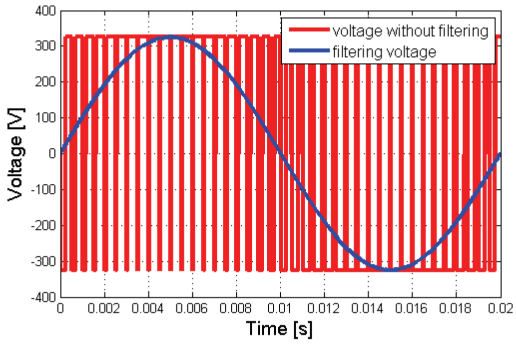
Using Fourier theory one can derive relation (4) for basic harmonic amplitude of output voltage of inverter

$$\frac{U_{1M}(\beta)}{U} = \frac{2\sqrt{2}}{\pi}\sqrt{1-\cos(\beta/2)}\,. \qquad (7)$$

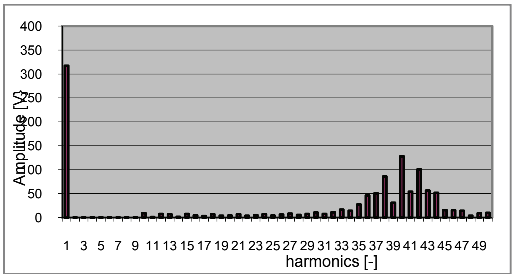
Considering converter scheme in Fig. 1a and *LCLC* filter in Fig. 2a under non-symmetrical control then the state-space equations are the same as (3), (5) with symmetrical output voltage of inverter $u(t)$.

Transient analysis and modelling of 2nd-order LC filter under bipolar PWM control

The output voltage of AC link inverter [9, 10] is depicted in Fig. 5a.The harmonic spectrum of that is shown in Figs. 5b, 5c.



a)



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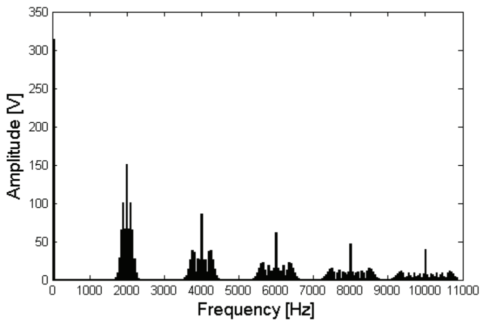

c)

Fig. 5. The output voltage of the 1-phase inverter under bipolar PWM control (a) and its harmonic content without filtering (b) and its frequency content (c)

The harmonics in the inverter output voltage waveform appear as a sidebands, centred around the switching frequency and its multiples. It follows, that output voltage does not have higher harmonic components around the fundamental frequency. Now is not necessary to use the output resonant filter tuned to fundamental frequency, but there should be used output resonant filter tuned to switching frequency, which is depicted in Fig. 2b.

Considering converter scheme in Fig. 1a and *LC* filter in Fig. 2b then the state-space equations can be written:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L}u(t) - \dfrac{r_L}{L}i_L - \dfrac{1}{L}u_C\,, \\ \dfrac{du_C}{dt} = \dfrac{1}{C}i_L - \dfrac{1}{C.r_C}u_C - \dfrac{1}{C}i_{LL}\,, \\ \dfrac{di_{LL}}{dt} = \dfrac{1}{L_L}u_C - \dfrac{R}{L_L}i_{LL}\,. \end{cases} \qquad (8)$$

After time discretization of system equations using implicit Euler's methods

$$\begin{bmatrix} i_L(i+1) \\ u_C(i+1) \\ i_{LL}(i+1) \end{bmatrix} = [\mathbf{J} - h\mathbf{A}]^{-1}\begin{bmatrix} i_L(i) \\ u_C(i) \\ i_{LL}(i) \end{bmatrix} + [\mathbf{J} - h\mathbf{A}]^{-1}\begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} u(t) * h\,, \quad (9)$$

where

$$\mathbf{A} = \begin{pmatrix} \frac{-r_L}{L} & \frac{-1}{L} & 0 \\ \frac{1}{C} & \frac{-1}{C \cdot r_C} & \frac{-1}{C} \\ 0 & \frac{1}{L_L} & \frac{-R}{L_L} \end{pmatrix}; \qquad (10)$$

i_L is current during the inductor L of *LCLC* filter; u_C is voltage of the capacitor C of *LCLC* filter; i_{LL} is current during the load R, L_L

Results of numerical simulation and experimental verifications of transient

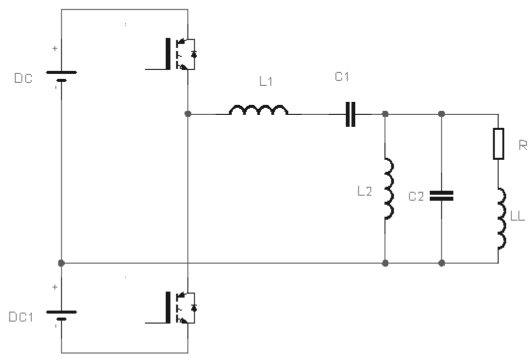

Fig. 6. Simulation circuit half-bridge connection of inverter with LCLC filter

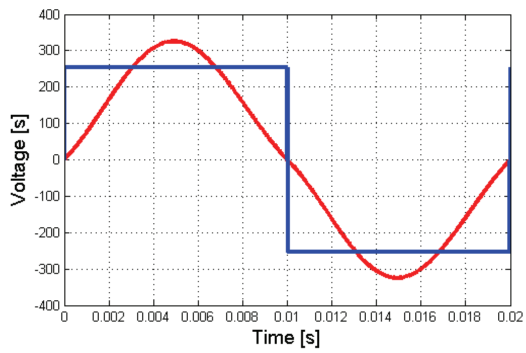

Fig. 7. LCLC filter output voltage (red) in steady-state with full-wide of impulses (symmetrical, β = 180°el.)

The output capacitor voltage of *LCLC* filter for load disconnect in time at maximum output filter voltage embodies overvoltage for symmetrical control (Figs.8, 12) and for non-symmetrical control too (Fig.10). The overvoltage is higher for the (resonant) quality factor Q equal two.

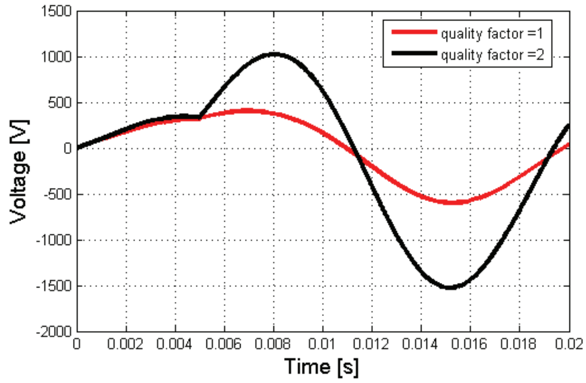

Fig. 8. Output capacitor voltage of LCLC filter for load disconnect in time at maximum output filter voltage, quality factor Q is equal one (red) and two (black)

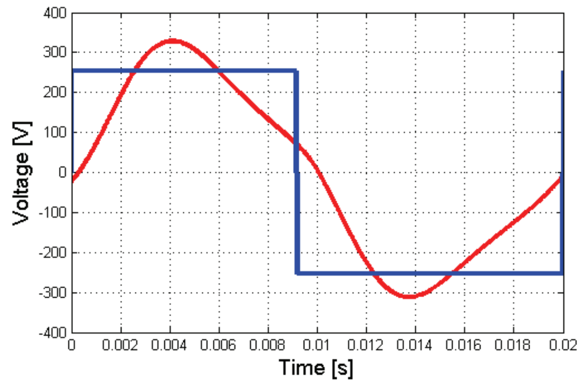

Fig. 9. Output capacitor voltage of LCLC filter under non-symmetrical phase control 165/180°el

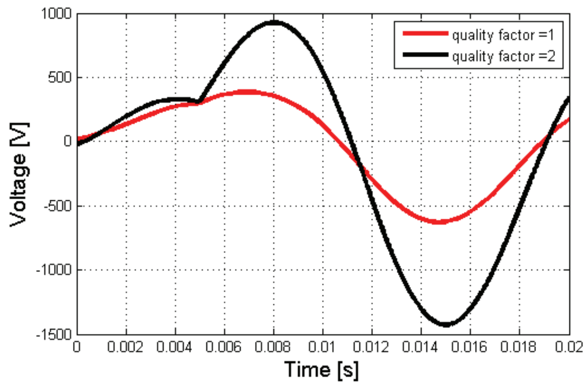

Fig. 10. Output capacitor voltage of LCLC filter for load disconnect in time of maximum output filter voltage under non-symmetrical phase control 165/180°el. for quality factor Q is equal one (red) and two (black)

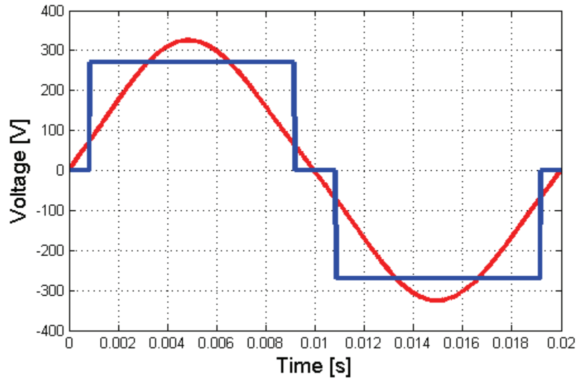

Fig. 11. Output capacitor voltage of LCLC filter under symmetrical control with no full-wide of impulses

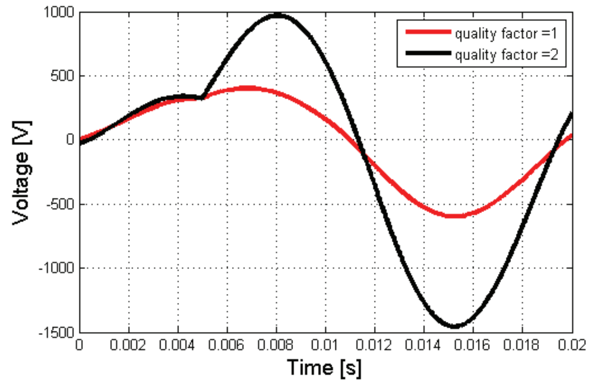

Fig. 12. Output capacitor voltage of LCLC filter for load disconnect in time of maximum output filter voltage under symmetrical control with no full-wide of impulses for quality factor Q is equal one (red) and two (black)

As it is shown on Fig. 13 and 14 load current has minor current overshoots in case of load start-up but bring one of the output capacitor voltage.

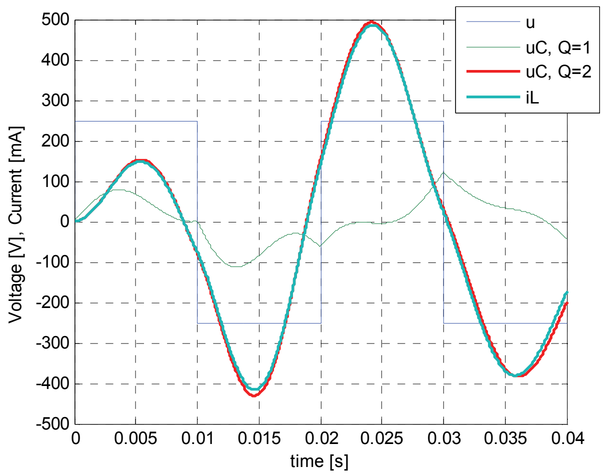

Fig. 13. Output capacitor voltage of LCLC filter u_C for two value of quality factor and input current of LCLC filter for no load start up with full-wide of impulses

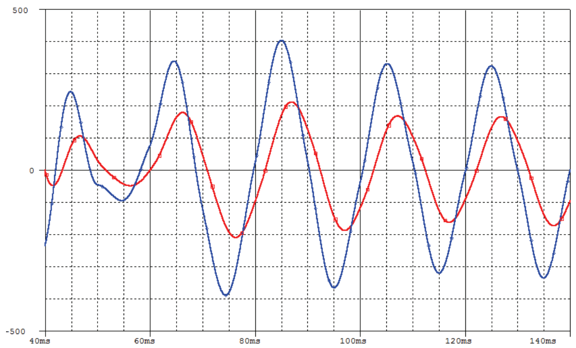

Fig. 14. Output capacitor voltage of LCLC filter u_C (blue) and load current i_{LL} (red) for load start up with no full-wide of impulses

In case of simulation of 2nd-order LC filter it is evident that output capacitor voltage of LC filter for load disconnect in time of maximum output filter voltage no embodies high overvoltage, Fig. 17. It has only temporary growth of voltage amplitude because saved energy of inductor is only 5% of load energy. This is better choice of filter realization (Fig. 18). The measured voltage of inductive load is shown on Fig. 19.

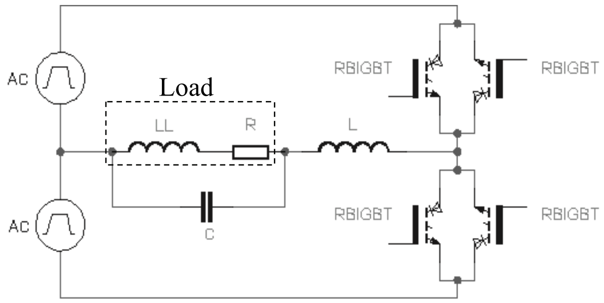

Fig. 15. Simulation circuit half-bridge matrix connection of inverter with LC filter

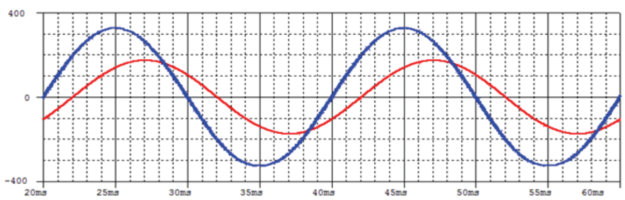

Fig. 16. The load current and voltage time behaviour with passive LC filter

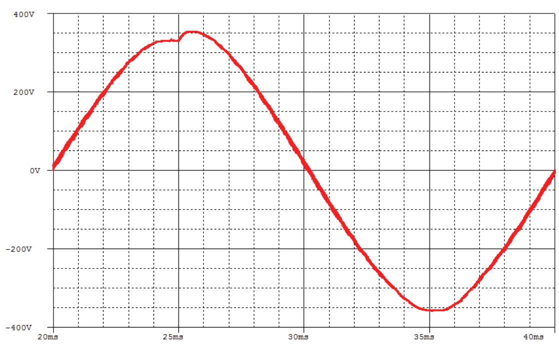

Fig. 17. Output capacitor voltage of matrix LC filter for load disconnection in time of maximum output filter voltage

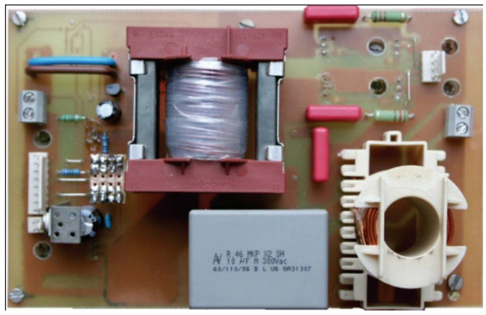

Fig. 18. The real half-bridge matrix connection of inverter with LC filter

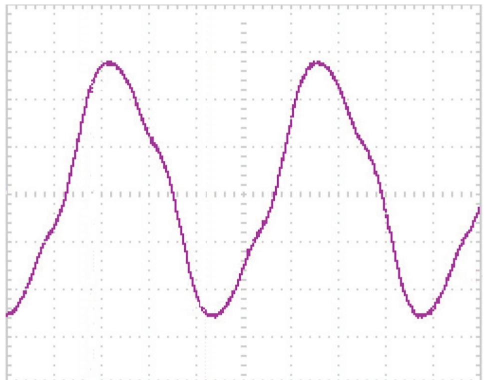

Fig. 19. The measured voltage of inductive load in half-bridge matrix connection of inverter with LC filter

Conclusions

The *LCLC* resonant filter for frequency of fundamental harmonic component, or *LC* filter tuned for switching frequency has been realised. Both filters have to remove higher harmonic components from the supplying voltage, but output load voltages have had the harmonic distortion roughly 5 %. Using non-symmetrical control the output voltage of inverter comprises all harmonic components, both odd and even ones, but output load voltage have had the small harmonic distortion. Simulation results as well as experimental verification confirm good quality of output quantities of the filter, voltage and current.

Acknowledgement

The authors wish to thank for the financial support to R&D operational program Centre of excellence of power electronics systems and materials for their components No. OPVaV-2008/2.1/01-SORO, ITMS 26220120003 funded by European regional development fund (ERDF), and VEGA 1/0470/09.

References

1. **Dobrucky B., Benova M., Spanik P.**: Using Complex Conjugated Magnitudes – and Orthogonal Park/Clarke Transformation Methods of DC/AC Frequency Converter// Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 5(93). – P. 29–34
2. **Dobrucky B., Prazenica M., Benova M.**: Converter Topology Design for Two–Phase Low–Cost Industrial and Transport Applications // Logistyka, 2009. – No. 6. – P. 11–14.

3. **Mohan N., Undeland T. M., Robbins W. P.**: Power Electronics: Converters, Applications, and Design. – John Wiley & Sons, Inc., 2003. – 667 p.
4. **Benova M., Dobrucky B., Szychta E., Prazenica M.** Modelling and Simulation of HF Half–Bridge Matrix Converter System in Frequency Domain // Proc. of Trans–Comp'09 Int'l Conf. on Computer Systems Aided Science, Industry and Transport. – Poland, Zakopane, 2009. – P. 39–42
5. **Zuckerberger A., Weinstock D., Alexandrovitz A.:** Single – Phase Matrix Converter // Proceeding of IEE Electrical Power Applications, 1997. – No. 4(144). – P. 235–240.
6. **Dobrucky B., Benova M., Kascak M.** The Theoretical Analysis of Power Resonant Filter under Non–sinusoidal Sources and Non–symmetrical Control // Proceedings of the 18th Technical Computing Bratislava Conference. – Bratislava, 2010. (In CD–ROM).
7. **Zaskalicka M., Zaskalicky P., Benova M., Abdalmula M. A. R., Dobrucky B.** Analysis of Complex Time Function of Converter Output Quantities Using Complex Fourier Transform/Series // Communications – Scientific Letters of the University of Zilina, 2010. – No. 1(12). – P. 23–30.
8. **Ang Y. A., Foster M. P., Bingham C. M., Stone D. A., Sewell H. I.,Howe D.** Analysis of 4th–order LCLC Resonant power converters // Proceeding of IEE Electrical Power Applications, 2004. – No. 2(131). – P. 169–181.
9. **Dobrucky B., Spanik P., Kabasta M.** Power Electronics Two–Phase Orthogonal System with HF Input and Variable Output // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 1(89). – P. 9–14
10. **Jeevananthan S., Dananjayan P., Madhavan R.** Novel Single–Phase To Single–Phase Cycloconversion Strategies: Mathematical And Simulations Studies // International Journal of Power And Energy Systems, 2007. – Vol. 27. – No. 4. – P. 414–423.

Received 2011 02 15

B. Dobrucky, M. Benova, S. Kascak. Transient Analysis and Modelling of 2nd- and 4th-Order LCLC Filter under Non-Symmetrical Control // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 5(111). – P. 89–94.

The paper shows how it is possible to obtain the harmonic sinusoidal voltage on the load side at non-harmonic periodical supplying from the converters. It can be used either LCLC resonant filter for frequency of fundamental harmonic component, or LC filter tuned for switching frequency. Both filters have to remove higher harmonic components from the supplying voltage to reach the harmonic distortion roughly 5 %. The paper deals mainly with analysis and modelling of 4^{th} order LCLC filter (of the first type) under non-symmetrical supply and with comparing to the other types of filtering. Simulation results as well as experimental verification confirm good quality of output quantities of the filter. Ill. 19, bibl. 10 (in English; abstracts in English and Lithuanian).

B. Dobrucky, M. Benova, S. Kascak. Antros ir ketvirtos eilės LCLC filtro pereinamojo proceso analizė ir modeliavimas taikant nesimetriškąją kontrolę // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 5(111). – P. 89–94.

Apžvelgiama galimybė gauti sinusinį įtampos signalą, kai, prijungus apkrovą iš keitiklių gaunami neharmoninės formos įtampos signalai. Tam gali būti panaudoti pagrindinės harmonikos rezonansinio dažnio LCLC filtrai arba persijungimo dažnio LC filtras. Abiem atvejais reikia pašalinti aukštesniąsias harmonikų dedamąsias. Darbe analizuojamos ketvirtos eilės LCLC filtras. Modeliavimo rezultatus patvirtina eksperimentinių tyrimų rezultatai. Il. 19, bibl. 10 (anglų kalba; santraukos anglų ir lietuvių k.).