TECHNICAL UNIVERSITY – SOFIA
Department Theoretical Electrical Engineering

# 11TH SUMMER SCHOOL

## ADVANCED ASPECTS OF THEORETICAL ELECTRICAL ENGINEERING

# Sofia'16

## PROCEEDINGS

Edited by: Valeri Mladenov
Snejana Terzieva

in the framework of

DAYS OF SCIENCE
OF THE TECHNICAL UNIVERSITY OF SOFIA

**Sofia'16, BULGARIA, 15-16.IX.2016**

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The Summer School is organized by the Department of Theoretical Electrical Engineering at the Technical University of Sofia in the framework of the “Days of Science of the Technical University of Sofia”, Sofia, Bulgaria, September 2016

Technical University of Sofia, Bulgaria

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Edited by: **Valeri Mladenov**
**Snejana Terzieva**

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# SIMULATION OF SINUSOIDAL VOLTAGE INVERTER USING REDUCING SWITCHING LOSSES PWM STRATEGY

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***Abstract**: The article examines the work of a converter that synthesizes sinusoidal voltage supply to the active-inductive load through method of controlled high-frequency pulses with sinusoidal pulse-width modulation. High frequency semiconductor key elements of the converter switched at zero current, i.e. with reduced switching losses, each high-frequency pulse transmitted to the load range specified quantity / dose / energy. The linear dependence on active power in load to the first harmonic amplitude of load voltage and regulation angle respectively is achieved. Simulations on the operation of the converter to achieve a sinusoidal voltage in the converter output are carried out. Simulink model of the investigated converter is composed.*

**Keywords:** *simulation, converter, PWM, power losses, model, SIMULINK*

## 1. INTRODUCTION

Pulse width modulation PWM is used in a variety of applications including sophisticated control circuitry [1, 2 and 3]. PWM is used in many industrial mostly for controlling the voltage of the DC –AC converters using the full bridge mode PWM feature. PWM been widely used for control of AC motors [4]. The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on and power is being transferred to the load, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero [6].

High frequency PWM power control systems are easily realisable with semiconductor switches. Almost no power is dissipated by the switch in either on or off state. However, during the transitions between on and off states, both voltage and current are nonzero and thus power is dissipated in the switches. By quickly changing the state between fully on and fully off (typically less than 100 nanoseconds), the power dissipation in the switches can be quite low compared to the power being delivered to the load. Modern semiconductor switches such as MOSFETs or insulated-gate bipolar transistors (IGBTs) are well suited components for high-efficiency controllers. By switching voltage to the load with the appropriate duty cycle, the output will approximate a voltage at the desired level. The switching noise is usually filtered with an inductor and a capacitor or both. There are more sophisticated methods to eliminate harmonics [5, 7].

## 2. MODEL OF THE SINUSOIDAL VOLTAGE INVERTOR

The first step in this work was to create the model of the inverter.

The circuit model of the studied sine voltage inverter is shown in Fig. 1.

In this case the studied system consists of the following blocks: high-frequency inverter, switch, filter-load [2].

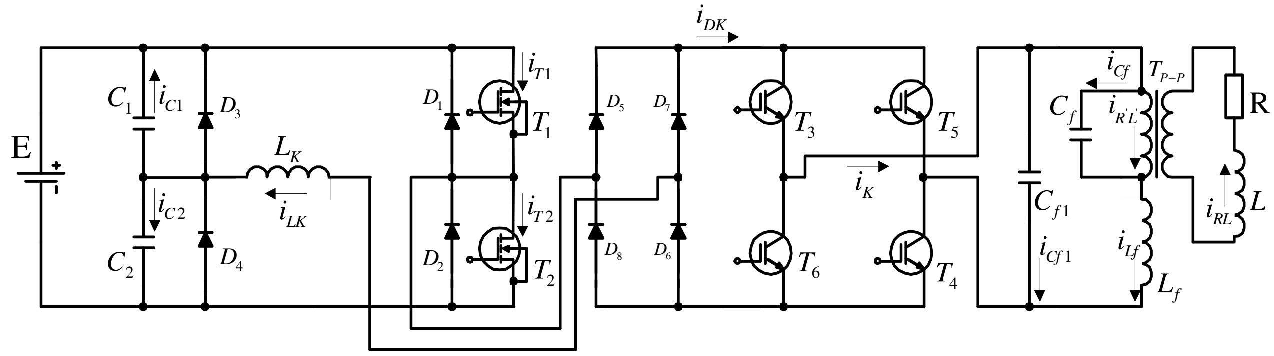

Fig. 1. Circuit model of the studied invertor

The high-frequency inverter includes elements: power source $E$; switching / dispensing / capacitors $C_1$ and $C_2$ /$C_1 = C_2$/; switching inductance $L_k$; transistors $T_1$ and $T_2$; reverse diodes $D_1$ and $D_2$; dosing diodes $D_3$ and $D_4$.

The commutator consists of a bridge rectifier / diode $D_5 \div D_8$ / and bridge inverter / IGBT modules $T_3 \div T_6$ and the corresponding set diodes diode - $D_9 \div D_{12}$/. The inverter operates at a voltage load frequency of 50Hz.

The filter contains the elements: inductance $L_f$; capacitors $C_f$ and $C_{f1}$, respecttively.

Active-inductive load / elements $R$ and $L$ / connects via a separating transformer to the converter.

## 3. ANALYSIS OF THE SINUSOIDAL VOLTAGE INVERTOR

A control signal $u_G$ is produced by Sinusoidal Pulse Width Modulation /SPWM/ [2].

The period of this signal perform equality. $T_{u_G} = \frac{1}{2}T_\sim$. $T_\sim$ and $f_\sim/f_\sim = \frac{1}{T_\sim}/$ are respectively the period and frequency of low frequency sinusoidal voltage, supplied to the active-inductive load.

Voltages $u_{GT1}$ and $u_{GT2}$ are voltage pulses respectively of transistors $T_1$ and $T_2$ of high frequency inverter / HFI /. The pulses have frequency $f$ and period $T$. They are submitted to the $T_1$ and $T_2$ in time slots. The frequencies fulfill the condition$f \gg f_\sim$.

Control voltages for $u_{GT1}$ and $u_{GT2}$ are obtained from a high-frequency pulse generator. Authorizing the operation of the generator is positive front of the control signal $u_G$. Each control pulse supplied to the transistors $T_1$ and $T_1$, contained in one time interval is marked with its starting point $t_j(j = 1 \div n,\ n = 2k,\ k = 1 \div \infty)$.

For $T_1$ are submitted pulses with odd number, but for $T_1$ - even number $j$.

Control system of converter always monitors a count on high-frequency pulses $u_{GT1}$ and $u_{GT2}$ for one time interval of SPWM control signal to be equal numbers.

Low-frequency bridge inverter / LFBI / work synchronously with SPWM signal $u_G$.

IGBT modules T3, T4; T5, T6 are controlled respectively by impulses $u_{GT3}, u_{GT4}, u_{GT5}$ and $u_{GT6}$ ($u_{GT3} \equiv u_{GT4}, u_{GT5} \equiv u_{GT6}$ ) with period $T_{\sim}$ and filling 50%. Couples of elements (T3, T4 and T5, T6) work opposite (anti-tact).

Currents $i_{T1}, i_{T2}$ in transistors$T_1$, $T_2$, the current through the switching inductance $L_k$ respectively have oscillatory nature.

Voltages $u_{C1}, u_{C2}$ of the capacitors $C_1, C_2$ immediately following the first half period of the operation of HFI are amended in the range of 0 to the level of the power source *E*. The voltages fulfill the condition

$$u_{C1} + u_{C2} = E \tag{1}$$

The capacitors $C_1, C_2$ are diluted from $E$ to 0 respectively, when the transistors $T_1$ is turned on and $T_2$ is turned off, respectively. The charge of capacitors $C_1, C_2$ from 0 to power source $E$ is performed at turning on transistors $T_2$ and $T_1$ is turned off, respectively.

In every discharge capacitor gives a precise quantity / dose / energy $W_C$, defined by the expression (2), which by the end of the corresponding half period from the work of HFI is transferred to the blocks filter-loads.

$$W_C = \frac{C_1.E^2}{2} \tag{2}$$

The bridge rectifier /D5 ÷ D8/, from the block converter, confronts current $i_{Lk}$, flowing through the commutation inductance $L_k$ of HFI

$$i_{Lk} = i_{T1} - i_{T2} \tag{3}$$

and converts it in the form $i_{Dk}$

$$i_{Dk} = i_{T1} + i_{T2} \tag{4}$$

The process of straightening guarantees zero initial conditions for currents, when transistors $T_1$, $T_2$ are switched of HFI.

The low-frequency bridge inverter LHBI is worked synchronously with control signal $u_G$. LHBI inverts the current by intervals $\frac{T_{\sim}}{2}$ in response to a half-period of low frequency sinusoidal voltage in inverter load.

LHBI converts the current $i_{Dk}$ in kind of$i_k$. The current $i_k$ is periodical and has period $T_{\sim}$. Each of high frequency current impulses, including in positive and negative half-wave of current $i_k$, is connected with a precise quantity / dose / energy $W_C$, transferred to the blocks filter-loads.

The energy of the high-frequency pulses of individual half-cycle of $i_k$ is initially accumulated in the filter capacitor $C_{f1}$. The current is the sum of low -frequency harmonic component at a frequency $f_{\sim}$ on which are superimposed high-frequency pulses, corresponding in time to those of the current. $i_k$ Filter inductance $L_f$ converts the energy of high-energy pulses of low frequency harmonic mode characteristic of filter-blocks load. The current $i_{Lf}$ has a sinusoidal shape and frequency $f_{\sim}$.

The capacitor $C_f$ is required for further filtering the voltage supplied to the active-inductive load, whereby it acquires the required sinusoidal shape.

The analysis of the processes in the scheme (Fig. 1) is carried out in consideration of semiconductor elements such as ideal keys.

The processes in the scheme of converter (Fig. 1) for the moment, in which the transistor T1 is opened, a T2 is clogged and operates one of the pairs IGBT modules /T3, T4 or T5, T6/ are described by system of integral-differential equations /IDE/ (5).

$$\left|\begin{aligned} i_{T1} &= i_{C1} + i_{C2} \\ L_k \frac{di_{T1}}{dt} + u_{Cf_1} &= u_{C1} \\ L_k \frac{di_{T1}}{dt} + u_{Cf_1} + u_{C2} &= E \\ i_{Cf_1} &= i_{T1} - i_{Lf}(t_j) \\ u_{Cf_1} &= \frac{1}{C_{f_1}} \int_{t_j}^{t} i_{Cf_1} dt \\ u_{C1} &= E - \frac{1}{C_1} \int_{t_j}^{t} i_{C1} dt \\ u_{C2} &= \frac{1}{C_2} \int_{t_j}^{t} i_{C2} dt \end{aligned}\right. \tag{5}$$

The initial conditions for the elements of HFI are $u_{C1}(t_j) = E$ , $u_{C2}(t_j) = 0$ and $i_{T1}(t_j) = i_{Lk}(t_j) = 0$ .

The initial conditions for the elements of filter-block load are accepted the instantaneous values for $t = t_j$ of voltages $u_{Cf_1}(t_j), u_{Cf}(t_j)$ and currents $i_{Lf}(t_j)$ and $i_{RL}(t_j)$.

Solutions for variables $u_{Cf}(t), i_{Lf}(t), i_{RL}(t)$ are obtained by analysis of sinusoidal mode in blocks filter-load.

For the moment, the scheme reflects the process, that the contour of HFI, consisting of the elements $C_k, T_1$ *and* $L_k$ brings a dose of energy in block filter-load.

The case, in which T2 is opened and T1 is clogged and works with either pair IGBT modules is completely analogous to those described by IDE (5).

## 4. RESULTS OF SIMULATION

The simulations of invertor with MATLAB software package are performed.

Simulink toolbox from the package is used. The Simulink model is shown in Fig. 2.

The Simulink model consists of high-frequency inverter, commutator, separating transformer, filter, active-inductive load and control block.

The high-frequency inverter contains of power source; the models switching /dispensing/ capacitors, switching inductance, transistors, reverse diodes and dosing diodes. The commutator contains models of bridge rectifier and bridge inverter.

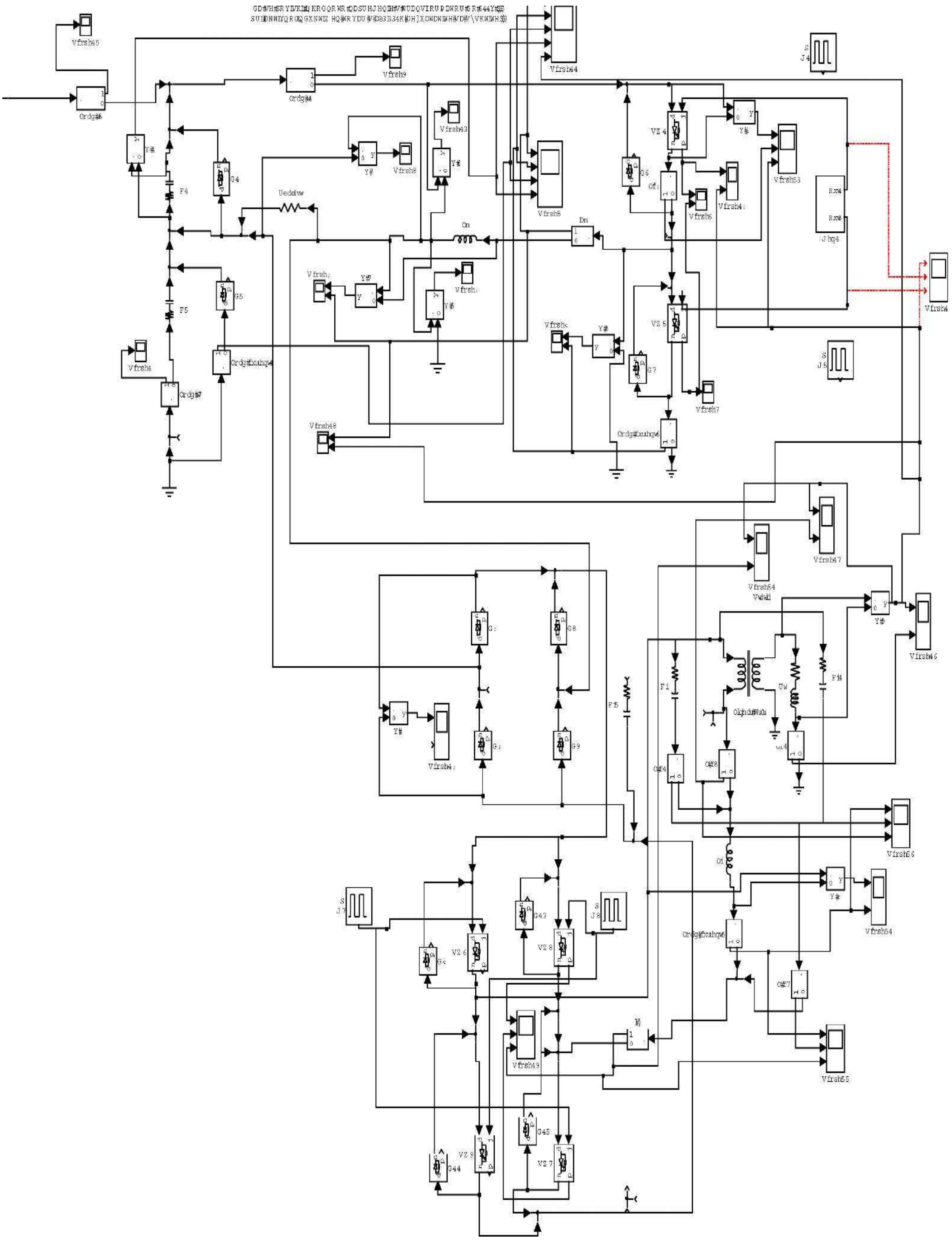

Fig. 2. Simulink model of the studied system

The filter contains the elements: inductance and filtering capacitors for alternative current and first harmonic of voltage.

The simulations are performed at different parameters of load / resistance and inductance/ and different power of consumer.

The nominal full power of investigated inverter is 600 VA. The load connected to the output is changed from pure active to active-inductive.

Voltages $u_{GT1}$, $u_{GT2}$ and currents $i_{GT1}$, $i_{GT2}$, obtained from a high-frequency pulse generator, are shown in fig. 3.

Transient process for forming of the sinusoidal voltage in load are shown in fig. 4.

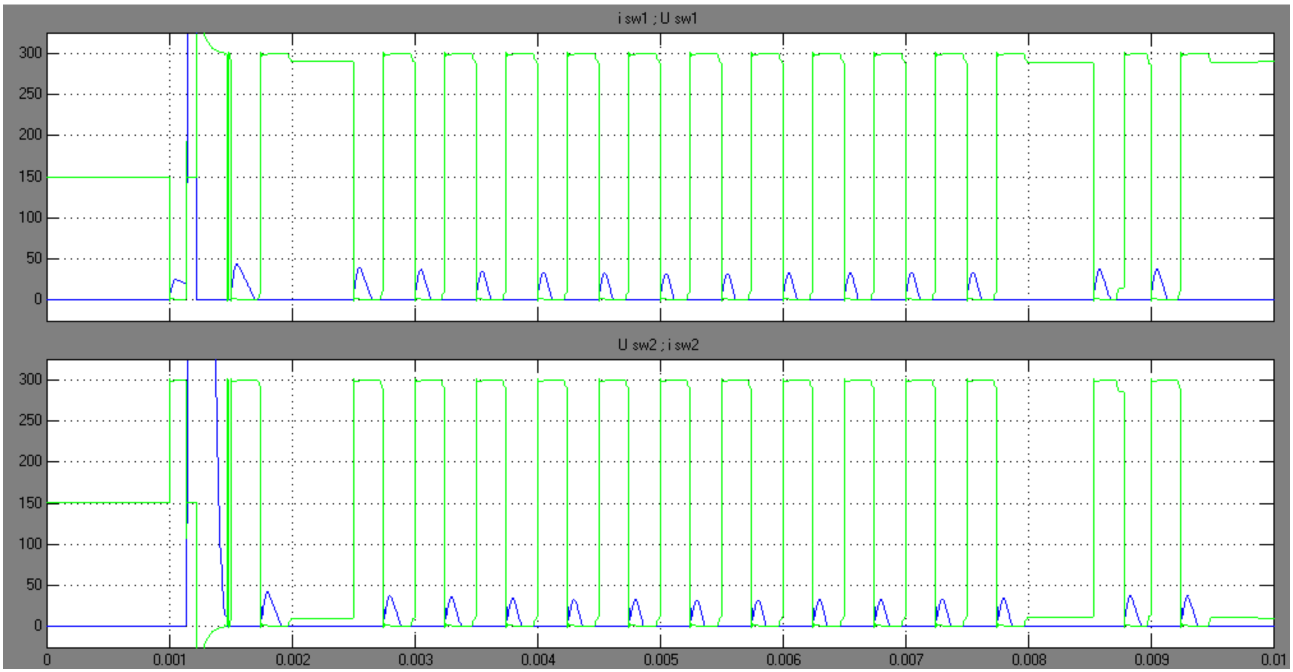

Fig. 3. Voltages and currents in commutated transistor T1 and T2 in HFI

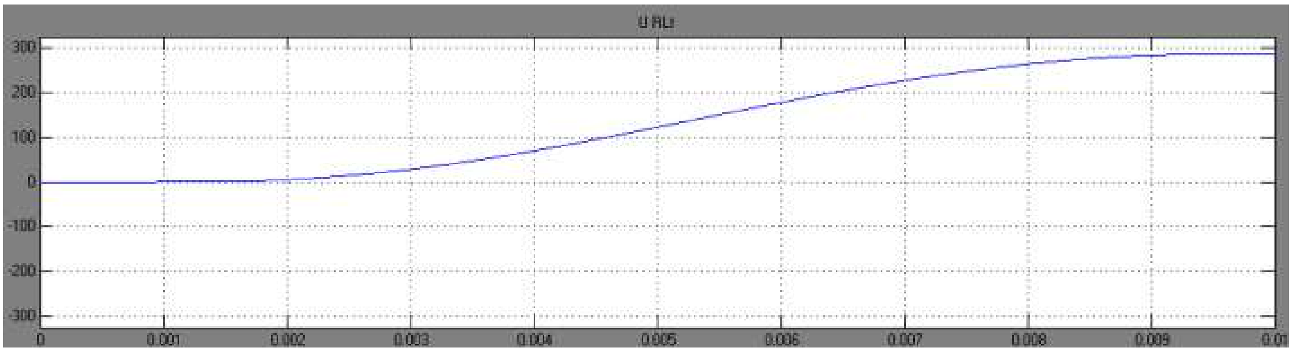

Fig. 4. Transient process for forming of the sinusoidal voltage

The currents in filtering inductance $L_f$ and capacitance $C_f$ are shown in fig. 5. They are not pure sinusoidal.

If it does not provide for additional measures to eliminate of harmonics, investigated inverter will not correspond to the highest requirements for electromagnetic compatibility, provided in Bulgarian and International standards for this class of devices [8, 9 and 10].

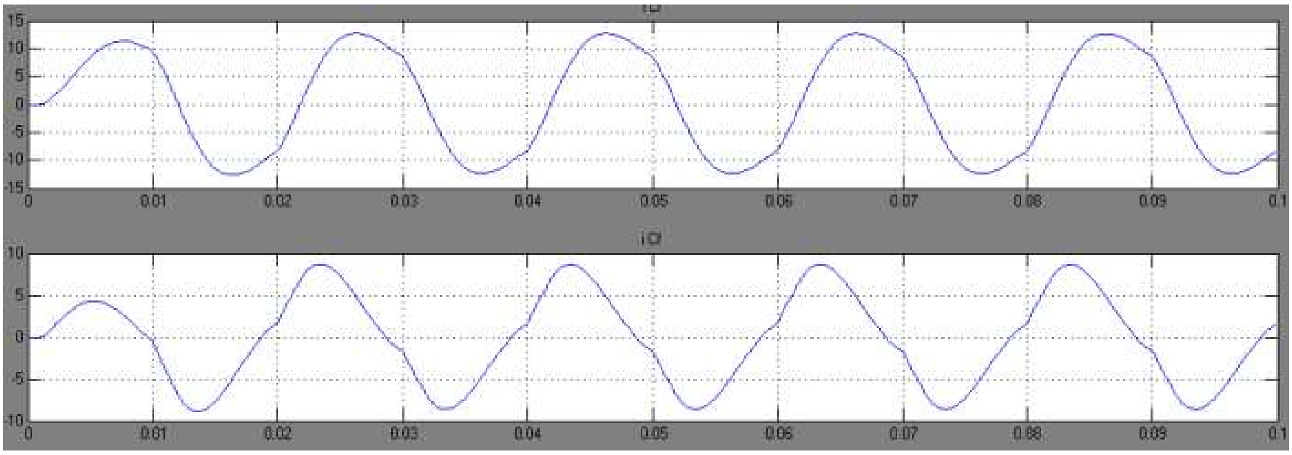

Fig. 5. Graphics of currents in filtering inductance $L_f$ and capacitance $C_f$

As a result of mutual compensation of inductance and capacitance and the action of the additional smoothing function of the separating transformer of the inverter output current through the load is sinusoidal.

The obtained almost of an ideal sinusoidal voltage trough active-inductive load and output current in divided transformer are shown in Fig. 6.

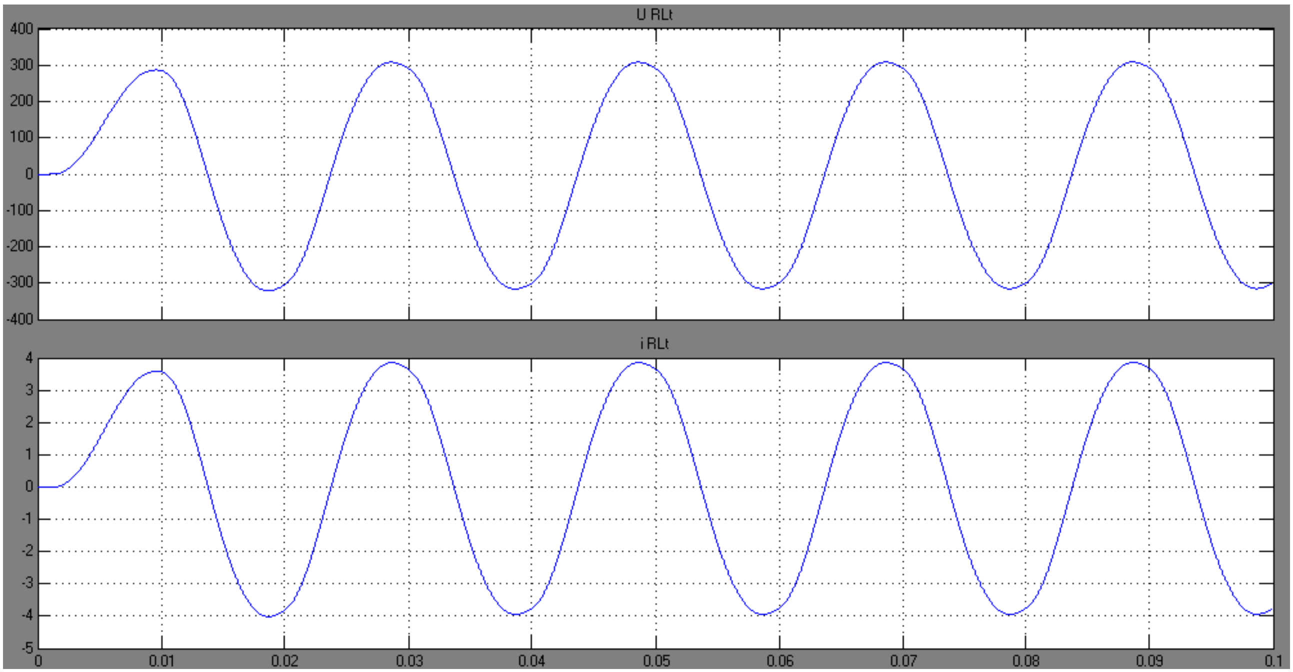

Fig. 6. Sinusoidal voltage trough active-inductive load and output current in divided transformer

## 5. CONCLUSION

The simulation model of the sinusoidal voltage invertor is created.

As a result of the analysis and simulations, obtained through the program package MATLAB 7.1 is proven the capabilities of the inverter for the synthesis of sinusoidal output voltage.

Obtaining of an ideal sinusoidal voltage leads to a significant reduction of harmonics in the load of the converter. This ensures low level of electromagnetic interference and improves electromagnetic compatibility.

Switching semiconductor elements of high-frequency inverter is performed at zero current, by using high-frequency current impulses, controlled by SPWM signal.

The energy supplied from the high-frequency inverter in the process of synthesizing of the sinusoidal output voltage is dosed. By this dosing, the power losses in the power controllers, divided transformer and filtering inductance are minimal.

The analysis and simulations allows determining the parameters of the sinusoidal mode in blocks of control and filter-load.

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