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MODELING OF A QUARTER BRIDGE FREQUENCY CONVERTER OF THE INDUCTIVE HEATING SYSTEMS

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Annotation*: In this article a review of existing realizations of the induction heating system frequecy converter and its working principles was done. Described the need for a simpler and more reliable frequency converter voltage supply scheme. The paper presents the concepts scheme, analytical dependences according to the circuit calculations and corresponding graphs of current interest dependencies. Proposed conclusions and recommendations for the implementation of the described scheme.*

Keywords*: Induction heating, control system, the resonance frequency, switching currents.*

МОДЕЛИРОВАНИЕ ЧЕТВЕРТЬ МОСТОВОГО ПРЕОБРАЗОВАТЕЛЯ ЧАСТОТЫ ДЛЯ УСТАНОВОК ИНДУКЦИОННОГО НАГРЕВА

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Аннотация: *В статье выполнен обзор существующих реализаций схем преобразователей для индукционного нагрева и их принципов действия. Указана необходимость разработки более простой и надежной схемы преобразователя частот питающего напряжения. В статье представлены принципиальные схемы, полученные аналитические зависимости расчетов цепей и построены соответствующие графики интересующих токовых зависимостей. Предложены выводы и рекомендации по реализации описываемой схемы.*

Ключевые слова*: индукционный нагрев, система управления, резонансная частота, токи коммутации.*

МОДЕЛЮВАННЯ ЧВЕРТЬ МОСТОВОГО ПЕРЕТВОРЮВАЧІВ ЧАСТОТИ ДЛЯ УСТАНОВОК ІНДУКЦІЙНОГО НАГРІВУ

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Анотація*: У статті виконано огляд існуючих реалізацій схем перетворювачів для індукційного нагріву та їх принципів дії. Вказана необхідність розробки більш простої і надійної схеми перетворювача частот живлячої напруги. У статті представлені принципові схеми, отримані аналітичні залежності розрахунків схем і побудовано відповідні графіки струмових залежностей що представляють інтерес. Запропоновано висновки і рекомендації з реалізації схеми що описувалась.*

Ключові слова*: індукційний нагрів, система управління, резонансна частота, струми комутації*

Introduction

Induction heating (IH) is a wildly used component of the most manufacturing operations associated with necessity to realize metal parts and designs local heating, for further processing or service. The essence of this physical phenomenon is based on Joule-Lenz heat using that is allocated out of internal currents, induced by an external electromagnetic field of the toolinductor that are located near the area of impact on the metal.

The purpose of this article is to describe the most economical inverter circuit realization of the inductor supplier with further proposing of the practical advice for the development of such schemes.

Publications analysis

Despite all the advantages of IH using that are described and proven in the literature [1–5] the choosing of the optimal power source realization that provides the required amplitude & frequency response of the output signal.

At the present stage of semiconductor elemental base engineering development, a frequency converter usually uses two circuit implementation, namely the bridge and half-bridge realizations.

The Principle of the scheme working, is concluded in diagonal pair clutching of gates that provides the bipolar voltage putted to the load Zn, herewith, the range of the amplitudes forms is doubled the primary supplying voltage Uпит.

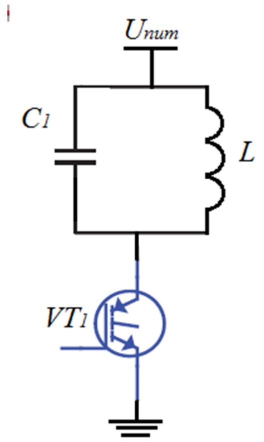
The scheme, where gates stand in two opposite bridge arm only, has the same principle of working. Capacitors, that stand in other two arms form a temporary current way in the diagonal bridge arms. Herewith, the capacitors value is chosen so that its charging been at linear part of charge characteristic and capacitors serve as the energy transfer buffers from supplier to load. In this case, the dynamic of current will be depend upon the own load's typical time constants only.

The most common way to get some practical outputs in the scheme electrodynamics process description gives us the inhomogeneous equation system solving that characterized by the connected load and the converter output voltage time form.

For example, to solve some given differential equations, external voltage presented in the form of unipolar or bipolar impulse sequence or in the form of the harmonic function sum – that are Fourier series component. In most case of inductive heating system, load refers to some RLC oscillating circuit or it inductively coupled set.

Analysis of the electromagnetic processes in induction heating

The quarter bridge frequency converter scheme on pict.1 is an alternative of the variants described above.



Pic. 1. frequency converter

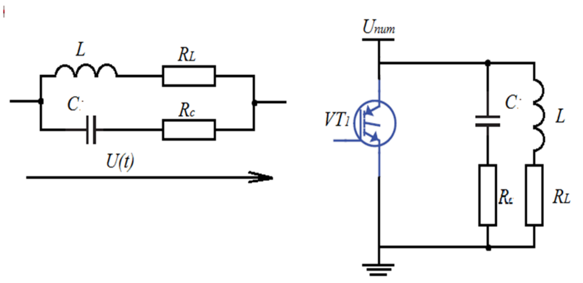
Its advantages consist in the simplicity and reliability, cause of exception of the critical work mode connected with a flow-through appearance, which lead to semiconductor and all system failure. So scheme like this is limited by more simple transistor driver and less difficult short circuit protect system.

Mainly, attention to the scheme consists in its distinctive electric process computation methodic.

Talking about the consideration of the scheme on pict.1 it is necessary to pay an attention on the correctness of the equivalent circuit form. For example, circuit (fog.1) mathematic modeling gives wrong results if the mathematically described scheme has the view like at the fig.2,a.

The reason being that, in this case, the real described scheme (fig.2, b) is difference to the original at pict.1.

Suppose, the transistor VT1 (fig.1) has an ideal performance characteristics and can be in two states only namely: ideal conductor, and absolutely open circuit. It mean, that external voltage source is considered or there is now counter that could include the voltage source and its influence on the LC resonance circuit is ignored.

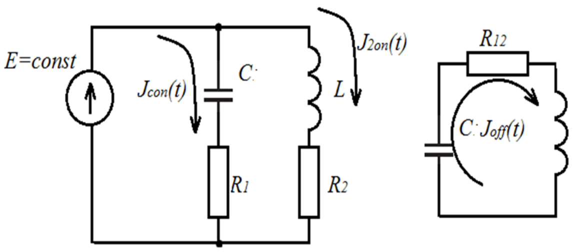


a b

Fig. 2. Wrong computational model presentation: a - computational circuit; b - analog.

This assumption allows system work considering in two boundary related modes namely:
- during open gate state *VT1*, the mode of the forced transition process. In the terms of mathematic below, system will have common and particular equation solving;
- during closed gate state *VT1*, the mode of the free transition process. Else, system will have common equation solving.

Next, let get electrodynamics process analytical relations in the scheme on fig.1. The required computational models determinations presented at fig.3.



a) b)

Fig. 3. Computational model: a- first mode circuit; b- second mode circuit.

For the first and second mode all unknown functions will have “on” and “off” indexation accordingly.

A model (fig.2.a) state equations

$$R_1C\frac{du_{con}}{dt}+u_{con}=E \qquad (1)$$

$$L\frac{di_{2on}}{dt}+R_2i_{2on}=E \qquad (2)$$

Using the well-known solving method, which assumes unknown function exchange, by product of two random functions, we’ll get full linear differential equation (1,2)

$$u_{con}(t)=C_1e^{-\frac{t}{\tau_C}}+E \qquad (3)$$

$$i_{2on}(t)=C_2e^{-\frac{t}{\tau_L}}+\frac{E}{R_2} \qquad (4)$$

where: C1, C2 – random integrative constants;

$\tau_C=R_1C,\ \tau_L=\dfrac{L}{R_2}$ – time constants.

According to the inductive current function and capacitor voltage function continuity conditions at the moments of commutation, let find unknown constants C_1, C_2. It is necessary to make a point, that all functions in each new commutation will have zero timing delay, and initial conditions for solving are determined by previous commutation function last value. That is why

$$u_{conN}(t=0)=u_{coffN-1}(t=t_{off}) \qquad (5)$$

$$i_{2onN}(t)(t=0)=i_{2onN-1}(t)(t=t_{off}) \qquad (6)$$

Following the appropriate substitutions, we obtain

$$C_1=u_{coffN-1}(t=t_{off})-E \qquad (7)$$

$$C_2=i_{2onN-1}(t=t_{off})-\frac{E}{R_2} \qquad (8)$$

Hereof

$$u_{conN}(t)=u_{coffN-1}(t=t_{off})e^{-\frac{t}{\tau_C}}+E(1-e^{-\frac{t}{\tau_C}}) \qquad (9)$$

$$i_{2onN}(t)=i_{2offN-1}(t=t_{off})e^{-\frac{t}{\tau_L}}+\frac{E}{R_2}(1-e^{-\frac{t}{\tau_L}}) \qquad (10)$$

To obtain the gate switching current, let differentiate the expression (9) and add it to the result (10), after what we get

$$i_{\Sigma N}(t)=i_{2onN-1}(t=t_{off})e^{-\frac{t}{\tau_L}}+\frac{E}{R_2}(1-e^{-\frac{t}{\tau_L}})+ \\ +\frac{E}{R_1}e^{-\frac{t}{\tau_C}}-\frac{u_{coffN-1}(t=t_{off})e^{-\frac{t}{\tau_C}}}{R_1} \quad (11)$$

Then, the model (fig.4b) state equation solving for free oscillation RLC circuit mode is needed

$$LC\frac{d^2u_{coffN}}{dt^2}+R_{12}C\frac{du_{coffN}}{dt}+u_{coffN}=0 \;\big|\div LC \quad (12)$$

Classic equation form

$$\frac{d^2u_{coffN}}{dt^2}+2\beta\frac{du_{coffN}}{dt}+\omega_0{}^2u_{coffN}=0 \quad (13)$$

where: $\beta=\frac{R_{12}}{2L}$ – damping rate, $\omega_0=\frac{1}{\sqrt{LC}}$ – resonance frequency.

Note: All further calculations will be performed and will describe the oscillatory circuit mode, i.e if the condition $R_{12}<2\sqrt{\frac{L}{C}}$ is performed.

The roots of the characteristic equation of the 2nd kind (13) will be $p_{1,2}=-\beta\pm i\omega$, where $\omega=\sqrt{\omega_0{}^2-\beta^2}$, and its general solution can be written as

$$u_{coffN}(t)=\left(C_3\cos(\omega t)+C_4\sin(\omega t)\right)e^{-\beta t} \quad (14)$$

Capacitance current equal to the inductance current

$$i_{2offN}(t)=C\beta e^{-\beta t}\left(C_3\cos(\omega t)+C_4\sin(\omega t)\right)+ \\ +C\omega e^{-\beta t}\left(C_4\cos(\omega t)-C_3\sin(\omega t)\right) \quad (15)$$

where C_3,C_4 – random integrative constants.

Find the unknown C_3,C_4 according to the initial conditions, which comply to similar previous mode functions value at the moment of the transistor clutching

$$u_{coffN}(t=0)=u_{conN}(t=t_{on}) \quad (16)$$

$$i_{2offN}(t=0)=i_{2onN}(t=t_{on}) \quad (17)$$

Out of the conditions (16,17) we've got

$$C_3=u_{conN}(t=t_{on}) \quad (18)$$

$$C_4=\frac{i_{2onN}(t=t_{on})+C\beta u_{conN}(t=t_{on})}{C\omega} \quad (19)$$

Making a substitution (18, 19) in (14.15), we obtain the final form of the unknown functions

$$u_{coffN}(t)=\Big(u_{conN}(t=t_{on})\cos(\omega t)+ \\ +\frac{i_{2onN}(t=t_{on})+C\beta u_{conN}(t=t_{on})}{C\omega}\sin(\omega t)\Big)e^{-\beta t} \quad (20)$$

$$i_{2offN}(t)=-\beta Ce^{-\beta t}\Big(u_{conN}(t=t_{on})\cos(\omega t)+ \\ +\frac{i_{2onN}(t=t_{on})+C\beta u_{conN}(t=t_{on})}{C\omega}\sin(\omega t)\Big)+ \\ +\omega Ce^{-\beta t}\Big(\frac{i_{2onN}(t=t_{on})+C\beta u_{conN}(t=t_{on})}{C\omega}\times \\ \times\cos(\omega t)+U_{conN}(t=t_{on})\sin(\omega t)\Big) \quad (21)$$

Having the appearance of interesting us functions it is necessary to present their graphic image correctly, taking to account that they are displaced in time in relation to each other on the size of gate n–commutation duration (as and including so on a shutdown) and exist only on the set interval accordingly. For example, the circuit current function at the powered-off transistor VT1 of 3th commutation will be written down as

$$i_{2off\,(N=3)}(t)=\left[\eta(t-(2T+t_{on}))-\eta(t-3T)\right]\times \\ \times\Big[-\beta Ce^{-\beta(t-(2T+t_{on}))}\Big(u_{con(N=3)}(t=t_{on})\times \\ \times\cos(\omega(t-(2T+t_{on})))+ \\ +\frac{i_{2on(N=3)}(t=t_{on})+C\beta u_{con(N=3)}(t=t_{on})}{C\omega}\times \\ \times\sin(\omega(t-(2T+t_{on})))\Big)+ \\ +\omega Ce^{-\beta(t-(2T+t_{on}))}\times \\ \times\Big(\frac{i_{2on(N=3)}(t=t_{on})+C\beta u_{con(N=3)}(t=t_{on})}{C\omega}\times \\ \times\cos(\omega(t-(2T+t_{on})))+ \\ +u_{con(N=3)}(t=t_{on})\sin(\omega(t-(2T+t_{on})))\Big)\Big] \quad (22)$$

where: $\eta(t)$ – Heaviside function;
T–gate actuation period.

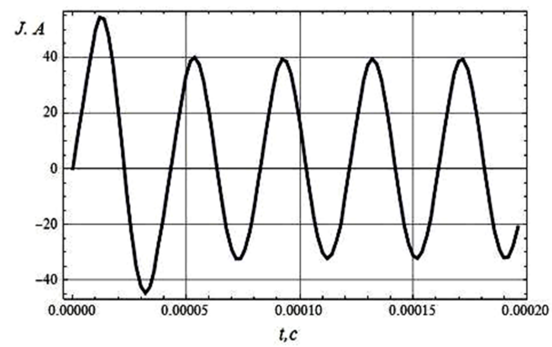
All found functions will be written by analogical character for a time real scale factor.

For the modeling was close to the real situation, we will accept the next parameters of oscillatory circuit on the fig.4 b.

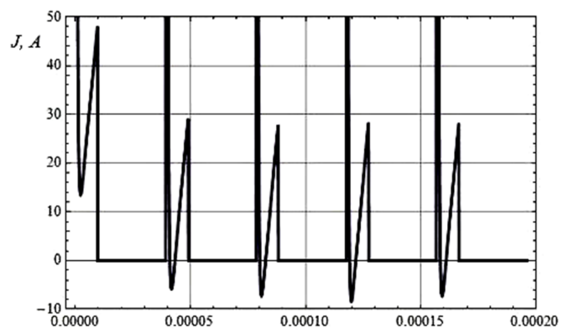
$R_1 = R_2$ =0,5Ohm
C =2uF
L =19uH
E =100V
Off-duty control factor makes 25%.

As a further system work description aim a degree and character of the transistor clutching frequency influence on it (general) indexes will be considered, namely: inductor current and it form, form and amplitude of the gate current, and, also, the influence of such not insignificant parameter as transistor control signal off-duty facto.

On the figures 4-6 the inductor current graphic are presented in case of frequency to equal resonance frequency of RLC contour and it rejection on +-20%

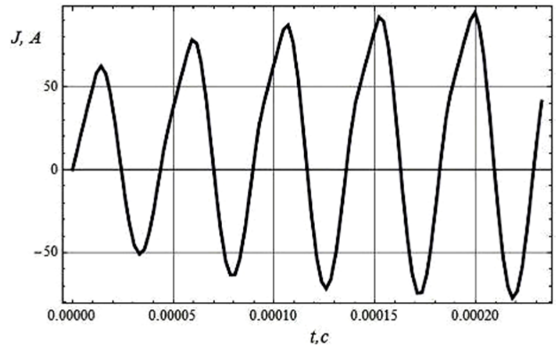


a



b

Fig. 4. Currents at resonant contour frequency: a – inductor current; b – gate current



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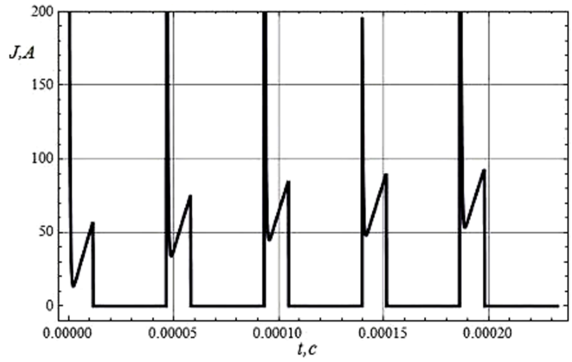
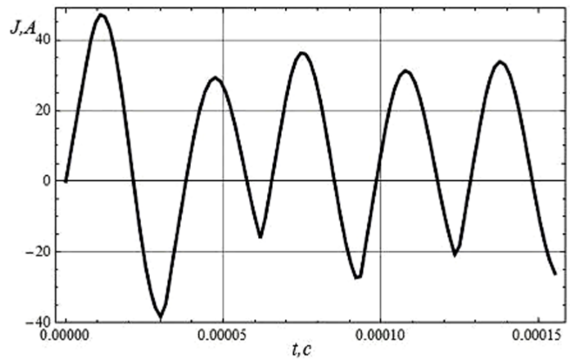
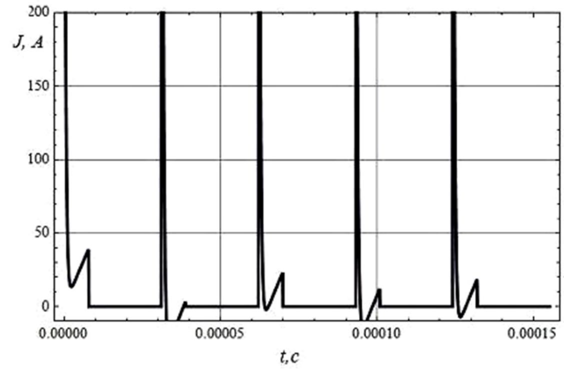


b

Fig. 5. Currents at +20%resonant contour frequency: a – inductor current; b – gate current



a



b

Fig. 6. Currents at -20%resonant contour frequency: a – inductor current; b – gate current

From the charts of gate current, it is possible to distinguish, that the first current troop landing, of the each commutation, corresponds to the energy accumulation in a capacity, and to the second - energy accumulation in inductance.

Thus duration of first substantially less duration of the second. A conclusion ensues from it, that basic load on a transistor makes an inductive store.

It is necessary to specify that the presence of the up-diffused connection conductor inductance of the system positively will influence to the system work, because, a priori, it will limit current throw amplitude at the moment of commutation.

As been obvious from the got results, transistor control frequency can substantially influence on the system quality indexes. So, at frequency equal to resonant of the oscillatory circuit, a leaked inductor current has the obviously expressed sin–wave character in the set mode and his peak value up to 35A. Reduction of frequency will result in distortion of inductor current form and will bring down its peak value (fig.7), and increase on 20% also will distort the form of current of inductor at the simultaneous increase of gate (fig.6) current. In both cases, appearances of the inductor current function fracture areas testifies to voltage jumps appearance that negatively affect works of transistor and can result in its shock.

Another one interesting question consists in transistor off-duty factor influence on the leak processes of the system. From early got charts, (fig. 4-6, b) it is possible to say, that the transistor clutching time increase must promote inductance accumulated energy (because capacity charge time is incomparable small).

The analogical charts at off-duty factor increasing up to 50% at the same frequency are presented at fig.7.

Really, the increase of off-duty factor results in the inductor current increase, but, not looking on seeming efficiency, results in greater distortion of current form from a sine–wave kind, than at the rejection of control signal frequencies.

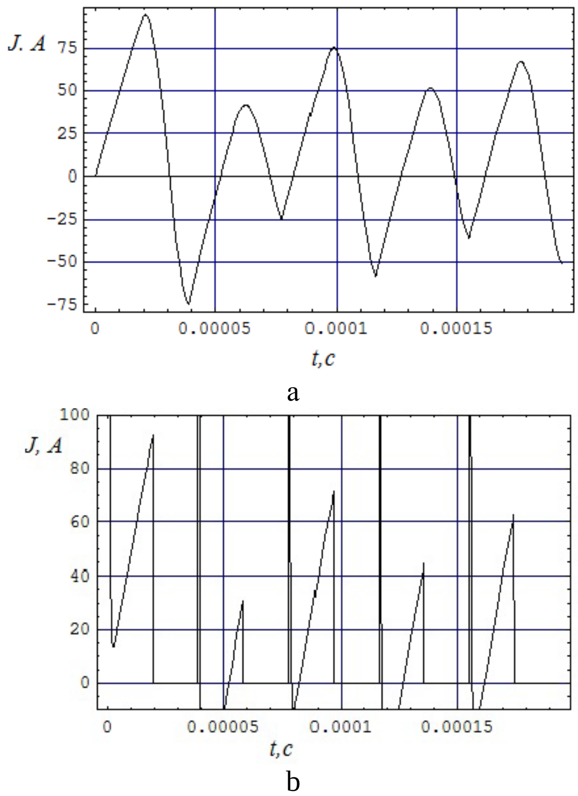


Fig. 7. Currents at resonant contour frequency and 50% off–duty factor: a – inductor current; b – gate current

Conclusions

1. Description of existent schemes of frequency converter is executed. Methodologies of their calculation are described.

2. An alternative the frequency converter scheme of more economical and reliable execution is presented.

3. Mathematical model of described electronic scheme is presented.

4. Basic functional dependences of currents and voltages of the system are got, graphic of currents at the different frequency parameters of semiconductor gate control signal are built.

5. By the built charts and estimations, the next conclusions about work of scheme are got:
– the most favorable system and gate work mode is realized when the transistor commutation frequency is equal to resonance frequency of RLC circuit;
– deviations of control frequency from own resonance results in distortions of inductor current form;
– the increase of frequency reduces middle am-

plitude of the inductor current, and also reduces the transistor current during commutation;
– reduction of frequency increases middle amplitude of the inductor current, and also increases the transistor current during commutation;
– an optimal value of control off-duty factor of the transistor is in the district of 25%, its reduction diminishes amplitude of inductor current at preservation of its sine–wave form, and increase to 50% distorts the form of inductor current and promotes loading on the transistor.

6. According to the above descriptions, exceeding of the transistor control frequency is assumed, or the inductance values rejection in a large side from required is permissible.

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