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PROGRAM

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11.09 – 14.09. 2019
Varna, BULGARIA

SCIENTIFIC PROGRAM

12.09.2019 10:00 – 10:15	OPENING OF THE CONGRESS CHAIRMAN: PROF.D.Sc. G. POPOV	CONFERENCE HALL 1

12.09.2019 10:15 – 12:45	PLENARY SESSION	CONFERENCE HALL 1

CHAIRMAN: PROF.DR. CVETKOVSKI S. (NM) CO-CHAIR: PROF. DR. GALINA NIKOLCHEVA (BG)

1	MICROSTRUCTURE FORMATION IN WHITE ETCHING CRACKS IN BEARINGS	Professor Dr. Eng. Roumen H. Petrov[2,1] Department of Electrical Energy, Metals, Mechanical Constructions & Systems (EEMMeCS)– Ghent University, Belgium [1] Department of Materials Science and Engineering, Delft University of Technology, the Netherlands [2]	60	BE NL
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3	METHOD OF PERMEABLE ELEMENTS FOR SIMULATION OF POWDER METALS FORMING PROCESSES	Dr.Sc. Bagliuk G.A. Frantsevich Institute for Problems of Materials Science, NAS of Ukraine, Kyiv,	61	UA
4	SYNTHESIS AND DESIGN OF HYPERBOLOID GEAR DRIVES: METHODOLOGY AND ASPECTS	Assoc. Prof. Abadjieva E. PhD.1,2 , Prof. Sc. D. Abadjiev V. PhD.2 Graduate School of Engineering Science, Akita University, Japan1 Institute of Mechanics, Bulgarian Academy of Sciences, Bulgaria 2	05	JP BG
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time for presentation 10-12 minutes,
questions after each presentation

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time for presentation 10-12 minutes,

CALCULATION OF THE PARAMETERS ON OUTPUT CURRENT IN FULL–BRIDGE SERIAL RESONANT POWER CONVERTER

Assos. prof. Dr. Eng. Stefanov G.[1], Prof. Dr. Eng. Sarac V.[2], Assist. M.Sc. Kukuseva Paneva M.[3], Assis. M.Sc. Citkuseva Dimitrovska B.[4], Assis. M.Sc. Veta Buralieva J.[5]
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Abstract: *In this paper for full–bridge serial resonant converter, exact general equations for dependencies of phase angle, the maximum voltage of the capacitor and the maximum value of the output current are derived. Mathematical analysis of the this dependence on the resonant circuit dumping frequency when it is excited with pulse voltage with a different frequency than the resonant one is made. This dependences derived in wide a band around the resonant frequency.*

Keywords: POWER CONVERTER, PHASE ANGLE, OUTPUT CURRENT, EQUATIONS

1. Introduction

In the analysis of serial resonant converters it is usual to use the resonant circuit frequency ω_0 for two reasons: 1) assuming that the value of the resistance of the resonant tank is very small the dumping is negligible and thus resonant ω_0 and damping ω_d angular frequencies have very close values; 2) active power is calculated using the phase angle between voltage and current first harmonics [1], [2], [3], [4]. However, at these converters in applications of induction heating there is an equivalent resistance of the resonant circuit and the resonant and dumping are different [5], [6], [7]. Also in these converters, the voltage waveforms are pulse and the current has a dumped sinusoidal form [8], [9]. In such cases is required the phase angle and maximum value on the output current of the converter be calculated in respect to the dumping frequency.

In this paper for H–bridge serial the resonant converter the explicit dependence of the output current of the converter from the deviation on the switching from damping frequency is determined. This calculation is made in a wide band around the resonant frequency.

2. Calculated of the output current of the serial resonant bridge converter

Calculation of the current in wide band around the resonant frequency based on calculate the value of the phase angle and maximal value on current in this wide band.

2.1 Phase angle dependence analysis

The knowledge of the dependence of the phase angle between the output voltage and current of the bridge converter is convenient for maintence operating the converter with constant power [10], [11], [12]. Fig. 1 shows a block diagram of the feedback control circuitry used in the direct phase control of full-bridge serial resonant converter [13], [14].

The microcontroller program has predefined values for the initial value of the switching frequency $fs_{,ref0}$ (or period $Ts_{,ref0} = 1/fs_{,ref0}$) and the desired or the reference phase difference between the output voltage and current φ_{ref} [15]. This phase difference would be zero or close to zero if maximum power transfer is needed, or have a specific value that corresponds to the desired output power when we like to control the power transfer.

Analysis of the series-resonant converters usually use the voltage and current first harmonics to determine the circuit parameters and behavior. Assuming that the resistance in the circuit is small, the resonant frequency ω_0 is used in the calculations.

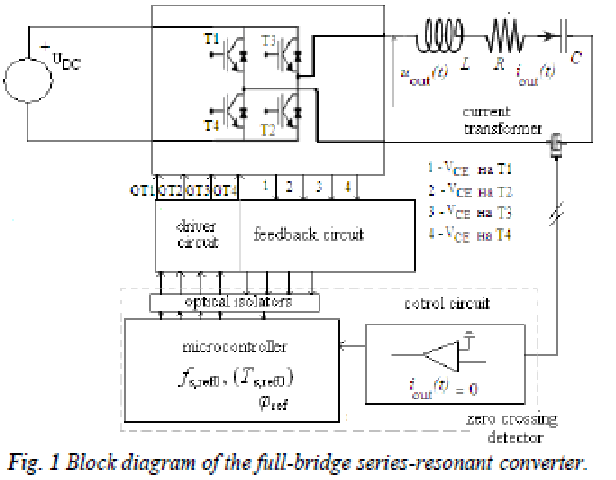


Fig. 1 Block diagram of the full-bridge series-resonant converter.

When a series resonant circuit, Fig. 2 is excited by a sine wave voltage, all waveforms have the same shape.

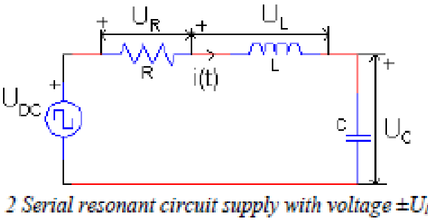


Fig. 2 Serial resonant circuit supply with voltage $\pm U_{DC}$.

When the supply voltage of serial resonant circuit is in form of the Heaviside step function, then the current oscillates around zero with angular dumping frequency ω_d, as shown in Fig. 3. When the voltage has square pulses waveform (duty ratio $D = 0.5$) and amplitude $\pm U_{DC}$, then in every half-period the current is a piece of the dumped oscillation of Fig. 3.

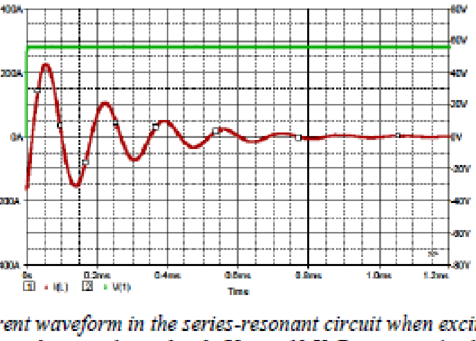


Fig. 3. Current waveform in the series-resonant circuit when excited by a Heaviside step voltage with amplitude $U_{DC} = 60$ *V. Parameters' values are* $R = 0.24\ \Omega$, $L = 26.5\ \mu H$ *and* $C = 26.6\ \mu F$ *with initial values* $i_L(0+) = -165$ *A and* $u_C(0+) = -163$ *V.*

When the circuit excitation with voltage pulses, the current is in the form:

$$i(t) = e^{-\alpha t} K \sin(\omega_d t - \varphi) = e^{-\alpha t} K \sin\left[\omega_d (t - t_\varphi)\right] \qquad (1)$$

For full-bridge serial resonant converter supplay with square voltage in [13], [14] is derived dependence on phase angle from damping and resonant circle frequency. This dependence is given with (2).

$$\varphi = \mathrm{arctg}\left(\frac{\sin(\pi \frac{\omega_d}{\omega_s})}{e^{+\frac{\pi}{2Q}\frac{\omega_0}{\omega_s}} + \cos(\pi \frac{\omega_d}{\omega_s})} \right) \quad (2)$$

2.2 Calculated the maximal value on the output current

In full-bridge serial resonant converter supply with voltage $\pm U_{DC}$, the output current is given with (1). In [1], [2], [3] [4], in calculate on the output current of the full—bridge serial resonant converter with assumptions $\omega_o \approx \omega_d \approx \omega_s$, $i_L(0^+) = 0$ and $u_C(0^+) = 0$ the phase angle, the maximum voltage of the capacitor U_{Cmax} and the constant K are :

$$\varphi = \mathrm{arctg}[\frac{\omega_0 L}{R}(\frac{\omega_s}{\omega_0} - \frac{1}{\omega_s \omega_0 LC})]$$

$$U_{Cmax} = U_{DC}\frac{1-e^{-\frac{\pi}{2Qx}}}{1+e^{-\frac{\pi}{2Qx}}}, \quad K = \frac{2}{1-e^{-\frac{\pi}{2Qx}}}\frac{U_{DC}}{\omega_d L} \quad (3)$$

With (3) the maximum voltage of the capacitor U_{Cmax} and the constant K are calculated in a small band around the resonant frequency and in calculated not taken to consideration the impact of the phase difference.

In this paper, first in calculation of the current in wide band around the resonant frequency for the phase angle we used above derivation exact equation (1) from [13], [14]. The second should be calculated the value constant K in this wide band. Determination of the constants K for the steady state solution can be done using two border conditions for this time interval, i.e. di/dt, $t = 0$ and di/dt, $t = T_s/2$. The voltage of the coil L is:

$$u_L(t) = L\frac{di(t)}{dt} = -LK\alpha e^{-\alpha t}\sin(\omega_d t) + LK\omega_d e^{-\alpha t}\cos(\omega_d t) \quad (4)$$

for $t = 0$

$$u_L(0) = L\frac{di(0)}{dt} = LK\omega_d \quad (5)$$

for $t = T_s/2$

$$u_L(\frac{T_s}{2}) = L\frac{di(\frac{T_s}{2})}{dt} =$$

$$-LK\alpha e^{-\alpha\frac{T_s}{2}}\sin(\omega_d\frac{T_s}{2}) + LK\omega_d e^{-\alpha\frac{T_s}{2}}\cos(\omega_d\frac{T_s}{2}) \quad (6)$$

$$\omega_d\frac{T_s}{2} = \frac{\omega_d}{\omega_s}\pi \cdot \alpha\frac{T_s}{2} = \frac{\alpha}{\omega_s}\pi \quad (7)$$

with this in (6) are obtained

$$u_L(\frac{T_s}{2}) = L\frac{di(\frac{T_s}{2})}{dt} =$$

$$-LK\alpha e^{\frac{\alpha\pi}{\omega_s}}\sin(\frac{\omega_d}{\omega_s}\pi) + LK\omega_d e^{\frac{\alpha\pi}{\omega_s}}\cos(\frac{\omega_d}{\omega_s}\pi) \quad (8)$$

On the other hand, at the series resonant circuit, when the current passing from 0^- in 0^+ in the moment $t = 0$, the voltage of the coil is:

$$u_L(0) = u_{Lmax} = U_{DC} - U_{Cmin} = U_{DC} + U_{Cmax} \quad (9)$$

From (5) and (9) for the constant K are obtained:

$$K = \frac{U_{DC} + U_{Cmax}}{L\omega_d} \quad (10)$$

In the moment $t = Ts/2$ when the current passing from 0+ in 0-, the voltage of the coil is:

$$u_L(\frac{T_s}{2}) = -u_{Lmin} = -(U_{Cmax} - U_{DC}) \quad (11)$$

From (6) and (11) for the constant K are obtained:

$$K = \frac{U_{Cmax} - U_{DC}}{L\left[\alpha\sin(\frac{\omega_d}{\omega_s}\pi) - \omega_d\cos(\frac{\omega_d}{\omega_s}\pi)\right]e^{\frac{\alpha\pi}{\omega_s}}} \quad (12)$$

with

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR}, \alpha = \frac{R}{2L}, \omega_0 \approx \omega_d \neq \omega_s, x = \frac{\omega_s}{\omega_d}$$

as and (10) and (12), can be determined the maximum voltage $U_{C\text{-}max}$ of the capacitor C, i.e.:

$$U_{Cmax} = U_{DC}\frac{\left[\alpha\sin(\frac{\pi}{x}) - \omega_d\cos(\frac{\pi}{x})\right]e^{\frac{\pi}{2Qx}} + \omega_d}{\omega_d - \left[\alpha\sin(\frac{\pi}{x}) - \omega_d\cos(\frac{\pi}{x})\right]e^{\frac{\pi}{2Qx}}} \quad (13)$$

With used on (13) and (10), after a certain number of transformations for the constant K are obtained:

$$K = \frac{2U_{DC}}{L\left[\omega_d - \left[\alpha\sin(\frac{\pi}{x}) - \omega_d\cos(\frac{\pi}{x})\right]e^{\frac{\pi}{2Qx}}\right]} \quad (14)$$

With the expressions (13) and (14) are determined the maximum voltage U_{Cmax} of the capacitor and the constant K in wide band around resonant frequency at the serial resonant converter.

From (13) and (14) with substituting $\omega_s = \omega_d$ are obtained the expressions, (3), for the maximum voltage of the capacitor U_{Cmax} and the constant K given in [1].

The maximum current of the converter is for $t = T_s/4$ and she can be calculated with used on (1) and (14), i.e:

$$I_{max} = Ke^{-\alpha\frac{T_s}{4}} = \frac{2U_{DC}}{L\left[\omega_d - \left[\alpha\sin(\frac{\pi}{x}) - \omega_d\cos(\frac{\pi}{x})\right]e^{\frac{\pi}{2Qx}}\right]}e^{-\alpha\frac{T_s}{4}} \quad (15)$$

With used (1), (2), (14) and (15) for the output current of the serial resonant converter in wide band are obtained:

$$i(t) = \frac{2U_{DC}}{L\left[\omega_d - \left[\alpha\sin(\frac{\pi}{x}) - \omega_d\cos(\frac{\pi}{x})\right]e^{\frac{\pi}{2Qx}}\right]}e^{-\alpha t} *$$

$$\sin\left[\omega_d t - \mathrm{arctg}\left(\frac{\sin(\frac{\pi}{x})}{e^{+\frac{\pi}{2Q}\frac{1}{x}} + \cos(\frac{\pi}{x})}\right)\right] \quad (16)$$

In (16) the of the output current of the serial bridge converter is calculation in relation to the deviation of the switching of damping frequency in a wide band around the resonant frequency.

In the Fig. 4 is shown graph of the maximum voltage of the capacitor U_{Cmax} obtained with (13) with RLC values $R = 0.24\ \Omega$, $L = 26.5\ \mu H$ and $C = 26.6\ \mu F$.

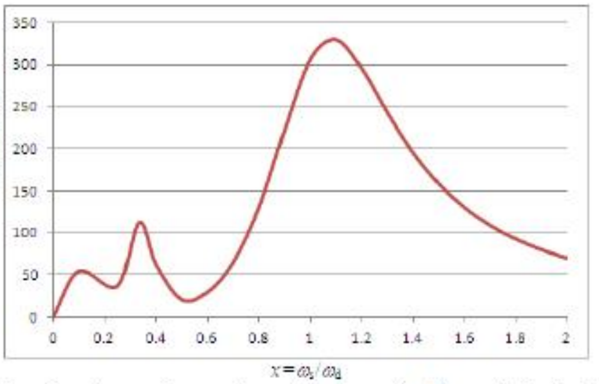


Fig. 4. Graph on the maximum voltage of the capacitor U_{Cmax} obtained with the exact equation (13).

In Fig. 5 is shown graph of the maximum output current of the converter for $t = T_s/4$ obtained with (15).

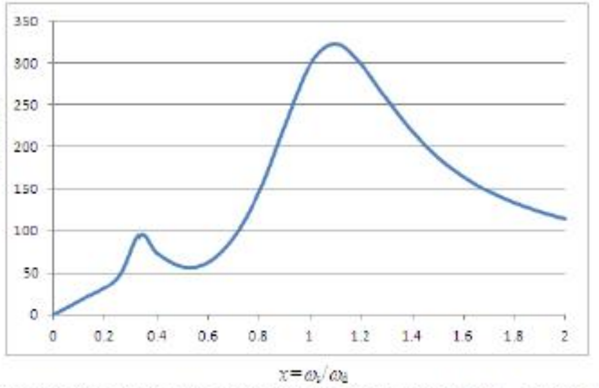


Fig. 5. Graph of the maximum output current of the converter I_{max} obtained with the exact equation (15).

3. Experimental results

A check of the theoretically derived equations in the preceding chapters is made using the full-bridge IGBT converter who operates in mode on the induction heating furnace with nominal output power converter from 15 kW and resonant frequency 5.994 kHz. In the Fig. 6 is shown control module on this converter.

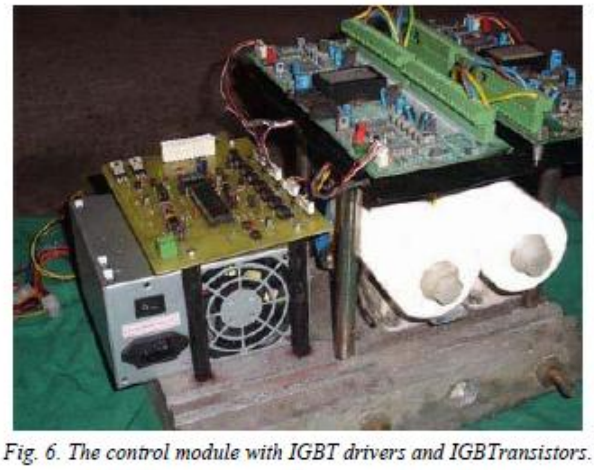
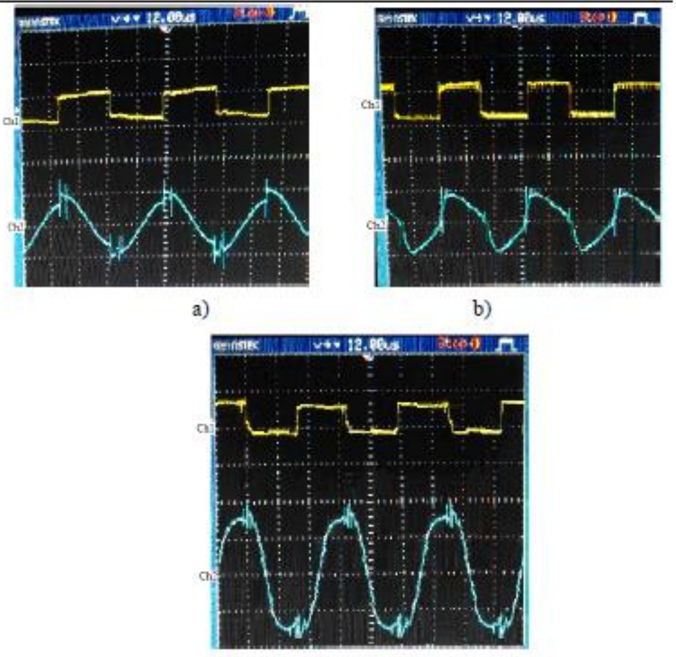


Fig. 6. The control module with IGBT drivers and IGBTransistors.

It is a serial resonant converter with a *RCL* load mentioned above. Resonant frequency is 5.994kHz. In the Fig. 7 is given wave form the on output converter voltage and current a) on a frequency 5,92 kHz, smaller from resonant, b) on the resonant frequency 5.994 kHz and c) at a higher frequency 6,15 kHz than the resonant.

In the Table I is given values on output converter voltage and current on wave form from Fig.7.



a) b) c)

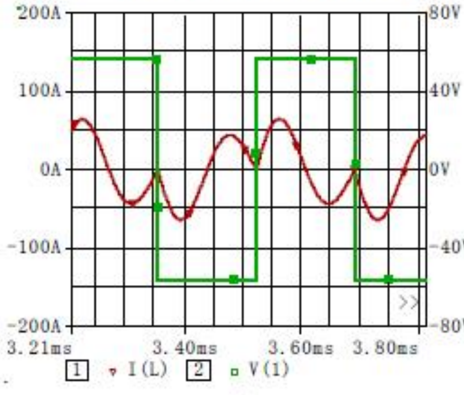
Ch1=100V/div, Ch2=300A/div, time=50µS

Fig. 7. Wave form the output converter voltage and current a) with a frequency smaller, b) at the resonant frequency and c) at a higher frequency than the resonance.

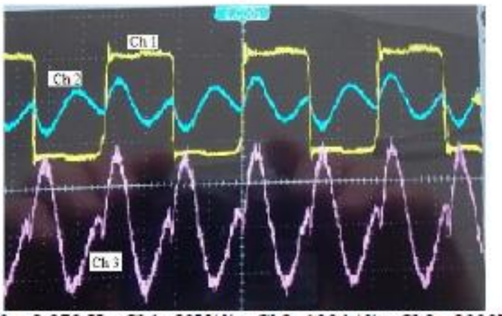
Table I: Values on output converter voltage and current on wave form from Fig.7.

f_s	effective value	
	U_o [V]	I_o [A]
5,92 kHz	55,60	244,00
6,00 kHz	56,10	247,20
6,15 kHz	55,70	244,00

In the Fig. 8 is given wave form the on output voltage and current of switching frequency $f_s = 0,5\,f_0 = 2\,979$ Hz, obtained with simulation in PSpice [16]. (a) and with an experiment (b).



a)



$f_s = 0,5\,f_0 = 2\,979$ Hz, Ch1=50V/div, Ch2=100A/div, Ch3= 2000W/div, time=80µS

b)

Fig. 8. Wave form on the output voltage and current of switching frequency $f_s = 0,5\,f_0 = 2\,979$ Hz, obtained with: a) simulation in PSpice and b) with an experiment.

In Fig 8 on the chanel 1 is given wave form on the output voltage, chanel 2 is wave form on the output current and chanel 3 is output converter active power.

3. Analysis of the results

From Fig. 5 we can see that the maximum value of the output current of the converter I_{max} according to the exact equation (15) is highest value for $x = 1.1$. Also and here for the values on $x < 0.6$ the maximum value of the output current has significant oscillations and for $x > 1.1$ this current decline with lower slope.

From Fig. 5 and Fig. 7b can see that for $f_s/f_0 = 1$, obtained is maximum current abound 300 A with exact equation (15), as and with experimantal results. For switching frequency above resonance $f_s/f_0 = 1.1$, the current has a greater value around 320 A.

Also from Fig.8 can see that for the frequency $f_s = 0{,}5\,f_0 = 2\ 979$ Hz maximal current value is around 60 A and it is the same current value of the graph of Fig. 5 obtained by the equation (15).

4. Conclusion

In this paper for full-bridge converter with serial resonant circuit, analytical are derived exact general equations for dependencies of the maximum voltage of the capacitor and the maximum value of the output current. This equations giving dependences on this parameters from the deviation on the switching from damping frequency in wide bands around resonant frequency. Derived expressions can be used for controlling of the full-bridge serial resonant converter. The results of the experimental testing are close to the values of the parameters obtained by the derived equations.. From these general equations can be obtained the equations for the case when $\omega_s \approx \omega_d \approx \omega_0$.

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