*International Journal of Scientific Research and Engineering Development-– Volume 6 Issue 3, May-June 2023*

*Available at www.ijsred.com*

RESEARCH ARTICLE OPEN ACCESS

# Load Characteristics of LLC Resonant DC-DC converter

Georgi Terziyski*, Angel Lichev**

*(Department Automation, Information and Control Engineering, University of Food Technologies - Plovdiv, Bulgaria
Email: georgi_terziyski@abv.bg

** (Department Electrical Engineering and Electronics, University of Food Technologies - Plovdiv, Bulgaria
Email: angel_lichev@abv.bg

----------------------------------------************************----------------------------------

## Abstract:

An LLC resonant DC-DC converter operating at a frequency above the resonant one is presented. Based on a research using the method of the first harmonic, the main dependencies have been determined for the currents through the power devices. The load characteristics of the converter are constructed and a methodology for its design is proposed.

*Keywords* **—LLC, resonant, DC-DC, converter**

----------------------------------------************************----------------------------------

## I. INTRODUCTION

LLC resonant DC-DC converters find extremely wide application in the practice of implementing power supplies for lasers, fluorescent lamps, welding machines, and also in photovoltaic applications [2, 4, 5, 6]. These resonant converters can operate in the entire load range - from no-load to short-circuit, which is why they are most often preferred, as they provide maximum efficiency while maintaining the conditions of soft commutation of the inverter's power devices [3, 7, 8]. Many authors [2, 4, 5, 6] recommend the use of such converters in PV applications. As a result of the theoretical study of these converters [9, 10, 11], equations for the output and load characteristics were obtained, a methodology for designing the converter was proposed and a computer simulation of its operation was made.

## II. CONVERTER ANALYSIS

The circuit of the LLC resonant DC-DC converter is shown in Fig.1. It is composed of an inverter (controllable switches $S_1 \div S_4$ with reverse diodes $D_1 \div D_4$), a resonant tank ($L_1$, $L_2$ and C), an uncontrollable rectifier ($D_5 \div D_8$), a capacitive filter ($C_F$) and a load resistor ($R_0$). It is assumed that only the first harmonics of the voltages and currents operate in the circuit, and all elements in the areideal (no losses are emitted in them), the power devices are switched instantly, and the ripples of the supply $U_d$ and the output $U_0$ voltages are negligibly small. The following designations are accepted:

$U_0^{'} = U_0 / U_d$ -normalized output voltage;

$I_0^{'} = I_0 /(U_d / \rho_0)$ - normalized output current;

$I_d^{'} = I_d /(U_d / \rho_0)$ - normalized input current;

$R_0^{'} = R_0 / \rho_0 = U_0^{'} / I_0^{'}$ - normalized load parameter;

$\rho_0 = \sqrt{L_1 / C}$ - characteristic impedance of the LC circuit;

$P_0^{'} = U_0 I_0 /(U_d^2 / \rho_0)$ - normalized output power;

$\nu = \omega_s / \omega_0$ - frequency ratio of the oscillating circle;

$\omega_s$ - operating frequency of the converter;

$\omega_0 = 1/\sqrt{L_1 C}$ - resonant frequency of the oscillating circle;

$a = L_2 / L_1$ - ratio between the two inductances in the oscillating circuit.

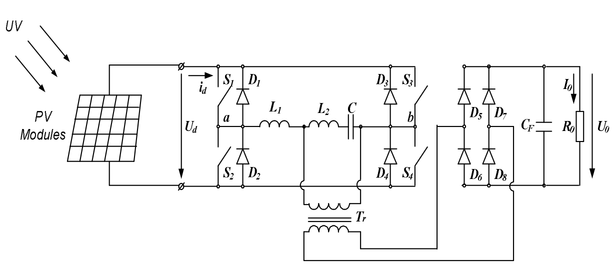


Fig.1. LLC resonantDC-DC converter

  

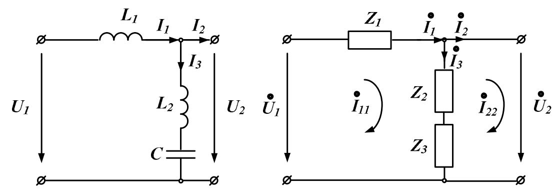


Fig.2. Resonant circuit

Toanalyzetheconverter [1] weassumethatthetwoschemesoftheresonantcircuitare equivalent, thenaccordingtothemethodofloopcurrentswedrawupthefollowingsystemofequations:

$$\begin{cases}(Z_1+Z_2+Z_3)\dot{I}_{11}-(Z_2+Z_3).\dot{I}_{22}=\dot{U}_1\\-(Z_2+Z_3.)\dot{I}_{11}+(Z_2+Z_3).\dot{I}_{22}=-\dot{U}_2\end{cases} \quad (1)$$

Afterformaltransformations, weexpress $\dot{U}_2$ , i.e.,

$$\dot{U}_2=\frac{\dot{U}_1.(Z_2+Z_3)-(Z_1.Z_2+Z_1Z_3).\dot{I}_{22}}{Z_1+Z_2+Z_3} \quad (2)$$

Letusreplacetheimpedancesofthecoilsandthecapacitoroftheresonantcircuitwiththeirequalities:

$$Z_1=j\omega L_1=j.\nu.\rho_0;$$
$$Z_2=j\omega L_2=a.Z_1=j.\nu.\rho_0.a; \quad (3)$$
$$Z_3=1/j\omega C=\rho_0/j.\nu.$$

Aftersubstituting (3) into (2) andformaltransformations, weget:

$$\dot{U}_2=\frac{\dot{U}_1(\nu^2-1)}{\nu^2.a+\nu^2-1}+j\frac{\nu.\rho_0.a.(1-\nu^2).\dot{I}_{22}}{\nu^2.a+\nu^2-1} \quad (4)$$

Thevectordiagramofthevoltagesfromtheresonantcircuithasthefollowingform:

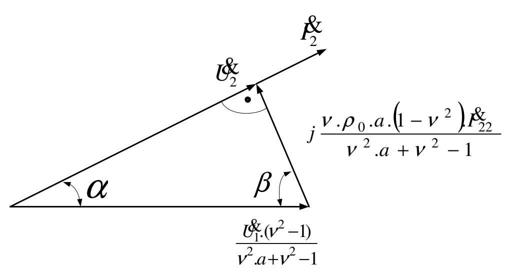


Fig.3. Vector diagram of the voltage

Fortheresultingrighttriangle, thePythagoreantheoremisvalid:

$$\dot{U}_2^2+\left[\frac{\nu.\rho_0.a.(1-\nu^2).\dot{I}_{22}}{\nu^2.a+\nu^2-1}\right]^2=\left[\frac{(\nu^2-1)\dot{U}_1}{\nu^2.a+\nu^2-1}\right]^2 \quad (5)$$

Afterformaltransformationsweget:

$$\dot{U}_2^2.(\nu^2.a+\nu^2-1)^2+\nu^2.\rho_0^2.a^2.(\nu^2-1)^2.\dot{I}_{22}^2=\dot{U}_1^2(\nu^2-1)^2 \quad (6)$$

where:

$$\dot{U}_1=\frac{2.\sqrt{2}}{\pi}.U_d$$
$$\dot{I}_{22}=\frac{\pi}{2.\sqrt{2}}.I_0 \quad (7)$$
$$\dot{U}_2=\frac{2.\sqrt{2}}{\pi}.U_0$$

Bysubstitutingthedependencies (7) in (6) andformaltransformationsinrelativeunits, weget:

$$U_0^{'}=\sqrt{\frac{\left[1-(\pi^4/64)\nu^2.a^2.I_0^{'2}\right](\nu^2-1)^2}{(\nu^2.a+\nu^2-1)^2}} \quad (8)$$

Thelastexpression (8) givestheequationoftherequiredoutputcharacteristics $U_0^{'}=f(I_0^{'},\nu,a)$.

From (8), theequationcanbeobtainedforthecontrolcharacteristics , forwhichtheoutputcurrent $I_0$ isexpressedbytheoutputvoltage $U_0$ andtheloadresistance $R_0$ . Asaresult, therequiredequation:

$$U_0^{'}=\frac{R_0^{'}(\nu^2-1)}{\sqrt{R_0^{'2}(\nu^2.a+\nu^2-1)^2+(\pi^4/64).\nu^2.(\nu^{'2}-1)^2.a^2}}, \quad (9)$$

where $R_0^{'}$ isthenormalizedvalueoftheloadresistor.

Theoutputpoweroftheconverterinrelativeunitscanbeexpressedbytheequationfortheoutputcharacteristics, aftermultiplyingitby $I_0^{'}$ :

$$P_0^{'}=\frac{I_0^{'}}{8.(\nu^2.a+\nu^2-1)}\sqrt{64.(\nu^2-1)^2-\pi^4.\nu^2.a^2.(\nu^2-1)^2.I_0^{'2}} \quad (10)$$

Foragivenvalueof $\nu$ , thefunction $P_0^{'}=f(I_0^{'},\nu,a)$ hasamaximumat

$$U_0^{'}=\frac{\nu^2-1}{\nu^2.a+\nu^2-1} \text{ и } I_0^{'}=\frac{4\sqrt{2}}{\pi^2.\nu.a} \quad (11)$$

$$P_{0\max}^{'}=\frac{4\sqrt{2}.(\nu^2-1)}{(\nu^2.a+\nu^2-1).\pi^2.\nu.a} \quad (12)$$

Therelativeresistanceoftheresistorinwhichthemaximumpowerisseparatedis:

$$R_{0\max}^{'}=\frac{\pi^2.\nu.a.(\nu^2-1)}{4\sqrt{2}.(\nu^2.a+\nu^2-1)} \quad (13)$$

For the effective value of the current through the coil of the resonant circuit, the expression is obtained:

  

$$I_1' = \sqrt{\frac{\pi^4.I_0'^2.(1-\nu^2.a)^2 + 64.\nu^2.U_0'^2}{8.\pi^2.(1-\nu^2.a)^2}} \qquad (14)$$

The average values of the currents through the diodes of the rectifier are determined based on the output current, given that each of them conducts one half-cycle:

$$I'_{D\_RECT\,AV} = \frac{I_0'}{2} \qquad (15)$$

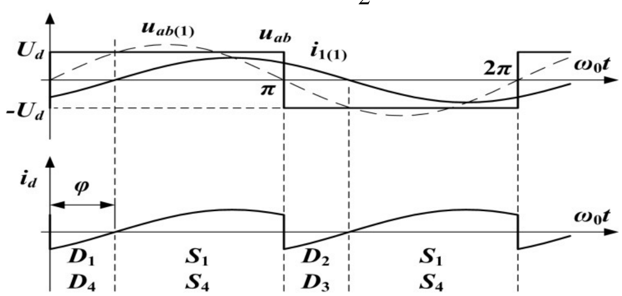


Fig.4. Waveforms of the inverter voltage and current [11]

It follows from the above that the normalized average values of the currents through the controlled switches are determined as follows:

$$I'_{S\,AV} = \frac{1}{2\pi}\int_0^{\pi-\varphi}\sqrt{2}I_1'\sin\omega t\,d\omega t = \frac{\sqrt{2}}{2\pi}I_1'(1+\cos\varphi) \qquad (16)$$

Analogously for the currents through the anti-parallel diodes we get:

$$I'_{D\,AV} = \frac{1}{2\pi}\int_{\pi-\varphi}^{\pi}\sqrt{2}I_1'\sin\omega t\,d\omega t = \frac{\sqrt{2}}{2\pi}I_1'(1-\cos\varphi) \qquad (17)$$

Then the normalized average value of the current consumed by the power source is:

$$I'_{d\,AV} = \frac{1}{\pi}\int_0^{\pi}\sqrt{2}I_1'\sin(\omega t-\varphi)d\omega t = \frac{2\sqrt{2}}{\pi}I_1'\cos\varphi \qquad (18)$$

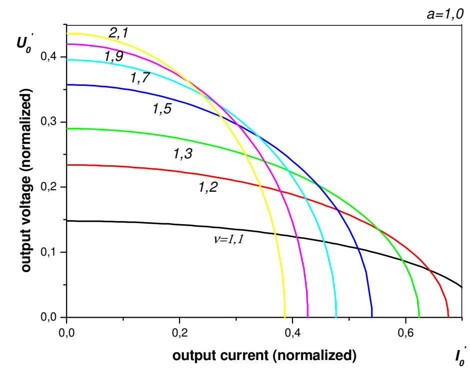


Fig.5. Dependencies of the voltage of the converter from the output current

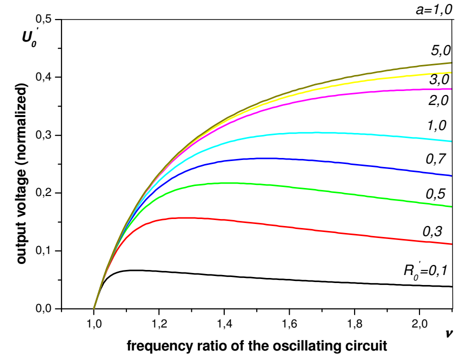


Fig.6. Dependencies of the voltage of the converter from the frequency ratio

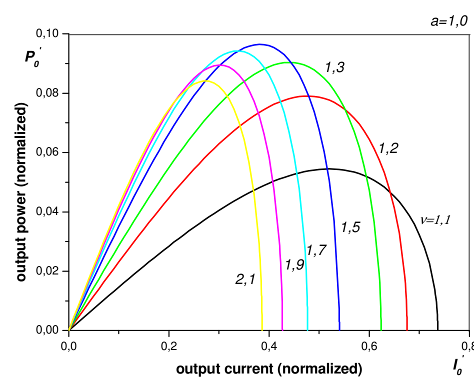


Fig.7. Dependencies of the power of the converter power from the output current

  

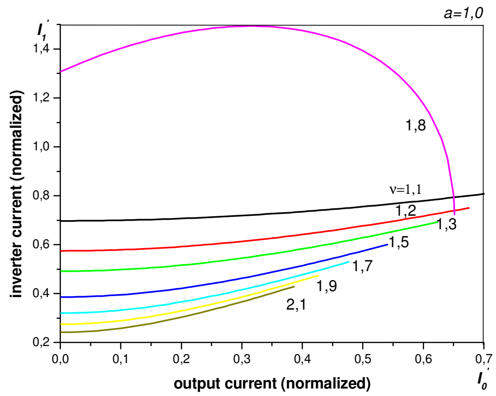


Fig.8. Dependencies of the current of the converter from the output current

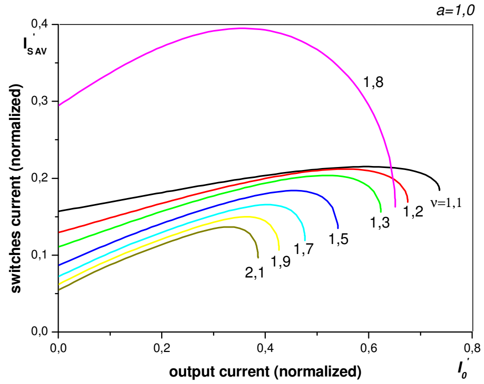


Fig.9. Dependencies of the average values of the currents through the controllable switches on the output current

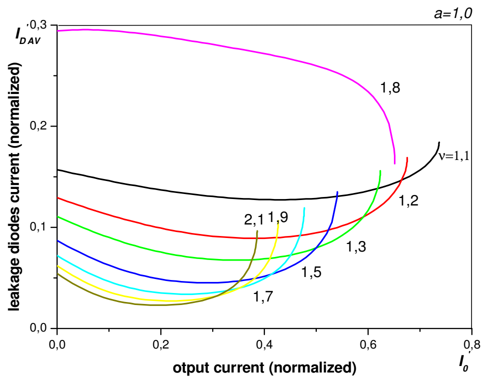


Fig.10. Dependences of the average values of the currents through the reverse diodes from the output current

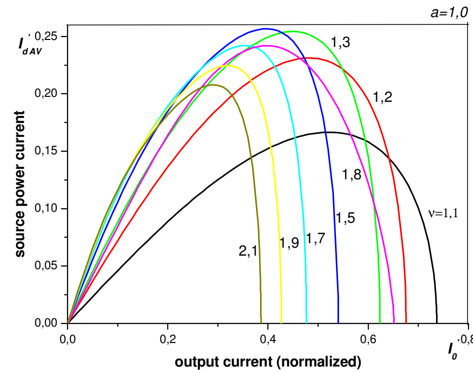


Fig.11. Dependencies of the average values of the current consumed by the power source

The resulting output characteristics given in Fig.5 show that when the converter is operated above its resonant frequency with increasing operating frequency, the short-circuit current decreases and the no-load voltage increases. It can be seen that these characteristics intersect and are inherent in a current-limited voltage source. Based on equation (9), the normalized control characteristics for different values of the load resistor $R_0^{'}$ are constructed. It can be seen that the displayed characteristics have a maximum, the value of which increases as the value of the load resistor increases $R_0^{'}$ , i.e. with the increase of $R_0^{'}$ increases the operating frequency at which this maximum is obtained. The obtained characteristics for the output power of the studied converter are given in Fig. 7 and show that when the converter is operating above its resonant frequency with increasing of the operating frequency, the short-circuit current decreases and the output power increases until the frequencyratio $\nu$ = 1,5. Increasing of beyond $\nu$ over 1,5 the output power is seen to decrease with decreasing of the short-circuit current. Based on equation (14), Fig. 8 shows normalized dependences of the current of the converter from the output current, obtained at a=1,0and different values of the frequencyratio $\nu$ > 1,0. It can be seen that the characteristics are similar and have a maximum that which, with increasing of the frequency ratio, shifts to the beginning of the coordinate system. Furthermore, the current of the converter always has a non-zero value over the entire range of the variation of the load. Moreover, with the frequency ratio$\nu$ = 1,8 the current through the converter can have a significant value, even with a small output current. Therefore, in this case, significant losses will also be observed in the studied converter. Based on equation (16), Fig. 9 shows normalized dependences of the average values of the currents through the controllable switches of the inverter from the output current, obtained at a=1.0 and different values of the frequency ratio $\nu$ > 1,0. From the characteristics, it can be seen that the average values of the currents through the controlled switches for the entire range of the load have non-zero values. On the other hand,$\nu$ = 1,8 the average value of the current through the controlled switches can be significant, thus increasing the losses. Based on equation (17), Fig. 10 shows normalized dependences of the average values of the currents through the reverse diodes of the inverter from the output current, obtained at a=1.0 and different values of the frequency ratio$\nu$ > 1,0. It can be seen from Fig. 10 that with an increase in the frequency ratio$\nu$ = 1,1-1,7 and$\nu$ > 1,9the characteristics are similar and have a minimum, which, with an increase in the frequency ratio, shifts to the beginning of the coordinate system. Furthermore, with the frequency ratio $\nu$ = 1,8, current through the reverse diodes of the inverter always has a non-zero value over the entire load variation range. Moreover, with the frequency ratio, the current through the reverse diodes of the inverter can have a significant value, even with a small output current. Based on equation (18), Fig. 11 shows normalized dependences of the average values of the current consumed by the power source, obtained at a=1.0 and different values of the frequencyratio $\nu$ > 1,0.

**Design of LLC Resonant DC-DC Converter**

WhendesigningtheconsideredresonantDC-DCconverter, thefollowingparametersareusuallyset: outputpower$P_0$, outputvoltage$U_0$andoperatingfrequencyf.Ifitisassumedthattheefficiencyoftheinverterisequaltoone, theparametersofthepowersourceare:

$$U_d = \frac{U_0}{U_0^{'}} = \frac{U_0}{\sqrt{\frac{\left[1-\left(\pi^4/64\right)\nu^2.a^2.I_0^{'2}\right](\nu^2-1)^2}{\left(\nu^2.a+\nu^2-1\right)^2}}} \quad (19)$$

$$I_d = \frac{P_0}{U_d} = \frac{P_0.\sqrt{\frac{\left[1-\left(\pi^4/64\right)\nu^2.a^2.I_0^{'2}\right](\nu^2-1)^2}{\left(\nu^2.a+\nu^2-1\right)^2}}}{U_0} \quad (20)$$

The values of the commutating elements $L_1$, C and $L_2$ are determined by the expressions for the maximum output power and the distortion of the resonant circuit:

$$P_0 = \frac{4\sqrt{2}(\nu^2-1)}{(\nu^2.a+\nu^2-1)..\pi^2.\nu.a}.\frac{U_d^2}{\sqrt{L_1/C}} \quad (21)$$

$$\nu = 2.\pi.f.\sqrt{L_1.C} \quad (22)$$

Then for $L_1$, C and $L_2$ the following dependences are obtained:

$$L_1 = \frac{2.\sqrt{2}.(\nu^2-1)}{\pi^3.a.(\nu^2.a+\nu^2-1)}.\frac{U_d^2}{f.P_0} \quad (23)$$

$$C = \frac{\nu.^2\pi.a.(\nu^2.a+\nu^2-1)}{8.\sqrt{2}.(\nu^2-1)}.\frac{P_0}{f.U_d^2} \quad (24)$$

$$L_2 = a.L_1 = \frac{2.\sqrt{2}.(\nu^2-1)}{\pi^3.(\nu^2.a+\nu^2-1)}.\frac{U_d^2}{f.P_0} \quad (25)$$

As a result of the design of the considered converter, the following output data are given:

$P_0 = 50\ W$ ; $f = 50\ kHz$ ; $U_d = 21{,}5\ V$ ; $\nu = 1{,}3$ .

The following values of the parameters were obtained:

$L_1 = L_2 = 4{,}89\ \mu H$ ; $C = 1{,}51\ \mu F$ ;

$U_0 = 21{,}5\ V$ ; $I_0 = 3{,}5\ A$ ; $R_0 = 6{,}14\ \Omega$ .

A computer simulation of the considered converter was performed with the OrCAD PSpice program. The changes in the supply voltage, the currents through the coils $L_1$ and $L_2$, the voltage across the commutating capacitor C and the voltage across the load resistor $R_0$ are shown.

  

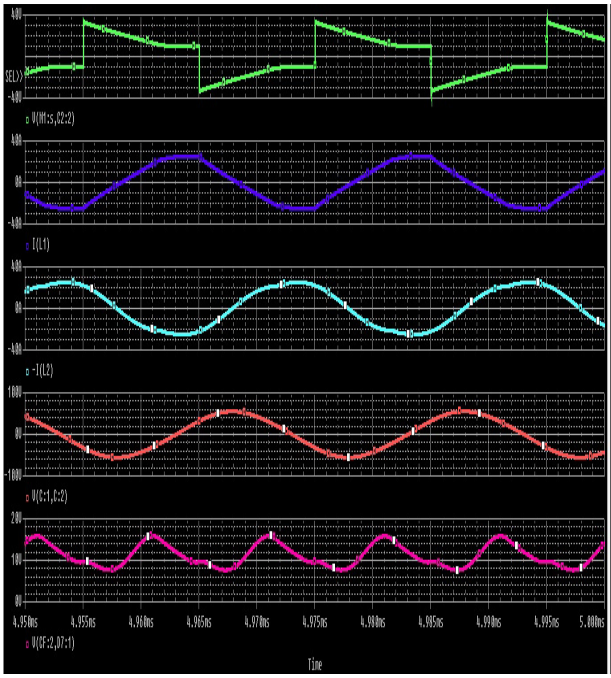


Fig.12. Computer simulation of the considered converter

**Conclusion**

It has been investigated a study of an LLC resonant DC-DC converter using the method of the first harmonic operating at a frequency above the resonant. Based on this study, the main dependences for the currents through the power devices of the inverter were determined. The load characteristics of the converter are constructed and a methodology for its design is proposed.

## REFERENCES

[1] I. Batarseh, "Resonant Converter Topologies with Three and Four Energy Storage Elements", IEEE Transactions on Power Electronics, Vol.9, No.1, pp.64 – 73, 1994.

[2] P. Pandey and P. Agnihotri, An Efficient LLC Resonant Converter Design for Photovoltaic Application, IEEE, 2019.

[3] N. Azura, S. Iqbal and S. Taib, LLC Resonant DC-DC Converter for High Voltage Applications, IEEE, 2014.

[4] V. Costa and M. Perdigao, A. Mendes et al., Analysis AND Simulation of a LLC-VI Resonat Converter for Solar Application, IEEE, 2017.

[5] M. Meghana and S. Naveenkumar, MPPT based LLC Resonant Converter for PV Applications, International Conference on Computation of Power, Energy, Information and Communication, 2017.

[6] A. Ragab and N. Saad, A. El-Sattar, LLC Resonant DC-DC Converter for Grid-Connected PV System, IEEE, 2017.

[7] J. Zeng, G. Zhang, S. Yu et al., LLC Resonant Converter Topologies and Industrial Application – A Review, Chinese Journal of Electrical Engineering, Vol.6, No.3, 2020.

[8] C. Buccella, C. Cecati, H. Latafat et al., Digital Control of a Half-Bridge LLC Resonant Converter, 15th International Power Electronics and Motion Control Conference, EPE-PEMC, 2012.

[9] A. Vuchev, Ts. Grigorova and I. Maradzhiev, Investigation of an LLC resonant DC/DC converter with a capacitive output filter, Part I – Load Characteristics, Proc. XXVIII International Scientific Conference Electronics – ET2019, Sozopol, Bulgaria, 2019.

[10] Ts. Grigirova, A. Vuchev and I. Maradzhiev, Investigation of an LLC resonant DC/DC converter with a capacitive output filter, Part II – Design Considerations, Proc. XXVIII International Scientific Conference Electronics – ET2019, Sozopol, Bulgaria, 2019.

[11] A. Vuchev, N. Bankov and G. Terziyski, Load Characteristics of LCC Resonant DC-DC Converter with Capacity Filter in the Load Cicuit, ICEST, 2010.

  