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međunarodni naučno - stručni skup

**INFORMACIONE
TEHNOLOGIJE**

SADAŠNJOST I BUDUĆNOST

Urednik
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IT'15

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SADRŽAJ

Dejan Popović, Lana Popović Maneski (<i>Rad po pozivu</i>) ROBOTIKA U REHABILITACIJI: EGZOSKELETI I PROTEZE ZA GORNJE EKSTREMITETE ROBOTICS FOR REHABILITATION: EXOSKELETONS AND PROSTHESES FOR UPPER LIMBS... 1	
Tomo Popović NAPREDNE TEHNIKE U PYTHON-U: DEKORATORI ADVANCED PYTHON TECHNIQUES: DECORATORS 7	7
Žarko Zečević, Zdravko Uskoković, Božo Krstajić NOVI ALGORITAM ZA ESTIMACIJU FAZORA U ELEKTROENERGETSKIM SISTEMIMA A NEW ALGORITHM FOR PHASOR ESTIMATION OF POWER SYSTEMS..... 11	11
Vladana Mrdak, Božo Krstajić PRIMJER IMPLEMENTACIJE RJEŠENJA ZA BACKUP I RESTORE PODATAKA AN IMPLEMENTATION EXAMPLE OF BACKUP AND RESTORE SOLUTION 15	15
Marija Blagojević, Maja Božović, Zoran Jevremović, Miloš Papić ANALIZA OBRAZACA PONAŠANJA KORISNIKA RAZLIČITIH STILOVA UČENJA U OKVIRU KOLABORATIVNIH MODULA ANALYSIS OF USERS' BEHAVIOUR PATTERNS OF STUDENTS WITH DIFFERENT LEARNING STYLES WITHIN THE COLLABORATION MODULES 19	19
Bogdan Mirković PRIKAZIVANJE ONTOLOGIJA U MIKS-METODSKIM ISTRAŽIVANJIMA MEĐUORGANIZACIONIH INFORMACIONIH SISTEMA PRESENTING ONTOLOGY IN MIXED METHOD RESEARCH OF INTERORGANIZATIONAL INFORMATION SYSTEMS..... 23	23
Bogdan Mirković INTEGRACIJA METODOLOGIJA U RAZVOJU SOFTVERA ZA PODRŠKU INFORMACIONOM SISTEMU INTEGRATION OF METHODOLOGY IN SOFTWARE DEVELOPMENT FOR SUPPORTING INFORMATION SYSTEM..... 27	27
Jelena Šoškić, Budimir Lutovac IMPLEMENTACIJA PROGRAMSKOG PAKETA WIPL-D ZA PRORAČUN PRILAGOĐENJA SA JEDNIM REAKTIVNIM ELEMENTOM IMPLEMENTATION OF THE WIPL-D PROGRAM PACKAGE FOR SINGLE STUB MATCHING.... 31	31
Luka Lazović, Ana Jovanović, Vesna Rubežić IMPLEMENTACIJA TEORIJE HAOSA U OPTIMIZACIJI LMS ALGORITMA PRIMJENJENOG NA LINEARNIM ANTENSKIM NIZOVIMA IMPLEMENTATION OF CHAOTIC BASED OPTIMIZATION OF LMS ALGORITHM APPLIED ON LINEAR ANTENNA ARRAYS..... 35	35
Sanja Bauk, Radoje Džankić O IZAZOVIMA PRIMJENE RFID TEHNOLOGIJE U LANCIMA SNABDIJEVANJA UPON CHALLENGES OF RFID TECHNOLOGY IMPLEMENTATION IN SUPPLY CHAINS 39	39

Novica Daković, Milovan Radulović FLATNESS I LQR UPRAVLJANJE FURUTA KLATNOM FLATNESS AND LQR CONTROL OF FURUTA PENDULUM	43
Tomislav B. Šekara, Milovan Radulović NOVA METODA ZA OPTIMIZACIJU PID REGULATORA ZASNOVANA NA PRINCIPU NESIMETRIČNOG OPTIMUMA A NOVEL METHOD FOR OPTIMIZATION OF PID REGULATORS BASED NON-SYMMETRICAL OPTIMUM METHOD	47
Vasilija Šarac PRIMENA SIMULINKA U SIMULACIJI ELEKTRIČNIH MAŠINA APPLICATION OF SIMULINK IN SIMULATION OF ELECTRICAL MACHINES	52
Vasilija Šarac IMPLEMENTACIJA SCADA SISTEMA U HIDORELEKTRANI “KOZJAK” IMPLEMENTATION OF SCADA SYSTEM IN HPP “KOZJAK”	56
Aleksandar Ristić, Dalibor Damjanović KRITIČKA ANALIZA UPOTREBE MEDIJA U OBRAZOVANJU NA UNIVERZITETU OREGON SA OSVRTOM NA MOGUĆU PRIMJENU PRIMJERA DOBRE PRAKSE NA UNIVERZITETIMA U REPUBLICI SRPSKOJ CRITICAL ANALYSIS OF THE USE OF MEDIA IN EDUCATION AT THE UNIVERSITY OF OREGON, WITH A REVIEW OF POSSIBLE IMPLEMENTATION OF GOOD PRACTICE AT UNIVERSITIES IN REPUBLIC OF SRPSKA	60
Edin Salković DIGITALIZACIJA PEDOLOŠKIH PODATAKA CRNE GORE DIGITAZING THE PEDOLOGIC DATA OF MONTENEGRO	64
Aleksandar Dedić JEDAN METOD MJERENJA NAPONA I STRUJE BAZIRAN NA MIKROKONTROLERU A MICROCONTROLLER BASED VOLTAGE AND CURRENT MEASUREMENT METHOD	68
Duško Parezanović, Dragan Vidaković KAKO SE POTPISUJE PORUKA HOW TO SIGN THE MESSAGE	72
Radiša Stefanović, Aleksa Srdanov NESPECIFICIRANI USLOVI U IMPLEMENTACIJI ALGORITAMA PRI REŠAVANJU LOGIČKIH ZADATAKA UNSPECIFIED CONDITIONS IN THE IMPLEMENTATION OF ALGORITHMS IN SOLVING LOGICAL PROBLEMS	76
Matija Ratković, Slavica Tomović, Nikola Žarić, Milutin Radonjić, Igor Radusinović EMULACIJA SDN MREŽA SOFVERSКИM ALATOM MININET SDN NETWORK EMULATION WITH MININET SOFTWARE TOOL	80
Slavica Tomović, Milutin Radonjić, Milica Pejanović-Đurišić, Igor Radusinović SOFVERSКИ DEFINISANE BEŽIČNE SENZORSKE MREŽE SOFTWARE DEFINED WIRELESS SENSOR NETWORKS	84

Jelena Šuh, Branislav Sisojević INFORMACIONO-KOMUNIKACIONI ALATI ZA UPRAVLJANJE IP/MPLS MREŽOM INFORMATION-COMMUNICATION TOOLS FOR IP/MPLS NETWORK MANAGEMENT	88
Blažo Popović, Ranko Vojinović ANALIZA WIFI MREŽA U URBANOM DIJELU PRIJESTONICE ANALYSIS OF WIFI NETWORKS IN URBAN PART OF OLD ROYAL CAPITAL	92
Veselin N. Ivanović, Nevena Radović, Srdjan Jovanovski, Zdravko Uskoković UNAPRIJEDJENA PROCEDURA ZA ESTIMACIJU LOKALNE FREKVENCije VISOKO NESTACIONARNIH DVO-DIMENZIONALNIH FM SIGNALA AN IMPROVED PROCEDURE FOR THE LOCAL FREQUENCY ESTIMATION OF HIGHLY NONSTATIONARY TWO-DIMENSIONAL FM SIGNALS.....	96
Mirza Mulešković NIVO RAZVIJENOSTI IKT U CRNOJ GORI I E-SERVISA ZA PREDUZEĆA LEVEL OF DEVELOPMENT OF ICT IN MONTENEGRO AND E-SERVICES FOR COMPANIES ..	100
Milan Marić, Duško Pavićević, Maja Medenica ONLINE UPARIVANJE VISOKOG OBRAZOVANJA I TRŽIŠTA RADA U CRNOJ GORI ONLINE MATCHING HIGHER EDUCATION AND LABOUR MARKET IN MONTENEGRO.....	104
Aleksandar Milenković, Dragan Janković PRIMENA MEDICINSKIH INFORMACIONIH SISTEMA U REPUBLICI SRBIJI – TRENUTNO STANJE I MOGUĆA UNAPREĐENJA APPLICATION OF MEDICAL INFORMATION SYSTEMS IN THE REPUBLIC OF SERBIA – CURRENT STATUS AND POSSIBLE IMPROVEMENTS	108
Obradović Milovan PODRŠKA ICT PRAĆENJU I MERENJU ZADOVOLJSTVA KORISNIKA ZDRAVSTVENE ZAŠTITE ICT SUPPORT TO MONITORING AND HEALTHCARE USERS SATISFACTION MEASUREMENT	112
Jelena Končar, Sonja Leković PRIMENA B2C ELEKTRONSKOG PLAĆANJA U REPUBLICI SRBIJI IMPLEMENTATION OF B2C ELECTRONIC PAYMENT IN REPUBLIC OF SERBIA	116
Zoran Milivojević, Zoran Veličković, Bojan Princević INHARMONIČNOST KONTRA OKTAVE STEINWAY B KLAVIRA INHARMONICITY OF CONTRA OCTAVE OF THE PIANO STEINWAY B.....	120
Milesa Srećković, Magdalena Dragović, Aleksandar Čučaković, Biljana Đokić Milošević, Nada Ratković Kovačević DIZAJN, SIMULACIJA I MODELOVANJE U INŽENJERSTVU U OKVIRU IZABRANIH PROBLEMATIKA DESIGN, SIMULATION AND MODELING IN ENGINEERING WITHIN SELECTED PROBLEMS.....	124
Mirko Kosanović, Miloš Kosanović ENERGETSKI PROFIL POTROŠNJE ENERGIJE U SENZORSKOM ČVORU ENERGY PROFILE OF ENERGY CONSUMPTION IN SENSOR NODE	128

Nataša Savić, Zoran Milivojević, Vidoje Moračanin ANALIZA EFIKASNOSTI POLYA RACIONALNOG PARAMETARSKOG INTERPOLACIONOG JEZGARA KOD PROCENE FUNDAMENTALNE FREKVENCije ANALYSIS OF EFFICIENCY OF POLYA RATIONAL PARAMETRIC INTERPOLATION KERNEL IN THE ESTIMATION OF FUNDAMENTAL FREQUENCY	132
Zoran Veličković, Zoran Milivojević, Miloško Jevtović PRIMENA ITERATIVNOG ALGORITMA ZA POPRAVKU KVALITETA EKSTRAHOVANOG VODENOG ŽIGA IZ VIDEA STRIMOVANOG U BEŽIČNOM OKRUŽENJU APPLICATION OF ITERATIVE ALGORITHM FOR ENHANCEMENT OF EXTRACTED WATERMARK FROM THE VIDEO STREAMED IN A WIRELESS ENVIRONMENT	136
Martin Čalasan, Vladan Vujičić, Gojko Joksimović, Nikola Šoć, Chen Hao PREGLED MATEMATIČKIH MODELA MORSKIH STRUJA REVIEW OF MARINE CURRENT MATHEMATICAL MODELS	140
Risto Bojović, Ivana Milošević, Hristina Bojović ULOGA MODELA SPIRALNE DINAMIKE U RAZVOJU IT SISTEMA THE ROLE OF SPIRAL DYNAMICS MODEL IN IT SYSTEMS DEVELOPMENT	144
Maja Kukuševa Paneva, Biljana Čitkuševa Dimitrovska, Goce Stefanov PREGLED INTEGRISANE ŠEME PO ELIPTIČKOJ KIRIVULJI OVERVIEW OF ELLIPTIC CURVE INTEGRATED SCHEME.....	148
Ana Grbović, Bojan Đordan PCS7 VREMENSKA SINHRONIZACIJA U HE PERUĆICA PCS7 TIME SYNHRONIZATION IN HPP PERUĆICA	152
Tomče Velkov, Ace Panev, Roman Golubovski, Sašo Gelev, Vlatko Čingoski, Goce Stefanov, Maja Kukuseva Paneva SISTEM ZA KONTROLU AMBIJENTA U STAKLENIKU AMBIENT CONTROL SYSTEM IN GREENHOUSE.....	156
Slavica Kostadinova, Vlatko Čingoski, Roman Golubovski, Sašo Gelev POVEĆANJE ENERGETSKE EFIKASNOSTI VODOVODNIH SISTEMA POBOLJŠANJEM FAKTORA SNAGE PUMPNIH POSTROJENJA INCREASING ENERGY EFFICIENCY OF WATER SUPPLY SYSTEMS WITH PUMP SYSTEMS POWER FACTOR IMPROVEMENT.....	160
Goran Klepov, Vlatko Čingoski, Roman Golubovski, Sašo Gelev, Goce Stefanov NOVI METOD UPRAVLJANJA ASINHRONIH MOTORA SA INTERMITIRANIM REŽIMOM RADA U NAPAJANJU ARTISTIČKIH (MUZIČKIH) FONTANA A NEW CONTROL METHOD FOR INDUCTION MOTORS IN INTERMITTED WORKING REGIME FOR ARTISTIC (MUSIC-DRIVEN) FOUNTAINS	164
Goce Stefanov, Sašo Gelev, Vlatko Čingoski, Vasilija Šarac, Roman Golubovski ODREĐIVANJE IZLAZNIH KARAKTERISTIKA KVAZI-REZONANTNOG KONVERTORA POMOĆU KOMPJUTERSKIH SIMULACIJA DETERMINATION OF OUTPUT CHARACTERISTICS OF QUASI-RESONANT POWER CONVERTER WITH COMPUTER SIMULATION.....	168

Temelkovski Ordan, Sašo Gelev, Roman Golubovski, Vlatko Čingoski, Goce Stefanov PRIMENA FAZI LOGIKE U SISTEMU UPRAVLJANJA TOPLOTNIM PODSTANICAMA APPLICATION OF FUZZY LOGIC IN CONTROL SYSTEMS ARE HEAT SUBSTATIONS	172
Blažo Popović, Srđan Jovanovski PREGLED 6LOWPAN STANDARDA ZA POVEZIVANJE IOT OVERVIEW OF 6LOWPAN STANDARD FOR CONNECTING IOT	176
Mirko Jovović, Budimir Bukilić MOBILNI OPERATIVNI SISTEMI I BEZBJEDNOST. KAKO SE ZAŠTITITI? MOBILE OPERATING SYSTEMS AND SECURITY. HOW TO PROTECT YOURSELF?	180
Bogdan Krivokapić, Uglješa Urošević, Zoran Veljović, Milica Pejanović-Đurišić OPORTUNISTIČKI PRISTUP SPEKTRU U KOGNITIVNIM RADIO MREŽAMA OPPORTUNISTIC SPECTRUM ACCESS IN COGNITIVE RADIO NETWORKS	184
Branko Džakula DINAMIČKO TESTIRANJE I ANALIZA KLIJET-SERVER KOMUNIKACIJE U ANDROID APLIKACIJAMA DYNAMIC SECURITY TESTING AND ANALYSIS OF CLIENT-SERVER COMMUNICATION IN ANDROID APPLICATIONS	188
Stefan Vujović, Miloš Brajović, Slobodan Đukanović UPOTREBA WEB I MOBILNIH APLIKACIJA U AGRİKULTURI WEB AND MOBILE APPLICATIONS IN AGRICULTURE	192
Branko Džakula, Slobodan Đukanović REVERZNI INŽENJERING I METODE ZAŠTITE ANDROID APLIKACIJA REVERSE ENGINEERING AND ANDROID APPLICATION SECURITY	196
Bojan Domazetović, Enis Kočan POBOLJŠANJE ENERGETSKE EFIKASNOSTI BEŽIČNIH SENZORSKIH MREŽA KROZ KOOPERATIVNO PROSLJEĐIVANJE ENERGY EFFICIENCY IMPROVEMENT OF WIRELESS SENSOR NETWORKS THROUGH COOPERATIVE RELAYING	200
Stevan Šandi, Tomo Popović, Božo Krstajić IMPLEMENTACIJA IEEE C37.118 KOMUNIKACIONOG PROTOKOLA U PYTHON-U PYTHON IMPLEMENTATION OF IEEE C37.118 COMMUNICATION PROTOCOL	204
Miloš Brajović, Ljubiša Stanković, Miloš Daković REKONSTRUKCIJA NESTACIONARNIH SIGNALA SA NEDOSTAJUĆIM ODBIRCIMA PRIMJENOM S-METODA I GRADIJENTNOG ALGORITMA ZA REKONSTRUKCIJU RECONSTRUCTION OF NON-STATIONARY SIGNALS WITH MISSING SAMPLES USING S-METHOD AND A GRADIENT BASED RECONSTRUCTION ALGORITHM	208
Igor Ognjanović, Ramo Šendelj, Ivana Ognjanović PISMENOST U OBLASTI SAJBER BEZBJEDNOSTI U CRNOJ GORI CYBER SECURITY AWARENESS IN MONTENEGRO	212

Jelena Ljucović, Ivana Ognjanović, Ramo Šendelj ANALIZA OBRAZOVNOG SISTEMA U OBLASTI SAJBER BEZBJEDNOSTI U CRNOJ GORI ANALYSES OF CYBER SECURITY EDUCATIONAL SYSTEM IN MONTENEGRO	216
Tripo Matijević, Snežana Šćepanović, Marija Radojičić, Ivan Obradović, Saša Tatar RAZVOJ OKRUŽENJA ZA SPAJANJE AKADEMSKOG I PREDUZETNIČKOG ZNANJA PRIMJENOM OTVORENIH OBRAZOVNIH RESURSA CREATING ENVIROMENT FOR BLENDING ACADEMIC AND ENTREPRENEURIAL KNOWLEDGE USING OPEN EDUCATIONAL RESOURCES.....	220
Dejan Tomović, Ramo Šendelj, Ivana Ognjanović DOS I DDOS NAPADI I NJIHOVE KONTRAMJERE DOS AND DDOS ATTACKS AND THEIR COUNTERMEASURES	224
Aleksandar Rašović KORPORATIVNO UPRAVLJANJE INFORMATIKOM ICT GOVERNANCE.....	228
Biljana Stamatović, Armin Alibašić IZBOR I PRIKAZIVANJE PODATAKA IZ XML BAZA PODATAKA SELECTING AND REPORTING DATA FROM XML DATABASE	232

ODREĐIVANJE IZLAZNIH KARAKTERISTIKA KVAZI-REZONANTNOG KONVERTORA POMOĆU KOMPJUTERSKIH SIMULACIJA DETERMINATION OF OUTPUT CHARACTERISTICS OF QUASI-RESONANT POWER CONVERTER WITH COMPUTER SIMULATION

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Sadržaj: U ovaj rad je analiziran kvazi-rezonanten konvertor. Pomoću kompjuterskih simulacija u programu PowerSim, određene su izlazne karakteristike ovog konvertora, odnosno zavisnosti snage i energetske efikasnosti od odstupanja radne od rezonantne frekvencije.

Abstract: In this paper the quasi-resonant power converter is analyzed. By computer simulations in PowerSim program are determined its output characteristics, ie the output power and efficiency from deviation of the operating from resonant frequency.

1. INTRODUCTION

Generally, semiconductor switching devices operate in Hard Switch Mode in various types of PWM DC-DC converters and DC-AC inverter topology employed in a power system. In this mode, a specific current is turned on or off at a specific level of voltage whenever switching occurs, [1], [2], [3]. This process results in switching loss. The higher the frequency the more the switching loss, which obstructs efforts to raise the frequency. Switching also causes an EMI problem, because a large amount of di/dt and dv/dt is generated in the process.

Higher energy conversion efficiency at high frequency switching can be obtained by manipulating the voltage or current at the moment of switching to become zero. This is called “Soft Switching”, which can be subcategorized into two methods: Zero-voltage switching and Zero-current switching. Zero-voltage switching refers to eliminating the turn-on switching loss by having the voltage of the switching circuit set to zero right before the circuit is turned on. Zero-current switching is to avoid the turn-off switching loss by allowing no current to flow through the circuit right before turn-ing it off. The voltage or current administered to the switching circuit can be made zero by using the resonance created by an L-C resonant circuit. This topology is named a resonant converter [1], [2].

In power electronics, according to the type of resonant circuit, mainly used three topologies of resonant converters, serial resonant converter, parallel resonant converter and quasi-resonant converter .

The resonant circular frequency ω_0 , damping circular frequency ω_d and damping constant α of the resonant circuit with inductance L , resistance R and capacitance C , powered by converter is:

$$\omega_0 = \frac{1}{\sqrt{LC}}, \alpha = \frac{R}{2L}, \omega_d = \sqrt{\omega_0^2 - \alpha^2} \quad (1)$$

In the serial and parallel resonant converter when switching frequency f_s of the converter is same by the resonant frequency f_0 of the resonant circuit, transferred energy from the converter to the load is maximum, Fig. 1 [1], [4]. In the Fig.1a can be seen that the output power P_o and

efficiency η at serial and parallel resonant converter is greatest when switching frequency f_s is same with resonant frequency f_0 , ie. $f_s = f_0$.

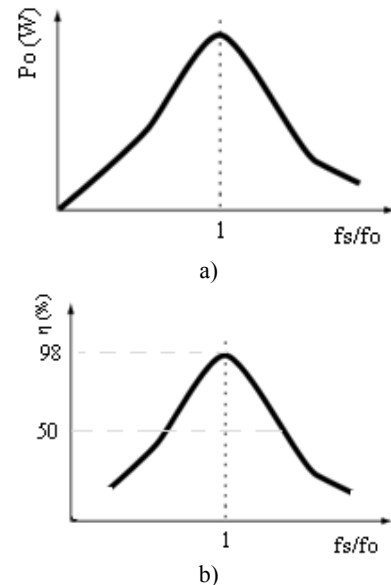


Fig.1 Output characteristics in power converter: a) depending on the output power P_o of the deviation of the switching f_s of the resonant frequency f_0 (normalized switching frequency f_s/f_0), b) depending on the efficiency η of the deviation of the switching f_s of the resonant frequency f_0

At quasi-resonant, although basic operating concept is similar to that of a series resonant converter, controlling the gate in the switching circuit is totally different. Purpose in this paper is for values of RCL elements obtained from the design of device for induction heating [4], to determine the power output and efficiency in this the topology of converter.

2. OPERATION MODE IN QUASI-RESONANT POWER CONVERTER

In the Fig. 2 is show equivalent circuit of the quasi-resonant power converter.

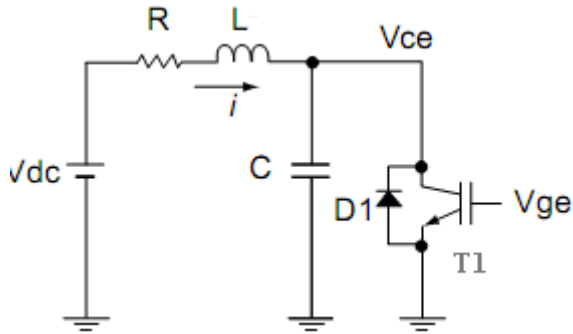


Fig. 2 Equivalent circuit of the quasi-resonant converter

In the Fig. 2, V_{dc} is voltage of DC-LINK circuit, R , L , and C are elements of the resonant circuit, $T1$ is IGBT transistor with his antiparallel diode $D1$, V_{ce} is voltage collector emitter and V_{ge} is voltage gate emitter of IGBT. In the Fig. 3 is shown waveforms of the current and voltage obtained with simulations on the circuit of Fig. 2 in PowerSim program [5].

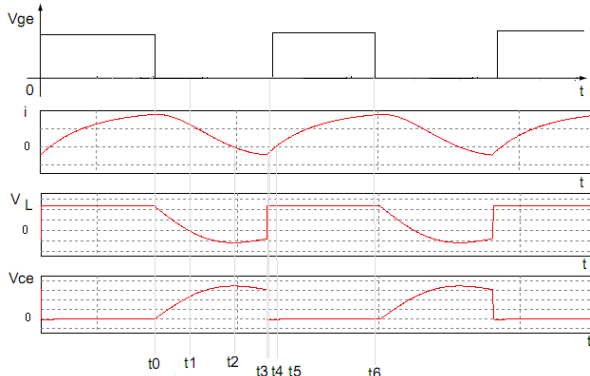


Fig. 3 Wave forms of the current and voltage in the circuit of Fig. 2.

Time interval $t0-t1$ (mode 1): As mentioned earlier, the switching circuit is turned off when the resonant current flowing through the circuit is at its peak, i.e. at $t0$. In this process, a turn-off switching loss occurs. The V_{ce} level is rapidly increased by the capacitor (C_r) to become DC-LINK (V_{dc}) at $t1$. Even when the switch is turned off at $t0$, the current keeps incrementing to reach its peak at $t1$, when V_{ce} becomes equal to V_{dc} , as DC-LINK is higher than the resonant voltage. At this point, the energy stored in the inductor begins to be transferred to the capacitor.

Time interval $t1-t4$ (mode 2): As V_{dc} is lower than V_{ce} after $t1$, the current decreases to zero at $t2$, when the resonant voltage reaches its maximum. This is also the point where the transfer of the energy stored in the inductor to the capacitor is completed. The peak level of the resonant voltage has a direct relationship with the turn-on time of the switch ($t5-t6$). After $t2$, the capacitor starts discharging the energy to the inductor, which causes the voltage and the current flowing in inverse to decrement and reach its minimum level at $t3$, i.e. $V_{ce}=V_{dc}$, respectively. Passing $t3$, the resonant current increases as $V_{ce}<V_{dc}$ and the discharge is completed at $t4$.

Time interval $t4-t5$ (mode 3): After $t4$, the energy sent by the capacitor and stored in the inductor, is converted to DC-LINK as the $D1$ diode is forward biased. The resonant current is flowing through $D1$ during the time $S1$ is turned on.

Time interval $t5-t6$ (mode 1): As the switching circuit remains turned on while the current is freewheeling through $D1$, the current flows in the right direction through the circuit and the inductor starts to store the energy, which makes it possible to do a zero voltage turn-on switching.

In $t6$, the switching circuit is turned off, returning to time $t0$. The peak level of the voltage is in direct relationship with the duty cycle D . So by adding or reducing on duty cycle or change of the frequency can manipulate transfer of the output energy.

3. DETERMINATION OF OUTPUT CHARACTERISTICS

The parameters of the resonant circuit $L = 23.93 \mu\text{H}$, $R = 1.14 \Omega$, $C = 10.6 \mu\text{F}$; switching frequency $f_s = 10000 \text{ Hz}$ and requirements power $P_o = 58 \text{ kW}$ are obtained with simulations of direct induction heatings on work piece iron in the computer program ELTA, product of the FluxControl [4]. In the Fig. 4 is show the circuit to simulation of quasi-resonant converter in the PowerSim program, which is used for determination of output characteristics [5].

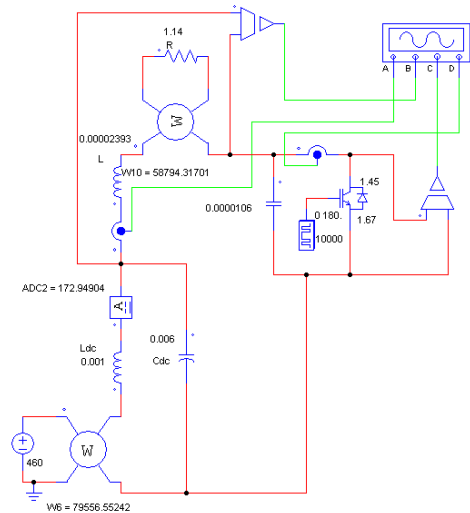


Fig. 4 Circuit to simulation of quasi-resonant converter in the PowerSim program, which is used for determination of output characteristics

In simulations is used model on IGBT transistor with voltage in conduct state $V_{ceSAST} = 1.67 \text{ V}$ and diode with forward voltage $V_F = 1.45 \text{ V}$. The DC-LINK voltage V_{dc} is set on the beginning on value 460 V so as to output power of the converter is $P_o = 58 \text{ kW}$ at switching frequency $f_s = f_0 = 10000 \text{ Hz}$.

3.1 Operation of quasi-resonant converter with constant output power

In the Table 1 is given values of the voltage, current, power and efficiency on the circuit on Fig. 4, obtained with simulations in PowerSim program. Values in the Table 1 are obtained so that to different switching frequency, DC-LINK voltage V_{dc} is changes until the output power get value 58 kW . Duty cycle D , all the time in simulations are holding on the value 0.5 .

Table 1 Values of the voltage, current, power, efficiency, resonant and switching frequency obtained with simulations on the circuit on Fig. 4, when the output power of the converter is constant $P_o \approx 58$ kW.

U_{dc} (V)	I_{dc} (A)	P_{dc} (kW)	P_o (kW)	f_0 (kHz)	f_s (kHz)	η (%)
438	213	93.29	58.70	9.98	16.00	62.9
446	209	93.21	58.60	9.98	15.00	62.9
454	204	92.62	58.68	9.98	14.00	63.4
460	198	91.08	58.63	9.98	13.00	64.4
464	191	88.52	58.73	9.98	12.00	66.3
464	182	84.44	58.70	9.98	11.00	69.5
460	173	79.58	58.79	9.98	10.00	73.9
450	164	73.80	58.54	9.98	9.00	79.3
438	157	68.76	58.80	9.98	8.00	85.5
422	154	64.99	58.63	9.98	7.00	90.2
406	154	62.52	58.44	9.98	6.00	93.5
395	157	62.00	58.77	9.98	5.00	94.8
388	159	61.69	58.25	9.98	4.00	94.4
384	159	61.06	58.30	9.98	3.00	95.5
378	159	60.10	58.50	9.98	2.00	97.3
372	160	59.52	58.45	9.98	1.00	98.2

In the Fig. 5 is shown output characteristics in quasi-resonant converter depending on the deviation of the switching f_s of the resonant frequency f_0 , ie normalized switching frequency f_s/f_0 , when the output power of the converter is constant $P_o \approx 58$ kW. In the Fig. 5a is show dependence of the efficiency η and in the Fig. 5b is show dependence of the DC-LINK voltage V_{dc} .

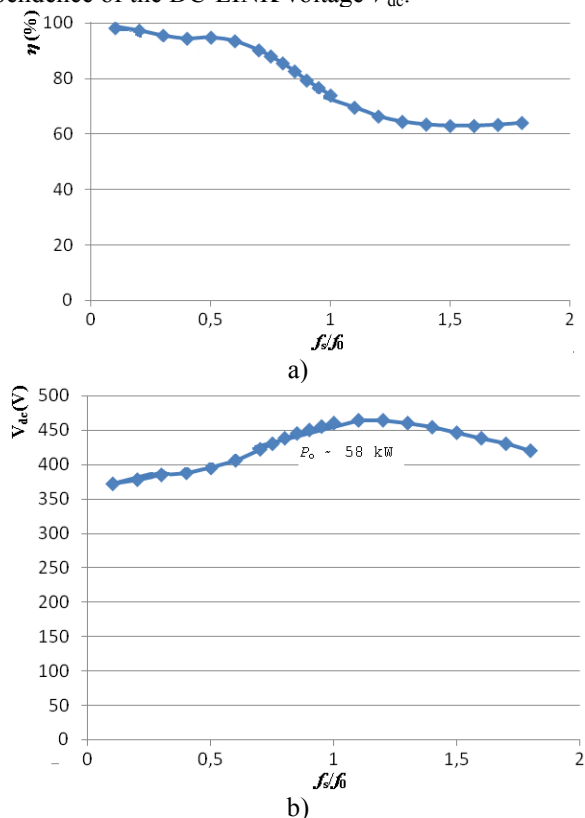


Fig. 5 Output characteristics of the converter dependend from normalized switching frequency f_s/f_0 when the output power

is constant $P_o \approx 58$ kW a) efficiency η and b) DC-LINK voltage V_{dc}

3.2 Operation of quasi-resonant converter with constant DC-LINK voltage

In the Table 2 is given values of the parameters obtained with simulations on the circuit on Fig. 4 on different switching frequency, but so that DC-LINK voltage V_{dc} is constant. And here, duty cycle D for all the time are holding on the value 0.5.

Table 2 Values of the voltage, current, power, efficiency resonant and switching frequency obtained with simulations on the circuit on Fig. 4 when DC-LINK voltage is constant $V_{dc} = 460$ V

U_{dc} (V)	I_{dc} (A)	P_{dc} (kW)	P_o (kW)	f_0 (kHz)	f_s (kHz)	η (%)
460	223	102.8	64.74	9.98	16.00	63.1
460	215	98.9	62.34	9.98	15.00	63.0
460	207	95.22	60.25	9.98	14.00	63.3
460	198	91.08	58.62	9.98	13.00	64.4
460	189	86.94	57.71	9.98	12.00	66.4
460	181	83.26	57.69	9.98	11.00	69.3
460	173	79.58	58.79	9.98	10.00	73.9
460	167	76.82	61.18	9.98	9.00	79.6
460	165	75.9	64.87	9.98	8.00	85.5
460	167	76.82	69.70	9.98	7.00	90.7
460	174	80.04	75.12	9.98	6.00	93.9
460	183	84.18	79.8	9.98	5.00	94.8
460	189	86.94	81.98	9.98	4.00	94.3
460	190	87.4	83.78	9.98	3.00	95.9
460	194	89.24	86.78	9.98	2.00	97.2
460	198	91.08	89.54	9.98	1.00	98.3

In the Fig. 6 is shown output characteristics in quasi-resonant converter in case when DC-LINK voltage is constant $V_{dc} = 460$ V.

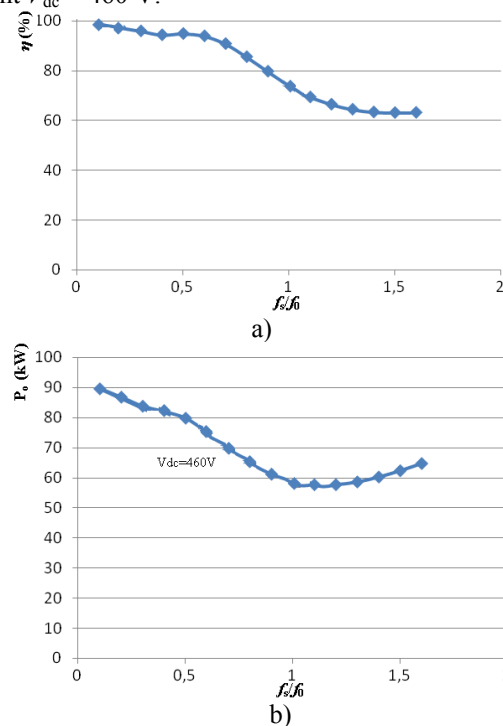


Fig. 6 Output characteristics of the converter depend from normalized switching frequency f_s/f_0 when DC-LINK voltage V_{dc} is constant a) efficiency η and b) the output power P_o . In the Fig. 6a is show dependence of the efficiency η of the deviation of the switching f_s of the resonant frequency f_0 , ie normalized switching frequency f_s/f_0 , and in the Fig. 6b is show dependence of the output power P_o of the converter (also of normalized switching frequency f_s/f_0).

In the Fig. 7 is shown waveforms of the current $i(t)$, as and voltages $V_L(t)$ and $V_{ce}(t)$ when the switching frequency is same by resonant, ie $f_s = f_0$.

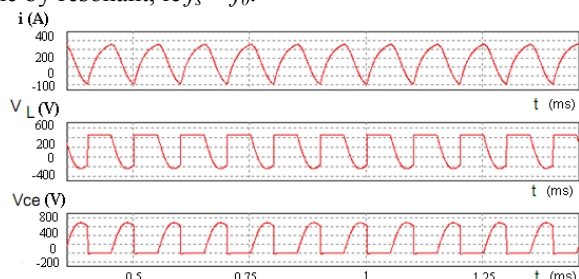


Fig. 7 Waveforms of the current $i(t)$, as and voltages $V_L(t)$ and $V_{ce}(t)$ when the switching frequency is same by resonant, ie $f_s = f_0 = 9.98$ kHz.

In the Fig. 8 is shown waveforms of the current $i(t)$, as and voltages $V_L(t)$ and $V_{ce}(t)$ when the switching frequency is greater from resonant, ie $f_s = 16$ kHz $>$ $f_0 = 9.98$ kHz.

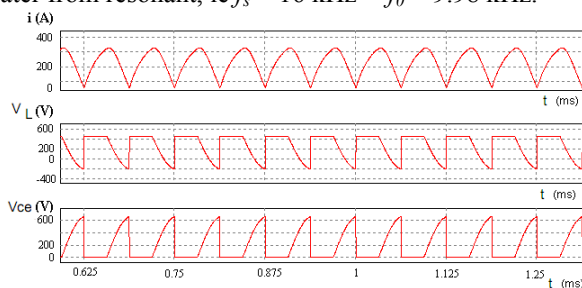


Fig. 8 Waveforms of the current $i(t)$, as and voltages $V_L(t)$ and voltages $V_{ce}(t)$ when the switching frequency is greater from resonant, ie $f_s = 16$ kHz $>$ $f_0 = 9.98$ kHz.

In the Fig. 9 is show waveforms of the current $i(t)$, as and voltages $V_L(t)$ and $V_{ce}(t)$ when the switching frequency is less from resonant, ie $f_s = 1$ kHz $<$ $f_0 = 9.98$ kHz.

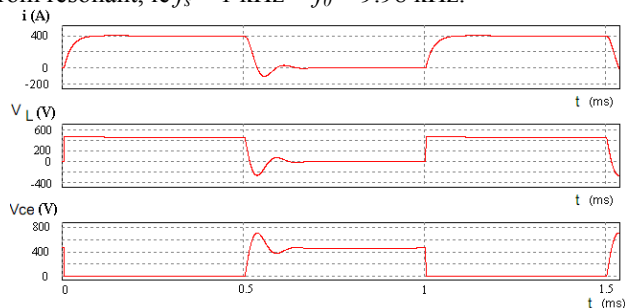


Fig. 9 Waveforms of the current $i(t)$, as and voltages $V_L(t)$ and $V_{ce}(t)$ when the switching frequency is less from resonant, ie $f_s = 1$ kHz $<$ $f_0 = 9.98$ kHz

3.3 Analysis of the results

From the table 1 and 2, as and the Fig. 5, 6, 7, 8 and 9 can be concluded:

1)At quasi-resonant converter the output power is not maximal on the resonant frequency as which is case in the serial and parallel converters.

2)The output power and the efficiency of the converter is greates to low switching frequency. In table 2, to frequency 1 kHz the output power is $P_o = 89.54$ kW, and efficiency is 98.3 %.

3)For high frequencies (13 kHz, 14 kHz, 15 kHz, 16 kHz), it can be considered that the converter operate with constant efficiency (though small).

4)For higher frequencies (11 kHz, 12 kHz, 13 kHz), but close to the resonant the converter operate with a constant output power $P_o \approx 58$ kW.

5)In the operation of the quasi-resonant converter special attention should be paid IGBT transistor to turn on in conditions of ZVS, moment t_4 in the Fig. 3. i.e. transistor turn on when the voltage collector-emitter is low. (diode is turn on in the time of inclusion of the transistor). This decrease switching losses and improves the efficiency of the converter.

6)In the Fig. 8, when the switching frequency is greater from resonant, can be seen that the IGBT transistor not turn on in conditions on ZVS, ie diode not is turn on when IGBT are turn on, and because in this time generate switching losses.

7)In the Fig. 9, when the switching frequency is less from resonant, can be seen that when IGBT is turn off and the voltage of coil passes through zero, appear oscillations by damping circular frequency ω_d . The appearance of these oscillations is limits lower frequency to what can be applied the quasi-resonant converter.

4. CONCLUSION

In the paper is analyzed the operation of the quasi-resonant converter. By the computer simulations in PowerSim program are determined output characteristics of this converter. Determined is frequencies band in which the converter operate with maximum power, frequencies band in which operate with constant power, as and frequencies band in which the converter operate with constant efficiency.

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