High voltage gain DC-DC resonant converter

M. A. Shamsinejad, R. Zare, M. Ramazani

Abstract --In this paper, a DC-DC resonant converter with high voltage gain and small size is studied. To reduce the size and weight of this converter, the operating frequency should be as high as possible. In this research, the frequency changes from 120 to 200 kHz. Due to the high operating frequency, it is necessary to reduce the switching losses using soft switching methods. Resonant converters are suitable choice for this purpose. Since the output voltage is high, the series structure can be a good choice.

Index Terms - DC-DC Resonant converter, High voltage, Soft switching, Series-Parallel.

I. INTRODUCTION

PERFORMANCE of DC-DC resonant converter with high output voltage is significantly affected by the non-ideal transformer with high conversion rate. The secondary windingis one of the resonantelements. Bothleakage inductanceandparasiticcapacitanceof windings can havea significant effecton thebehaviorof converters. Thus a good topologywith high voltagegain is one that has possibility of removingthesenoises.TheDC-DCresonant converter isa suitable choice forhighvoltagegain. Because theycan use leakageinductanceand capacitance of transformer windingsaspart of resonancecircuit. Softswitchingtechniquescan alsobe usedtoeliminateor reducetheswitchinglosses. Moreover In this research, the series-parallel resonant converter is selected because it has advantages of both series and parallel converters and moreover it hasn't disadvantages of them.

The design and control of resonant converters are complicate. In this paper we present a simple method todesign a high voltage gain DC-DC resonant converter. This method is based on the analysis of the first harmonic.The outputpower can becontrolledbychanging theduty cycle. The frequencyis automaticallyadjustedto ensureoptimalcommutation.Thismethodis named"variable frequencyphaseshiftcontrol" [1- 4].

In the following, the power circuit of resonant converter determined andanalyze ofits behavior and the stress on the elements are calculated. The simulation results for a 5kW/15kVresonant converter with operating frequency of 120 kHzat low load and 200 kHz at full load are presented. Finally the simulation results are validated by experimental tests.

II. SERIES-PARALLEL RESONANT CONVERTER

There are different topologiesfor resonantconverter. In this research, a resonant converter with1 inductor and 2capacitors (LCC)is studied[5, 9].At frequencies higher than the resonant frequency, the parallel capacitor CP helps to increase the voltage.Equation (1) indicates the voltage gain of the converter with the approximation proposed in [10].

$$\frac{V_o}{nV_{in}} = \frac{4}{\pi}\frac{k_{21}}{k_v} \tag{1}$$

$$k_{21} = \frac{V_{Cp(1)}}{V_{AB(1)}} = \frac{1}{\sqrt{[1-\alpha\left(f_{sn}{}^2-1\right)\left(1+\frac{tan(|\beta|)}{\omega C_p R_e}\right)]^2+[\alpha\left(f_{sn}{}^2-1\right)\frac{1}{\omega C_p R_e}]^2}} \tag{2}$$

$$k_v = 1 + 0.27\sin\frac{\theta}{2} \tag{3}$$

$$\alpha = \frac{C_p}{C_s} \tag{4}$$

$$f_{sn} = f_s/f_o \tag{5}$$

$$f_o = 1/(2\pi\sqrt{L_s C_s}\,) \tag{6}$$

In these equations:

n	Conversion rate of transformer
k_V	Coefficient between the output voltage referred to the primary side and the amplitude of first harmonic of V_{Cp}
β	Phase angle between first harmonic of transformers current and voltage
R_e	Equivalent resistance of converter RC model
f_{sn}	Normalized switching frequency
f_s	Switching frequency
f_o	Series resonant frequency

Fig.1.presents a full bridge, series-parallel DC-DC resonant converter, with high voltage gain which operatesat frequency over thanresonant frequency.

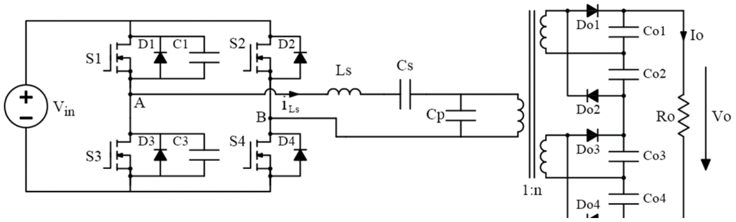

Fig.1. Series-Parallel resonant converter

In this converter, theoperating frequencydepends onthe loads variations. Because, the load determines the effect of capacitorC_p.In fullload, only a small part of resonance current pass from parallel resonantcapacitorC_p. So itactsasaseries resonant converter and resonant

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Mohammad Ali Shamsinejad (m_sh_80@yahoo.com), Reza Zare and Mohsen Ramazani are with Faculty of Electrical and Computer Engineering, The University of Birjand, Birjand, Iran

frequencyisapproximatelyequalto theresonant frequency ofthe series converter. Similarly, in smallload, a small part of resonance current pass from series resonantcapacitorC_s. So itactsasaparallel resonant converter.

III. CIRCUIT ANALYSIS

Capacitors C_1 and C_3 help to zero voltage switching of power MOSFETs S_1 and S_3 in turn off mode. Resonant inductor Ls is the sum of transformer leakage inductance with a series external inductance. Parallel resonant capacitor C_p is also the sum of parasitic capacitor of the secondary coils of the transformer and an auxiliary capacitor. Equivalent circuit of series-parallel resonant converter is shown in Fig.2.In this figure, the output quantities of transformers delivered to its primary.Diodes D_1, D_2, D_3 and D_4, are the internal diode of power MOSFETs. Fig.3.indicates$V_{AB}$and resonance current of converterinoptimal mode. Switches S_1 and S_3become turn on in ZVS[1] mode(at t_2 and t_4). In theother leg of inverter, switches S_2 and S_4becomes turn on in ZVS mode and turn off in ZCS[2]mode (at t_1 and t_3).

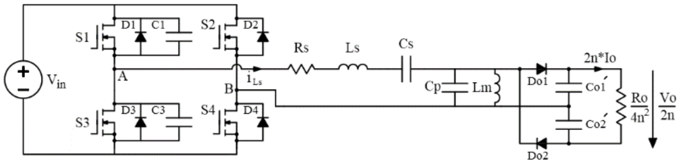

Fig.2. Equivalent circuit of series-parallel resonant converter

So there arenoswitchinglosses. The inversediodesD_2 and D_4 don't conductandin theorythey arenot necessaries.But in experimental set, the commutation cannot be occurringin zero current and need to a dead time between 2 switch of each leg. Thus we cannot eliminate these diodes. Parasitic Capacitor of MOSFETs can be used as loss les snubber. Diodes D_1 and D_3 can be slower because there are not any direct current from freewheeling diodes to power switches. Thus the internal diode of MOSFET can be used as a freewheeling diode.

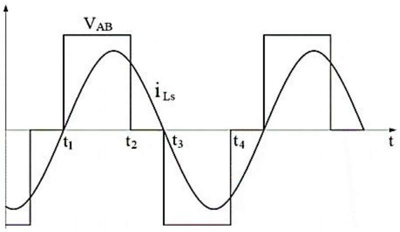

Fig.3. Optimum commutation mode

IV. DESIGN OF SERIES-PARALLEL RESONANT CONVERTER

In this section,design of series-parallel resonantconverter based on study of the first order harmonic is done. It can be finding from Fig.3.andFig.4.thatthe resonance current i_{Ls} is almost sinusoidal. But the waveforms V_{AB}, i_T and V_{Cp}haven't sinusoidal form. Since the power delivered to the load depends on the input voltage and resonancecurrent i_{Ls} and due to the sinusoidal form of current i_{Ls}, only the first harmonic of voltage is important in power transmission. Thus the design process based on the first harmonic of voltage correctly predicts the output power and the stress on the circuit elements.A simpleand effectivemethodpresented by Ivenskyin[10].Hemodeled therectifierandcapacitorfilter withaRCcircuit.The resonance current supposed sinusoidal (see Fig.3.). According to Fig.4.,$V_{Cp}$and input current of rectifier are notin phase.

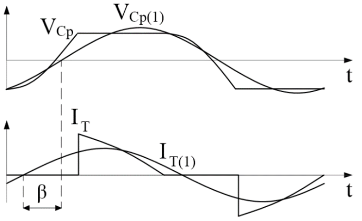

Fig.4. Voltage signal of C_p and input current of rectifier

Thefirstharmonic of rectifiercurrent is lead compare to parallelcapacitorvoltage. Thusoutputload canbeapproximatedby anRCload. Fig.5.illustratesthismodel.k_V is a coefficient betweenthe output voltageof transformerreferred to theprimary sideandthefirstharmonicof parallel capacitor voltage, which will be explainin the following.

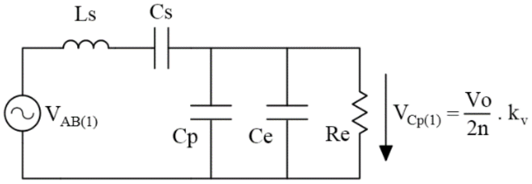

Fig.5. RC model of series-parallel resonant converter

R_e and C_e(equivalentoutputresistance and capacitance ofRC model) calculate by the following equations:

$$R_e = \frac{R_O {k_v}^2}{2n^2} \qquad (7)$$

$$C_e = \frac{2n^2}{\omega R_O {k_v}^2} tan\ (|\beta|) \qquad (8)$$

Here after the equations of series-parallel resonantconverter is going to calculate thestresseson theconverterelements[11].Themain characteristic of the transducer is determined.We are going to design a converter with the following specification:

Input voltage 300 V, Output voltage 15 kV, Output current 0-300 mA, Output power 0 – 5 kW

According to theprocessdescribed in[10] andwithrespect to theC_p,nandoutput values, the outputrectifierconductionangleobtainfromthe followingequation.

$$\theta = 2tan^{-1}\left(\sqrt{\frac{4.n^2}{f_S.C_p.R_O}}\right) = 2tan^{-1}(\sqrt{\frac{4.n^2 I_O}{f_S.C_p.V_O}}) \qquad (9)$$

$$\beta = -0.4363\ sin\ (\theta) \qquad (10)$$

$$\omega C_p R_e = \frac{{k_v}^2.\pi}{4\ tan\ (\frac{\theta}{2})^2} \qquad (11)$$

Inverteroutput voltageandResonancecurrentwaveformsare shownin Fig.6.Thefirstharmonicofinverter outputvoltageis:

$$V_{AB(1)} = \frac{4}{\pi} . V_{in} . \cos\ (\phi) \qquad (12)$$

Whereaccording toFig.6, $\varphi$is the phasebetween $V_{AB(1)}$andtheresonancecurrent calculateas follows:

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[1] Zero Voltage Switching

[2] Zero Current Switching

$$\phi = tan^{-1}\left(\begin{matrix}\frac{\alpha}{\omega C_p R_e}\left[f_{sn}{}^2\left(1+\left[\omega C_p R_e + tan\,|\beta|\right]^2\right)-1\right]\\ -\left[\omega C_p R_e + tan\,|\beta|\right]\left[1+\alpha\left(1+\frac{tan\,|\beta|}{\omega C_p R_e}\right)\right]\end{matrix}\right) \qquad (13)$$

$$D = \gamma/\pi \qquad (14)$$

$$\phi = \frac{\pi}{2} - \frac{D\pi}{2} \qquad (15)$$

Where Drepresents theduty cycleofthe converter, and gistheangleofthe duty cycle.

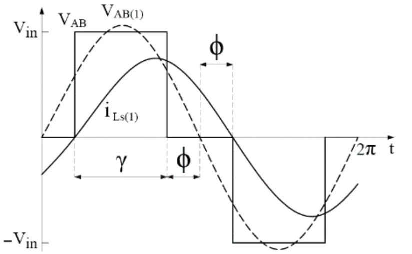

Fig.6. Phase angle between the first harmonic of output inverter voltage and resonance current

By mixing equations (13) and (15), the duty cycle calculates:

$$D = 1 - \frac{2}{\pi}\, tan^{-1}\left(\begin{matrix}\frac{\alpha}{\omega C_p R_e}\left[f_{sn}{}^2\left(1+\left[\omega C_p R_e + tan\,|\beta|\right]^2\right)-1\right]\\ -\left[\omega C_p R_e + tan\,|\beta|\right]\left[1+\alpha\left(1+\frac{tan\,|\beta|}{\omega C_p R_e}\right)\right]\end{matrix}\right) (16)$$

Duty cycle describedas a function of the normalized switching frequency $f_{sn}$and conduction angle θ.By replacing equation (15) in (12), the inverter output voltage is:

$$V_{AB(1)} = \frac{4}{\pi} \,.\, V_{in} \,.\, sin(\frac{D\pi}{2}) \qquad (17)$$

Finally,the output voltage of resonant converter calculates by the following equation:

$$\mathrm{V_o} = \frac{16}{\pi} \,.\, \frac{\mathrm{k_{21}}}{\mathrm{k_V}} \,.\, \mathrm{n} \,.\, \mathrm{V_{in}} \,.\, \sin(\frac{\mathrm{D}\pi}{2}) \qquad (18)$$

By the definite values of α, n, V_{in}, I_o, V_o and resonant elements, the operating frequency calculate.So the parameters are calculable. For example, using the following equation,peak resonance current of inductor is:

$$I_{PLs} = \frac{f_{sn}\,.\alpha}{2n\,(1+cos\,(\theta))} \,.\, \frac{V_o}{Z_s} \qquad (19)$$

$$Z_s = \sqrt{L_s/C_s} \qquad (20)$$

Turn off current of S_1 and S_3 are:

$$I_{Soff} = I_{PLs} \,.\, sin\,(D\pi) \qquad (21)$$

The RMS current of S_1 and S_3 switches are:

$$I_{Srms} = \frac{I_{PLs}}{2} \,.\, \sqrt{D - \frac{sin\,(2D\pi)}{2\pi}} \qquad (22)$$

The series capacitor voltage is:

$$V_{PCs} = \frac{I_{PLs}}{2.\pi.f_S.C_S} \qquad (23)$$

The first step is designing the resonance circuit elements under constraints such as maximum stress on the elements or values of parasitic elements. The maximum duty cycle occur when the output current and power is maximum(330mA 5kW).It will be shown in the simulation results. Ideally, the maximum duty cycle is one(D=1). But in order to imposedead time between the switching,duty cycleis usually below 0.9.The designing process is an iterative method. The output voltage,input voltage, frequency and load resistance ($R_{o\ min}$, $R_{o\ max}$) is given. We have to do the following steps [12].Designing process start from determination ofV_{in} and $R_{o\ min}$ values.

1.Determine thevalue ofθ, Dandα.

2.Calculation of Parametersk$_V$, β, $\omega C_p R_o/n^2$, $\omega C_p R_e$, f_{sn}, k_{21}andn.

3 Calculation of $C_p$from equation$\omega C_p R_o/n^2$ and $C_s$from$\alpha = C_p/C_s$. and$L_s$fromequations(5) and(6).

4.Calculation of stresson thecircuit elements.

5. Repeating the above steps fordifferentvalues ofθ**,**Dandα.

6.Repeating the steps1 through4 forV_{in}, $R_{o\ max}$.

7. Theoptimalvaluesforθ, Dandαbased onhigherefficiency, lowercosts, lowerweight and volume, smallerfrequencyrangeand appropriatestress.

V. SIMULATION RESULTS

According to theDesigning steps in the previous section, the simulationforthe desired outputvoltageunder low loadand full load is done. Parametersused in thesimulationare:

P_o= 50 kW, V_{in}=300 V, n=12 turn, C_1=C_3=200 pF, C_s=39 nF, C_p=19 nF, L_s=60 mH, C_{h1}= C_{h2}= C_{h3}= C_{h4}=120 nF.

Simulation output voltage and current ofseries-parallelresonantconverteris shownin Fig.**7**.

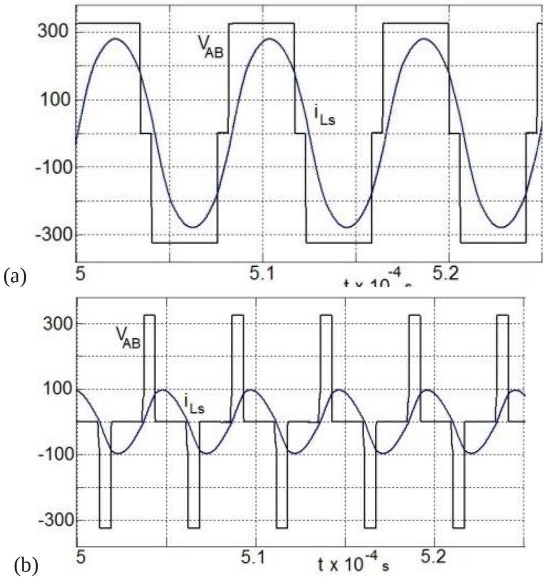

Fig.7. Output voltage and current of series-parallel resonant converter in
(a)High load(The current multiplied by 10)
(b) Low load (The current multiplied by 10)

Fig.8.shows the output voltage of converter.

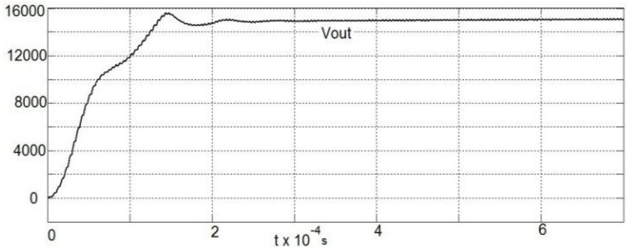

Fig.8. Output voltage of series-parallel resonant converter

VI. EXPERIMENTAL SET

The elements values are the same as designed and used in simulation (section 5). Operating frequency is 120 – 200 kHz.

A Sawtooth generation

Dueto the optimal commutation mode, switching frequency for the various set points should be strictly regulated. Asawtoothwaveformwith fix amplitude and variable frequency is necessary. To generating this signal, theidea ofa closed loopcan be used[13].In this idea, asawtooth produce byRP[1] pulse which is coincidewith thezero crossing ofthecurrent. Fig.9.shows block diagram of thismethod, where the converter output voltage(V_c) istheinput of control circuit.

In order todesignK_{p1}andK_{p2}coefficients in this figure, the equations thatdescribethebehavior ofthe systemshouldbe solved. Thesecoefficients shouldbedetermined so thatthe system response is quickanddistortion level of sawtoothwaveform is in an acceptable domain.

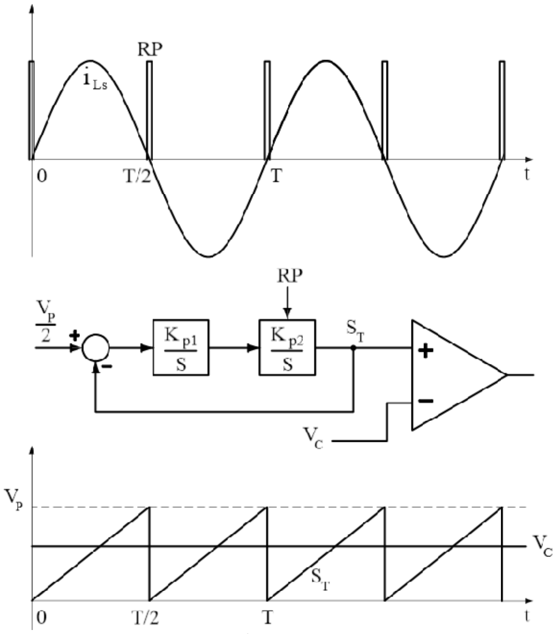

Fig.9.Sawtooth waveform with constant amplitude

Fig.10.indicatesthe production method of RP signal or zero crossing detector of current. To compensate the time delay of the circuit elements such as Op Amps, Drivers, Switches, etc., the current compare by 2 positive and negative constant levels.Fig.11.shows the practical result ofthezero crossingcircuit.

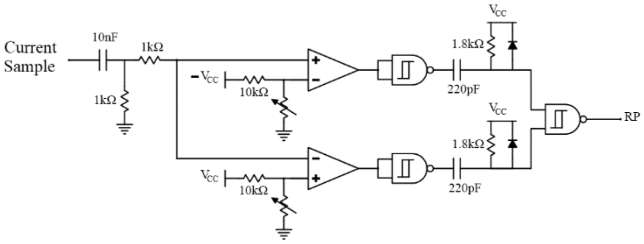

Fig.10. Zero crossing detector circuit

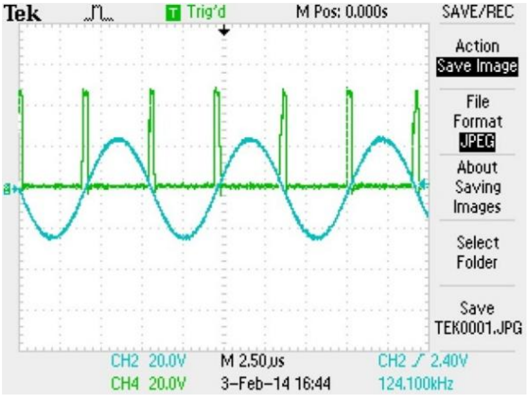

Fig.11. Zero crossing signal

Fig.12.presentsthesawtoothwaveform generator circuit with constantamplitude. In this figure, RPis thecurrentzero crossing signal. Fig.13.shows the sawtoothwaveform withconstant amplitudeatfrequencies 100 kHz and 180 kHz.

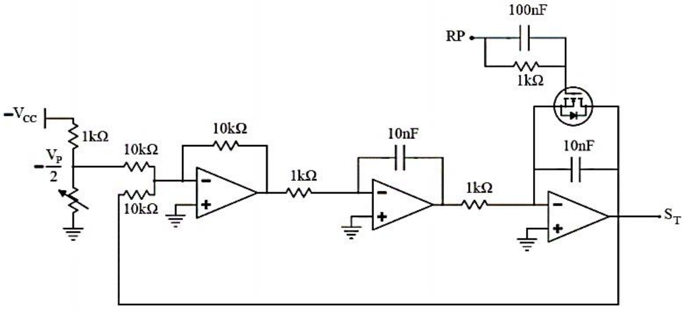

Fig.12.Sawtooth waveform generator circuit

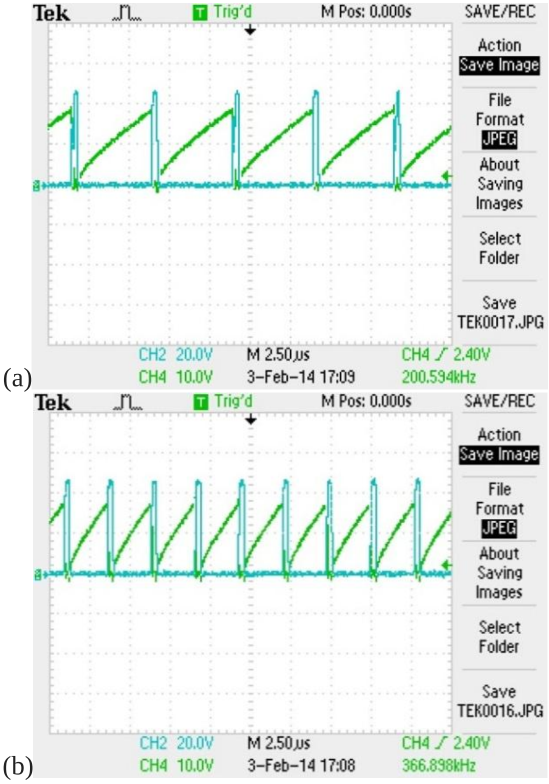

Fig.13.Sawtoothwaveform :(a) 100 kHz, (b) 180 kHz

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[1] Reset Pulse

B Control circuit

Fig.14.presents the generationcircuit of gatesignals forthe powerswitches. The"PP" isthe PWM signalof switcheswhich determine duty cycle of theinverter. In this circuit, the current compare by 2 voltage levels. Thus a "JK flip-flop" employed. Gatesignals S_1-S_3presented in Fig.15.(a) andgatesignalsS_2andS_4presented in Fig.15. (b).

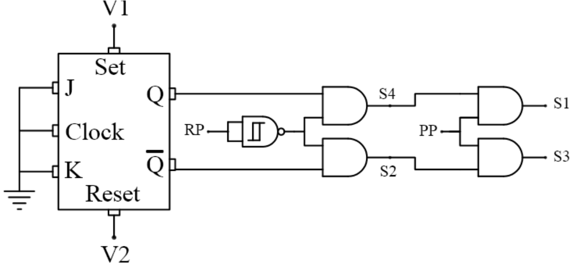

Fig.14. Generation of Gate signals

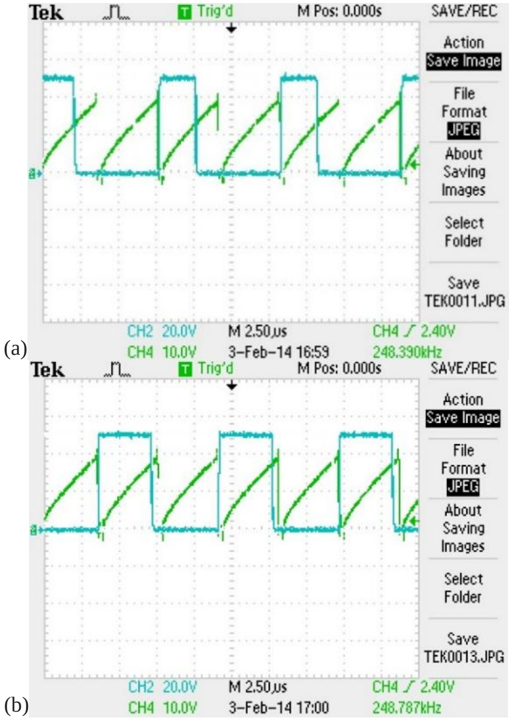

Fig.15. Gate signals: (a) S_1-S_3, (b) S_2 - S_4

The control board is shown in Fig.16. It contains two main parts: sawtooth generation waveform and power switches gate signals.

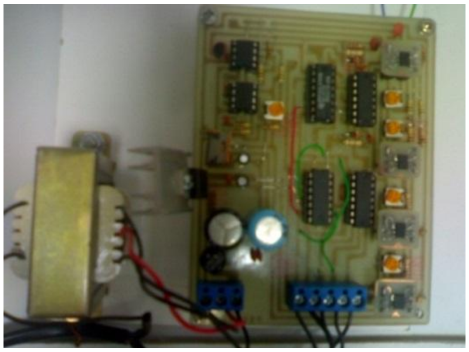

Fig.16. Control board

C Drivers

One of themain parts ofthe power circuitis the trigger circuit of switches. Topreventthe short circuits in inverter legs,the gate commands have to beisolated. Fig.17 shows the driver circuit. Anopto-coupler is used for isolation of firing signals and IC driver for switching of MOSFETs, theoutput ofthetransformeranddriverhavebeendisplayedin the image below.

D Power circuit

The implemented circuit contains (Fig.18.):

Gate drive circuit with opto-couplers and IC drivers, Inverter with its power switches, resonance circuit, output transformer, rectifier and output capacitors with many capacitor and diodes in series to support high voltage.

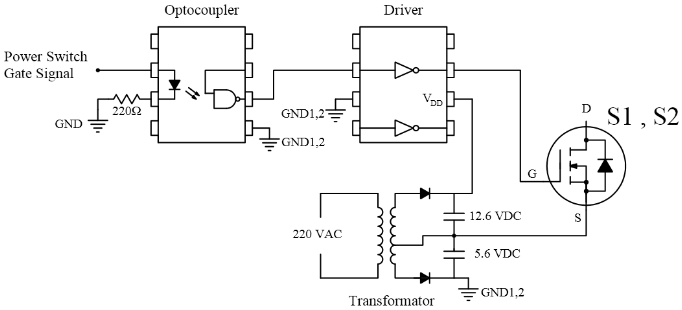

Fig.17. Driver circuit

E Experimental results

According the laboratory limits and security problems, the system is tested with a 10 V DC power supply. The load resistance is 6200 Ω.

Fig.19. (a) shows inverter outputvoltageandcurrentwaveforms. In this figure, thesquare waveform is inverter outputvoltageandsinusoidalwaveform is its current. The peak value of voltage is about 10V and peak current is about 0.7A. Fig.19. (b) shows the output voltage of series-parallel resonantconverter which divided by 2. So the real output voltage is 350V. It means that the convert rate of this resonant converter is 350/10=35. If it connects to a power supply with $220\sqrt{2}$ V, the output voltage will be more than 10 kV.

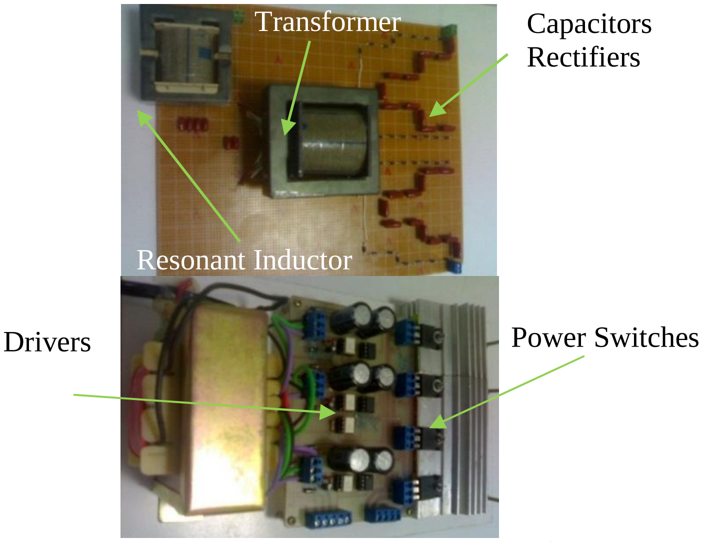

Fig.18. Drivers, inverter switches, resonant elements and transformer

VII. CONCLUSION

Performance of DC-DC converters with high output voltage is significantly affected by the non-ideal transformer with a high conversion rate and the high number of turns of the secondary. Resonant converters often used in high-voltage DC-DC converters because they can use the leakage inductance and capacitance of coils as resonance circuit elements. In addition, using soft switching techniques in these converters provide the possibility of increasing the efficiency and switching frequency. By increasing the operating frequency, it significantly reduces size and weight of system. In this paper, theoretical analysis on series-parallel resonant converter was performed and the results confirmed by simulation and experimental tests.

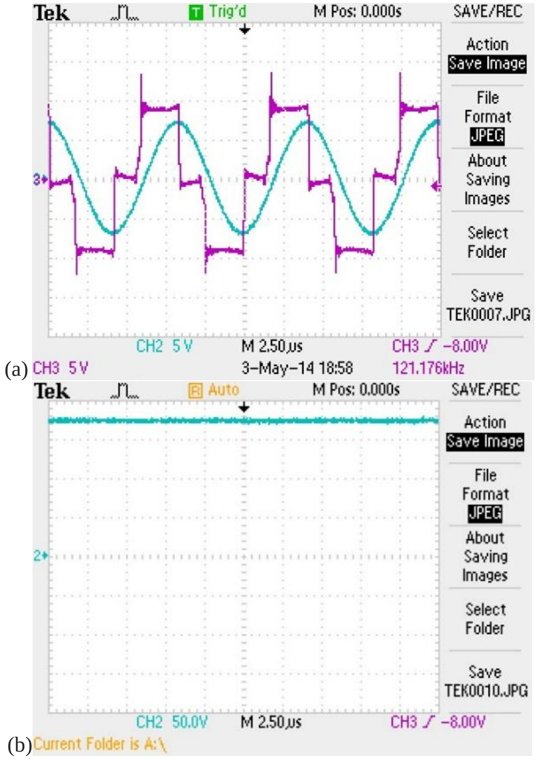

Fig.19.Experimental results: (a) Output voltage (5V/div) and current (0.5A/div) of inverter, (b) Output voltage (divided by 2)

VIII. REFERENCES

[1] A. Abrishamifar, "Switching Power Supplies", 4th ed. Iran, Iran University of Science and Technology, 2013.

[2] M. Rashid, "Power Electronics: Circuits, Devices & Applications", 4th ed. Iran, Tehran, Noor Pardazan, 2008.

[3] F. Canales, P. Barbosa and F. C. Lee, "A zero-voltage and zero-current switching three-level DC/DC converter", IEEE Transaction on Power Electronics, 2002, 898-904.

[4] F. Liu, J. Yan, X.Ruan, "Zero-Voltage and Zero-Current-Switching PWM Combined Three-Level DC/DC Converter", IEEE Transactions On Industrial Electronics, 57, (5), 2010, pp. 1644-1654.

[5] J. M. Aonso, C. Blanco, E. Lopez, "Analysis and Design of a LCC Resonant Converter for High Intensity Discharge Lamps", Technical Proceedings of the IV IEEE International Power Electronics Congress, 1995, pp. 102-107.

[6] F. S. Cavalcante, "High Output Voltage Series-Parallel Resonant DC-DC Converter for Medical X-Ray Imaging Applications", PhD thesis, Swiss federal institute of technology, Zurich, Switzerland, 2006.

[7] H. MollaAhmadianKaseb ,A.Karimpour , N.Pariz, F.Tahami, "Hybrid Modeling of a DC-DC Series Resonant Converter: Direct Piecewise Affine Approach", IEEE Transactions on Circuits and Systems Part I: 59, (12), 2012, pp. 3112-3120.

[8] P. Chandrasekhar, "Performance of soft-switched DC-DC resonant converter for Electrolyzer", 4th International Symposium on Resilient Control Systems (ISRCS), Aug. 2011, pp. 95-100.

[9] R. Seyezhai, G.Ramathilagam, P.Chitra, V.Vennila, "Investigation of Half-Bridge LLC Resonant DC-DC Converter for Photovoltaic Applications", International Journal of Innovative Research In Electrical, Electronics, Instrumentation And Control Engineering, June 2013, 1, (3).

[10] G. Ivensky, A. Kats, and S. Ben-Yaakov, "An RC load model of parallel and series-parallel resonant DC-DC converters", IEEE Trans. on Power Electronics, 1999, 515-521.

[11] F. S. Cavalcante, J. W. Kolar, "Design of a 5kW High Output Voltage Series-parallel Resonant DC-DC Convertor", 34th IEEE Power Electronic Specialists Conference, Acapulco, Mexico, 2003, Vol. 4, 1807-1814.

[12] R. W. Erickson, "Comparison of Resonant Topologies in High-Voltage DC Applications", IEEE Transactions on Aerospace and Electronic Systems, May 1988, Vol. 24, No. 3, 263-274.

[13] H. Pinheiro, P. K. JAIN, G. JOÓS, "Self-Sustained Oscillating Resonant Converters Operating Above the Resonant Frequency", IEEE Transactions on Power Electronics, 1999, Vol.14, No.5, 803-815.