DESIGN OF LCL RESONANT CONVERTER FOR ELECTROLYSER

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Abstract: An Electrolyser linked with a DC bus are analyzed and discussed in this paper. An electrolyser is a part of renewable energy system which generates hydrogen from water electrolysis. An LCL series parallel resonant converter (SPRC) for an electrolyser application is simulated and implemented. A three element resonant converter capable of driving voltage type load with load independent operation is analyzed. Detailed experimental results obtained from a MOSFET based DC-DC resonant converter are presented to verify the analysis. The MATLAB simulated results show that the output of converter is free from the ripples, constant current, regulated output voltage and this type of converter can be used for electrolyser application. This converter has advantages like high power density, low EMI and reduced switching stresses. The simulation results are verified with the experimental results.

Keywords: DC-DC converter, embedded controller, electrolyser, LCL filter, renewable energy sources, resonant converter.

1. INTRODUCTION

In the recent years the technology development of the fuel cells energy storage systems allowed the use of the fuel cell as an alternative to the commonly used battery storage systems. In distributed energy source applications electrolytic hydrogen offers a promising alternative for long-term energy storage of renewable energy. In the present paper a distributed energy source is described and discussed focusing on the interaction among the several parts connected to the electrical DC bus. A key role inside this technical environment is played by the machines used for the hydrogen production. The stored hydrogen is fed to a fuel cell to produce electricity. The main target of the analysis is the evaluation of a DC-DC converter topology that supplies the electrolyser in order to obtain the optimization of the converter efficiency. The converter switches which have been used are super junction MOSFET’s with reduced forward resistance in the conduction mode and improved dynamic characteristics in the switching transients. Resonant converters possess several desirable features like zero voltage switching, zero current switching, high frequency operation, high efficiency, small size and low electromagnetic interference. The series resonant converter (SRC) and parallel resonant converter (PRC) are basic resonant converter topologies. The merits of SRC include better load efficiency and inherent DC blocking of the isolation transformer due to the series capacitor in the resonant network. However the load regulation is poor and output voltage regulation at no load is not possible by switching frequency variations. On the other hand, PRC offers no-load regulation but suffers from poor load efficiency and lack of DC blocking for the isolation transformer. For better regulation, the LCL SPRC has been demonstrated experimentally with independent load when operated at resonant frequency making it attractive for application as a constant voltage power supply. It has been found from the literature [1]-[10] that the LCL tank circuit connected in series parallel with the load and operated in above resonant frequency improves the load efficiency and independent operation. LCL SPRC is expected the speed of response, voltage regulation and better load independent operation. The LCL SPRC has been module and analyzed for estimating various responses. The closed loop module for LCL SPRC has been simulated using MATLAB/Simulink for comparing the performance with

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existing converter. The converter strategy control allows a zero voltage transient on the power switches of the full-bridge inverter. Several simulation runs have been carried out in order to better understand the impact of the DC-DC converter chosen in the system application. Finally the experimental converter prototype are presented and discussed. The output is hydrogen feeding a suitable storage tank as shown in Fig. 1.

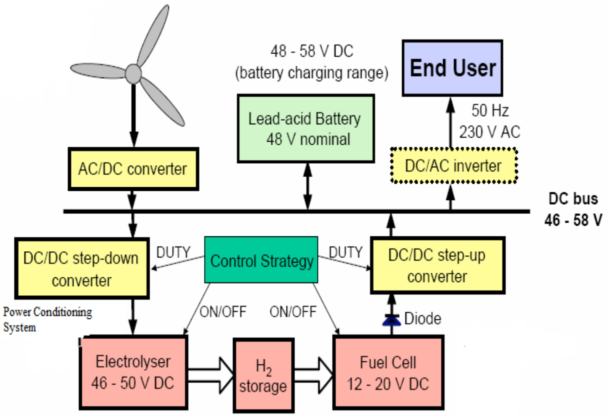


Fig. 1. Distributing renewable energy source system.

In order to understand the behavior of the electrolyser system and for the suitable design of the supply DC-DC converter, a characterization on an actual electrolyser has been carried out. The electrolyser is connected to the DC bus through a DC-DC power converter. During periods when the load demand exceeds the renewable resource input, a fuel cell operating on the stored hydrogen would provide the balance of power. To ensure proper flow of power between the system elements, the available energy from different sources are coupled to a low voltage DC bus. A direct connection of DC bus to the electrolyser is not suitable because it lacks the ability to control the power flow between the renewable input source and the electrolyser. Therefore, a power conditioning system, usually a DC-DC converter is required to couple the electrolyser to the system bus. High-frequency (HF) transformer isolated, HF switching dc-dc converters are suitable for this application due to their small size, light weight and reduced cost. To increase their efficiency and to further increase the switching frequency while reducing the size, cost and EMI problems, soft-switching techniques will be used in this paper. Resonant converters offer low switching losses due to zero voltage switching (ZVS) making them popular for high frequency applications. The emphasis, however, has mostly been on the analysis, design and optimization of resonant converters for constant output voltage power supplies.

2. PAST EXPERIENCES

Analysis and design of LCL type series resonant converter has been done by Bhat in 1994[1]. G.S.N Raju used LCL resonant converter with PWM control analysis in 1984[6]. Bo Yang and F. C. Lee proposed LLC type resonant converter for front end DC-DC converter in 2002[3]. LCL resonant converter with clamp diodes has been done by Mangesh Borage and Sunil Tiwari in 2007[8]. Todor A. Filchev, Dimitre D. Yudov, Vencislav and V. Valchev were investigated the DC-DC resonant converter for power distribution applications in 2004[10]. Miller used resonant switching power conversions during (1976). Deepak S.Gautam and Ashoka K.S.Bhat, has given the comparison of soft-switched DC-DC converters for electrolyser applications in 2006. Very fewer reports are available using DC-DC series parallel resonant converter with LCL filter for electrolyser application. An attempt has been made in the present work to implement DC-DC converter with LCL filter using embedded microcontroller in open loop and closed loop control.

3. FILTER TOPOLOGIS

In order to choose an optimal filter topology considering an inverter in DC-DC converter for electrolyser, parameters like efficiency, weight and volume have to be considered. Regarding efficiency, filter topologies with reduced losses are required, though those are relatively small when compared to losses in the inverter. Weight and volume are considered as critical characteristics at offshore applications due to difficulties with transportation, installation and maintenance. The filter cost depends basically on the amount of components and materials used, for example the magnetic material for the core of inductors. Last, but certainly not least, the filter shall be able to perform its task within a certain degree of independence of the output parameters, like resonance susceptibility and dynamic performance are of major importance.

As proposed in [10] and [12], filters connected to the output of an inverter have basically the following circuit configuration as seen in Fig. 2.

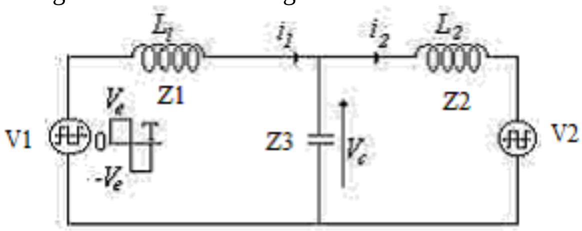


Fig. 2. The Equivalent Circuit.

A. L Filter

This topology (Z1 is finite, Z3 is infinite and Z2=0) consists on just an inductive filter connected in series with the converter. Although being the topology with the fewer number of components the system dynamics is poor due to the voltage drop across the inductor causing long time responses.

B. LC Filter

This topology (Z1 is finite, Z3 is finite and Z2=0) has Z3 as a result of association of a capacitor and an inductor. With higher values of capacitance, the inductance can be reduced, leading to reduction of losses and cost. Nevertheless, very high capacitance values are not recommended, since problems may arise with inrush currents, high capacitance current at the fundamental frequency.

C. LCL Filter

When compared with the previous topology, the LCL filter has the advantage of providing a better decoupling between filter and output impedance and a lower ripple current stress across the second inductor (since the current ripple is reduced by the capacitor, the impedance at the output side suffers less stress when compared with the LC topology). Like the LC filter, increasing the capacitor value reduces filter cost and weight but with similar drawbacks.

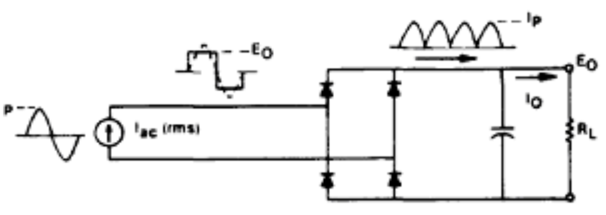
4. ANALYSIS AND DESIGN OF FULL BRIDGE LCL SPRC

A typical LCL filter is shown in Fig. 2, where V_1 is the inverter output voltage, V_c is the voltage across the filter capacitor and V_2 is the output of the resonant circuit.

$$V_c = V_1 - L_1 \frac{di_1}{dt}$$

$$V_2 = V_c - L_2 \frac{di_2}{dt}$$

The full bridge converter applies a square wave of voltage to a resonant network. The resonant network has the effect of filtering the higher harmonic voltages so that, essentially, a sine wave of current appears at the input to the resonant circuit. This fact allows classical ac analysis techniques to be used. The analysis proceeds as follows. In the ac analysis, the output rectifier and the filter are replaced by the equivalent ac resistance and the square-wave input voltage source is replaced by its fundamental sinusoidal equivalent. The power transfer from input to output is assumed to be only via the fundamental component and the contribution of all the harmonics is neglected (Robert L Steigerwarld, 1988, Robert W. Erickson, 2001). The equivalent ac resistance for the rectifier with capacitive filter and the RMS value of the fundamental component of square-wave voltage (input to resonant tank) are given by



$$R_{ac} = \frac{E_{ac}(rms)}{I_{ac}(rms)} = \frac{\pi^2}{8}\frac{E_o}{I_o} = \frac{\pi^2}{8} R_L$$

and $V_{in,rms} = \dfrac{2\sqrt{2}}{\pi} V_d$

The resonant frequency and the normalised switching frequency is defined as

$$w_o = \frac{1}{\sqrt{LC}} \quad \text{and} \quad w_n = \frac{w}{w_o}$$

The characteristic impedance and Q of the resonant network is

$$Z_n = \sqrt{\frac{L}{C}} \quad \text{and} \quad Q = \frac{w_o L}{R_L} = \frac{Z_n}{R_L}$$

The voltage and current gain is defined as

$$M = \frac{V_o}{V_d} \quad \text{and} \quad H = \frac{I_o}{V_d / Z_n} = MQ$$

The voltage and current base values are given by

$$V_b = V_d \quad \text{and} \quad I_b = I_{in} = \frac{V_d}{Z_{in}}$$

For a rectifier with an inductor output filter, the sine wave voltage at the input to the rectifier is rectified, and the average value takes to arrive at the resulting dc output voltage. For a capacitive output filter, a square wave of voltage appears at the input to the rectifier while a sine wave of current is injected into the rectifier. For this case the fundamental component of the square wave voltage is used in the ac analysis.

48V DC is converted into high frequency AC using as inverter. The output of the inverter is filtered using LCL filter. This is stepped down to 5V by using a step down transformer. Further this is rectified and filtered using

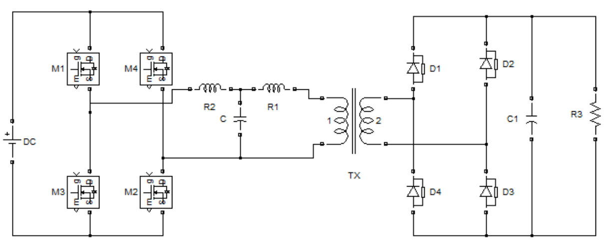


Fig. 3. LCL Series-Parallel Resonant DC-DC Converter.

C filter. The circuit of series-parallel LCL resonant DC-DC converter is shown in the Fig. 3. Soft switching of the switches is done using LCL circuit in the output of the inverter. The even harmonics in the output of the rectifier are filtered using C filter. Driving pulses are applied to the MOSFET in such a way that the pulse width coincides with the resonant period.

A switch network (S1-S4) produce a square wave voltage output therefore the input voltage is replaced by the voltage source $v_s(t)$ with amplitude V_s. The output is replaced by depend voltage sink $v_{Rl}(t)$ with amplitude V_{Rl}.

The fundamental components are:

$$v_s(t) = \frac{4V_t}{\pi}\sin(w.t) \;;\quad V_s = \frac{4V_t}{\pi}$$

$$v_{R1}(t) = \frac{4V_o}{\pi}\sin(w.t) \;;\quad V_{R1} = \frac{4V_o}{\pi}$$

The complex amplitudes of the currents and voltages are used for the analysis. Therefore the equations that describe the circuit from Fig.3 are given by:

$$\dot{V}_s = \dot{V}_c + 2\cdot s\cdot L_o\cdot \dot{I}_1 \qquad \text{-----------}\ (1)$$

$$\dot{V}_{R1} = 2\cdot s\cdot L_o\cdot \dot{I}_2 - \dot{V}_c \qquad \text{-----------}\ (2)$$

$$\dot{V}_c = \frac{(\dot{I}_2 - \dot{I}_1)}{s\cdot C} \qquad \text{-----------}\ (3)$$

$$\dot{V}_{R1} = -\dot{I}_2\cdot R_{e2} \qquad \text{----------}\ (4)$$

where L_1=L_2 and $L_o = L_1/2 = L_2/2$

From (1),(2),(3) and (4), the voltage transfer function is:

$$H(s) = \frac{V_{R1}}{V_s} = \frac{1}{1 + 4.s.L_o/R_o + 2.s^2.L_o.C + 4.s^3.L_o^{\,2}.C/R_e}$$

The magnitude of *H*(*j*□) is:

$$\|H(jw)\| = \frac{1}{\sqrt{(1-2.F^2)^2 + 16.F.Q^2(1-F^2)^2}}.$$

Where $F = w_s / w_o$ is the normalized switching frequency.

$w_o = 1/\sqrt{C.L_o}$ is the resonant frequency,

$Q = Z_o / R_e$, is the ac quality factor of the resonant circuit, and

$$Z_o = \sqrt{L_o/C}$$

The resonant frequency as a function of the load resistor is given in Fig. 4. However in described ideal circuit the load can be neglected.

As shown in Fig 4. the voltage transfer ratio i.e the ratio of the amplitudes of the first harmonic of the voltages, is plotted versus the normalized frequency F for four values of Q.

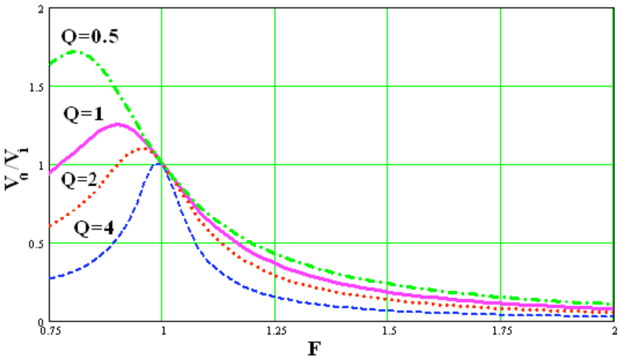


Fig.4. Frequency response of the LCL resonant tank

5. SIMULATION RESULTS

To describe the operation of the proposed LCL resonant converter for electrolyser application, simulation results were obtained using Matlab/Simulink for the 12.5W converter and 20 KHz switching frequency. Scopes are connected to measure resonant output voltage, driving pulses and load voltage. Waveforms are presented in the following order: gating signals; output of the inverter; resonant tank circuit output voltage; output of the rectifier and load voltage.

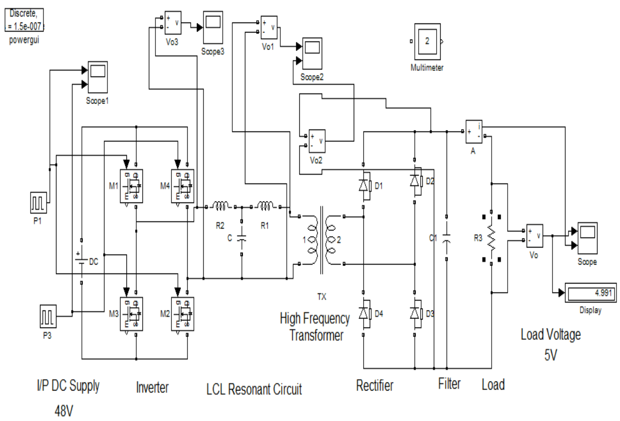
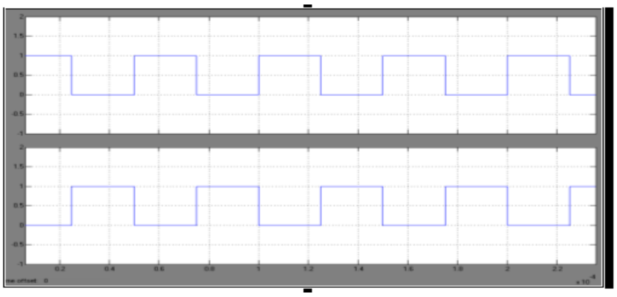
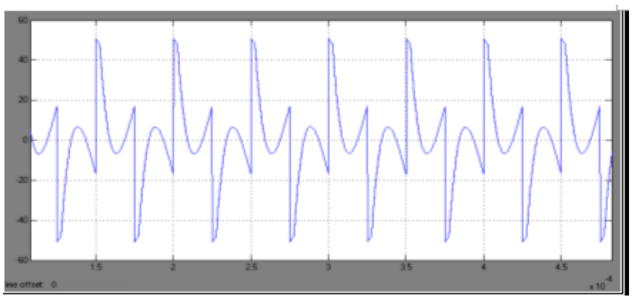


Fig. 5. LCL Resonant DC-DC Converter

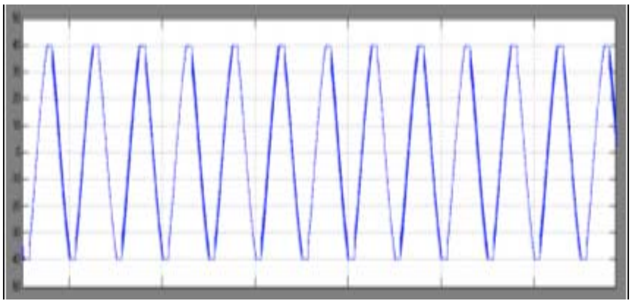
The closed loop circuit model of DC-DC converter with LCL resonance is shown in Fig. 7. Scopes and displays are connected to measure the output voltage. A disturbance is given at the input by using two switches. Output voltage is sensed and it is compared with the reference voltage. The error signal is given to the controller. The output of PI controller controls the dependent source. Input voltage with disturbance is shown in Fig. 8. The output voltage of closed loop system is shown in Fig. 9. The disturbance is applied at 3.0 secs. The control circuit takes proper action to reduce the amplitude to the set value and settles after 0.5 secs. Thus the closed loop system reduces the steady state error.



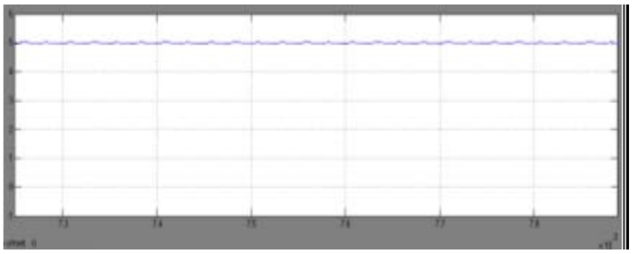
(a)



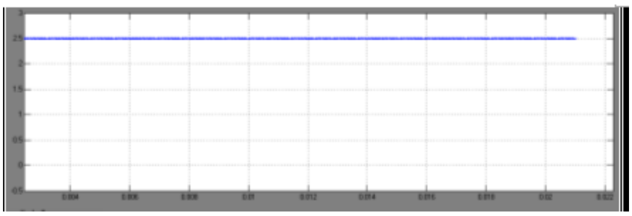
(b)



(c)



(d)



(e)

Fig. 6. (a) Driving Pulses (b) Inverter output voltage (c) Output of the resonant tank (d) Output voltage of the rectifier (e) Load Voltage (5V)

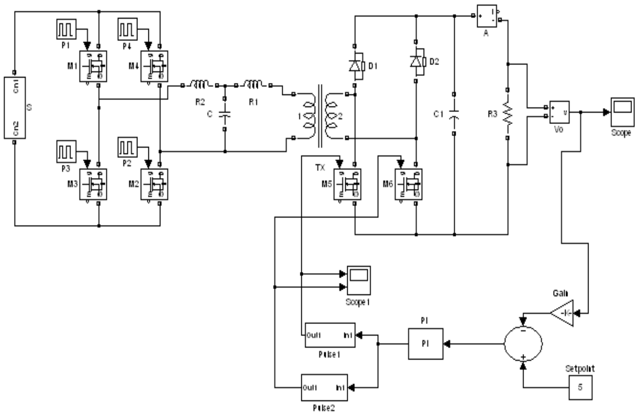


Fig. 7. Closed loop controlled LCL Resonant DC-DC Converter

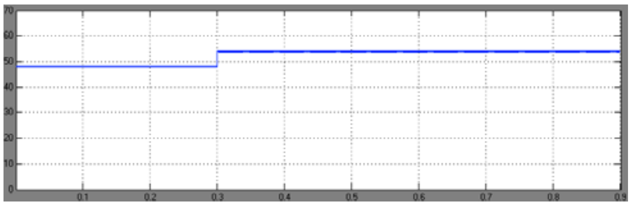


Fig. 8. Input Voltage with Disturbance

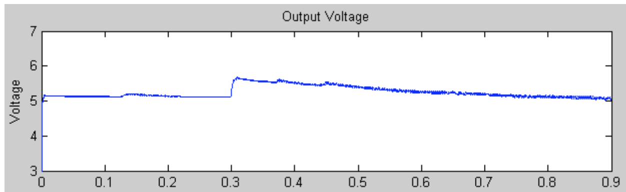


Fig. 9. Output Voltage Waveform with Disturbance

6. EXPERIMENTAL RESULTS

An experimental converter was built in the laboratory based on the design example and it is tested. Embedded controlled gating signals, high speed MOSFETs and a high frequency transformer were used in the experimental converter. The modulation of the driving signals for the converter device is used as a control parameter to maintain the supply voltage value at the request value of 5v. It is clearly shown in figures that the power losses in the occurrence of the turn on switching are maintained very low by means of the resonant operation. The hardware implementation details are shown in Fig. 10.The hardware consists of power circuit and microcontroller based control circuit. The pulses are generated by using the ATMEL microcontroller 89C2051. These pulses are amplified using the driver IC IR2110 as shown in Fig. 11. Fig. 12(a) to (e) shows some typical waveforms obtained at full load. Experimental waveforms clearly demonstrate the ZVS for all the switches. They also demonstrate the theoretical predictions. It is to be observed that the experimental results co inside with the simulation results.

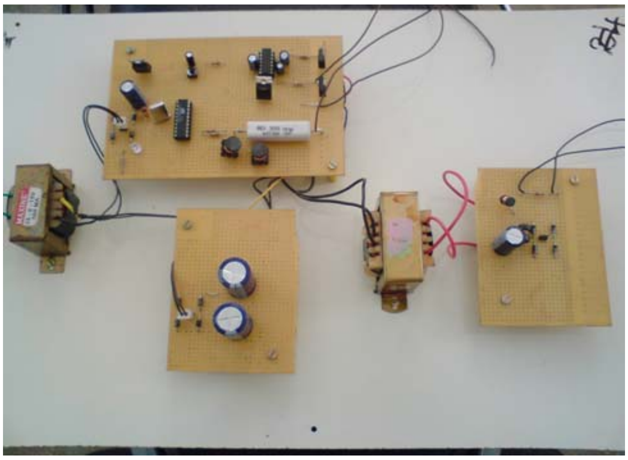


Fig. 10. Embedded controlled full bridge LCL resonant converter. (Hardware Layout)

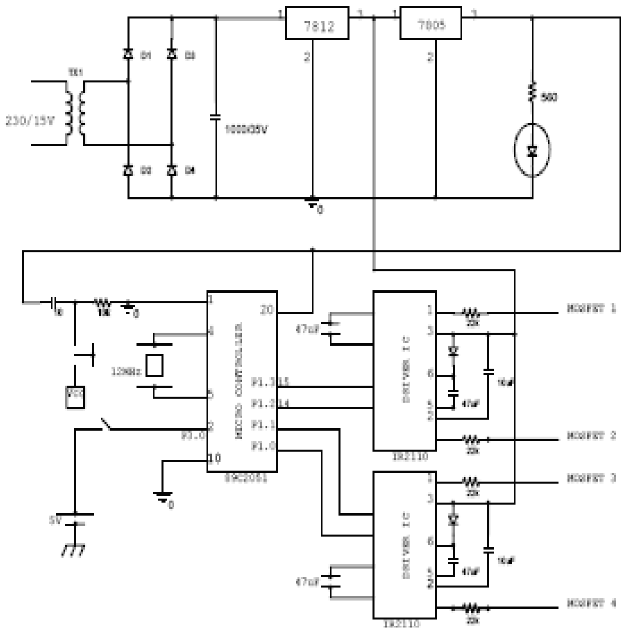
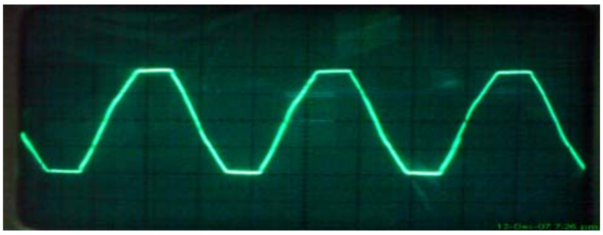
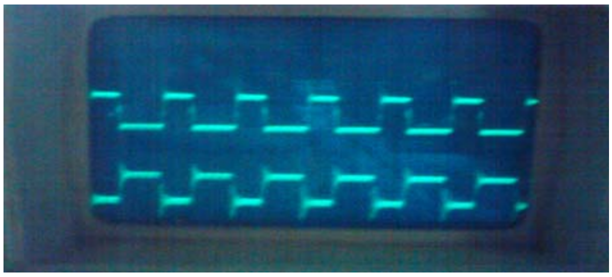


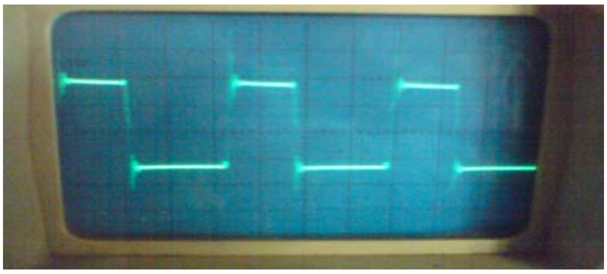
Fig. 11. Control circuit for generating the Driving Pulses.



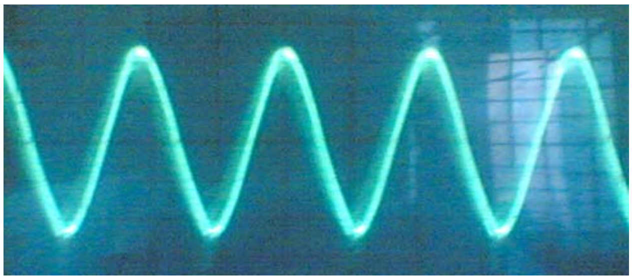
(a) AC Input Voltage.



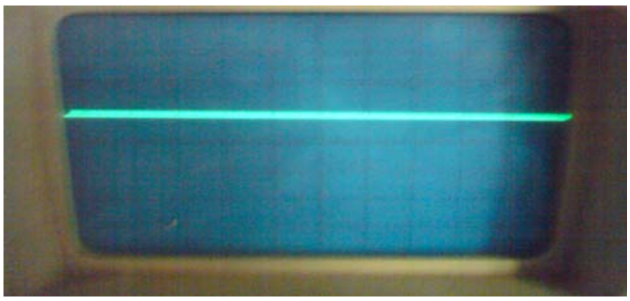
(b) Driving Pulses.



(c) Inverter Output Voltage.



(d) Output voltage of LC Resonant Inverter.



(e) Output of DC-DC Converter. (Load Voltage)

Fig. 12 (a) to (e) Experimental waveforms obtained at full load.

7. CONCLUSION

An approximate analysis of the resonant LCL converter was carried out, based on the equivalent circuit concept and applying the fundamental harmonics method. DC-DC converter system is simulated and tested in laboratory. The electrical performances of the converter have been analyzed by simulation runs and experimental tests indicate that the output of the inverter is nearly sinusoidal. The output of the rectifier is pure DC due to the presence of C filter at the output. DC-DC converter with LCL filter is a viable alternative to the existing converters, due to the advantages like reduced di/dt, low switching losses with high efficiency. The converter maximizes the efficiency through the zero voltage switching and the use of super-junction MOSFET as switching devices with high dynamic characteristics and low direct voltage drop. The experimental results closely agree with the simulation results.

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