Design Consideration of LLC Resonant Converter for Electrolyser

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Abstract: Electrolytic hydrogen offers a promising alternative for long-term energy storage of renewable energies (RE). The long-term excess energy with respect to load demand has been sent to the Electrolyser for hydrogen production and then the fuel cell has utilized this stored hydrogen to produce electricity when there were insufficient wind and solar energies with respect to load requirements. The RE system components have substantially different voltage-current characteristics and they are integrated on the DC bus through a power conditioning devices for optimal operation. The DC power required by the Electrolyser system is supplied by the DC-DC LLC resonant converter. The simulation and experimental results show that the power gain obtained by this method clearly increases the hydrogen production and storage rate from wind-PV systems.

1. Introduction

Over recent years, it has been recognized that the combustion of fossil fuels has significantly increased the proportion of carbon dioxide in the atmosphere, with many postulating that this has and will continue to cause changes in global climate. A continuing net global temperature rise and increasing occurrence of extreme climate events are anticipated during the forthcoming century. It is therefore imperative that energy systems based on the utilization of non-fossil sources be developed and exploited as early as possible. The existence of considerable wind resources in remote places and the high costs of supplying electricity in those places suggest that these might be the first places to benefit from a switch to a hydrogen-based fuel economy. To date, the possibility of using wind power and photovoltaic power plants with electrolyzers to generate hydrogen has received little attention for renewable energy systems [1]-[3]. The combination of a battery bank with long-term energy storage in the form of hydrogen can significantly improve the performance of stand-alone RE systems. Also, the overall RE system performance is very sensitive to local weather conditions. Thus, to achieve an adequate performance from such a complex system, one requires appropriate components and a well-designed control system in order to achieve autonomous operation and energy management in the system [4]–[7]. 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 as shown in Figure 1. The DC power required by the Electrolyser system is supplied by the LLC resonant DC-DC converter. The Conventional PWM technique processes power by controlling the duty cycle and interrupting the power flow. All the switching devices are hard-switched with abrupt changes of currents and voltages, which results in severe switching losses and noises. Meanwhile, the resonant technique process power in a sinusoid

Received: May 19th, 2010. Accepted: August 1st, 2011

form and the switching devices are softly commutated. Therefore, the switching losses and noises can be dramatically reduced. For this reason, resonant converters have drawn a lot of attentions in various applications [1-3]. Among many resonant converters, the half-bridge LLC-type resonant converter has been the most popular topology for many applications since this topology has many advantages over other topologies; it can achieve zero voltage switching (ZVS) over the entire operating range, and all essential parasitic elements, including junction capacitances of all semi-conductor devices and the leakage inductance of the transformer,

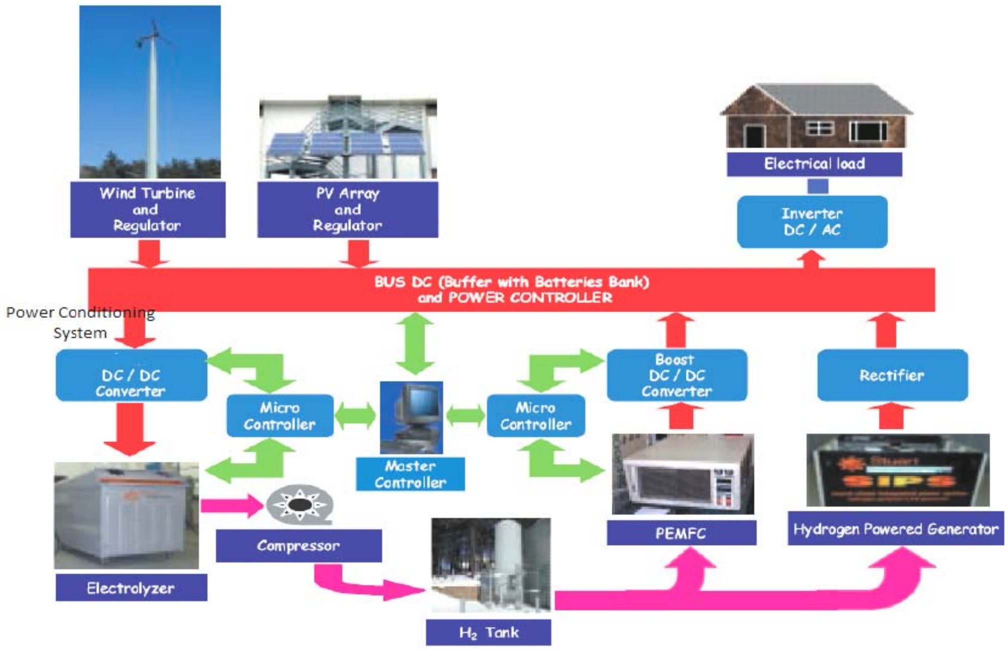

Figure 1. Stand-alone Renewable Energy System

are utilized to achieve soft-switching. The design procedure is verified through an experimental prototype converter of the 250W half-bridge LLC resonant converter. The primary side stage of LLC resonant converter can be built as a full-bridge or half-bridge type and the output stage can be implemented as a full-bridge or center tapped rectifier configuration with capacitive output filter. Figure 2.1, shows the half-bridge implementation of the LLC resonant converter with full-bridge output rectifier, where L_m is the magnetizing inductance and L_{lkp} and L_{lks} are the leakage inductances in the primary and secondary, respectively. Figure 2.2 shows the typical waveforms of the LLC resonant converter. Since the magnetizing inductor is relatively small, there exists considerable magnetizing current (I_m) as shown in Figure 2.2.

2. Operation Principle and Fundamental Approximation

The half-bridge inverter composed of Q_1 and Q_2 applies a square wave voltage (V_d) to the resonant network. The current is lagging the voltage applied to the resonant network which enables the MOSFETs to be turned on with zero voltage.

It is important to note that the equivalent load resistance shown in the primary side is different from actual load resistance. Figure 2.2 shows how this equivalent load resistance is derived. The primary side circuit is replaced by a sinusoidal current source, Iac and a square wave of voltage, V_{RI} appears at the input to the rectifier. Considering the transformer turns the ration (n=Np/Ns), the equivalent load resistance shown in the primary is obtained as

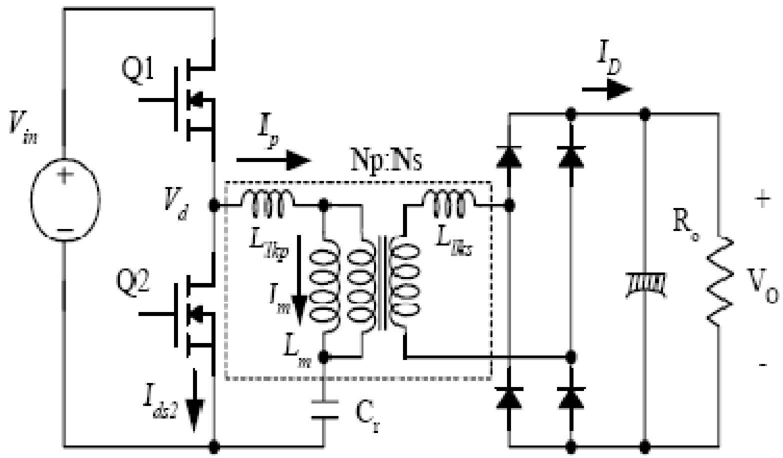

Figure 2.1. A schematic of half-bridge LLC resonant converter

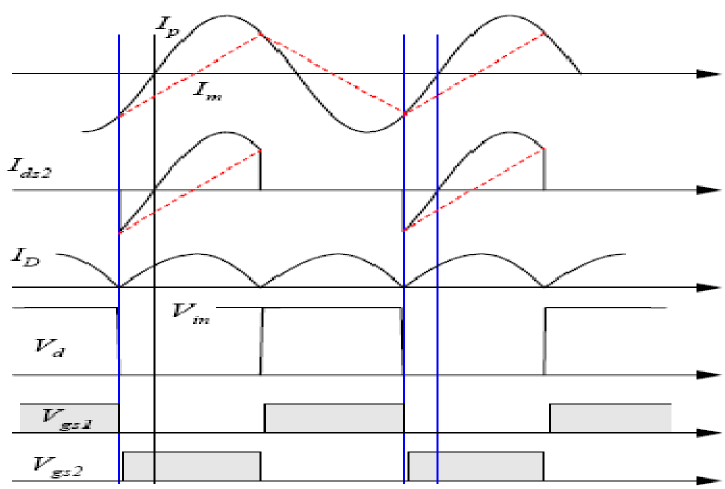

Figure 2.2 Typical waveforms of half-bridge LLC resonant Converter

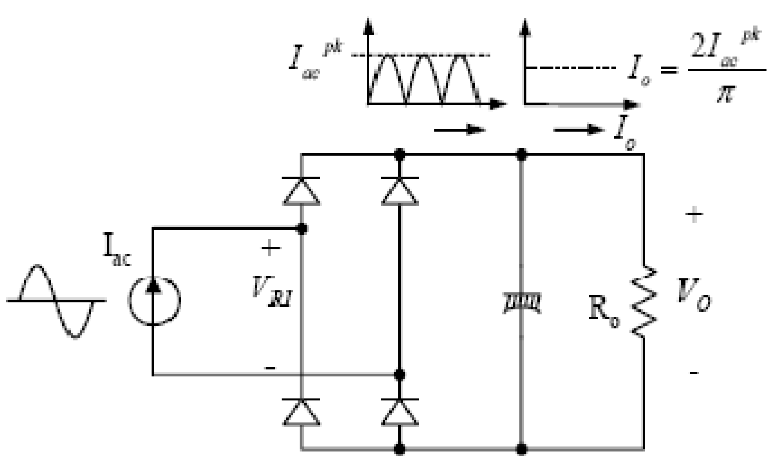

Figure 2.3. Equivalent Load resistance Rac

$$R_{ac} = {}^{8n^2}/_{\pi^2}\, R_o \tag{1}$$

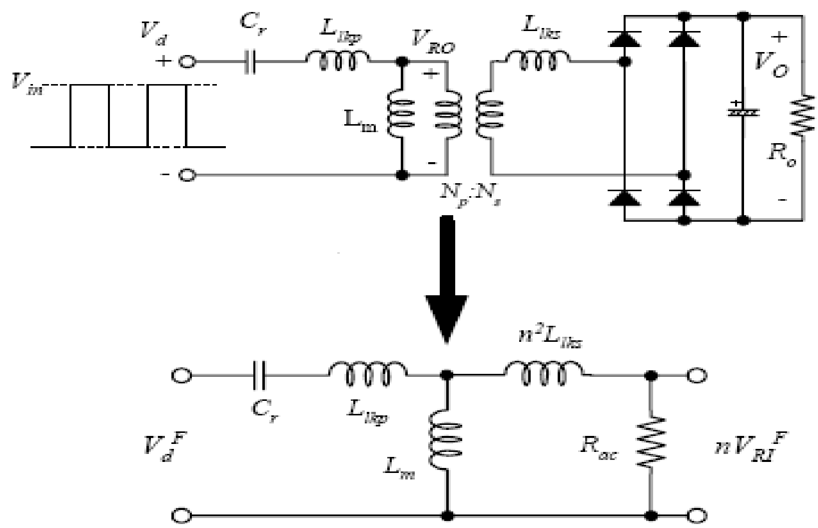

Figure 2.4. AC equivalent circuit for the LLC resonant converter

With the equivalent load resistance obtained in (1), the characteristics of the LLC resonant converter can be derived. Using the AC equivalent circuit of Figure 2.4, the voltage gain is obtained as

$$M = \frac{2nV_o}{V_{in}} = \left| \frac{(\frac{\omega^2}{\omega_p^2})\frac{k}{k+1}}{j(\frac{\omega}{\omega_o}).\left(1-\frac{\omega^2}{\omega_o^2}\right).Q\left(\frac{(k+1)^2}{2k+1}\right)+(1-\frac{\omega^2}{\omega_p^2})} \right| \tag{2}$$

Where

$$\omega_o = \frac{1}{L_r C_r} \quad \omega_p = \frac{1}{L_p C_r}, \quad k = \frac{L_m}{L_{lkp}} \tag{3}$$

$$Q = \frac{\sqrt{L_r/C_r}}{R_{ac}} \tag{4}$$

The gain at the resonant frequency (wo) is also simplified as

$$M_{\omega=\omega_o} = \frac{L_m + n^2 L_{lks}}{L_m} = \sqrt{\frac{L_p}{L_p - L_r}} = \frac{k+1}{k} \tag{5}$$

The equation (2) is plotted in Figure 2.5, for different Q values with k=5 and f_o=100 kHz. As observed in Figure 2.5, the LLC resonant converter shows nearly load independent characteristics when the switching frequency is around the resonant frequency. This is a distinctive advantage of the LLC-type resonant converter over conventional series-resonant converters. Therefore, it is natural to operate the converter around the resonant frequency to minimize the switching frequency variation at light load conditions.

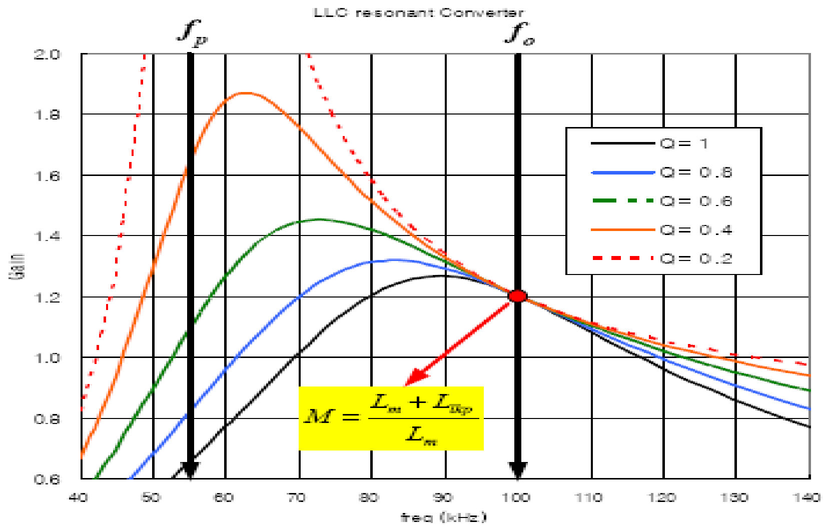

Figure 2.5. Typical gain curves of the LLC resonant converter

The operation range of the LLC resonant converter is determined by the available peak voltage gain. The frequency where the peak gain is obtained exists between fp and fo as shown in Figure 2.5. As Q decreases (as load decreases), the peak gain frequency moves to fp and higher peak gain is obtained. Meanwhile, the peak gain frequency moves to fo and the peak gain drops as Q increases (as load increases).

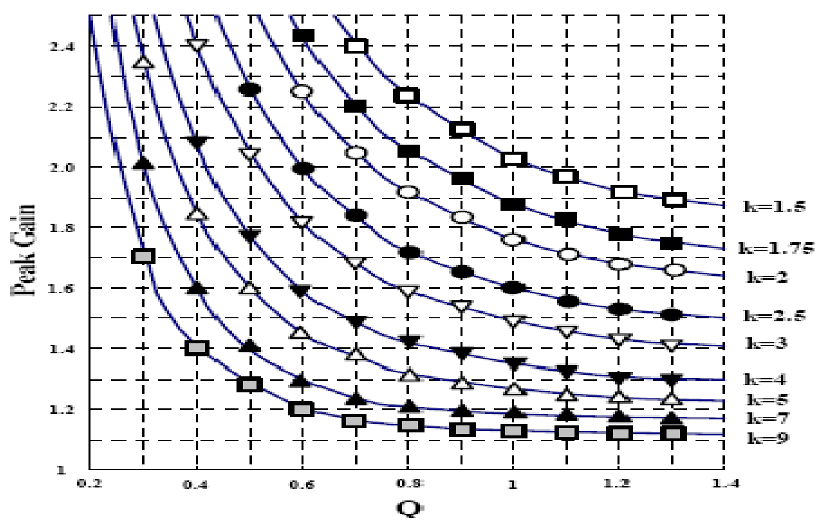

Figure 2.6. Peak gain versus Q for different k values

3. Design of LLC resonant converter

The parameters need to be designed are:

Transformer turns ratio: n

For Half Bridge LLC resonant converter, the turn's ratio will be:

$$\boldsymbol{n = V_{in}/2\,V_o}$$

For Full Bridge, $\boldsymbol{n = V_{in}/V_O}$

The turn's ratio was chosen to be 5.

Series resonant inductor: Lr

$$L_r = \frac{1}{(2\pi f_o)^2 C_r}$$

Resonant capacitor: Cr

$$C_r = \frac{1}{2\pi Q f_o R_{ac}}$$

Magnetic Inductance Lm

$$L_m = \frac{(k+1)^2}{(2k+1)} L_r$$

Resonant inductor ratio: L_m/L_r

The specifications for the design are:
Input voltage range: 150 V to 200 V
Output voltage: 14 V
Maximum load: 1.5 Ohm
Maximum switching frequency: 200 kHz

Specifications of The 250w LLC Resonant Coverter

In order to let the circuit be stable when the load is changed, the circuit parameters are designed in detail [5], [6]. Table I, II and III are the specifications and key components of the 250W LLC converter, respectively.

Table 1.

Normalized Gain	**Resonant Frequency**	**Quality Factor**	**Normalised Frequency**	**Inductor Ratio**
$M = \frac{V_O}{V_{DC}/2}$	$f_o = \frac{1}{2\pi\sqrt{L_r C_r}}$	$Q_r = \frac{\sqrt{L_r/C_r}}{R}$	$f_n = \frac{f}{f_o}$	$L_n = \frac{L_m}{L_r}$

Table 2

Parameter	Value
Input Voltage Vin	150 V
Output Voltage Vo	13.5 V
Output Current Io	18.5A
Output Power Po	250 W

Table 3
Key Components of The LLC Resonant Converter.

Component	Value
Magnetic Inductor Lm	0.1 µH
Resonant Inductor Lr	0.8 µH
Resonant Capacitor Cr	0.75 µF
Duty Ratio D	0.48
Quality Factor Q	0.3
Switching Frequency fs	200 kHz
Turns Ratio n	5

DC/DC converter for hydrogen generation

This DC-DC LLC resonant converter reduces a nominal 150 volts to 13.5 volts with constant current. The output current is normally 18.5 amps. Two electrons are needed to separate the two hydrogen atoms from the oxygen atom in a water molecule. The voltage drives the reaction, but increasing the voltage will not increase the hydrogen generation unless there is also an increase in current. Therefore, this DC/DC converter is designed to run in constant-current mode. This constant-current converter is designed so that no matter what the temperature or concentration of the electrolyte is it will try to put out a constant 18.5 amps. This is not a pulse width modulation scheme (PWM). Although PWMs are easy to design and cheap to build, they are not appropriate for this application. The reason is they still deliver albeit in pulses. Since amps are proportional to electrons per second, it is the amps that produce the hydrogen.

4. Simulation Results

The simulation circuit of half bridge LLC resonant converter with C filter is developed using the blocks of simulink. The simulation circuit and their current and voltage waveforms are shown in Figure 4.1 and Figure 4.2.

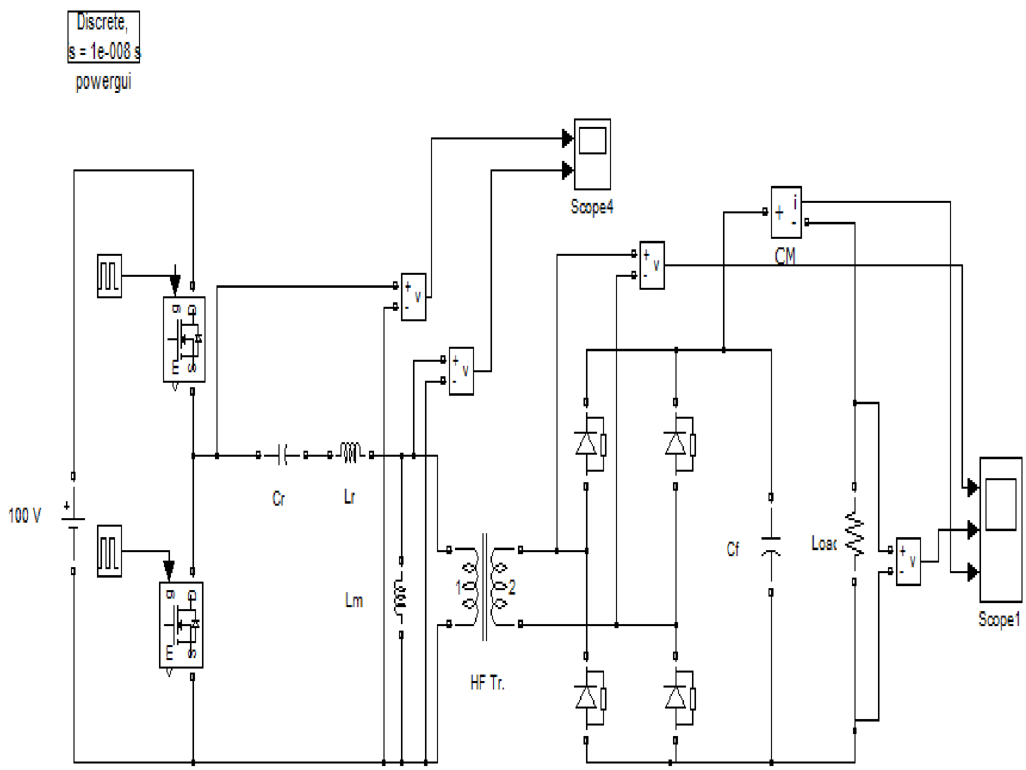

Figure 4.1. Simulation Circuit of Half Bridge LLC Resonant Converter

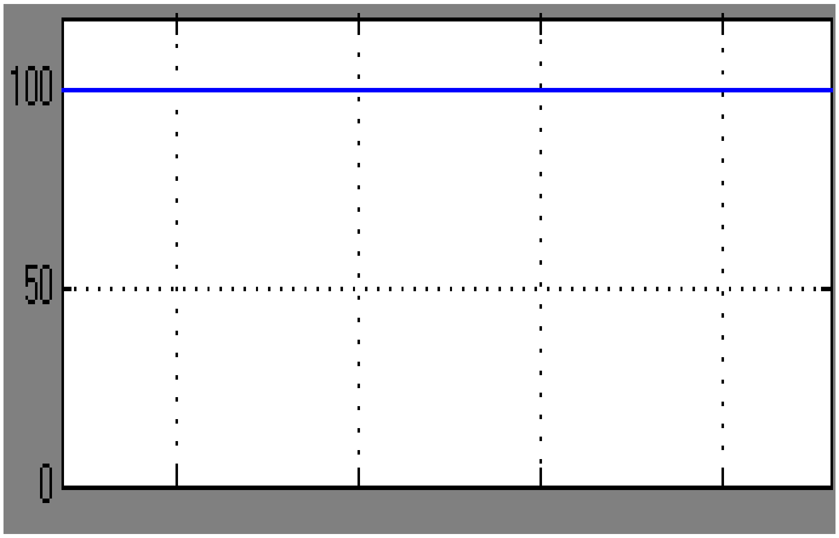

Figure 4.2(a) DC Input Voltage

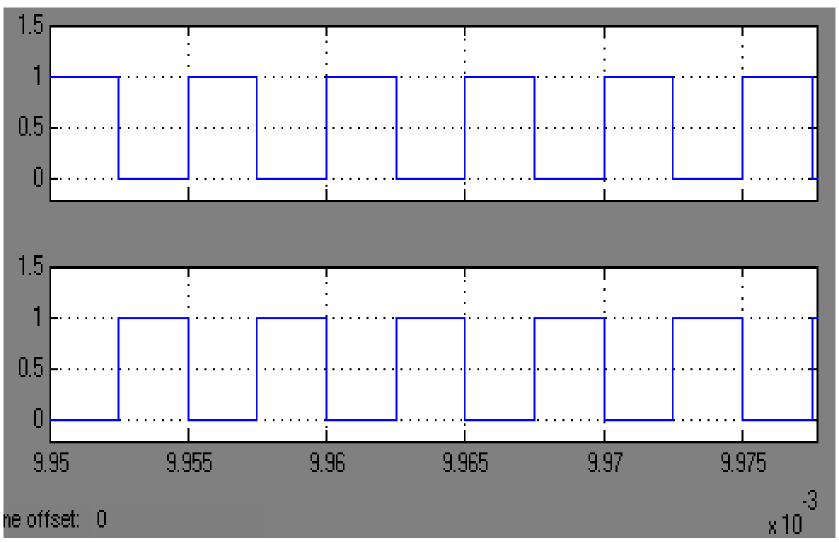

Figure 4.2(b) Driving Pulses of Q1 and Q2

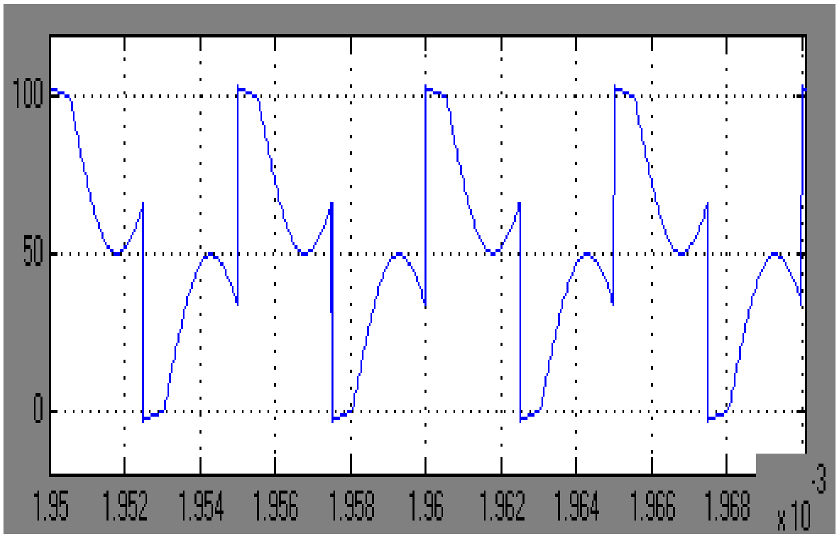

Figure 4.2(c) Output Voltage of the Inverter

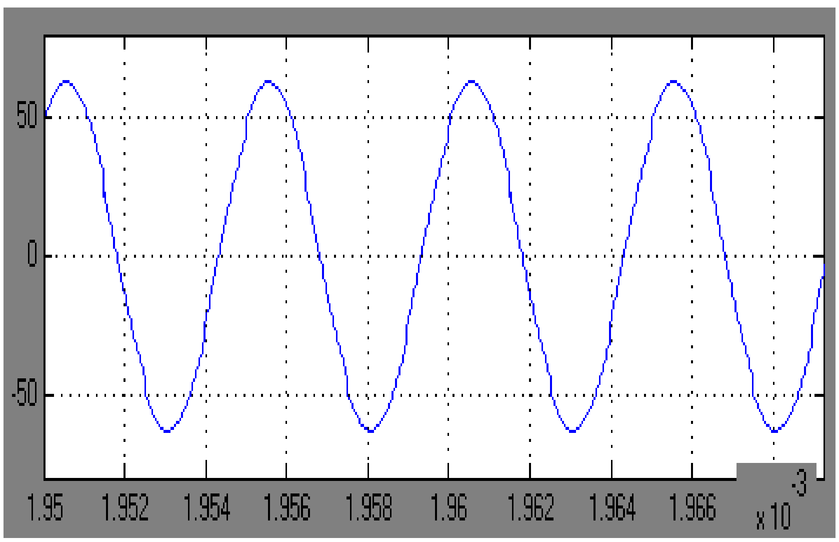

Figure 4.2(d) Output voltage of the LLC resonant inverter

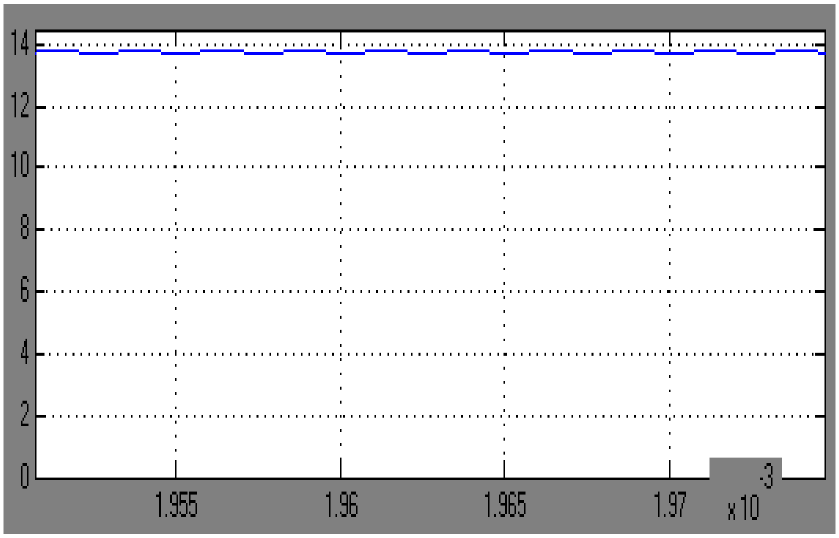

Figure 4.2(e) Output current of the converter fed to the electrolyser

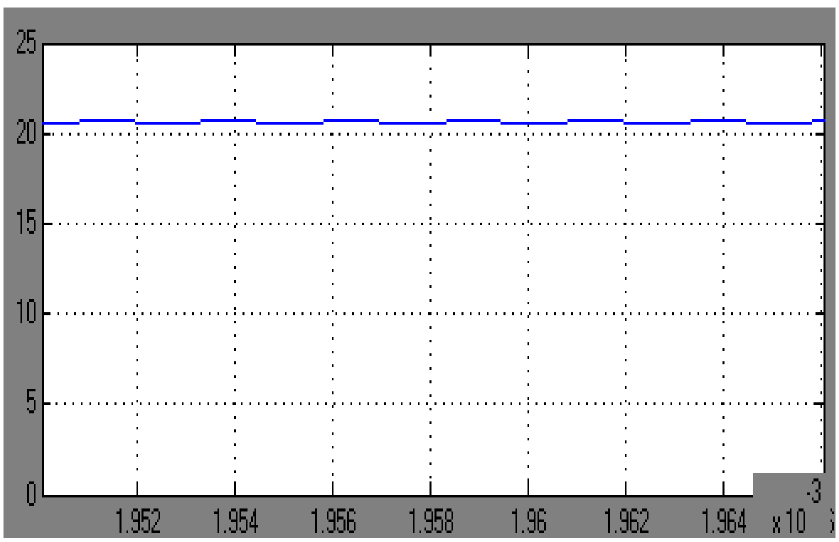

Figure 4.2(f) Output Voltage of the converter fed to the electrolyser

5. Experimental Results

In order to show validity of the previous analysis and design consideration, an experimental prototype converter of the 250 W half-bridge LLC resonant converter has been built and tested. The schematic of the converter and circuit components are shown in Figure 5.1. The input voltage is 150Vdc~200Vdc and the output is 13.5 V/18.5 A. The pulses are generated by using the ATMEL microcontroller 89C2051. These pulses are amplified using the driver IC IR2110 as shown in Figure 5.2. The modulation of the driving signals as shown in Figure 5.3(a) for the converter device is used as a control parameter to maintain the supply voltage value at the request value of 13.5 V. The Oscilloscopes of the different levels of voltage waveforms are shown in Figure 5.3. It's clear that MOSFET is turned-on under ZVS condition over the entire range of load.

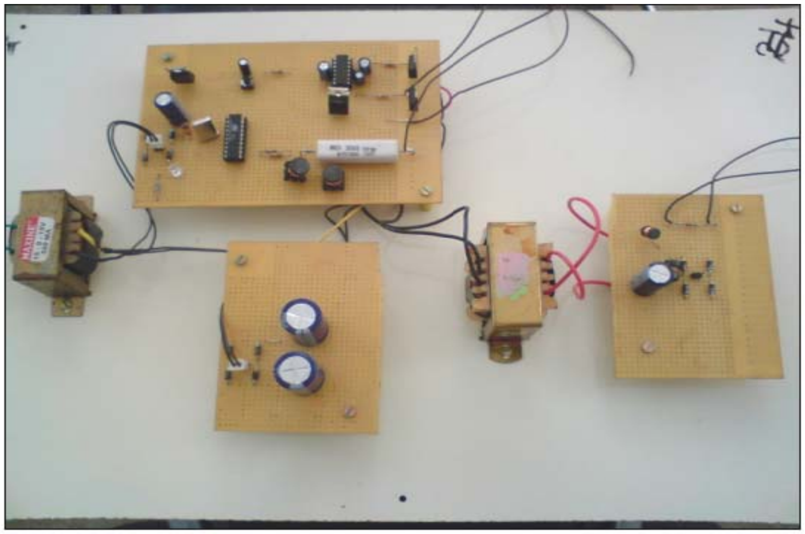

Figure 5.1 Hardware Layout of the Half Bridge LLC Resonant Converter

The ratio (k) between L_m and L_{lkp} is determined as 6.5, which results in the gain at the resonant frequency as

$$M_{(\omega = \omega o)} = \text{——} = 1.15$$

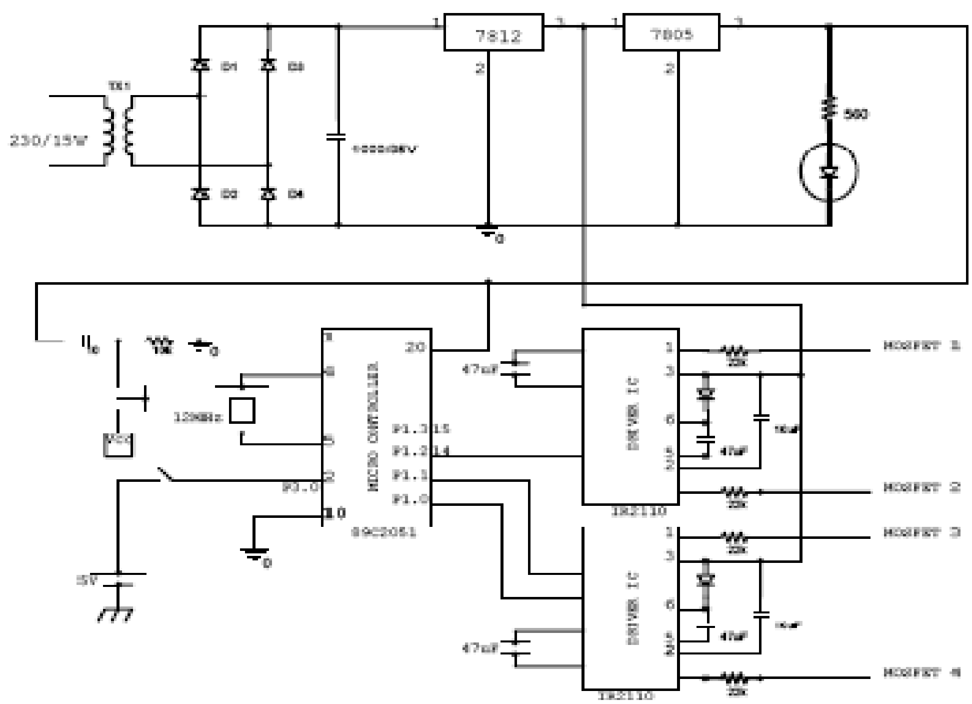

Figure 5.2. Control circuit for generating the Driving Pulse

Since the input voltage varies over wide range, if the converter is designed to operate only below resonance frequencies, the excessive circulating current can deteriorate the efficiency. Thus, the converter is designed to operate above resonance at high input voltage conditions and below resonance at low input voltage to minimize the conduction loss caused by circulating current. The minimum gain at full load is determined as 1.0.

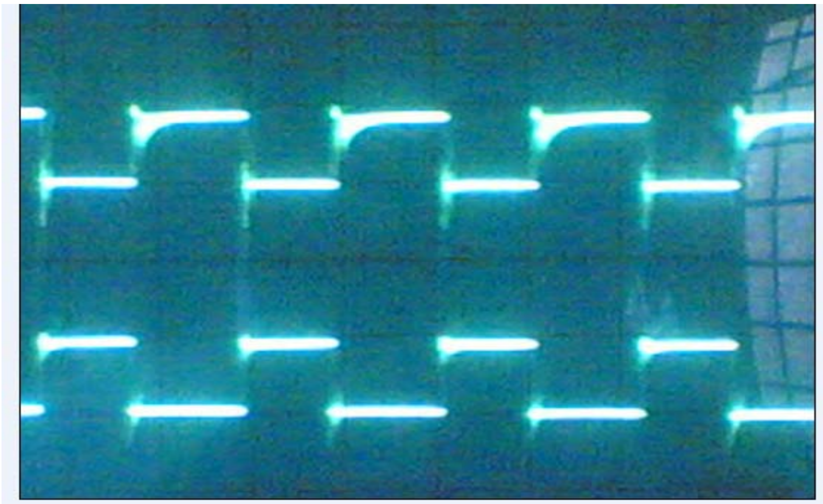

Figure 5.3(a) Oscilloscope of the Driving Pulses

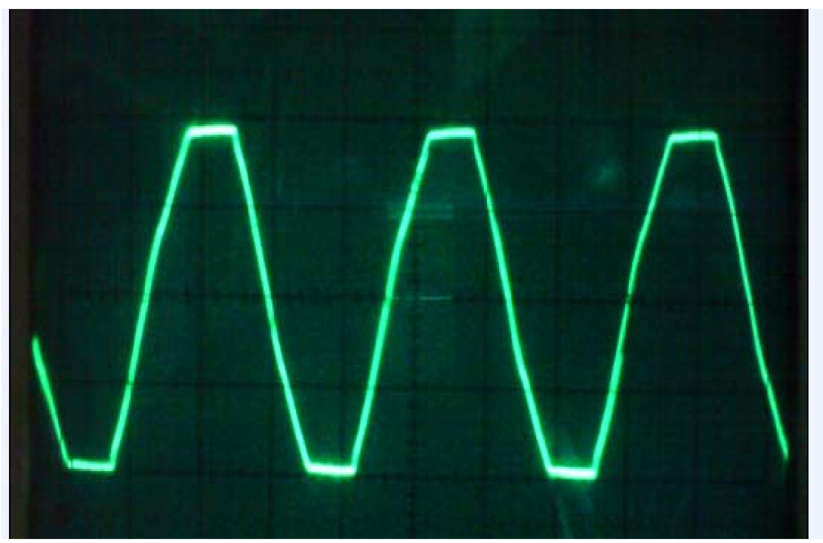

Figure 5.3(b) Oscilloscope of the Inverter Output

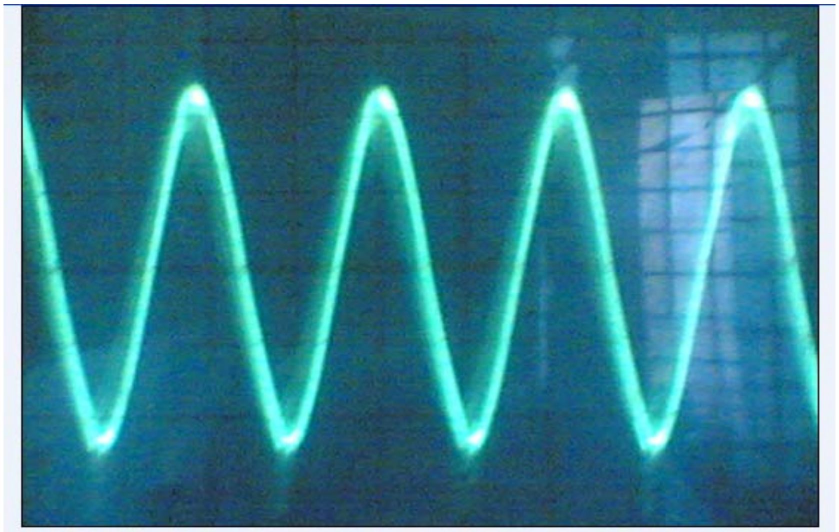

Figure 5.3(c) Oscilloscope of the LLC Resonant Inverter Voltage

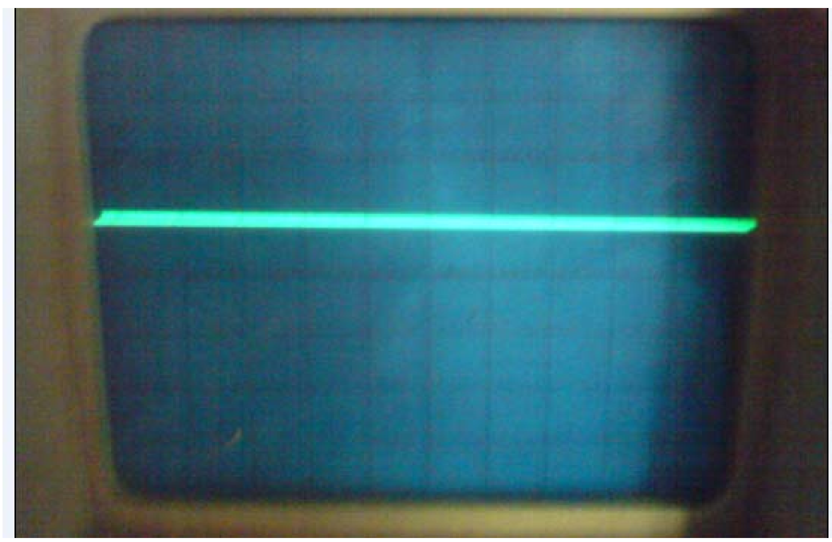

Figure 5.3(d) Oscilloscope of the Converter Output Voltage

Conclusion

This paper has presented design consideration for the LLC resonant DC-DC converter for electrolyser application. The design procedure was verified through experimental results. The power control of a wind–hydrogen energy system has been addressed. The proposed controller basically combines a maximum power point tracking algorithm that suits the captured power to the requirements of the electrolyzer. The power conditioning circuit is designed using concepts of resonant mode control theory to produce the hydrogen from electrolyser. The proposed solution is very simple to implement and shows a very fast response.

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