A Comparative Analysis of DC-DC Converters for Renewable Energy System

R.Samuel Rajesh Babu, Joseph Henry

Abstract: This paper presents a comparative analysis of DC-DC Converters for Renewable Energy System. It has been proved that DC-DC converter with transformer is suitable for Electrolyser application. Due to high input and output voltage differences, the topologies with a high frequency voltage matching transformer are analyzed. The comparative analysis is done with and without Transformer topology in order to achieve zero voltage switching for the power switches and to regulate the output voltage. The MATLAB simulation results and experimental results show that the output of converter is free from ripples and has regulated output voltage.

Index Terms: DC-DC converter, electrolyser, renewable energy sources and resonant converter.

I. Introduction

Electrolysis is an electrochemical process in which electrical energy is the driving force for chemical reactions. An electrolytic compound is decomposed by passing a current through it. Water is decomposed to hydrogen and oxygen by passing a current through it in the presence of suitable substances called electrolytes[1]-[2]. Electric current causes positively charged hydrogen ions to migrate to the negatively charged cathode, where a reduction takes place in order to form hydrogen atoms. The atoms formed will combine to gaseous hydrogen molecules (H_2). On the other hand, oxygen is formed at the other electrode (the positively charged anode). The stoichiometry of the reaction is two volumes of hydrogen to one volume of oxygen. The most important part in the construction of electrolysis units is to use adequate electrodes to avoid unwanted reactions which produce impurities in the hydrogen gas.

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A. Methods of hydrogen production through water electrolysis

Despite the fact in the discovery of electrolytic water decomposing was first observed in acidic water. In industrial plants alkaline medium is preferred because corrosion is more easily controlled and cheaper construction materials can be used for acidic electrolysis technology. Other methods of hydrogen production such as proton exchange membrane electrolysis and steam electrolysis have been developed in recent years. Hydrogen could also be generated as a byproduct during chloralkali production[3]-[4]. The stored hydrogen is fed to a fuel cell to produce electricity. The main aim of this analysis is to obtain 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. The converter strategy control allows a zero voltage transient on the power switches of the full-bridge inverter.

B.Renewable electrolysis

Renewable electrolysis is a process that uses renewable electricity to produce hydrogen by passing an electrical current through water. Renewable energy sources such as photovoltaics, wind, biomass, hydropower, and geothermal can provide clean, sustainable electricity[5]-[6].Renewable electrolysis is hindered by the difficulty of producing hydrogen from renewable sources in a cost-competitive manner. To realize the potential of renewable electrolysis, the costs of renewable technologies as well as the capital requirements for electrolysers must be lowered, and renewable electrolysis systems must be optimized.Factors that limit widespread use of renewable technologies include inherent variability and seasonal energy production. The hydrogen produced from renewable electrolysis can be used in fuel cells or internal combustion engines to produce electricity during peak demand or low power production. This hydrogen can also be used as transportation fuel.

C. Hydrogen production from RES

The RE system components have substantially different voltage-current characteristics and they are integrated on the DC bus through power conditioning devices for optimal operation[7]-[8]. Electrolytic hydrogen offers a promising alternative for long-term energy storage of renewable energy (RE). The long-term excess energy with respect to load

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demand has been sent to the electrolyser for hydrogen production and then the fuel cell has utilized this stored hydrogen to produce electricity when wind and solar energies are insufficient. The DC power required by the electrolyser system is supplied by the DC-DC converter.

Electrolysis of water is the best way to produce eco-friendly hydrogen because:

(i) Water on earth is abundant
(ii) Hydrogen is provided from abundant renewable energy Sources.
(iii) Oxidation of Hydrogen for the production of electrical energy (in fuel cells) produces only water, which can be recycled.

The cost of hydrogen production from solar energy is rather high, approximately 100$/GJ. Except the photovoltaic panels required for this process, water electrolysis units are also expensive. Aeolic energy usage cost for the production of hydrogen is nowadays 15-20$/GJ.

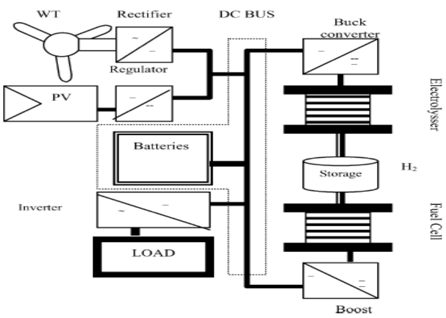

Fig 1.Block diagram of a typical renewable energy system

The basic model to describe the dynamics of an Renewable energy system with Hydrogen storage(RESHS) is shown in fig.1. It integrates sub-models of the electrolyser, the fuel cell, the batteries, the power interfaces (buck and boost converters) and the storage system. Interdependency issues (hydrogen consumption cannot exceed production) are taken into account. Special attention is given to the characterization of the system's major components in the transient state, and use simple and realistic assumptions to describe the behaviour for short and long-term operation of the RESHS. During periods of excess load demand over the input renewable resources, a fuel cell operating on stored hydrogen would provide a balance of power[9]-[10].

To ensure a 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 renewable input source and the electrolyser[11].

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, DC-DC converter is suitable for this application due to their small size, light weight and reduced cost[12]-[13].

D. Past Experiences

Iwakura C et al has presented the Electrochemical properties of hydrogen (1995). Kreuter W and Hofmann H has illustrated that Electrolysis is the important energy transformer in a world of sustainable energy(1998). Neagu C et al has described that the electrolysis of water is an actuation principle for RES(2000). Renewable energy systems based on hydrogen for remote applications has been done by Agbossou K et al(2001). Menzl F et al has introduced a Windmill-electrolyser system for a hydrogen based energy supply(2001). Lehmann J et al has proposed a wind-hydrogen fuel cell chain (2002).Long-term performance of stand-alone renewable energy system for hydrogen production has been done by Kolhe M et al (2002). C. Elam et al has presented a Renewable electrolysis integrated system development and testing(2004). S. Kelouwani et al has developed a Model for energy conversion in renewable energy system with hydrogen storage (2005). J. I. Levene et al has implemented the Analysis of Hydrogen Production from Renewable Electricity Sources (2005). D. S. Gautam has implemented a Soft-Switched DC-DC Converters for Power Conditioning of electrolyser in a Renewable Energy System(2006). Electrolyser in H2 Self-Producing Systems Connected to DC Link with Dedicated Phase Shift Converter has been done by Cavallaro C et al (2007). Optimum Controlled Full Bridge LC Resonant Converter for Electrolyser Application has been done by P. Chandrasekhar (2009). Andrijanovits A et al has designed a Three-level half- bridge ZVS DC-DC converter for electrolyser integration with renewable energy systems (2011).

This work deals with the comparison of with and without Transformer type DC-DC converters.

II. DC-DC CONVERTER CIRCUIT TOPOLOGIES

1. With Transformer
2. Without Transformer

Analysis of selected converters

The selected converters are designed for the worst operating conditions of: minimum input voltage, V_{in} = 48 V; maximum output voltage, V_o = 200 V; and maximum output power(2 kW for each cell); switching frequency, f_s = 10 kHz; inverter output pulse-width, $\delta = \pi$.

The basic circuit diagram of the DC-DC converter is a modified series (LCL type) resonant converter with capacitive output filter[14]-[15]. The converter operates in lagging PF mode for very wide variations in load and supply voltage, thus ensuring ZVS for all the primary switches. The peak current through the switches decreases with load current.

The fundamental component of the square wave input voltage is applied to the resonant network and the resulting sine waves of current and voltage in the resonant circuit are computed using classical AC analysis. For a rectifier with an inductor output filter, a sine wave voltage appears at the input, and the average arrives at the resulting DC output voltage.

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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. The even harmonics in the output of the rectifier are filtered using an LC filter. Driving pulses are applied to the MOSFET in such a way that the pulse width coincides with the resonant.

This paper presents a comparative analysis of DC-DC converters using with and without transformer (fig 2,3), in order to achieve zero voltage switching for the power switches and to regulate the output voltage. DC-DC converter with Transformer has advantages like high efficiency, high power density, low EMI, reduced switching stresses, high circuit efficiency and stable output voltage.

DESIGN PARAMETER	RATING
INPUT VOLTAGE	48V
L1	25mH
L2	50mH
C1	200 Pico Farad
C2=C3	100 Pico Farad
C4	2000 Pico Farad
T_{on}	50%
T_{off}	50%
T	100%
Switching Frequency	50KHz
Transformer Ratio	1:4
Diode	IN 4007
MOSFET	IRF840
Output Voltage	200V
Output Current	10A
Output Power	2KW

The above values are found to be a near optimum for the design specifications.

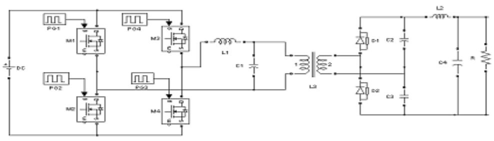


Fig 2 DC-DC Converter with Transformer

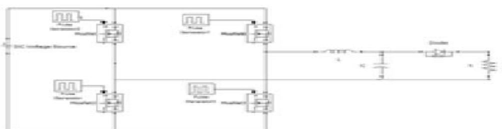


Fig 3 DC-DC Converter without Transformer

III SIMULATION RESULTS OF DC-DC CONVERTER WITH TRANSFORMER

The simulation is done using Matlab simulink and results are presented. Scope is connected to display the output voltage.

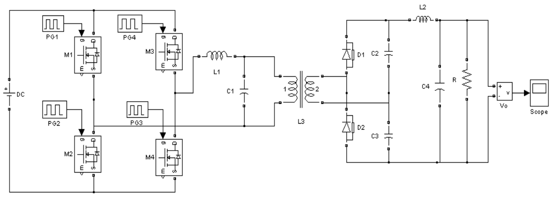


Fig 4 Circuit diagram of DC-DC converter with Transformer

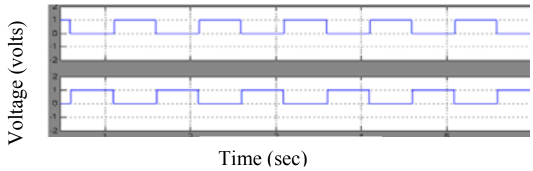


Fig 5 Driving Pulses(X axis-Time(sec),Y axis-Amplitude)

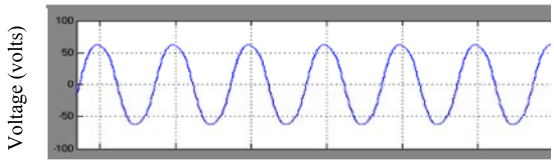


Fig 6 Inverter output voltage with LC filter (X axis-Time (sec),Y axis-Amplitude)

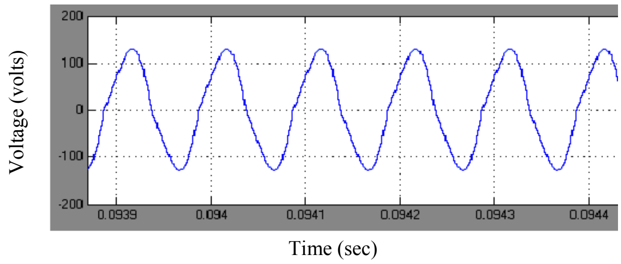


Fig 7 Transformer secondary voltage (X axis-Time(sec),Yaxis-Amplitude)

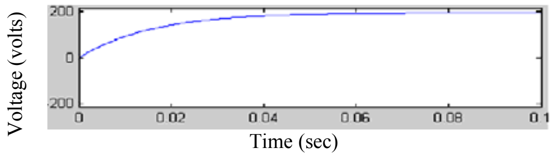
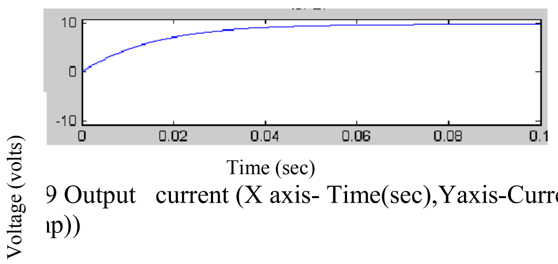


Fig 8 Output voltage (X axis- me(sec),Yaxis-Amplitude)



9 Output current (X axis- Time(sec),Yaxis-Current ıp))

Fig 4 shows the circuit diagram of DC-DC converter with Transformer. Fig 5 shows the Driving Pulses.Fig 6 shows the Inverter output voltage with LC filter .Fig 7 shows the Transformer secondary voltage .Fig 8 shows the Output voltage of DC-DC converter with Transformer. Fig 9 shows the Output current of DC-DC converter with Transformer.

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IV SIMULATION RESULTS OF DC-DC CONVERTER WITHOUT TRANSFORMER

The simulation is done using Matlab simulink and results are presented. Scope is connected to display the output voltage.

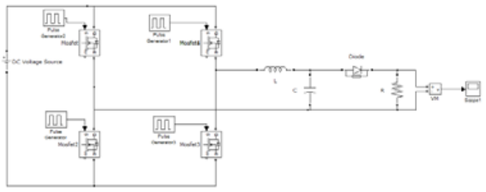

Fig 10 Circuit diagram of Transformerless DC- DC converter

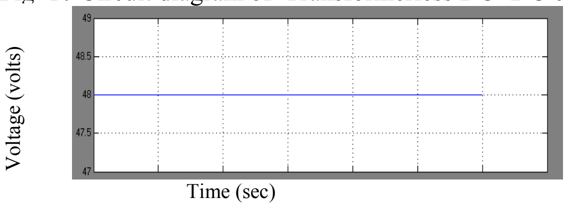

Fig 11 Input voltage waveform (X axis-Time(sec),Yaxis-Amplitude)

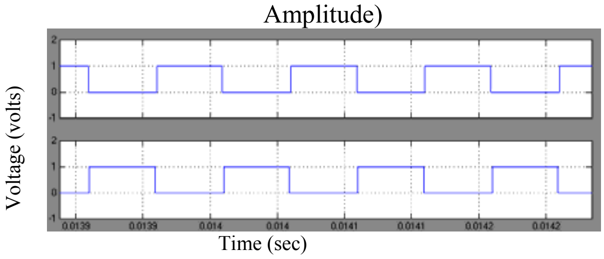

Fig 12 Switching pulse for mosfet's
(X axis-Time(sec),Yaxis-Amplitude)

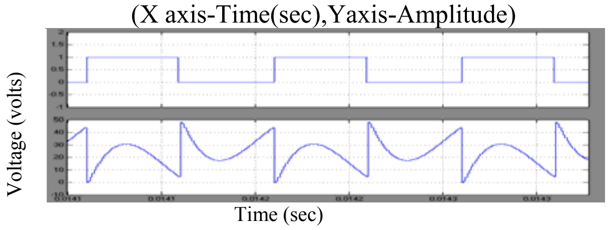

Fig 13 Gate voltage and drain to source voltage
(X axis-Time(sec),Yaxis-Amplitude)

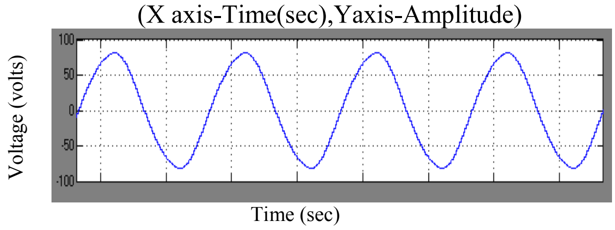

Fig 14 Output voltage waveform
(X axis-Time(sec),Yaxis- Amplitude)

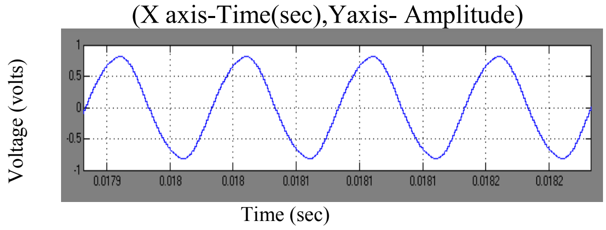

Fig 15 Output current waveform
(X axis-Time(sec),Yaxis-Current (Amp))

Fig 10 shows the Circuit diagram of Transformerless DC-DC converter . Fig 11 shows the Input voltage of Transformerless DC- DC converter . Fig 12 shows the Switching pulse for mosfet's . Fig 13 shows the Gate voltage and drain to source voltage. Fig 14 shows the Output voltage of Transformerless DC- DC converter . Fig 15 shows the Output current of Transformerless DC- DC converter .

V EXPERIMENTAL RESULTS OF DC-DC CONVERTER WITH TRANSFORMER

The hardware is fabricated and tested in the laboratory with resistive load. Pulses required by the MOSFETs are generated by using a ATMEL microcontroller 89C2051.These pulses are amplified by using a driver amplifier.

The following values are found to be a near optimum for the design specifications:

Input Voltage	48V
L1=L2	50µH
C1=C4	2200µF,63V
C2=C3	1000µF,63V
R	20Ω
MOSFET	IRF840, 10 A,10-500V
Regulator	LM7805,LM7812,5-24V
Driver IC	IR2110,+500V or+600V
Diode	IN4007
Crystal Oscillator	230/15 V,500Ma,50Hz
Microcontroller	AT89C2051,2.7V to 6V,0Hz to24MHz

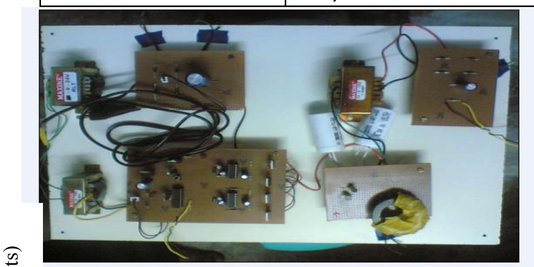

Fig. 16 –Experimental setup of DC-DC converter with Transformer

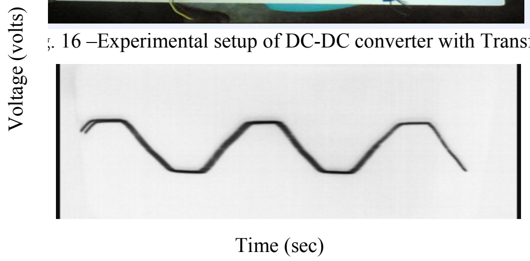

Fig. 17- Ac input voltage
(X axis 1 unit =1ms,Yaxis 1 unit =10V)

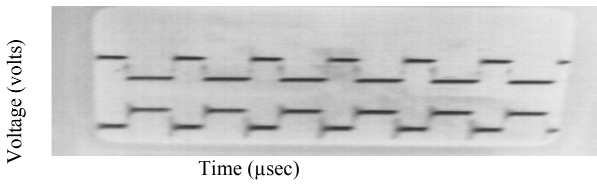

Fig. 18 - Driving pulses
(X axis 1 unit =0.5µs,Yaxis 1 unit =5V)

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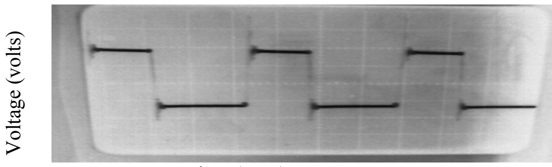

Fig. 19- Inverter output voltage without filter
(X axis 1 unit =0.5µs,Yaxis 1 unit =10V)

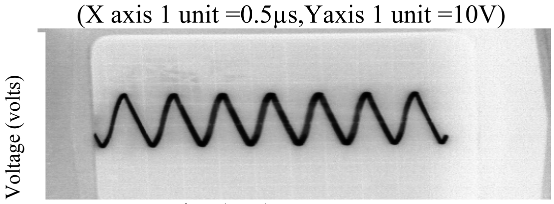

Fig. 20- Inverter output voltage with filter
(X axis 1 unit =0.5µs,Yaxis 1 unit =10V)

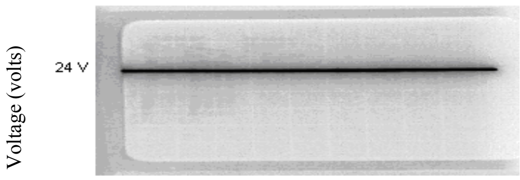

Fig. 21 - DC output voltage
(X axis 1 unit =1ms,Yaxis 1 unit =10V)

Fig. 16 shows the Experimental setup of DC-DC converter with Transformer . Fig. 17 shows the Ac input voltage. Fig. 18 shows the Driving pulses. Fig. 19 shows the Inverter output voltage without filter . Fig. 20 shows the Inverter output voltage with filter. Fig. 21 shows the DC output voltage.

VI EXPERIMENTAL RESULTS OF DC-DC CONVERTER WITHOUT TRANSFORMER

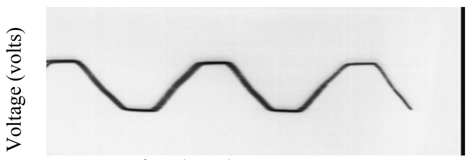

Fig. 22 - Ac input voltage (X axis 1 unit =1ms,Yaxis 1 unit =10V)

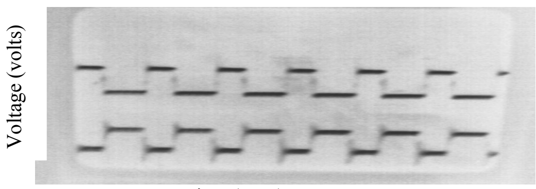

Fig. 23 - Driving pulses (X axis 1 unit =0.5µs,Yaxis 1 unit =5V)

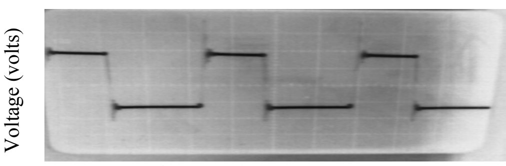

Fig. 24 - Inverter output voltage without filter
(X axis 1 unit =0.5µs,Yaxis 1 unit =10V)

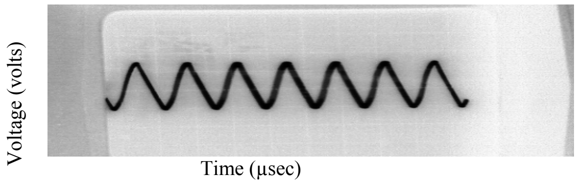

Fig. 25 - Inverter output voltage with filter
(X axis 1 unit =0.5µs,Yaxis 1 unit =10V)

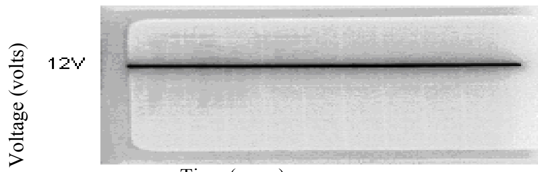

Fig. 26 - Dc output voltage
(X axis 1 unit =1ms,Yaxis 1 unit =10V)

Fig. 22 shows the Ac input voltage of DC-DC converter without Transformer . Fig. 23 shows the Driving pulses . Fig. 24 shows the Inverter output voltage without filter. Fig. 25 shows the Inverter output voltage with filter. Fig. 26 shows the DC output voltage.

VII.COMPARISON OF DC-DC CONVERTER WITH AND WITHOUT TRANSFORMER

TABLE 1 WITH TRANSFORMER

Vin	Pin	Vo	Pout	EFFICIENCY
48	2251	196	1923	85%
24	605	98	488	81%
12	231	48	187	80%

Table 1 gives the efficiency with transformer.

TABLE 2 WITHOUT TRANSFORMER

Vin	Pin	Vo	Pout	EFFICIENCY
48	3487	50	2416	69%
24	869	30	569	65%
12	282	14	182	64%

Table 2 gives the efficiency without transformer.

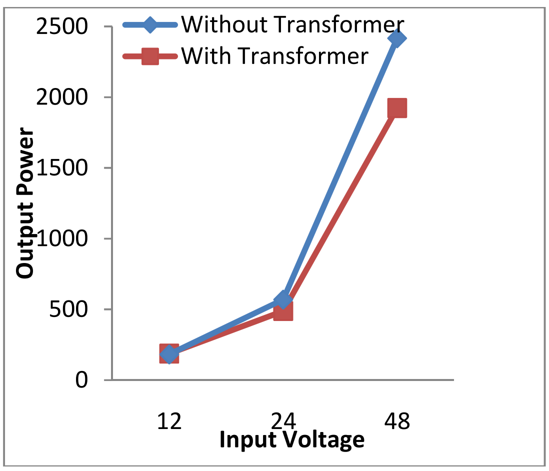

Fig 27 Output power Vs Input voltage

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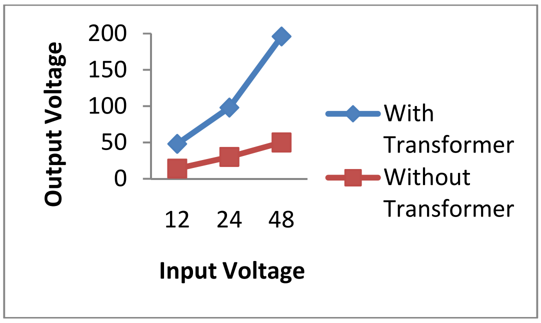

Fig 28 Output voltage Vs Input voltage

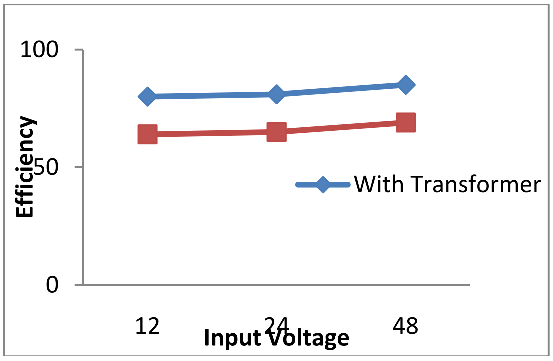

Fig 29 Efficiency Vs Input voltage

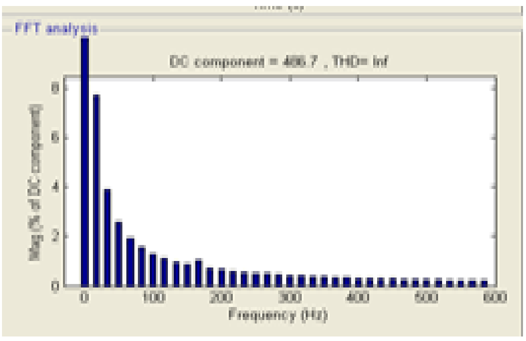

Fig 30 FFT Analysis of DC-DC converter with Transformer

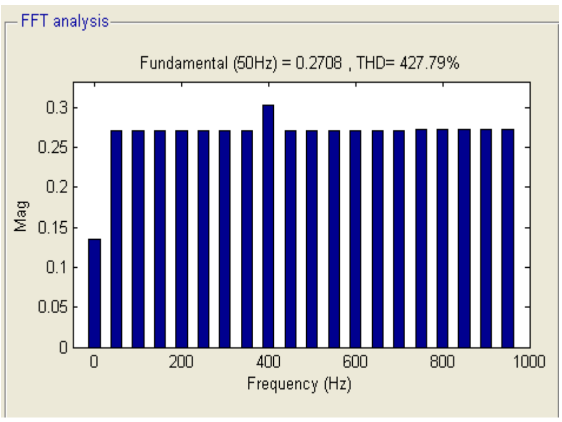

Fig 31 FFT Analysis of DC-DC converter without Transformer

VIII. CONCLUSION

This paper portrays a comparative analysis of DC-DC Converters for Renewable Energy System . 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. It has been proved that DC-DC converter with transformer has the desirable features for electrolyser application. Theoretical predictions of the selected configuration have been compared with the MATLAB simulation results. The converter operates in lagging PF mode for a very wide change in load and supply voltage variations, thus ensuring ZVS for all the primary switches. The peak current through the switches decreases with load current. The simulation and experimental results indicate that the output of the inverter is nearly sinusoidal. The output of rectifier is pure DC due to the presence of LC filter at the output. It can be seen that the efficiency of DC-DC converter with transformer is 15% higher than the converter without transformer.

REFERENCES

[1] Iwakura C, Tanaka M, Nakamatsu S, Inoue H, Matsuoka M and Furukawa N , "Electrochemical properties of Ni/(Ni + RuO2) active cathodes for hydrogen evolution in chlor-alkali electrolysis", Electrochimica Acta 40(8),1995,pp 977-982.

[2] Kreuter W, and Hofmann H, "Electrolysis is the important energy transformer in a world of sustainable energy", Int. J. Hydrogen Energy 23(8), 1998, pp 661-666.

[3] Neagu C, Jansen H, Gardeniers H, and Elwenspoek M, "The electrolysis of water: An actuation principle for RES" , Mechatronics, 2000,pp 571-581.

[4] Agbossou K, Chahine R, Hamelin J, Laurencelle F, Anouar A, St-Arnaud J-M, Bose TK, "Renewable energy systems based on hydrogen for remote applications", Journal of Power Sources 96,2001,pp168-172.

[5] Menzl F., Wenske M., Lehmann J, "Windmill-electrolyser system for a hydrogen based energy supply", in Nummer 2: Regenerative Energien, 2001.

[6] Lehmann J., Luschtinetz T., Menzl F., "The wind-hydrogen-fuel cell chain", in 14 th World Hydrogen Energy Conference, Montreal, Canada, June 9-13, 2002.

[7] Kolhe M, Agbossou K, Kelouwani S, Anouar A, Fournier M, Hamelin J, and Bose TK, "Long-term performance of stand-alone renewable energy system for hydrogen production", WHEC 2002, 14 th World Hydrogen Energy Conference,Montreal, 9-13 June 2002.

[8] C. Elam, B. Kroposki, G. Bianchi, and K. Harrison, "Renewable electrolysis integrated system development and testing," DOE Hydrogen Program, Progress Report FY2004, 2004.

[9] S. Kelouwani, K. Agbossou, , R. Chahine, "Model for energy conversion in renewable energy system with hydrogen storage", Journal of Power Sources 140 ,2005,pp 392–399.

[10] J. I. Levene, M. K. Mann, R. Margolis, and A. Milbrant, "Analysis of Hydrogen Production from Renewable Electricity Sources," NREL, 2005,pp 560-566.

[11] D. S. Gautam, "Soft-Switched DC-DC Converters for Power Conditioning of electrolyser in a Renewable Energy System," *M.A.S Thesis,* Dept. of ECE, University of Victoria, 2006.

[12] Cavallaro C, Chimento F, Musumeci,S, Sapuppo C, Santonocito C, "Electrolyser in H2 Self-Producing Systems Connected to DC Link with Dedicated Phase Shift Converter" Clean Electrical Power, 2007.ICCEP '07. International Conference on 21-23 May 2007 632 – 638.

[13] P. Chandrasekhar, S. Rama Reddy, "Optimum Controlled Full BridgeLC Resonant Converter for Electrolyser Application " , in Proceedings of the World Congress on Engineering and Computer Science 2009 Vol I, WCECS2009,October20-22,2009.5229131

[14]Chandrasekhar P,Reddy S.R , "Performance of soft-switched DC-DC resonant converter for Electrolyzer " , in Resilient Control Systems(ISRCS),4thInternationalSymposiumon2011,95-100.

[15] Andrijanovits A, Vinnikov D, Roasto I, Blinov A, "Three-level half-bridge ZVS DC/DC converter for electrolyzer integration with renewable energy systems", in Environment and Electrical Engineering (EEEIC),10th International Conference , 8-11 May, 2011.

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