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Novel Step up Converter with Multi Winding Transformer for Fuel Cell Applications

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Abstract: ***This project presents a new step-up converter for fuel cell applications. The step-up converter is an electronic device which is used to boost-up the voltage levels. Fuel cell converts chemical energy into electrical energy at low levels which can be supplied to remote areas. The low level voltages can be step-up to higher levels by applying converters. The voltage gain and efficiency of coupled inductor based step-up converter can be improved by replacing coupled inductor with multi winding transformer. The above design is implemented and verified in MATLAB simulink platform.***

Keywords: Fuel cell, multi winding transformer, coupled inductor, voltage gain, and efficiency.

1. Introduction

In the modern world electrical energy is essential for the several needs and is generated by several sources like coal, nuclear energy, water, wind etc. The above methods which are used for the power generation are having many disadvantages. The cost of generation is high and there is no possibility to serve the electricity in the remote areas where the transmission and distribution system does not exist.

Fuel cells can be replaced in place of other sources to supply energy to remote areas[1]. Fuel cells convert s chemical energy into electrical energy [10]-[11]. So, there is no chance of releasing pollutants and these are small in size, portable, high conversion efficiency [4]. The output voltage of a fuel cell is low So, a step-up converter is employed to boost-up the output voltage of the fuel cell.

The step-up gain of a conventional boost converter is limited by the effect of power switch, resistance of inductors and conduction losses due to extreme duty cycle[8]-[12]. So, the boost converter can be operated in fly back mode of operation in which an isolation is given between the primary and secondary[5]-[9]. Here zero voltage switching and zero current switching modes are preferable to achieve high efficiency [3],[6],[13]. Introducing coupled inductor technology is also an advantage to improve the performance of converter [2]-[3].

The coupled inductor technology can be replaced by Multi-winding transformer to achieving achieve high voltage gains and improve the converter efficiency.

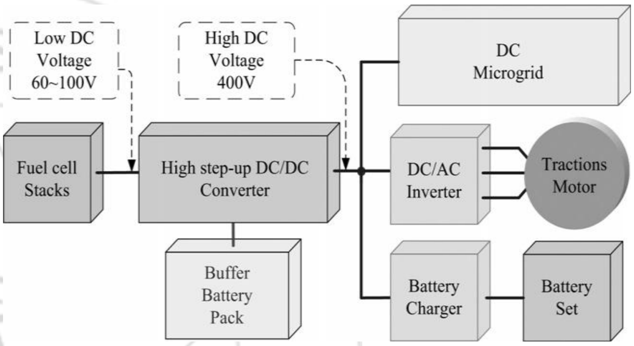

Figure 1: Fuel cell energy supply with a step up converter

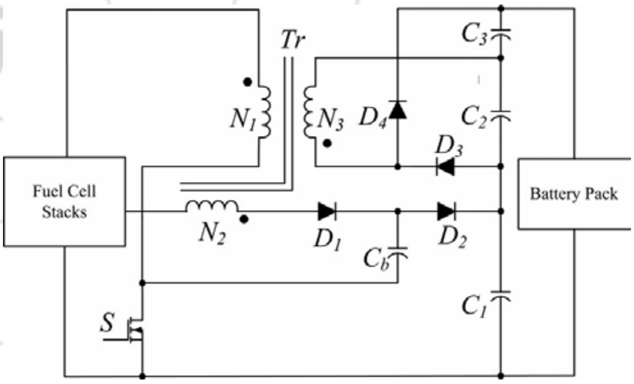

Figure 2: Single line diagram of coupled inductor based converter for fuel cells

2. Operating Principle of the Proposed Converter

The proposed fly back converter employs a boost converter fed to voltage- doublers circuit for the conversion ratio to be high. The switched capacitor used improves step-up performance. The turns ratio of coupled inductor can be varied to enhance the output levels.

The proposed converter has the following advantages.
1) As we can use the transformer with more than one secondary windings which can be used for higher voltages.

2) The recycled leakage energy to the output terminal enhances efficiency.
3) The voltage stress across the main switch is low so the performance of the converter will improves.
4) By using the multi winding transformer the proposed converter possesses more flexible adjustment of voltage conversion ratio and voltage stress on each diode.

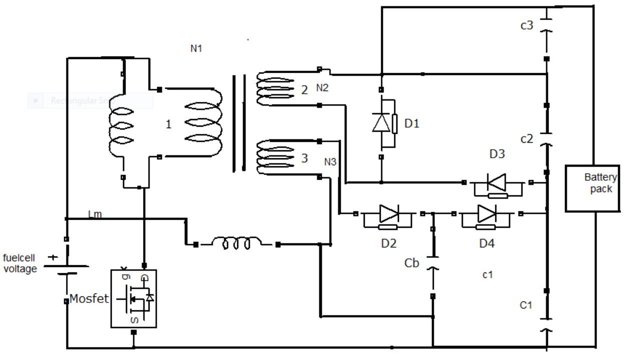

Figure 3: Single line diagram of proposed converter with multi winding transformer for fuel cells.

The proposed model consists of a multi winding transformer, a power switch S, diodes $D_{1,}, D_2, D_{3\,,}$ D_4 and a switched capacitors in parallel to the load output capacitors $C_{1,}, C_2, C_{3\,,}$ and leakage inductors $L_{k1,}, L_{k2}, L_{k3\,,}$

Mode 1 [$t_{0,}t_{1,}$]: This mode is considered at very initial time of operation. During this time interval the main switch S is turned on. The current path is through the switch only and the diodes $D_{1,}, D_{2,}$ and $D_{4,}$ are in reverse biased. The primary leakage current $i_{lk1,}$ will raise linearly, and the energy which is stored in the magnetising inductance will transfers to the output capacitor and load via diode $D_{3.}$

Mode 2 [$t_{1,}, t_2$]: During this the switch S is still in the turn-on state and the current path is through the main switch. But the diodes $D_{1,}, D_4$ are in the forward condition and the diodes $D_{2,}, D_3$ are in the reverse bias condition. The current path direction is shown in the fig5 (b). The input voltage still charges the magnetising inductor L_m and leakage inductor L_{k1},and the currents through the inductors increases linearly. The energy from DC source $V_{in,}$ transfers to the secondary side of the coupled inductor in order to charge the capacitor $C_{3.,}$ The capacitor$C_{b,}$ is *energised* by the series LC circuit.

Mode 3 [t_2, t_3]: During this interval of operation,The switch S is turned OFF at t_2. Diodes D_1 and D_4 are still in forward biased, Diodes D_2 and D_3 are in the reverse bias condition. The current path is shown in fig.5(c). The magnetising current and LC series current charge the parasitic capacitor C_o of the MOSFET.

Mode 4 [t_3, t_4]: In this interval also the switch is in conduction. The diodes D_1, D_2, D_4 are forward biased. The direction of the current path is shown in the fig.5(d). The current flowing through the diode 4 will charges the capacitor C_3 and decreases linearly. The total voltage of V_{in}, V_{lm}, V_{cb} is added which are charging the clamped capacitor C_1 and remaining energy is transferred to the load.

Mode 5 [t_4, t_5]: Between this time interval the switch is still in the turn off state. Also the diodes D_1 and D_4 are in the turn off condition. The diodes D_2 and D_3 are in the forward biased condition. For this mode the current path direction is shown in the fig.5 (e). The clamped capacitor C_1 charged by the primary side and the load is also supplied by the transformer.

Mode 6 [t_5, t_6]: During this interval the switch is still in the turn-off state. The diodes D_1, D_2, D_4 are still in turn off state but the only diode D_3 is in turn on state. During this interval the current path direction is shown in the Fig.5(f). The current in the leakage inductor drops to zero. The magnetising inductor continuously transfers energy to the third leakage inductor and the capacitor C_2 .The energies are discharged from $C_{1,}C_3$ to the load. The diode current i_{d3} charges $C_{2\,,}$ and supplies the load current

3. Steady state analysis of the proposed converter

For the proposed converter the steady state performance is analysed by considering the following assumptions. In steady state the performance of the proposed converter it is better than some other converters due to its own advantages. The assumptions which are taken into the consideration are all the leakage inductances are to be neglected and all the components are taken without any parasitic components. The voltages V_{c1}, V_{c2}, V_{c3} are considered to be constant. The voltages are considered to be constant due to infinitely large capacitances. In steady state the step-up gain, voltage stresses on main switch and conduction losses are calculated by considering the above assumptions. The above parameters improve better by the proposed converter.

a) Step-up gain

Gain is an important parameter to estimate the steady state performance of the converter and it can be referred as the ratio of output voltage to the input voltage The output voltage is obtained by charging of output capacitors. The voltage stored in the capacitors is the load output voltage.

The transformer turns ratio is taken as 1:2:1. The voltage stored in capacitor C_3 is V_{c3} is given by the following equation.

$$V_{c3} = n_2 V_{in} \quad (1)$$

During turn-on time of the switch, capacitor C_3 charges and during turn-off time, the capacitors C_2 and C_1 will charge.

Voltage stored in the capacitor C_1 is given by

$$V_{c1} = \left[\frac{2-D+n_3(1-D)}{1-D}\right] \quad (2)$$

The voltage across the C_2 can be expressed as

$$V_{c2} = n_3[V_{c1} - 2V_{in}] \quad (3)$$

Load voltage is the sum of the individual capacitor voltages obtained in steady state. Here the output voltage is maintained constant due to the voltage second balance and capacitor charge balance phenomena. The output voltage is given by

$$V_0 = V_{c1}+V_{c2}+V_{c3} \quad (4)$$

By substituting all the above values in the following equation

$$M_{CCM} = \frac{V_0}{V_{in}} = \frac{n_3(1-D)+2-D+n_2}{1-D} \quad (5)$$

Equation (5) shows the high step-up gain which can be obtained by varying turns ratio of the multi winding transformer as per the requirements. The Duty ratio versus step-up gain under various turns ratio is plotted in fig(6).

b) Voltage stress

Voltage stress on the main switch diodes causes delays in the conduction times and the current flowing through the circuit is effected by voltage stresses. The voltage stress with the multi winding transformer is quiet low. The voltage stress on the main switch is given below.

$$Ms = \frac{V_{s1}}{V_{out}} = \frac{1}{2+(D-1)n_2+n_3} \quad (6)$$

When the switch „S" is turned OFF the diodes D_2, D_4 are in forward bias and D_1, D_3 are in reverse bias. So the voltage stress of diodes D_1, D_3 are as follows.

$$M_{D1} = \frac{V_{D1}}{V_{out}} = \frac{1+n_2}{2-D+(D-1)n_2+n_3} \quad (7)$$

$$M_{D4} = \frac{V_{D4}}{V_{out}} = \frac{n_3}{2-D+(D-1)n_2+n_3} \quad (8)$$

After some duration the main switch „S" is turned on and then the diodes D_2, D_3 are reverse biased. Therefore there exists voltage stress on the diodes D_2, D_3. Their voltage stresses are obtained as follows.

$$M_{D2} = \frac{V_{D2}}{V_{out}} = \frac{1}{2-D+(D-1)n_2+n_3} \quad (9)$$

$$M_{D3} = \frac{V_{D3}}{V_{out}} = \frac{n_3}{2-D+(D-1)n_2+n_3} \quad (10)$$

The duty cycle versus voltage stress is plotted in the fig(9).

c) Analysis of conduction losses

Conduction losses in the converter affect its performance and reduce efficiency. Conduction losses cause decrease in output voltages. Losses are caused by resistance and leakage reactance offered by the components. Different losses are due to reverse recovery problems in diodes, core losses, switching losses. The resistances in the leakage inductors r_{l1} , r_{l2} , r_{l3} and the resistances of the diodes r_{D1} , r_{D2} , r_{D3} and r_{D4} and the main switch on state resistance R_{Ds-ON}.

The conduction losses and currents passing through the components in the circuit are calculated by small-ripple approximation technique. Power supplied to load based on the phenomenon voltage second balance and capacitor charge balance.

$$\frac{V_0}{V_{in}} = \frac{\frac{2-D+n_2}{1-D} - K}{1+\frac{\alpha}{R_L}(1-D)^2+\frac{r_{l3}}{R_L D(1-D)}+\frac{\beta}{R_L(1-D)}+\frac{\gamma}{R_L D}} \quad (11)$$

Where

$$K = \frac{V_{D1}+V_{D2}+V_{D3}+V_{D4}}{V_{in}}$$

$$\alpha = (1+n_2)D\, r_{L1}+(1+n_3)D\ r_{DS}$$

$$\beta = (1+2\,n_2+n_3)\ r_{L1}+r_{L3}+r_{D3}+r_{D2}+(2+n_2+2n_3)+r_{DS}$$

$$\gamma = r_{L2}+r_{D1}+r_{D4}+(1+n_2+n_3)\,r_{D3}$$

The expression for the conversion efficiency can be expressed as

$$\eta = \frac{(V_{in}-n_3)(1-D)+(2-D+n_2)(V_{D1}+V_{D2}+V_{D3}+V_{D4})}{V_{in}(1-D)+\frac{\alpha}{R_L}+\frac{V_{l3}}{R_L D}+\frac{\beta}{R_L}+\frac{\gamma}{R_L(1-D)}} \quad (12)$$

the above expressions shows the efficiency of the converters will change by varying the duty cycle .

d). Comparison between the proposed converter with coupled inductor based step-up converter

The proposed converter with a multi winding transformer has better performance compared to coupled inductor based converters. Multi winding transformer is having one primary and more than one secondary with different turns ratio. Due to multiple secondaries the output voltage levels are high. In comparison between the proposed converter and other converters n_2 is defined as the turn"s ratio $\frac{N_2}{N_1}$, and n_3 is defined as the turn"s ratio $\frac{N_3}{N_1}$. By varying the duty cycle D the voltage gain can be improved. The plot between the duty cycle versus voltage gain is shown in fig(8). By observing the graph it is clear that the voltage gain is better than other converters. The range of duty cycle is chosen between 0.1<D<0.6 . For duty cycle more than 0.6 the efficiency will reduces and the performance of the converter is poor .

The voltage stress on the main switch and the diodes leads to the delay in conduction times. Conduction loss also increases due to the diode voltage stress. As the duty cycle increases the voltage stress also increases. In this proposed method, voltage stresses are reduced due to less circulating currents. Conversion efficiency is also better compared to coupled inductor based step-up converter due to less leakage reactance , less circulating currents and reduced voltage drops across the diodes and main switch. Conversion efficiency is also varied by varying the duty cycle. Normally the operating range of duty cycle for a better efficiency is 0.1<D<0.6 . For duty cycle greater than 0.6 causes reduction in efficiency. Duty cycle versus conversion efficiency is plotted in the fig(7) is shown.

4. Design and analysis of the proposed Converter

A) Design guidelines

The given converter consists of fuel cell stack, step-up converter with multi winding transformer, controlling switch, capacitors for charging and discharging. Duty cycle applying arrangement is there for varying outputs. The rated output power is 3 KW and operating voltage is 60V. Multi winding transformer is designed with the turns ratio 1:2:1 it is initially designed to obtain the output voltage 440 V and the duty cycle range from 0.1 to 0.6. The magnetising inductors with some number of turns on the secondary side has been designed based on percentage of current ripple of magnetising inductor and their equations are

$$I_{Lm} = \frac{1+n_2}{2-\mathrm{Dmax}} I_{o,max} \quad (13)$$

$$L_m = \frac{V_{in,min}}{\Delta I_{Lm}} I_{o,max} \quad (14)$$

The capacitors are designed by considering the voltage ripple percentage of the capacitor under full-load operation and their relations are given as

$$C_1 = C_2 = \frac{I_{o,max}}{\Delta V_c} \quad (15)$$

$$C_2 = C_2 = \frac{I_{o,max}}{\Delta V_c} \quad (16)$$

B) Simulation results

The proposed converter with a multi winding transformer for the fuel cell applications, is designed in MATLAB simulink platform. The output voltage of the fuel cells is given as the input to the converter which is having in the range from 0.1-0.6 duty ratio. The turns ratio of the multi winding transformer is taken as 1:2:1 .

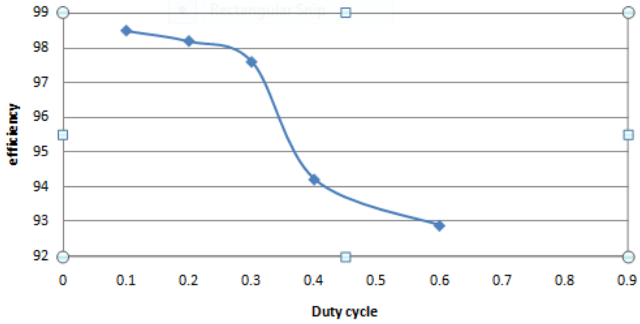

Figure 4: Duty cycle Vs efficiency for coupled inductor based converter

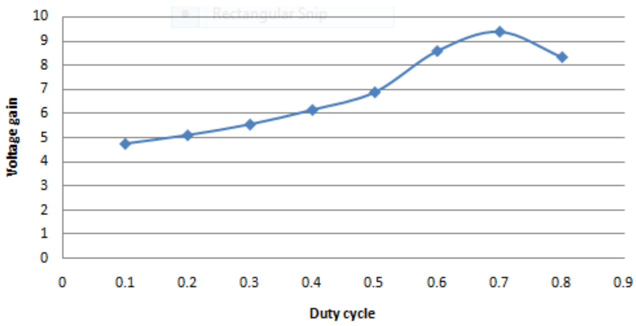

Figure 5: Duty cycle Vs voltage for coupled inductor based converter

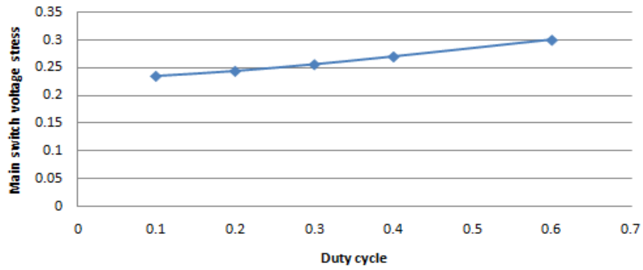

Figure 6: Duty cycle Vs main switch voltage stress for coupled inductor based converter

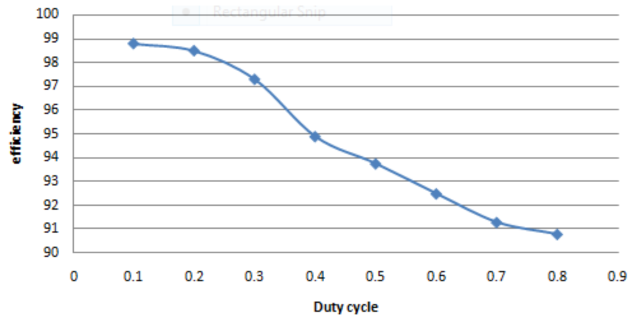

Figure 7: Duty cycle Vs efficiency for multi winding transformer based converter

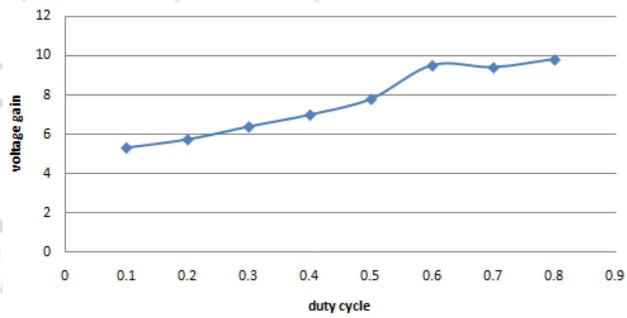

Figure 8: Duty cycle Vs voltage gain for multi winding transformer based converter

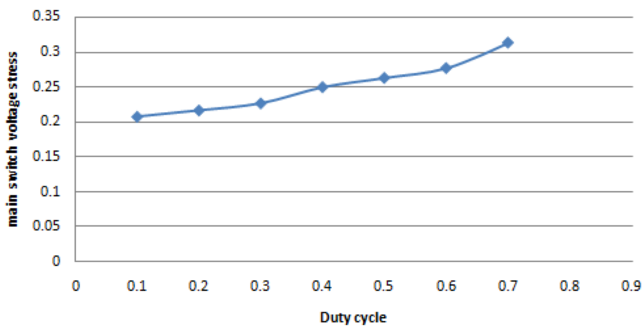

Figure 9: Duty cycle Vs main switch voltage stress for the multi winding transformer based converter

Hence for the proposed converter voltage gain, conversion efficiency and voltage stresses are obtained from the expressions (4), (6)and (12) which are plotted in the fig.(4),(5)and(6).

The output power rating is 3KW. The value of L_{k1} is 3 KW V_{GS} is control signal to the MOSFET and V_{DS} is the voltages stress across the switch. The capacitor is charged by the current i_{D1} and i_{d2} flowing through D_2 are shown in fig (6). V_{D1}, V_{D2}, V_{D3}, V_{D4} are the diode voltage stresses through the diode D_1, D_2, D_3, D_4 and the maximum conversion efficiency is 98.5% .

5. Conclusion

In this project, a multi winding transformer based step up converter is designed in MATLAB simulink and the simulation results are verified successfully. By introducing multi winding transformer in fly back converter, high step up conversion is obtained. Diode stresses are reduced and voltage gain is improved with better conversion efficiency . Thus, the proposed converter gives the better performance compared to coupled inductor based converter.

References

[1] Kuo-Ching Tseng, Jang-Ting Lin, and Chi-Chih, Step-up converter with Three-winding coupled Inductor for fuel cell energy source applications, applications, IEEE transcactions on power electronics, Vol 30, no2 february 2015.
[2] S. Jemei, D. Hissel, M. C. Pera, and J. M. Kauffmann, "A new modeling approach of embedded fuel-cell power generators based on artificial neural network," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 437–447, Jan. 2008.
[3] M. H. Todorovic, L. Palma, and P. N. Enjeti, "Design of a wide input range dc–dc converter with a robust power control scheme suitable for fuel cell power conversion," *IEEE Trans. Ind. Electron.*, vol. 55, no. 3, pp. 1247–1255, Mar. 2008.
[4] K. Jin, M. Yang, X. Ruan, and M. Xu, "Three-level bidirectional converter for fuel-cell/battery hybrid power system," *IEEE Trans.Ind. Electron.*, vol. 57, no. 6, pp. 1976–1986, Jun. 2010.
[5] C. T. Pan and C. M. Lai, "A high-efficiency high step-up converter with low switch voltage stress for fuel-cell system applications," *IEEE Trans.Power Electron.*, vol. 57, no. 6, pp. 1998–2006, Jun. 2010.
[6] E. H. Kim and B. H. Kwon, "Zero-voltage- and zero-current-switching full-bridge converter with secondary resonance," *IEEE Trans. Ind. Electron.*, vol. 57, no. 3, pp. 1017–1025, Mar. 2010.
[7] F. Liu, J. Yan, and X. Ruan, "Zero-voltage and zero-current-switching WM combined three-level dc/dc converter," *IEEE Trans Ind. Electron.*, vol. 57, no. 5, pp. 1644–1654, May 2010.
[8] Y. Jang and M. M. Jovanovic, "A new three-level soft-switched converter,"*IEEE Trans. Power Electron.*, vol. 20, no. 1, pp. 75–81, Jan. 2005.
[9] Y. Jang and M. M. Jovanovic, "A new family of full-bridge ZVS converters," *IEEE Trans. Power Electron.*, vol. 19, no. 3, pp. 701–708, May 2004.
[10] M. Jain, M. Daniele, and P. K. Jain, "A bidirectional dc–dc converter topology for low power application," *IEEE Trans. Power Electron.* vol. 15, no. 4, pp. 595–606, Jul. 2000.
[11] S. Lee and S. Choi, "A three-phase current-fed push-pull DC–DC converter with active clamp for fuel cell applications," in *Proc. IEEE APEC* 2010, pp. 1934–1941.
[12] E. Adib and H. Farzanehfard, "Zero-voltage transition current-fed fullbridge PWM converter," *IEEE Trans. Power Electron.*, vol. 24 no. 4, pp. 1041–1047, Apr. 2009.
[13] R. Y. Chen, T. J. Liang, J. F. Chen, R. L. Lin, and K. C. Tseng, "Study and implementation of a current-fed full-bridge boost dc–dc converter with zero-current switching for high-voltage applications," *IEEE Trans. Ind. Appl.*, vol. 44, no. 4, pp. 1218–1226, Jul. Aug. 2008.