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.

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.

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 inducances 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...
\[ V_{c2} = n_2[V_{c1} - 2V_{in}] \]  

Equation (3) 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.

\[ M_{CCM} = \frac{V_0}{V_{in}} = \frac{n_3(1-D)+2-D+n_2}{1-D} \]  

Equation (5) shows the high step-up gain which can be obtained by varying turns ratio of the multi winding transformer phenomena. The output voltage is obtained in steady state. Here the output voltage is obtained as follows.

\[ M_{CCM} = \frac{V_0}{V_{in}} = \frac{n_3(1-D)+2-D+n_2}{1-D} \]  

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

\[ V_0 = V_{c4} + V_{c2} + V_{c3} \]  

By substituting all the above values in the following equation

\[ M_{CCM} = \frac{V_0}{V_{in}} = \frac{n_3(1-D)+2-D+n_2}{1-D} \]  

(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 multiwinding transformer is quiet low. The voltage stress on the main switch is given below.

\[ M_{CCM} = \frac{V_0}{V_{in}} = \frac{n_3(1-D)+2-D+n_2}{1-D} \]  

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.

\[ M_{D1} = \frac{V_{D1}}{V_{out}} = \frac{1+n_2}{2-D(1-n_2)+n_3} \]  

\[ M_{D4} = \frac{V_{D4}}{V_{out}} = \frac{n_3}{2-D(1-n_2)+n_3} \]  

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.

\[ M_{D2} = \frac{V_{D2}}{V_{out}} = \frac{1+n_2}{2-D(1-n_2)+n_3} \]  

\[ M_{D3} = \frac{V_{D3}}{V_{out}} = \frac{n_3}{2-D(1-n_2)+n_3} \]  

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 \( R_{DS} \).

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.

\[ V_0 = \frac{2-D+n_2}{1-D} \frac{K}{R_L} \frac{\beta}{R_L (1-D)} + \frac{\gamma}{R_L (1-D)} \]  

Where

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

\[ \alpha = (n_2+3) r_{l1} + (n_3+3) r_{D} \]  

\[ \beta = (1+2 n_2 + n_3) r_{l2} + (n_3+3) D + r_{D} \]  

\[ \gamma = n_2 r_{l3} + (1+2 n_2 + n_3) r_{D3} \]  

The expression for the conversion efficiency can be expressed as

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

the above expressions show 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 \( N_2 / N_1 \), and \( N_3 \) is defined as the turn’s ratio \( N_3 / N_1 \). 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...
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

\[ I_{Lm} = \frac{1+n_2}{2-D_{\text{max}}} I_{o,\text{max}} \]  
\[ L_m = \frac{V_{i,n_{\text{min}}}}{\Delta I_{Lm}} I_{o,\text{max}} \]  

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

\[ C_1 = C_2 = \frac{I_{o,\text{max}}}{\Delta V_c} \]  
\[ C_2 = C_2 = \frac{I_{o,\text{max}}}{\Delta V_c} \]

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.

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 \( V_{D2} \) 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