Fuel cell based distributed generation using Re-lift Luo converter

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Abstract - In this paper fuel cell based distributed generation for driving the brushless dc motor is presented. The low voltage extracted from the fuel cell has been increased to the utility voltage using re-lift Super-lift technique. The proposed converter with a simple structure effectively enhances voltage transfer gain, promising high efficiency and power density solution using single active switch, producing reduced ripple voltage and current. The working operation of the proposed converter has been discussed in detail. The Solid oxide fuel cell (SOFC) mathematical modeling has been presented for constant fuel utilization. Both the open-loop and closed loop control strategies are presented under different load-torque condition for the drive system. The conventional PI controller is devised for closed loop control operation and its performances are evaluated using Simulink/ Matlab platform.

Key Words: Distributed generation, Relift super-lift technique, SOFC, Constant fuel utilization

1. INTRODUCTION

The progress of any nation primarily depends on the energy sector which paves way for socio-economic up-liftment of the people. But the ever-demanding energy consumption threatens the depleting conventional fossil fuels, increasing global warming and greenhouse gas emissions. So energy harnessing should be met by other alternate renewable energy sources to curtail the energy crisis problem and global warming issues. Fuel cell technology is one among the renewable promising a safe, clean, eco-friendly, reliable and sustainable energy solution. They are electrochemical devices that convert chemical energy into electrical energy directly in a single stage processing. Thus they are simpler, flexible, and modular when compared to conventional power plants. They operate silently without any moving parts and combustion of gas resulting zero emission of greenhouse gases. The other advantages include their placement sites independent of geographic boundaries, not intermittent in nature, featuring high efficiency, even at part-load conditions. Thus they are suitable for power generation promoting the energy security and can be connected to the power grid to provide supplemental power. They also function as a standalone on-site power generator for ranches, dairy farms, flower growers and residences which are located far off from the power utilities [1].

1.1 Problem Statement

A dc-dc converter accepts a low voltage, high current input from the fuel cells and convert the power to a high voltage output [3]. But this green technology powered by the fuel cell is limited by its sluggish response to the sudden load changes [10] with high ac ripples in its output dc voltage. So the major challenge lies in the development and selection of a suitable ripple mitigating power conditioning unit (PCU) to compensate for these limitations and its applicability to interface to the power utility applications. The PCU is thus the prime topic of this paper.

1.2 Power Conditioning Unit

The success of the power conditioning unit vests in the performance of the dc-dc converter to meet the demand requirements, ability to cope with the fuel cell behavior ensuring safe and stable operation despite the voltage variations. The transformer based DC-DC converters such as fly-back converter, push-pull converter, forward converter, half-bridge converter, bridge converter, and Zeta converter suffer from reduced overall operating efficiency due to leakage inductance, core loss. The inclusion of a transformer increases the operational cost, installation space and weight. They add objectionable ripples in the current flowing out of the fuel cell [8], besides the power switch of these converters is subjected to high voltage stress due to the leakage inductance of the transformer. Hence transformer-less DC-DC converters are of prime choice.

2. PROPOSED CONVERTER TOPOLOGY

The re-lift Luo converter analysed in this paper is a series of advanced step-up dc-dc power conversion topologies based on the super-lift (SL) technique, which increases the output voltage stage-by-stage in geometric series using a simple structure [2]. This technique effectively enhances the voltage transfer gain besides mitigating the effects of parasitic elements for wide range of duty ratio [1]. They provide high efficient and high power density solution with reduced ripple voltage and current. The conventional cascade boost DC-DC converters utilizes ‘n’ no of power switches for n stages of power conversion while in the re-lift Luo converter only one power switch is incorporated
reducing the circuit control complexity, gate drive requirements, switching losses thus enhancing the converter efficiency, involving less no of protective circuits, cooling, making the converter simple, compact in size. The positive output super-lift Luo re-lift converter shown in Fig.1 consists of only one static switch S, five diodes, four capacitors and two inductors.

2.1 Circuit Operation

When the power switch S is turned on, the diodes \( D_1, D_5 \) are on and the equivalent circuit during switch-on condition is obtained. During switch-on period, the first elementary power stage composed of \( L_1, D_1, D_2, C_1 \) is charged by the input source voltage \( V_{in} \). The voltage \( V_1 \) which is the output voltage of the elementary power stage appears across capacitor \( C_2 \). It is given by

\[
V_{C2} = V_1 = \left( \frac{2-k}{1-k} \right) V_{in} \tag{1}
\]

The voltage re-lift power conversion is obtained by the topology formed by the inductor \( L_2 \) and the capacitor \( C_3 \) to form a parallel connected pump circuit (super-lift pump) to absorb the stored energy from the preceding stage of the capacitor \( C_2 \). Thus the capacitor \( C_3 \) is charged to \( V_1 \) during the switch on mode period.

\[
\begin{align*}
\Delta \text{i}_{L_2} &= \frac{V_1 kT}{L_2} = \frac{(V_o - 2 V_1)(1 - k)T}{L_2} \\
L_2 &= \left( \frac{2-k}{1-k} \right) - 1 \\
\text{i}_{L_1} &= \frac{V_{in} kT}{L_2} \\
L_1 &= \frac{I_{in}}{2-k}
\end{align*}
\tag{7}
\]

Therefore the variation ratio of inductor current \( L_1 \) is

\[
\xi_1 = \frac{\Delta \text{i}_{L_1}}{\text{i}_{L_1}} = \frac{k(1-k)7V_{in}}{2L_1 I_{in}} = \frac{k(1-k)^24R}{2(2-k)^2L_1} \tag{11}
\]

Similarly the variation ratio of inductor current \( L_2 \) is

\[
\xi_2 = \frac{\Delta \text{i}_{L_2}}{\text{i}_{L_2}} = \frac{k(1-k)7V_0}{2L_1 I_{0}} = \frac{k(1-k)^27V_0}{2(2-k)L_1 I_{0}} \tag{12}
\]

The variation ratio of the output voltage is

\[
\epsilon = \frac{\Delta v}{V_0} = \frac{1-k}{2(k-1)c_4} \tag{13}
\]
3. SYSTEM DESCRIPTION

![Block diagram of the proposed system](image)

Figure 4 shows the general block diagram of the proposed system. The proposed fuel cell geared drive system consists of a Solid Oxide fuel cell stack, re-lift Luo converter, inverter with a control circuit for driving the Brushless-dc motor coupled load.

3.1 Solid Oxide Fuel Cell

SOFCs are highly instant reactive efficient fuel cell variants which reduces corrosion and heat management problems. It paves way for a more economical system using Ni in place of costly Platinum, thus tolerating carbon monoxide emission and its flexibility to feed any other forms of fuel, either hydrogen or hydrocarbon derived fuels.

Each of the electrode reactions constitutes a half-reaction [4].

Anode Reaction: \( \text{H}_2 + \text{O}_2 \rightarrow \text{H}_2\text{O} + 2\text{e}^- \)  
Cathode Reaction: \( \frac{1}{2}\text{O}_2 + 2\text{e}^- \rightarrow \text{O}_2^- \)

The overall chemical reaction that takes place inside the fuel stack is given as

\[ \text{H}_2 + \frac{3}{2}\text{O}_2 \rightarrow \text{H}_2\text{O} \]  

The assumptions made for the fuel cell model are given as:
- The fuel cell reactions are assumed to be in equilibrium.
- The cathode and anode inlet and exit temperature of the fuel cell is assumed to be equal.
- The gases behave as ideal gases.
- Gas leakage is negligible.

3.2 Solid Oxide Fuel Cell Mathematical Modeling

The developed SOFC model is based on the reference [9]. Gibbs’ free energy is referred to as the energy extracted from the fuel cell to do external work, regardless of any change in pressure or volume of the fuel reactants and products. Under standard operating conditions of temperature of 25°C and pressure of 0.1 MPa the change in Gibbs’ free energy of formation per mole is given as

\[ \Delta \bar{G}^\circ = (\bar{G}^\circ)_{\text{H}_2\text{O}} - (\bar{G}^\circ)_{\text{H}_2} - \frac{1}{2} (\bar{G}^\circ)_{\text{O}_2} \]  

The reversible open circuit voltage in terms of the Gibb’s free energy of formation is given as

\[ E^o = -\frac{\Delta \bar{G}}{2F} \]

The change in Gibbs’ free energy \( \Delta \bar{G} \) varies from its STP value with changes in pressure and temperature which eventually leads to change in stack voltage of the fuel cell.

\[ \Delta \bar{G} = \Delta \bar{G}^\circ - RT \ln \left( \frac{p_{\text{H}_2} p_{\text{O}_2}^{0.5}}{p_{\text{H}_2\text{O}}^{0.5}} \right) \]

Where \( R \) - Universal gas constant=8314 J/ (kmol K)
\( T \) - Operating temperature
\( p_{\text{H}_2} \) - partial pressure of hydrogen
\( p_{\text{O}_2} \) - partial pressure of oxygen
\( p_{\text{H}_2\text{O}} \) - partial pressure of water

Using (19) in (20) yields Nernst voltage at standard temperature with varying pressure values.

\[ E = E^o + \frac{RT}{2F} \ln \left( \frac{p_{\text{H}_2} p_{\text{O}_2}^{0.5}}{p_{\text{H}_2\text{O}}^{0.5}} \right) \]

Fuel flow utilization factor is given from [5] as,

\[ U_f = \frac{\text{amount of fuel (H2) that reacts with O2}}{\text{amount of fuel (H2) which enters the anode}} = \frac{\text{qH}_2 \text{ react}}{\text{qH}_2 \text{ inside}} = \frac{\text{mfH}_2 \text{ react}}{\text{mfH}_2 \text{ inside}} \]

Where \( \text{qH}_2 \text{ react} \) - molar flow rate of hydrogen reacting with the oxygen.
\( \text{qH}_2 \text{ inside} \) - molar flow rate of hydrogen entering the anode.

To calculate partial pressure of gases, Ideal gas law is used.

For hydrogen, \( p_{\text{H}_2}V_{\text{an}} = n \text{H}_2RT \)
\[ pH_2 = \frac{nH_2RT}{V_{an}} \]  
\( V_{an} \) - Volume of anode channel
\( nH_2 \) - hydrogen moles in the channel

Taking the first-order derivative of the above equation yields,

\[ \frac{d}{dt} (pH_2) = \frac{d}{dt} \left( \frac{nH_2RT}{V_{an}} \right) = \frac{qH_2RT}{V_{an}} \]  
\[ \frac{d}{dt} (pH_2) = \frac{RT}{V_{an}} [qH_2\text{inside} - qH_2\text{outside} - qH_2\text{react}] \]  

The amount of hydrogen reacts depends upon the demand load current and the total capacity of the number of cells connected in series with the stack which is given as,

\[ q_{H_2\text{react}} = \frac{N_0I_c}{2F} \]  

Being \( N_0 \) and \( 2F \) are numerics,

\[ q_{H_2\text{react}} \propto I_c = 2K_rI_c \]  

Where \( N_0 \) - no of cells connected in series
\( I_c \) - fuel cell current
\( K_r \) - modelling const = \( \frac{N_0}{4F} \)

Upon substituting and integrating on both sides of the equation and upon Laplace transformation yields

\[ pH_2 = \frac{1}{2F} \ln \left[ q_{H_2\text{inside}} - 2KrI_c \right] \]  
\[ \text{Similarly } pO_2 = \frac{1}{2F} \ln \left[ q_{O_2\text{inside}} - 2KrI_c \right] \]  
\[ pH_2O = \frac{1}{2F} \ln \left[ q_{H_20\text{inside}} - 2KrI_c \right] \]  

where \( \tau_{H_2} = \frac{V_{an}}{KH_2RT} \)

Nernst stack voltage is given from [6],

\[ V_{fc} = E_0 - V_{activation} - V_{ohmic} - V_{conc} \]  

Where \( E_0 = No \{E^0 + \frac{RT}{2F} \ln \left( \frac{pH_2}{pH_20^{0.5}} \right) \} \)

### 3.3 Brushless DC Drive system

The high performance feature work horse Brushless dc motor is chosen for our simulation study. Table 1 shows the switching logic used for electronic commutation.

<table>
<thead>
<tr>
<th>Table - 1: Switching logic in Brushless DC drive system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching pattern</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>#1</td>
</tr>
<tr>
<td>#2</td>
</tr>
<tr>
<td>#3</td>
</tr>
<tr>
<td>#4</td>
</tr>
<tr>
<td>#5</td>
</tr>
<tr>
<td>#6</td>
</tr>
</tbody>
</table>

### 4. SIMULATION RESULTS

The simulation has been developed for the SOFC fed brushless drive system using re-lift Super lift technique with parameters listed in Table 1, Table 2 and Table 3.

<table>
<thead>
<tr>
<th>Table - 1: Proposed Converter parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of the parameters</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>Input voltage</td>
</tr>
<tr>
<td>Output voltage</td>
</tr>
<tr>
<td>Inductor</td>
</tr>
<tr>
<td>Capacitor</td>
</tr>
<tr>
<td>Capacitor</td>
</tr>
<tr>
<td>Switching frequency</td>
</tr>
<tr>
<td>Conduction Duty ratio range</td>
</tr>
<tr>
<td>Used Conduction Duty ratio</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table - 2: SOFC model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parametric indices</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Universal gas constant</td>
</tr>
<tr>
<td>Faraday's constant</td>
</tr>
<tr>
<td>Ideal standard potential</td>
</tr>
<tr>
<td>Ohmic loss polarization for each cell</td>
</tr>
<tr>
<td>Absolute stack temperature</td>
</tr>
<tr>
<td>Air inlet temperature (pre-heated)</td>
</tr>
</tbody>
</table>
Fuel compressor pressure 100 psi
Air blower pressure 3 atm pressure
Initial fuel cell stack current 100 A
No of cells arranged serially 65
Maximum fuel flow utilization 90%
Minimum fuel flow utilization 80%
Optimum fuel flow utilization 85%
Molar constant for hydrogen 8.43x10^-4 kmol/S.atm
Molar constant for Oxygen 2.52x10^-3 kmol/S.atm
Molar constant for water 2.81x10^-4 kmol/S.atm
Ratio of hydrogen to oxygen 1.145
Response time of fuel processor 5 sec
Electrical Response time 0.8 sec

Table -3: Brushless dc motor model parameters

<table>
<thead>
<tr>
<th>Parametric indices</th>
<th>Symbols</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator resistance per phase</td>
<td>Rs</td>
<td>2.8750 ohm</td>
</tr>
<tr>
<td>Stator inductance per phase</td>
<td>Ls</td>
<td>8.5 mH</td>
</tr>
<tr>
<td>No. of poles pairs</td>
<td>p/2</td>
<td>4</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>J</td>
<td>0.8x10^-3 Kg.m^2</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>F</td>
<td>1x10^-3 Nms</td>
</tr>
<tr>
<td>Voltage constant</td>
<td>Kv</td>
<td>56.8335 V/rpm</td>
</tr>
<tr>
<td>Torque constant</td>
<td>KT</td>
<td>0.54372 Nm-A</td>
</tr>
<tr>
<td>Flux established by magnets</td>
<td>Ф</td>
<td>0.06784 V.s</td>
</tr>
</tbody>
</table>

4.1 Open loop control of BLDC motor

Case: 1 Steady-state operating condition.

The simulation is performed for constant load torque of about 3 Nm and the performances are evaluated. Figure 7 shows the rotor speed of the drive system for the applied constant load torque.
Figure 11 and figure 12 shows the drive dc link voltage and the proposed converter current.

**Fig - 11**: Drive dc link voltage

**Fig - 12**: Proposed converter current

Case 2: Dynamic load torque disturbances

The simulation is performed for load torque variation of 0 Nm to 1 Nm and to 3 Nm at time t=0 sec, 1 sec and 2 sec respectively and the drive’s response is studied under open loop system. The observed changes are the drop in inverter output voltage shown in figure 13, dynamic speed changes of the rotor seen in figure 14.

**Fig - 13**: Drop in inverter output voltage from the time of load torque variation

**Fig - 14**: Speed variation due to load torque disturbances

Figure 15 shows the corresponding changes in stator currents and the back-emf waveforms and the figure 16 shows the dynamically developed motor torque under variable load torque conditions.

**Fig - 15**: Stator per-phase current and the back-emf waveform variation

**Fig - 16**: Developed motor torque under variable load torque condition

4.2 Closed loop Speed control of BLDC motor

To tackle the load torque disturbances and source voltage variations, to have a constant speed control for the drive PI controller is implemented. The PI controller parameters chosen are $K_p = 0.001205$ and $K_i = 0.018$. The desired reference speed of the drive system is implemented by a Proportional-Integral speed controller. The error signal
which is the difference between the actual and desired speeds is given to the PI controller, which adjusts the duty cycle of the PWM generator which in turn adjust the corresponding re-lift Luo converter voltage required to maintain the desired speed.

The load torque variation is presented at about t=1 sec from 0 Nm to 3 Nm. and from 3 Nm to 5 Nm at t=2 sec. The PI controller is able to dynamically handle these changes and thus robust in its control action maintaining the speed to the set speed reference.

Figure 18 shows the constant drive speed accomplishment of PI controller control action under dynamically load torque variations. The desired speed is attained with the transients vanishing out quickly for every torque variations.

The FFT analysis shown in the figure 21 was performed for the drive output voltage and the THD observed was 3.83% which is well below 5% of the IEEE standard of harmonic limits.

Table 1: Performances indices of the proposed P/O SL Luo converter Re-lift circuit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Results Obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{fuel cell}}$</td>
<td>57 V</td>
</tr>
<tr>
<td>$I_{\text{fuel cell}}$</td>
<td>200 A</td>
</tr>
<tr>
<td>Output voltage $V_0$</td>
<td>513 V</td>
</tr>
<tr>
<td>Voltage transfer gain M</td>
<td>9</td>
</tr>
<tr>
<td>Peak to peak current ripple $\Delta i_{L_1}$</td>
<td>1.71 A</td>
</tr>
<tr>
<td>Peak to peak ripple current $\Delta i_{L_2}$</td>
<td>0.57 A</td>
</tr>
<tr>
<td>Steady state current in L2, $i_{L_2}$</td>
<td>400 A</td>
</tr>
<tr>
<td>Steady state current in L1, $i_{L_1}$</td>
<td>133.33 A</td>
</tr>
<tr>
<td>Variation ratio of inductor current $L_1$, $\xi_1$</td>
<td>2.137 x 10^{-3}</td>
</tr>
<tr>
<td>Variation ratio of inductor current $L_2$, $\xi_2$</td>
<td>2.137 x 10^{-3}</td>
</tr>
<tr>
<td>Variation ratio of the output voltage, $\xi$</td>
<td>1.267 x 10^{-4}</td>
</tr>
</tbody>
</table>

5. CONCLUSION

In this paper, the proposed re-lift Luo converter with a simple construction utilizing only a single switch guaranteeing reduced switching loss is implemented to produce a high voltage transfer gain, stable and ripple free output. A constant fuel utilization mode is designed for increased fuel cell performance by the load current tracking scheme. The proposed power conditioning unit along with the PI
controller has the ability to cope with the slow fuel cell behavior, satisfies the dynamic load demand requirements ensuring safe, stable operation and accomplishes a desired speed control for the drive system. Thus the proposed re-lift Luo converter can be considered as an efficient interface for Solid oxide fuel cell distributed generation.

REFERENCES


