A Power Control Scheme to Improve the Performance of a Fuel Cell Hybrid Power Source for Residential Application

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Abstract - This paper describes a power control scheme to improve the performance of a fuel cell-battery hybrid power source for residential application. The proposed power control scheme includes a power control strategy to control the power flow of the fuel cell hybrid power system and a digital control technique for a front-end dc-dc converter of the fuel cell. The power control strategy enables the fuel cell to operate within the high efficiency region defined by the polarization curve and efficiency curve of the fuel cell. A dual boost converter with digital control is applied as a front-end dc-dc converter to control the fuel cell output power. The digital control technique of the converter employs a moving-average digital filter into its voltage feedback loop to cancel the low frequency harmonic current drawn from the fuel cell and then limits the fuel cell output current to a current limit using a predictive current limiter to keep the fuel cell operation within the high efficiency region as well as to minimize the fuel cell oxygen starvation.

Keywords: fuel cell, hybrid power source, digital control, digital filter.

I. INTRODUCTION

Fuel cells have been considered as a primary energy source for the next generation electric utilities. Interest in fuel cell systems arises not only because of their essentially zero pollution emission but also because of their high efficiency, which is higher than that of a conventional power plant [1, 8].

One of its applications for medium power is the residential power system, where a fuel cell hybrid power system is required to meet the domestic load profile. A typical domestic power profile has a peak to average power ratio of between around 9~15 [5], and hence a fuel cell system alone would significantly over-rate the fuel cell to satisfy the peak power and suffer from poor utilization. Fuel cell-battery hybrid power sources can meet these peak power demands with higher specific power and efficiency than the fuel cell alone while still preserving high energy density [6, 7]. The fuel cell of the hybrid power source supplies the power required by the load and charges the battery, and the battery provides a supplementary power. Since the dynamic response of a fuel cell is not fast enough to satisfy the load transient and the peak power demand, the power flow between the power sources and the load should be controlled properly. The power control strategy manages the power flow among the different power sources and the load based on the state of charge (SOC) of battery and the power demand and maintains the SOC of battery at a proper level to protect the battery from being damaged due to the over-charge or over-discharge. The hybrid power system includes several power converters to interface with the domestic load and the utility (Fig.1). Among them, a front-end dc-dc converter has important roles such as the regulation of the fuel cell output current and the dc bus voltage.

This paper presents a new power control scheme for a fuel cell hybrid power source for residential application which includes a power control strategy to control the power flow between the power sources and the load and a digital control technique for the front-end dc-dc converter. By the proposed power control strategy, the fuel cell operation is maintained within the high efficiency region decided by the polarization curve and efficiency curve of the fuel cell. A dual boost converter with digital control is applied as a front-end dc-dc converter to control the fuel cell output current. The dc current drawn from the fuel cell includes a 120Hz harmonic current induced by the single phase ac load, which not only make it difficult to regulate the front-end dc-dc converter properly but also draw the current more than the fuel cell can output instantly with the fuel amount fed to the stack. The digital control technique of the converter adopts a moving-average digital filter and cancels the 120Hz harmonic current and then limits the fuel cell current to a current limit determined by the air amount fed to the fuel cell stack using a predictive current limiter to avoid the fuel cell oxygen starvation and improve the fuel cell durability.

Fig.1 Fuel cell-battery hybrid power source

II. POWER CONTROL STRATEGY

The goal of the power control scheme is to operate the fuel cell hybrid power source with high efficiency while maintaining the required performance for residential
application. This is achieved by the proposed power control strategy running in the power controller (Fig.1), which controls the fuel cell to operate within its high efficiency region. Fig.2(a) shows a typical polarization curve and power density curve of a PEM fuel cell where the power density is a product of potential and current density. The power density curve of a cell presents that there is a maximum power density a fuel cell may reach. It does not make sense to operate a fuel cell at a point beyond this maximum power point, because the same power output can be obtained at a lower current and higher voltage. The fuel cell efficiency is defined as a ratio between the electricity produced and hydrogen consumed, and expressed as following equation;

\[
\eta_{\text{cell}} = \frac{V_{\text{cell}} \cdot I}{W_{\text{H2}}} = \frac{V_{\text{cell}} \cdot I}{\Delta H \cdot \frac{1}{nF}} = \frac{V_{\text{cell}}}{1.482} \tag{1}
\]

where \(W_{\text{H2}}\) = energy value of hydrogen consumed in joules per second
\(\Delta H = \) hydrogen’s high heating value (286 kJmol\(^{-1}\)).

The efficiency curve of a PEM fuel cell is depicted in Fig. 2(b). It is noted that the efficiency is much lower at the maximum power density and in the low power density region due to the power loss of the balance of plant. Therefore, a fuel cell operation in the low efficiency region should be avoided to achieve the high efficiency considering the power losses of the balance of plant and power conversion system. The minimum power and the maximum power that the fuel cell system can output in the high efficiency region should be determined based on the required output power and the minimum desirable efficiency [4]. The typical minimum fuel cell net efficiency of the residential application is around 42%.

The proposed power control strategy calculates the fuel cell power \(P_{\text{fc}}\) based on the SOC of battery and the power demand \(P_{\text{load}}\) and regulates the power flow so that the fuel cell operation can be maintained with high efficiency between the minimum power \(P_{\text{min}}\) and the maximum power \(P_{\text{max}}\) which are corresponding to the minimum power density \(p_1\) and the maximum power density \(p_2\) respectively in Fig. 2(b), while maintains the battery SOC at the proper level. The fuel cell is turned off and the battery supplies the power to the load when the calculated fuel cell power is lower than the minimum power \(P_{\text{min}}\) for the efficiency (Fig. 3). The calculated fuel cell power \(P_{\text{fc}}\) and the battery power \(P_{\text{bat}}\) are sent to the fuel cell controller and the bidirectional dc-dc converter respectively, and the power generated by the fuel cell is controlled by regulating the air amount fed to the stack based on the fuel cell power \(P_{\text{fc}}\). As a result, the fuel cell operation is always maintained within the high efficiency region defined by the currents, \(I_{\text{min}}\) and \(I_{\text{max}}\) and the voltages, \(V_{\text{min}}\) and \(V_{\text{max}}\), which are corresponding to \(I_1, I_2, V_1\) and \(V_2\) in Fig. 2(a).

* \(P_{\text{bl}}\): Available power from the battery when SOC is 1.
A. Battery State of Charge

The lead acid batteries with a bi-directional dc-dc converter are used for supplying peak power to the load. A pack of 25Ah, 12V batteries are connected to the dc bus in parallel. To predict the battery performance, an internal resistance equivalent circuit model is used (Fig.4). In this paper, the battery SOC is kept between 0.8 and 1 for residential application. The SOC value can be evaluated by integrating the battery current according to (2);

\[
SOC = \frac{Q_i - \int idt}{Q_n}
\]  

(2)

where \(Q_i\) is the initial battery charge and \(Q_n\) the rated ampere hour of the battery.

![Battery equivalent circuit model and bi-directional dc-dc converter](image)

**Fig.4** Battery equivalent circuit model and bi-directional dc-dc converter

III. DIGITAL CONTROL TECHNIQUE FOR DUAL BOOST CONVERTER

A dual boost converter is hired as a front-end dc-dc converter of the fuel cell to control the fuel cell current effectively and reduce the inductor size and the switch rating. To control the fuel cell current properly under the current limit determined by the amount of air and hydrogen fed to the stack is a critical issue for avoiding fuel starvation and improving the fuel cell durability, where the fuel amounts are calculated based on the fuel cell power \(P_{fc}\) produced by the power control strategy. However, the fuel cell used in the residential application suffers from 120Hz or 100Hz ripple current and a peak current during switching period and load transition. In order to address these barriers, a moving-average digital filter and a predictive current limiter are adopted in this paper (Fig.5). The PI control is introduced into both the voltage control loop and dual current control loop of the converter which is operated in the continuous conduction mode.

A. Cancellation of 120Hz Harmonic Current

The 120Hz harmonic current drawn from the fuel cell by the single phase ac load not only degrades the performance of fuel cell but also makes it difficult to regulate the fuel cell current under the current limit. The magnitude of the 120Hz harmonic current is highly dependent on the voltage control loop characteristic and the size of capacitor \(C_d\) in the dc bus.

The output voltage and current of a single phase dc-ac converter in Fig.1 are defined simply as follows,

\[
vo(t) = \sqrt{2} V_{o.rms} \sin(\omega ot)
\]  

(3)

\[
i_o(t) = \sqrt{2} I_{o.rms} \sin(\omega ot - \phi)
\]  

(4), where \(\phi\) is power factor angle.

The instantaneous output power \(P_o(t)\) is

\[
P_o(t) = vo(t)i_o(t) = V_{o.rms}I_{o.rms} \cos(\omega ot - \phi)
\]

Considering power balance with assumption that \(v_d(t)\) is a constant dc value \(V_d\), the dc current \(i_d(t)\) is

\[
id(t) = I_d + i_d.h(t) = \frac{V_{o.rms}I_{o.rms}}{V_d} \cos\phi - \frac{V_{o.rms}I_{o.rms}}{V_d} \cos(2\omega ot - \phi)
\]  

(5)

\[
ic(t) = -i_d.h(t)
\]  

(6)

where the 120Hz harmonic current as large as the fundamental current is included in the dc bus current. The dc bus voltage with a voltage ripple caused by the 120 Hz current ripple across \(C_d\) is expressed as follows,

\[
v_d(t) = V_d + \frac{1}{C_d} \int ic(t)dt = V_d(1 + k \sin(2\omega ot - \phi))
\]

where \(k = \frac{V_{o.rms}I_{o.rms}}{2\omega C_d V_d}\)

(7)

The steady state voltage error calculated in the voltage control loop of dual boost converter becomes.
\[ \text{verr}(t) = V_d - \text{vd}(t) = -\frac{V_{o,ms} \cdot l_{rms}}{2 \omega C_d V_d} \sin(2 \omega t - \phi) \]  
(8)

, and the current command from the voltage loop is the voltage error multiplied by the voltage loop gain. Therefore, a large 120Hz harmonic current which is 180° phase shifted from the 120Hz ripple voltage of the dc bus is induced at the fuel cell output terminal.

The proposed digital control scheme for the dual boost converter employs a moving-average digital filter into the voltage feedback loop to remove the 120Hz voltage ripple component included in the measured voltage, which cancels the 120Hz harmonic term of the current command (Fig.5). The moving-average digital filter is expresses as follows;

\[ f(n) = \frac{1}{N} \sum_{k=n-1}^{n} f(kT) \]  
(9)

where \( N \) is a period corresponding to 1/120.

B. Predictive Current Limiter

After the 120Hz harmonic component of the fuel cell current is eliminated using the moving-average digital filter, the fuel cell current is limited by a predictive current limiter adjusted by the air amount fed to the fuel cell stack in order to avoid the oxygen starvation in the cathode channel (Fig.5). The current limit value calculated by the fuel cell controller is derived as following equations. The air amount for a fuel cell power \( P_{fc} \) is

\[ \text{Air} = 3.57 \times 10^{-7} \times \frac{n P_{fc}}{V_{fc}} \quad \text{[kgs\textsuperscript{-1}]} \]  
(10)

\[ P_{fc} = V_{fc} \times i_{fc} \]  
(11)

Therefore, the current limit \( I_{\text{limit}} \) for the air amount fed to the stack is obtained as follows;

\[ I_{\text{limit}} > \frac{\text{Air}}{n \times 3.57 \times 10^{-7}} \]  
(12)

\[ I_{\text{limit}} \leq I_{\text{max}} \]  
(13)

where \( n \) is the number of cells and \( I_{\text{max}} \) is the upper limit of fuel cell current of the high efficiency region.

The PI controller of the current control loop in Fig.5 regulates the current at every switching time and, but it can not limit the peak current to the current limit during the switching period effectively. In this paper, a predictive current limiter is proposed to limit the peak current to the current limit during switching cycle, where the maximum allowable duty ratio \( d_{\text{max}} \) for the next switching cycle is calculated based on the sampled inductor currents of the present cycle, the input voltage \( V_{fc} \) of the present and next step, the output voltage of the converter \( V_d \) and the duty ratio of the previous step. The determined maximum duty ratio \( d_{\text{max}} \) limits the peak current of the input inductors dynamically not only during each switching period but also during the load transition. In digital control, the inductor current is sampled at the beginning of each switching cycle but the duty ratio calculated at the present step can be applied at the next switching cycle because of the time required to complete computation. Therefore, the inductor peak current needs to be predicted one cycle ahead in order to limit the peak current to the current limit predetermined by the air amount.[2] For simplicity, the current through the inductor \( L_1 \) only is described in this paper (Fig.5).

The inductor current \( i_{L1}[n+1] \) and the peak current \( I_p[n+1] \) at \((n+1)^{th}\) interval in Fig.7 can be described as follows;

\[ i_{L1}[n+1] = i_{L1}[n] + \frac{V_{fc}[n]}{L_1} d_{L1}[n-1] T_s \]  
(14)

\[ + \frac{V_{fc}[n] \cdot V_{d}[n]}{L_1} (1 - d_{L1}[n-1]) T_s \]

\[ I_p[n+1] = i_{L1}[n+1] + \frac{V_{fc}[n+1]}{L_1} d_{L1}[n] T_s \]  
(15)

where the output voltage \( V_{d}[n] \) is assumed as constant between the consecutive switching intervals but the input voltage \( V_{fc}[n] \) should not be assumed as constant because the fuel cell stack voltage is a current controlled voltage source.

From (14) and (15), the maximum allowable duty ratio of \( i_{L1} \) to be applied at the \((n+1)^{th}\) interval is derived as;

\[ d_{L1, \text{max}}[n] = \frac{L_1 f_s}{V_{fc}[n+1]} \left( \frac{I_{\text{limit}} - i_{L1}[n]}{2} - \frac{V_{fc}[n]}{V_{fc}[n+1]} \right) \]  
(16)

\[ + \frac{V_{d}[n]}{V_{fc}[n+1]} (1 - d_{L1}[n-1]) \]

Fig.6 Principle of moving-average digital filtering.

Fig.7 Inductor current waveform
where \( f_s \) is the switching frequency and \( V_{fc}[n+1] \) can be estimated using (14) and the approximated V-I curve of the fuel cell stack.

The calculated maximum duty ratio \( d_{L1,\text{max}}[n] \) of \( i_{L1} \) limits the peak current \( I_{p}[n+1] \) to \( Im_{\text{lim}}/2 \) at the (n+1)th interval so that the fuel cell system can avoid the oxygen starvation at the cathode channel.

IV. SIMULATION RESULTS

To verify the feasibility of the proposed power control scheme for the fuel cell hybrid power source, a prototype converter design and simulation are carried out with the design parameters as follows:

- Output power \( P \): 1.5kW
- Output voltage \( V_d \): 84V
- Inductor \( L_1, L_2 \): 60uH
- Output capacitor \( C_d \): 5600uF
- Switching frequency \( f_s \): 20kHz
- Input voltage \( V_{fc} \): 40V ~ 60V

Figure 8 shows the V-I curve of PEM fuel cell designed by KIER.

In order to achieve the fuel cell operation in the high efficiency region, the fuel cell is operated between the minimum power of 300W and the maximum power of 1.5kW, which secures the fuel cell net efficiency of 47% to 55% theoretically. Figure 9 presents the power flow among the power sources and the load by the proposed power control strategy when \( \text{SOC}_{\text{min}} = 0.8 \) and \( \text{SOC}_{\text{max}} = 1 \). The battery is discharged to supply the supplementary power to the load when the power demand is higher than the maximum power \( P_{\text{max}} \) or the present SOC is higher than 0.9, and charged when the power demand is lower than the maximum power \( P_{\text{max}} \) and the present SOC is lower than 0.9.

The moving-average filter is employed to reduce the 120Hz ripple current induced from the fuel cell in this paper. Figure 10 shows the result waveforms of inductor current when there is 5% peak to peak voltage ripple at the dc bus. The inductor current ripple is reduced from 23A to 3.8A at \( t=30\text{msec} \) by using the moving-average filter while the output voltage ripple is increased from 6V to 8.3V. The 120Hz ripple of the inductor current becomes negligible as it goes to the steady state.

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predictive current limiter so that the oxygen starvation of the fuel cell system can be avoided where the current limiter of $I_{limit1}$ is 17A (Fig. 11).

![Inductor current with a predictive current limiter](image)

The simulation results show that the proposed power control strategy controls the power flow between the power sources and the load properly and the digital control technique limits the fuel cell current to the current limit determined by the air amount fed to the fuel cell stack.

V. CONCLUSIONS

This paper has presented a new power control scheme for a fuel cell-battery hybrid power source for residential application which includes a power control strategy to control the power flow between the power sources and the load and a digital control technique for the dual boost converter. The proposed power control strategy enables the fuel cell to operate within the high efficiency region. The digital control technique of the dual boost converter adopts a moving-average digital filter and cancels the 120Hz harmonic current and then limits the fuel cell current to the current limit properly using a predictive current limiter to minimize the fuel cell oxygen starvation and improve the fuel cell durability.

REFERENCES