Effect of Load Modeling on Low Frequency Current Ripple in Fuel Cell Generation Systems

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Abstract – In this work, an accurate analysis of low frequency current ripple in residential fuel cell power generation systems is performed based on the proposed residential load model and its unique operation algorithm. Rather than using a constant dc voltage source, a proton exchange membrane fuel cell (PEMFC) model is implemented in this research so that a system-level analysis considering the fuel cell stack, power conditioning system (PCS), and the actual load is possible. Using the attained results, a comparative study regarding the discrepancies of low frequency current ripple between a simple resistor load and a realistic residential load is performed. The data indicate that the low frequency current ripple of the proposed residential load model is increased by more than a factor of two when compared to the low frequency current ripple of a simple resistor load under identical conditions. Theoretical analysis, simulation data, and experimental results are provided, along with a model of the load usage pattern of low frequency current ripples.

Keywords: Low frequency current ripple, Residential load modeling, Rectification load, Power conditioning system, Modeling and simulation

1. Introduction

To reduce global warming and the exhaustion of fossil fuels, the research and development of new renewable energy sources and related technologies are becoming more and more relevant. In particular, fuel cell power generation systems offer a number of advantages, such as high efficiency and regular power generation, when compared to conventional or other renewable energy sources. Fuel cell power generation systems are incorporated into numerous applications, from high-capacity power plants used for grid connection to low capacity power generators for stand-alone, transportation, and portable applications. As such, fuel cell power generation systems must not only meet basic performance levels, but also possess high efficiencies, high reliability, a long lifetime, and specific safety features if they are to be implemented in the near future. Although various factors affect fuel cell systems, the effect of low frequency current ripple, which is generated from power conditioning systems (PCSs), has a particular influence on fuel cell systems [1]-[2].

PCSs are necessary in order to convert the dc power from a fuel cell into ac power for a commercial frequency in residential power generation (RPG) systems. Low frequency current ripple components are rectification effects, which arise from the use of inverter switches, and appear as a 100 Hz or 120 Hz pulsating current in single-phase systems. Low frequency current ripples, especially ripple

signals of less than 400 Hz, have been the reported cause of many negative effects, such as: 1) slower cathode surface response, 2) an increase in fuel consumption by more than 10%, 3) oxygen starvation, 4) a reduction in operating lifetime, and 5) malfunctions in fuel cell power generation systems [3], [4]. Accordingly, the limitation standards regarding low frequency current ripple are specified in various technical reports and manufacturers' manuals. According to the Fuel Cell Handbook (7th Ed., 2004), for 10 kW systems used for stand-alone fuel cell power generation systems, the 120 Hz ripple component should not exceed 15% and the 60 Hz ripple component should be limited to 10% at 10%-100% loads [5]. For example, the Ballard Nexa 1.2 kW PEMFC is set to a 120 Hz current ripple limit of up to 35% of the peak-peak value, or up to 24.7% of the root mean square (rms) value [6]. The 120 Hz ripple, which arises under stand-alone loads in single-phase systems, is strictly regulated. In a three-phase system, the lowest current ripple appears as 360 Hz and the ripple size is much smaller than that found in a single-phase system due to the phase overlap. Residential loads are primarily rectification loads applied to a single-phase source and can be considered as the worst condition from a low frequency ripple point of view. Therefore, consideration of a single-phase RPG system, which is mainly a rectification load, is essential.

To improve the performance of a fuel cell stack, research in the power electronics field has been carried out in an attempt to reduce low frequency current ripple. To reduce the ripple, a design methodology was proposed in [7] so as to select the required capacity of a passive energy storage component, such as a capacitor. In addition, an advanced active control technique was proposed in [7] to incorporate a current control loop in a dc-dc converter. In particular, an active control technique presented the possibility for reduc-

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ing ripple currents by employing a control strategy instead of additional hardware components. An impedance model of the fuel cell stack was also proposed in order to evaluate the effects of current ripple [8]. On the other hand, a technique was proposed to minimize input ripple current in a three-phase pwm inverter when unbalanced/nonlinear loads are supplied [9]. The proposed technique has the advantage of reducing ripple currents in unbalanced load conditions. However, such a technique is not applicable to single-phase systems, such as those found in residential applications.

One drawback of previous research on ripple current was that the studies were carried out under simple load conditions using only a resistor. Such experiments do not represent actual residential load conditions. In RPG systems, the fuel cell system powers several home appliance loads such as an air-conditioner, a refrigerator, a TV, a computer, and so on. These are mostly rectification loads, not resistor loads, which mean that an analysis of the generation pattern of low frequency current ripples must be carried out for practical residential load models.

In order to analyze the generation pattern of low frequency current ripple, the authors propose a new residential load model in this work. To develop the proposed residential load model, representative home appliances are selected and their electrical characteristics are modeled by a combination of R-L-C components. Furthermore, the daily load usage pattern is then realized using a specific switching algorithm so that the generation pattern of the low frequency current ripples, according to a 24-hour operation pattern, can be analyzed. For an accurate analysis, a PEMFC model is implemented instead of using a constant dc voltage source, so that a system-level analysis considering the fuel cell stack, power conditioning system, and actual load is possible. In Section VI, the influence of load conditions and the effect of PCS topological structures and their constituent power electronics devices are analyzed. A detailed theoretical explanation of the proposed model and algorithm is also presented, along with the results of simulation and experiments.

2. Analysis of Low Frequency Current Ripples

To examine the generation and propagation of low frequency current ripple according to the load conditions, a single-phase RPG system was considered. As shown in Fig. 1, the system consists of a step-up full bridge dc-dc converter and a single-phase inverter.

2.1 Generation and Propagation Mechanism of Low Frequency Current Ripple

Unipolar sinusoidal pwm (spwm), as shown in Fig. 2(a), is commonly used for single-phase inverters. The output voltage appears as a pulsating waveform, as shown in Fig. 2(b). For connection at the grid, a low pass LC filter is used to eliminate high frequency components. The final output voltage becomes a 60 Hz sinusoidal waveform, as

shown in Fig. 2(c). The filtered output voltage and current of the inverter are expressed in (1) and (2).

$$v_o(t) = V_m \cos(\omega t + \theta) \quad (1)$$

$$i_o(t) = I_m \cos(\omega t + \phi) \quad (2)$$

where, θ and ϕ represent phase angles.

The generation and propagation mechanism of low frequency current ripple can be explained using the energy conservation law. The angular frequencies of the output voltage and current are both ωt , and the output power is calculated by multiplying (1) and (2). The frequency of the output power of a single-phase inverter has twice the angular frequency of $2\omega t$, and can be derived as shown in (3).

$$P_{out}(t) = (V_m I_m / 2) \{ \cos(2\omega t + \theta + \phi) + \cos(\theta - \phi) \} \quad (3)$$

Based on the energy conservation law described in (4) and neglecting inverter power dissipation, the powers at the dc link and the ac output should be identical.

$$V_d I_d^*(t) = v_o(t) i_o(t) \quad (4)$$

where, I_d^* is the filtered dc link current, which consists of a pure dc component and a sinusoidal component at twice the fundamental frequency. The I_d term is the inverter input current, which consists of I_d^* and the high frequency components due to inverter switchings.

Fig. 1. Block diagram of power conditioning system for fuel cell.

Fig. 2. Operation principle of unipolar sinusoidal pulse width modulation: (a) Reference and carrier waveforms, (b) pwm output voltage before filtering, and (c) Sinusoidal output voltage with LC filter.

When (3) and (4) are properly rearranged, the frequency and shape of the dc link current (I_d^*) is the same as the counterparts of the output power. The dc link current can then be expressed as (5) because the dc link voltage is generally regulated by the voltage controller of the dc-dc converter.

$$I_d^* = (V_m I_m / 2V_d) \{ \cos(2\omega t + \theta + \phi) + \cos(\theta - \phi) \} \quad (5)$$

When the converter loss is neglected, the fuel cell current (I_{FC}) shows a 120 Hz ripple component on top of the pulsating dc current. This is due to the switching behavior of the full bridge dc-dc converter, as described by (6).

$$I_{FC} = V_d I_d^* / V_{stack} \quad (6)$$

where, V_{stack} is the output voltage of the fuel cell stack.

The output voltage of the fuel cell stack has both static and dynamic characteristics. For the static characteristics, the operating voltage of the fuel cell stack, as described by (7), is the Nernst voltage minus the activation, ohmic, and concentration polarizations.

$$V_{stack_static} = N \left(E - (i + i_n) r - \frac{RT}{2\alpha F} \ln \left(\frac{i + i_n}{i_{ec}} \right) + \frac{RT}{2F} \ln \left(\frac{i + i_n}{i_L} \right) \right) \quad (7)$$

where, N is the number of cells, E is the Nernst voltage, i is the current density, i_n denotes the internal current density, r is the sum of the ionic, electronic, and contact resistance, R represents the gas constant, T is the temperature in K, α is the transfer coefficient, F is Faraday's constant, i_{ec} denotes the exchange current density, and i_L is the limit current density.

A practical fuel cell stack has dynamic characteristics. An equivalent electrical model indicating the dynamic characteristics of a unit cell can be presented as an RC first-order time delay circuit, as shown in Fig. 3. This characteristic is called the “charge double layer” phenomenon. In this phenomenon, potential differences, caused by the accumulation of hydrogen ions and electrons on both sides of an electrolyte, arise while gathering the responsive minimum gas density [10]. The voltage loss (v_c) and time constant (τ) due to the charge double layer can be derived as shown in (8) and (9), respectively.

$$dv_c / dt = (i / C_{cdy}) - (v_c / \tau) \quad (8)$$

$$\tau = C_{cdy} R_a = [C_{cdy} (V_{act} + V_{con})] / i \quad (9)$$

where, v_c is the voltage loss due to the charge double layer, C_{cdy} is an equivalent capacitance, τ is the time constant, R_a denotes the sum of the activation polarization resistance and the concentration polarization resistance, V_{act} is the activation polarization, and V_{con} is the concentration polarization.

Consequently, the fuel cell stack voltage (V_{stack}) can be expressed as shown in (10) [10]-[12].

Fig. 3. Charge double layer of a fuel cell: (a) Equivalent model at the surface of a fuel cell cathode, and (b) Electrical equivalent circuit of a unit cell.

$$V_{stack} = E - V_{ohmic} - v_c \quad (10)$$

where, V_{ohmic} is ohmic polarization.

2.2 Analysis of Low Frequency Current Ripples According to the Load Conditions

When a pure resistor load is connected to a single-phase PCS system, the inverter output current (i_o) becomes a sinusoidal waveform that is in-phase with the output voltage (v_o) and has the same frequency as ωt . Therefore, the phase angles of θ and ϕ become zero in (1)-(3). The output power is always a positive value; it has a dc value, twice the output current frequency, and a small high frequency component. Figs. 4(a) and (b) depict the equivalent circuit, voltage, and current waveforms when a pure resistor load is connected to the inverter.

The rectification load is a load which includes a rectifier. The rectifier needs to convert ac into dc in order to supply

Fig. 4. (a) Equivalent circuit under simple resistor load condition, and (b) Voltage and current waveforms under simple resistor load condition.

power, of variable voltage and/or frequency, from a source of constant voltage and frequency. Most home appliances have this kind of rectification load. The load consists of a power conversion system that includes a diode rectifier, filter capacitor, dc-dc converter, and an inverter at the load side which can be represented as a resistive, inductive, or capacitive load. The inverter current of the PCS is chosen to be in compliance with the electrical potential difference of the input voltage and the output voltage of the rectification load. This means that the inverter output waveforms of the fuel cell PCS are very complicated when compared to a simple resistor load condition.

Figs. 5(a) and (b) depict the practical circuit and an equivalent circuit of the rectification load, respectively. A line inductance (L_s) and resistance (R_s) are included in the circuit because a long cable is generally required to connect the PCS output terminal to the load. The final load (R_{load}) behind a dc link capacitor (C_d) can be modeled using a pure resistor. Shown in Fig. 6 are the voltage and current waveforms at the rectification load.

In *Mode 1* ($t_0 < t < t_1$) and *Mode 4* ($t_3 < t < t_4$), the dc link voltage and current are given by (11) and (12), respectively.

$$dv_{load} / dt = -(v_{load} / C_{load} R_{load}) \quad (11)$$

$$i_d = 0 \quad (12)$$

In *Mode 2* ($t_1 < t < t_2$) and *Mode 3* ($t_2 < t < t_3$), the dc link voltage and current equations are given by (13) and (14), respectively.

$$|v_o| = R_s i_d + L_s (di_d / dt) + v_{load} \quad (13)$$

$$i_d = C_{load} (dv_{load} / dt) + (v_{load} / R_{load}) \quad (14)$$

The complete voltage and current equations of the dc link can be expressed by (15) and (16), respectively [13].

Fig. 5. (a) Practical circuit under rectification load condition, and (b) Equivalent circuit under rectification load condition.

$$v_{load}(t) = v_{load}(t_3 / \omega) e^{-(t-t_3 / \omega) / (C_{load} R_{load})} \quad (15)$$

$$i_d = C_{load} \frac{d}{dt} (v_d(t_3 / \omega) e^{-(t-t_3 / \omega) / (C_{load} R_{load})}) + \frac{1}{R_{load}} (v_{load}(t_3 / \omega) e^{-(t-t_3 / \omega) / (C_{load} R_{load})}) \quad (16)$$

A large nonlinear current is generated when the rectification loads are connected to the PCS. As such, the peak current becomes much greater than that found in the simple resistor load condition, even if the average current is identical. For this reason, a much larger low frequency current ripple affects the fuel cell stack, as analyzed in Section 2.1. Figs. 7(a) and (b) show aspects of the generation and propagation of low frequency current ripples for simple resistor load and rectification load conditions, respectively.

Fig. 6. Voltage and current waveforms under rectification load condition.

Fig. 7. Aspect of generation and propagation of low frequency current ripples: (a) Under simple resistor load condition, and (b) Under rectification load condition.

3. Modeling of a Residential Load and a 24-hour Operation Pattern

As previously mentioned, low frequency ripples vary by the load conditions, even if the system specifications and operating conditions are identical. Therefore, modeling of practical loads is strongly required so as to properly design and examine the performance of the PCS for the RPG system. In this section, the electrical modeling of a practical residential load is implemented. Low frequency ripple, according to the time utilization of residential loads during the day, are analyzed by considering models of the load usage pattern of an ordinary household [1].

3.1 Electrical Modeling of a Practical Residential Load

Most loads used in an ordinary household are rectification loads. According to a recent project in Korea, six representative home appliances such as refrigerators, TVs, electric rice cookers, computers, washing machines, and air-conditioners are selected as the load for this study [14].

Table 1 shows the detailed power consumption, watt-hours, daily usage times, and electrical models of specific home appliances. One such appliance, a 680 liter class refrigerator (SRT686UTCE: Samsung Electronics Company) uses around 60 kW of power per month in common usage. Since the refrigerator is operating all day, it has an average daily power consumption of 1.992 kW. Assuming 83 W of power is consumed per hour, the load impedance can be calculated as 1,157 ohms. The refrigerator can be modeled as a rectifier, dc link capacitors, and a load, which is the motor's impedance for the compressor (which can be modeled by a pure resistor). A Samsung Electronics plasma display panel (PDP), the SPD-42Q92HD, was also analyzed and its rated power consumption is about 410 Wh. The PDP also includes a rectifier in order to convert power from ac to dc because a high voltage is required to generate the plasma. The electric rice cooker, computer, washing machine, and air-conditioner are modeled on the same principle, reflecting their practical characteristics.

Table 1. Electrical characteristics and modeling of residential loads

Item	Watt-hour (Wh)	Daily usage(h)	Electrical model	R (Ω)	C (μ F)
Refrigerator	83	24	C+RL	1,157	680
TV	410	6	C+R	234	680
Rice cooker (warming / cooking)	135 / 1,100	15 / 0.5	R	711 / 87	-
PC +Monitor	240 + 38	5	C+R	345	680
Washing machine	150	1	C+RL	640	680
Air-conditioner	2,600	1	C+RL	36	680
Lighting	150	8	R	640	-

3.2 Modeling of a Daily Residential Load Profile

Fig. 8 shows a weekday demand load curve for an ordinary household for each of the four seasons. These data were provided by the Korea Energy Management Corporation (KEMCO) for each of the four seasons [15].

The general pattern of home appliance power consumption is that more power is used in the morning and after sunset. Power consumption during different seasons seems to indicate an increase during the summer, with increased lighting loads during the autumn months. The load pattern during spring can be considered to be the load between the summer and the autumn seasons. Therefore, the peak power consumption appears in the summer season after sunset. In this research, home appliance consumption patterns during the summer were selected for analysis.

Fig. 8. Daily demand load usage pattern of ordinary household in Korea according to seasons.

3.3 Implementation of a Residential Load Bank

By combining the electrical modeling of residential loads with the daily residential load pattern in Sections 3.1 and 3.2, a residential load bank was implemented using a PSIM 6.0 simulation program. The daily residential load pattern, shown in Fig. 9, was realized using Gating Block for Switch, a function of PSIM [16]. It is usually necessary to include at least three or four cycles of a periodic wave in order to analyze its harmonics [17]. Therefore, to analyze the 120 Hz ripple, the minimum sampling period must be:

$$T_{SP} \geq 3 / f_{S,120Hz} \quad (17)$$

where, T_{SP} is minimum sampling period.

Among the loads, the shortest operation time was set to 30 min for the cooking mode of the electric rice-cookers. The minimum required simulation time to analyze at least three cycles of the 120 Hz ripple can be expressed as:

$$T_{Sim} \geq (3 / f_{S,120Hz}) \cdot (24 / t_{load,min}) \quad (18)$$

where, T_{Sim} is the entire simulation time, and is the minimum operation time of the loads.

To acquire reliable harmonics data, the 24-hour period must be scaled down into slightly more than 1.2 s. Consequently, the simulation time was set at 2 s, and the gating time was converted from 1 hour into 15 degrees by using the *Gating Block for the Switch*. To provide reasonable results for the simulation conditions, ripple variation due to a load change was examined in the six modes. This means that one mode represented 4 hours.

Fig. 9. Load profile of 6-home appliances scaled down 24 hours to 2 sec and 360degrees.

4. Simulation Results

The validity of the theoretical analysis of low frequency current ripple under the proposed residential load condition was verified by both computer simulation and experiments.

Details of the simulation circuit and parameters are shown in Fig. 10 and Table 2, respectively. As previously mentioned, the generation of low frequency current ripple is independent of the characteristics of the fuel cell stack; such characteristics include the flow-field pattern, gas-flow between cells, gas channel geometry sizes, and so on. However, for an accurate analysis of an entire fuel cell generation system, the Ballard Nexa 1.2 kW PEMFC stack was used because it is a well-known and highly reliable fuel cell stack [6]. The nonlinear V-I characteristics and dynamic characteristics due to the charge double layer effect of the PEMFC stack were modeled in Matlab/Simulink. The power conversion circuit and the proposed residential load model were implemented using a PSIM simulation tool. Therefore, in this work, Matlab/Simulink and PSIM

Table 2. PCS simulation parameters

Parameters	Symbols	Value [unit]
Maximum power	P	3.844 [kW]
Fuel cell voltage	V_{fc}	26-45 [Vdc]
DC Link voltage	V_{dclink}	380 [Vdc]
Output voltage	V_{out}	220 [Vac]
Converter switching frequency	f_{swc}	60 [kHz]
Inverter switching frequency	f_{swi}	10 [kHz]
DC link capacitor	C_d	3,360 [μ F]
Output filter capacitor	C_o	5 [μ F]
Load capacitor	C_{load}	3,400 [μ F]
DC link inductor	L	1 [mH]
Output filter inductor	L_o	3 [mH]

were used interchangeably so as to analyze the exact ripple current phenomena.

The characteristics of the fuel cell stack voltage exhibit exponential behavior due to a double-layer effect at the load step changes. These characteristics are detailed by the electro-chemical equations described in (7)-(10). Fig. 11 shows the static and dynamic characteristics, at the load step changes. Detailed simulation parameters of fuel cell stack are described in Table 3.

Fig. 12(a) shows the fuel cell, dc link and inverter current for a constant pure resistor load at 1 kW. Fig. 12(b) depicts the harmonics spectrum of the fuel cell current, specifically at the 120 Hz ripple. The fundamental and 120 Hz components of the fuel cell current are 26.12 A and 5.48 A, respectively. Therefore, approximately 20% of the 120 Hz ripple was generated.

The fuel cell current and other waveforms for a rectification load instead of the simple resistor load are shown in Fig. 13(a) and the harmonics spectrum is shown in Fig. 13(b). The fundamental and 120 Hz components of the fuel cell current are 22.44 A and 8.52 A, respectively. Therefore, about 38% of the 120Hz ripple was generated. Although the system power under each load condition was identical, the peak current was considerably increased by more than 150% with approximately 50 A, even when the average current of the fuel cell was the same. This increase was due to large nonlinear current.

Fig. 10. Simulation circuit to analyze low frequency current ripples.

Fig. 11. Dynamic characteristics of fuel cell stack due to charge double layer.

Fig. 12. (a) Fuel cell current, dc link current, inverter voltage and current under simple resistor load condition, and (b) Harmonic spectrum of the fuel cell current.

Fig. 13. (a) Fuel cell current, dc link current, inverter voltage and current under rectification load condition, and (b) Harmonic spectrum of the fuel cell current.

Table 3. Fuel Cell Modeling Simulation parameters [10]

Parameters	Symbols	Value [unit]
Nernst voltage	E	1.229 [V]
Internal current density	i_n	2 [mA.cm ⁻²]
Resistance	r	0.1 [ohm.cm ⁻²]
Gas constant	R	8.3144 [J.mol K ⁻¹]
Temperature	T	343.15 [K]
Faraday's constant	F	96,485 [C.mol ⁻¹]
Exchange current density	i_{ec}	0.0017 [mA.cm ⁻²]
Number of cells	N	48
Resistance of charge double layer	R_a	0.1 [ohm.cm ⁻²]
Capacitance of charge double layer	C_{cdy}	0.6 [F]

Using the developed simulation model of the fuel cell stack, current trajectories of the fuel cell stack according to the load conditions are shown in Fig. 14. For a simple resistor load, the range of current fluctuation was from approximately 22 A to 32 A.

For the rectification load, the current fluctuation was even larger and ranged from about 12 A to 46 A. Such high current directly harms the fuel cell stack in that it creates oxygen starvation and causes an increase in fuel consumption. This is because the fuel cell operates in the mass transportation region. Because the maximum permissible stack current is 46 A, nuisance tripping, such as in an overload situation, can also occur due to a sudden voltage drop.

The generation ratio of the low frequency current ripple is changed by the capacitance of the rectification load. However, because voltage ripple due to capacitance is reduced exponentially, a variation in the ratio is not significant when the capacitance is above a certain value. Fig. 15

Fig. 14. Fuel cell current trajectories according to load conditions.

Fig. 15. 120Hz ripple components according to load capacitances.

Fig. 16. Fuel cell current and distribution of low frequency current ripples according to daily load variation.

shows the ratio of 120 Hz ripple components according to load capacitance. There was no real influence on the ripple when the capacitance was greater than 3,200 μF .

Fig. 16 shows the simulation results of a downscaled daily load variation for the ordinary household modeled in Figs. 8 and 9. From these data, the authors determined the aspect and distribution of the generation of daily low frequency current ripple in an ordinary household.

Fig. 17 shows the results of the analysis of a 120 Hz harmonic at a simple resistor load with the proposed practical residential load model under the same operation conditions. The 120 Hz ripple component with the proposed rectification loads is lowest, at 27.5%, during the period from 12:00-4:00 p.m., which are the least busy hours (Mode IV). The 120 Hz ripple component is highest, at 41.8%, after 8:00 p.m., which are the busiest hours (Mode V). In particular, between 8:00 p.m. and 10:00 p.m. (the timeframe of the busiest hours (MODE VI)), 45% of the 120 Hz ripple, which is equivalent to 31.04 A, was generated while the fundamental component was 68.49 A. In conclusion, the pattern and amount of the 120 Hz ripple current showed totally different behavior when the simple resistor load was replaced by a realistic rectification load under the same conditions.

Fig. 18 shows the dc link capacitance required to reduce the 120 Hz current ripple at the rectification load by as

Fig. 18. Required dc link capacitance to reduce.

much as the current ripple at the simple resistor load. A 120 Hz ripple component was measured to be 21% under a simple resistor load when a 3,360 μF dc link capacitor was used. In the case of the rectification load, in order to keep the 120 Hz ripple at the same magnitude as in the simple resistor load condition, a 6,000 μF dc link capacitor was required. This value is approximately 1.8 times higher than that used for the resistor load condition. Since 45% of the 120 Hz ripple was generated under the maximum load condition, a dc link capacitor which is three times larger is required to reduce the 120 Hz ripple to a level under the simple resistor load.

Fig. 17. Daily distribution of 120Hz harmonic component under simple resistor load and under proposed practical residential loads model.

5. Experimental Verification and Discussion

The validity of the theoretical analysis and the simulation results of the low frequency current ripple under the proposed residential load condition has been verified by experiment. A laboratory prototype of a 1 kW FC-PCS, which consists of a voltage-fed full-bridge dc-dc converter and a single phase full-bridge inverter (as shown in Fig. 19(a)) is implemented. The main controller is a MCP56F803 16-bit fixed point processor by Freescale and the analog pwm controller, adopted for dc-dc converter control, is a TL494 by Texas Instruments. The experimental setup shown in Fig. 19(b) is then built up by the 1.2 kW Ballard Nexa PEMFC with an input power source and load banks. The load banks are implemented by pure resistors for the simple resistive load condition and an ac-dc diode rectifier

Fig. 19. Experimental setup.

module with load capacitors for the rectification load condition. The load capacity is determined as 1 kW of the maximum power and is divided by six modes, as simulation result in Fig. 16, in order to simulate realistic residential loads and load usage patterns. Details of the parameters of the system and the load bank are listed in Tables 4 and 5, respectively. A WT3000 power analyzer by YOKOGAWA is used to analyze the harmonic components of the fuel cell current.

Fig. 20(a) shows the fuel cell current, including the low frequency ripple components in the simple resistor load, at 1 kW. The fuel cell current has approximately 24.1% of the 120 Hz.

Fig. 20(b) displays the fuel cell current in the rectification load (instead of the simple resistor load) even if other conditions are identical. Due to the load capacitors of the ac-dc diode rectifier, the inverter current has a snappy, non-linear shape. The 120 Hz ripple component appears larger than the simple resistor load condition. It is generated approximately 37.6% of the resistor load condition. The 120 Hz ripple component is considerably increased by more than 156% because of the huge nonlinear current.

Table 4. PCS Hardware parameters

Parameters	Symbols	Value [unit]
Rated power	P	1.2 [kW]
Fuel cell voltage variation	V_{fc}	26-45 [Vdc]
Rated DC Link voltage	V_{dlink}	380 [Vdc]
Rated Output voltage	V_{out}	220 [Vac]
Converter switching frequency	f_{swc}	60 [kHz]
Inverter switching frequency	f_{swi}	10 [kHz]
DC link capacitor	C_d	3,400 -6,800[uF]
Output filter capacitor	C_o	5 [uF]
Load capacitor	C_{load}	3,400 [uF]
DC link inductor	L	1 [mH]
Output filter inductor	L_o	3 [mH]

Table 5. Load bank parameters

Modes [Capacity]	Simple R-Load [Ω]	Realistic Rectification Load	
		C_{load} [uF]	Value [Ω]
Mode I [500W]	100	3,400	200
Mode II [100W]	480		800
Mode III [250W]	200		400
Mode IV [100W]	480		800
Mode V [1,000W]	50		100
Mode VI [500W]	100		200

Fig. 20. Fuel cell current, inverter output current and voltage waveforms at 1kW load condition: (a) Under simple resistor load, and (b) Under rectification load. (ch1: 20[A/div]; ch2: 10[A/div]; ch3: 350 [V/div]; 20[ms/div]).

Figs. 21(a)-(f) show the generation aspects of low frequency current ripples when a simplified daily load pattern is applied using a rectification load. The 120 Hz ripple component is obviously generated more than 20% in entire operation modes.

Figs. 22(a)-(d) show the reduction aspects of low frequency current ripples according to the dc link capacitances at a 500 W test condition. The dc link capacitors are 680 uF/400 WV electrolyte capacitors composed with 5 to 10 in parallels. This enables the use of 3,400 uF to 6,800 uF dc link capacitances. The results indicate that more than 5,440 uF of dc link capacitance is required to reduce the 120 Hz ripple to a level that is as low as the ripple under the simple resistor load at 500 W.

The minor disparities between the results of the simulation and the experiment appear to arise mainly from the lower crest factor, which is in turn due to the huge nonlinear inverter current. In addition, the distribution of the resistor values is limited because physical metal-clad resistors were used. As a result, mismatch among resistor values between the simulation model and the experiments exists. Line (or stray) inductance and parasitic capacitances are also present in the experimental setup. Nevertheless, the experimental results indicate almost the same aspect of low frequency current ripples as that found through analysis and simulation, especially for the 120 Hz component. Therefore, a fuel cell system, which is used in an RPG application with a stand-alone type, should be considered to have relatively high current ripples, as observed in the re-

Fig. 21. Fuel cell current, inverter output current and voltage waveforms according to daily load variation under rectification load: (a) Mode I with 500W, (b) Mode I and II with 100W, (c) Mode II with 250W, (d) Mode III-V with 100W, (e) Mode VI with 1kW, and (f) Mode VI with 500W. (ch1: 20[A/div]; ch2: 10[A/div]; ch3: 350[V/div]; 20[ms/div]).

Fig. 22. Decreasing of low frequency current ripple according dc link capacitances at 500W condition: (a) At 3,400uF, (b) At 5,440uF, (c) At 6,120uF, and (d) At 6,800uF. (ch1: 20[A/div]; ch2: 10[A/div]; ch3: 350[V/div]; 20[ms/div]).

sults of this study. It should also be considered during research on ripple reduction.

6. Discussion of Other Factors: Power Electronic Topologies and Devices

Although the topological structures and power electronics devices of the PCS are generally determined according to the capacity of an RPG system, the effects of PCS topologies and related power electronics devices should be considered. In this section, assuming the same residential load, the effects of other factors, such as PCS topological

structures and energy storage devices (such as capacitors and inductors), are examined.

While the topology of a single-phase inverter is mostly a full-bridge type with 4-switches, pwm switching strategies have different options, such as bipolar and unipolar spwm. The pwm strategies affect high frequency ripple components rather than low frequency current ripples. Thus, the effect of topological structures and the pwm switching strategies of the inverter can be ignored.

The dc-dc converters have numerous topological structures. Among these, a step-up full-bridge converter, a boost converter, and a push-pull converter are suitable for RPG applications when considering the low voltage characteristic of the fuel cell stacks and a system capacity of around 1

kW to 5 kW [4]. These converters can be classified into two groups: isolation types and energy storage devices. In this study, a boost converter, which represents a non-isolated and current-fed type dc-dc converter, and a voltage-fed full-bridge converter, which represents an isolated and voltage-fed converter, were adopted. The input current of the boost and full-bridge converters were determined by the duty ratio, output current, and turns ratio of a transformer (for the full-bridge converter only). Therefore, the topological structures of the dc-dc converters also do not affect low frequency current ripples.

To analyze the effect of energy storage capacitors, the fuel cell current can be derived as function of dc link capacitance (C_d) by rearranging (4)-(6) as follows:

$$i_{FC}(t) = \frac{1}{V_{FC}} \left[V_{o,rms} I_{o,rms} \cos(\theta - \phi) + V_{o,rms} I_{o,rms} \cos(2\omega t + \theta + \phi) - \frac{V_{o,rms} I_{o,rms} \cos(2\omega t + \theta + \phi) \cos(\theta - \phi)}{2\omega C_d V_d^2} - \frac{(V_{o,rms} I_{o,rms})^2 \sin(4\omega t + 2(\theta + \phi))}{4\omega C_d V_d^2} \right] \quad (19)$$

This result indicates that low frequency current ripples are significantly affected by the energy storage capacitors in an inversely proportional manner. Fig. 23(a) shows the correlation between the magnitude of a 120 Hz ripple and the capacitance when compared to mathematical analysis and simulation results.

Fig. 23. Comparison results between derived equations and PSIM simulation results: (a) In case of capacitors, and (b) In case of inductors.

Fig. 24 shows the fuel cell current of the boost converter, including the switching and low frequency ripples. In order to analyze the effect of energy storage inductors, the fuel cell current can be derived as a function of the inductance (L) as follows:

$$\frac{I_{\max,a} + I_{\min,a+1}}{2} - \frac{I_{\max,a} + I_{\min,a}}{2} = \frac{\cos(2\omega T^*(a+1) + \theta + \phi) - \cos(2\omega T^*(a+D) + \theta + \phi)}{8\omega L C_d V_d} - V_{o,rms} I_{o,rms} \quad (20)$$

As in the case of the capacitance, low frequency current ripples are affected by the energy storage inductors in an inversely proportional manner. Fig. 23(b) shows the correlation between the magnitude of a 120 Hz ripple and the inductance when compared to mathematical analysis and simulation results. The results of the mathematical analysis are in good agreement with the simulation results.

The analysis results indicate that the topological structures of the PCS do not influence low frequency current ripples. However, the energy storage devices in the PCS, such as the capacitors and inductors, can have a significant influence on low frequency current ripples.

Fig. 24. Fuel cell current including low frequency and switching ripples.

7. Conclusion

In this work, the generation and propagation of low frequency current ripples generated by a PCS for fuel cells were analyzed. The generation aspects of ripple current under simple resistor and rectification loads were also studied. A residential load model was developed, along with a daily demand load pattern. It was proposed that a realistic load model should be considered for the reduction and/or elimination of low frequency current ripple. It is expected that the analysis and the proposed model will be useful in the optimal design of a PCS for fuel cell systems.

References

- [1] J. S. Kim, H. S. Kang, B. K. Lee and W. Y. Lee, "Analysis of low frequency ripple current of a fuel cell system based on a residential load bank modeling," in *Proc. IEEE International Conferences on Electrical Machines and Systems (ICEMS)*, Seoul, Korea, Oct. 2007.
- [2] B. Wahdame, D. Candusso, X. Francois, F. Harel, M.-C. Pera, D. Hissel and J. M. Kauffmann, "Analysis of a fuel cell durability test based on design of experiment approach," *IEEE Trans. Energy Convers.*, Vol. 23, No. 4, pp. 1093-1104, Dec. 2008.
- [3] R. S. Gemmen, "Analysis for the effect of inverter ripple current on fuel cell operating condition," *J. Fluids Eng.*, Vol. 125, No. 3, pp. 576-585, 2003.
- [4] D. K. Choi, B. K. Lee, S. W. Choi, C. Y. Won and D. W. Yoo, "A novel power conversion circuit for cost-effective battery-fuel cell hybrid systems," *J. Power Sources*, Vol. 152, No. 1, pp. 245-255, Dec. 2005.
- [5] "EG&G Technical Services, Inc. Science Applications International Corporation," in *Fuel Cell Handbook*, 7th ed. Vol. DOE/NETL, chapter 8, Nov. 2004.
- [6] *Nexa™ (310-0027) Power Module User's Manual*, Ballard Power Systems Inc., 2003.
- [7] C. Liu and J. S. Lai, "Low frequency current ripple reduction technique with active control in a fuel cell power system with inverter load," *IEEE Trans. Power Electron.*, Vol. 22, No. 4, pp. 1429-1436, July 2007.
- [8] W. J. Choi, J. W. Howze and P. Enjeti, "Development of an equivalent circuit model of a fuel cell to evaluate the effects of inverter ripple current," *J. of Power Sources*, Vol. 158 (2006), pp. 1324-1332, 2006.
- [9] W. Shireen, R. A. Kulkarni and M. Arefeen, "Analysis and minimization of input ripple current in PWM inverters for designing reliable fuel cell power systems," *J. of Power Sources*, Vol. 156 (2006), pp. 448-454, 2006.
- [10] J. Larminie and A. Dicks, *Fuel Cell Systems Explained*, 2nd ed., Wiley, 2003, pp. 17-59.
- [11] S. Y. Choe, J. W. A, J. G. Lee and S. H. Baek, "Dynamic simulation for a PEM fuel cell system with a PWM DC/DC converter," *IEEE Trans. Energy Convers.*, Vol. 23, No. 2, pp. 669-680, June 2008.
- [12] K. P. Adzakpa, K. Agbossou, Y. Dube, M. Dostie, M. Fournier and A. Poulin, "PEM fuel cells modeling and analysis through current and voltage transient behaviors," *IEEE Trans. Energy Convers.*, Vol. 23, No. 2, pp. 581-591, June 2008.
- [13] N. Mohan, T. M. Undeland and W. P. Robbins, *Power Electronics: Converters, Applications and Design*, 3rd ed., Wiley, 2003, pp. 79-120.
- [14] Korea Ministry of Knowledge Economy (MKE), [Online]. Available: <http://www.mke.go.kr>.
- [15] Korea Energy Management Corporation (KEMCO), [Online]. Available: <http://www.kemco.or.kr>
- [16] *PSIM User's Guide*, Version 6, 2003.
- [17] E. Kreyszig, *Advanced engineering mathematics*, 9th ed., Wiley, 2005.

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