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Fuel sensor-less control of a liquid feed fuel cell under dynamic loading conditions for portable power sources (*I*)

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ABSTRACT

This work presents a novel fuel sensor-less control scheme for a liquid feed fuel cell system that operates under dynamic loading conditions and is suitable for portable power sources. The proposed technique utilizes the operating characteristics of a fuel cell, such as voltage, current and power, to control the supply of liquid fuel and regulate its concentration. As verified by systematic experiments, this scheme controls effectively the supply of fuel under dynamic loading conditions and pushes the system toward higher power output. The primary features and advantages of sensor-less fuel control are as follows. When the fuel concentration sensor is excluded, the cost of a liquid feed fuel cell system is decreased and system volume and weight are reduced, thereby increasing specific energy density and design simplicity, and shortening system response time. Notably, temperature compensation for measurement data is unnecessary. With a decreased number of components, the control scheme improves durability and reliability of liquid feed fuel cells. These advantages will help commercialization of liquid feed fuel cells as portable power sources.

1. Introduction

A liquid feed fuel cell, like the direct methanol fuel cell (DMFC), is widely recognized as a potential candidate for portable power sources. A DMFC differs from a Proton Exchange Membrane Fuel Cell (PEMFC), in that the former uses methanol as fuel rather than hydrogen, eliminating the problem of hydrogen storage, reducing the risk of explosion and significantly increasing the convenience and safety of fuel cells. Thus, DMFC is more adaptable to portable applications such as in laptops, PDAs and camcorders.

Methanol concentration is a factor that significantly affects DMFC performance. Methanol crossover from anode to cathode through a polymer electrolyte membrane is a well-known problem that hinders the development of DMFC [1,2]. Due to methanol crossover, practical operation of DMFC requires accurate control of methanol concentration within a predetermined range. The conventional approach is to use a methanol concentration sensor in a closed loop of fuel circulation. However, many requirements for methanol concentration sensors for DMFC exist, the concentration sensing range must be wide, resolution and accuracy around the operating point must be high, and system response must be rapid. Additionally, methanol sensors should tolerate metallic ion impurities such as Fe^{3+} and Cu^{2+}, tolerate CO_2 bubbles for in-line operation, be stable over the long term, have a wide range of operating temperatures, and be adaptable to miniaturization for tight packaging and system integration [3]. Yet, existing products do not meet all desirable criteria. Furthermore, methanol sensors developed using the electrochemical methods have issues such as deterioration and degradation of the Membrane Electrolyte Assembly (MEA) over time, which result in poor stability and durability. Methanol sensors based on physical properties, such as density, refractometry or sound speed, are also sensitive to carbon dioxide bubbles in the fuel loop. Furthermore, methanol concentration sensors, regardless of whether they are designed using physical or electrochemical principles [4], markedly depend on temperature. Therefore, experimental tasks such as calibration are necessary when a methanol sensor is utilized. Although the fuel sensor approach can be used to control fuel concentration, it nevertheless has the shortcomings of increased weight, size, complexity and cost of a liquid feed fuel cell.

Very few studies have focused on fuel sensor-less control of liquid feed fuel cells that can reduce cost and complexity associated with use of fuel concentration sensors. Acker et al. [5] developed a method for regulating methanol concentration based on system operating characteristics. Zhang et al. [6] presented an indirect approach for determining methanol concentration in a fuel stream

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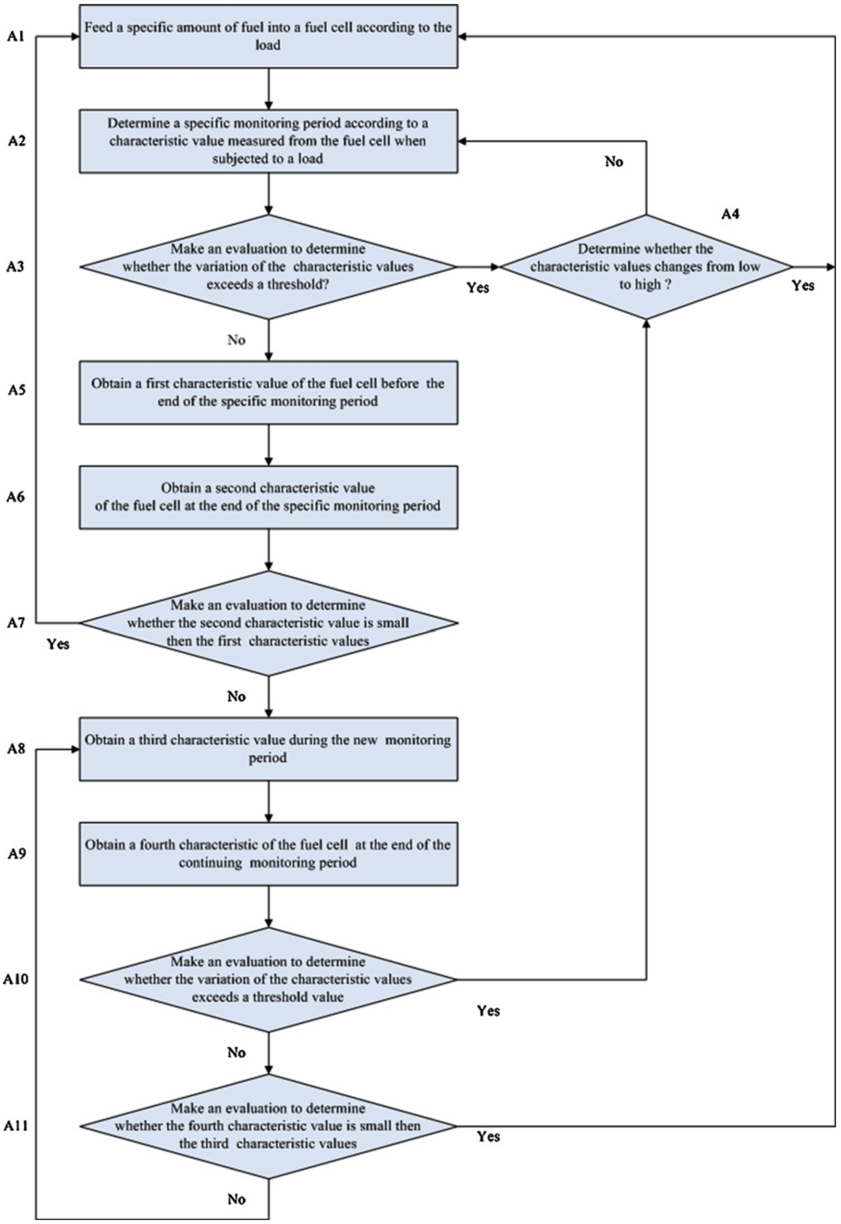

Fig. 1. Flow chart of the IR-DTFI control scheme in which variations are judged by difference.

based on measurements of fuel stream temperature as it enters the fuel cell stack, operating temperature of the fuel cell stack and load current. Chiu and Lien [7] proposed an interpolation algorithm based on constant concentration surfaces to estimate the concentration of methanol in a single cell system. All these approaches may be affected by catalyst and membrane degradation. Furthermore, little published information exists on the transient response of a liquid feed fuel cell subjecting to dynamic loading under fuel sensor-less control. That is of paramount importance when the liquid feed fuel cell serves as a multi-level charger or a power source, which provides electric power to different portable applications.

We had presented a novel fuel sensor-less control algorithm, Impulse Response based on Discrete Time Fuel Injection (IR-DTFI), for a liquid feed fuel cell under steady loads [8]. During fuel cell reaction, the cell's operating characteristics, such as potential, current and power are measured to control fuel supply and regulate fuel concentration to optimize performance. This algorithm is adopted, and the technology is transferred to the fuel cell industry in Taiwan. The IR-DTFI control scheme is scheduled to be applied to DMFC chargers. The DMFC chargers can output 5, 9, 12, and 17 V for portable applications such as PDAs or cell phones.

This work presents a modified Impulse Response based on Discrete Time Fuel Injection control scheme (still abbreviated as IR-DTFI in the following text) for a liquid feed fuel cell under dynamic loading conditions and evaluates the feasibility of it on the portable system, which provides easy and simple control of fuel supply using an experimentally verified algorithm. The operating characteristics of the stack are applied to control the DMFC without need to determine the fuel concentration. This approach can work even when the MEA deteriorates gradually. Fuel can be a hydrogen-rich liquid fuel such as methanol or ethanol. Thus, the DMFC is adopted as an example liquid feed fuel cell to demonstrate the effectiveness of the IR-DTFI control algorithm.

2. System description

2.1. The IR-DTFI control strategy for DMFC system under dynamic load conditions

Our previous work [8–12] had shown the design and fabrication of the bipolar plate, the stack, and the membrane electrode assembly which are used in this study. More details can be found in our previous work. Fig. 1 is a flow chart depicting steps of the IR-DTFI method for supplying fuel to a fuel cell. According to Fig. 1, the flow starts from step A1, a specific amount of a fuel is fed into a fuel cell with regard to the load. Then the flow proceeds to step A2, a specific monitoring period is determined according to a characteristic value measured from the fuel cell when subjected to a load, and then the flow proceeds to step A3. It is noted that the characteristic value can be current, voltage or power measured from the fuel cell. Fig. 2 plots the polarization curve of a fuel cell operating at optimum condition. As shown in Fig. 2, the power curve having a maximum power $P_{\max}$ and the corresponding $I_{\max}$ is a suggested value for deciding the minimum duration of the specific monitoring period. The control unit determines the specific monitoring period, at any other discharging condition, inversely proportional to $I_{\max}$. There are some modifications with this rule concerning the fuel efficiency and the detail will be discussed in Section 3.2. The minimum specific monitoring period is the duration that the fuel cell can sustain the load $I_{\max}$ within the injection of the specific amount of fuel.

At step A3, during the specific monitoring period, the load is detected to determine whether the variation of characteristic value exceeds a threshold, if so, then the flow proceeds to step A4 for further evaluation; otherwise, the flow proceeds to steps A5, A6 and A7 for determining whether the specific amount of fuel is enough. The load is considered to be varying when the variation of a characteristic value exceeds a predetermined threshold value at any time during the specific monitoring period. The fuel cell of Fig. 3, connecting to a piping for feeding methanol and air and for exhausting water and carbon dioxide, is comprised of: an anode, a cathode and a proton exchange membrane. A load is provided for connecting the anode with the cathode, and thereby, a circuit connecting the anode, the load and the cathode is achieved. In addition, the load is connected to the measurement devices, which can be a voltmeter or galvanometer. By the signals received from the measurement device, a controller unit of the fuel cell can control a fuel feeding unit for supplying fuel to the fuel cell.

The step A4 is executed for determining whether the characteristic value changes from low to high, and if so, the flow proceeds to step A1, otherwise, the flow proceeds to step A2. In step A4, the characteristic value decreasing or increasing is evaluated by determining whether the difference between the selected characteristic value is a positive or a negative value, or by determining whether a slope obtained from a curve, profiling the variation of the characteristic value, is a positive value or a negative value. If the variation of the characteristic value does not exceed the threshold value during the specific monitoring period, the flow will proceed to a process, step A5, for determining whether the remaining fuel in the fuel cell is sufficient. At step A5, a first characteristic value of the fuel cell is obtained during the specific monitoring period. The first characteristic value is a value selected from the group consisting of the minimum voltage, minimum current and minimum power measured during the specific monitoring period. Then the flow proceeds to step A6. At step A6, a second characteristic value of the fuel cell is obtained at the end of the specific monitoring period; and then the flow proceeds to step A7. At step A7, an evaluation is made to determine whether the second characteristic value is small than the first characteristic value. If so, then the flow proceeds back to step A1 for injecting fuel into the fuel cell system again as the fuel had been exhausted to a certain extent; otherwise, the flow proceeds to step A8 as there is still excess fuel remaining in the fuel cell. At step A8, a third characteristic value of the fuel cell is obtained before the beginning of injection delay period; and then the flow proceeds to step A9. At step A9, a fourth characteristic value of the fuel cell is obtained at the end of the continuing injection delay period; and then the flow proceeds to step A10. At step A10, an evaluation is made to determine whether the variation of the characteristic value exceeds a threshold value; if so, then the flow proceeds to step A4; otherwise, the flow proceeds to step A11. The function of step A10 is similar to step A3, which is set up to detect the occurrence of the dynamic load. At step A11, an evaluation is made to determine whether the fourth characteristic value is small than the third characteristic value; if so, then the flow proceeds back to step A1. Otherwise, there is still excess fuel remaining in the fuel cell system and thus the flow proceeds back to step A8 for continuing the monitoring of whether the excess fuel in the fuel cell system is exhausted. Therefore, the fuel supply of the fuel cell is under consistent monitoring and adjustment for sustaining the fuel cell to operate continuously and normally.

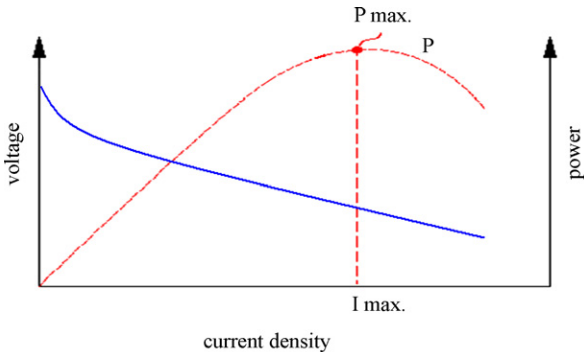

Fig. 2. Determination of the minimum specific monitoring period via the polarization curve.

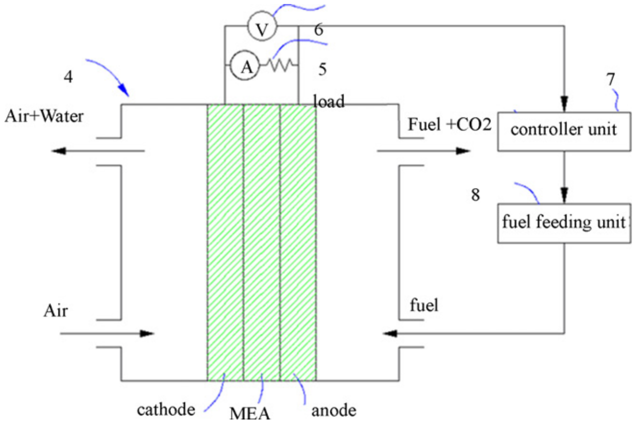

Fig. 3. Schematic diagrams of the measurement system, system control, and fuel-feeding unit for verification and evaluation of the IR-DTFI control scheme.

However, except for varying the duration of the monitoring period, it can be controlled by varying the amount of fuel to be injected into the fuel cell system while maintaining the duration of the monitoring period to be constant. We will present this point of view in the next report in the near future. The fuel supply of the fuel cell is governed by the amount of fuel injected into the fuel cell system at each cycle and the modulation of the specific monitoring period.

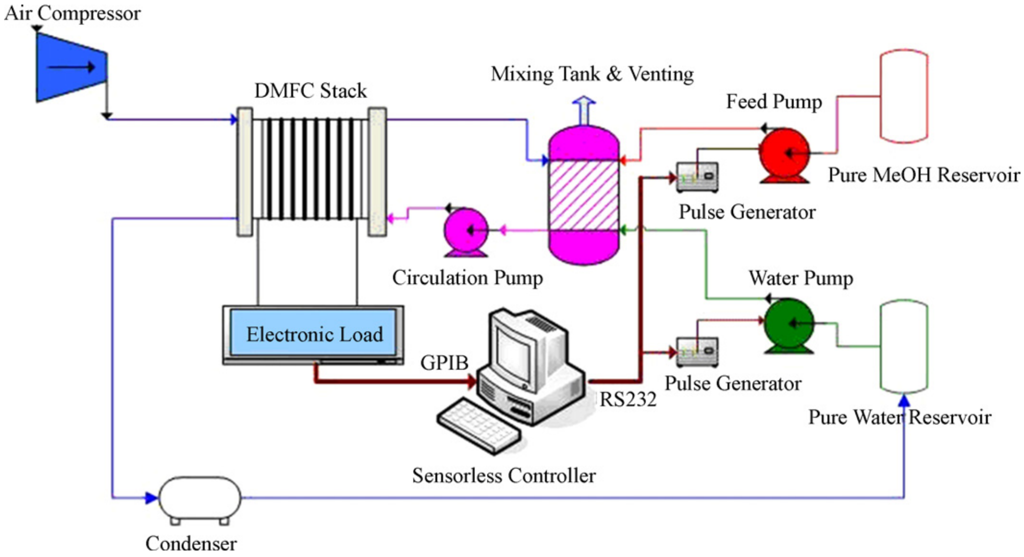

Fig. 4. Test apparatus for evaluating the IR-DTFI control algorithm.

2.2. *Test apparatus for evaluation of the IR-DTFI control algorithm*

Fig. 4 shows the test apparatus for evaluation of the IR-DTFI control algorithm applied to DMFC, the system comprising:

(1). An electronic load instrument (Chroma, 6310) was used to serve as dynamic load and it measured voltage and current response to evaluate the performance of the IR-DTFI control algorithm.
(2). A feed pump, in fluid transmission with a pure methanol reservoir and a mixing tank, was applied to inject neat methanol to the mixing tank.
(3). A circulation pump, in fluid transmission with the mixing tank and a DMFC, was used to deliver the methanol solution and the flow rate was obtained by weighing the fuel delivered per minute.
(4). Two pulse generators (GW INSTEK PHS-3610) which are actuated by a computer generated pulses to drive the feed pump and water pump.
(5). A small mixing tank was applied to mix the neat methanol with pure water to a predetermined concentration range, wherein the carbon dioxide bubble produced from anode outlet could be used to create turbulence thereby increased the mixing rate and consumed no extra power.
(6). A measurement system setup for the analysis was controlled through a personal computer with homemade program written in LabVIEW. Two programmable power supplies were controlled to drive the feed pump and water pump. An electronic load, a DVD player and a notebook PC were applied alternatively as the dynamic loads. National Instrument USB9221, USB9215 and Tektronix AC/DC current probe A622 were used for measuring voltage and current. NI USB9211 and two k-type thermocouples were applied for temperature measurement. Neat methanol was used herein as a fuel and air as an oxidant. Digital refractometer #PA203, manufactured by Misco Cooperation, was adopted externally to measure the concentration of the methanol solution sampled from the inlet of anode compartment. A discrete time-pulsed fuel injection method was developed to inject pure methanol into the mixing tank for a short duration when the operating characteristic was below a calculated value. The specific monitoring period was inversely proportional to the quantity of pure methanol injected to the mixing tank. The controlling algorithm can be implemented using a microprocessor, such as the 8051 microprocessor for portable devices and is simple and cost-effective. The measurements verify the performance of the IR-DTFI control strategy. All experiments were conducted at room temperature (24–29 °C) at a relative humidity of 43–70% under the normal ambient conditions of portable electronic devices. The stacks temperature is affected by the stacks themselves so that the stacks operate in a self-heating mode. The system control unit controls the supply of water at a fix rate, about $0.12\,\mathrm{cm}^3\,\mathrm{min}^{-1}$ that was determined experimentally. The fuel feeding referred to in this study is mainly the feeding of neat methanol.

3. Results and discussion

3.1. *Methanol crossover and concentration*

The methanol crossover occurs owing to the concentration gradient, electro-osmotic drag and pressure gradient [13]. However, methanol dissolves completely when mixed with water, which leads to an increased crossover rate in the Nafion membrane. Extensive research has focused on developing alternative electrolyte membranes or modifying Nafion membranes [14–16], both of which are more resistant to methanol crossover and less expensive than Nafion film. The DMFC has reduced fuel efficiency due to direct oxidation of methanol at the cathode. Consequently, the cathode endures a mixed potential that results in reduced potential of the cathode reaction. Due to these effects, overall cell voltage and performance of a direct methanol fuel cell are reduced.

The way to avoid methanol crossover is to keep the fuel concentration as low as possible. However, power output becomes low and unstable when the methanol concentration falls below a specific range. When the methanol concentration surpasses that predetermined range, output power can be sustained but fuel efficiency will be low. If the methanol concentration is excessive, methanol crossover becomes an issue. Regulating fuel supply is essential in maintaining the methanol concentration in a predetermined range such that the DMFC system can operate with optimum fuel efficiency.

3.2. The relationship between the fuel supply and dynamic load

This study aims at the development of the fuel sensor-less control method for the operating liquid feed fuel cells under dynamic loading conditions. According to Faraday's law, the electrolysis of the methanol in the DMFC is a function of load current (1).

$$M_O = \frac{1}{nF}\int I\,\mathrm{d}t \tag{1}$$

M_O: amount of methanol electro-oxidized (mol); t: time required for electro-oxidation current to fall from I to zero (s); I: current (A); n: number of electrons exchanged; and F: Faraday's constant (96,480 A s mol^{-1}).

The methanol is supplied via a feed pump in the active DMFC system. With regard to the quantity of methanol supply in this study, the pulse width for driving the feed pump is specified as a constant in the control unit. Additionally, the specific monitoring period is defined as a control variable. During the fuel supply at each cycle, as the length of the specific monitoring period increases, the fuel supply decreases. With regard to this rule, a small methanol fuel supply is suitable for the low-load condition. However, under a high load condition, as the length of specific monitoring period decreases, the number of times fuel must be re-supplied increases. Therefore, the demand for methanol is high under the high-load condition. To the first approximation, when the pulse width for driving the feed pump is fixed, the specific monitoring period is inversely proportional to the stack current. Hence, as long as the specific monitoring period at some fixed point of load is estimated accurately through experiments, the system can calculate the other specific monitoring periods by multiplying the ratio of the two loads current with the predetermined monitoring period to handle the dynamic loading conditions, as in Eq. (2). A series of systematic experiments are performed to analyze this assumption.

$$T_2 = T_1 \times \frac{I_1}{I_2} \tag{2}$$

Two experiments were performed for the verification process of Eq. (2). One experiment calculated the specific monitoring period (T_2) at each load (I_2) with a predetermined monitoring period (T_1) at a fixed load (I_1: 80 mA cm^{-2}) using the relationship of inversely proportional ratio of the two current as in Eq. (2). Second, individual experiments for each load were conducted to obtain the accurate set of specific monitoring periods. The experiments were conducted by applying the IR-DTFI algorithm and tuning manually the specific monitoring period at each load to obtain the accurate set of specific monitoring periods. When the accurate set of specific monitoring periods was obtained, the system typically attained temperature balance with very little injection delay, as determined by the measurement system.

Whether the calculated monitoring periods are accurate is determined by the voltage response at each load. Fig. 5 presents the experimental results. An obvious difference in voltage responses existed at low current density levels of 4 and 2 mA cm^{-2}. The voltage differences at these two loads are 2.64 and 2.55 V, respectively, implying that the calculated monitoring period is too long. Methanol evaporated away during the prolonged monitoring period and fuel supply was insufficient.

Fig. 6 shows the experiment result of the fuel efficiencies of the stack to its corresponding load with a specific monitoring period obtained through experimentation. An empirical formula for fuel efficiency function (η_{fuel}) was obtained by curve fitting the fuel efficiency (Fig. 6).

$$\eta_{\text{fuel}}(I) = (-6.56\ \exp -5)I^2 + 0.01\,I + 0.294 \tag{3}$$

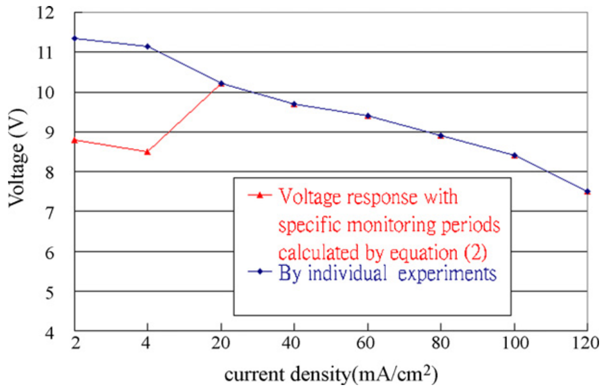

Fig. 5. Voltage responses under different specific monitoring periods.

At a low boiling point of 64.7 °C, methanol is highly miscible with water and the escaping vapor takes some methanol away from the mixing tank. The evaporation rate varies with temperature. Therefore, the quantity of methanol escaping with the vapor also varies with operating temperature and load. Thus, the consumption of methanol in DMFC can be classified into three parts: oxidation of methanol at the anode; methanol crossover from anode to cathode; and methanol escaping with the vapor. All of those factors are included in fuel efficiency function. Moreover, the value of the specific monitoring periods must be modified by the function of fuel efficiency, as in the following equation:

$$T_2 = T_1 \times \frac{I_1}{I_2} \times \frac{\eta_{\text{fuel}}(I_2)}{\eta_{\text{fuel}}(I_1)} \tag{4}$$

The empirical formula modifies the calculated specific monitoring period, and this rule is applied to the following experiments. Through modulation of the specific monitoring periods, the IR-DTFI algorithm allows the system to react under dynamic loading conditions. Fig. 7 presents three curves for specific monitoring periods. One curve is calculated using Eq. (2), the other obtained experimentally at each load, and the third curve calculated by Eq. (4). The curve obtained experimentally at each load and the curve calculated by Eq. (4) are very close except at 2 mA cm^{-2}. That may be attributed to extrapolation error caused at the curve ends.

3.3. Verification of the IR-DTFI control algorithm

When DMFC are applied as power sources for electronic products such as DVD players, PDAs or laptops, the loads act roughly like constant current with different levels. A series of dynamic loading patterns were designed systematically to verify the effectiveness of

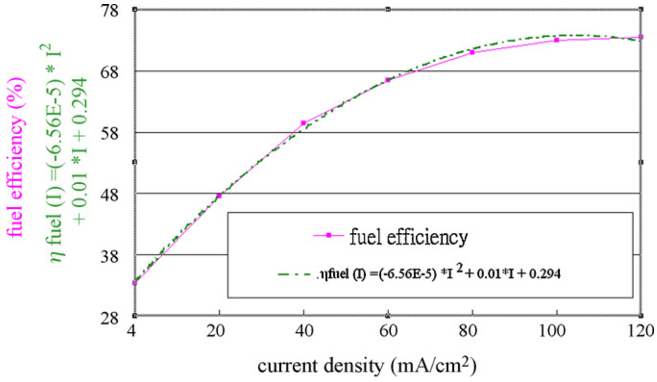

Fig. 6. Fuel efficiency curves at each load for a 25-W stack.

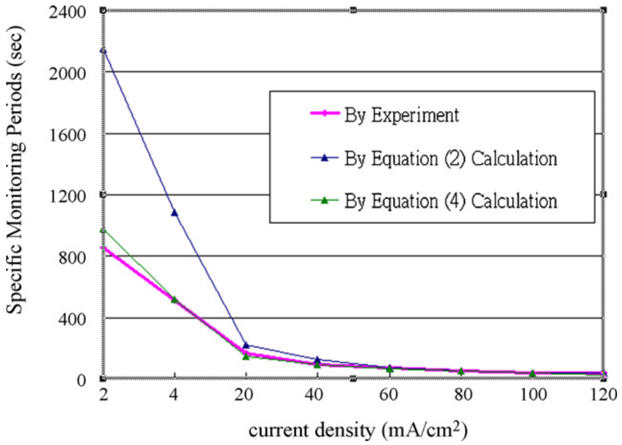

Fig. 7. Specific monitoring periods for different approaches.

the IR-DTFI control algorithm applied to DMFC operation. The loading patterns, used in this study, try to simulate conditions of, for example, a charger operating with different output current levels, frequently on–off switch, instantaneous loading with high power demands from low load conditions (with BOP operation). The varying load was provided by an electronic load, Chroma 6310, which can set the load at different currents level on the fuel cell as well as measuring its voltage versus current responses. The measurement system together with the electronic load was fully automatic controlled by a personal computer. The stack was a 22-cell with active area of 25 cm^2 MEAs. During the tests described in this section, methanol solution was fed at a flow rate of 158 ml min^{-1}, while air was supplied through an air pump with high pressure drop at a flow rate of 6 l min^{-1}. The measurements were conducted several times to ensure repeatability. A refractometer was applied to measure the methanol concentration externally to evaluate the control algorithm. That assisted in getting insight of the variation of methanol concentration during the tests. An Electronic load, a DVD player and a notebook PC are adopted to serve as the dynamics loads for the evaluation of IR-DTFI control scheme. The details are as follows.

3.3.1. Electronic load test mode

When DMFC is applied to serve as a power source for a notebook or a DVD player, the frequently on–off switch is naturally. As the portable electronics is switched off, the load mainly demanded by BOP. When the electronic load is set in constant current mode, the load will sink a current according to the programmed value regardless of input voltage. The constant pulse loads provided by electronic load are program controlled by home-made LabVIEW software. Fig. 8 plots the performance of a 22-cell stack under constantly pulsed loads of 0.8 A (BOP) and 2.5 A (full load) for 80-min operation. This experiment shows that the IR-DTFI algorithm is capable of controlling the fuel supply for a DVD player or a notebook PC. When the DVD player or the notebook PC is switched off, the load is to sustain the BOP operation. Fig. 9 plots the characteristics of 22-cells stack under constantly pulsed loads of 0.8, 1, 1.5 and 2 A for 170-min operation. The loads are dynamic switched between 0.8 and 1 A at the time interval of 0–60 min, between 0.8 and 1.5 A at the time interval of 60–120 min and between 0.8 and 2 A at the time interval of 120–170 min. The cell responds quickly, and reversibly, to the changes of the load of which the magnitude is varying systematically. This experiment shows that the IR-DTFI algorithm is capable of controlling the fuel supply for multifunctional charger with multi-level charge capability. As seen in both Figs. 8 and 9, when the load changed, the voltage changes abruptly and instantly. Every time the DMFC was loaded from low current to high current, the stack power responded quickly to a certain value and then elevated slowly under the IR-DTFI control algorithm. When the load is switched from low to high, the initial fuel concentration and mass transport of methanol after load switch is not enough for the high load condition, and the system injected more fuel at the time after the switching of load from low to high. The new specific monitoring period calculated by Eq. (4) is decreased and the fuel concentration in the mixing tank increases gradually which leads to a gradual lift of stack power. The methanol concentration measured by the refractometer was between 0.9 and 1.9 wt.% during the tests.

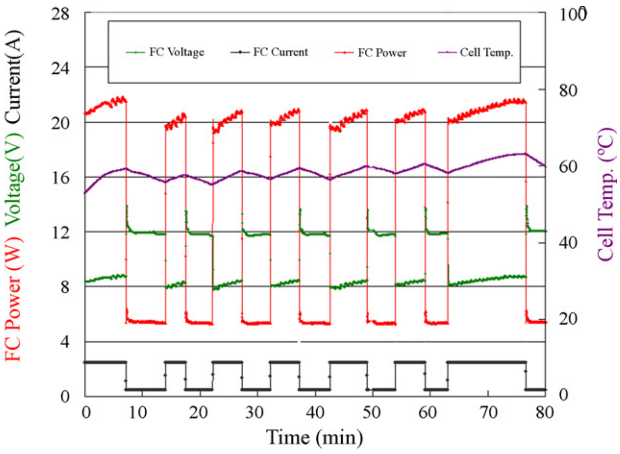

Fig. 8. Transient characteristics of a stack under constantly pulsed loads of 0.8 and 2.5 A.

3.3.2. DVD player test mode

Fig. 10 plots the system characteristics with the load using a DVD player and BOP for 220-min operation. The DVD player was switched on and off randomly. The BOP consumed approximately 6 W and the DVD player consumed 8–10 W. When DVD player is switched on, the stack output was maintained at approximately 14 W output under the control of IR-DTFI algorithm. When DVD Player was switched off, the stack output 6–7 W for BOP operation. The methanol concentration in the mixing tank was 1.2–2.2 wt.% throughout the experiment. The fuel efficiency was around 0.9–1.0 Wh cm^{-3}. The experimental result for the DVD player demonstrated that the IR-DTFI algorithm effectively controlled the supply of methanol and was suitable for liquid feed fuel cells.

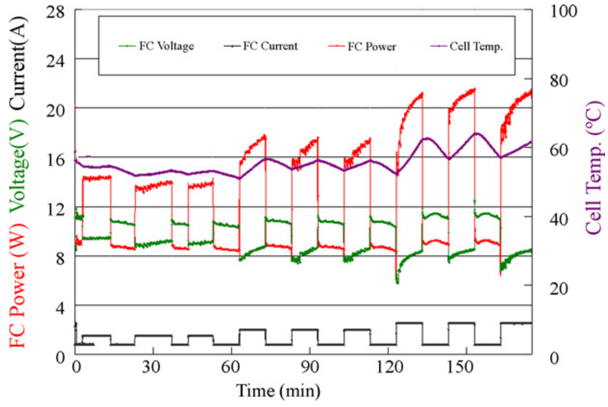

Fig. 9. Transient characteristics of a stack under constantly pulsed loads of 0.8, 1, 1.5 and 2 A.

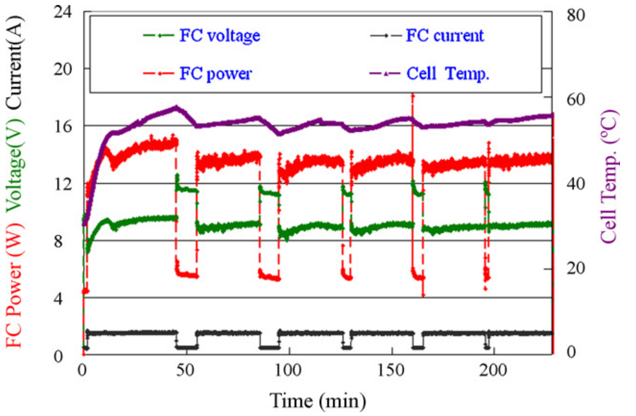

Fig. 10. The 220-min stability test for stack performance for a DVD player (room temperature of 25 °C, anode flow rate of 158 ml min^{-1} and cathode flow rate of 6 l min^{-1}).

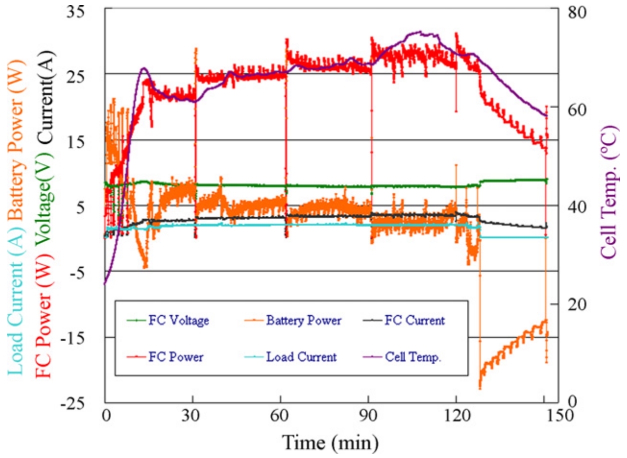

Fig. 11. The 150-min stability test of stack performance in hybrid mode for a notebook PC (room temperature of 25 °C, anode flow rate of 158 ml min^{-1} and cathode flow rate of 6 l min^{-1}).

3.3.3. Notebook PC test mode

Fig. 11 illustrates an experiment result of using a stack with 25 W to supply power to a notebook. DMFC with 22-cell was hybrid with Li-ion battery under the fuel supplying method of IR-DTFI. A DC/DC converter was need to obtain the require voltage for DMFC power source. The DMFC system experienced a quick start-up within 5-min to reach 45 °C As the stack temperature rose, the stack power increased and the battery power decreased. At the time of 125 min, the notebook PC was switched off, so the stack power was applied to charge the Li-ion battery and sustained the BOP. The Li-ion battery was charged full gradually. In the meantime, the stack current began to decrease quasi-linearly from 3.2 to 1.7 A in the end, and the stack temperature, maintained by self-heat, dropped gradually from 70 to 58 °C under IR-DTFI control scheme.

As shown in Fig. 11, the fuel cell operating according to the IR-DTFI algorithm can automatically regulating its fuel supply for providing power output under dynamic load. The feed pump used in the portable power sources system does not need high accuracy. This is of special cost priority to the portable power source system. The control system only has to guarantee that the supply quantity of fuel is a little more than what is actually needed for DMFC. The inaccuracy of feed pump and measurement uncertainty will cause the system to accumulate excess fuel, which will be regulated through the comparison process of IR-DTFI algorithm.

From all experiments, the methanol concentration was controlled within the range of 0.9–2.2 wt.%, which was the gross result of different experiments and in part came from refractometer measurement uncertainty. The methanol concentration in the experiment was controlled by varying the duration between two injections when the quantity of methanol injected at each time is fixed. The injection quantity was related to pulse width driving the feed pump. The control algorithm results in power fluctuations that are key features of the IR-DTFI control scheme. These fluctuations were measured at the stack terminal and could be regulated through the conditioning circuit for the load or could be decreased by reducing the pulse width driving the feed pump. Further experiments in a near future study will show that the IR-DTFI control method still holds when the quantity injected varies and the duration between two injections is fixed.

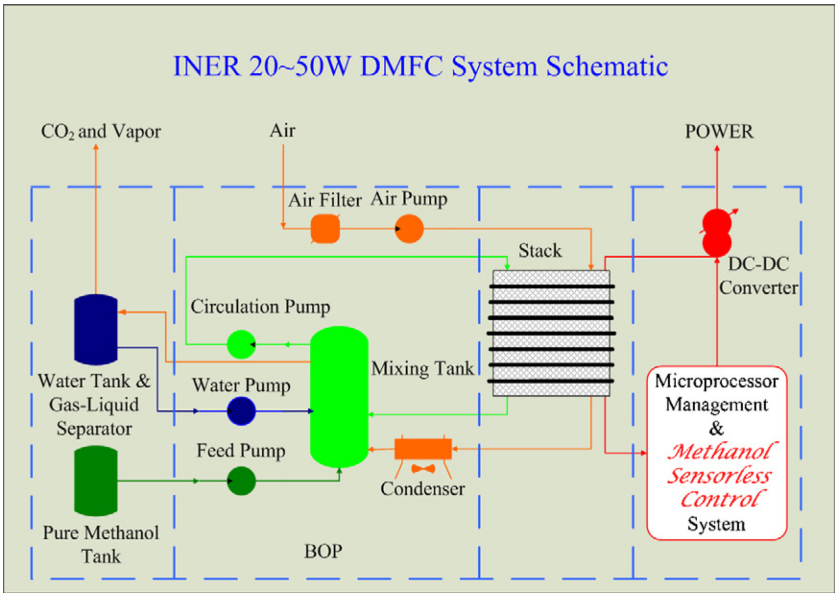

Fig. 12. Schematic diagram of an INER portable DMFC system.

Fig. 13. A notebook PC powered by a portable DMFC system.

Experimental results systematically confirm that the IR-DTFI control algorithm can control the DMFC such that it functions well under dynamic loading. Moreover, a DVD player and a notebook PC are used as real loads for verifying the IR-DTFI control algorithm. Fig. 12 shows a schematic diagram of Institute of Nuclear Energy Research (INER) portable DMFC system. Fig. 13 shows the DMFC Power Pack for a notebook PC, embedded with the IR-DTFI control algorithm and an Intel 8051 processor. Consequently, the advantages of the IR-DTFI control algorithm, such as reducing the weight and volume of DMFC and cost, extending lifetime, increasing reliability and simplifying the control algorithm, makes the liquid feed fuel cell system highly promising for portable applications.

4. Conclusions

The novel fuel sensor-less control algorithm, the IR-DTFI algorithm, for a liquid feed fuel-cell system under dynamic loading was presented and verified experimentally. Design considerations and experimental results for supplying fuel to a liquid feed fuel cell system are presented. The IR-DTFI algorithm controls the system using operating characteristics of the liquid feed fuel cell system. An experimentally verified equation has been introduced to predict the specific monitoring periods under dynamic loading. Accordingly, the IR-DTFI control algorithm can sustain the dynamic loading and can push the system toward higher power output. The IR-DTFI control algorithm can survive even when the stack degrades continuously. A microprocessor, such as those of the Intel 8051 series, can implement the simple cost-effective algorithm in portable devices.

The features and advantages of the IR-DTFI control scheme are as follows. When the methanol sensor is excluded, the cost of the DMFC system is reduced, as are system volume and weight, which leads to increased specific energy density, design simplicity and short system response time. Few components in the design scheme improve the durability and reliability of the DMFC system. Furthermore, temperature compensation for measurement data is unnecessary and the control scheme is suitable for applications in systems using any fuel type. Thus, the IR-DTFI control techniques are valuable and could be adopted in fuel cell systems.

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