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Performance Test of 1 kW PEM Fuel Cell System to Determine Its Empirical Model

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Abstract: The proton exchange membrane fuel cell (PEMFC) has a higher power density, so it is suitable to be utilized for powering electric vehicles (EVs) and supporting the grid's power balance and voltage stability. As its load will vary during operation, the PEMFC system have to manage the fuel feed following load variations. In this study, a dead-end anode-type PEMFC system with a rated power of 1 kW is used to investigate its performance under current loading rates of 0–28 A in steady-state conditions. From the test results, the empirical models were derived and simulated in MATLAB. The test is conducted by measuring the PEMFC stack's current, voltage, hydrogen flow rate, and purging behavior. The experimental results show a nonlinear correlation between stack current and voltage as well as its efficiency of hydrogen consumption to the electricity generated. The hydrogen flow rate exhibits a linear relationship to the generated power output in normal operation, neglecting the purging flow rate. Meanwhile, the total consumed hydrogen, including purging process, performs an exponential result which indicates more hydrogen was consumed for purging. Moreover, the observed purging behavior shows that the load current affects the purging interval time in an exponential decay manner. Some possible control methods are then discussed to control the hydrogen flow that dynamically follow the load variation and enable a not-complete purge; thus, the hydrogen consumption could be optimized and the excess hydrogen during the purging could be minimized.

Keywords: PEMFC, fuel cell, hydrogen, control system, purging, electric vehicles.

1. Introduction

The impact of greenhouse gas emissions which are mostly produced by fossil fuels, has become the background for many countries and companies to switch from fossil fuels to renewable energy resources, such as solar energy, hydropower, wind energy, biomass energy, and hydrogen energy systems. Fuel cells with pure hydrogen as its fuel is one of the future energy technologies that have low carbon emissions with the only byproducts of the electrochemical reaction are water and heat. A fuel cell consists of the electrolyte membrane, anode, and cathode plate where the electrochemical reaction occurs and transforms hydrogen or methanol as chemical energy fuel into direct current (DC) electricity[1)].

Fuel cells will generate electricity as long as hydrogen supply is available. This promising technology can help accelerate the aim of achieving zero emissions. Fuel cells have a big potential to be applied in renewable-energy-based power generation. With electrolyzer, fuel cells can be operated either as grid-forming or grid-following generators to stabilize the voltage and frequency of a power grid[2,3)]. Moreover, fuel cell electric vehicles (FCEVs) have been considered as one of the primary substitutes for internal combustion engines (ICEs)[4)] and as a complementary technology of electric vehicles[5)] for achieving the target of zero emissions in the transportation sector.

There are several types of fuel cells based on their catalyst materials, i.e., alkaline, proton exchange membrane (PEM), solid oxide fuel cells, molten carbonate, and direct methanol fuel cells. PEM fuel cells (PEMFC) is a commonly used one that has a low operating temperature, fast startup capability, and high power density[6,7]. PEMFC is more likely to be used for application in the transportation sector, where currently the main market is trucks and forklifts[8], and as backup power in the telecommunication sector[9]. Moreover, even though the current investment cost of PEMFC is higher than alkaline fuel cells as it uses precious metal catalysts [10], it is projected that with the development of PEMFC in stack level, system size, and manufacturing scale, PEMFC will become cost competitive[11].

The membrane stack that composes the PEMFC consists of membrane electrode assemblies (MEA) flanked by a bipolar plate, then sealed with a gasket, and both ends are connected by a current-collecting plate[1]. Bipolar plates, which are usually made by low porosity polymer-graphite composite, have an important role in transporting reactant gasses, distributing hydrogen and air uniformly across the anodes and the cathodes, carrying the current from the electrode to the end plates, providing heat and water management, and separating the individual cells[12]. Inter-mixing or leaking of gas is prevented by a gasket seal. The current collector plate will flow electrons from the anode to the cathode through loads that are connected between them. PEMFC primarily uses water, so it has a low operating temperature (below 100°C) with an efficiency that is achievable in practice up to 50% and 60% when it uses a pure hydrogen fuel source, therefore it is ideal and applicable for powering automobiles and battery replacement[13]. The heat as nearly half of the byproduct of electrochemical reaction is also should be managed between 65°-80°C to make PEMFC optimal in its operation and have a longer lifetime[13]. Too high in temperature can dehydrate and shrink the membrane, lower the output voltage, and damage the PEMFC stacks[14].

As of late, several commercial PEMFCs include an air-cooled fuel cell stack system with various materials that combines air cooling and oxidant supply channels, which has also enhanced the heat dissipation effect, and decreased system complexity and material costs when compared to traditional water-cooled fuel cells. Several studies to improve the performance of air-cooled fuel cells have been conducted, such as by creating ultrathin bipolar plates using stainless steel sheet and metal stamping that had outstanding voltage consistency, quick temperature response, and high power density[15,16]. Also, an air-cooled PEMFC stacks with a concave-convex dual-channel bipolar plate has been proved that it could boost air velocity from 1 m/s to 1.5 m/s[17]. A dual air-cooled PEMFC stack has also demonstrated greater performance during a quick loading process, making it a dependable power source for backup and emergency power[18].

As most applications of PEMFC such as in electric vehicles (EV) need a higher power to fulfill the system requirements, a numbered cell of PEMFC must be stacked in series to get a higher total voltage and in parallel to obtain a larger total current. When hydrogen and air pressure fed to PEMFC stacks anode and cathode is higher, the kinetics reaction of electrochemical reactions increases, and those results in higher power density but lower in net power due to higher parasitic power requirement[1]. This causes a fuel cell to have a current-to-voltage polarization curve; when the cell current increases, the cell voltage will decrease. At low current density, as the current increases the voltage will drop sharply due to activation losses. At higher current density, after anode and cathode have been activated, along with the increment of cell current, the ohmic losses of the fuel cells membrane will reduce the cell voltage linearly. And as the current continues to increase and the chemical reaction inside the cell reaches its transport limit, the cell voltage decreases drastically[19,20]. Because of this polarization characteristic, a proper voltage control of the power converter that connects the fuel cell to loads or a power grid is crucial as it may cause overmodulation, oscillations, and harmonics[2].

As its load will vary during its operation, PEMFC will have to carefully manage the fuel feed following the current variations. The bigger power drawn from a fuel cell, a higher volume of hydrogen is needed. Improper hydrogen feeding control can lead to hydrogen starvation and damage to the fuel cell membrane. Moreover, during its operation, water and crossed-over nitrogen will accumulate on the anode side. This will reduce the absorption of hydrogen and cause performance degradation, which can be overcome by purging the fuel cell using hydrogen gas. Certain purging strategies should be implemented that ensure an optimal purging time and interval to prevent reducing fuel cell efficiency and wasting of hydrogen[21].

A control system of hydrogen fed in PEMFC is eventually needed to manage the hydrogen fed following the dynamic of load variation. Migliardini et al[22] have studied hydrogen feeding control for both dead-end and flow-through configurations. The flow-through control provided some advantages, such as controlling flooding phenomena, a simple purging control, air stoichiometric ratio, optimizing stack efficiency, and reducing the effect of reactant starvation during transient operation phases to fast degradation. Yean-Der Kuan used an on-chip programmable system to control PEMFC operating temperature and water management based on the investigated PEMFC purging time interval and the related characteristics[23]. Thermal control is proposed by Mahjoubi et al[24] to ensure the FC stack is operated in its optimum operating zone based on load current, stack temperature, and air stoichiometry. Yasin et al[25] proposed a dynamic integral sliding mode control to regulate and boost the output voltages of PEMFC under given load variations. Fan et al[26] demonstrated voltage-based control logic of PEMFC purging in a light-duty vehicle that it is capable of sustaining a fuel utilization of 97.84% with appropriate voltage recovery.

The amount of hydrogen consumed by a PEMFC in a dead-end mode is determined by how often the purging occurred and the flow rate as well as the pressure during the PEMFC operation and purging process. Therefore, the PEMFC performance is tested by varying its load capacity to analyze the operating parameters such as stack voltage and current, purging interval, and its hydrogen consumption. This study then evaluated the measured parameters to derive the empirical model of the considered fuel cell system. The models are derived and simulated in MATLAB. An accurate model will help to design the optimal control of a fuel cell operation. This model can be used as a reference for hydrogen feeding control to minimize the excess hydrogen during its normal operation and purging process. The detailed recorded parameters, analysis results, models, and the proposed new control configuration are presented below.

2. The Considered System and Method

2.1 PEM Fuel Cell System

In this study, the considered fuel cell system is a 1 kW PEMFC H-1000XP. The H-1000XP fuel cell stack system is an air-cooled, lightweight, and compact PEM-type fuel cell. The H-1000XP was specially developed for the SHELL Eco-marathon event[27]. This fuel cell system is designed according to the SHELL Eco-marathon rules, which only requires a start-up in the form of a 12-13V battery to start and then use its own fuel. The H-1000XP can produce a direct current of up to 33A. Its operating voltage ranges from 46V (no load) to 30V (full load). The detailed specifications of the fuel cell system are shown in Table 1. To operate the H-1000XP, a 12 or 13 VDC external power supply is required with a current higher than 4 A and hydrogen gas pressure of 0.5 bar or a flow rate of 13.5 L/min. The start-up of the H-1000XP is carried out after all hydrogen installations and the fuel cell system have been completed. These conditions should be monitored by the controller to ensure the system could operate safely.

2.2 Testing Configuration

To optimize the electrochemical reaction process in the fuel cell stack, the PEMFC should be controlled by managing appropriate parameters such as stack temperature, humidity, hydrogen, and air flow rate to prevent fuel starvation. Hydrogen and air are supplied to the stack at a specified amount and stoichiometric ratio to generate the rated power of the PEMFC system[28]. However, it is difficult to control hydrogen-air management following the variation of current and power load demands mainly in automotive applications. An improper hydrogen-air management may cause fuel starvation which can damage the fuel cell membrane and catalyst layer[29]. Hence, an efficient hydrogen-air supply management system is required to increase the efficiency of hydrogen consumption and system performance. To develop an efficient hydrogen supply control for the H-1000XP PEMFC, it is necessary to analyze the operation behaviour of the PEMFC system.

In this study, the hydrogen flow for H-1000XP PEMFC uses the dead-end mode configuration. At the hydrogen input side, there are 2 valves, i.e., manual and solenoid valves. When the system starts running, the controller will send a command to open the inlet solenoid valve. When the system stops running or if there is a gas leak detected, the controller will close this valve. The outlet solenoid valve will be opened during the purging process, which is triggered by the data of the stack's current and voltage. Meanwhile, the stack temperature data are used as the reference to control the fan. Due to the limitation of getting adequate data through the FC controller, a data logger is added to record load current and voltage, which are assumed equal to the stack current and voltage. In addition, a digital mass flow meter is installed to get the hydrogen flow rate, total consumption, and purging data. The configuration of the PEMFC H-1000XP and the additional instruments during the testing are illustrated in Fig. 1. The real apparatus of the testing system is shown in Fig. 2.

Table 1. Specifications of PEMFC H-1000XP.

Type of fuel cell	PEM
Number of cells	50
Peak power	1100W
Rated current	30V @ 33.3A
DC Voltage	25V - 48V
Reactants	Hydrogen and Air
Composition	99.999% dry H_2
H_2 pressure	7.2 – 9.4 Psi
Flow rate at rated output	13.5 L/min
Efficiency stack @1000W	48% @ 30V
External temperature	5-35°C
Max stack temperature	65°C
Humidification	Self-humidified
Cooling	Air

3. Result and Discussion

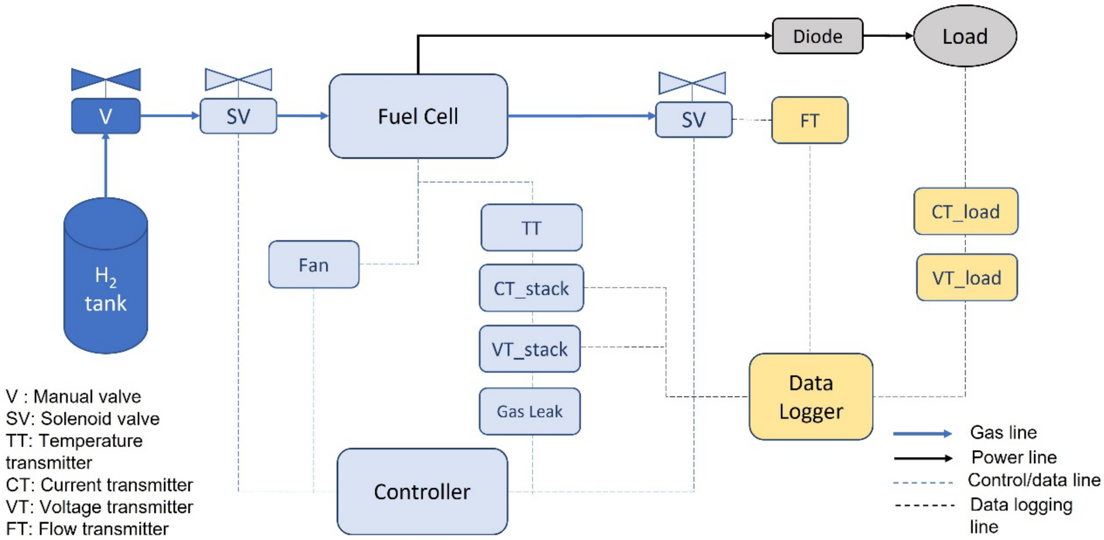

Fig. 1: Schematic of PEMFC H-1000XP testing configuration.

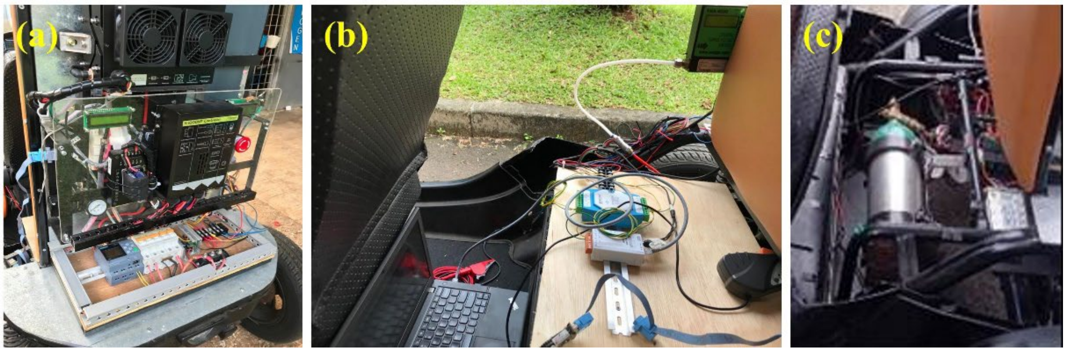

Fig. 2: (a) PEMFC H-1000XP stack, controller, fan, and controlled valves (b) flow meter and data logger, (c) pressurized hydrogen fuel tank.

The performance test of the PEMFC H-1000XP has been conducted by connecting a variable DC load to the stack. During the tests, the load current is ramped up with a step of 1 A. Then, the additional data logger will record stack current, voltage, and hydrogen flows. Because of the limitation of the equipment for the experimental data recording, the data are recorded with a time interval in seconds so that the dynamic response could not be observed. Therefore, in this paper, the steady-state models of the stack are presented.

3.1 I-V Polarization

Knowing the correlation between current and voltage of a fuel cells stack is essential. An accurate model that represents the function between I-V of a stack is crucial to analyze the performance of a fuel cells and to help in the process of designing fuel cells control. The results of the stack's test performance show that the stack voltage changes following the load variations, as shown in Fig. 3. This characteristic represents the polarization curve of the fuel cell stack. The voltage of the stack decreases as the load current is drawn from the cells increases. The voltage stack should be kept not less than the minimum load operating voltage to ensure continuous operation of the system. Therefore, the data recording stops until the stack voltage drops to 25V, as stated in its technical specification in Tabel 1, that the minimum operating voltage of PEMFC H-1000XP is 25V.

From Fig. 3 it can be seen that stack voltage drops almost linearly along with the increment of stack current. However, apparently a linear model doesn't properly fit with the I-V polarization curve of the PEMFC H-1000XP. Therefore, a nonlinear model is then derived to get a more accurate model. Figure. 4 shows the comparison of the linear and fit nonlinear model curves. The correlation between stack current and voltage as shown by the fitted nonlinear model curve in Fig. 4 is described in Eq. 1 as follow:

$$V_{stack} = a_1 + a_2 e^{a_3 I_{stack}} \quad (1)$$

where V_{stack} is the stack voltage, I_{stack} is the stack current, a_1 , a_2 and a_3 are the coefficients of the nonlinear model. Based on the test result data of the considered PEMFC H-1000XP, the value of a_1, a_2 and a_3 are 20.3623, 18.7485 and -0.0489 respectively.

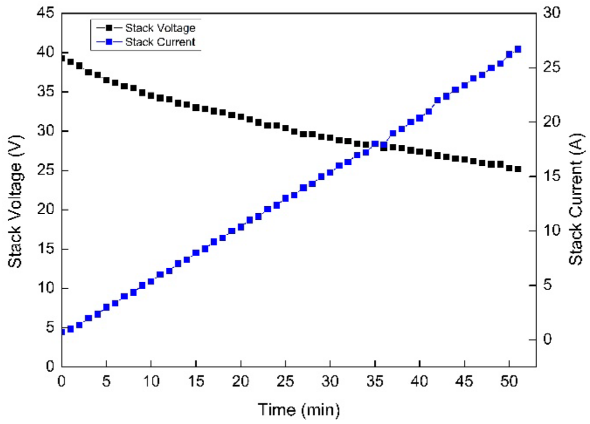

Fig. 3: Stack voltage and stack current of the H-1000XP's stack load test results.

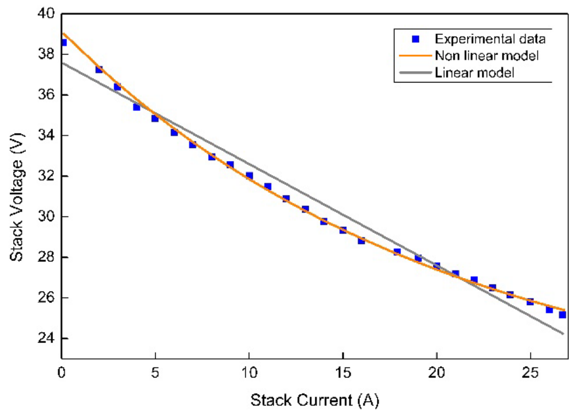

Fig. 4: Stack voltage versus stack current fitting model.

3.2 FC Efficiency

To determine FC efficiency as a system, in this study, the correlation between electrical energy supplied to the load connected to stack and the hydrogen consumed by stack is observed. During the performance tests, the stack experienced purgings with a certain pattern. The detailed purging behavior of the PEMFC H-1000XP will be covered in the next section. This study will determine two stack efficiency models. The first model only considered the hydrogen consumed during the normal operation; while the second model used the total hydrogen consumed, including hydrogen consumed during purgings. The hydrogen consumption is recorded using a mass flow meter, as shown in Fig. 2 (b).

The heating higher value (HHV) of a fuel cells is 39.4 kWh/kg hydrogen, while its lower heating value (LHV) is 33.3 kWh/kg hydrogen. Theoretically, if all the Gibs energy is converted to electricity, the maximum possible electrical efficiency of a fuel cell is 83%[30]. Meanwhile, Fig. 5 shows a linear relationship of hydrogen flow rate with power drawn from the tested 1 kW PEMFC in normal operation; the purging flow rate is neglected. From the curve shown in Fig. 5, the derived model is defined as,

$$m_{H2} = b_1 + b_2 P_{fc} \quad (2)$$

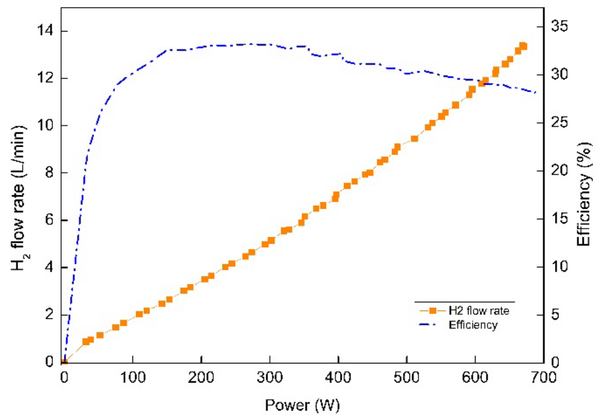

Fig. 5: Hydrogen flow rate and system efficiency as a function of power output in normal operation.

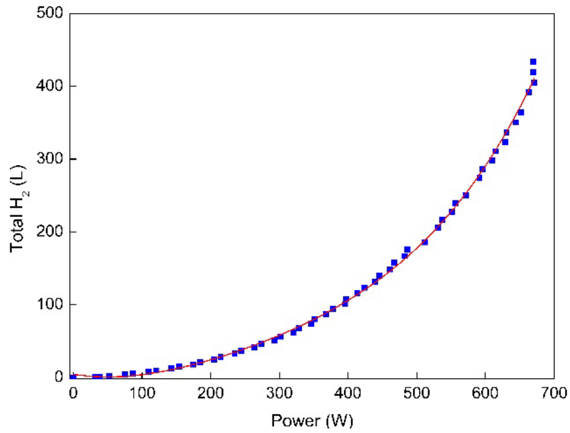

Fig. 6: Total consumed hydrogen including purging process to the generated power output and its fitting curve.

where m_{H2} is the hydrogen flowrate (L/min), $P_{fc}$is the power drawn from the PEMFC, and b_1 and b_2 are the intercept and gain of the model. The value of b_1 and b_2 are 0.6988 and 0.02122, respectively. From Eq. (2) then, we can calculate the PEMFC system efficiency. From the test result, the average efficiency of the fuel cell system is 30%, whilst the efficiency of the PEMFC system mentioned in its technical specification is 33%. Meanwhile, Fig. 6 shows the total consumed hydrogen curve, including hydrogen consumed during purging, to the generated power. From the results in Fig. 5 and Fig. 6, it indicates that fuel cell system efficiency varies depending on its operating power toward its rated power. The efficiency of the system tends to deceased near its rated power. This occurred because more hydrogen was needed for purging.

3.3 Purging Interval

Besides the polarization effect, the accumulated impurities including water in the stack also lead to voltage loss. To overcome this, a PEMFC system incorporated purging procedure at certain interval. When a higher current withdrawn from the stack, the purging interval becomes shorter as a faster chemical reaction causes a bigger amount of impurities. In addition, to improve stack durability and prevent an abnormally high start-up voltage that could damage the PEMFC stack, especially after a long period of shutdown, purging is required. In the purging process, accumulated oxygen seeps through to the anodes and mixes with hydrogen leftover from the previous operation[1]. During the performance tests, the stack experienced purgings with a particular pattern. The purging behavior is observed from the open or closed status of the outlet valve and the hydrogen flow rate recorded from the flow meter. During the purging time, the solenoid outlet valve is fully open, and the hydrogen flow rate increases significantly, as shown in Fig. 7. Due to the limitation of the instruments, the on/off duration of the valve cannot be measured in this experiment. Nevertheless, the interval time between two purging can be observed as shown in Fig. 8.

In the initiation state, there is no-load current, the purging occurs after 10 seconds. Hereafter, in the operation state, the purging frequency increases as the load current increases. Therefore, it could be ascribed that the purging process is affected by the system load. This happened because when a bigger current is drawn, a faster chemical reaction occurs inside the fuel cell so that the impurities will accumulate faster as well. Therefore, a faster purging interval is needed. From Fig. 8, the correlation between purging interval time and the load current is in the exponential decay function, and it is defined as,

$$t_{purging} = c_1 + c_2 e^{c_3 I_{load}} \quad (3)$$

where $t_{purging}$ is the purging interval (s), c_1, c_2, and c_3 are constants value of 8.117, 7.3841, and -0.00681 respectively, and I_{load} is load current (A).

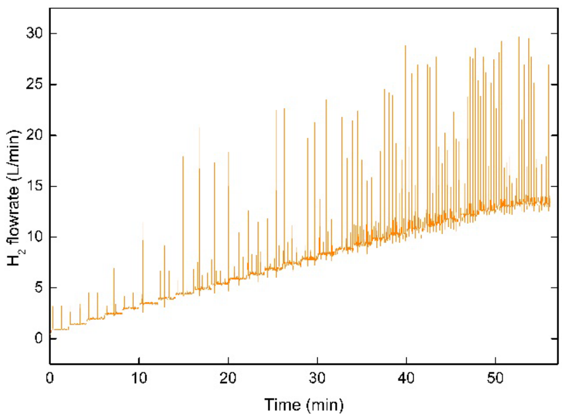

Fig. 7: Hydrogen flow rate, including purging flow rate in steady state test condition.

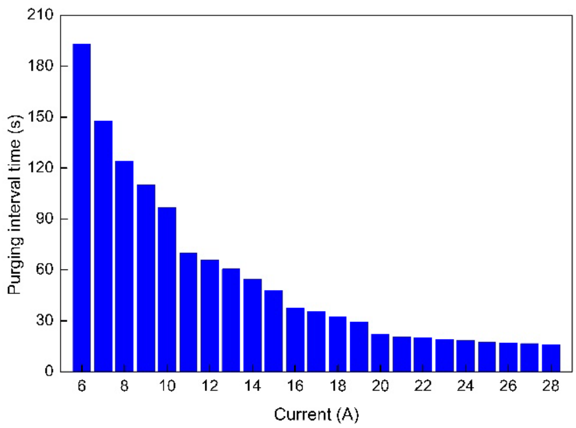

Fig. 8: Interval time between purging to the load current

3.4 Hydrogen Consumption

Performance test of the PEMFC H-1000XP in dynamic conditions is performed on a hybrid fuel cell electric car driving test. The hybrid system in terms of lithium batteries and hydrogen usage in the fuel cell[31]. The performance of the hydrogen fuel consumption is evaluated as described in Table 2. The flow of hydrogen supply, stack current and load current during the driving test are shown in Fig. 9. The stack current is the output of the fuel cell, while the load current is the accumulated output of fuel cell and battery. As explained in Fig. 1, the fuel of the existing system is controlled by solenoid valves. The on/off duration of the valve is regulated by the controller with a certain value. This existing control system has limitations in response to dynamic EV load variations, as indicated in the fluctuating load current in Fig. 9. Therefore, a more adaptive control system is required to optimize the hydrogen feeding control system.

Table 2. Performance test of PEMFC H-1000XP in dynamic conditions using hybrid fuel cell electric car.

Parameter	Value
H_2 consumption	± 27.72 L
Duration	± 23 minutes
Distance	± 2.13 km

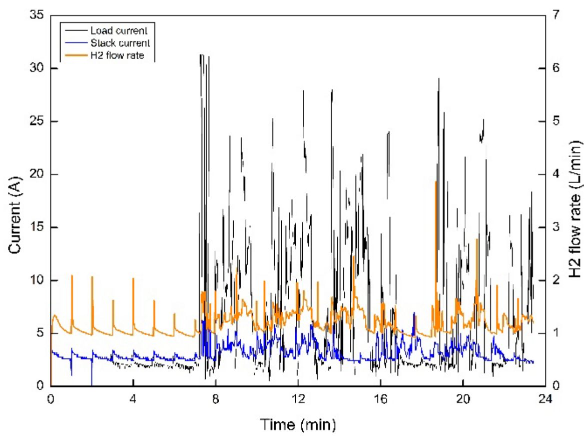

Fig. 9: Hydrogen flow rate, stack and load current of PEMFC H-1000XP testing result in dynamic test condition.

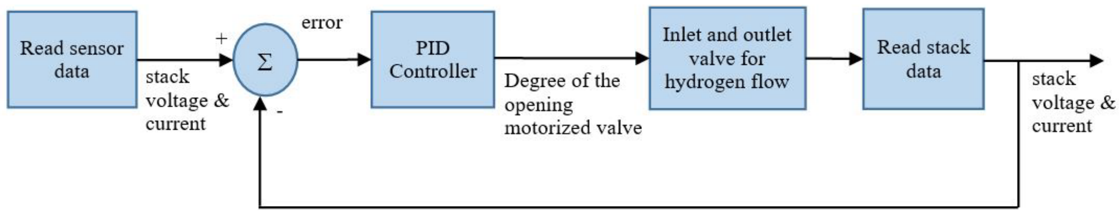

Fig. 10: Flow diagram of the control process of the hydrogen feeding control system.

3.5 Discussion

In this section, the opportunities that can be used In this section, the opportunities that can be used for further research in optimizing the operation control of PEMFC will be discussed. First, from the I-V polarization curve, the model can be used as a reference for the voltage control of the power converter that connects load to the fuel cell. For an example, in PV system application, refer to solar panel I-V curve, control methods such as PWM and MPPT are used to obtain PV optimal power.

Second, the possibility to control the flow of hydrogen to the fuel cell. A study in[32] suggested that if it is possible, reducing hydrogen loss is more important than removing nitrogen and water so a shorter purging interval can be applied as well as a not complete purge. Meanwhile, in[33], the researchers developed a linear model between relative humidity, current load, and convection to determine the purging time of PEMFC working in a closed environment and found that with the model, the time between two purges can be maximized. However, based on the test results, the existing PEMFC control shows that the correlation between stack current and purging interval time is an exponential decay function, while the correlation between stack current and the drop of voltage stack is nonlinear. Therefore, the testing result from this study can be used as a preliminary stage for research on controlling hydrogen fed of a PEMFC with a dead-end mode.

Currently, during its operation, the considered PEMFC inlet hydrogen valve is set to be fully opened at all times, while the outlet valve will be fully opened every time purging occurred. With this configuration, there will be a quite high amount of hydrogen will be wasted. On the other hand, the oxygen feeding in this considered PEMFC is not monitored and controlled as the PEMFC uses oxygen from the atmospheric air. Even though the use of pure oxygen will improve the oxygen partial pressure, but it will only increase a small magnitude of the PEMFC voltage and will increase the cost to provide oxygen tank.

Based on the test results, it can be assumed that it is possible to make a model that considers the stack current and stack voltage to determine purging cycle duration and purging interval. From the PEMFC configuration shown in Fig. 1, it is also possible to modify the inlet and outlet valve to the motorized valves to control the in-flow of hydrogen dynamically following the load variation and enable a not-complete purge to minimize hydrogen loss, thus the hydrogen consumption could be optimized and the excess hydrogen during the purging could be minimized. To optimize this hydrogen feeding control, additional pressure and humidity sensors will be applied to the new system as a reference input for the control process.

Third, a pulse width modulation (PWM) control system can be implemented to control the absorbed air flow by the fan, response to the temperature, load current and stack voltage of the PEMFC. PWM signal is used to control supplied power to the fan by switching the signal on and off at a high frequency. Thus, the fuel cell operation temperature can be effectively controlled by adjusting cooling fan operation[34].

For the next study, the hardware controller that will be used is a PLC (programmable logic control), therefore a proportional integral derivate (PID) controller will be developed to model the algorithm to control the motorized inlet and outlet hydrogen valves. PID controller is chosen as this algorithm will be implemented to a PLC hardware which is supported with library modules related to PID controller, therefore it will be easier to implement the proposed algorithm. Moreover, PID controller is easy to execute and maintain[35] and also does not need a bigger number of iterations to get a convex solution compared to stochastic methods such as genetic algorithm and PSO; thus, it is expected to get quick response control. PID controller also has been proven robust in controlling the opening degree of the fuel governor valve of a diesel generator[36].

Figure 10 shows the diagram block of the proposed PID controller implementation to control hydrogen feeding of the PEMFC stack. Figure 10 focuses only to illustrate the PID algorithm, other processes such as initial purging and gas leak detection are not shown in this diagram. The gain of P, I, and D constants of the PID controller will be determined by modeling the cooperation of the nonlinear relation between stack voltage and current and the exponential decay relation between stack current and purging interval time. The stack voltage is used as the set point of the PID controller, while the output of PID controller is the information of how many degrees the inlet and outlet hydrogen motorized valves should be opened.

4. Conclusion

This study presents the performance test of a 1 kW PEMFC with dead-end anode type and analyzes the correlation of the test parameters to determine its empirical models. The experiment is conducted by measuring the PEMFC stack's current, voltage, hydrogen flow, and purging interval under current loading rates of 0–28 A in steady-state conditions. From the measured data, it can be inferred that the correlation between load current and the drop of load voltage is in exponential function. Meanwhile, the hydrogen flow rate increases linearly along with the increment of generated power with a constant rate of change of 0.02122, in normal operations without considering the purging flow rate. However, near the rated power of the system, the efficiency of the system tends to decrease, with a maximum and average efficiency of 33% and 30%, respectively. The total consumed hydrogen, including the purging, is obtained at 433 L with power rates of 0-670 W for 50 mins duration in steady-state operations. The correlation of the total hydrogen and the generated power shows an exponential correlation, which indicates more hydrogen was consumed for purging when the current load increased. Furthermore, the test result shows that the purging interval will decrease exponentially along with the increment of current load. Based on these results, it can be ascribed that it is possible to make a model that considers the stack current and stack voltage to determine purging cycle and purging interval. Therefore, this study inferred that adaptive control, such as PID controller, is needed to control the in-flow of hydrogen dynamically following the load variation and enable a not-complete purge to minimize hydrogen loss.

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