CHAPTER 4

RESULTS AND DISCUSSION

The purpose of this chapter is to discuss the results of the fuel cell model, experiment and hybrid model system, and the comparison of the hybrid system. First part will shows the results of PEM fuel cell model under the effect of parameters in order to understand the behavior and performance of fuel cell. Then, the experiment and model of hybrid system results discussed under the load conditions. Finally, the comparison of both model and experiment of the hybrid system are presented.

4.1 Results of PEMFC Model

This section described the results of PEM fuel cell model with difference operating conditions. Performance of a single cell can be shown by the polarization curve as shown in Figure 4.1. The characteristic of polarization curve of fuel cell shows the relationship between outputs voltages of fuel cell (blue line) which is fuel cell generated with the increasing of current density. The output voltage of fuel cell is depending on parameters as explained in Equations (2.26) through (2.65). To understand the effect of parameters to output voltage of fuel cell, mathematical model of a single fuel cell has developed. Parameters that affected to output voltage are hydrogen pressure, operating temperature, transfer coefficient, exchange current density, internal resistance, and limiting current density.

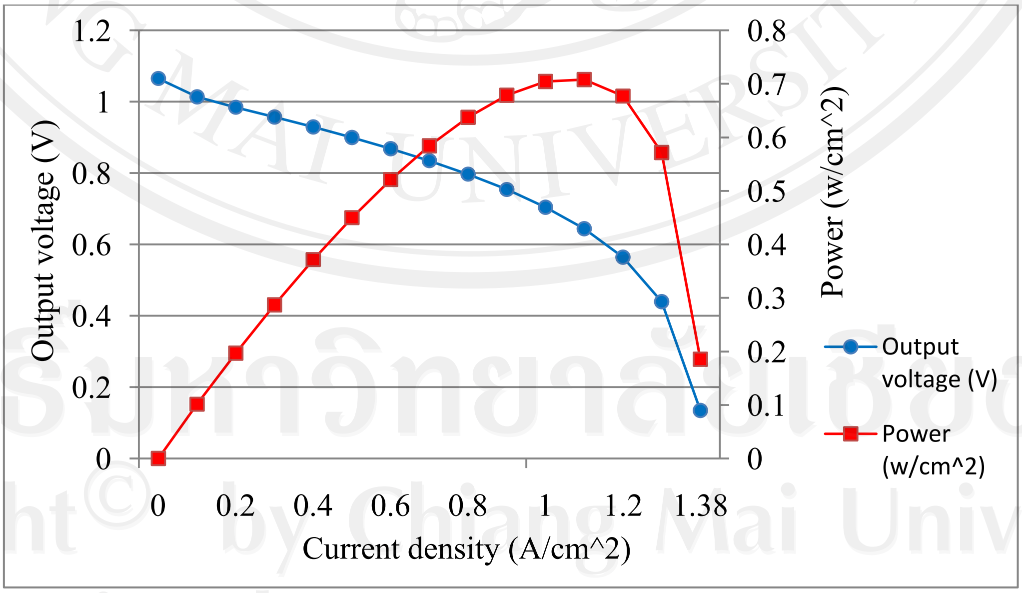


Figure 4.1 Polarization curve of single cell

Figure 4.1 shows output voltage of single cell dropped when current density is increased. In the other hand, output power of fuel cell increased when current density is increased and dropped when it reach to maximum power about 0.7 watts at 1.1 A for current density with output voltage about 0.63 voltages.

4.1.1 The effect of pressure to fuel cell output voltage

Figure 4.2 shows the effect of operating pressure on fuel cell output voltage. In this model, the operating pressures increased from 1 to 3 bars, and maintain the other parameters are constant. Output voltage of fuel cell with operating pressure 3 bars is the highest than others and average output voltage increase is 0.02V. These model results agree with Lin W., et al (2003). The performance of the fuel cell improves with the increase of pressure. The higher open circuit voltage at the higher pressure can be explained by the Nernst Equation. The overall polarization curves shift positively as the pressure increase. The model result shows agreement to the Equation (2.26) that the output voltage of fuel cell depends on operating pressure.

$$E = E_O + \frac{RT}{nF}\, ln\left(\frac{P_{H2}P_{O2}^{0.5}}{P_{H2O}}\right)$$

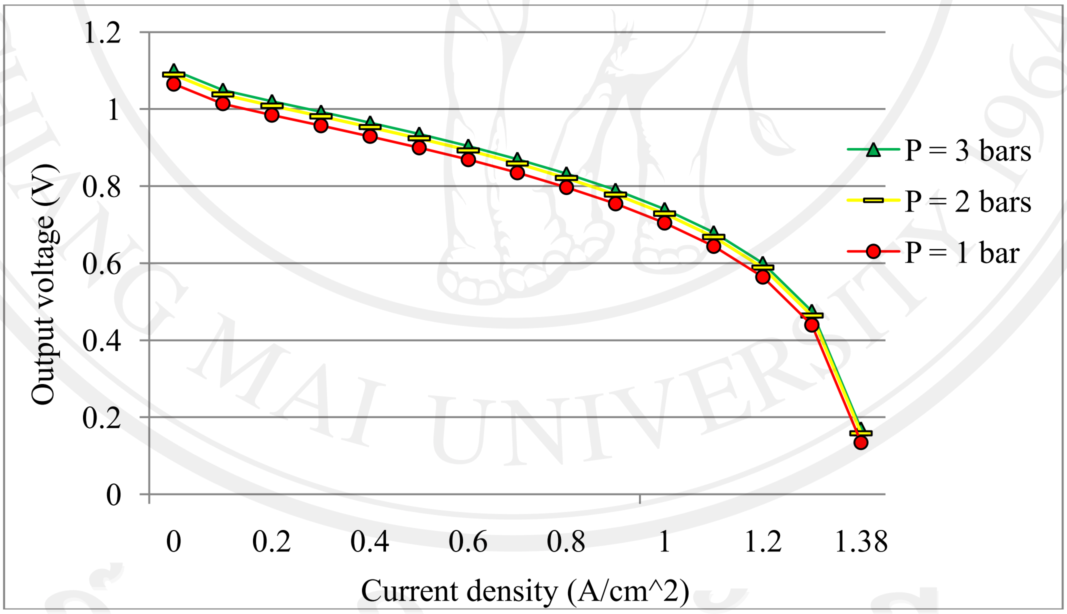


Figure 4.2 The effect of operating pressure to fuel cell output voltage

4.1.2 The effect of temperature to fuel cell potential

Fuel cell can be operated with various operating temperature. But, it must be an appropriate operating temperature range for a fuel cell. Figure 4.3 shows the result of changing operating temperature affect the fuel cell performance. This model is varied the operating temperature from 40°C to 80°C by keeping the other parameter constantly. Output voltage of fuel cell decreased when increased the operating temperature with the average 0.04V of increasing temperature 40°C to 80°C. The operation temperature affected to the water saturation temperature which is a function of cell operating temperature as shown in Equation (4.1).

$$\log_{10} P_{sat} = -2.1794 + 0.02953T_C - 9.1837e^{-5}T_C^2 + 1.4454e^{-7}T_C^3 \quad (4.1)$$

To calculate Nernst voltage, the hydrogen and oxygen partial pressure needed to determine and it is a function of water saturation temperature, operation temperature, and current density as shown by Equation (4.2) and (4.3) for partial pressure of hydrogen and oxygen, respectively.

$$p_{H2} = 0.5\left(\frac{P_{H2}}{exp^{\left(\frac{1.653\,i}{T_K^{1.334}}\right)}}\right) - P_{H2} \quad (4.2)$$

$$p_{O2} = \left(\frac{P_{air}}{exp^{\left(\frac{4.192\,i}{T_K^{1.334}}\right)}}\right) - P_{H2O} \quad (4.3)$$

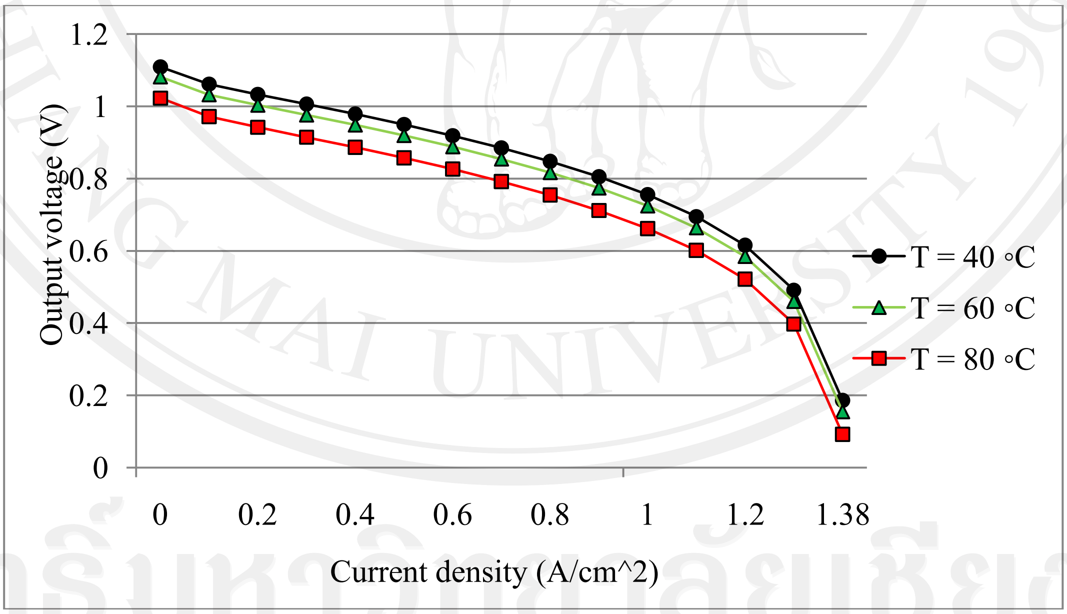


Figure 4.3 The effect of the operating temperature to fuel cell output voltage

4.1.3 The effect of transfer coefficient to fuel cell potential

The output cell voltage depends on the transfer coefficient, which is a ratio of number of electrons transferred in the overall reaction per stoichiometric number. The transfer coefficient has a strong effect on fuel cell performance as shown in Figure 4.4. The result of the model with varies the transfer coefficient from 0.2 to 1, normally the transfer coefficient is recommended at 1, (Frano Barbir, 2005). Changing of the transfer coefficient mostly affected the fuel cell performance at the initial part of the polarization curve with average output volt 0.26V increases.

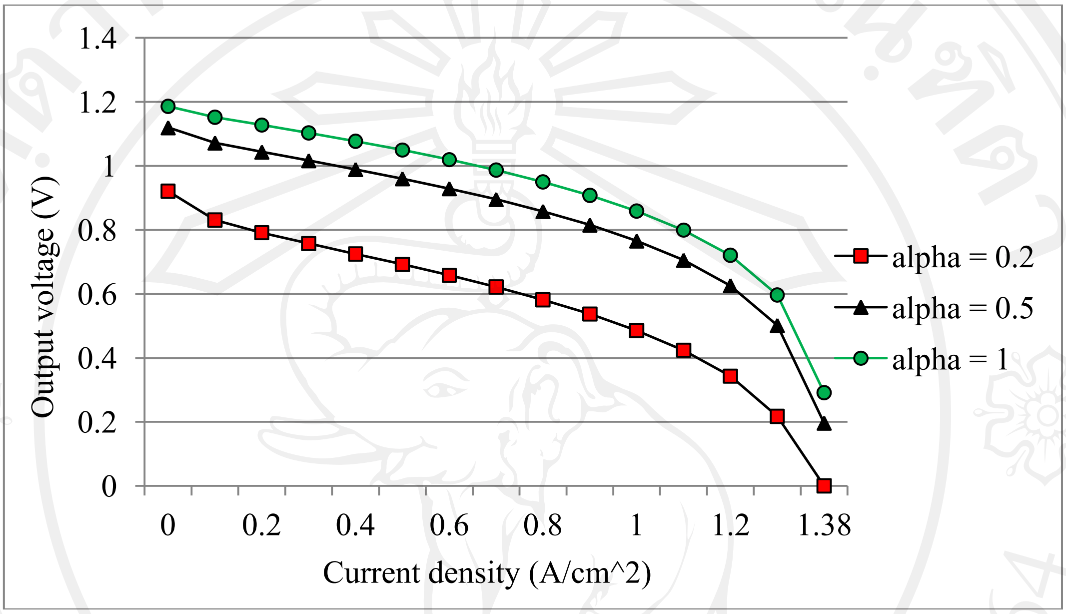


Figure 4.4 The effect of transfer coefficient to fuel cell potential at operating temperature 40°C and operating pressure at 1 bar.

4.1.4 The effect of exchange current density to fuel cell potential

Exchange current density is one of parameter which affected to the voltage losses in the system. Exchange current density is analogous to the rate constant in chemical reaction in the system. Figure 4.5 shows the output voltage of fuel cell when the exchange current density is varied. The higher the exchange current density, the lower the energy barrier that the charge must overcome moving from electrolyte to the catalyst surface and vice versa. In other words, the higher the exchange current density, the more current is generated at any over potential and the average output voltage increased 0.05V with decreasing exchange current density from $3x10^{-4}$ to $3x10^{-8}$. A/cm^2.

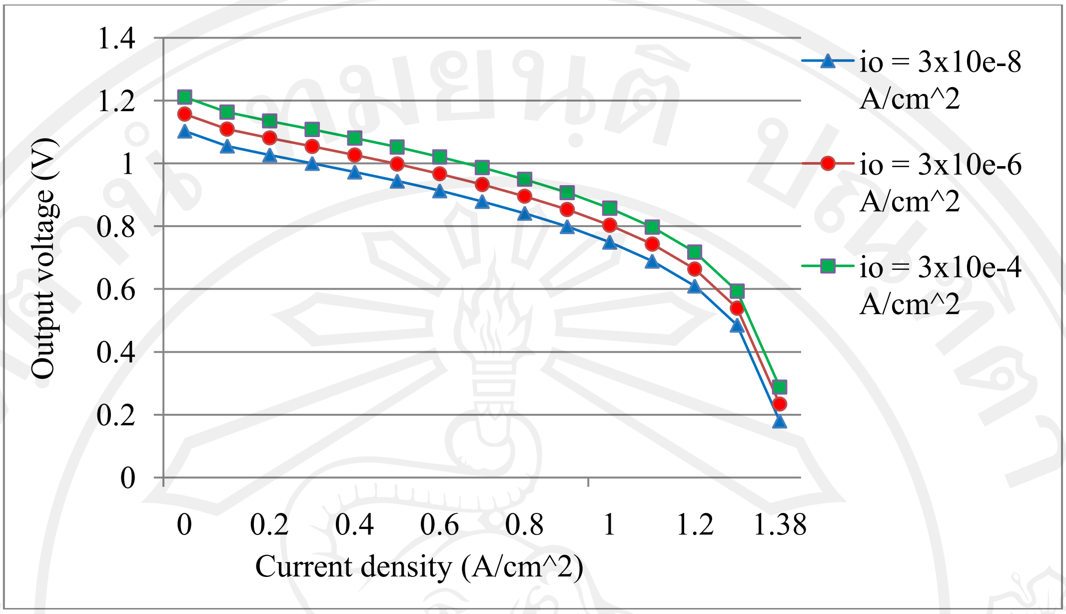


Figure 4.5 The effect of exchange current density to fuel cell potential at operating temperature 40°C and operating pressure at 1 bar.

4.1.5 The effect of internal resistance to fuel cell potential

The internal resistance is depending on graphite or graphite/polymer composites which use as conductor. The internal resistance affected the output voltage of fuel cell called ohmic losses. Ohmic losses are directly proportional to internal resistance. The ohmic losses are mostly apparent in the middle section of the polarization curve. Figure 4.6 shows the effect of internal resistance to fuel cell voltage when the internal resistance increased, the fuel cell voltage decreased. Internal resistance is material properties to induce electricity and it is a function of operating temperature. If the operating temperature is high, the internal resistance is high. The average voltage dropped when increased the resistance from 0.1 to 0.2 Ω-cm^2 is 0.03V.

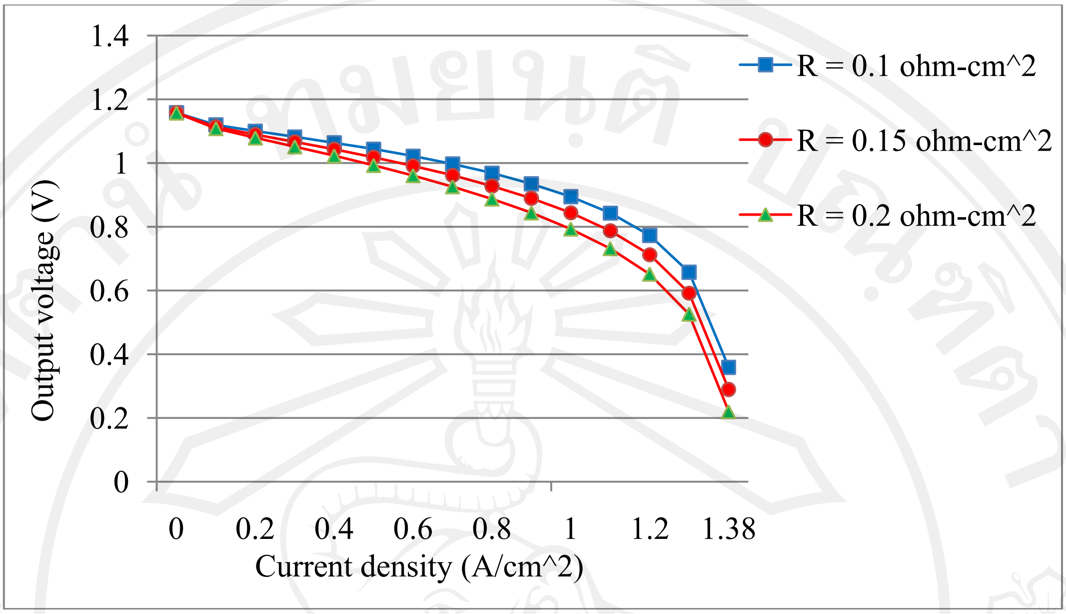


Figure 4.6 The effect of internal resistance to fuel cell potential at operating temperature 40°C and operating pressure at 1 bar.

4.1.6 The effect of limiting current density to fuel cell potential

Figure 4.7 shows the effect of limiting current density to concentration losses of the system. The concentration losses are most significant in the tail of polarization curve. Limiting current density only has an effect at very high current densities approaching the limiting current density. At low current density there is almost no effect, as shown in Figure 4.7 and the average increase output voltage is 0.10V with increases limiting current density from 1.4 to 1.7A/cm^2. Limiting current density is a maximum of fuel cell in order to generate the current density.

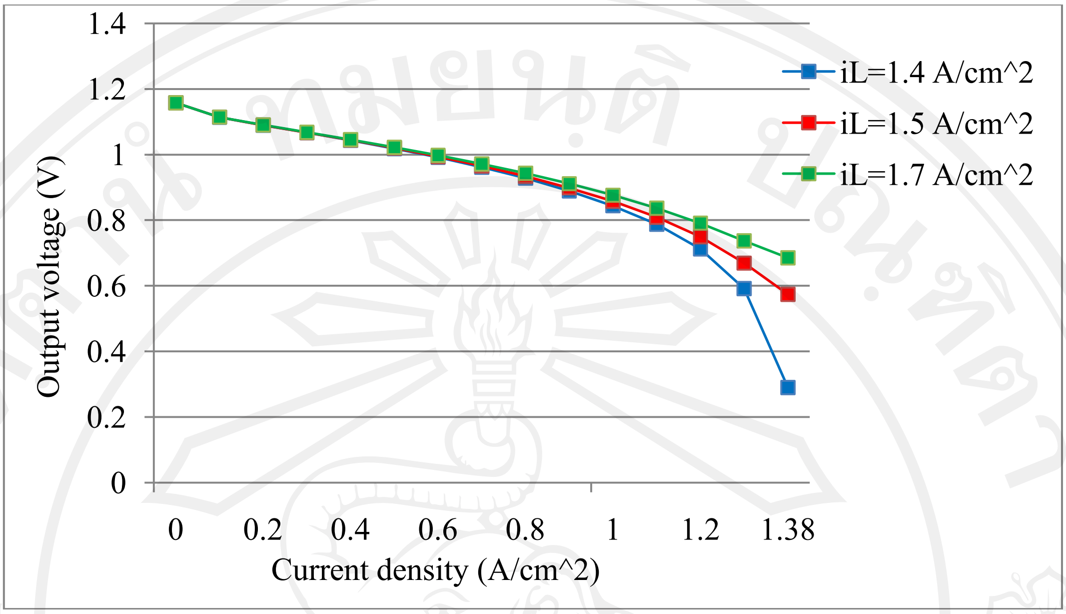


Figure 4.7 The effect of limiting current density to fuel cell potential at operating temperature 40°C and operating pressure at 1 bar.

4.1.7 The effect of load current changed to fuel cell potential

This section determines the effect of current load conditions, which affects the behavior and performance of the single cell. The characteristic output voltage of fuel cell can be expressed at any time, *t* by:

$$V(i,t) = E^0 - \Delta V_{act}(i,t) - \Delta V_{ohm}(i,t) - \Delta V_{conc}(i,t) \qquad (4.4)$$

The simulation result of a single cell with load current condition and time can be shown in Figure 4.8. Figure 4.8 shows the output voltage of fuel cell responses to load current conditions. The numerical model takes totally simulated time about 1 second in order to predict the output voltage responded to load current when it rapidly increased and dropped. The result shows that the input load current increased the output voltage of fuel cell decreased (Sampath et al, 2003). The output voltage directly responded to the changing of load current condition.

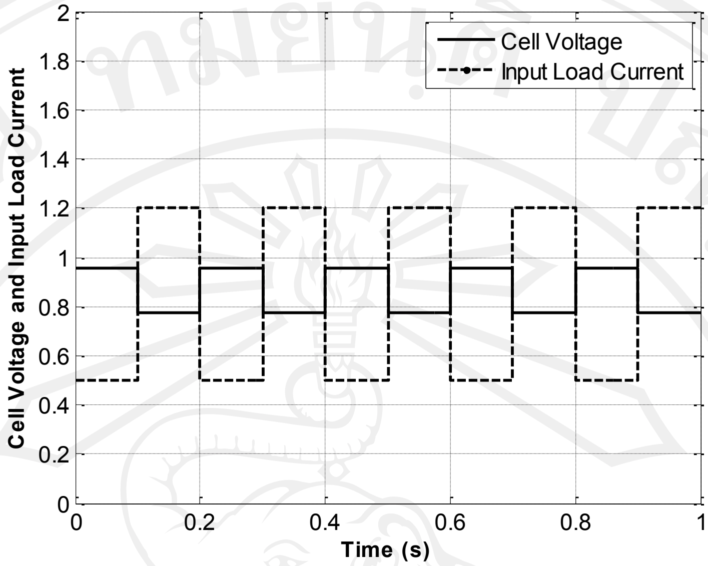


Figure 4.8 The output voltage of fuel cell changed when the load current has been changed as in step waveform

4.1.8 Sensitivity Analysis of fuel cell performance

This section analyses the sensitivity of parameters, which affects to fuel cell potential. The parameters that affect to fuel cell potential are operating pressure, operating temperature, transfer coefficient, exchange current density, internal resistance, and limiting current density. As shown in section 4.1.1 to 4.1.6. Sensitivity analysis is selected at the low, middle, and high range of current density at 0.1, 0.6, and 1.2A, respectively. Each value of parameters is varied when other parameters were held constant. Equation (4.5) uses to analyst the sensitivity of parameters.

$$P_{FC} = Ax + B \tag{4.5}$$

where P_{FC} is the fuel cell power of each current density;
x is the value of each parameters at any current density;
A and B are constant value.

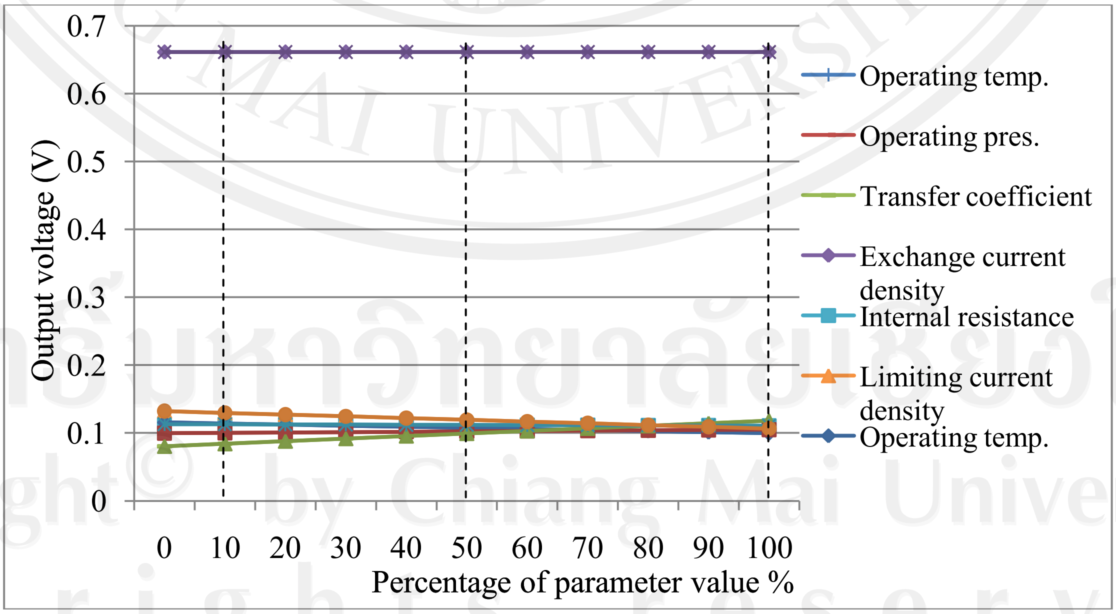
Table 4.1 shows the range of parameters for sensitivity analysis and Table 4.2 shows the A and B values of each parameter. Figure 4.9 (a), (b), and (c) show the sensitivity analysis of parameters at 0.1A, 0.6A, and 1.2A, respectively. Considering sensitivity with increasing 10% 50% and 100% of parameter value, the slope of each graph indentifies the sensitivity of parameters to fuel cell potential. At 0.1A, the transfer coefficient is the highest sensitivity to fuel cell potential at the low current density as shown in Figure 4.9 (a). This is because of the electrochemical reaction take place. Demand of current density is too low at 0.1A, but the number of electron transferred is high in overall reaction. At 0.6 and 1.2A, the internal resistance is highest sensitivity to fuel cell potential. At middle current density and high current density, the resistance of material is high with increased temperature by the reaction causes the fuel cell potential decreased as shown in Figure 4.9 (b) and (c). The second sensitivity parameter is limiting current density, which occurs at high current density.

Table 4.1 Range of parameters for sensitivity analysis.

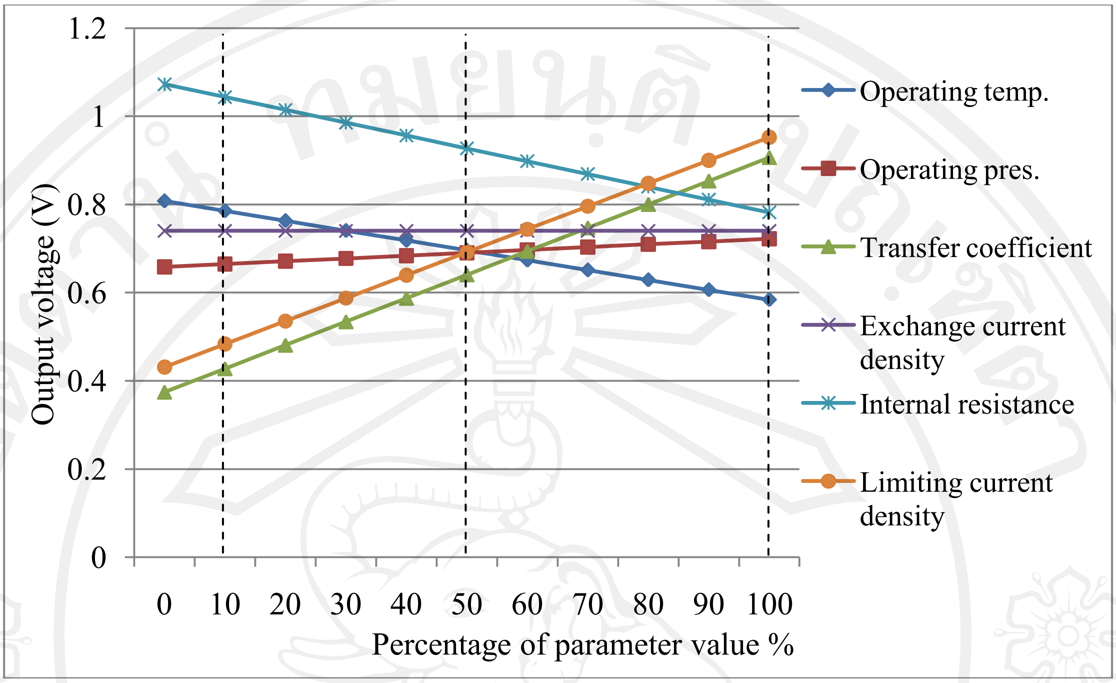
Parameters	Maximum value	Minimum value
Operating pressure (bar)	3	1
Operating temperature (℃)	80	40
Transfer coefficient (-)	1	0.2
Exchange current density (A/cm^2)	3x10^{-4}	3x10^{-8}
Internal resistance (Ω cm^2)	0.2	0.1
Limiting current density (A/cm^2)	1.7	1.4

Table 4.2 The constant value of *A* and *B* of sensitivity analysis of fuel cell potential

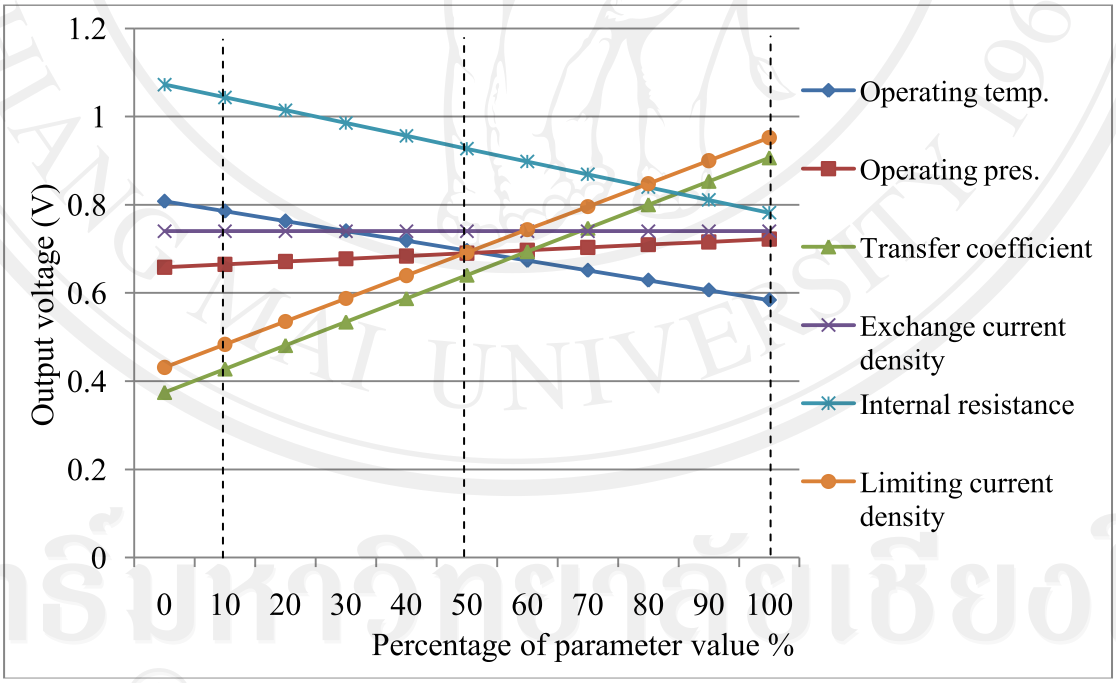
Parameters (*x*)	At 0.1 A		At 0.6 A		At 1.2 A	
	A	B	A	B	A	B
Operating pressure	0.0017	0.0998	0.0106	0.5117	0.0213	0.6584
Operating temperature	-0.0002	0.1156	-0.0013	0.6101	-0.0028	0.8079
Transfer coefficient	0.0377	0.0804	0.2544	0.3773	0.5315	0.3748
Exchange current density	-0.0053	0.6612	-0.0323	0.38819	-0.0647	0.74
Internal resistance	-0.011	0.1130	-0.366	0.6496	-1.452	1.0724
Limiting current density	-0.0151	0.1322	0.0124	0.5774	0.3063	0.4313



(a)



(b)



(c)

Figure 4.9 Sensitivity analysis of parameters affect to fuel cell potential
a) At low current density 0.1A b) At middle current density 0.6A, and
c) At high current density 1.2A

4.1.9 The hydrogen flow rate at any load current

The electrons are generated or consumed by electrochemical reactions. The current, i produced by an electrochemical reaction is a direct measure of the rate of the electrochemical reaction. The unit of current is ampere (ampere is a coulomb per second, C/s). From Faraday's law, the current can be found:

$$i = \frac{dQ}{dt} \tag{4.6}$$

where Q is the charge (C);
t is time (s).

Thus, the current described the rate of charge transfer. If each electrochemical reaction event results in the transfer of number of electrons, n. Then, the current can be calculated from:

$$i = nF\frac{dN}{dt} \tag{4.7}$$

where $\frac{dN}{dt}$ is the rate of the electrochemical reaction (mol/s);
F is Faraday's constant.

Hydrogen is treated as ideal gas and the molar flow rate is related to the volumetric flow rate via the ideal gas law:

$$\frac{dN}{dt} = \frac{P(dV/dt)}{RT} \tag{4.8}$$

where $\frac{dV}{dt}$ is the volumetric flow rate and $\frac{dN}{dt}$ at STP. (*T=298.15K, R=0.082 L.atm/mol.K, and P= 1 atm*)

If we integrate a rate, Equation (4.5), we obtain an amount of the charge.

$$\int_0^t i dt = \int_0^Q dQ \tag{4.9}$$

or
$$Q = i \cdot t \tag{4.10}$$

or
$$Q = nFN \tag{4.11}$$

The total amount of electricity produced, as measured by the accumulated charge, Q in coulombs, is proportional to the number of moles of material processed in the electrochemical reaction. The number of hydrogen mole process can be calculated:

$$N_{H2} = \frac{Q_{total}}{nF} \tag{4.12}$$

4.1.9.1 Simulation model of the relationship of hydrogen flow rate and load current conditions

Experiment of the hydrogen consumption rate to current load condition is done by tested data from the Nexa™ stack fuel cell tested with 110 cm^2 of reactant area of each cell. The time step of increasing load current and changing of hydrogen flow rate are took every 1 minute. Load current is varied from 0 to 45 A (Table 3.5). The empirical model is compared with simulation model of hydrogen flow rate at any load current as shown by (Adisorn, 2011):

$$\text{Hydrogen consumption rate, } \dot{V}_{H2} = 0.116229\left(\frac{cc}{sec}\right) \times n_{cell} \times I \tag{4.13}$$

The reactants may, and in some cases must, be supplied in excess of consumption. For example, this is always necessary on the cathode side where water is produced and must be carried out from the cell with excess flow. The ratio between the actual flow rates of a reactant at the cell inlet and the consumption rate of that reactant is called the stoichiometric ratio, *S*.

$$S = \frac{\dot{m}_{act}}{\dot{m}_{cons}} = \frac{\dot{V}_{act}}{\dot{V}_{cons}} \tag{4.14}$$

Figure 4.10 shows the comparison of hydrogen consumption rate between experiment and simulation model. In simulation, the model assumes the stoichiometric ratio, *S*=1.2, that means the actual the flow rate of a reactant at cell inlet higher that the consumption rate 120% of hydrogen utilization. The results of both simulation and experiment have the same trend increasing of hydrogen consumption rate with changing load current. Considering the exact of prediction uses the value of coefficient of determination (R^2), which can be obtained from;

$$R^2 = \frac{\sum_{i-1}^{N}\left[HC_{p,i} - HC_{ex,av}\right]^2}{\sum_{i-1}^{N}\left[HC_{ex,i} - HC_{ex,av}\right]^2} \tag{4.15}$$

where $HC_{p,i}$ is the hydrogen fuel consumption value from the prediction, $HC_{ex,av}$ is the average hydrogen fuel consumption value from experiment, and $HC_{ex,i}$ is the hydrogen fuel consumption value from experiment. Root mean square error (RMSE) is also determined by:

$$RMSE = \left[\frac{1}{N}\sum_{1}^{N}\left(HC_{p,i} - HC_{ex,i}\right)^2\right]^{1/2} \tag{4.16}$$

where *N* is the number of data collector.

The result of R^2 is 0.99 and *RMSE* is 0.2. In the real condition, hydrogen fed to Nexa™ fuel cell higher than the reaction needed. The excess or non-reaction hydrogen in the process will purge out off the fuel cell.

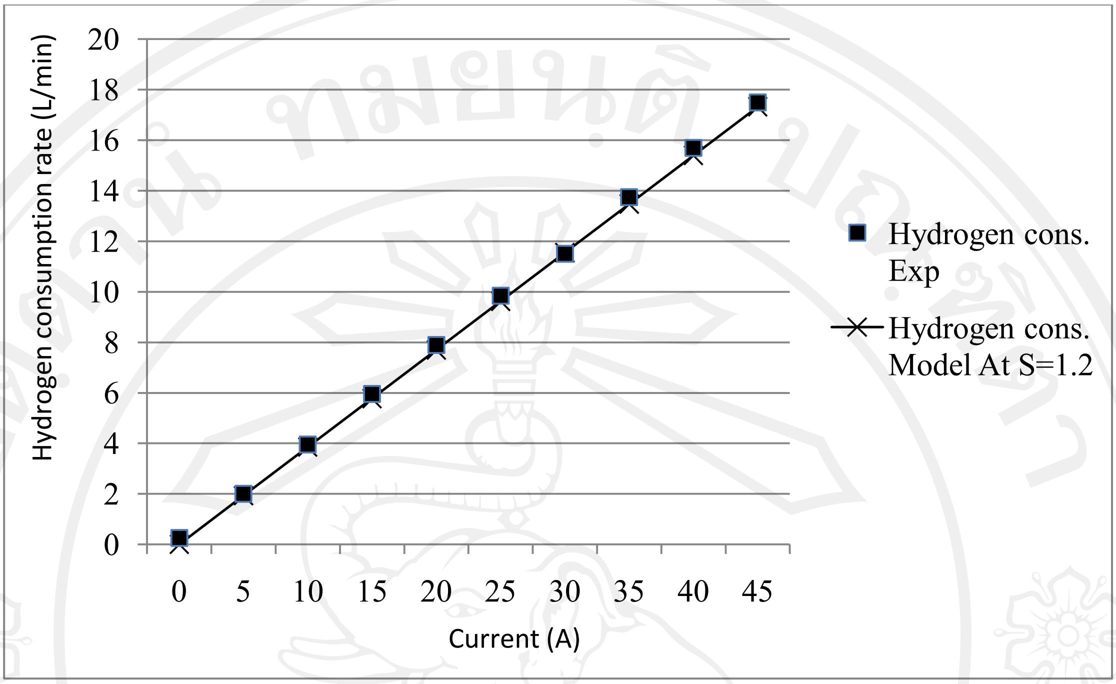


Figure 4.10 Comparison of hydrogen consumption rate at any load current

4.1.10 Verification of the simulation model

This section is to present the validation of the model with the experimental of the Nexa^{TM} fuel cell in order to verify the accuracy of the numerical model.

4.1.10.1 Verification of the fuel cell model

The verification of the fuel cell model was accomplished with the experimental of the 1200 watts Nexa^{TM} as shown in Figure 4.11. Figure 4.11 shows the comparison of the numerical model result and the experiment result of Nexa^{TM} under load conditions which varied from 0 to 46 amp with the average error 2.29% (maximum error is 4.47% at the maximum load current and minimum error is 0.78% at the minimum load current). The operating temperature is 40°C and the operating pressure is 1 bar. The numerical model which developed can be predicted the behavior of the stack fuel cell as well.

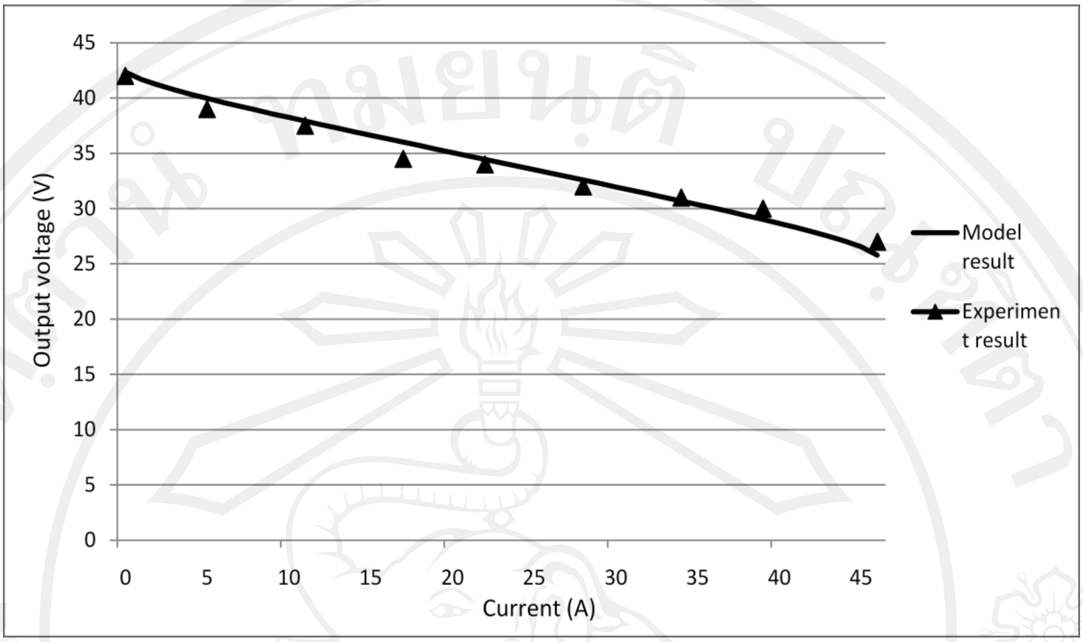


Figure 4.11 Verification results of the numerical model and experimental of a stack fuel cell Nexa™

4.2 The Experiment Results

4.2.1 The Experiment results of Fuel Cell

This section purposed the understanding the behavior of the Nexa™ fuel cell under load conditions. The test station of the fuel cell is set the operating of hydrogen pressure at 1 bar, operating temperature is an ambient temperate (28.4°C) and increased load current range from 0 to 38 A. Figure 4.12 shows the output voltage of fuel cell with increasing load current every 2 A in 120 seconds. The output voltage at each point is the average output voltage during current load constant. The result shows that during increasing at the load current range from 0 to 10 A, the output voltage of fuel cell is decreased and there is small fluctuation (because of the fuel cell system have parasitic load, such as cooling fan, solenoid valves, and air compressor etc), but after increased the load current higher than 10 A the output voltage of fuel cell is oscillations. Because of the supply of hydrogen is not enough for the reaction and it may contain some inert gases that the hydrogen cannot contact to the active surface of the membrane and the system has to supply power to parasitic loads also. Stack fuel cell system has been designed to purge cell in order to release the inert gases and refill pure hydrogen into the system. So, the output voltage of the fuel cell fluctuation is expectedwhen the reaction occurred. Another cause of this behavior is flooding in the system, (Nirunsin, 2011), which occurred at high load current. The cell voltage increased when the purge cell is operated and open a solenoid valve to purge gases and induce pure hydrogen to the system. At high load current gave high fluctuation of the output voltage.

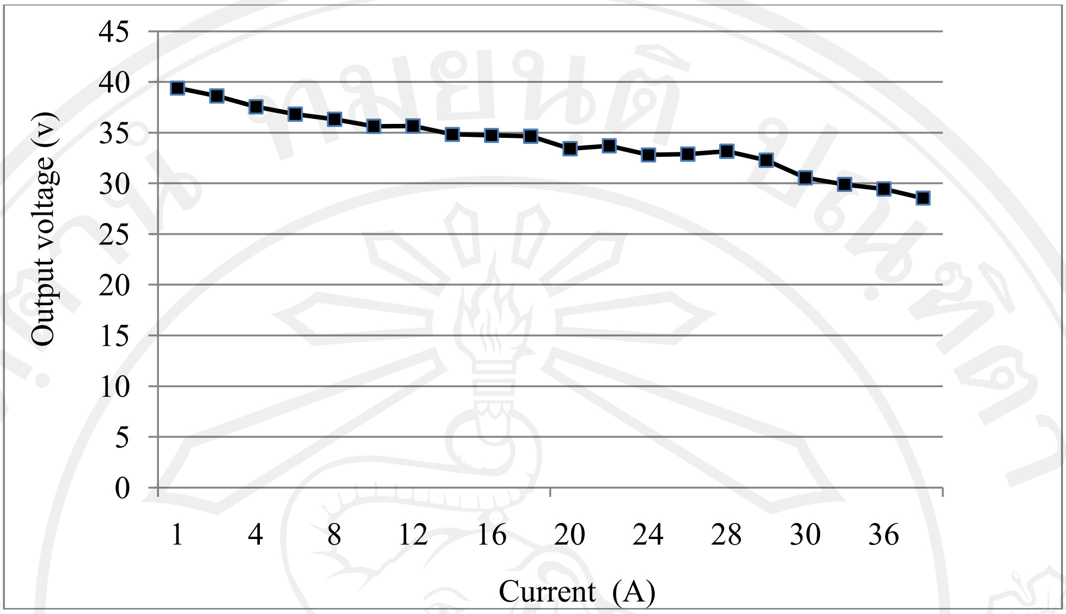


Figure 4.12 Stack cell output voltage with operating pressure of hydrogen at 1 bar under load current conditions

Figure 4.13 shows the comparison of increasing of hydrogen pressure from 1 bar to 3 bars at the load conditions. The results of the output voltage of fuel cell are the same trend with the output voltage at 1 bar as shown in Figure 4.12. From these results, the output voltage of stack fuel cell at 1 bar, 2 bars and 3 bars have the same trend during 10 seconds. The output voltage decreased with increased current loads. The output voltages did not have must fluctuation, but, after increased more currents, the fluctuation is significant. The fluctuation is occurred as the reason water flooding in the stack cell, parasitic load with increased the cooling fan speed, and solenoid valves for purge cell. The output voltage dropped when increased the load current. But, at the high load current, the output voltages fluctuate and the difference of fluctuation range of output voltage from 2 to 8 voltages. This phenomena of voltage fluctuate may damage electronic equipments. To avoid this problem, the voltage regulator needed in order to keep the output voltage stable. The DC/DC converter is used in this experiment. The input voltage of DC/DC is the range from 19 to 72VDC with 89% efficiency. The output DC voltage range is 23-30 VDC with 40A. This research is focused on the application of the hybrid system on electronic device with 24 VDC.

Figure 4.14 shows the comparison of stack fuel cell temperature which operated at difference operating pressure from 1 to 3 bars. Stack cell temperature increased continuously from ambient temperature with increased load current until the stack cell temperature reached 65^{O}C. The unit control system started the cooling fan and increase speed in order to cooling the stack cell not over this point. It is the limiting operation temperature of the system. Stack cell temperature depended on increasing of load current. At high load current, the system needed high hydrogen and oxygen to reaction in order to generate enough power to supply load.

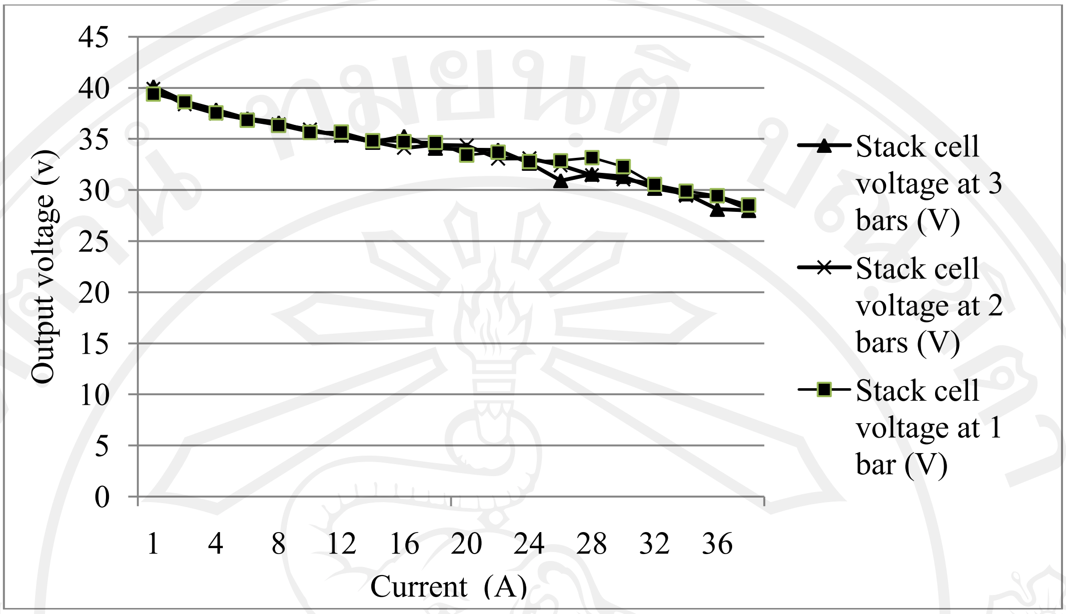


Figure 4.13 Stack cell output voltage with operating pressure of hydrogen at 1, 2 and 3 bars under load current changed

Figure 4,15 shows the comparison of hydrogen fuel consumptions with varied fuel pressure of the fuel cell under load conditions. The hydrogen fuel consumption is measured in liter per minute. The results show that hydrogen fuel consumption with different operating pressure is almost the same with any load conditions as shown in Table 4.3, and simulation model of fuel consumption can be expressed:

$$\dot{V}_{H2} = ai^2 + bi + c \qquad (4.17)$$

where *a, b,* and *c* are the constant value from experiment:

a = -0.004744,
b = 0.424857, and
c = 0.74968
i is the load current (A);
$\dot{V}_{H2}$ is hydrogen consumption rate (L/min)

Table 4.3 The R^2 and *RMSE* of the hydrogen consumption rate at difference operating pressure under load conditions.

	H_2 at 1 bar	H_2 at 2 bars	H_2 at 3 bars
R^2	0.98	0.98	1
RMSE	0.017	0.019	0.020

Simulation model as shown in Figure 4.16 can predict the hydrogen consumption rate at any load condition and operating pressure. The results show the agreement of simulationresult with experiment.

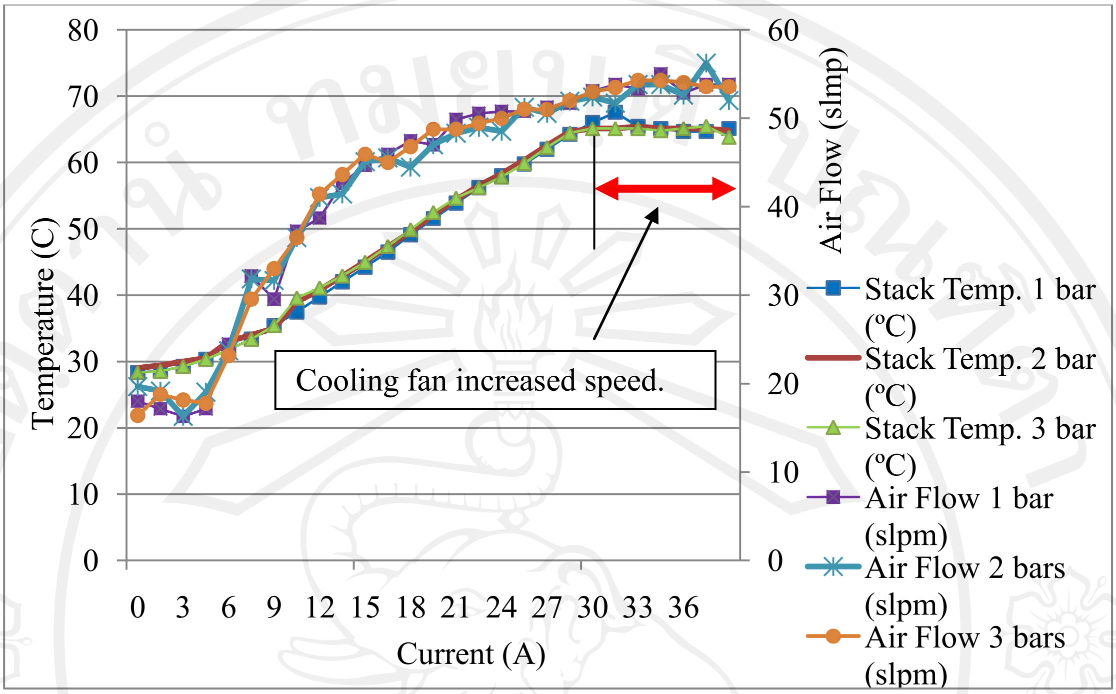


Figure 4.14 Temperature of stack fuel cell with operating pressure of hydrogen at 1 to 3 bars and air flow under load current conditions

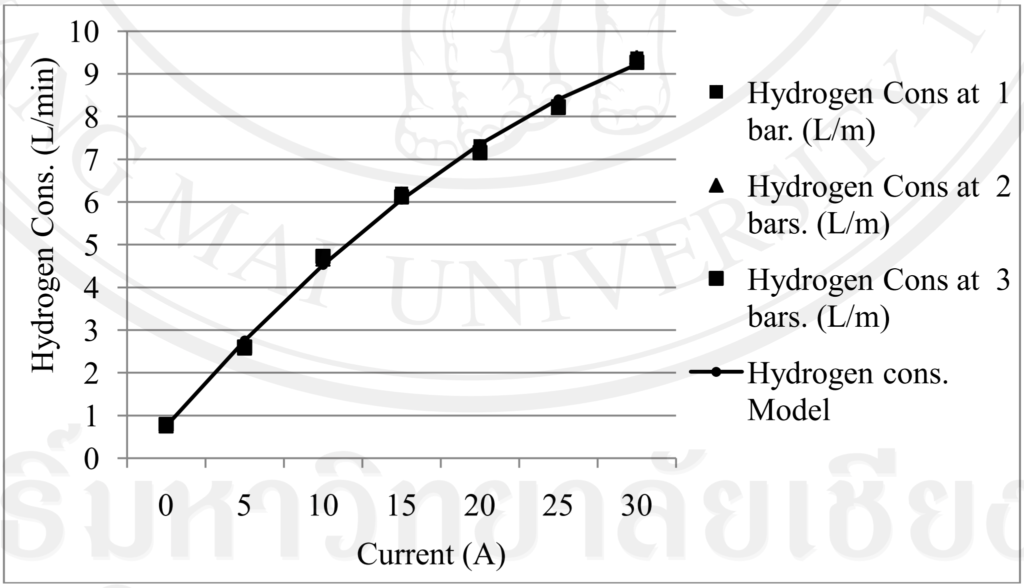


Figure 4.15 Comparison of hydrogen consumptions with operating pressure changing from 1 to 3 bars under load current conditions

That means the fuel cell system is designed to control the hydrogen flow rate at constant flow rate whatever the operating pressure changed. The fuel consumption is varied with the current only.

Another parastic load which affected to output voltage of fuel cell is soleniod valve, which controlled by purge cell voltage. Purge cell voltage is a define voltage for soleniod valve, which controlled the input of hydrogen and release the inert gases out off the system during the operation. Figure 4.16 shows the relationship of the between purge cell voltage (black line) and output voltage of fuel cell (red line). Increasing load current cause the output voltage of the fuel cell dropped as shown in the previous section. The first part of the increasing low load current (at the left hand side of graph), the output voltage is gradually dropped and the time of purge cell voltage operate is widely followed with the time of voltage droping. Whenver the increasing load current high, the output voltage of the system is high cause the frequency of purge cell voltage operate is high in order to open soleniod valve to release the inert gases and drive water out off the system and supply pure hydrogen to the system.

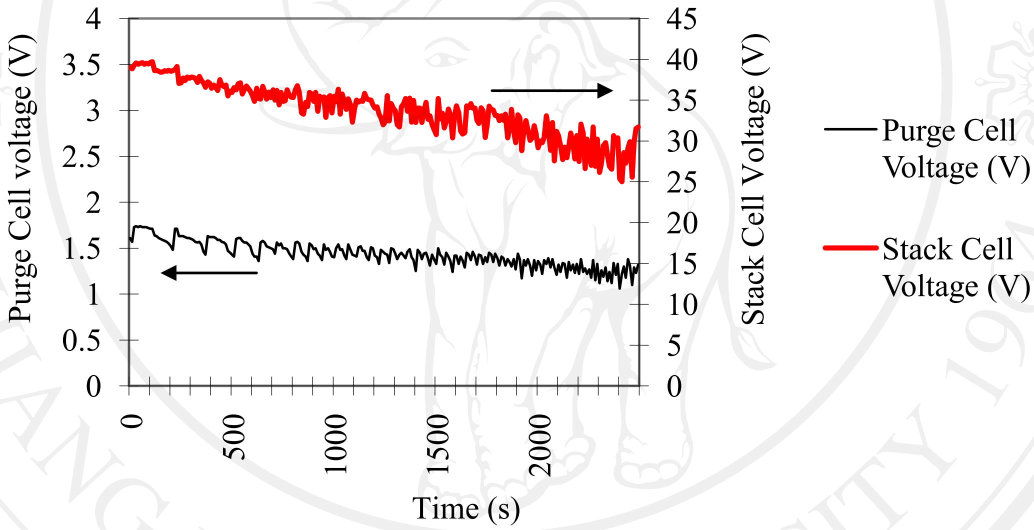


Figure 4.16 The relationship of purge cell voltage and the increasing of output voltage of stack fuel cell

4.2.2 The Experiment Results of Hybrid System

This section presents the experimental results of hybrid system. The output voltage of fuel cell and electric generator are controlled to 24 VDC in order to combine two power sources to gether with the same output voltage. The experiment is setup to study the behavior of hybrid system in three difference cases. The first and second cases are the switching operation. First case, fuel cell operates as the main power source untill the load power is higher that the set point, (in this case, 5% higher or lower than set point.) electric generator is connected to the system and fuel cell is disconnected. Second, an electric generator operates as main power source and it will be switched to fuel cell power source whenever the load power is higher than the set point. Third, both of fuel cell and electric generator work together as a hybrid power source to supply the electronic load.

4.2.2.1 Switching case 1: Fuel cell is the main power source

Figure 4.17 and 4.18 show the switching cases results of first case. The fuel cell (blue line) is operated as the main power source at 200 watts and gasoline generator (red line) will be operated when the load power (green line) higher than 200 watts. The sampling time is 5 seconds. The result shows that the system is able to work appropriately and can supply the load power condition as well. For the first 60 seconds, the fuel cell is worked and supplied the load power at 200 watts untill the load power increaed higher than the setpoint (5% of setpoint or 210 watts), then the controll unit will send the signal to start the engine, it took at least (average) 4 seconds to initiate the power from gasoline generator to ready to supply the load power, then the controller connects the generator to the system and disconnect the fuel cell from the system. During this time, fuel cell still supplies the load power for 4 seconds before it is disconnected. Then, gasoline generator supplied the load power. After 120 minutes, the load power dropped from 240 watts to120 watts. When the load power dropped less than the set point, controller will send the signal to start the fuel cell, it take an average time 3 seconds to ready and has enough power to supply load. So that, gasoline generator still supplied load power for more 3seconds before it is disconnected and let the fuel cell supply load power.

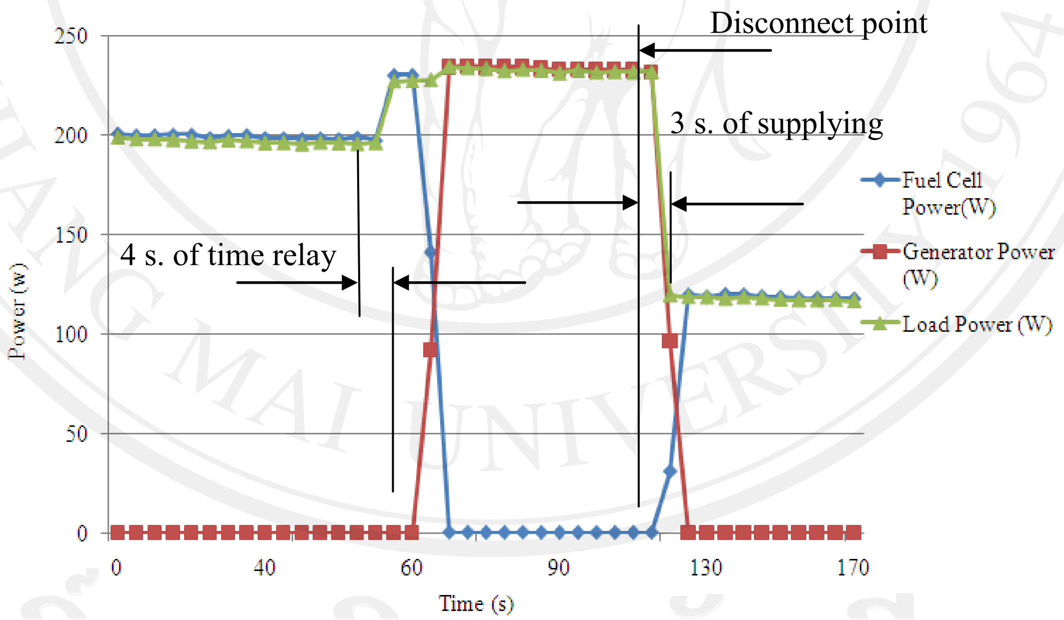


Figure 4.17 The power of both fuel cell and gasoline generator with the load power conditions in the first case of fuel cell operates as the main power source and gasoline generator work as add-on power source with set point at 210 watts

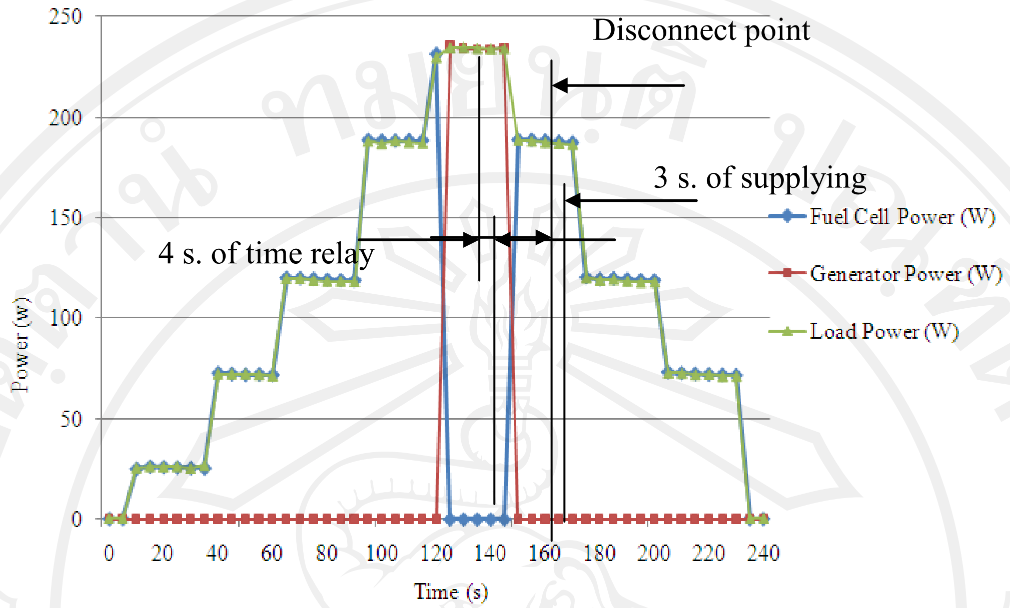


Figure 4.18 The power of both fuel cell and gasoline generator with the load power conditions in the first case of fuel cell operates as the main power source and gasoline generator work as add-on power source

4.2.2.2 Switching case 2: Gasoline generator is the main power source

Figure 4.19 shows the results of the second case, the gasoline generator is woked as the main power source at 200 watts and fuel cell will be operated when the load power exceeded 200 watts. The sampling time is 5 second. The result shows that the system is able to work appropriately and can supply the load power condition as well. For the first 60 seconds, the gasoline generator is worked and supplied the load power at 200 watts untill the load power increaed higher than the setpoint (5% of setpoint or 210 watts), then the control unit will send the signal to initiate the fuel cell. It took 3 seconds of average time to start fuel cell and ready to supply power. So that, gasoline generator still supply load power atlease for 3 seconds before the system is disconnect and connect fuel cell to the system. After 120 minutes of running time, the load power dropped from 240 watts to120 watts. When the load power dropped less than the set point, controller will send the signal to start gasoline generator, it take an average time 4 seconds to ready and has enough power to supply load. So that, fuel cell still supplied load power for more 4 seconds before it is disconnected and let the gasoline generator supply load power. It shows that the fuel cell and gasoline generator quickly responded to load conditions with time relay least than 5 seconds. It shows that both of fuel cell and gasoline generator can be work as main power source or add-on power source in case one system power source is fail. Figure 4.20 shows the result of switching case 2with gasoline generator worked as the main power source same as previous operation, but difference step operation. The set point of this test is 180 watts. There is some voltage difference at the operation time of fuel cell. Fuel cell can supply higher power than load power. Becaurse of some power of fuel cell have to supply the electronic device which connected in the control unit system, such as volt meter, amp meter, and etc. After that decrease the load power suddenly, the fuel cell is disconnected and asoline generator is connect and supplied load power. The results of thses study is to show the power responding of both fuel cell and gasoline generator to load conditions.

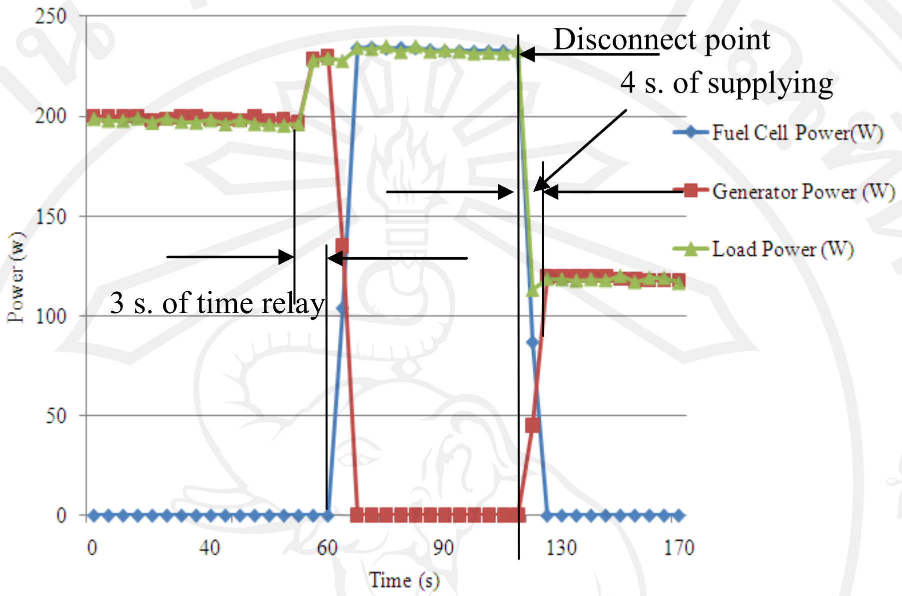


Figure 4.19 The power of both fuel cell and gasoline generator with the load power conditions in the case of gasoline generator operates as the main power source and fuel cell work as add-on power source with set point at 210 watts

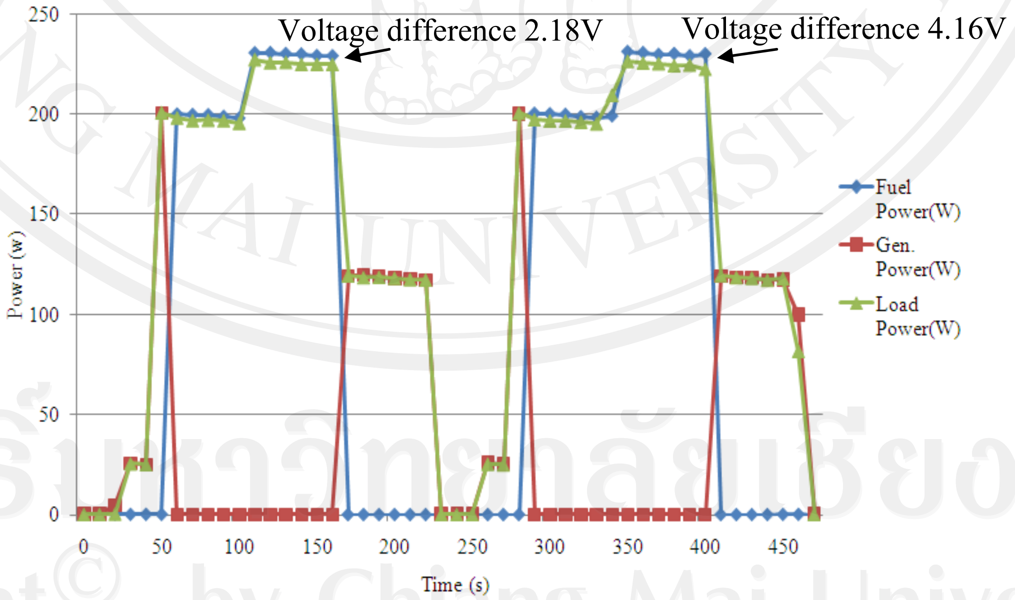


Figure 4.20 The power of both fuel cell and gasoline generator with the load power conditions in the case of gasoline generator operates as the main power source and fuel cell work as add-on power source with set point at 180 watts

4.2.2.3 Hybrid case 3: Fuel cell and Gasoline generator supply to load power

Figure 4.21 shows the result of the third case that fuel cell and gasoline generator both supplied power to load power. The set point of this test is set to 260 watts. First, the fuel cell supplied the load power with stepup from 0 untill it reach to set point. The results show that fuel cell can supply stepup of load power very well untill load power above set point. Control unit detected and sent the signal to start gasoline generator, it take 4 seconds for average time to reach power that can be supply load power. Then, control unit will connect gasoline generator to the system while fuel cell is operating. Both of power source shared the load power with fuel cell supplied 158.86 watts and gasoline generator supplied 190.35 watts of full load power at 340.93 watts. From the experiment, fuel cell works 46.59% of full load. This can be clearly understand that on the line connection of fuel cell system there is power resistant higher that line connection of gasoline generrator.

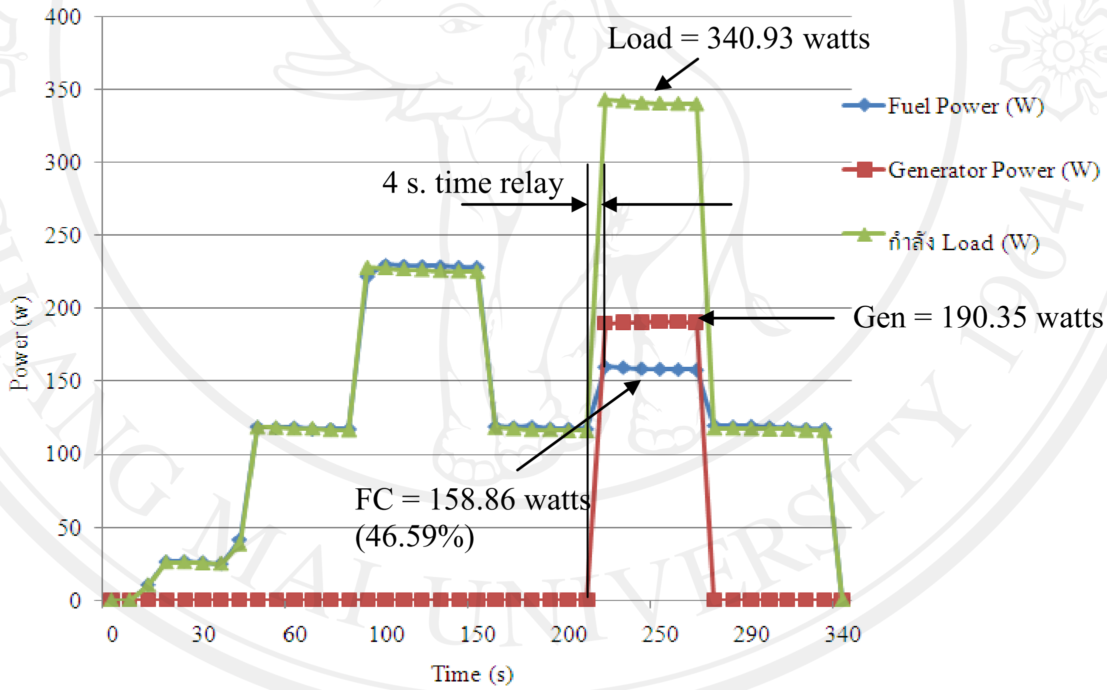


Figure 4.21 Third case of hybrid system to power load conditions: Fuel cell works as the main power source

Figure 4.22 shows the result of third case that fuel cell and gasoline generator supplied power to load power. The set point of this test is set to 260 watts. First, the gasoline generator supplied the load power with stepup from 0 untill it reach to set point. The results show that gasoline generator can supply stepup of load power very well untill load power above set point. Control unit detected and sent the signal to start fuel cell, it take 3 seconds for average time to reach power that can be supply load power. Then, control unit will connect fuel cell to the system while gasoline generator is operating. Both of power source shared the load power with fuel cell supplied 156.8 watts and gasoline generator supplied 192.82 watts of full load power at 341.08 watts. From the experiment, fuel cell works 45.97% of full load. This can be clearly understand that on the line connection of fuel cell system there is power resistant higher that line connection of gasoline genrerator same as last tested.

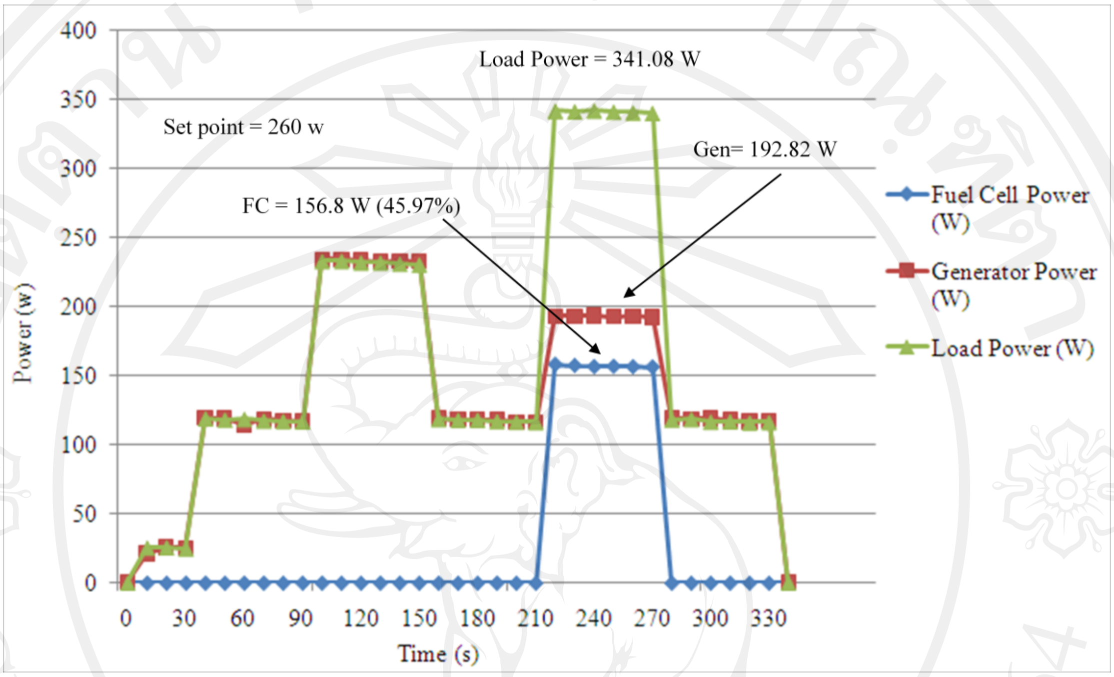


Figure 4.22 Third case of hybrid system to power load conditions: Gasoline generator works as the main power.

The difference of the power between fuel cell and electric generator output occurred from specific characteristic of electronic equipments which used inside the DC/DC converter and AC/DC converter. From the experiment of the hybrid power responds to load conditions. In both case of the hybrid system has the fuel cell or generator stand alone or together to supply the load power can be determined the operation strategy at appropriate performance of the hybrid system in the next section.

4.2.3 The Experiment results of fuel consumption of gasoline generator

This section presents the relationship of the load power and fuel consumption of the gasoline fuel used for electric generator as shown in Figure 4.23

$$y = (0.000314x) + 0.49763 \tag{4.18}$$

where y denote the gasoline fuel uses during the specific time, and x denote the load power which applied to the system in w-hr

Considering the exact of prediction uses the value of coefficient of determination (R^2) which can be determined;

$$R^2 = \frac{\sum_{i-1}^{N}[GC_{p,i} - GC_{ex,av}]^2}{\sum_{i-1}^{N}[GC_{ex,i} - GC_{ex,av}]^2} \quad (4.19)$$

where $GC_{p,i}$ is the gasoline fuel consumption value from the prediction, $GC_{ex,av}$ is the average gasoline fuel consumption value from experiment, and $GC_{ex,i}$ is the gasoline fuel consumption value from experiment

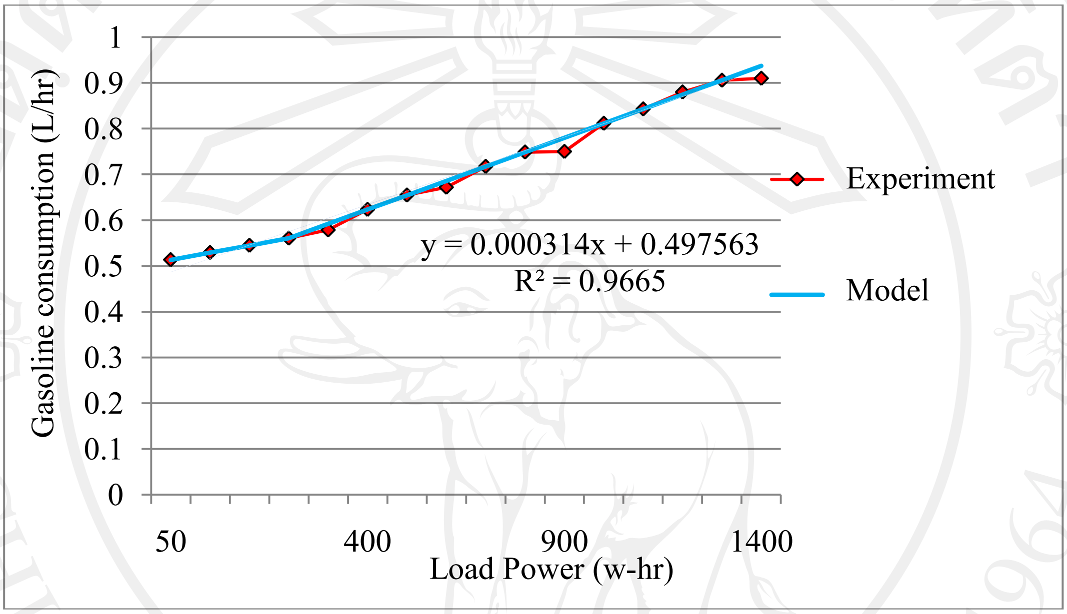


Figure 4.23 Relationship between load power and fuel consumption of gasoline fuel

4.3 The Simulation Model Results of Hybrid System

The simulation model of the hybrid system is developed and tested following in Chapter 3. First case study; fuel cell operates as the main power sourceand electric generator work as add-on power source. Second case study; the electric generator operates as main power source with fuel cell work as add-on power source. Third case study; both of fuel cell and electric generator work together as a hybrid power source to supply the electronic load.

4.3.1 The 1st case simulation model results

Figure 4.24 and 4.25 show the result of simulation model of switching case 1: Fuel cell operates as the main power source. The operation of fuel cell (red line) starts at 200 watts with the set point of the system above 200 watts that let the system disconnect fuel cell out off the system. Load power (blue line) starts from 200 watts constant and stepup at 60 seconds to 240 watts for 30 seconds, and then, step down to 120 watts. First operation, fuel cell can supply the load power very well. When the load changed over 200 watts, the system will disconnect fuel cell out off the system and conncet gasoline generator (green line) to the system. In the simulation model, the system resistance is set to 0.001Ω along both system line connect of fuel cell and gasoline generator.

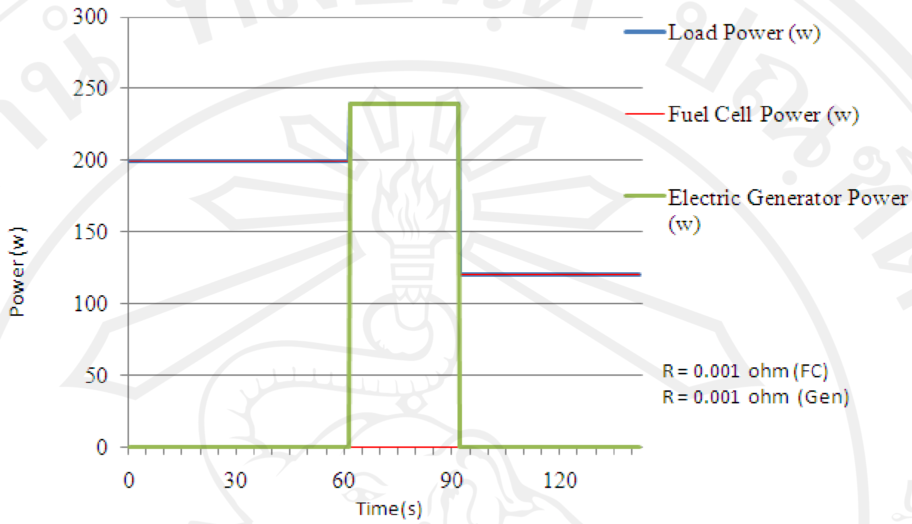


Figure 4.24 Switching case 1: Fuel cell operates at the main power source with the set point at 210 watts

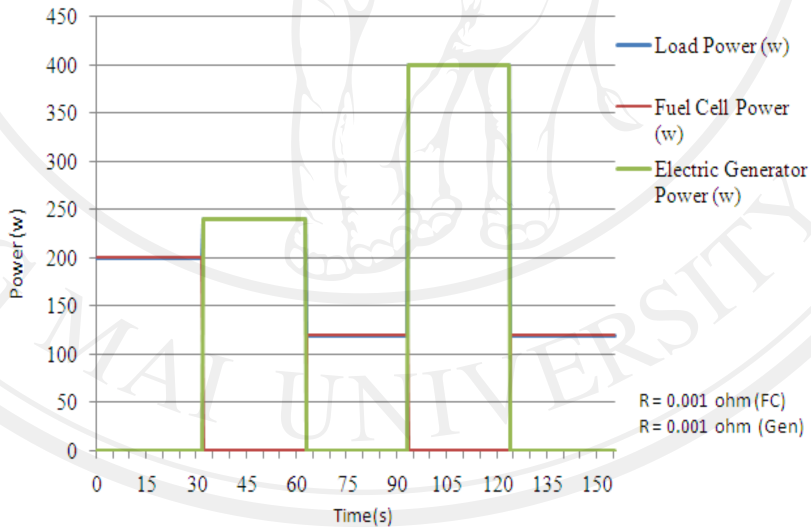


Figure 4.25 Switching case 1: Fuel cell operates at the main power source with the set point at 210 watts and operate at 400 watts maximum

4.3.2 The 2nd case simulation model results

Figure 4.26 and 4.27 show the result of simulation model of switching case 2: Gasoline generator operates as the main power source. The operation gasoline generator (green line) starts at 200 watts with the set point of the system above 200 watts that let the system disconnect gasoline generator out off the system. Load power (blue line) starts from 200 watts constant and stepup at 60 seconds to 240 watts for 30 seconds, and then, step down to 120 watts. First operation, gasoline generator can supply the load power verry well. When the load changed over 200 watts, the system will disconnect gasoline generator out off the system and conncet fuel cell (red line) to the system. In the simulation model, the system resistance is set to 0.001Ω along both system line connect of fuel cell and gasoline generator. The results show that the system response to the step load change very well. The simulation is designed to switch on-off of both fuel cell or gasoline generator when the load power changed.

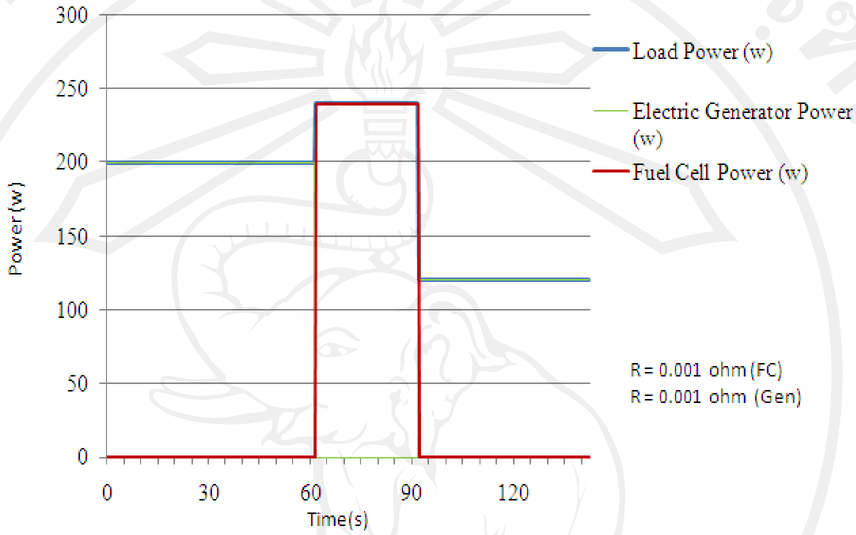


Figure 4.26 Switching case 2: Gasoline generator operates at the main power source with the set point at 210 watts

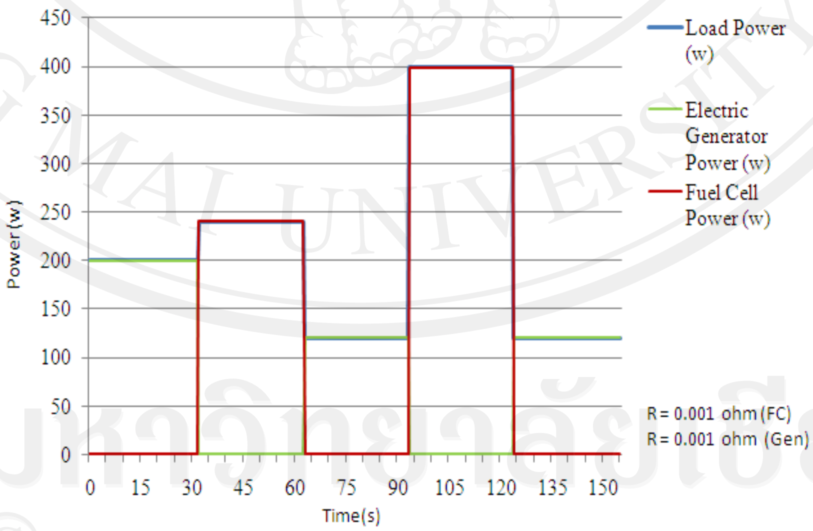


Figure 4.27 Switching case 2: Gasoline generator operates at the main power source with the set point at 210 watts and operate at 400 watts maximum

4.3.3 The 3rd case simulation model results

Figure 4.28 amd 4.29 show the simulation result of hybrid system of fuel cell and gasoline generator power sources. In the model, the overall resistance of the system of fuel cell is set to 0.001 Ω, and overall resistance of gasoline generator is set to 0.005 Ω. This part, the fuel cell is designed to supply load power not over 200 watts, in case of higher load power than 200 watts, gasoline generator will supply to excess power, that is 40 watts. In this case, fule cell operates 83% of full load.

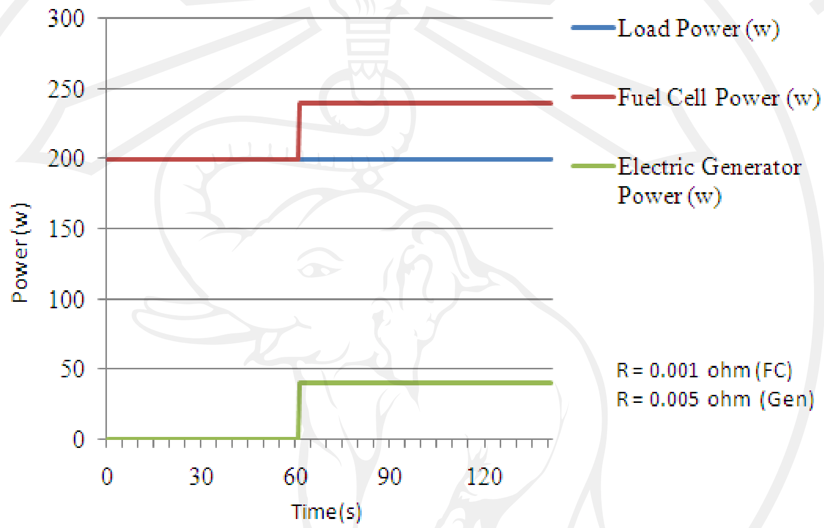


Figure 4.28 Hybrid case 3: Fuel cell operates at the main power source with gasoline generator supply the exceed power

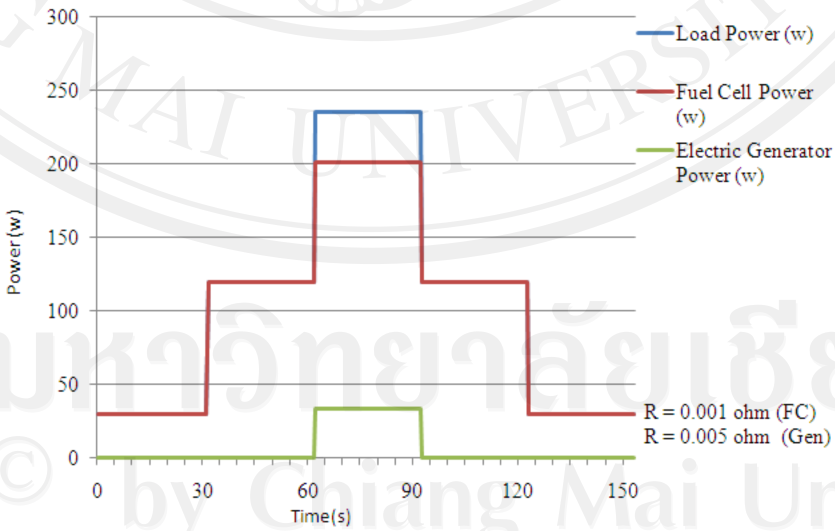


Figure 4.29 Hybrid case 3: Fuel cell operates at the main power source with gasoline generator supply the exceed power with step load condotion

Figure 4.30 shows the hybrid system that is designed fuel cell, first, supply to load power at 200 watts. If any load power exceed the 200 watts, gasoline generator will be connected to the system while fuel cell is still operating. In this case, the overall resistance of both fuel cell and gasoline system are 0.001 Ω. The result shows that at the load power over 200 watts, both power sources shared load power and supplied 120 watts (0.5 of full load) of load power. Figure 4.31 shows the result of simulation that let both power sources supply power to load at the first two second and let the step load change up and down. The result of this case show that the system can operates and supply the load power quite well. The overall resistances of both system are 0.001Ω, equally.

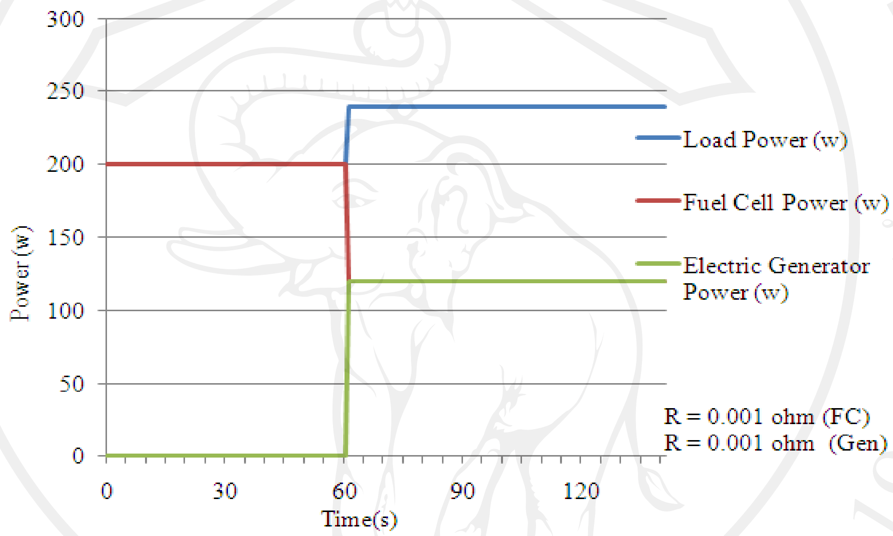


Figure 4.30 Hybrid case 3: Fuel cell and gasoline generator supply equally power

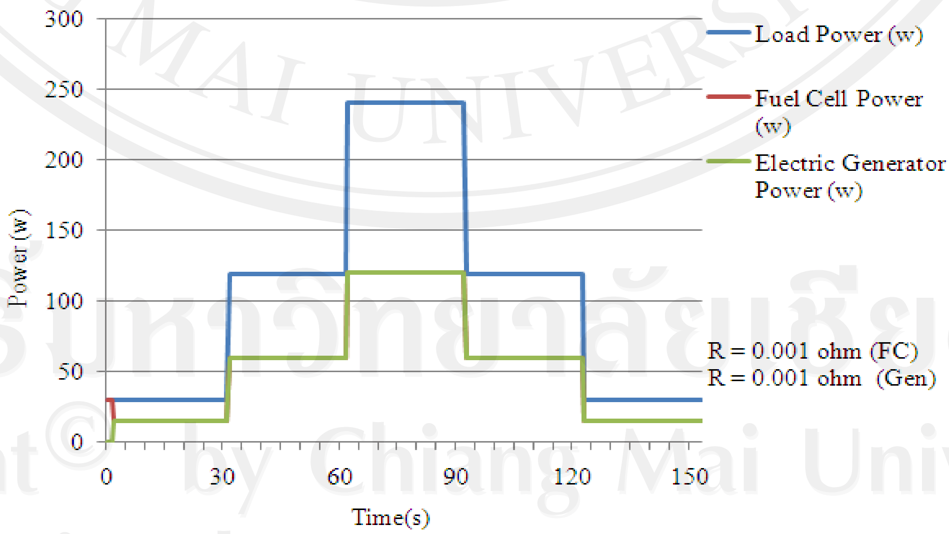
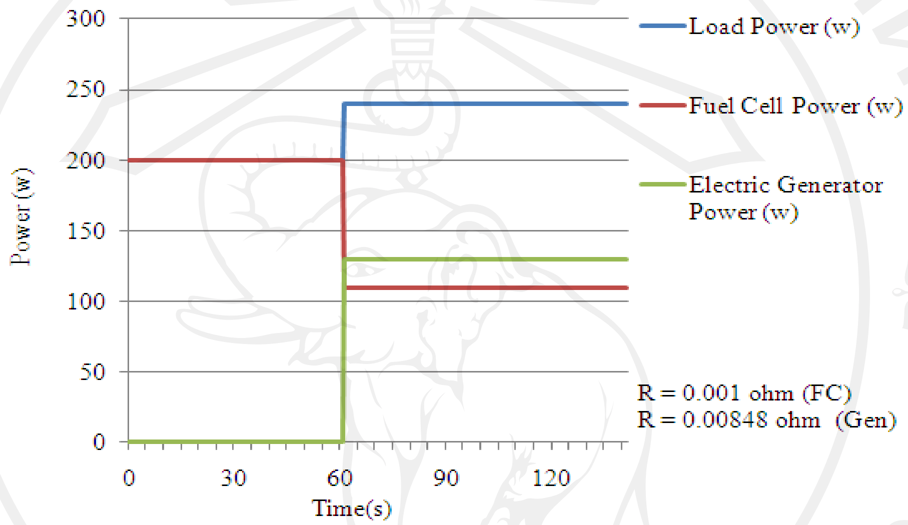
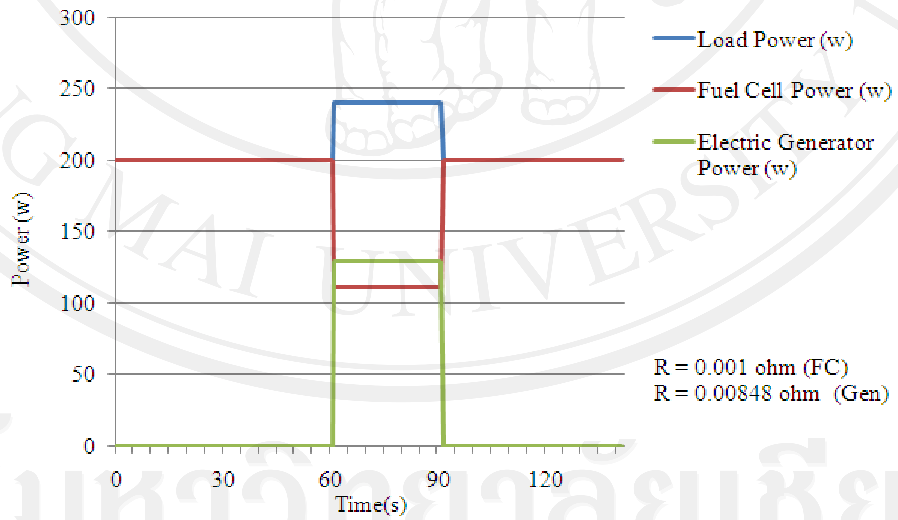


Figure 4.31 Hybrid case 3: Fuel cell and gasoline generator supply equally power with step load condition

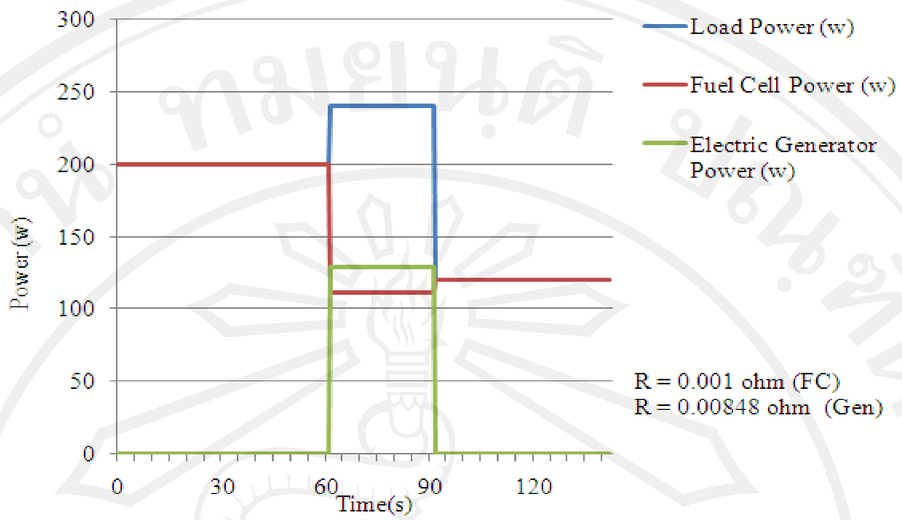
Figure 4.32 shows the simulation results of the hybrid system in case of fuel cell system has resistance 0.001Ω, and gasoline generator has 0.00848Ω for resistance. Simulation results show that the fuel cell will supply load power at 46% of full load. From this result, it shows that if we increase the resistance of gasoline generator higher than fuel cell resistance 0.00748Ω cause the supply power of gasoline generator to the system higher than fuel cell 54% of load conditions as shown in Figure 4.32 (a), (b), (c), and (d).



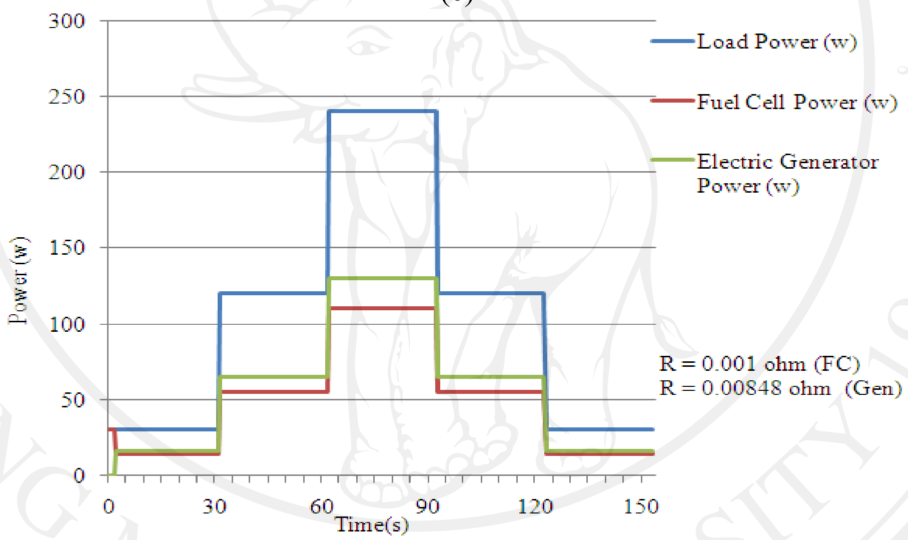
(a)



(b)



(c)



(d)

Figure 4.32 Hybrid case 3: Fuel cell operates at the main power source with gasoline generator is the supported power with difference operation (a), (b), (c), and (d) with the gasoline generatore resistance is 0.00848Ω

4.3.4 Comparison result of hybrid system

Figure 4.33 shows the comparison result of simulation model and experiment. In the model is set the gasoline generator resistance to 0.00848Ω. The result shows that during step load changing from 30 voltages in 30 seconds, then increase load power to 120 watts and keep it constant for 30 seconds, after that increase the load power to 240 watts for 30 seconds, and then, decrease the load power to 120 and 30 watts, respectively. During the operation at 30 watts, there is an error of voltages of both fuel cell and gasoline generator are 1.62V (13.34% error) and 2.76V (20.51% error). At the load power 120 watts, the error of voltages of both fuel cell and gasoline generator are 1.42V (2.65% error) and 1.77V (2.66% eroor). And, at the load power 240 watts, the error of voltages of both fuel cell and gasoline generator are 7.20V (6.98% error) and 3.35V (2.51% error). At the low power condition, the error of both fuel cell and gasoline generator output voltage measured is higher than other load condition. *RMSE* of the fuel cell is about 0.852 and gasoline generator is 0.54.

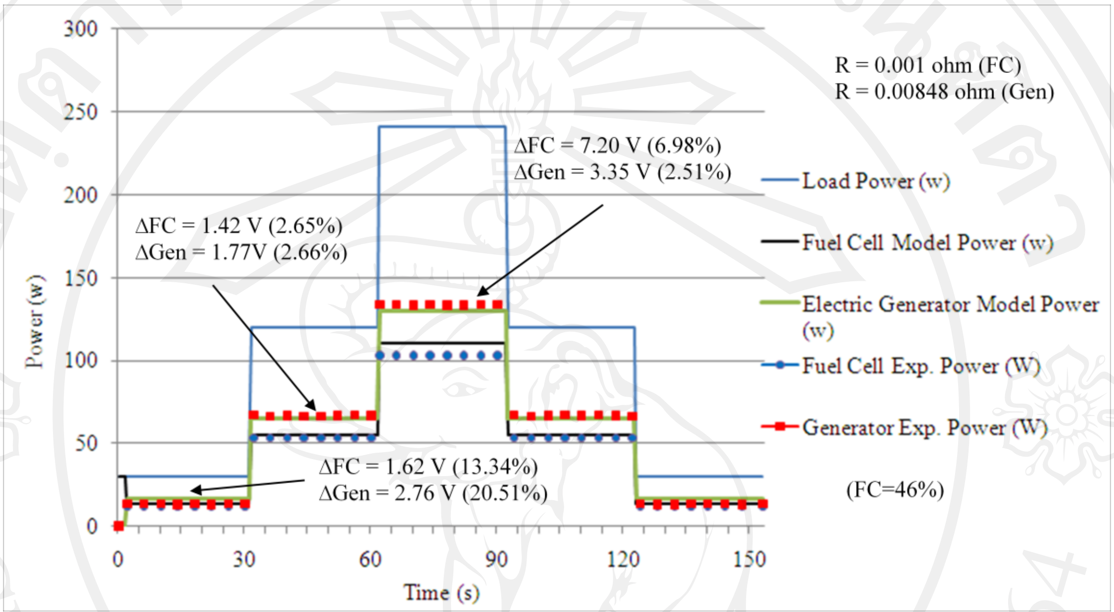


Figure 4.33 Comparison Hybrid system operates at step load condition with gasoline generator resistane 0.00848Ω

4.3.5 Energy Balance

Energy balance is the sum of all energy inputs must be equal to the sum of all energy outputs. The energy balance in Equation (3.45) is introduced to check the consistency of the oxygen stoichiometry S_{O2} during the fuel cell operation at 25°C at room temperature of hydrogen/air fuel cell, with 65% relative humidity. The fuel cell generated 1200 kW at 35A with 46 cells in series. The operating temperature is 65°C . The operation uses 1.2 of hydrogen stoichiometry. From the energy balance, we found that the S_{O2} is 5.54 to maintain the desired operating temperature of 65°C while the S_{O2} from the experiment is 4.98. The error is 11.24%

4.4 Operation strategy for optimal performance of the fuel cell and electric generator hybrid system

From the experiment of hydrogen consumption rate in section 4.2.1, we converted the hydrogen consumption rate per hour at load conditions in W-hr as shown:

$$\dot{V}_{H2} = -0.00016P^2 + 0.68898P + 42.17654 \quad (4.20)$$

where *P* is the rate power generation in W-hr.

Figure 4.34 shows the relationship of power and hydrogen consumption rate. This section will describe the operation strategy for optimal performance of the hybrid system in the point of fuel consumption and cost. From empirical model Equation (4.17) and (4.19) are used to predict the hydrogen and gasoline fuel consumption under load conditions. Then, the results from prediction will be used to analyze the operation strategy for optimal performance of the fuel cell and gasoline generator hybrid system. The limitation of rate power generation in Equation (4.20) is not over than 4.365 kW-hr.Table 4.4 shows the fuel consumption of both hydrogen fuel and gasoline fuel with the relationship of cost. The hydrogen cost is 0.6 Baht/liter and gasoline is 38.89 baht/liter.

The operation of the switching case 1, 2 and hybrid case can be shown by the operation procedures which respect to fuel cell: gasoline generator in percent of operation (%). In the results of operation procedure, the operation with fuel cell to gasoline generator at 0:100, the operation cost is 34.08 baht per hour and the operation of 100:0, the operation cost is 383.13 baht per hour. At the operation 50:50, the operation cost is 265.52 baht per hour. Moreover, if we compare the operation strategy at 90:10 with 10:90 of the operation procedure, we found that the operation cost of 90:10 is 380.65 baht per hour, and 10:90 is 106.14 baht per hour. From these results, we conclude that the operation of fuel cell at 10% of operation with 90% operation of gasoline generator is the best operation for hybrid case with low cost operation in hour.

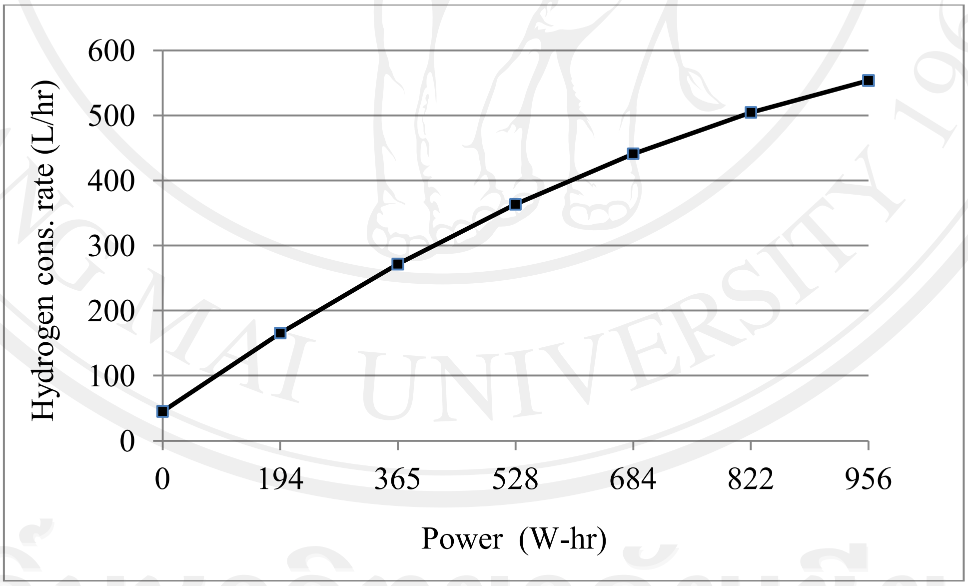


Figure 4.34 Hydrogen consumption rate in L/hr

Table 4.4 Relationship of fuel consumption and cost.

Operation procedure ($Gas.:H_2$) %	Fuel cell power (W-hr)	Gasoline generator power (W-hr)	Hydrogen Cons. (L/hr)	Cost (Baht)	Gas. Cons. (L/hr)	Cost (Baht)	Total cost (Baht)
0:100	0	1200	0	0	0.87	34.08	34.08
10:90	120	1080	122.55	73.53	0.84	32.61	106.14
20:80	240	960	198.32	118.99	0.80	31.15	150.13
30:70	360	840	269.47	161.68	0.76	29.68	191.36
40:60	480	720	336.02	201.61	0.72	28.21	229.82
50:50	600	600	397.96	238.78	0.69	26.74	265.52
60:40	720	480	455.30	273.18	0.65	25.27	298.45
70:30	840	360	508.02	304.81	0.61	23.80	328.62
80:20	960	240	556.14	333.68	0.57	22.33	356.02
90:10	1080	120	599.65	359.79	0.54	20.86	380.65
100:0	1200	0	638.55	383.13	0	0	383.13