CHAPTER 3

METHODOLOGY

This chapter describes the experimental procedure and numerical model of proton exchange membrane fuel cell and internal combustion engine generator hybrid system. Fuel cell modeling is developed in order to understand the behavior of fuel cell under various load changed conditions. Then, the experimental is conducted on the 1200 Watts fuel cell (Nexa^{TM}) system. The electronic load (KENIL BATTERY Machine) with maximum discharge 100 Voltages and maximum discharge current 50 Amps is used to test the performance of fuel cell. The electrical generator with 2.7 kW maximum outputs is used as a hybrid power source. Finally, the numerical model of fuel cell, electrical generator and the hybrid system is operated and analyzed. Figure 3.1 shows the block diagram of this research procedure that is classified into two group: numerical model and experiment.

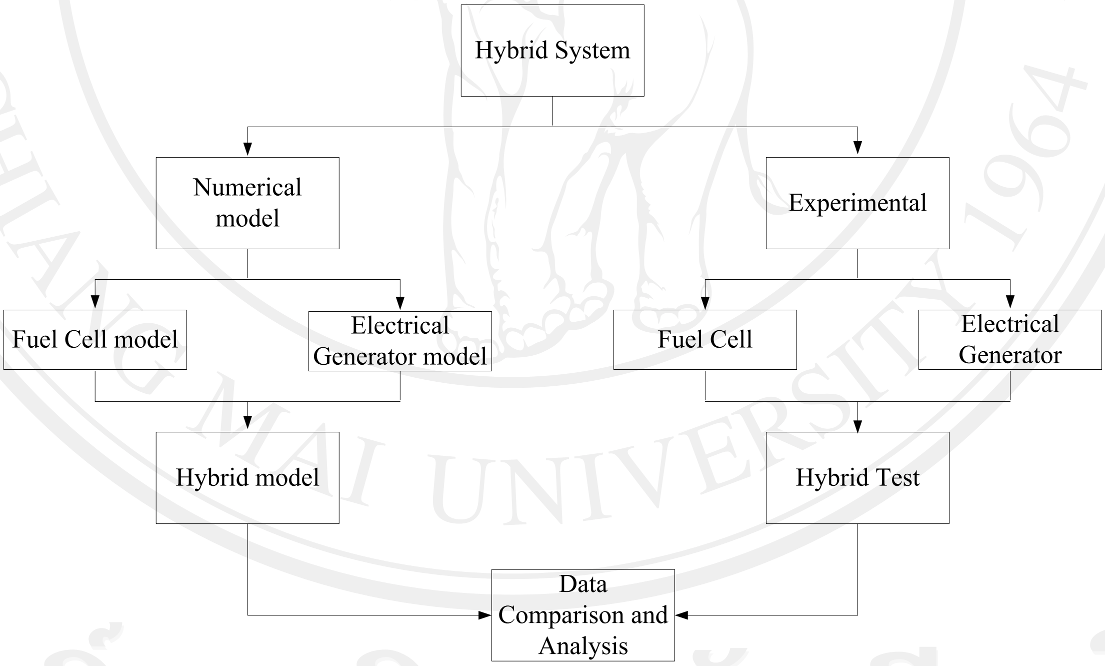


Figure 3.1 The research procedures of hybrid system

3.1 Fuel cell model

Numerical model of a fuel cell is developed to study the behavior and performance of the proton exchange membrane fuel cell (PEMFC). Theoretically, PEMFC's performance depending on various of parameters and operating conditions, such as operating temperature, operating pressure, applied current density, ohmic losses, exchange current density, limiting current density, activity coefficient and current loses and so on. Figure 3.2 shows the schematic of a PEMFC numerical model. The model of stack cell consists of 4 modules. Nernst equation module is the simulation of chemical reaction, which occurred inside a fuel cell. Input of the module are partial pressure of hydrogen , partial pressure of oxygen, partial pressure of water (liquid water is produced in a fuel cell), and operating temperature. The output module is the open circuit cell potential. Activation losses module is the loss due to reaction kinetics at the electrodes of a PEMFC. The inputs of this module are operating temperature, load current, an activity coefficient, and an exchange current density for reaction with constant value. Concentration losses module is an affect of concentration losses due to mass transport. The input module is operating temperature, load current and limiting current density with constant value. The last module is Ohmic losses module that is resistance of ions flow in electrolyte and resistance of the flow of electrons through electrically conductive fuel cell components. The potential output of 4 modules combined together and multiplied with number of stack cell will get the stack cell voltage. The model investigates the behavior and performance of a stack cell by changing partial pressure of hydrogen and changing load conditions.

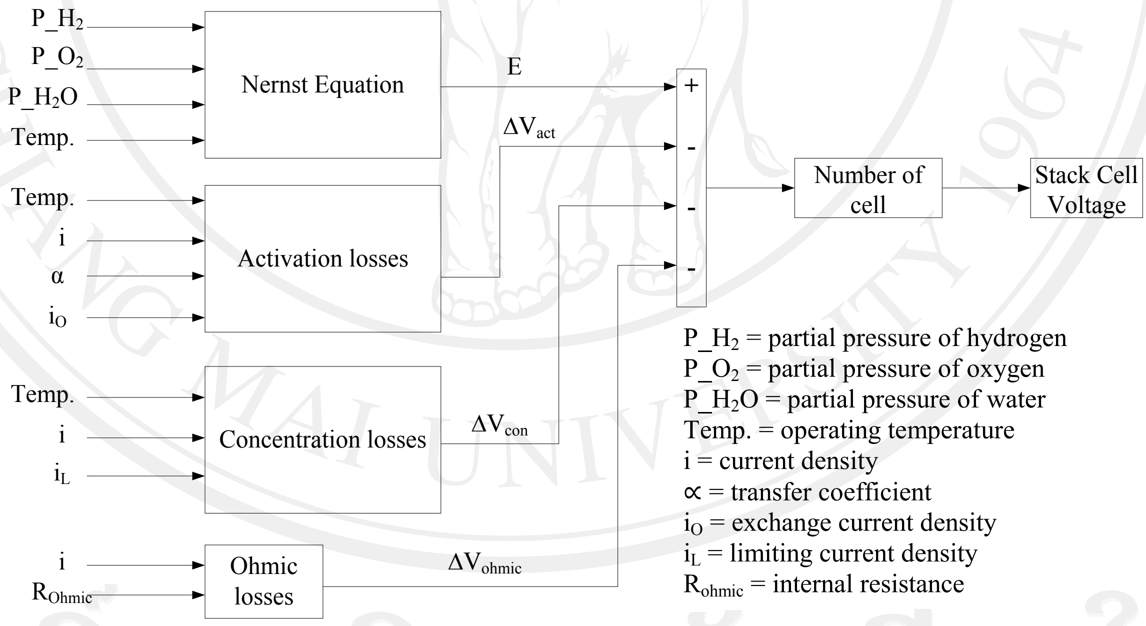


Figure 3.2 The schematic of a PEMFC stack module

Figure 3.3 shows the calculation flowchart of PEM fuel model. Model procedure starts with input parameters of the model these are current density, gas constant, operating temperature, partial pressure of hydrogen, oxygen, and water vapor, and theoretic cell voltage. Then, the model will calculate the cell voltage by using equation (2.37), after that, the activation losses will be calculated by using equation (2.61). The Ohmic losses, then determines by using equation (2.70), then, the concentration losses is calculated following equation (2.76), then, the output cell voltage is determined by using equation (2.77). Finally, the fuel consumption during the load condition is calculated using equation (2.87)

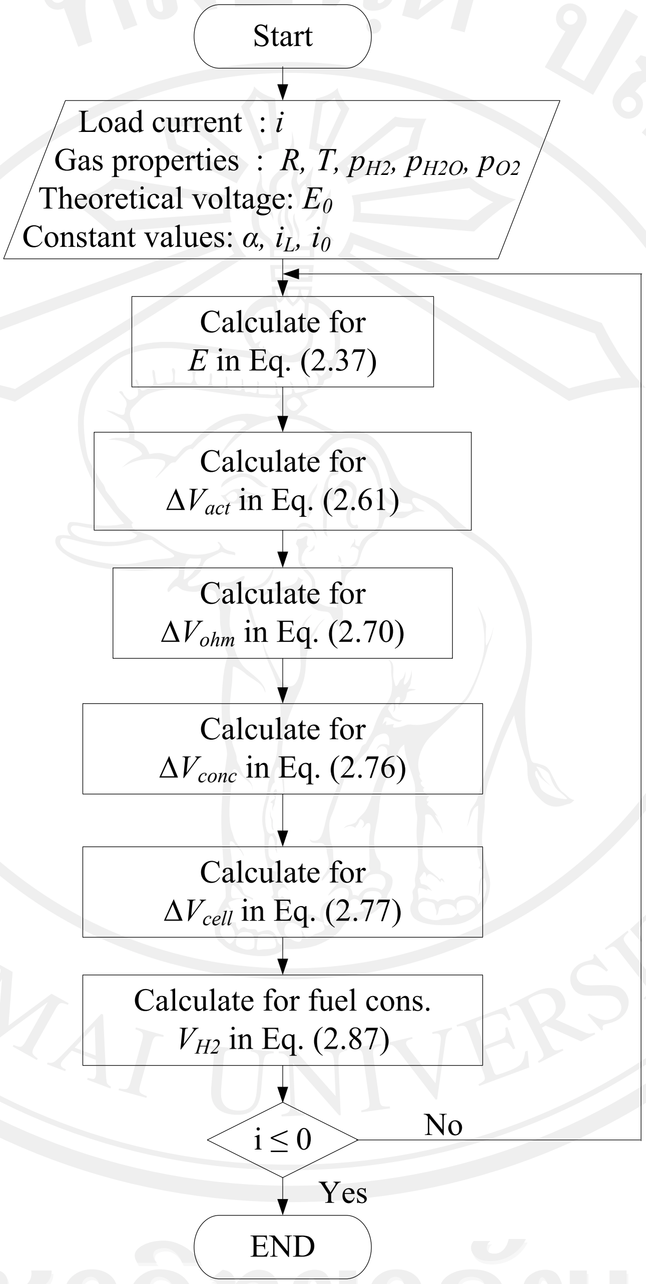


Figure 3.3 Calculation procedure flowchart of the of PEM fuel model

The assumptions of PEM fuel cell model are:

- Fuel cell operates in the steady state;
- Fuel cell operates under isothermal conditions;
- The gas flow is laminar and incompressible;
- The reactants are pure hydrogen and air are treat as ideal gases;

- The anode reaction kinetics is ignored because the anode activation losses is usually much smaller than cathode;
- Effects of liquid water accumulation are not treated;
- No water accumulation in the anode;
- No net water transport through the membrane.

Single cell model is developed by varying the parameters in order to study the effect of parameters to fuel cell parameters to polarization curve as follows:

3.1.1 Case 1: The effect of pressure to fuel cell potential

Fuel cell potential is a function of pressure as shown in Equation (2.26). The operating pressure of both hydrogen and oxygen will affect to fuel cell potential. In this case, the operating pressure of hydrogen and oxygen will be varied from 1 to 3 bars (normally operating pressure is not less than 1 bar and also operating pressure should not operate at high pressure to prevent gas leakage and membrane damage) in order to investigate the effect of pressure to fuel cell potential under others parameters are kept constant as shown in Table 3.1.

3.1.2 Case 2: The effect of temperature

The reaction between oxygen and hydrogen is an exothermic process, which means that there is energy released in the process. Also, from Equation (2.26), fuel cell potential is a function of temperature. The temperature will be varied to investigate the fuel cell potential. The operating temperature of proton exchange membrane is operated at low temperature about 80°C. So, the operating temperature is varied from 40°C to 80°C.

3.1.3 Case 3: The effect of transfer coefficient

Transfer coefficient is the change in polarization that leads to change in reaction rate for fuel cells. The transfer coefficient is a ratio of the number of electrons transferred in the overall reaction to the stoichiometric number. So that, it will be investigate in order to understand the effect of transfer coefficient to fuel cell potential. Transfer coefficient will be varied from 0.2 to 2 (Newman et al, 1991 and Larminie et al, 2003)

3.1.4 The effect of exchange current density

Exchange current density in electrochemical reaction is analogous to the rate constant in chemical reaction. At the open circuit, the fuel cell potential can be calculated from Nernst equation which is current density is not generated. The rate at which these reactions proceed is an exchange current density. In this section will be investigate the behavior of fuel cell potential to the exchange current density.

3.1.5 The effect of internal resistance

Internal resistance or ohmic losses are one of the effects to fuel cell potential as shown in Equation (2.59). The internal resistance will be varied from 0.1 to 0.2 (This is the typical conductivity values for selected fuel cell materials, Frano Barbir, 2005, Nirunsin, 2011) in order to investigate the performance of fuel cell.

3.1.6 The effect of limiting current density

Limiting current density is also one of the effects to fuel cell potential as shown in Equation (2.65). It shows the reactant concentration at the catalyst surface. A fuel cell cannot produce current density more than the limiting current density.

3.1.7 The effect of load current changed

Load current or current density is one of parameter, which effected to fuel cell potential. In this section, load current will be varied in order to investigate the fuel cell performance. Fuel cell model is developed with a single cell and stack cell. Table 3.1 shows the fuel cell model parameters which were initial value to input in the model.

Table 3.1 Model parameters (Colleen, 2008)

Parameters	Value
Partial hydrogen pressure, P_H_2 [bar]	1 bar
Partial oxygen pressure, P_O_2 [bar]	1 bar
Partial water pressure, P_H_2O [bar]	1 bar
Operating Temperature, *Temp.* [K]	60°C
Theoretical potential, E_o [V]	1.229 Volts
Activity coefficient, $\propto$	1
Exchange current density, i_o [A/cm^2]	3x10^{-6} A/cm^2
Activation area, A [cm^2]	120 cm^2
Number of stack cell, N	47
Internal resistance, R_{Ohmic} [ohm-cm^2]	0.15
Limiting current density ,i_L [A/cm^2]	1.6 A/cm^2
Faraday's constant, F [C/mol]	96,485 C/mol
Gas constant, R [J/mol K]	8.314 J/mol.K
Number of electrons per molecule, [n]	2
Load current ,I [Amp]	0 to 40 Amp

From this parameter will be the initial value to develop the model of 1200 watts fuel cell which used in this research. The model of 1200 watts will be used to validation with the Nexa^{TM} stack fuel cell which used as the power source.

3.2 Gasoline generator model

Mathematical model of gasoline generator is developed in order to combine this model with PEM fuel model.

Gasoline generator model started with empirical model of gasoline fuel consumption related to load conditions of gasoline generator type

$$\dot{m}_{gas} = 0.000314P_{load} + 0.49763 \tag{3.1}$$

where $\dot{m}_{gas}$ denotes the gasoline fuel used during the specific time, and P_{load} denotes the load power which applied to the system and can be calculated from:

$$P_{load} = iV \tag{3.2}$$

The input power of the gasoline engine can be calculated from:

$$P_{i,g} = \dot{m}_{gas} LHV_{gas} \tag{3.3}$$

where $P_{i,g}$ is the input power of the gasoline engine
LHV_{gas} is the low heating value of gasoline.

The output power of the gasoline generator can be determined;

$$P_{gen} = iV\, cos\theta \tag{3.4}$$

where P_{gen} is the output power of gasoline generator (kW).
i is the load current (Amp).
V is the output voltage of gasoline generator (V)
$cos\theta$ is power factor

The total efficiency, η_T of the gasoline generator can be calculated from:

$$\eta_T = \frac{P_{gen}}{P_i} \tag{3.5}$$

Gasoline generator model can be present and the calculation procedure can be shown in Figure 3.4. The simplifying assumptions of the model are:

- The crankshaft rotational speed is set to be constant.
- The output voltage of the system is constant at 220VAC.
- No friction loss in the system.
- The rotational speed of both crankshaft of gasoline engine and electric generator is equally.
- No effect of operating temperature of the engine.

The input model is current load, low heating value, output voltage of the system, and power factor. The mass flow rate is calculated during load condition, and then, the load power, engine power, and generator power are determined.

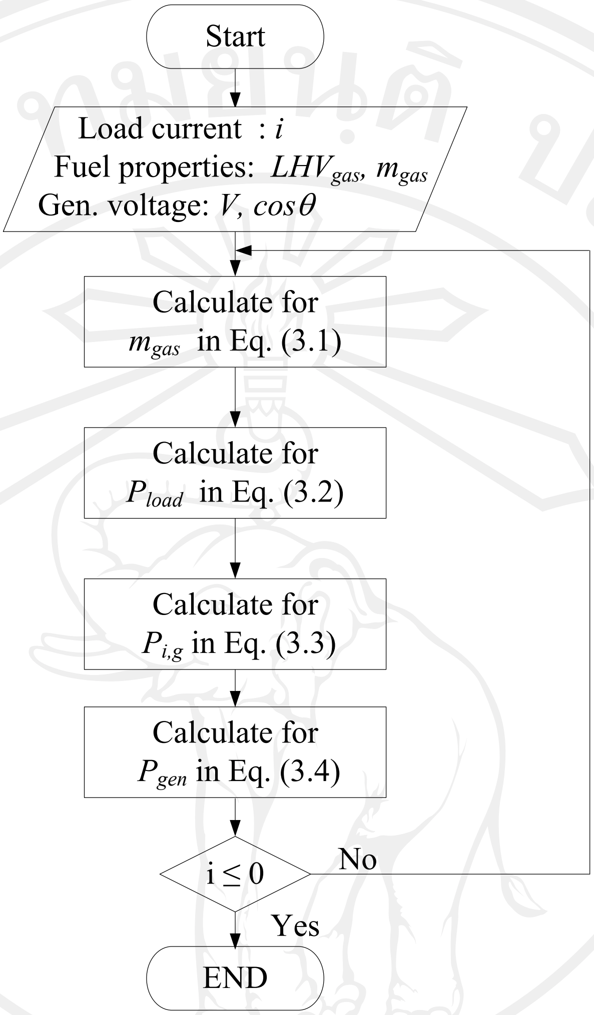


Figure 3.4 Calculation procedure flowchart of gasoline generator model

3.3 Experimental

This section will show the experimental devices and wiring connection of the system. The experiment will be tested fuel cell under load condition. The experimental system consists of test station of stack fuel cell (which consisted of hydrogen tank, Nexa^{TM} Fuel cell power module, personal computer, electronic load, gasoline generator, and control unit.

3.3.1 Test Station of Stack Fuel Cell

The behavior of stack fuel cells under various load condition were observed by 1200 watts test station at Rajamagala University of Technology Thanyaburi as shown in Figure 3.5. Nexa^{TM} fuel cell test station consisted of hydrogen tank, control unit, monitoring display, Nexa^{TM} Fuel cell power module, pressure regulator, and cooling system.

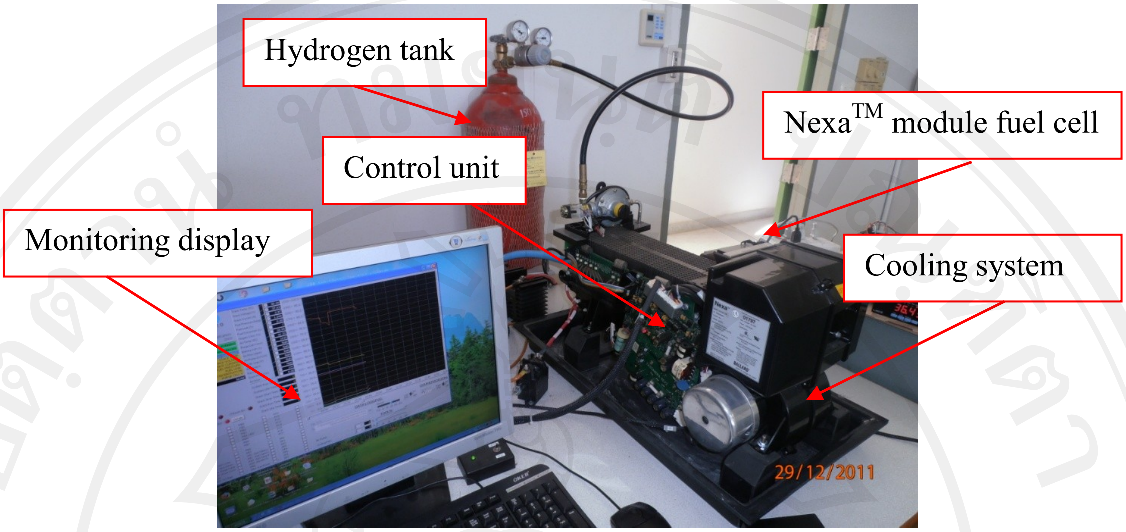


Figure 3.5 Nexa^{TM} Fuel cell power modules

3.3.2 The Nexa^{TM} PEM fuel cell module

The Nexa^{TM} PEM fuel cell module produces unregulated DC power. The PEM fuel cell uses pure hydrogen and air. Water and heat are the only by-products of the reaction. This stack cell provides 1200 watts of net output power. The output voltage varies with power, ranging from about 43 VDC at system idle to about 26 VDC at full load. Figure 3.6 illustrates the Nexa^{TM} system schematic. This diagram also shows the system boundary and important interface connections to the DC module. Hydrogen tank is connected to the system and hydrogen fuel is fed through the connecting line (red line) through the main gas valve. Hydrogen regulator controls the hydrogen pressure before feed to stack cell. The purge valve works as the purge system which purge the amount of nitrogen and product water in the air stream which was slowly migrates across the fuel cell membrane and gradually accumulates in the hydrogen stream out off the system. Oxidant air is supplied by using air compressor (green line). The mass flow rate of oxidant air depends on load demand. Operating temperature is controlled by cooling fan. All data will be measured and sent to fuel cell controller, and then, display on the monitoring screen. The specification of output and input data of the Nexa^{TM} fuel cell module are shown in Table 3.2 and Table 3.3, respectively.

Table 3.2 The output specification of the Nexa^{TM} fuel cell module.

Outputs	Requirement	Definition	Quantity
Power	Rate Power	Capacity at standard condition	1200W
	Voltage	Operating voltage range	22V to 50 V
		Voltage at rated power	26V

Table 3.3 The input specification of the Nexa^{TM} fuel cell module

Inputs	Requirement	Definition	Quantity
Fuel	Purity	Lowest acceptable concentration of hydrogen	99.99% H_2 (vol)
	Pressure	Allowable range of inlet supply pressure	70-1720kPa (g)
	Temperature	Allowable range of inlet supply temperature	5°C -80°C
	Consumption	Maximum fuel consumption at rated power	<18.5 SLPM
Power conditioning	Current Ripple	Maximum acceptable current ripple at 120Hz, with respect to average DC net output current	24.7% RMS 35% peak-peak

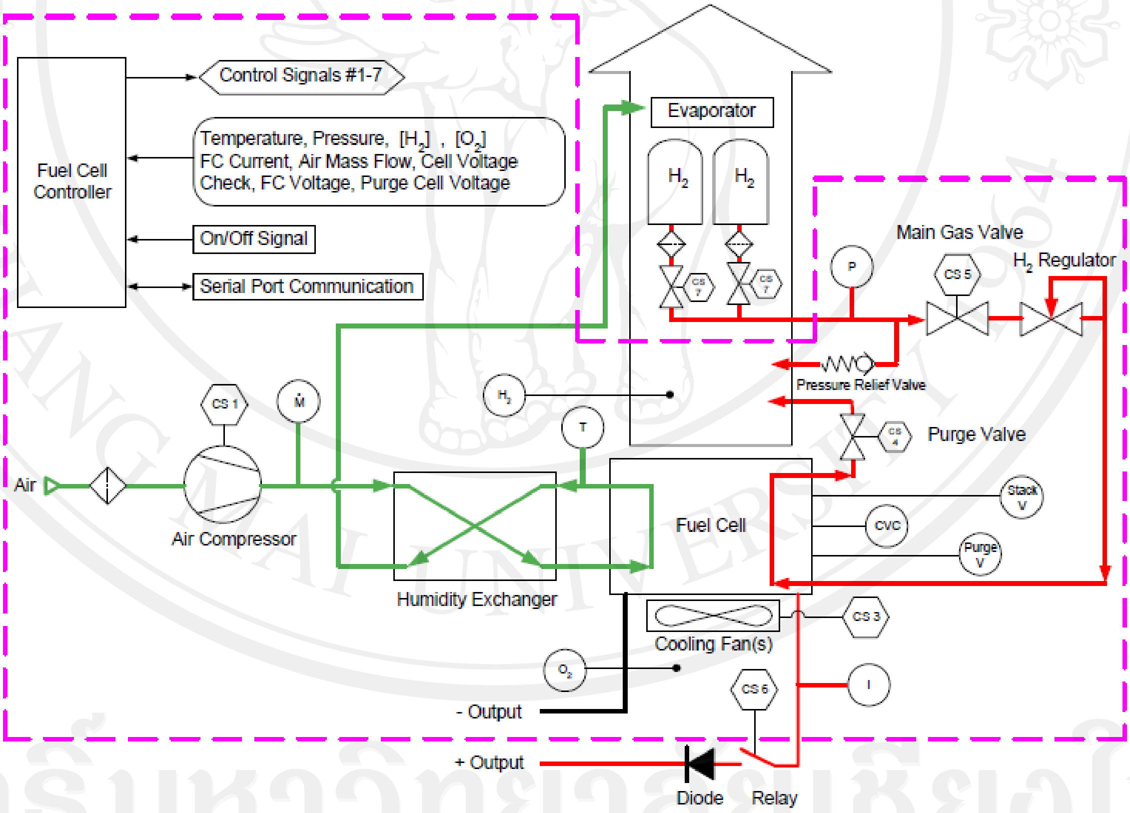


Figure 3.6 Nexa^{TM} fuel cell schematic (Ballard, 2003)

The fuel cell stack is pressurized with hydrogen during operation. The regulator assembly continually replenishes hydrogen, which is consumed in the fuel cell reaction. Nitrogen and product water in the air stream slowly migrates across the fuel cell membranes and gradually accumulates in the hydrogen stream. The accumulation of nitrogen and water in the anode results in the steady decrease in performance of certain key fuel cells, which are termed "purge cells" (to release the inert gases, nitrogen and water, out of the cells). In response to the purge cell voltage, a hydrogen purge valve at the stack outlet is periodically opened to flush out inert constituents in the anode and restore performance. Purged hydrogen is discharged into the cooling air stream before it leaves the Nexa™ system, as shown in diagram. Hydrogen quickly diffuses into the cooling air stream and is diluted to levels many times less than the lower flammability limit.

Nexa^{TM} fuel cell module has the characteristic of polarization curve of the fuel cell can be shown in Figure 3.7. Figure 3.7 illustrates the system parasitic load as a function of net current and net output power. To support Nexa™ system operation, the fuel cell stack provides power to the air pump, cooling fan, as well as onboard sensors, actuators and controllers. The auxiliary power requirement at system idle is approximately 35 watts. Auxiliary loads increase with increasing current, primarily to support higher air pump and cooling fan duty. At rated system power approximately 250 watts of auxiliary load is required. By using the polarization curve provides in Nexa Fuel cell manual (Ballard, 2003) as shown in Figure 3.7, and the interpolation the value to get the output voltage and output power as shown in Table 3.4.

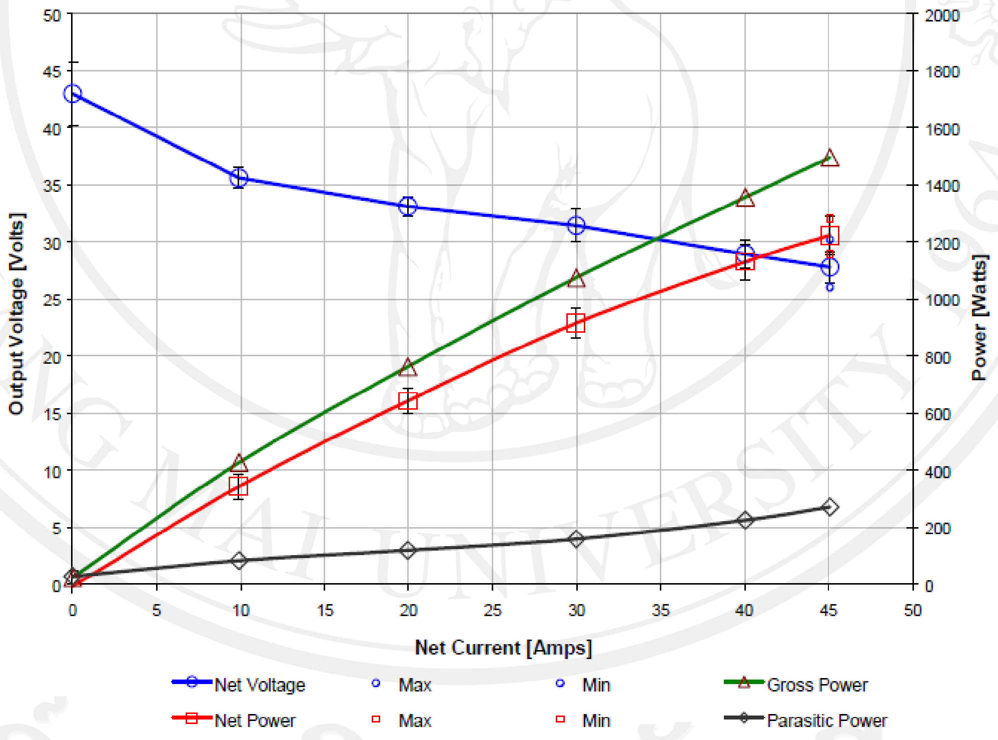


Figure 3.7 Polarization and Power Curves of Nexa^{TM} module (Ballard, 2003)

Table 3.4 The interpolation value of Polarization curve from Figure 3.7

Current (A)	Voltage (V)	Power (W)	Load (Ω)
0	43	0	∞
5	39.5	197.5	7.9
10	36	360	3.6
15	35	525	2.33
20	34	680	1.7
25	33	825	1.32
30	32	960	1.067
35	30.5	1067.5	0.87
40	29	1160	0.725
45	27	1215	0.6

The amount of hydrogen consumption that would be used by the Nexa^{TM} fuel cell will be estimated from Figure 3.8. The control system of the Nexa^{TM} fuel cell has been designed to provide the H_2 consumption and efficiency of the Nexa^{TM} fuel cell module to determine how much hydrogen would be needed if the Nexa^{TM} fuel cell were to be used for certain application. Figure 3.8 shows the hydrogen consumption rate results for fuel cell. As the power demand increases, so does hydrogen consumption rate, shown in m^3/min; however, the data is not at standard pressure and temperature. According to Nexa^{TM} Fuel Cell manual, the fuel cell can operate within the pressure range 70 to 1720 kPa and temperature range from 278 to 353K (5-80°C). The middle range pressure and temperature were selected for the model to be 895kPa and 315K, respectively. The ideal gas law was used to calculate the volume per minute that would be consumed given an operating point on the polarization curve, a pressure, and temperature.

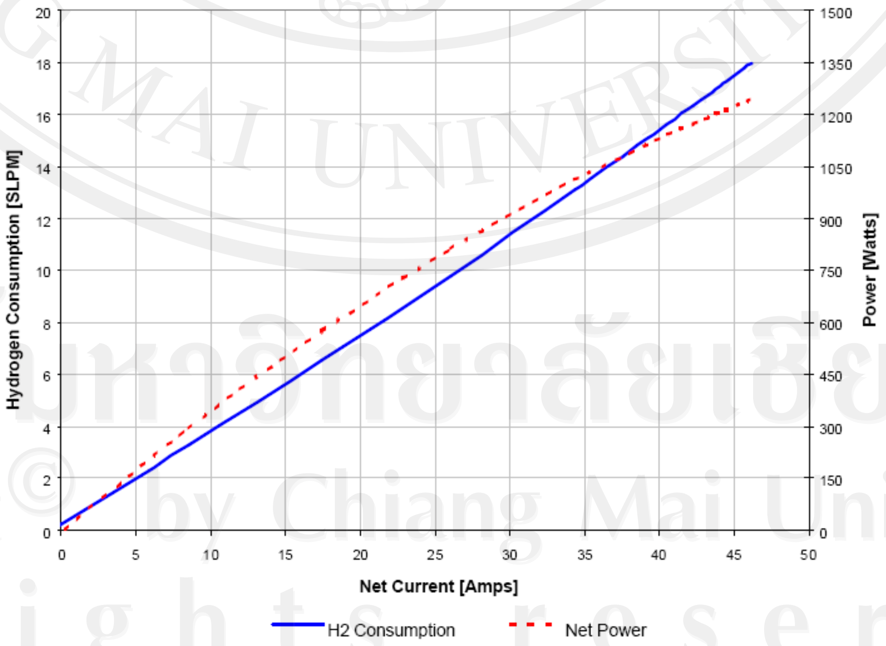


Figure 3.8 Hydrogen consumption rates of Nexa^{TM} Fuel Cell (Ballard, 2003)

The results and the calculation procedure can be done by two steps. First, the number of moles of gas must be calculated. The number of moles of matter never changes, regardless of pressure and temperature. However, volume does change with these two parameters. Therefore, to determine the volume of hydrogen being consumed at standard temperature and pressure, the moles of gas being consumed at a specified temperature and pressure must be calculated first. Then, the new volume can be determined using the standard temperature and pressture, 101 kPa and 273K, respectively.

From the Nexa^{TM} Fuel Cell manual, 18 standard liters per minutes (SLPM) are consumed at 273K and 1.013x10^{5}Pa. First, the amount of moles per minutes (n) will be found to convert to the new temperature and pressure chosen for the model. The calculation is found using the ideal gas law:

$$pv = nRT \tag{3.6}$$

Then

$$n = \frac{pv}{RT} = \frac{(1.013 \times 10^5 Pa)(18 \times 10^{-3} m^3/min)}{\left(\frac{8.314 J}{mol.K}\right)(273 K)} = 0.804\, mol/min \tag{3.7}$$

Then, the new liters per minute can be calculated from:

$$v = \frac{nRT}{p} = \frac{(0.804\, mol/min)\left(8.314 \frac{J}{mol.K}\right)(315 K)}{895\, kPa} = 0.002\, m^3/min \tag{3.8}$$

The hydrogen consumption can be estimated from the Nexa^{TM} fuel cell shown in Table 3.5.

Table 3.5 The hydrogen consumption with current load conditions from Figure 3.8 with running time 1 min for each current changed.

Current (A)	Hydrogen consumption (SLPM)
0	0.25
5	2.0
10	3.95
15	5.95
20	7.9
25	9.85
30	11.5
35	13.75
40	15.70
45	17.5

The efficiency of the Nexa^{TM} Fuel Cell module can be done concurrently with the flow rate calculation of hydrogen consumption. From Equation (2.16), Gibbs free energy is 237.42 kJ/mol. The efficiency of the fuel cell can be determined from:

$$\eta = \frac{P_{out}}{P_{in}} \tag{3.9}$$

where P_{out} is the maximum output power of Nexa^{TM} Fuel Cell that is 1200W.

$$P_{in} = \Delta G \times n \tag{3.10}$$

Then,

$$P_{in} = \frac{237.42kJ}{mol} \times 0.804mol/\min = 190.885\ kJ/min$$

$$P_{in} = 3181.428\,J/\sec = 3181.428\ W \tag{3.11}$$

Substitution Equation (3.10) to (3.9), the efficiency of the fuel cell can be estimated:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{1200\,W}{3181.428W} = 37.7\% \tag{3.12}$$

Requirement for the other operating parameters can be prescribed based on the maximum output power of 1200W. Size requirements must be set for the mass flow rate of gases, gas temperature, gas pressure, operating temperature. Table 3.6 shows the maximum design criteria and data acquisition during test procedure.

Table 3.6 Design criteria for fuel cell test station

Criteria	Minimum	Maximum
Power	43W	1200W
Temperature control	Room temperature	65°C
Pressure control	Atmospheric	300 kPa gauge
Data acquisition		
Voltage	0 V	43 V
Power	0 W	1200W
Temperature	Room temp.	65°C
Mass flow rate of H_2	0 LPM	18 LMP

3.3.3 Electronic Load

Electronic load is a device which driving forces the entire fuel cell. Fuel cells are low voltage and high current devices, so that, the electronic load must have the capability to measure and draw loads from fuel cell. Electronic load used in this research has maximum discharge voltage is 100 VDC, and maximum discharge current 50 ADC. This model offers the selectable mode such as constant current mode (CA), constant voltage mode (CV) and constant power mode (CP). Figure 3.9 shows connecting modules diagram of the test station with stack cell, control unit, electronic load, and data collector unit. Figure 3.10 shows the electronic load, which connected and used as an electronic load.

- Maximum discharge voltage is 100 VDC
- Maximum discharge current 50 ADC
- Precision of Voltage <+ 0.2%F.S

- Precision of Current <+ 0.2%F.S
- Precision of Time <+ 5S/24hrs
- Current control range 0.2% - 100% of scale

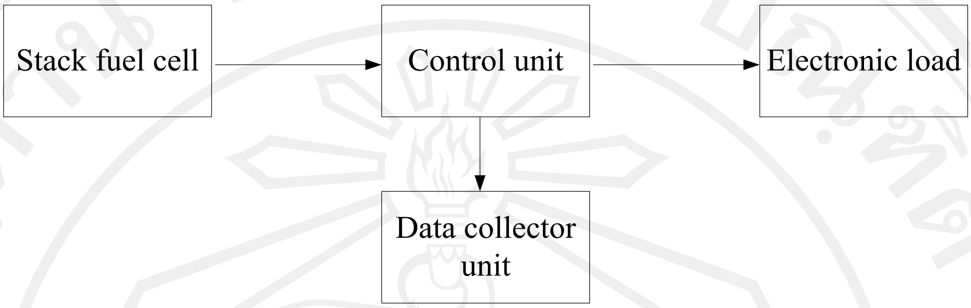


Figure 3.9 Connecting diagram of test station of stack cell

The electronic load is connected to control unit. All data from fuel cell, electronic load is sent to data collector unit to display output power from fuel cell whenever there is load changed.

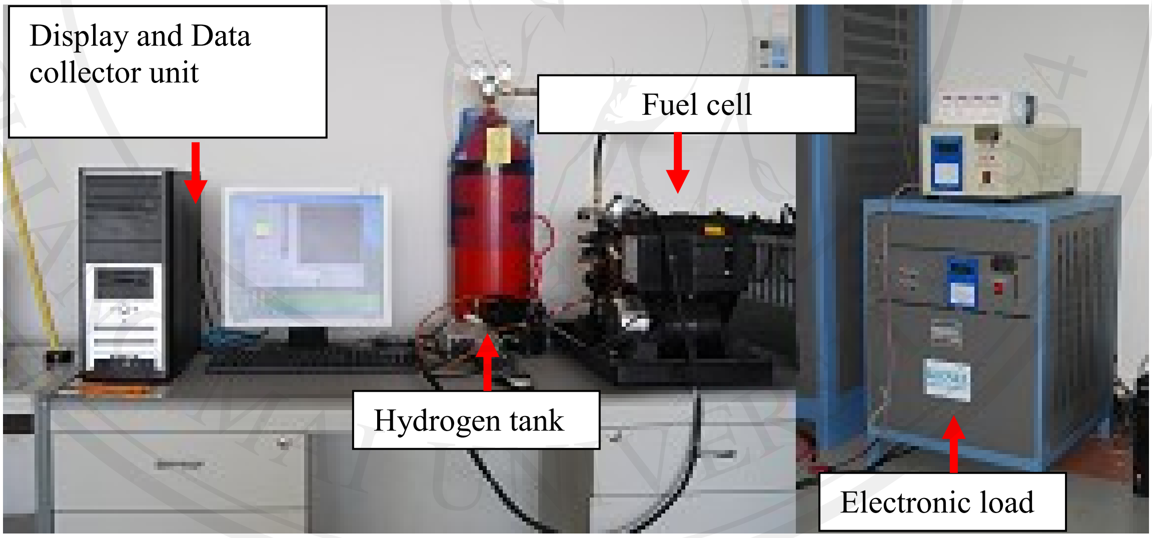


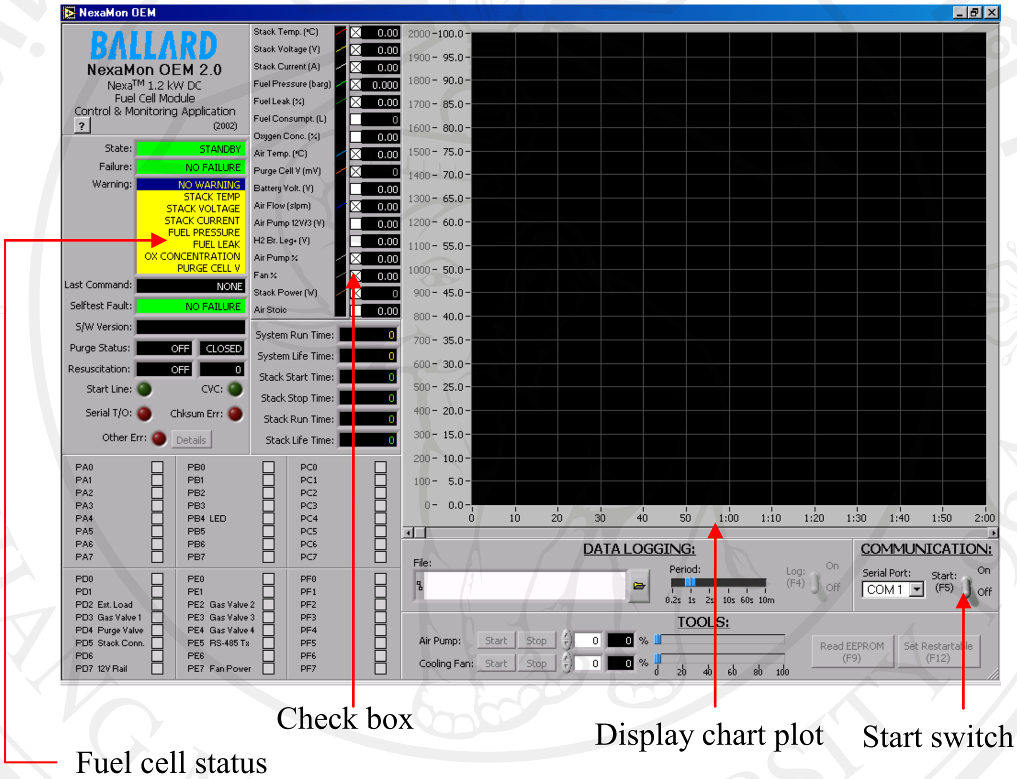
Figure 3.10 Electronic loads which assembled to fuel cell

The experiment is tested under various load conditions and hydrogen pressures by varying load current from 0 to 40 amps, and different fuel pressure from 1 to 3 bars. The operating temperature is tested at the ambient temperature. Air flow rate and air cooling are automatically adjusted to reach the load power. In this section, the load changing characteristic is studied in order to understand the behavior of Nexa^{TM} stack fuel cell under load condition.

3.3.4 Hydrogen Tank

Hydrogen tank is used to fill the gas hydrogen in the high pressure with 65 liters gas compressed at 150 bars and connected to the Nexa^{TM} stack fuel cell. Pressure regulator is connected to hydrogen to control the pressure inlet to fuel cell.

Figure 3.11 shows monitor display present of output parameters of fuel cell. All parameters can be selected the check box. The chart plots the progress of the checked process variables.



NexaMon OEM

BALLARD NexaMon OEM 2.0 Nexa^{TM} 1.2 kW DC Fuel Cell Module Control & Monitoring Application (2002)

State: STANDBY
Failure: NO FAILURE
Warning: NO WARNING
STACK TEMP
STACK VOLTAGE
STACK CURRENT
FUEL PRESSURE
FUEL LEAK
OX CONCENTRATION
PURGE CELL V
Last Command: NONE
Selftest Fault: NO FAILURE
S/W Version:
Purge Status: OFF CLOSED
Resuscitation: OFF 0

Stack Temp. (°C) ☒ 0.00
Stack Voltage (V) ☒ 0.00
Stack Current (A) ☒ 0.00
Fuel Pressure (barg) ☒ 0.000
Fuel Leak (%) ☒ 0.00
Fuel Consumpt. (L) ☐ 0
Oxygen Conc. (%) ☐ 0.00
Air Temp. (°C) ☒ 0.00
Purge Cell V (mV) ☒ 0
Battery Volt. (V) ☐ 0.00
Air Flow (slpm) ☒ 0.00
Air Pump 12V/3 (V) ☐ 0.00
H2 Br. Leg+ (V) ☐ 0.00
Air Pump % ☒ 0.00
Fan % ☒ 0.00
Stack Power (W) ☒ 0
Air Stoic ☐ 0.00

System Run Time: 0
System Life Time: 0
Stack Start Time: 0
Stack Stop Time: 0
Stack Run Time: 0
Stack Life Time: 0

Serial Port: COM 1

Air Pump: 0 0 %
Cooling Fan: 0 0 %

Check box

Display chart plot

Start switch

Fuel cell status

Figure 3.11 Monitoring display of the fuel cell parameters

3.3.5 Electrical Generator test station

Figure 3.12 shows the electrical generator with power by gasoline engine connecting to AC generator to produce 220 VAC. This research is designed the system operate with direct current (DC) to supply the electricity devices at the output 24 VDC. An AC/DC inverter is needed. The gasoline generator with maximum output 2.7 kW is used to be as hybrid power source. The measurement range and accuracy of AC/DC inverter are following:

- Input voltage range 180-264 VAC
- Output voltage adjust range 22-26.4 VDC
- Output current range 0-25A
- Output voltage tolerance ±1.0%
- Line regulation ±0.5%
- Load regulation ±0.5%

The YAMANO gasoline generator model YG 3500DC is used as the power source with the specification as followed:

- Maximum output power 2.7 kW at 65 hp/3600 rpm
- Rated output 2.5 kW
- Rated voltage 220V
- Rated frequency 50Hz
- Rated factor 1.0
- Gasoline is fuel
- 4 stroke engine
- Displacement 196 mL

(a) (b)

Figure 3.12 (a) Gasoline Generator with output is 220 VAC and (b) AC/DC inverter with output is 24 VDC

3.3.6 Hybrid test station

Figure 3.13 shows the block diagram of module connecting of the hybrid system. Stack fuel cell module with DC power output about 43 voltages is connected to DC/DC converter in order to keep the output voltage constant at 24 VDC. The generator module with the output voltage 220VAC is connected to AC/DC inverter to generate output voltage at 24VDC. Both of modules connect to control unit module. DC/DC converter connects to control unit box with input power from both DC/DC converter and AC/DC inverter are load current and voltage at 24 VDC. The operation strategy of the hybrid system is design to supply the electronic devices which operated at low voltage at 24 VDC, such as electronic circuit system, automation systems, and programmable logic control (PLC), and low electricity components power. Hybrid system is test under electronic load conditions. The measurement ranges and accuracy of the DC/DC converter are following:

- Input voltage range 19-72VDC
- Output voltage adjust range 23-30V
- Output current range 0-40A
- Output voltage tolerance ±1.0%
- Line regulation ±0.5%
- Load regulation ±0.5%

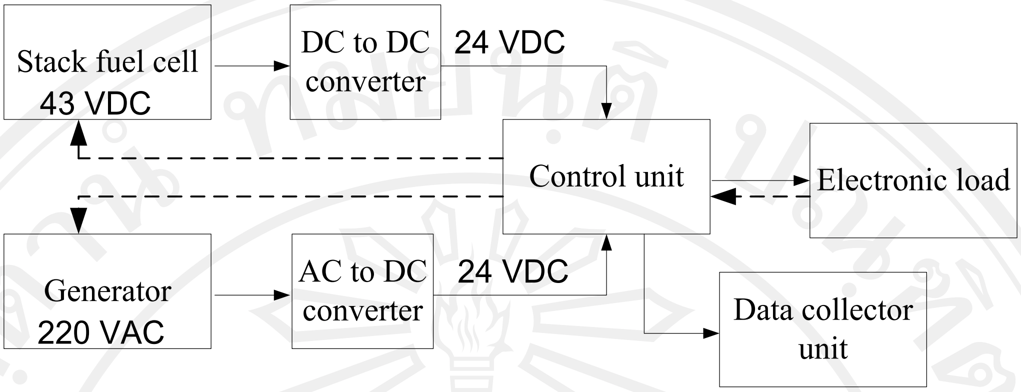


Figure 3.13 Connecting diagram of hybrid system

3.3.6.1 Control unit box

Control unit box as shown in Figure 3.13 function as switching unit. The input parameters to control unit box are current and voltage of fuel cell from DC/DC converter, current and voltage of gasoline generator from AC/DC inverter, and current from electronic load (using current constant mode). The output parameters of the control unit box are current and voltage to electronic load and data collector unit. The signals to start and stop of both fuel cell and gasoline generator are the output parameter. The operation procedure of hybrid system and function of control unit box will be explained in the next section.

Figure 3.14 shows the wiring diagram of control unit box which controlled the operation of the hybrid system consists of both fuel cell and electrical generator. The system can operate in 3 cases. First, the stack fuel cell is set to be a main power source to supply the load, if the load power is higher than set point, fuel cell will be disconnect from the system and let gasoline generator supply the load power to the system. When stack fuel cell run as the main power source to supply the power to electronic load, DC power meter #1 will check the output voltage from fuel cell. Then, it sent the signal to micro controller via RS485. Micro controller will send signal through RD2, the relay is closed. In case of the load power is higher than the set point of the system, the DC power meter # 3 will send the signal to micro controller to switch the power to gasoline generator relay to connected and supply the power to load and disconnect the relay of fuel cell from the system. Second case, the gasoline generator is set to be a main power source to supply the load, if the load power is higher than set point, gasoline generator will be disconnect from the system and let fuel cell supply the load power to the system. The operation of the system can be described, when electric generator run as the main power source to supply the power to electronic load, DC power meter #2 will check the output voltage from electric generator. Then, it sent the signal to micro controller via RS485. Micro controller will send signal through RD3, the relay is closed. In case of the load power is higher than the set point of the system, the DC power meter # 3 will send the signal to micro controller to switch the power to fuel cell relay to connected and supply the power to load and disconnect the relay of electric generator from the system. In both cases, the test conditions are observed the behavior when the system operates under various load conditions. All data and operation strategy can be operating from personal computer. Third case, the hybrid system will allow two power sources supply the power to load whenever the load power exceeded the set point value.

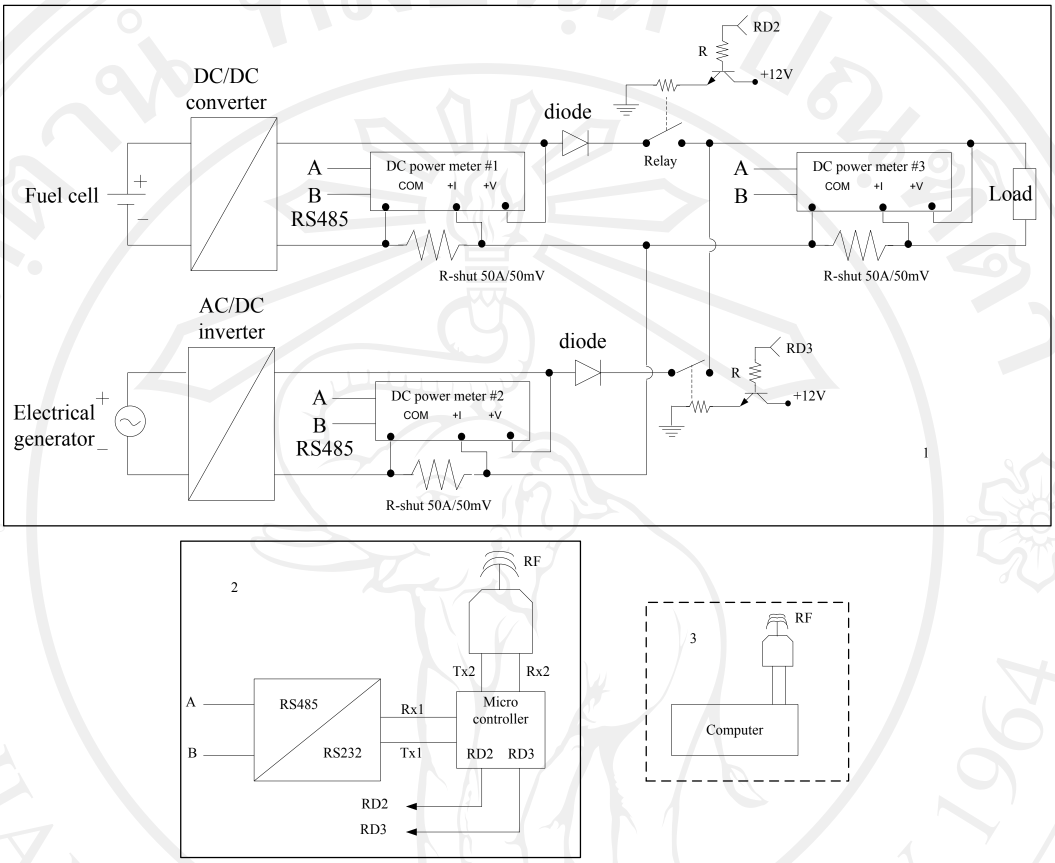
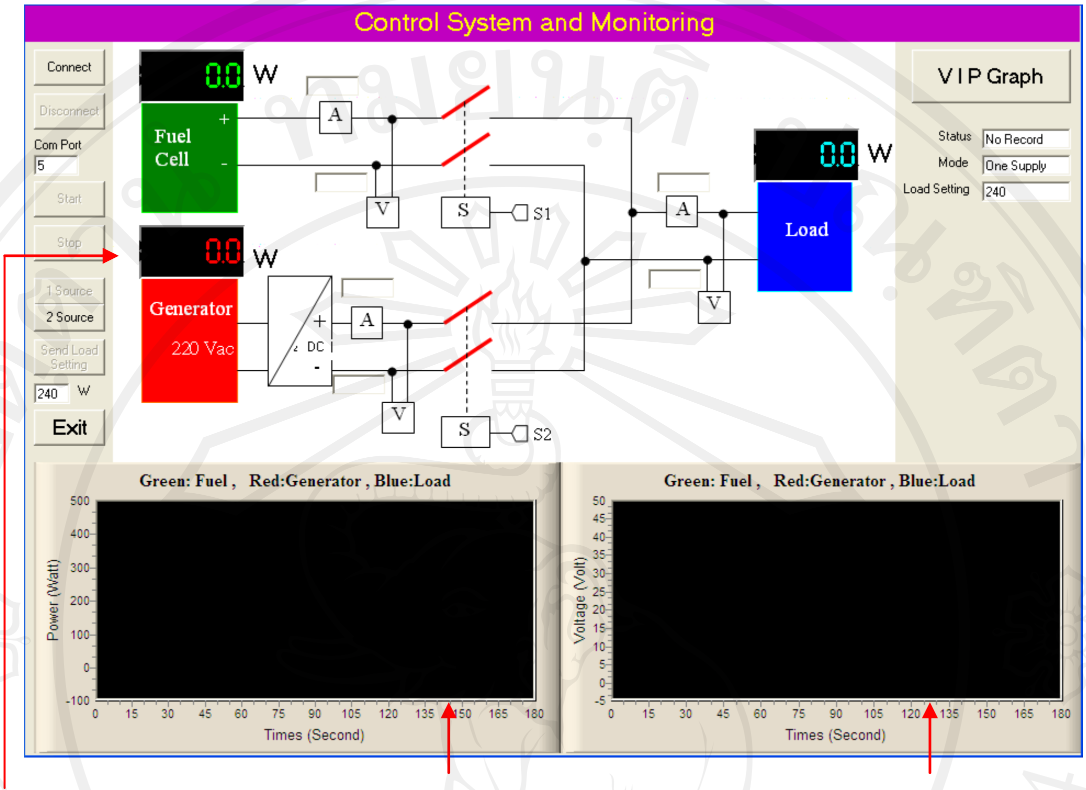


Figure 3.14 Wiring diagram of the hybrid system consists of (1) wiring diagram of 2 power source modules (2) the micro controller with RS485, and (3) data collector

Figure 3.15 shows the display connection of hybrid system with display on personal computer. Set point and operation strategy can be done by set value in the screen display. Screen display consists of input data (set point and operation strategy) and output graph of both output voltage and output power of fuel cell, electric generator and load.



Com Port: 5

240 W

Status: No Record

Mode: One Supply

Load Setting: 240

Watt meter

Power chart

Voltage chart

Figure 3.15 Display and monitor the wiring connection of hybrid system

3.3.7 Experimental procedure for Fuel Consumption of Fuel Cell

The concept of the hybrid system between fuel cell and electric generator, which used the gasoline engine power source is to find out the fuel consumption of each power sources under vary load conditions. This section tested the fuel cell consumption of hydrogen. The procedure of the experiment is following;

- Prepare the fuel cell test station as shown in Figure 3.16 by connecting the fuel cell module to electronic load.

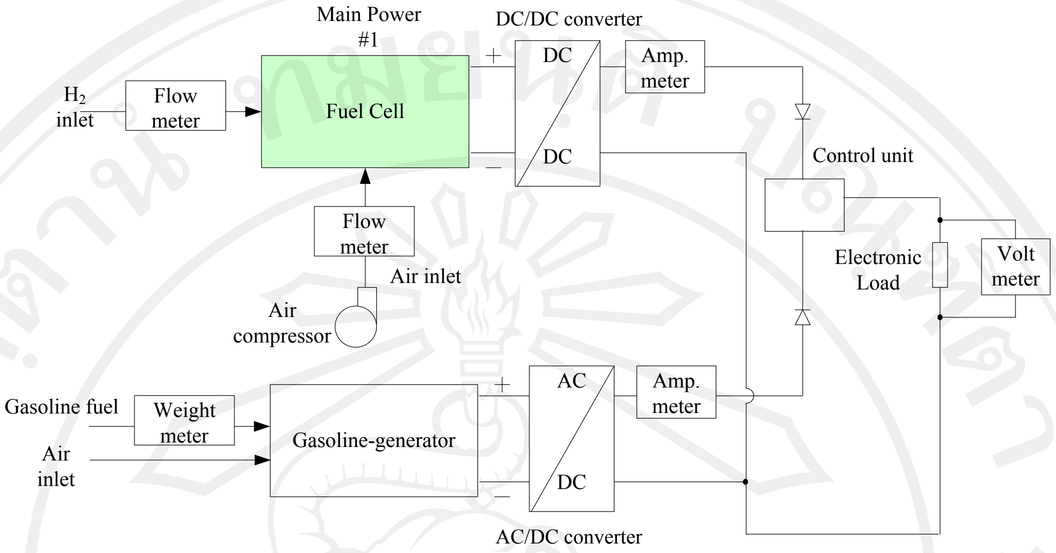


Figure 3.16 Schematic diagram of the fuel cell test hydrogen fuel consumption

- Set the hydrogen pressure range from 1 to 3 bars to determine fuel consumption at difference hydrogen pressure.
- Electronic load can be varying from 0 to 40 amp by stepping up every 2 amp in 2 minutes
- Hydrogen flow rate and air flow rate are recorded
- Data Analysis and determine the relationship between fuel consumption and load power.
- Investigation kinetic of the fuel consumption by empirical model.

3.3.8 Experimental procedure for Fuel Consumption of Gasoline Generator

This section describes the procedure of the experimental of gasoline fuel consumption in the system as shown in Figure 3.17.

- Prepare the gasoline generator and connect it with the electric load.
- Electronic load can be varying from 0 to 40 amp by stepping up every 2 amp in 2 minutes
- Gasoline fuel weight is recorded for every load conditions
- Data Analysis and determine the relationship between fuel consumption and load power.
- Investigation kinetic of the fuel consumption by empirical model.

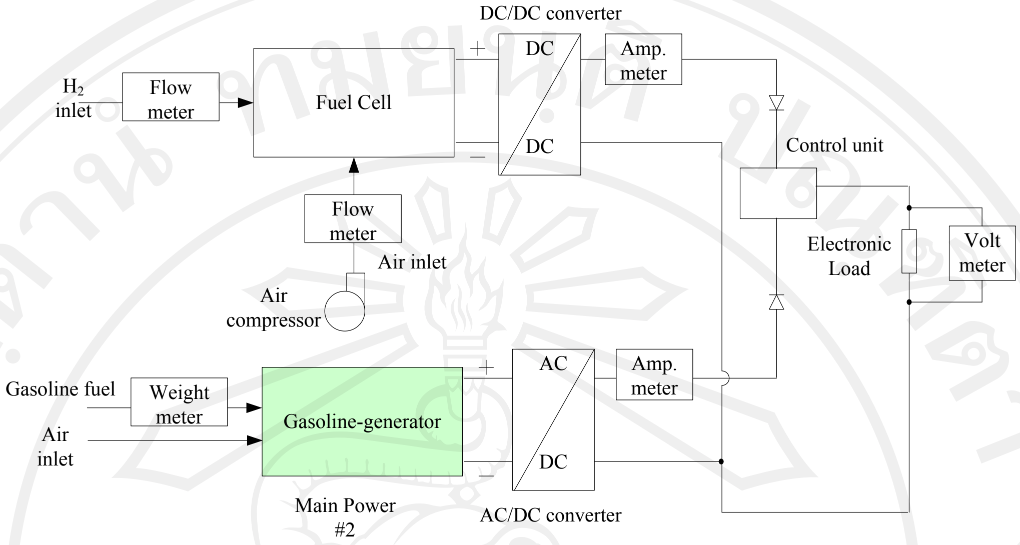


Figure 3.17 Schematic diagram of the gasoline generator test fuel consumption

3.3.9 Experimental procedure for Fuel Consumption of Hybrid System

This section describes the procedure of the experimental of gasoline fuel consumption in the system as shown in Figure 3.18.

- Prepare the hybrid system and connect it with the electric load.
- Electronic load can be varying from 0 to 40 amp by stepping up every 2 amp in 2 minutes
- Gasoline fuel hydrogen fuel is recorded for every load conditions
- Data Analysis and determine the relationship between fuel consumption and load power.
- Investigation kinetic of the fuel consumption by empirical model.

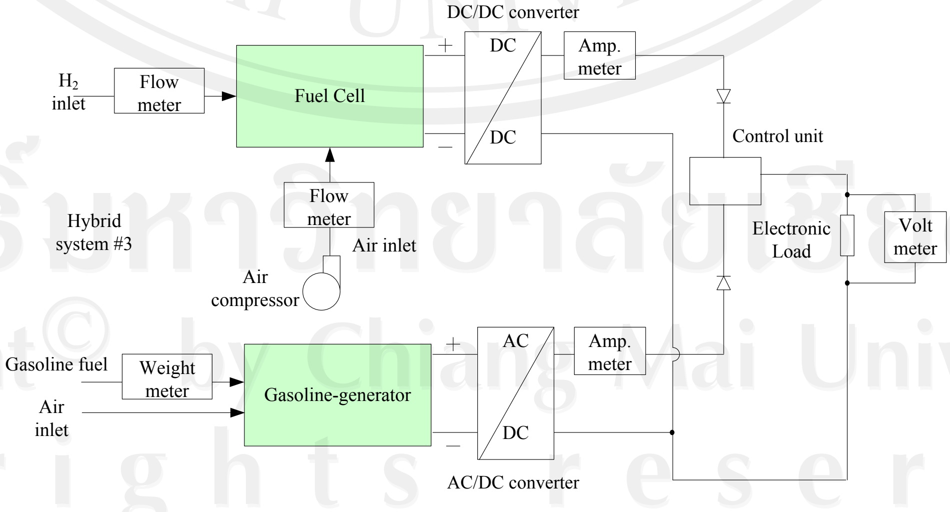


Figure 3.18 Schematic diagram of the hybrid system test fuel consumption

3.3.10 Experimental procedure of hybrid test station

The procedure for each experiment is as follows:

- Connect Nexa fuel cell module to test station and control unit box.
- Connect gasoline generator to test station and control unit box.
- Connect electronic load to test station and control unit box.
- Open hydrogen valve to feed gas hydrogen to the fuel cell system and adjust the hydrogen pressure at pressure regulator to designed operating pressure.
- Power on the personal computer and turn on the NexaMon OEM software program.
- Switch on start switch at the communication on the screen.
- Switch on the power supply 5V and switch on the communication switch of fuel cell system.
- Set the display and check box of the parameters.
- Power on the control unit box of hybrid system and switch on the gasoline generator in standby mode.
- Turn on the data collector unit and set the maximum power as set point where the power sources will be operated. Choose the operation strategy: Single power source or hybrid power source.
- Select the operation strategy to the case study: Case1, Case 2, or Case 3
- Turn on the electronic load and set the current profiles of load conditions and start the experimental.
- Save all data to the data collector.

The experiment procedure of the hybrid system starts with connecting all wiring of the devices as shown in Figure 3.18.. Then, open hydrogen valve, turn on computer and switch on the power of fuel cell communication. Set the parameter display on the screen. Then, power on the electronic load and set the load condition profiles. Turn on the control unit box. Select the operation strategy on the computer screen: switching case 1, switching case 2, or hybrid case 3. In the switching case 1, the fuel cell will be operated as the main power source and gasoline generator works as the add-on power sources in the case of fuel cell cannot supply load condition. The control system will check the power set point and compare with the power input, if power input less than the set point: fuel cell work and supply power to the load. If power input greater than the set point: fuel cell will be disconnected and the system will connect gasoline generator to the system. In the switching case 2, gasoline generator will be operated as the main power source and fuel cell works as the add-on power sources in the case of gasoline generator cannot supply load condition. The control system will check the power set point and compare with the power input, if power input less than the set point: gasoline generator work and supply power to the load. If power input greater than the set point: gasoline generator will be disconnected and the system will connect fuel cell to the system. Last case, the hybrid system, fuel cell will work as the main power source until the load power greater than the set point, the control system will connect gasoline generator to the system and let both power sources supply power to load power condition.

3.4 Hybrid Model

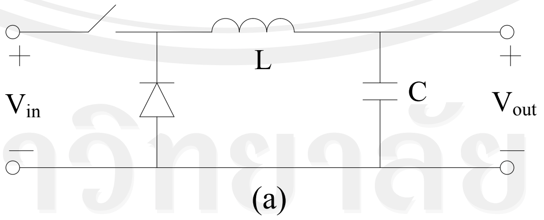
Model of the hybrid system consists of two main models. First model is stack fuel cell model with connected to DC/DC converter model to generate the output voltage 24 VDC to supply the electronic load. Second model is electric generator model with output voltage 220 VAC which is connected to AV/DC converter to convert the output voltage from 220 VAC to 24VDC.

3.4.1 DC/DC converter or Buck converter model

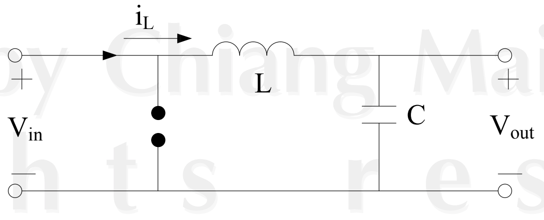
The output voltage from fuel cell is DC voltage at 43 voltages and reduced with changing load condition. In order to keep the output voltage of the fuel cell system constantly at the specific voltage at 24 VDC, buck converter is introduced. This converter is a simple circuit diagram that produces a lower average output voltage than its DC input voltage. The output voltage from buck converter range can be done by varying the duty cycle of the switch. The converter assumes two circuit diagram modes which depended on the position of the switch as shown in Figure 3.19. Mode 1: the switch is closed, the diode is reverse-biased and represents an open circuit; therefore, the input current charges the inductor (L). The voltage across the inductor is the difference of the input voltage and the output voltage. Mode 2: the switch is opened; the inductor resists the interruption of current by producing a voltage that forward biases the diode. The inductor current, i_L, remains continuous and circulates through the diode. For the inductor to maintain the current, diode must discharge. In this state, the voltage across the inductor is the difference between 0 and the output voltage, making it negative. Because of the steady-state inductor basic, the average voltage across the inductor must be zero. Therefore, the output voltage is governed by the following equation:

$$V_{out} = V_{in} d \tag{3.13}$$

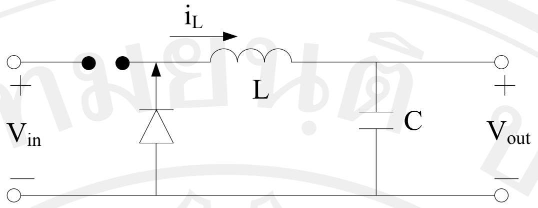
where V_{out} is the output voltage (V)
V_{in} is the input voltage (V)
d is the switch duty cycle



(a)



(b)



(c)

Figure 3.19 Buck converter operation (a) basic of buck converter topology, (b) topological mode 1: switch closed, and (c) topological mode 2: switch open

From the diagram of buck converter, the inductor must be determined the inductance of the system and can be calculated by;

$$L = \frac{V_{out}\ (1-d)}{I_{rip}\, I_{out}\, f} \tag{3.14}$$

where L is the inductance (mH)
I_{rip} is the ripple current
I_{out} is the output current (Amp)
f is the frequency (Hz)

The capacitor is also must be determined by:

$$\Delta V = \frac{I_{out}}{4Cf} \tag{3.15}$$

Then,

$$C = \frac{I_{out}}{4\Delta V f} \tag{3.16}$$

3.4.2 AC/DC inverter model

As mentioned in the previous section, the input of the fuel cell is 24 VDC to the control unit box. In order to get 24VDC from gasoline generator, the AC/DC inverter is used. A diode bridge rectifier is used as shown in Figure 3.20. A single phase bridge diode is used for electronic load that use direct current (DC). The operation of the single phase bridge diode can be present by the waveform of the AC voltage waveform: when the input voltage (AC) is positive, diodes number 1 and 2 conducts, while diodes number 3 and 4 are reverse biased and open circuited and when the input voltage is negative, diodes number 3 and 4 conduct while diodes number 1 and 2 are reverse biased and open circuited. Then, the DC output voltage is full wave rectifier sinusoid. The capacitor is used to keep the smooth DC waveform. The size of capacitor can be calculated:

$$C = \frac{P}{2fV_{peak}\, V_{ripple}} \tag{3.17}$$

where P is the output power (W)

V_{peak} is the maximum peak voltage (V)
v_{ripple} is the voltage ripple of peak voltage (V)

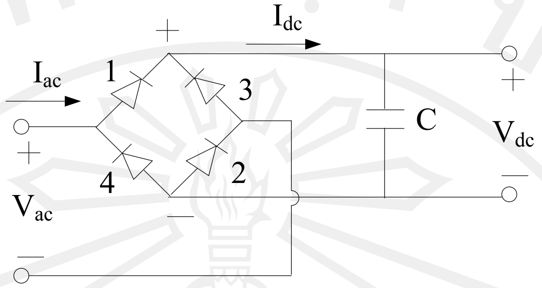


Figure 3.20 Single Phase Diode Bridge Rectifiers

3.4.3 Dynamic model of the fuel cell

The hydrogen flow rate of anode side can be determined from the derivative of the partial pressure as follows (Zhihao et al, 2006):

$$\frac{dp_{H2}}{dt} = \frac{RT}{V_{an}}\left(q_{H2}^{in} - q_{H2}^{out} - q_{H2}^{r}\right) \tag{3.18}$$

where R is the universal gas constant (1/kmol.K);
T is the absolute temperature (K);
V_{an} is the volume of the anode;
p_{H2} is the hydrogen partial pressure (atm);
q_{H2}^{in} is the hydrogen input flow rate (kmol/s);
q_{H2}^{out} is the hydrogen output flow rate (kmol/s); In the small size fuel cell such as Nexa^{TM} fuel cell module, q_{H2}^{out} can be set to 0, it is because of the channel of the anode is usually a dead-end (Assumed);
q_{H2}^{r} is the hydrogen flow rate that reacs inside the stack fuel cell (kmol/s).

Fundamental of an electrochemical relationship, the reacting of hydrogen flow rate can be determined:

$$q_{H2}^{r} = \frac{N_0 I_{FC}}{2F} = 2K_r I_{FC} \tag{3.19}$$

$$K_r = \frac{N_0}{4F} \tag{3.20}$$

Where F is the Faraday's constant (C/kmol);
K_r is the modeling constant (kmol/As);
N_0 is the number of the cells connected in series in the stack.

3.4.4 Fuel cell mass balance

Fuel cell mass balance is the sum of all mass inputs equal to the sum of all outputs. The inputs parameters are the flows of gas fuel and oxidant plus water vapor exist in those gases. The outputs parameters are the flows of unused gas fuel and oxidant, plus water vapor exist in the gases, plus any liquid water present in either fuel or oxidant exhaust. Fuel cell mass balance can be expressed as:

$$\sum(\dot{m}_i)_{in} = \sum(\dot{m}_i)_{out} \tag{3.21}$$

where the subscribe i represents the species of gases, such as H_2, O_2, N_2, $H_2O_{(g)}$ and $H_2O_{(l)}$.

3.4.4.1 Inlet flow rate

All the gas flow rates at inlet are proportional to current and number of cells. This is because of the output cell power is determined:

$$W_{el} = n_{cell} V_{cell} I \tag{3.22}$$

where n_{cell} is the number of cells;
V_{cell} is the output voltage of fuel cell (V);
I is the load current (Amp).

All the flow rates are also proportional to output power of fuel cell and inversely proportional to cell voltage;

$$I \cdot n_{cell} = \frac{W_{el}}{V_{cell}} \tag{3.23}$$

From hydrogen mass flow rate (g/s), it can be calculated by;

$$\dot{m}_{H2,in} = S_{H2}\dot{m}_{H2,cons.} = S_{H2}\frac{M_{fuel}}{2F} I \cdot n_{cell} \tag{3.24}$$

where $\dot{m}_{H2,in}$ is the hydrogen mass flow rate at inlet;
$\dot{m}_{H2,cons}$ is the hydrogen mass flow rate consumption;
S_{H2} is the stoichiometric ratio of hydrogen;
M_{fuel} is the hydrogen molecular.

In case of hydrogen is in a gas mixture, with hydrogen, r_{H2} volume and molar fraction, and then the mixture flow rate is:

$$\dot{m}_{fuel} = \frac{S_{H2}}{r_{H2}}\frac{M_{fuel}}{2F} I \cdot n_{cell} \tag{3.25}$$

Oxygen mass flow arte in g/s can be calculated:

$$\dot{m}_{O2,in} = S_{O2}\dot{m}_{O2,cons.} = S_{O2}\frac{M_{O2}}{2F}I \cdot n_{cell} \tag{3.26}$$

In case of fuel cell use air instead of oxygen, the oxygen mass flow rate in g/s can be determined:

$$\dot{m}_{air,in} = \frac{S_{O2}}{r_{O2}}\frac{M_{Air}}{4F}I \cdot n_{cell} \tag{3.27}$$

Nitrogen mass flow rate in g/s is:

$$\dot{m}_{N2,in} = S_{O2}\frac{M_{N2}}{4F}\frac{1-r_{O2in}}{r_{O2in}}I \cdot n_{cell} \tag{3.28}$$

Water vapor in hydrogen inlet the fuel cell in g/s can be calculated:

$$\dot{m}_{H2OinH2in} = S_{H2}\frac{M_{H2O}}{2F}\frac{\varphi_{an}P_{vs(T_{an,in})}}{P_{an}-\varphi_{an}P_{vs(T_{an,in})}}I \cdot n_{cell} \tag{3.29}$$

Water vapor in fuel inlet in g/s is:

$$\dot{m}_{H2Oinfuelin} = \frac{S_{H2}}{r_{H2}}\frac{M_{H2O}}{2F}\frac{\varphi_{an}P_{vs(T_{an,in})}}{P_{an}-\varphi_{an}P_{vs(T_{an,in})}}I \cdot n_{cell} \tag{3.30}$$

Water vapor in oxygen inlet in g/s is:

$$\dot{m}_{H2OinO2in} = S_{O2}\frac{M_{H2O}}{4F}\frac{\varphi_{ca}P_{vs(T_{ca,in})}}{P_{ca}-\varphi_{ca}P_{vs(T_{ca,in})}}I \cdot n_{cell} \tag{3.31}$$

Water vapor in air inlet in g/s is:

$$\dot{m}_{H2OinAirin} = \frac{S_{O2}}{r_{O2}}\frac{M_{H2O}}{4F}\frac{\varphi_{an}P_{vs(T_{an,in})}}{P_{an}-\varphi_{an}P_{vs(T_{an,in})}}I \cdot n_{cell} \tag{3.32}$$

3.4.4.2 Outlet flow rates

The equation of the outlet mass flow rates must be accounted for reactants consumption, water generation, and water net transport across the membrane. The unused hydrogen flow rate is:

$$\dot{m}_{H2out} = (S_{H2}-1)\frac{M_{H2}}{2F}I \cdot n_{cell} \tag{3.33}$$

The net water transport is:

$$\dot{m}_{H2OinH2out} = \dot{m}_{H2OinH2in} - \dot{m}_{H2OED} + \dot{m}_{H2OBD} \tag{3.34}$$

$$\dot{m}_{H2OED} = \varepsilon \frac{M_{H2O}}{F} I \cdot n_{cell} \tag{3.35}$$

$$\dot{m}_{H2OBD} = \beta\varepsilon \frac{M_{H2O}}{F} I \cdot n_{cell} \tag{3.36}$$

where ε is a number of water molecules per proton;
β is back diffusion

The water vapor content/flux at anode outlet is smaller of total water flux at anode outlet and the maximum amount the exhaust gas can be determined (saturation):

$$\dot{m}_{H2OinH2out,V} = min\left[(S_{H2} - 1)\frac{M_{H2O}}{2F}\frac{P_{vs(T_{an,out})}}{P_{an} - \Delta P_{an} - P_{vs(T_{an,out})}} I \cdot n_{cell} \cdot m_{H2OinH2out}\right] \tag{3.37}$$

where ΔP_{an} is the pressure drop on the anode side.

The amount of liquid water is the difference between the total water present at the exhaust and water vapor:

$$\dot{m}_{H2OinH2out,L} = \dot{m}_{H2OinH2out} - \dot{m}_{H2inH2out,V} \tag{3.38}$$

At similar set of equation may be applied for the cathode exhaust. Oxygen flow rate at the outlet unused oxygen is equal to oxygen supplied at the inlet minus oxygen consumed in the fuel electrochemical reaction:

$$\dot{m}_{H2out} = (S_{O2} - 1)\frac{M_{O2}}{4F} I \cdot n_{cell} \tag{3.39}$$

Nitrogen flow rate at the exit is the same as the flow rate at the inlet.

$$\dot{m}_{N2,out} = \dot{m}_{N2,in} = S_{O2}\frac{M_{N2}}{4F}\frac{1-r_{O2in}}{r_{O2in}} I \cdot n_{cell} \tag{3.40}$$

Depleted air flow rate is then simply a sum of oxygen and nitrogen flow rates:

$$\dot{m}_{airout} = \left[(S_{O2} - 1)M_{O2} + S_{O2}\frac{1-r_{O2in}}{r_{O2in}} M_{N2}\right]\frac{I \cdot n_{cell}}{4F} \tag{3.41}$$

Water content in the cathode exhaust is:

$$\dot{m}_{H2OinAirout} = \dot{m}_{H2OinAirin} + \dot{m}_{H2Ogen} + \dot{m}_{H2OED} - \dot{m}_{H2OBD} \tag{3.42}$$

The water vapor content/flux at cathode outlet is the smaller of total water flux at cathode outlet and the maximum amount the exhaust gas can be determined (saturation):

$$\dot{m}_{H2OAirout,V} = min\left[\frac{(S_{O2}-r_{O2in})}{r_{O2in}}\frac{M_{H2O}}{4F}\frac{P_{vs(T_{ca,out})}}{P_{ca}-\Delta P_{ca}-P_{vs(T_{ca,out})}} I \cdot n_{cell} \cdot m_{H2OinAirout}\right] \quad (3.43)$$

where ΔP_{ca} is the pressure drop on the cathode side.

The amount of liquid water is the difference between the total water present at the exhaust and water vapor:

$$\dot{m}_{H2OinAirout,L} = \dot{m}_{H2OinAirout} - \dot{m}_{H2inAirout,V} \quad (3.44)$$

3.4.5 Fuel cell energy balance

Fuel cell energy balance is the sum of all energy inputs is equally to the sum of all energy outputs, which can be determined:

$$\sum(H_i)_{in} = W_{el} + \sum(H_i)_{out} + Q \quad (3.45)$$

where $\sum(H_i)_{in}$ is the sum of all enthalpy inputs to the fuel cell;
W_{el} is the electric power produced;
$\sum(H_i)_{out}$ is the sum of all enthalpy outputs of fuel cell;
Q is heat flux out of the fuel cell.

The parameters inputs are the enthalpies of all the flows into the fuel cell, namely fuel and oxidant, plus enthalpy of water exist in those gases. For each dry gas or a mixture of dry gases, the enthalpy in J/s can be determined:

$$H = \dot{m}\, c_p T \quad (3.46)$$

where $\dot{m}$ is mass flow rate of gas or mixture (g/s)
c_p is specific heat (J/g.K)
T is temperature in °C

Note that the use of temperature in degree Celsius implies that 0°C has been selected as a reference state for all enthalpies. If a gas is combustible, that is, it has a heating value, its enthalpy is then:

$$H = \dot{m}\left(c_p T + h_{HHV}^{0}\right) \quad (3.47)$$

where h_{HHV}^{0} is the high heating value of that gas (J/g) at 0°C. Typically, heating values are reported and tabulated at 25°C. The difference between the heating value at 25°C and 0°C is the difference between enthalpies of reactants and products at those two temperatures. For hydrogen:

$$h_{HHV}^{0} = h_{HHV}^{25} - \left(c_{p,H2} + \frac{1}{2}\frac{M_{O2}}{M_{H2}}c_{p,O2} - \frac{M_{H2O}}{M_{H2}}c_{p,H2O(l)}\right)\cdot 25 \quad (3.48)$$

Enthalpy of water vapor can be calculated:

$$H = \dot{m}_{H2O(g)}\left(c_{p,H2O(g)}T + h_{fg}^{0}\right) \tag{3.49}$$

Enthalpy of liquid water can be calculated:

$$H = \dot{m}_{H2O(l)}\left(c_{p,H2O(l)}T\right) \tag{3.50}$$

Figure 3.21 shows the calculation procedure flowchart of hybrid system. All parameters are input to the model and are calculated following in section 3.2 and 3.3. Then, the strategy operations of hybrid system is selected which desigbed to operated the system in 3 cases as mention in previous section in order to ivestigate the behavior and power responding to load conditions. First case study; fuel cell operates as the main power source. Second case study; an electric generator operates as main power source and third case study; both of fuel cell and electric generator work together as a hybrid power source to supply the electronic load.

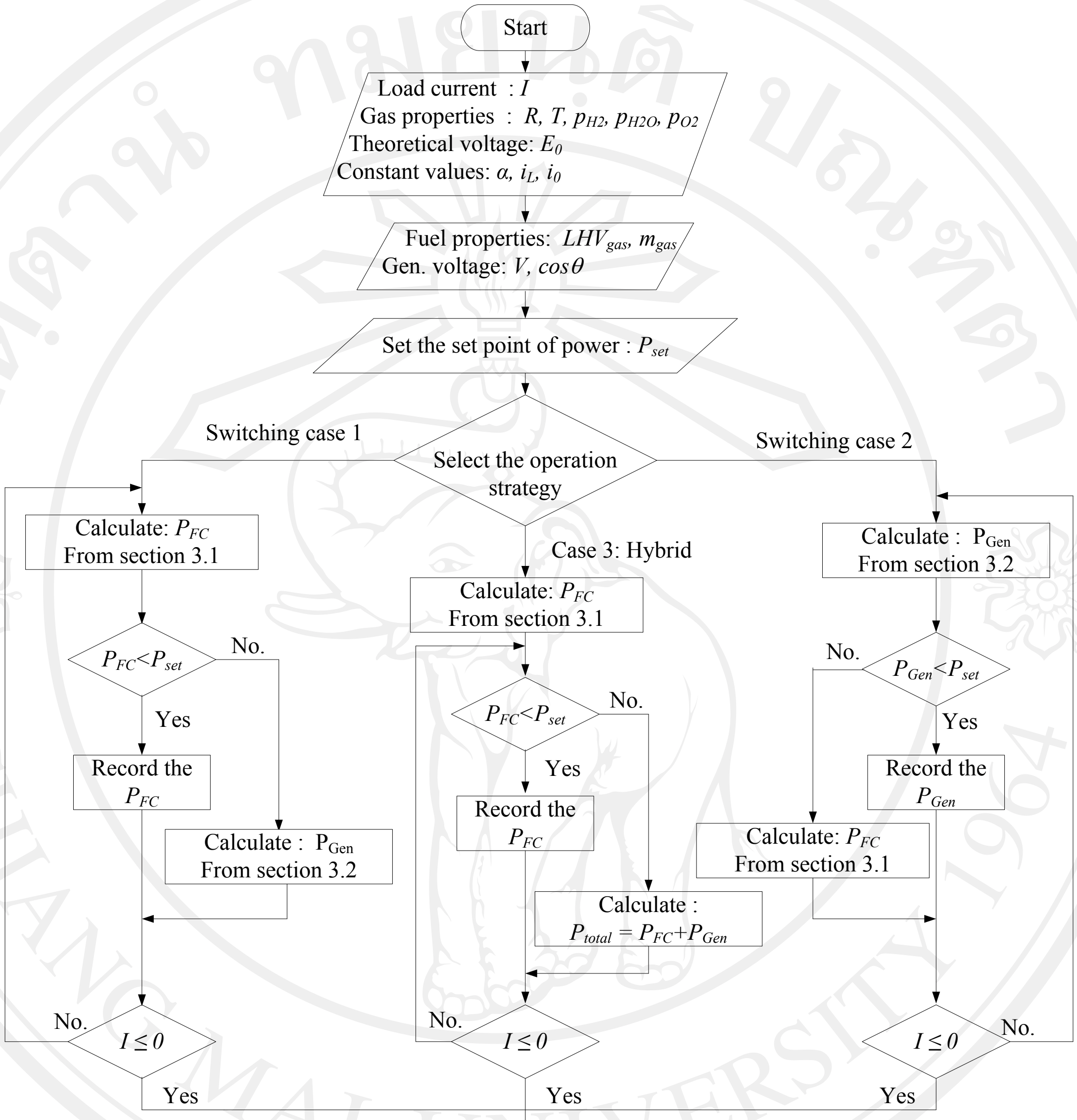


Figure 3.21 Calculation procedure flowchart of hybrid system