CHAPTER 3 METHODOLOGY

The aim of this work is to apply the stability analysis based on passivity concept to proton exchange membrane fuel cell (PEMFC) and to design the passivity based controller for this process. There are seven steps in the analysis as shown in Figure 3.1. The details of each step are described below.

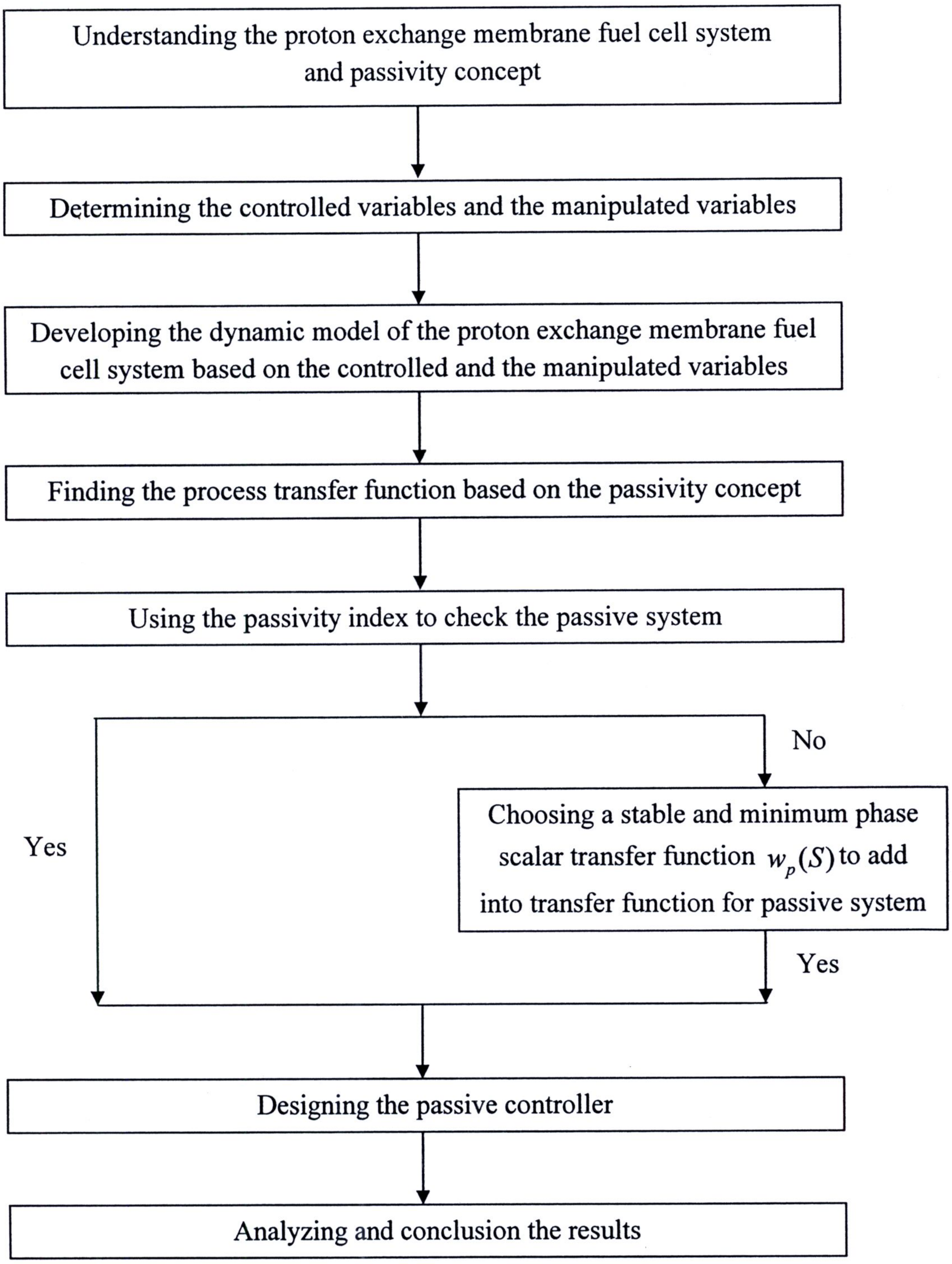

Figure 3.1 The methodology

3.1 Understanding the proton exchange membrane fuel cell system and passivity concept

First of all, the overview of proton exchange membrane fuel cell (PEMFC) was studied from the literature reviews. There were three sections (control volume) in macroscopic of PEMFC which were the cathode channel, the anode channel and the fuel cell body. The dynamic behavior was studied from the book of PEM fuel cell modeling and simulation using Matlab. In this step, the mass and energy dynamic model of all three sections were considered. The auxiliary equipments connected with PEMFC were also studied in order to manage the energy supply for PEMFC. There were the hydrogen supply system, the air supply system and the thermal management. Moreover, the concept of passivity was understood in order to apply into the PEMFC system. Figure 3.2 illustrated the proton exchange membrane fuel cell including the auxiliary equipments.

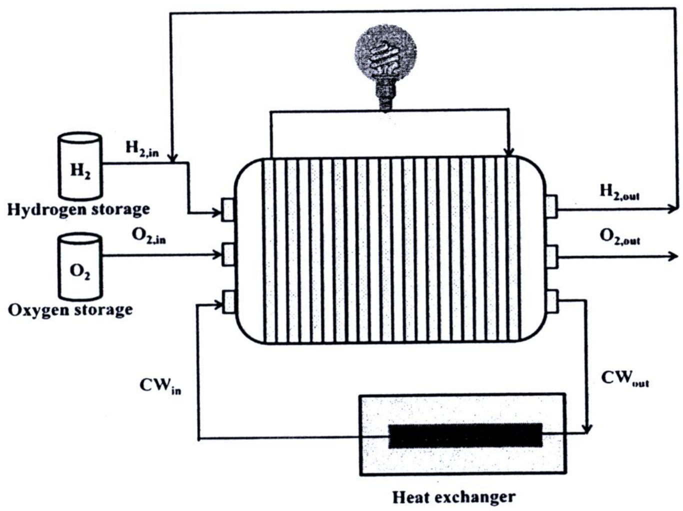

Figure 3.2 The proton exchange membrane fuel cell including the auxiliary equipments

In this work, the amount of hydrogen and oxygen was assumed to be regularly produced from electrolyzer, the water electrolysis which decomposed water molecule into oxygen and hydrogen [15]. Since the high cost of hydrogen, the hydrogen consumption was reduced by re-circulating the excess hydrogen to its inlet.

3.2 Determining the controlled and the manipulated variables of the process

In this step, the controlled and manipulated variables of proton exchange membrane fuel cell system were determined. The PEMFC system consisted of three control loops, the controlled variables were the hydrogen and oxygen pressure in anode and cathode channel, and the stack temperature by manipulation of the hydrogen and oxygen flowrate, and the cooling water flowrate. Since, the hydrogen and oxygen pressure and the stack temperature directly affected to the relative humidity and the cell voltage, the relative humidity was controlled by manipulation of the cooling water flowrate, while the cell voltage was controlled by manipulation of the hydrogen and oxygen flowrate. The paring of the controlled and the manipulated variables were illustrated in Table 3.1.

Table 3.1 The paring of the controlled and the manipulated variables

Controlled variable	Manipulated variable
Stack temperature (T_s)	Cooling water flowrate ($\dot{m}_{cw}$)
Hydrogen partial pressure (P_{H_2})	Hydrogen flowrate ($\dot{m}_{H_2}$)
Oxygen partial pressure (P_{O_2})	Oxygen flowtare ($\dot{m}_{O_2}$)

3.3 Developing the dynamic model of the proton exchange membrane fuel cell system based on the controlled and the manipulated variables

After the controlled and manipulated variables were obtained, the dynamic models of the proton exchange membrane fuel cell were proposed. The dynamic model of mass was presented in the form of continuity equation, the momentum equation was not included as this work concerning with macroscopic level. For the dynamic model of energy, the kinetic and potential energy of the gases were neglected. However, there were some assumptions used in this work in order to derive a simplified nonlinear dynamic PEMFC model as following:

Assumption

1. Proton exchange membrane fuel cell is 5kw Ballard stack.
2. All gas components are assumed to be an ideal gas [12]
3. Hydrogen gas and oxygen gas are produced by the electrolyzer [23]
4. The voltage loss between each individual cell is neglected.

The PEMFC dynamic models were divided into mass and energy models which can be illustrated as following:

Mass transfer modeling:

Anode:
$$\frac{V_{an}}{RT_s}\frac{dP_{H_2}}{dt} = \dot{m}_{H_2,in} - k_{an}(P_{H_2} - P_{H_2,in}) - \frac{NI}{2F} \tag{3.1}$$

Cathode:
$$\frac{V_{cat}}{RT_s}\frac{dP_{O_2}}{dt} = \dot{m}_{O_2,in} - k_{cat}(P_{O_2} - P_{O_2,out}) - \frac{NI}{4F} \tag{3.2}$$

Energy transfer modeling:

Fuel cell stack:
$$c_t\frac{dT_s}{dt} = K_{conv,amb}(T_{amb} - T_s) + \frac{NI}{2F}\Delta H - V_{stack}I - \frac{\dot{m}_{cw}\, c_{p,w} Mw_w (T_s - T_c)}{1000} \tag{3.3}$$

The numerical values of all parameters were shown in Appendix A based on the 5kW Ballard PEM fuel cell.

3.4 Finding the transfer function of PEMFC system based on the passivity concept

Since the dynamic models of PEMFC system were the nonlinear system, linearization of all equations should be done before finding the transfer function. First of all, the linear dynamic models were written in the form of state space using Equations 2.19-20. In this work, the state, the manipulated and the controlled variables were presented in Table 3.1. After that, the transfer function of PEMFC system and disturbance in matrix form (Equations 2.21-22) were found out using Matlab.

3.5 Using the passivity index to check the passive system

The passivity index was used to indicate that the system was passive or not by using Equation 2.25. If the system is non-passive, it was necessary to add a stable and minimum phase scalar transfer function $w_p(s)$ into transfer function of the system for passive system. The minimum phase scalar transfer function was found by solving the optimization problem 1 (Equation 2.29). Therefore, this process would be guaranteed stable from the passive concept.

3.6 Designing the passive controller

After the PEMFC system was passive system, the multi-loop PI controller was designed for each loop control. The parameters of PI controller that make the PEMFC system be stable are obtained by solving problem 2 (Equations 2.34-35). Then, the weighting function was absorbed into the controller by using Equation 2.36 to make the PEMFC system was decentralize unconditionally stable.

3.7 Analyzing and conclusion the result

In this step, the results of the process was analyzed that the process was stable or not. Then, verify the passive controller for stabilizing the process. Finally, conclude the overall works.