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Optimal Feedback Linearization Control of PEM Fuel Cell

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***Abstract*—**This paper presents a new method to design nonlinear feedback linearization controller for PEMFCs (Polymer Electrolyte Membrane Fuel Cells). A nonlinear controller is designed based on nonlinear model to prolong the stack life of PEMFCs. Since it is known that large deviations between hydrogen and oxygen partial pressures can cause severe membrane damage in the fuel cell, feedback linearization is applied to the PEMFC system so that the deviation can be kept as small as possible during disturbances or load variations. To obtain an accurate feedback linearization controller, tuning the linear parameters are always important. So in proposed study NSGA (Non-Dominated Sorting Genetic Algorithm)-II method was used to tune the designed controller in aim to decrease the controller tracking error. The simulation result showed that the proposed method tuned the controller efficiently.

***Keywords*—**Feedback Linearization controller, NSGA, Optimal Control, PEMFC.

I. Introduction

A FUEL cell is an electrochemical energy device that converts the chemical energy of fuel directly into electricity and heat with water which are product of the chemical reaction. As a renewable energy source, the fuel cell is widely regarded as one of the most promising energy sources because of its high energy efficiency, extremely low emission of oxides of nitrogen and sulfur, and very low noise, as well as the cleanness of its energy production. In order to generate a reliable and efficient power response and to prevent membrane damage as well as detrimental degradation of the stack voltage and oxygen depletion, it is necessary to design a better control scheme to achieve optimal air and hydrogen inlet flow rates.

To apply a suitable nonlinear control scheme, it is necessary to obtain a PEMFC accurate mathematical modeled. Several researches has been done, for obtaining the PEMFC model, ranging from stationary and dynamic models [1]-[6] to the control design applied to a fuel cell vehicle and a distributed generation system [7], [8]. An accurate nonlinear dynamic model needs to be developed for the fuel cell system as well as an advanced controller design technique, considering the nonlinearity and uncertainty that need to be proposed. Purkrushpan et al. [1] developed a control-oriented PEMFC model that includes flow characteristics and dynamics of the compressor and the manifold (anode and cathode), reactant partial pressures, and membrane humidity. However, because of the non-linear relationship between stack voltage and load, and the state equations [1], [5], it is a challenge to develop a nonlinear controller for the PEMFC.

A fuzzy control system for a boost dc/dc converter of a fuel cell system was developed in [9]. Neural optimal control was presented for the PEMFC by using an Artificial Neural Network (ANN) in [10]. However, instead of controlling the PEM fuel cell system, the neural optimal control is mainly used to derive a new architecture to synthesize an approximated optimal control by means of the ANN, where the PEM fuel cell was chosen as a test bed. Also a comprehensive nonlinear model which is proper for feedback linearization control is introduced on [11]. An adaptive inverse controller using Radial Basis Function Neural Network (RBFNN) to PEMFC system is designed on [12].This control scheme has the advantage of not needing to identify the dynamical parameters of the system for design and scheduling of the controller parameters. Also an adaptive controller for PEM is designed on [13] that the adaptive 2DOF controller is used in order to obtain certain control performances for membrane conductivity management. The controller is implemented with 2 PID structures and an adaptation rule which was based on gain-scheduling method.

In this paper a nonlinear feedback linearization controller for nonlinear PEMFC is designed. To improve accuracy of proposed design, the control parameter of feed-back linearization is tuned by NSGA-II. It is common to use pole placement or Lyapunov theory to obtain linear control parameter, but it is not an accurate way to tune these parameters. So we used NSGA_II optimization algorithm to tune these parameter in an optimal way. Based on [14], NSGA-II, in most problems, is able to find much better spread of solutions and better convergence near the true optimal solution compared to other Evolutionary Algorithm (EA). So we used NSGA-II method to tune the linear controller parameters by considering our objectives in an optimal way. Based on author research there is no report of using this method for optimizing the feedback linearization parameters. The simulation result showed by using this method more accurate and precise feed-back linearization is achieved.

The paper is organized as follows: in Section II we proceed with a brief overview of mathematical model of PEMFC model, whereas feedback linearization method explained in Section III, and the procedure to design stabilizing controller is illustrated on IV. The NSGA-II explained in Section V. Then in Section VI we proceed with the numerical simulation of classic feedback linearization, linear control and introduced method, while the conclusions are provided in Section VII.

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II. Mathematical Model of PEMFC

A PEM fuel cell consists of a polymer electrolyte membrane sandwiched between two electrodes. In the electrolyte, only ions can exit and electrons are not allowed to pass through. So, the flow of electrons needs a path like an external circuit from the anode to the cathode to produce electricity because of a potential difference between the anode and cathode. The overall electrochemical reactions for a PEMFC fed with a hydrogen-containing anode gas and an oxygen-containing cathode gas are as follows:

$$\begin{aligned} &Anode: 2H_2 \leftrightarrow 4H^+ + 4e^- \\ &Cathode: O_2 + 4H^+ + 4e^- \leftrightarrow 2H_2O \\ &Overall: 2H_2 + O_2 \leftrightarrow 2H_2O + electricity + heat \end{aligned}$$

The PEMFC is composed of the following components: Anode Plate, Anode Gas Diffusion Layer, Anode Catalyst Layer, PEM, Cathode Catalyst Layer, Cathode Gas Diffusion Layer and Cathode Plate. From Anode side, the hydrogen enters through the anode gas diffusion layer (GDL) and reaches the anode catalyst layer (CL). Here, in the presence of the catalyst, hydrogen separates from its electron and travels through the PEM on the other side as proton H^+. Meanwhile, the electron is transferred through the load towards the cathode plate where it reaches the cathode GDL.

Oxygen molecules, O_2 which are present in the cathode GDL, due to the presence of catalyst on cathode side, they separate into individual oxygen atoms and further a combination reaction takes place. One oxygen atom and two H^+ protons with a couple of electrons coming through the load, they form an H_2O water molecule. During this reaction, an electromotive force is exhibited with respect to the load and heat is released in the environment. On the anode side, a fuel processor, a so-called reformer, that generates hydrogen through reforming methane or other fuels like natural gas, can be used instead of the pressurized hydrogen tank. A pressure regulator and purging of the hydro-gen component are also needed. On the cathode side, an air supply system containing a compressor, an air filter, and an air flow controller are required to maintain the oxygen partial pressure. On both sides, a humidifier is needed to prevent dehydration of fuel cell membrane. In addition, a heat exchanger, a water tank, a water separator, and a pump may be needed for water and heat management in the FC systems [15]-[17].

Producing a higher voltage, multiple cells have to be connected in series. Typically, a single cell produces voltage between 0 and 1 V based on the polarization I–V curve, which expresses the relationship between stack voltage and load current [15], [17]. The output stack voltage V_{st} [15] is defined as a function of the stack current, reactant partial pressures, fuel cell temperature, and membrane humidity:

$$V_{st} = E - V_{activation} - V_{ohmic} - V_{concentration} \tag{1}$$

In above equation, E is the thermodynamic potential of the cell or reversible voltage based on the Nernst equation, $V_{activation}$ is the voltage loss due to the rate of reactions on the surface of the electrodes, V_{ohmic} is the ohmic voltage drop from the resistances of proton flow in the electrolyte, and $V_{concetration}$ is the voltage loss from the reduction in concentration gases or the transport of mass of oxygen and hydrogen. Their equations are given as follows [15]:

$$E = N_0[V_0 + (RT/2F)\ln(P_{H_2}\sqrt{P_{O_2}} / P_{H_2}O_c)] \tag{2}$$

$$V_{activation} = N\frac{RT}{2\alpha F}\ln\left(\frac{I_{fc}+I_n}{I_o}\right) \tag{3}$$

$$V_{ohm} = NI_{fc}r \tag{4}$$

$$V_{concentration} = Nm\exp(nI_{fc}) \tag{5}$$

where P_{H_2}, P_{O_2}, and $P_{H_2O_C}$ are the partial pressures of hydrogen, oxygen, and water, respectively. Subscript c means the water partial pressure, which is vented from the cathode side. The voltage parameters of cell can be seen on Table I.

TABLE I
Cell Voltage Parameters

Parameter	Definition
N	Cell Number
V_0	Open Cell voltage [V]
R	Universal gas constant [$j/gm-mol-k$]
T	Temperature of the fuel cell [K]
F	Faraday constant
α	Charge transfer coefficient
I_{fc}	Output current density [A/cm^2]
I_0	Exchange current density [A/cm^2]
I_n	Internal current density [A/cm^2]
m and n	Constant in the mass transfer voltage
r	Area-specific resistance [$k\Omega cm^2$]

The nonlinear equation of PEMFC Anode and Cathode side are obtained from [11] as follows:

Anode side equations:

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_A}\left[u_a k_a Y_{H_2}\lambda_{H_2} - C_1 I_{fc} - (u_a k_a \lambda_{H_2} - C_1 I_{fc})F_{H_2}\right] \tag{6}$$

$$\frac{dP_{H_2O_a}}{dt} = \frac{RT}{V_A}\left[\begin{array}{l} u_a k_a \lambda_{H_2}\dfrac{\varphi_a P_{vs}}{P_{H_2} + P_{H_2O_A} - \varphi_a P_{vs}} - \\ \left(u_a k_a \lambda_{H_2} - C_2 I_{fc}\right)F_{H_2O_A} - C_2 I_{fc} \end{array}\right] \tag{7}$$

Cathode side equations:

$$\frac{dP_{O_2}}{dt} = \frac{RT}{V_C}\left[u_c k_c Y_{O_2}\lambda_{air} - \frac{C_1}{2}I_{fc} - \left(u_c k_c Y_{N_2}\lambda_{air} - \frac{C_1}{2}I_{fc}\right)F_{O_2}\right] \tag{8}$$

$$\frac{dP_{N_2}}{dt}=\frac{RT}{V_C}\left[u_c k_c Y_{N_2}\lambda_{air}-u_c k_c \lambda_{air} F_{N_2}\right] \quad (9)$$

$$\frac{dP_{H_2O_C}}{dt}=\frac{RT}{V_C}\begin{bmatrix} u_c k_c \lambda_{air}\dfrac{\varphi_c P_{vs}}{P_{O_2}+P_{N_2}+P_{H_2O_c}-\varphi_c P_{vs}}+C_1 I_{fc} \\ -(u_c k_c \lambda_{air}+C_1 I_{fc}+C_2 I_{fc})F_{H_2O_c}+C_2 I_{fc} \end{bmatrix} \quad (10)$$

where u_a and u_c are the input control variables, k_a and k_c the conversion factors, $Y_{H_2}, Y_{O_2}, Y_{N_2}$ are the initial mole fractions and set to be 0.99, 0.21, and 0.79, respectively. ϕ_a and ϕ_c are the relative humidity's on the anode and the cathode sides, respectively, P_{vs} is the saturation pressure, which can be found in the thermodynamics tables, F_{H_2}, $F_{H_2}O_A$, F_{O_2}, F_{N_2} and $F_{H_2O_c}$ are the pressure fractions of gases inside the fuel cell, given as follows:

$$F_{H_2}=\frac{\mathrm{pH_2}}{\mathrm{pH_2}+\mathrm{pH_2}O_a}, F_{H_2O_a}=\frac{\mathrm{pH_2}O_a}{\mathrm{pH_2}+\mathrm{pH_2}O_a}, F_{O_2}=\frac{\mathrm{pO_2}}{\mathrm{pO_2}+\mathrm{pN_2}+\mathrm{pH_2}O_c} \quad (11)$$
$$F_{N_2}=\frac{\mathrm{pN_2}}{\mathrm{pO_2}+\mathrm{pN_2}+\mathrm{pH_2}O_c}, F_{H_2O_c}=\frac{\mathrm{pH_2}O_c}{\mathrm{pO_2}+\mathrm{pN_2}+\mathrm{pH_2}O_c}$$

III. Feedback Linearization Control

In this section, we present the feedback linearization technique. Feedback linearization is a control design methodology that uses a feedback signal to cancel inherent dynamics and simultaneously achieves a specified desired dynamic response [18]. To exemplify the working principle of the feedback linearization, consider a system of order n with the same number m of inputs u and outputs y and affine in the control inputs. This type of system can be mathematically represented by:

$$\begin{aligned}\dot{x}&=f(x)+G(x)u\\ y&=h(x)\end{aligned} \quad (12)$$

where f and h are vector fields in R^n and R^m, respectively, and G is an $n\times m$ control effectiveness matrix. The procedure to obtain the feedback linearization for system inversion consists of consecutive time differentiations of y until an explicit dependence on u appears. To each derivative, a new state vector is associated and the derivative of the last state vector is given by a nonlinear expression (the virtual control) to complete the transformation [19].Assuming now $h(x)=x$, the first-order time-derivative of y is given by:

$$\dot{y}=\dot{x}=f(x)+G(x)u \quad (13)$$

Since an explicit dependence on u was already found, the linear relation can be imposed if $G(x)\neq 0$ by selecting:

$$u=G(x)^{-1}[\dot{x}-f(x)] \quad (14)$$

Replacement of the inherent dynamics with the desired dynamics results in the control that will produce the desired dynamics.

$$u=G(x)^{-1}[\dot{x}_d-f(x)] \quad (15)$$

where subscript d denote the desired dynamic. The desired dynamic is usually obtained by linear controllers, such as PD.

A. Controller Design

Up to here the MI-MO (Multi Input-Multi Output) dynamic nonlinear model of PEMFC is derived from (6-10), and the structure of feedback linearization controller is illustrated. In this section the procedure of implementing feedback linearization controller on a PEMFC is stated. We used feedback linearization in order to minimize the difference ΔP between the hydrogen and oxygen partial pressures. The main purpose of keeping ΔP in a certain small range is to protect the membrane from damage, and therefore, prolong the fuel cell stack life [20], [1]. Because the fuel cell voltage is a function of the pressures, each pressure needs to be appropriately controlled to avoid a detrimental degradation of the fuel cell voltage. The stack current is considered as a disturbance to the system instead of an external input [21]. Consider the following MIMO nonlinear system with a disturbance:

$$\begin{aligned}\dot{X}&=f(X)+\sum_{i=1}^{m}g_i(X)u_i+p(X)d,\quad i=1,2,\dots,m\\ y_1&=h_1(X)\\ &\vdots\\ y_m&=h_m(x)\end{aligned} \quad (16)$$

where $X\subset R^n$ is the state vector, $U\subset R^m$ is the input or control vector, $y\subset R^P$ is the output vector, and f(x) and g(x), $i=1,2,\dots,m$ are n-dimensional smooth vector fields. The d represents the disturbance variables, and $p(x)$ is the dimensional vector field directly related to the disturbance. By considering (6)-1(0), the defined outputs and the disturbance, and separating the control inputs, the nonlinear dynamic system model of PEMFC is rewritten as follows:

$$\begin{aligned}\dot{X}&=f(x)+g_1(x)u_1+g_2(x)u_2+p(x)d\\ \begin{bmatrix}y_1\\y_2\end{bmatrix}&=\begin{bmatrix}x_1\\x_3\end{bmatrix}=\begin{bmatrix}h_1(x)\\h_2(x)\end{bmatrix}\end{aligned} \quad (17)$$

where:

$$X=\begin{bmatrix}P_{H_2}\\P_{H_2O_A}\\P_{O_2}\\P_{N_2}\\P_{H_2O_C}\end{bmatrix};\ U=\begin{bmatrix}u_a\\u_c\end{bmatrix};\ Y=\begin{bmatrix}P_{H_2}\\P_{O_2}\end{bmatrix}$$
$$d=I_{fct};\ f(x)=0;$$

$$g_1(x) = RT\lambda_{H_2}\begin{bmatrix} \frac{k_a Y_{H_2}}{V_A} - \frac{k_a}{V_A}\frac{x_1}{x_1+x_2} \\ \frac{k_a \varphi_a P_{vs}}{V_A(x_1+x_2-\varphi_a P_{vs})} - \frac{k_a}{V_A}\frac{x_1}{x_1+x_2} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$g_2(x) = RT\lambda_{air}\times\begin{bmatrix} 0 \\ 0 \\ \frac{k_c Y_{O_2}}{V_C} - \frac{k_c}{V_C}\frac{x_3}{x_3+x_4+x_5} \\ \frac{k_c Y_{N_2}}{V_C} - \frac{k_c}{V_C}\frac{x_4}{x_3+x_4+x_5} \\ \frac{k_c \varphi_c P_{vs}}{V_C(x_3+x_4+x_5-\varphi_c P_{vs})} - \frac{k_c}{V_c}\frac{x_5}{x_3+x_4+x_5} \end{bmatrix}$$

$$p(x) = RT\times\begin{bmatrix} -\frac{C_1}{V_A} + \frac{C_1 x_1}{V_A(x_1+x_2)} \\ \frac{C_1 x_2}{V_A(x_1+x_2)} - \frac{C_1}{V_A} \\ -\frac{C_1}{2V_c} + \frac{C_1 x_2}{2V_C(x_3+x_4+x_5)} \\ 0 \\ -\frac{C_1}{V_C} - \frac{C_1 x_5}{V_c(x_3+x_4+x_5)} - \frac{C_2 x_5}{V_C(x_3+x_4+x_5)} + \frac{C_2}{V_C} \end{bmatrix}$$

From (17), the MIMO nonlinear PEMFC system is ready to develop a nonlinear control law. Normally, the disturbance in (17) cannot be directly used in the control design because an additional necessary condition—that the disturbance can be measured and the feed-forward action is allowed—has to be satisfied [22], [23]. Otherwise, the linearized map between the new input v and the output y does not exist. The condition renders the following control law by using the measurement of the disturbance.

$$U = -A^{-1}(x)f(x) + A^{-1}(x)v - A^{-1}(x)p(x)d \tag{18}$$

From (17), it can be seen that $f(x)=0$, that leads to:

$$U = A^{-1}(x)v - A^{-1}(x)p(x)d \tag{19}$$

Because each control variable u shows up after the first derivative of each $y_1 = x_1 \quad y_2 = x_3$, the relative degree vector $[r_1 \quad r_2]$ is $[1 \quad 1]$, and the decoupling matrix $A(x)$ is defined as:

$$A(x) = \begin{bmatrix} L_{g_1}h_1(x) & L_{g_2}h_1(x) \\ L_{g_1}h_2(x) & L_{g_2}h_2(x) \end{bmatrix} \tag{20}$$

where $L_{g_1}h_1(x)$ is Lie derivative of a scalar function $h_1(x)$ with respect to a vector function g_1.

$$A(x) = \begin{bmatrix} \frac{k_a Y_{H_2}\lambda_{H_2}}{V_A} - \frac{k_a Y_{H_2}}{V_A}\frac{x_1}{x_1+x_2} & 0 \\ 0 & \frac{k_c Y_{O_2}\lambda_{air}}{V_C} - \frac{k_c\lambda_{air}}{V_c}\frac{x_3}{x_3+x_4+x_5} \end{bmatrix} \tag{21}$$

where $A(x)$ is nonsingular at $x = x_0$. Additionally, the matrix v and $p(x)$ in (17) are given as follows:

$$v = \begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} \quad p(x) = RT\begin{bmatrix} -\frac{C_1}{V_A} + \frac{C_1.x_1}{V_A(x_1+x_2)} \\ -\frac{C_1}{2V_C} + \frac{C_1}{2V_C(x_3+x_4+x_5)} \end{bmatrix} \tag{22}$$

The control law given in (17) yields decoupled and linearized Input–output behavior:

$$\dot{P}_{H_2} = v_1 \qquad \dot{P}_{O_2} = v_2 \tag{23}$$

The outputs P_{H_2} and P_{O_2} are decoupled in terms of the new inputs v_1 and v_2. Thus, two linear subsystems, which are between the input v_1 and the hydrogen partial pressure $y_1 = P_{H_2}$, and between the input v_2 and the oxygen partial pressure $y_2 = P_{O_2}$, are obtained. By mentioning that $\dot{y}_1 = \dot{x}_1$ and $\dot{y}_2 = \dot{x}_3$, in order to ensure that y_1 and y_2 are adjusted to the desired values (in atmosphere) of y_{1d} and y_{2d}, the stabilizing controller is usually designed by linear control theory using the pole-placement strategy [24].

In this paper NSGA_II method is introduced to design the stabilizer controller and the result will be compared with designed controller in [11].

IV. Stabilizing Controller

The outputs P_{H_2} and P_{O_2} are decoupled in terms of the new inputs v_1 and v_2. Thus, two linear subsystems, which are between the input v_1 and the hydrogen partial pressure $y_1 = P_{H_2}$, and between the input v_2 and the oxygen partial pressure $y_2 = P_{O_2}$, are obtained. Furthermore, note that $\dot{y}_1 = \dot{x}_1$, $\dot{y}_2 = \dot{x}_3$. So, in order to ensure that y_1 and y_1 are adjusted to the desired values 3 (in atmosphere) of y_{1d} and y_{2d}, the stabilizing controller is designed by linear control theory using the pole-placement strategy [24]. The new control inputs are given by;

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} \dot{y}_{1d} - k_{11}e_1 \\ \dot{y}_{2d} - k_{21}e_2 \end{bmatrix} \tag{24}$$

where $e_1 = y_1 - y_{1d}$, $e_2 = y_2 - y_{2d}$. Even though the nonlinear system PEMFC is exactly linearized by feedback linearization, there may exist a tracking error in the variation of the parameters, especially when the load changes. To eliminate this tracking error, the integral terms are added in the closed-loop error equation as in [23] and [11]:

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} \dot{y}_{1d} - k_{11}e_1 - k_{12}\int e_1 dt \\ \dot{y}_{2d} - k_{21}e_2 - k_{22}\int e_2 dt \end{bmatrix} \tag{25}$$

From (24), the error dynamics can be obtained as follows:

$$\begin{aligned} \ddot{e}_1 + k_{11}\dot{e}_1 + k_{12}e = 0 \\ \ddot{e} + k_{21}\dot{e}_2 + k_{22}e_2 = 0 \end{aligned} \tag{26}$$

By appropriately choosing the roots of the characteristics of $s^2 + k_{11}s + k_{12}$ and $s^2 + k_{21}s + k_{22}$, asymptotic tracking will be achieved. The overshoots also become small by choosing $k^2_{11} \geq 4k_{12}$ and $k^2_{21} \geq 4k_{22}$ [23], [24]. The problem in this method is the finding of the appropriate parameter of k_{11}, k_{12}, k_{21}, and k_{22}. Due to nonlinear properties of model and controller, finding these parameters is a sophisticated and frustrating problem. In order to tackle this problem, we used NSGA_II algorithm.

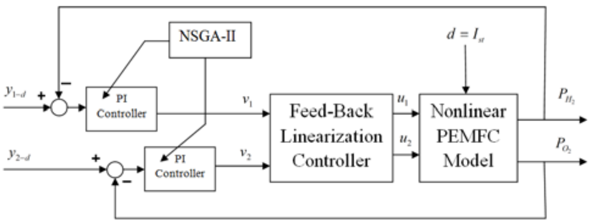

Fig. 1 Overall view of designed controller structure

V. Non-Dominated Sorting Genetic Algorithm-II

Genetic Algorithm (GA) is a directed random search technique that is widely applied in optimization problems. This is especially useful for complex optimization problems where the number of parameters is large and the analytical solutions are difficult to obtain. As we mentioned above, tuning the linear controller gain is really crucial for obtaining an accurate controller, therefore in this paper, we suggest a non-dominated sorting-based Multi Objective EA (MOEA), called Non-Dominated Sorting Genetic Algorithm-II (NSGA-II). This method was selected to alleviate these problems of other MOEA methods:

1) Computational complexity,
2) Non-elitism approach,
3) The need for specifying a sharing parameter [14].

By using this method we tried to optimize the PI linear parameter which have significant role in the behavior of designed controller. In optimization process we considered following objectives.

VI. Numerical Simulation

In this paper we used the combination of feedback linearization control and NSGA_II as we described. The overall view of designed controller is depicted on Fig. 1. The NSGA-II algorithm is used to choose the optimal parameter of PI controller. To find the effectiveness of the introduced method we should compare the result of this new method with classical methods such as linear PI controller and also pure feedback linearization. In feedback linearization control, it is common to use pole-placement method to choose the linear controller gains, so we decided to compare the introduced method with this procedure. The reference model parameters in (26) were selected as $k_{12} = k_{22} = 5$ and $k_{11} = k_{21} = 1$ to establish the mentioned condition. While in this paper, these gains are selected by NSGA-II method, to obtain accurate gains, which have significant effect on controller accuracy [24]. As it can be seen on Fig. 1, two PI controller gain should be tuned. Therefore, 4 parameters are tuned by the NSGA-II optimization algorithm, while following objectives were considered:

1) Minimizing the P_{H_2} tracking error.
2) Minimizing the P_{O_2} tracking error.

In standard NSGA-II Crossover probability P_c is 0.9 and mutation probability P_m is $1/n$ (n is the number of decision variables, $n = 12$). The distribution indices for crossover and mutation operators are $\eta_c = 20$ and $\eta_m = 20$ respectively. In our optimization process, the population size is 20, and optimization repeated for 100 generation. The range of decision variable for controller gain is selected between 0.1 and 100. This variable range selection is based on numerous simulation results, to eliminate the singularity in simulations. By optimizing the controller gains, following gains were obtained:

$$\begin{aligned} k_{11} = 153.149735,\ k_{12} = 21.646415 \\ k_{21} = 97.808318,\ k_{22} = 12.511219 \end{aligned} \tag{27}$$

The results of numerical simulation are presented on Figs. 2-5. As it can be seen on Figs. 2 and 3, by using the PD_NSGA method, a much more accurate controller is obtained, and the desired value (3 atmosphere) is obtained in proposed design, while the linear and nonlinear controller were incapable in accurate pressure control of desired values. Another advantage of proposed design is minimum control effort. Control effort is an important factor in designing controller, which is in direct relation with control deflection ($\int u^2 dt$) it can be seen on Figs. 4, 5 that designed controller has minimum control deflection in comparison of pure feedback linearization controller and linear controller, which leads to minimum control effort.

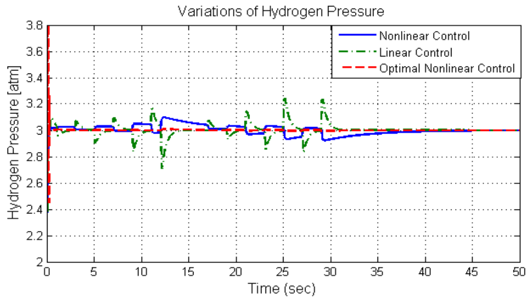

Fig. 2 The comparison of Hydrogen pressure control

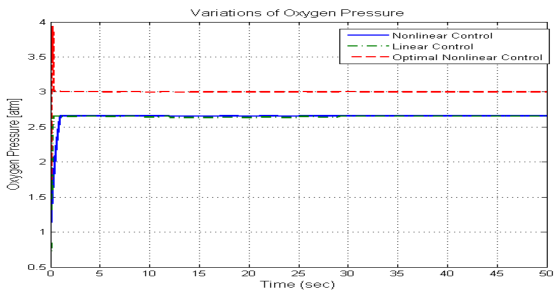

Fig. 3 The comparison of Oxygen pressure control

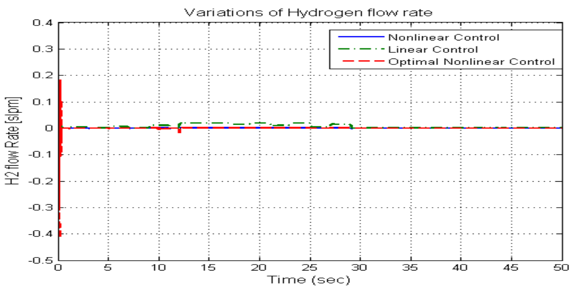

Fig. 4 Variation of Hydrogen flow rate

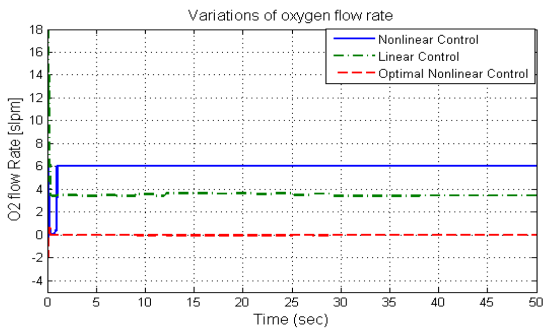

Fig. 5 Variation of Oxygen flow rate

VII. Conclusion

In this paper a new approach for designing optimal feedback linearization controller for PEM fuel cell is introduced. The accuracy of feedback linearization method depends on linear controller gains which are attached to it. These linear gains are usually obtained by classical methods, such as pole placement. These methods suffer from lack of accuracy. To tackle this problem, we introduced NSGA-II for tuning the linear control parameters. By using this method, the linear control parameters are tuned by considering our objective in an optimal way. The simulation results show that the proposed method significantly increased the feedback linearization controller accuracy.

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