FUZZY CONTROLLER DEVELOPMENT FOR A PEM FUEL CELL SYSTEM

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Abstract: A Polymer Electrolyte Membrane (PEM) fuel cell system model that is suitable for control study is presented in this paper. The PEM mathematical model is then used for the controller development to improve system performance. Within the University research facilities, there is a PEM Fuel Cell Test station (PEM –FCT) available, so the PEM-FCT is used for the modelling and controller study. A fuzzy set-point weighted PID controller is designed to improve the performance of the fuel cell system. The underlying idea of our controller design is to use a fuzzy based system to support the operation of a PID controller. The new control strategy is implemented on a PC based computer model of the FCT system and simulated. The results indicate that the control strategy has improved the system performance dramatically.

Keywords: Modelling, Mathematical model, PID control, Fuzzy control, Simulation.

1. INTRODUCTION

Fuel cell technology is currently the subject of much research effort in the power systems community at large, see, for example (Parten, and Maxwell, 2001; Lasseter, 2001; Sedghisigarchi and Feliachi, 2004; Boccaletti *et al*, 2006), using variety of configurations, modelling and control algorithms. For enhanced reliability, control topologies with performance improvements are preferable. Fuel cell technology become more and more popular in the power industry due to the limited amount of fossil fuels and the effects fossil fuels are having on the environment. The fuel cell is considered a future electrical power source for automotive, portable electronics and stationary applications. Modelling of the fuel cell is a true multi-physics task since it involves electrostatics, fluid dynamics, transport of species, heat and electrochemical reactions.

A fuel cell is an electrochemical energy conversion device which converts the chemicals hydrogen and oxygen into water and in the process produces electricity. Fuel cells are able to provide large amounts of current and hence power, but the only requirement is the constant flow of reactants. It is this supply of reactants which presents one of the several challenges encountered by fuel cell system investigators. There are several types of fuel cells each using a different chemistry. Fuel cells are usually classified by the type of electrolyte they use. Some types of fuel cells work well for use in stationary power generation plants and others maybe useful for powering a car. The PEM fuel cell is commonly used to power a vehicle. To analyse the dynamic problems of controlling a fuel cell system and to develop control schemes for alleviating these problems it is necessary to derive a dynamic model for fuel cell systems.

The paper begins by developing a mathematical model of the PEM fuel cell system (PEMFC). The model is then bridged to the model of Fuel Cell Test station (FCT). Within the University research facilities, there is a PEM-FCT station available so the PEM-FCT is used for model validation. To this end, comparisons are made between the simulation results from the PEMFC model which is implemented in MATLAB/Simulink and FCT test data. A general agreement exists, thus in this study, we use the PEMFC model to represent the PEM-FCT station. The PEMFC model is then used for the controller development to improve system performance. A Fuzzy set-point weighted PID control strategy is developed to improve the performance of the system.

2. MODEL OF THE FCT SYSTEM

The Fuel Cell Test station (FCT) available within the University research facilities was designed and manufactured in partnership with Fuel cell Technologies Inc (see Fig.1). The test station consists of five subsystems. The gas delivery subsystem, fuel cell subsystem, humidification subsystem, load subsystem and control subsystem. The block diagram shown in Fig.2 gives an overview of the present setup which utilizes a single fuel cell membrane electrode assembly. The gas delivery subsystem delivers the reactants (gases) of hydrogen to the anode and oxygen to the cathode. It consists of hydrogen and compressed air tank along with inlet filters, pressure regulators and flow meters and controllers. The fuel cell subsystem is the heart of the FCT. Here within the fuel cell membrane electrode assembly the chemical process occurs, which produces electricity to power end uses. It consists of the typical fuel cell structure of anode and cathode plates separated by a PEM material. In view of the structure of this FCT system, we modelled the mathematical model of PEM-FCT system and in the reminder of this section detail of the PEMFC model are described.

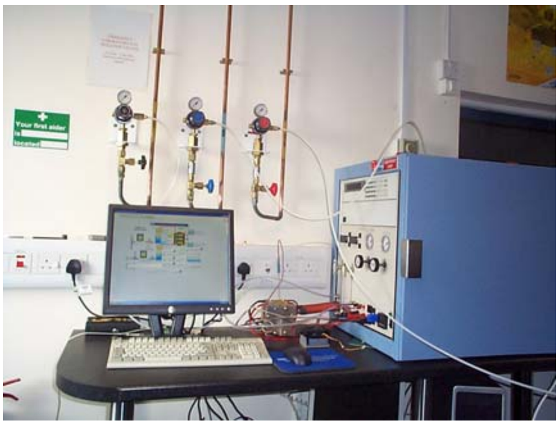


Figure 1. Fuel Cell Test station system

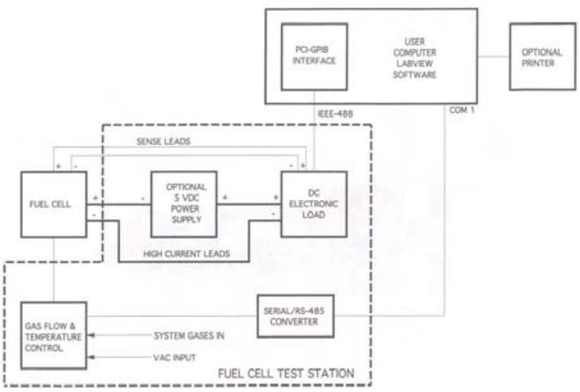


Figure 2. Block diagram of FCT system

The system model contains four main interacting sub-systems; cathode and anode flow, the membrane hydration, and cell voltage (see Fig.3). The electrochemical reaction at the membranes is assumed to occur instantaneously and the temperature is assumed to be constant. For the cathode and anode mass flow behaviour, the principle of conservation of mass is used to obtain the governing equations. Furthermore, to derive this closed form of expressions to the fuel cell system the following assumptions are made; the fuel cell is fed with hydrogen and air only, however some time nitrogen, is also fed to the fuel cell system, but the nitrogen is only used as a purge to clear the system if required, so we ignored the usage of nitrogen in the system modelling. The electrode channels are small enough that the pressure drop across them is negligible; ideal gas law is applicable to all gases (Thanapalan *et al,* 2008).

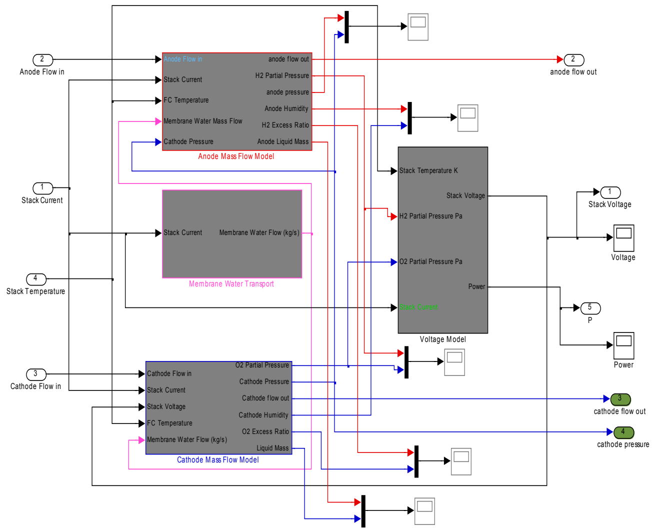


Fig.3 Structure block diagram of PEMFC model system

Cathode and anode flow

Applying the principle of conservation of mass the governing equations of cathode and anode flows can be written as follows;

$$\dot{m}_{O_2} = W_{O_2,in} - W_{O_2,out} - W_{O_2,reacted} \qquad (1)$$

$$\dot{m}_{w,ca} = W_{v,ca,in} - W_{v,ca,out} + W_{v,gen} + W_{v,mbr} \qquad (2)$$

The flow rates of each element in the above equations are determined using thermodynamic and psychometric properties of gas upstream. The rate of oxygen reacted and water generated in the fuel cell reactions are calculated from the cell current, i_{FC} using the electrochemical equations;

$$W_{O_2,reacted} = M_{O_2} \frac{i_{FC}}{4F} \qquad (3)$$

$$W_{v,gen} = M_v \frac{i_{FC}}{2F} \qquad (4)$$

Where F is the Faraday number, M_{o_2} and M_v are the molar mass of oxygen and vapour respectively.

$$\dot{m}_{H_2} = W_{H_2,in} - W_{H_2,out} - W_{H_2,reacted} \quad (5)$$

where, $W_{H_2,in}$, $W_{H_2,out}$ and $W_{H_2,reacted}$ are the hydrogen mass flow in, out and reacted respectively.

$$\dot{m}_{w,an} = W_{v,an,in} - W_{v,an,out} - W_{v,mbr} \quad (6)$$

The rate of hydrogen reacted in the fuel cell reaction is calculated from the cell current is given by

$$W_{H_2,reacted} = M_{H_2} \frac{i_{FC}}{2F} \quad (7)$$

Membrane hydration- it captures the effect of water transport across the membrane. Both water content and mass flow are assumed to be uniform over the surface area of the membrane, and are functions of cell current and relative humidity of the gas in the anode and cathode. The mass flow of vapour across the membrane $W_{v,mbr}$ is calculated using mass transport principles and membrane properties (Thanapalan *et al,* 2008, Pukrushpan, *et al,* 2002).

$$W_{v,mbr} = M_v A_{fc} \cdot \left(\frac{n_d . i_{FC}}{F} \right) \quad (8)$$

where n_d is the electro-osmotic coefficient. It is assumed that the relative humidity in the anode can be controlled at 100%. The supplied hydrogen is regulated by a valve that uses proportional control to maintain a minimum pressure difference across the membrane.

The oxygen partial pressure P_{O_2} is modelled by using the following expression;

$$P_{O_2} = \frac{m_{O_2} . R_{O_2}}{V_{ca}} T \quad (9)$$

where, m_{O_2} is the mass of oxygen in the cathode, R_{O_2} oxygen gas constant, and V_{ca} fuel cell cathode volume.

Similarly, the hydrogen partial pressure P_{H_2} is modelled by the following expression

$$P_{H_2} = \frac{m_{H_2} . R_{H_2}}{V_{an}} T \quad (10)$$

where m_{H_2} is the mass of hydrogen in the anode, R_{H_2} hydrogen gas constant and V_{an} fuel cell anode volume.

oxygen partial pressure P_{O_2} and hydrogen partial pressure P_{H_2} are then inputted to the cell voltage subsystem block.

Cell voltage- The fuel cell voltage is calculated by subtracting the fuel cell losses or overvoltages from the fuel cell open circuit voltage, E, and is given by the following equation (Dufour,*et al.,* 2003; Correa *et al.,* 2004; Mueller, *et al.,* 2007)

$$v_{fc} = E - v_{act} - v_{ohm} - v_{conc} \quad (11)$$

where

$$E = \frac{1}{2F}\left\{ \Delta G + \Delta S(T - T_r) + RT\left(\ln(P_{H_2}) + \frac{1}{2}\ln(P_{O_2}) \right) \right\} \quad (12)$$

where E is the potential of the cell obtained in an open circuit. F is the constant of Faraday; ΔG is the change in the free Gibbs energy; ΔS is the change of the entropy; R is the universal constant of the gases; while P_{H_2} and P_{O_2} are the partial pressures of hydrogen and oxygen respectively. Variable T denotes the cell operation temperature and T_r is the reference temperature.

The activation overpotential v_{act} , including anode and cathode can be calculated as follow;

$$v_{act} = -\left\{ \varsigma_1 + \varsigma_2 T + \varsigma_3 . T . \ln\left(\frac{P_{O_2}}{5.1 \times 10^6 . e^{\frac{-498}{T}}} \right) + \varsigma_4 . T . \ln(i_{FC}) \right\} \quad (13)$$

where ς 's represent parametric coefficient for the cell model. i_{FC} is the cell operating current.

The ohmic voltage drop v_{ohm} is determined by the following expression.

$$v_{ohm} = i_{FC}\left(\rho_m . t_m / A_{fc} + c \right) \quad (14)$$

In this model a general expression for resistance is defined to include all the important parameters of the membrane. The resistance to the transfer of protons through the membrane is assumed to be a constant (c) and included in the equation as an additional term. ρ_m is the specific resistivity of the membrane for the electron flow. t_m is the thickness of the membrane, A_{fc} is the cell active area.

The voltage drop due to the mass transport can be determined by

$$v_{con} = -B . \ln(1 - \theta) \quad (15)$$

and

$$\theta = (i_{FC} / A)\left((i_{FC} / A)_{\max} \right)^{-1} \quad (16)$$

where B is a parametric coefficient, that depends on the cell and its operation state.

The PEM-FCT station parameters, which can be found in the FCT manual (FCT manual, 2005), were used to run the model presented above. An extensive simulation is carried out and a simulation result for a typical case is presented in this paper as an example (see Fig.4). Both the FCT data and the simulation data were plotted to the same scale, which enables an easier comparison of the variables of interest, such as voltage (v) and power (P). The anode flow (af) and cathode flow (cf) were used to drive the model. There exists reasonably good correlation; however some discrepancies are evident, which might be an indication that some unstable factors in the real FCT have not been included in the model. Overall the PEMFC model represents the FCT station. The PEMFC model is used to develop controllers to the FCT station to improve system performances. Remaining sections for the paper focus on the controller development of FCT system.

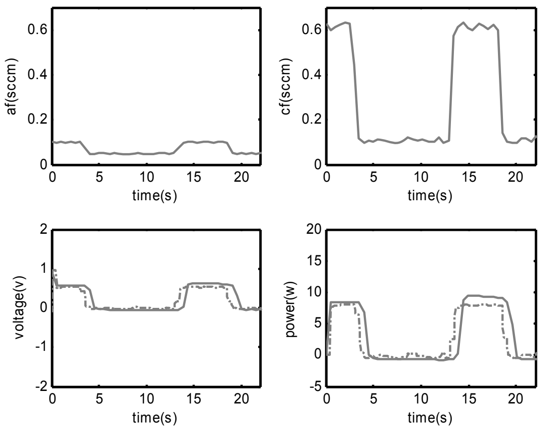


Figure 4 Comparison of simulation model and FCT responses (model ------ FCT ——)

3. Fuzzy set-point weighting PID controller

3.1 PID control

PID (Proportional - Integral - Derivative) control is widely used in industry to control many different systems. A conventional PID controller is developed for the FCT system using the PEMFC model. The values of the gains set for the conventional PID controller are listed in Table 1. The output response is shown in Figure 5. The solid line, doted and dashed lines are indicating the reference voltage, cell output voltage with the manufacturer control (mfc) and with PID controller respectively. The improvement in system dynamic performance with the PID controller can be clearly seen from Figure 5.

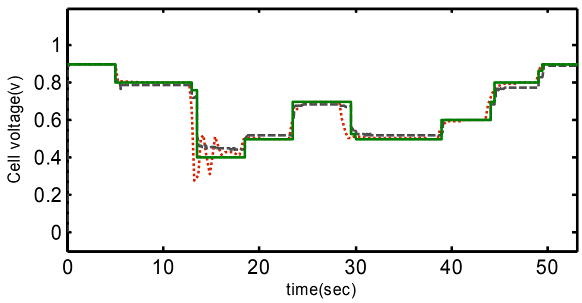


Figure 5. The responses of cell voltage
Using a PID controller
(Ref —— PID − − − mfc ·······)

Table 1. Gains of the PID controller

	K_P	K_i	K_d
PID	5	0.15	0.0005

3.2 Fuzzy set-point weighting method

It is always a problem in practice to determine a suitable set of parameters for a conventional PID controller. In general, it is not easy to satisfy different design specifications at the same time. A method to cope with this problem proposed by some researchers is to weight the set-point for the proportional action by a coefficient $0 < b < 1$ (Astrom and Wittenmark, 1995). In this way, the control law becomes:

$$u(t) = K_P e_b(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}, \qquad (17)$$

where $e_b(t) = b \cdot y_d(t) - y(t)$. From previous study (Driankov, 1998) with this modification, the overshoot in system responses can be greatly reduced, but this increases the value of the rise time. It is desired to have a low overshoot and fast responses. So the fuzzy set-point weighting method is proposed and appears to be very effective. The method consists of two steps: 1) setting the PID control gains based on the experience of operators; 2) determining, through a fuzzy inference system, the value of the set-point weight. The expression of the modified PID controller can be written as:

$$u(t) = K_P(b(t)y_d(t) - y(t)) + K_d \frac{de(t)}{dt} + K_i \int_0^t e(\tau)d\tau \quad (18)$$

$$b(t) = \omega + f(t) \qquad (19)$$

where ω is a positive constant less than or equal to one and $f(t)$ is the output of the fuzzy mechanism which consists of five triangular membership functions for the two inputs $e(t)$ (see Figure 6) and $\dot{e}(t)$ and nine triangular membership functions for the output (see Figure 7). Note that $e(t)$ and $\dot{e}(t)$ are normalized to the range of [-1, +1] using two constant parameters K_{in1} and K_{in2} respectively. Furthermore, the de-fuzzified output will be multiplied by another scalar constant K_{out} . There are different ways for assigning the values of the scaling coefficients and defining the shapes of the membership functions, such as, the Ziegler-Nichols method to tune the parameters (Williams *et al,* 2007).

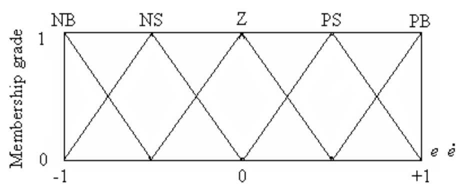


Figure 6. Membership functions for the two inputs e and $\dot{e}$

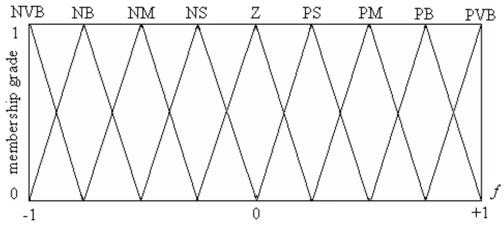
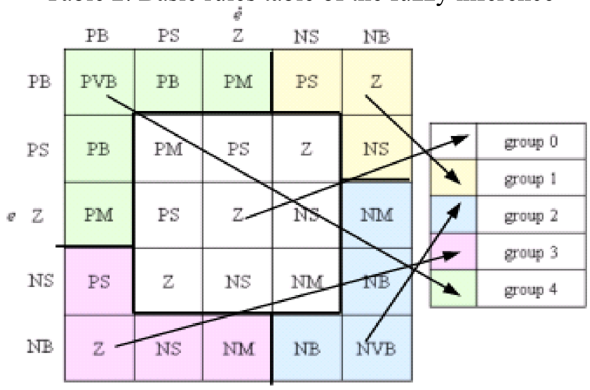


Figure 7. Membership functions for the output

3.3 Fuzzy rules and fuzzy controls

The fuzzy rules are shown in Table 2 and the definitions of the linguistic variables are described in Table 3.

Table 2. Basic rules table of the fuzzy inference



e \ $\dot{e}$	PB	PS	Z	NS	NB
PB	PVB	PB	PM	PS	Z
PS	PB	PM	PS	Z	NS
Z	PM	PS	Z	NS	NM
NS	PS	Z	NS	NM	NB
NB	Z	NS	NM	NB	NVB

Table 3. Linguistic variables in the fuzzy inference system

Linguistic	Linguistic meanings
NVB	Negative Very Big
NB	Negative Big
NM	Negative Medium
NS	Negative Small
Z	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big
PVB	Positive Very Big

The structure of the fuzzy controller is shown in Figure 8.

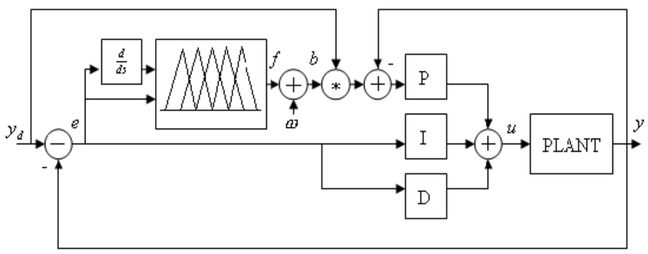


Figure 8. Control scheme with the fuzzy set point weighting (FSW) methodology

In the real process of the system, e and Δe can be positive or negative. A linguistic value of 'Zero' for e means that the measured current output is near to the set-point of the system output. A 'Zero' for Δe means that the changes in output is very small, i.e. $\Delta e(t) = e(t) - e(t-1) \approx 0$. The sign and the magnitude for Δu constitute the value of the control signal. In Table 2, the top row of the table shows the change-of-error Δe and the left column is the error e. The cells of the table at the intersection of rows and columns contain the linguistic value for the output corresponding to the value of the first input written at the beginning of the row and to the value of the second input written on the top of the column.

Table 2 includes 25 rules, which take into account not only the errors but also the changes-of-errors as well. It describes the dynamics of the controller. The rules are organised into five groups:

- Group 0: For this group of rules, both e and Δe are (positive or negative) near to zero which indicates the steady-state behaviour of the process.
- Group 1: $e(t)$ is Positive Big or Small which implies that output $y(t)$ is significantly below the set-point. At the same time since $\Delta e(t)$ is negative, so $y(t)$ is moving towards the set-point.
- Group 2: y(t) is either close to the set-point ($e(t)$ is Zero and Negative Small) or significantly above it (Negative Big). At the same time, since $\Delta e(t)$ is negative, $y(t)$ is moving away from the set-point. The control here is intended to reverse this trend and make $y(t)$ start moving back to the set-point.
- Group 3: $y(t)$ is Negative Big or Negative Small, which means that $y(t)$ is below the set-point. At the same time, $y(t)$ is moving towards the set-point since $\Delta e(t)$ is positive.
- Group 4: For this group of rules, $e(t)$ is either close to the set-point (Positive Small, Zero) or significantly below it (Positive Big). At the same time since $\Delta e(t)$ is positive, $y(t)$ is moving away from the set-point.

FSW controller parameters were optimized using Patten Search Method (PSM). The idea is to search for the optimal values of the parameters of the FSW controller with respect to a determined objective function. We search for the values of K_{in1} , K_{in2} , K_{out} and ω in order to minimize the value of the Integrated Absolute Error (IAE)

$$IAE = \int_0^t \left| y_{sp}(t) - y(t) \right| dt \qquad (20)$$

By choosing a suitable upper bound for the value of K_{out} and suitable lower bounds for the values of K_{in1} and K_{in2} it is guaranteed, from a practical point of view, that the system will never be unstable. The values of the scaling gains and weighting factor set for the FSW-method are listed in Table 4. The output response is shown in Figure 9.

Table 4. Gains of the FSW controller

K_{in1}	K_{in2}	K_{out}	ω
1.88	0.0005	5	0.98

The system dynamic performance with the FSW controller is an improvement on that obtained by the PID controller as can be seen from Figures 9 and 10.

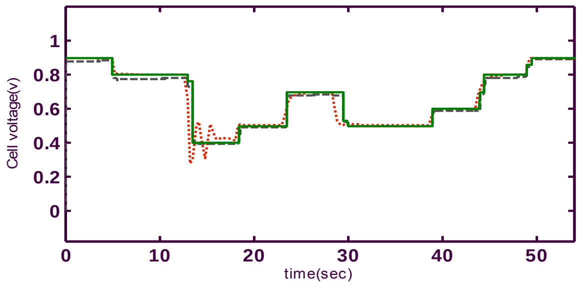


Figure 9. The responses of cell voltage using a FSW controller
(Ref —— FSW – – – mfc ·······)

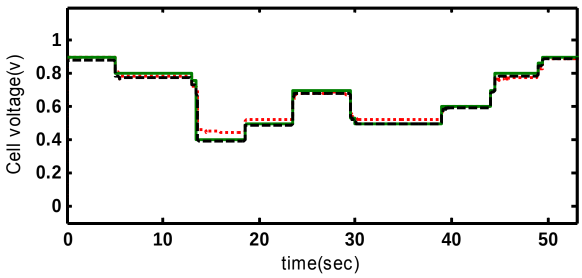


Figure 10. Comparison of cell voltage responses using PID and FSW controllers
(Ref —— FSW – – – PID ·······)

4. CONCLUDING REMARKS

The paper describes a fuel cell system modelling and simulation study. A mathematical model for a fuel cell system has been developed for simulation study and control analysis. For the simulation study in this paper a Fuel Cell Test station is used. The model responses are compared with FCT data. Correlation in the main is satisfactory but anomalies are present. Possible reasons for those anomalies are suggested. Overall satisfactory results are achieved. This paper also described a PID controller and Fuzzy Set-Point weight PID control. The structure of the controller and the fuzzy rule tables are described. Simulation studies have been conducted and the results show that the proposed control strategies lead the system to have an improved dynamic performance. Further studies are on going in the research group to investigate the experimental performance of FCT control.

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