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Design and Implementation of a Preemptive Disturbance Rejection Controller for PEM Fuel Cell Air-feed System Subject to Load Changes

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Abstract – The paper focuses on the control of air feed system on the PEM fuel cell subject to load changes. For this purpose, a robust regulatory controller (termed as Robustness Tracking Disturbance Overall Aggressiveness (RTDA) controller) is developed to control oxygen excess ratio and compared with widely accepted schemes namely Proportional Integral Derivative (PID), Model Predictive Control (MPC). In all the control schemes, the control objectives aim to maintain the desire oxygen excess ratio while keeping the compressor voltage at its nominal working point under input and output operational constraints. The two different scenarios: (1) Robustness Output tracking and (2) Disturbance rejection for each configuration are compared using computational time and performance indicators like Integral Square Error (IS E). The novel contribution of this work is the comparison of the performance of the schemes with respect to computational time. Simulation results allow evaluating effectiveness of the RTDA controller and the performance of each configuration applied to Polymer Electrolyte Membrane (PEM) Fuel cell air feed system.

Keywords: PEM fuel cell, Air feed control, PID, MPC, RTDA controller and ISE.

1. Introduction

For a decade, fuel cell technology is an alternative solution for green energy which enables wide applications, such as portable power sources and other industrial applications [1]. In these years, there were a lot of developments in fuel cell technology. This work addresses only Polymer Electrolyte Membrane (PEM) fuel cell which is an electrochemical cell that develops electric energy from chemical reagents. The PEM cells works at very low temperature, highly reliable, high efficiency, less corrosive and small in size. A PEM fuel cell contains anodic and cathodic regions and a polymer membrane electrolyte, and producing water as a waste out. It is noted that the good result with respect to performance, efficiency and lifetime of fuel cells are fully depending on proper control. So, the study of implementation of optimal controls for fuel cells is fully necessary.

Many control strategies have been developed for fuel cells ranging from Proportional Integral Derivative (PID) Controller, feedforward, Fuzzy logic, LQR, neural networks and Model Predictive Control. According to the literature point of view, there are few articles about control PEM fuel cells. The authors [2] gave an analysis about control on power output of DC/DC converter which is used to connect with PEM fuel cells to the load. This paper addressed only the control of power output from PEM fuel cell. The authors [3] have developed a lower control scheme in a standalone PEM fuel cell dealing with complete electrical power train. In their work, they have developed lower level control as compared to more complex control schemes.

The authors [4] have designed an optimal control law for a PEM fuel cell. In their work, a linear quadratic regulator is proposed to control the air supply of fuel supply system. The main reasons for making their control law unsuitable for this application are LQR does not handle constraints and Computational complexity is high.

The authors [6] have discussed on a predictive control law with constraints for PEM fuel cell. Their work is focused on design of non-linear predictive control law for the same. MPC has highly complex with respect to its design and computational complexity. Practically it is quite inappropriate for this application. The authors [8] have proposed a novel design of sliding mode control (SMC) which is a combination of SMC and feedforward component, to avoid oxygen starvation during change in load. The authors [9] have developed a neural based optimal control for PEM Cell. But online training and hardware implementation is also very difficult in neural network.

Robustness, Tracking, Disturbance Rejection -overall Aggressiveness controller (RTDA) is a next generation controller which is the combined feature of classical PID controller and model predictive controller (MPC). It utilizes digital technology to implement a simplified model prediction with transparent tuning parameters. The RTDA controller consists of a simplified linear model predictive control scheme that makes use of precisely the same

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process reaction curve information required for tuning PID controllers. In addition, its three primary tuning parameter σ_R, σ_T and σ_D, are not only related directly to the attributes of robustness, set-point tracking (or trajectory following), and disturbance rejection, they are also normalized to lie between 0 and 1. An auxiliary fourth parameter, relate to the overall controller aggressiveness, arises from the model predictive formulation independently of the three main tuning parameters, it is also normalized between 0 and 1 [10, 11]. The RTDA configuration proposed in this paper is capable of handling the uncertainties and satisfying the desired references while keeping at its nominal working point.

The three optimal control schemes used in this paper, Proportional Integral Derivative (PID), linear model-based predictive control (LMPC), minimize a multi-objective function and Next generation regulatory - RTDA controller. A number of advantages make the RTDA control scheme suitable for the PEM fuel cell applications are: less computational complexity, handles constraints and meets the time domain specifications and allows multi-objective optimization. Furthermore, the RTDA controller can introduce robustness naturally. The main contribution of this paper is to present and compare an advanced optimization-based control schemes for air feed system that can meet the requirements for PEM fuel cell. It has been observed that there is no work in the literature which compares PID, MPC, and RTDA trajectory for PEM fuel cells from computational point of view. The simulation results are discussed and compared based on time domain specifications and performance indicators like ISE and total computational time. The paper is prepared and presented as follows: Section I gives the basic mathematical equations describing PEM fuel cell system. Section III addresses the design of proposed closed loop configuration. Section IV proposes and compares the simulation results in two different sections Servo response, and Regulatory response under additive load disturbances. Finally, Section V gathers the conclusions of the work and gives some further work lines.

2. Modeling of PEM Fuel Air Feed System

The PEM fuel cell utilizes chemical reagents to generate electric power. The system comprises of a fuel cell, a pressurized tank and control valve for hydrogen supply, a compressor and a cooling fan for humiliation [12]. The power output of the PEM cell depends on the inflow of hydrogen from anode side and the inflow of oxygen from the cathode side. The difference between the pressure ratio of anode and cathode is regulated by the control values, which incorporates that mass flow rate of hydrogen and oxygen is interdependent. Depending on the reactant demand of the fuel cell, the consumption of air may increase or decrease. When the supply of air to fuel cell doesn't meet the requirement, it leads to starvation which may cause degradation of fuel cell stacks, uneven distribution of reactant in between the fuel cell stack, reduction in fuel cell voltage and cell reversal. Hence for better operation of the fuel cell, the oxygen excess ratio in the cathode side alone is controlled using optimal controllers. The oxygen excess ratio (δ_{O_2}) represents the ratio of oxygen entering the cathode $(W_{O_{2,i}})$ the oxygen consumed by the stacks of fuel cell $(W_{O_2,rct})$.

$$\delta_{O_2} = \frac{W_{O_{2,i}}}{W_{O_2,rct}} \tag{1}$$

The oxygen consumed inside the fuel cell can be obtained easily as it is proportional to the stack current (I_{st}) and it depends on the oxygen molar mass (M_{O_2}), number of stacks in the fuel cell N and the Faraday constant F.

$$W_{O_2,rct} = M_{O_2}\frac{NI_{st}}{4F} \tag{2}$$

The oxygen supplied by the compressor depends upon the mass fraction of oxygen (X_{O_2}) and the air flow in the inlet $(W_{a,i})$ which is given by

$$W_{O_{2,i}} = W_{a,i} * X_{O_{2,}} \tag{3}$$

The mass fraction of oxygen obtained from nitrogen molar mass, oxygen molar mass and mole fraction of oxygen $(y_{O_{2,i}})$ is given by

$$X_{O_2} = \frac{y_{O_{2,i}}M_{O2}}{y_{O_{2,i}}M_{O2}+(1-y_{O_{2,i}})M_{N_2}} \tag{4}$$

The air flow in the inlet depends on the total mass flow rate provided by the compressor is given as,

$$W_{a,i} = \frac{1}{1+\omega_i}W_i \tag{5}$$

The oxygen humidity ratio is obtained from the product of ratio of molar mass of vapour and inlet air with the pressure ratio of vapour to dry air.

$$\omega_i = \frac{M_v}{M_{a,i}}\frac{p_{v,i}}{p_{a,i}} \tag{6}$$

The molar mass of the inlet air is obtained as

$$M_{a,i} = y_{O_2}M_{O_2} + (1-y_{O_2})M_{N_2} \tag{7}$$

The dry air pressure $(p_{a,i})$ is the difference between vapour pressure and cathode inlet pressure

$$p_{a,i} = p_i - p_{v,i} \tag{8}$$

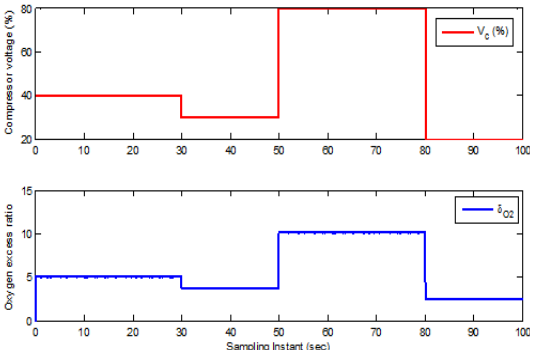


Fig. 1. Open loop response of the model

The vapour pressure is obtained from the relative humidity of inlet air and the saturated vapour pressure at a particular temperature

$$p_{v,i} = \phi_i p_{st}(T_i) \tag{9}$$

The open loop response of the identified model is shown in Fig. 1. The model of the system taken is represented in transfer function as

$$G(s) = \frac{0.1268}{0.0141s+1} \tag{10}$$

The discrete-time state space model of the system is given by

$$\dot{x} = 8.3157e - 04x + 0.0141u \tag{11}$$

$$y = 8.9929x \tag{12}$$

3. Design of Next Generation Regulatory Controller

The regulatory controller utilizes the parameters of a first order process model. The model error is the difference between the model outputs from the actual process. It involves estimation of present disturbance and prediction of future disturbance. Then the stipulated error is estimated to calculate the control input, which is given to system to track the output. The RTDA control scheme flow is illustrated in Fig. 2.

3.1 Reformation of the model

The actual dynamics of the process is usually approximated to first order model, is used as it gives better approximation for the actual dynamics of the process. The transfer function model of the system is given by

$$y(s) = \frac{K}{\tau s+1} u(s) \tag{13}$$

Here a discretized form of the model is used for model prediction

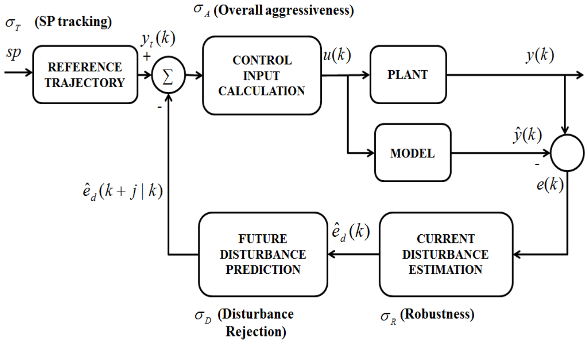


Fig. 2. Block diagram of RTDA Controller

$$\hat{y}(l+1) = \alpha\hat{y}(l) + \beta u(l) \tag{14}$$

The control action $u(l)$ is restricted to remain the same for the whole prediction horizon. Hence only the 1st control move $u(l)$ is allowed to be maintained for entire P-step horizon,

$$u(l+i) = u(l) \tag{15}$$

The predicted process output for each next P-step horizon is obtained as,

$$\hat{y}(l+i) = \alpha^i \hat{y}(l) + \beta\eta_i u(l)\ for\ 1 \le i \le P \tag{16}$$

where

$$\eta_i = \frac{1-a^i}{1-a}$$

This prediction must be updated to include the effect of unmeasured disturbances, and other sources of modeling error.

3.2 Error updation

As the first order model is an approximation of a process, the model predicted output has deviation from the actual output of the process hence the prediction needs to be updated. The model mismatch given by,

$$e(l) = y(l) + \hat{y}(l)(25)e(l) = e_m(l) + e_d(l) \tag{17}$$

Using Bayesian estimation principle, $e_d(l$ is estimated as

$$\hat{e}_d(l) = \sigma_R \hat{e}_d(l-1) + (1-\sigma_R)e(l) \tag{18}$$

The equation for the estimate of future error is given as,

$$\hat{e}_d\left(l+\frac{j}{l}\right) = \hat{e}_d(l) + \frac{\alpha}{1-\alpha}[1-\alpha^i]\nabla_{e_d}(l)$$
$$for\ 1 \le j \le P \tag{19}$$

where $\nabla_{e_d}(l)$ is difference in error between two consecutive error values, is given by

$$\nabla e_d(l) = e_d(l) - e_d(l-1) \tag{20}$$

The parameter α is now replaced with a tuning parameter $(1-\sigma_d)$ to give,

$$\hat{e}_d(l+j|l) = \hat{e}_d(l) + \frac{1-\sigma_D}{\sigma_D}[1-(1-\sigma_D)^j]\nabla\hat{e}_d(l) \tag{21}$$

Here σ_d have the control response corresponds to disturbances and it is scaled to lie between 0 and 1. Using the above stated error estimation, the corrected prediction output for *P*-step prediction horizon is given by

$$\tilde{y}(l+i) = \hat{y}(l+i) + \hat{e}_d(l+i|l)\ for\ 1 \le i \le P \tag{22}$$

This is a set of *P* equations with the single unknown variable $u(l)$, the current control action.

3.3 Reference trajectory

Reference trajectory is to be defined in which $sp(l)$ represents the set-point to be tracked to attain the desired process output. Let the desired trajectory $y_t(l)$, be given by

$$y_t(k) = \sigma_T y_t(l-1) + (1-\sigma_T) * sp(l) \tag{23}$$

When alternation in set-point values is not known in advance then the immediate past set-point values is taken for current set-point values, and then it is obtained as

$$y_t(l+j) = \sigma_T y_t(l) + \left(1-\sigma_T^j\right) * sp(l)\ for\ 1 \le j \le \infty)$$

where, σ_T is the trajectory tracking tuning parameter

3.4 Control input calculations

The control action $u(l)$ is the minimization of the deviation of the model predicted output from the reference trajectory for P-step horizon which is needed for the model predicted output. The objective function of the controller is given as

$$\min_{u(l)} \sum_{i=1}^{N} \left(y_t(l+i) - \tilde{y}(l+i)\right)^2 \tag{24}$$

Consider,

$$r_i(l) = y_t(l+i) - \tilde{y}(l+i) \tag{25}$$

From the corrected prediction output Eq. (22)

$$r_i(k) = \Psi_i(l) - \beta\eta_i u(l) \tag{26}$$

where

$$\Psi_i = y_t(l+i) - a^i\hat{y}(l) - \hat{e}_d(l+i|l) \tag{27}$$

where, $\Psi_i(l)$ represents the stipulated error

Through the objective function the control input $u(l)$ is obtained as

$$u(l) = \frac{1}{b}\frac{\sum_{i-1}^{N}\eta_i\Psi_i(l)}{\sum_{i=1}^{N}\eta_i} \tag{28}$$

The prediction horizon length P depends on the total aggressiveness parameter σ_A is given by,

$$P = 1 - \frac{\tau}{t_s}\ln(1-\sigma_A) \tag{29}$$

where, t_s is the sampling time.

4. Results and Discussions

The comprehensive performance analysis of the control scheme is presented in this section. In this simulation, the algorithm of RTDA control scheme and other control schemes such as MPC [14] and PID[15] (for comparison) were executed on Intel core5 machine which operates at 2.50GHz, 4GB RAM. The PEM fuel cell air feed System sampling time of 0.1 second was considered. Each configuration is discussed with respect to two scenarios: (1) δ_{O_2} tracking and (2) Disturbance rejection under change in load. An additive load disturbance at ±10% step change in compressor voltage $V_c$is considered with respect to its nominal value. Thereforethe control signals received by the air feed system would be $\Delta u + u$.

The comparative performance study of all closed-loop configurations are prepared and presented in this section in respect to servo operation and additive disturbances rejection under change in load. Fig. 3 shows the schematic block diagram of controller implementation in PEM fuel cell air feed system.

4.1 Servo tracking

It is noted and observed from the Fig. 4 that PID control scheme provides high oscillations and overshoot. However it is faster response due to its simplicity in design. As compared to PID, MPC ensures no steady state error and zero overshoot and also gives smooth response. But it takes

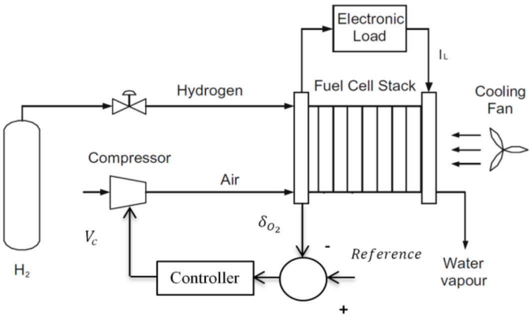
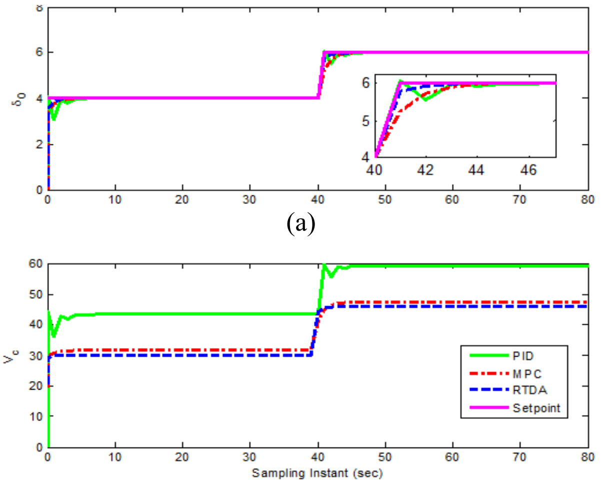


Fig. 3. Schematic diagram of controller implementation



(a)

(b)

Fig. 4. Servo responses of control schemes (a) Process output $\boldsymbol{\delta_{O_2}}$ (b) Manipulated variable $\boldsymbol{V_c}$

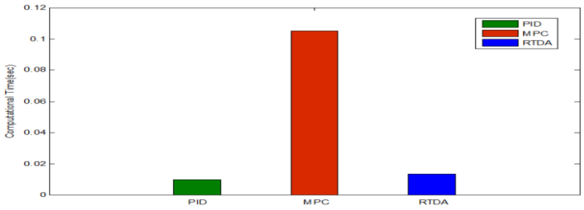


Fig. 5. Comparative performance Indicators in regulatory operation of all control schemes in regulatory operation

more time to track the set point. RTDA controller provides zero steady state error, less rise time, no overshoot, less settling time and smooth response which leads to proper control action at the output tracking. Hence RTDA control scheme is better than PID and MPC controller for servo operation.

4.2 Regulatory operation

The observations from the Fig. 5 are that PID scheme giveszero steady-state error. However, this control scheme assures high oscillations and the worst performances for rejecting the load disturbance profile presented above in Fig. 5(a). PID does not handle constraints, thus it is exceeded. Therefore, this control scheme ranks both the output tracking and disturbance rejection performances at third position.

The MPC control scheme provides no oscillations in process output δ_{O_2} and performs constraints handling in compressor voltage V_c narrowing upper constraint $0 \leq u \leq 80$. In addition to this, it assures the best performance in both output tracking and disturbance rejection under additive load by providing negligible steady-state error (less than 1%) and smoothen response. But its total computational effort is too high. Therefore, MPC control scheme ranks both the output tracking and disturbance rejection performances at second position.

The RTDA controller gives faster response with no oscillations, input and output operational constraints and error free steady state. In addition to the above, it reduces the computational effort when compared to PID and MPC. Also it gives the best performance in both output tracking and disturbance rejection under additive load changes.

Therefore, RTDA control scheme ranks both the output tracking and disturbance rejection performance at first position.

4.3 Concluding observations

The classical control PID scheme does not deal with constraints and also requires proper tuning to meet the requirements, whereas MPC has the knowledge of handling constraints with optimization and control. Hence MPC turns into a more powerful algorithm to meet the requirements of the PEM fuel cell air feed system. But in respect to computational complexity, MPC gives inappropriate performance. In order to meet all the above requirements for a control on the air supply of PEM fuel cell system, RTDA is proposed for PEM fuel cell air feed system to meet the time domain specifications, constraints handling and less computational complexity. In order to compare all the control schemes from a computational point of view, the PID, MPC and RTDA controllers are implemented for air supply on the PEM fuel cell to observe corresponding total computational time.

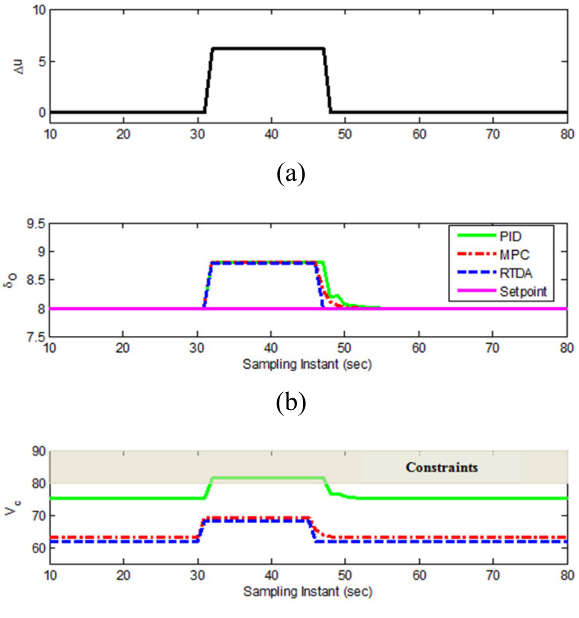
In order to have a good performance assessment of all closed loop configurations for this application, a bar comparison is given for time domain specifications and computational time. The Tables 1 & 2 give a complete idea to determine that which control scheme is superlative for real time implementation from performance analysis and computational point of view as shown in Fig. 6 & 7. From these results, a recommendation is concluded that RTDA controller is best and appropriate for the control of air feed in PEM fuel cell in real time. The future work of this

Table 1. Servo tracking - comprehensive performance analysis of all closed loop configurations

Control schemes	Performance indicator	Computational complexity
	Integral square error (ISE)	Computational time (Sec)
PID	1.115	0.0097
MPC	0.3898	0.1050
RTDA	0.2701	0.0133

Table 2. Regulatory operation-comprehensive performance analysis of all closed loop configurations

Control schemes	Performance indicator	Computational complexity
	Integral square error (ISE)	Computational time (Sec)
PID	1.115	0.0097
MPC	0.3898	0.1050
RTDA	0.2701	0.0133



(a)

(b)

(c)

Fig. 6. Disturbance rejection responses of all control schemes (a) Disturbance profile (b) Process output δ_{O_2} (c) Manipulated variable V_c

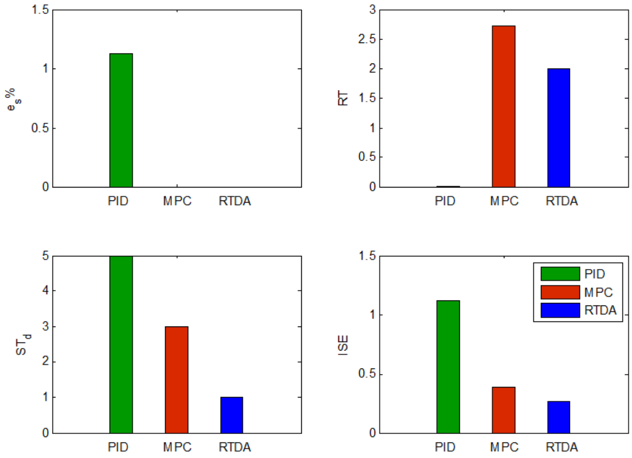


Fig. 7. Comparative performance Indicators in regulatory operation of all control schemes

paper is to implement these algorithms in a real-time environment.

5. Conclusion

The paper addresses design of development of an appropriate optimal control scheme for the air supply circuit of a PEM fuel cell. The aim to be fulfilled a fast response of the control scheme in order to avoid oxygen starvation during measurable load disturbances. The dynamics of PEM fuel cell is required to manage nonlinearities and uncertainties by providing a proper controller. The solution is given through a RTDA controller that is based on a combination of PID and MPC. The RTDA control scheme gives the fast set point tracking under load without increasing the computational effort. This paper also compares the performance of RTDA controller with other control schemes like PID and MPC. Finally conclusions and recommendations are made from the result obtained. though a conclusion may review the main results or contributions of the paper, do not duplicate the abstract or the introduction. For a conclusion, you might elaborate on the importance of the work or suggest the potential applications and extensions.

Appendix

In this study, PID controller parameters are optimized by the algorithm used in [15]. The PID tuned values is tabulated in Table 3.

Table 3. PID Configuration Settings

Parameters	K_p	K_i	K_d
Value	1.3	4.991	0.2

The simulated MPC controller settings are tabulated in Table III. The weighted matrices W_e and W_u are tuned using the formulae $W_u = B^T B$ and $W_e = C^T C$ respectively [14]. It is also noted that the weighted matrices W_e and W_u should be less to get the reliable output and minimum steady state error. $0 \le u \le 80$ is the imposedconstraints on the manipulated variable (i.e. compressor voltage).

Table 4.MPC Controller settings

Parameters	Values
Prediction horizon (m)	10
Control horizon (n)	1
Weighting factor We	15
Weighting factor Wu	2
Final simulation time	100

The simulated RTDA controller settings are tabulated in Table 5. These parameters are optimized by observation method and some inferences are noted as follows:

(i) Robustness factor $\boldsymbol{\sigma_R}$ is increased to improve steady state response.
(ii) Overall Aggressiveness factor $\boldsymbol{\sigma_A}$ should be less value to reduce the settling time.
(iii) Tracking factor $\boldsymbol{\sigma_T}$ is tuned to get good transient response.
(iv) Disturbance rejection factor is tuned to anticipate the uncertainties and disturbances affecting the plant.

Table 5. RTDA Controller settings

Controller	σ_R	σ_T	σ_D	σ_A
RTDA	0.4	0.35	0.89	0.2

Nomenclature

$W_{a,i}$	Air flow in the inlet (kg s^{-1})
$X_{O_2,i}$	Mass fraction of oxygen
M_{O_2}	Oxygen molar mass (kg mol^{-1})
M_{N_2}	Nitrogen molar mass (kg mol^{-1})
$y_{O_2,i}$	Mole fraction of oxygen
ω_i	Oxygen humidity ratio
p_i	Cathode inlet pressure (N m^{-2})
$p_{v,i}$	Vapour pressure (N m^{-2})
$p_{a,i}$	Dry air pressure (N m^{-2})
p_{st}	Saturated vapour pressure (N m^{-2})
W_i	Air Flow provided by compressor (kg/s)
$W_{O_{2,i}}$	Oxygen ingoing at cathode (kg/s)
u	Control input
K	Steady state gain
τ	Time constant
t_s	Sampling time
e	Model mismatch in RTDA
σ_T	Tracking parameter
σ_D	Disturbance parameter
σ_A	Aggressiveness parameter
$\Psi_i(k)$	Stipulated error
σ_T	Tracking parameter

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