Degradation Avoiding Start Up and Shut Down of Fuel Cell Stacks for Automotive Application Using Two Plant Model Predictive Control

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***Abstract*—Exposure of fuel cell membranes to open circuit voltage results in the dissolution of the platinum in the catalyst layer, as well as corrosion of the carbon support. It is, therefore, important that the cells' potential inside a fuel cell stack be brought to zero at the start of the inactive phase. A shut down procedure to avoid open circuit voltage for fuel cell stacks is presented. The air supply is shut off first and a dummy current used to consume all the remaining oxygen reducing the voltage to zero ending up with nitrogen and water only. The hydrogen supply is then shut off leaving some hydrogen in the anode. Two zero dimensional models are developed: one (nonlinear) describes the fuel cell stack during normal operation and the second (linear) describes the system during shut down or start up. A model predictive control algorithm is employed to track the power demand during operation using the first model and to perform the shut down / start up procedure using the second model ensuring avoidance of open circuit voltage as well as the air/hydrogen front which causes severe degradation. Different criteria (maximum/minimum dummy current, supply shut off speed, final anode pressure level) can be incorporated into the controller to adapt its performance to any particular stack.**

***Index Terms*—Fuel cell, shut down, star up, model predictive control, nonlinear system**

I. Introduction

In fuel cell operation, especially in automotive application, start up and shut down procedures contribute significantly to cell/stack degradation [1]–[3]. Two major degradation effects are open circuit voltage (OCV) and air/hydrogen front, both of which are pronounced during start up and shut down procedures.

If the fuel cell is shut down by simply dropping the current to zero, the nonzero concentration of oxygen and hydrogen in the cathode and anode, respectively, will cause the cell/stack to be in a state of OCV. Two factors are of most interest when examining OCV-caused degradation [4]. The first one is carbon support corrosion as well as migration and dissolution of the platinum catalyst. The confirmation of this effect is seen in the reduction of the electrochemical surface area (ECSA) [5]. The second effect is caused by increased concentration of radical peroxide, since the gas crossover rate is high due to no reactants' consumption at OCV. The elevated radical peroxide concentration causes membrane decomposition [6].

The second major degradation effect is the air/hydrogen front that forms during start up if there is air on both sides (cathode and anode) at the beginning of the active phase. OCV could be avoided by filling the anode with air at shut down, even though this is not always possible, especially in automotive application where the air compressor is not even connected to the anode supply manifold. This approach, in turn, causes the air/hydrogen front to form on the anode side at the next start up, when fresh hydrogen is introduced. The front causes "reverse current" [3], [7]–[9], leading to severe carbon corrosion and platinum dissolution.
In contrast, a better approach would be to keep the hydrogen in the anode channel for as long as possible. However, the oxygen would then permeate from cathode to anode, but this problem can be solved by using a dummy current during the shutdown procedure to consume all the oxygen leaving the system with hydrogen, nitrogen and water only [10]–[12].
In this paper, a model based controller is proposed to control the operation of fuel cell during normal operation, shut down and start up. For normal operation, a successive linearisation model predictive controller (SLMPC) is used. The nonlinear control oriented model used by the SLMPC knows the complete dynamics of the system. For further details, the reader is referred to authors' previous work [13]–[15]. The focus of this work is, however, on the shut down and start up model. During shut down, the air supply and exhaust are shut off leaving the system in a closed cathode state which is modelled as a tank full of air, having the current as the only actuating variable capable of removing the oxygen. The start up procedure is opposite from the shut down - the air supply and exhaust are open and then, after the cathode has been replenished, the controller switches to the SLMPC and normal operation resumes. The model describing the shut down is a linear one, and a linear model predictive controller (MPC) can be used to deplete the remaining oxygen in the cathode, reducing the voltage to zero. The switching between the SLMPC and the

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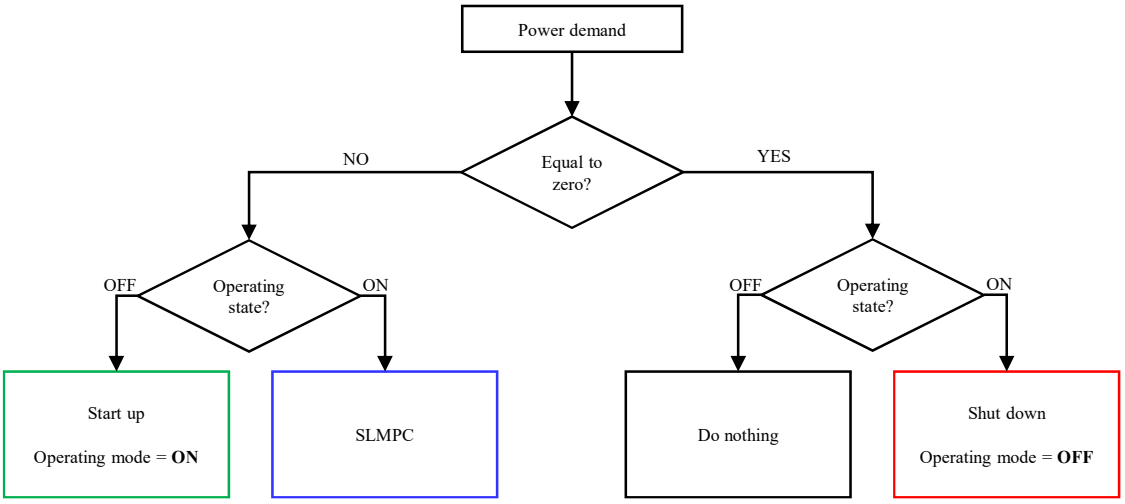

Fig. 1. Controller switching between normal operation, shut down and start up based on the power demand and operating mode

shut down / start up controller depends on the power demand and operating mode of the fuel cell. If the power demand is different from zero and the fuel cell system is already running, the SLMPC is used to deliver the desired power demand and ensure safe and efficient operation. On the other hand, if the power demand is different from zero and the fuel cell is not running, it means that the start up procedure should be performed. If, however, the power demand is zero and the fuel cell is runing, it means that it should be shut down and if the power demand is zero and the fuel cell was off, it should then stay off and no control is necessary. The controller switching based on the power demand and operating mode is illustrated in Fig. 1. The benefit of this procedure is that it avoids OCV and the air/hydrogen front, and the benefit of this type of controller (MPC) is that it can impose constraints on different quantities, such as the maximum dummy current drawn to remove the oxygen, keeping the system from doing any abrupt changes, ensuring safety.

This paper is organised as follows: In section II, the full nonlinear control oriented fuel cell model is presented, as well as the shut down model. In section III, the controller design is shown with all the performance requirements and constraints. In section IV, results showing the system behavior during shut down / start up is shown as well as the controller switching. Finally, the paper is concluded in section V.

II. Fuel Cell Model

In this section, the fuel cell model will be briefly presented. For more detail, the reader is referred to [13]. The fuel cell system is described with a nonlinear state-space zero-dimensional (0D) model consisting of 9 internal states which's dynamics are described by first order ordinary differential equations. The explanation of each state is brought in Table I.

TABLE I
Fuel Cell Sytem States

State	*State description*
m_{O2}^{ca}	Oxygen mass in cathode
m_{N2}^{ca}	Nitrogen mass in cathode
m_{vap}^{ca}	Water vapor mass in cathode
m_{liq}^{ca}	Liquid water mass in cathode
m_{H2}^{an}	Hydrogen mass in anode
m_{N2}^{an}	Nitrogen mass in anode
m_{vap}^{an}	Water vapor mass in anode
m_{liq}^{an}	Liquid water mass in anode
$a_{m,d}$	Dynamic membrane activity

A. Full model

The model is separated into the cathode, anode and membrane submodels described by differential equations.

The rate of change of the oxygen mass in the cathode is given by the equation

$$\dot{m}_{O_2}^{ca} = W_{in}^{ca} y_{O_2,in}^{ca} - \frac{1}{4F} I N_{cells} M_{O_2} - W_{out}^{ca} y_{O_2}^{ca} \quad (1)$$

where W_{in}^{ca} in the inlet mass flow of air, $y_{O_2,in}^{ca}$ is the mass fraction of oxygen at the cathode inlet, depending on inlet humidity, I is the current drawn from the fuel cell, F is the Faraday constant, N_{cells} is the number of cells in the stack, M_{O_2} is the molar mass of oxygen, W_{out}^{ca} is the outflow of air, dependant on the backpressure valve position α_{ca} [13] and

$y_{O_2}^{ca}$ is the mass fraction of oxygen in the cathode.
The nitrogen dynamics are described by the equation

$$\dot{m}_{N_2}^{ca} = W_{in}^{ca} y_{N_2,in}^{ca} - k_{perm}\left(p_{N_2}^{ca} - p_{N_2}^{an}\right) - W_{out}^{ca} y_{N_2}^{ca} \quad (2)$$

where $y_{N_2,in}^{ca}$ and $y_{N_2}^{ca}$ have the analogous meaning as $y_{O_2,in}^{ca}$ and $y_{O_2}^{ca}$ in (1), $p_{N_2}^{ca}$ and $p_{N_2}^{an}$ are the partial pressures of nitrogen in the cathode and anode, respectively and k_{perm} is the nitrogen membrane permeability.
The rate of change of the water vapor mass in the cathode is given by the equation

$$\begin{aligned}\dot{m}_{vap}^{ca} = W_{in}^{ca} y_{vap,in}^{ca} + \frac{1}{2F} I N_{cells} M_{H_2O} - W_{out}^{ca} y_{vap}^{ca} + \\ + \dot{m}_{vap,mem} - \dot{m}_{phase}^{ca}\end{aligned} \quad (3)$$

where the terms $W_{in}^{ca} y_{vap,in}^{ca}$ and $W_{out}^{ca} y_{vap}^{ca}$ are the water vapor inflow and outflow, respectively, $\frac{1}{2F} I N_{cells} M_{H_2O}$ is water formation due to the electrochemical reaction, $\dot{m}_{vap,mem}$ is the water transferred from the anode through the membrane due to the combination of electroosmotic drag and backdiffusion and $\dot{m}_{phase}^{ca}$ is the amount of water that is condensed [13].
The liquid water dynamics is described by the equation

$$\dot{m}_{liq}^{ca} = \dot{m}_{phase}^{ca} - W_{liq}^{ca} \quad (4)$$

where W_{liq}^{ca} is the outflow of liquid water from the cathode [13].

The anode states are described by analogous equations with complementary variations listed in Table II. A furher difference in the cathode and anode description is that the anode is pressure driven, so there exists a supply manifold pressure p_{sm}^{an} from which is then calculated the inlet hydrogen flow. Also, at the anode outlet, there is a purge valve which is used to remove the excess nitrogen and water in the anode [15].

TABLE II
VARIATIONS IN EQUATIONS OF CATHODE SUBMODEL FOR ANODE DYNAMICS DESCRIPTION

State in anode	***Analogous equation***	***Variation***
m_{H2}^{an}	(1)	Hydrogen consumption: $\frac{1}{2F} I N_{cells} M_{H_2}$
m_{N2}^{an}	(2)	Nitrogen permeation: $+k_{perm}\left(p_{N_2}^{ca} - p_{N_2}^{an}\right)$
m_{vap}^{an}	(3)	Membrane water transfer: $-\dot{m}_{vap,mem}$

The dynamic wetting and drying of the membrane is described by the following equation:

$$\dot{a}_{m,d} = -\frac{1}{\tau_{am}}\left(a_{m,d} - a_m\right) \quad (5)$$

where τ_{am} is the wetting/drying time constant and a_m is the membrane relative humidity as explained in [13]. The voltage of the stack V is calculated using the electrochemical model developed in [16] and the power of the stack is then $P_{st} = VI$, chosen as the output of the system. The inlet airflow W_{in}^{ca}, cathode backpressure valve position α_{ca}, anode supply manifold pressure p_{sm}^{an} and the current I are actuation variables which are manipulated during operation and used for control. The system is then summarized with the state vector $\boldsymbol{x}$, input vector $\boldsymbol{u}$ and output variable y:

$$\boldsymbol{x} = \begin{bmatrix} m_{O2}^{ca} \\ m_{N2}^{ca} \\ m_{vap}^{ca} \\ m_{liq}^{ca} \\ m_{H2}^{an} \\ m_{N2}^{an} \\ m_{vap}^{an} \\ m_{liq}^{an} \\ a_{m,d} \end{bmatrix} \quad \boldsymbol{u} = \begin{bmatrix} W_{in}^{ca} \\ p_{sm}^{an} \\ I \\ \alpha_{ca} \end{bmatrix} \quad y = P_{st}. \quad (6)$$

Equations (1)-(5) and their anode analogue form a vector field $\boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u})$ and together with the output equation denoted as $h(\boldsymbol{x}, \boldsymbol{u})$ lead to the nonlinear state-space model:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}) \quad (7a)$$

$$y = h(\boldsymbol{x}, \boldsymbol{u}) \quad (7b)$$

B. Shut down model

During shut down (SD), the cathode inflow and outflow are shut off as explained in section I. Formally, it means that the inlet airflow W_{in}^{ca} and the backpressure valve position α_{ca} are both set to zero. As a result, the dynamics of the oxygen mass in the cathode (1) during shut down is simply described by the linear differential equation

$$\dot{m}_{O_2}^{ca} = -\frac{1}{4F} I N_{cells} M_{O_2}, \quad (8)$$

where the current I is the only actuation variable u_{SD}. If the state variable for the shut down model is chosen as $x_{SD} = m_{O_2}^{ca}$, then the linear system is defined as:

$$\dot{x}_{SD} = b\ u_{SD}, \quad (9)$$

where $b = -\frac{1}{4F} N_{cells} M_{O_2}$. The control goal during shut down after the cathode has been sealed off and the anode pressure fixed, is to deplete the oxygen mass from the cathode in order to avoid OCV and the air/hydrogen front.

III. CONTROLLER DESIGN

In this section, the model based control design will be presented for normal operation, shut down and start up of the fuel cell system.

A. Successive linearisation MPC

During normal operation, the system is controlled with a successive linearisation model predictive controller [14], [15]. The SLMPC uses the full model (7) to predict the behavior of the system and determine the optimal control action to safely and efficiently fulfill the required power demand. The system (7) is instantaneously linearised every timestep k, around the

current state and input ($\boldsymbol{x}_k$,$\boldsymbol{u}_k$) obtaining a linear system valid in the vicinity of the linearisation point:

$$\begin{aligned}\dot{\boldsymbol{x}}_L = \boldsymbol{f}(\boldsymbol{x}_k, \boldsymbol{u}_k) + \frac{\partial \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u})}{\partial \boldsymbol{x}}\Big|_{\boldsymbol{x_k}, \boldsymbol{u_k}} (\boldsymbol{x}_L - \boldsymbol{x}_k) + \\ + \frac{\partial \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u})}{\partial \boldsymbol{u}}\Big|_{\boldsymbol{x_k}, \boldsymbol{u_k}} (\boldsymbol{u}_L - \boldsymbol{u}_k),\end{aligned} \tag{10}$$

where $\boldsymbol{x}_L$ and $\boldsymbol{u}_L$ are the state and input vector of the linearised system, respectively. If we define the system matrix as

$$\boldsymbol{A}_k = \frac{\partial \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u})}{\partial \boldsymbol{x}}\Big|_{\boldsymbol{x_k}, \boldsymbol{u_k}}, \tag{11}$$

the input matrix as

$$\boldsymbol{B}_k = \frac{\partial \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u})}{\partial \boldsymbol{u}}\Big|_{\boldsymbol{x_k}, \boldsymbol{u_k}}, \tag{12}$$

and the off-equilibrium term as

$$\boldsymbol{K}_{x,k} = \boldsymbol{f}(\boldsymbol{x}_k, \boldsymbol{u}_k) - \boldsymbol{A}_k \boldsymbol{x}_k - \boldsymbol{B}_k \boldsymbol{u}_k, \tag{13}$$

the linear system used for the prediction in the SLMPC then reads

$$\dot{\boldsymbol{x}}_L = \boldsymbol{A}_k \boldsymbol{x}_L + \boldsymbol{B}_k \boldsymbol{u}_L + \boldsymbol{K}_{x,k}. \tag{14}$$

The model is then discretised and if the index in the prediction is chosen as i, then the discrete linearised system reads:

$$\boldsymbol{x}_{L_{i+1}} = \boldsymbol{A}_{d,k} \boldsymbol{x}_{L_i} + \boldsymbol{B}_{d,k} \boldsymbol{u}_{L_i} + \boldsymbol{K}_{d,x,k} \tag{15}$$

where the index d denoted matrices in discrete time. Taking the prediction model in the velocity form [17], one finally obtains

$$\Delta \boldsymbol{x}_{L_{i+1}} = \boldsymbol{A}_{d,k} \Delta \boldsymbol{x}_{L_i} + \boldsymbol{B}_{d,k} \Delta \boldsymbol{u}_{L_i} \tag{16}$$

with $\Delta \boldsymbol{x}_{L_i} = \boldsymbol{x}_{L_i} - \boldsymbol{x}_{L_{i-1}}$ and $\Delta \boldsymbol{u}_{L_i} = \boldsymbol{u}_{L_i} - \boldsymbol{u}_{L_{i-1}}$. The term $\boldsymbol{K}_{d,x,k}$ cancelled itself out when applying the difference operator on (15). Using the model (16), an objective function is formed which, when minimised, gives the optimal control move $\Delta \boldsymbol{u}_{k+1}$ with the goal of delivering the required power demand as it can be found in authors' previous work in [14], [15].

B. Shut down MPC

When the controller switches from normal operation to shut down mode, meaning that the power demand has become zero (see Fig. 1), the model used for the prediction, as well as the control goal, change. The model used for prediction is no longer (7), but (9). The control goal is no longer tracking the power demand, but reducing the oxygen mass in the cathode to zero. At the moment of switching, the controller is first instructed to set the anode supply manifold pressure to 1.35 bar, and to reduce the cathode inlet air flow and backpressure valve position to zero. Then, the shut down MPC is formulated in the following way.

The goal of the shut down MPC is to deplete the oxygen mass. The objective function J that has to be minimised is then:

$$J = \sum_{i=1}^{N_p} ||\hat{x}_{SD_{k+i}}||^2_{\mathcal{Q}} + \sum_{j=1}^{N_c} ||u_{SD_{k+j}}||^2_{\mathcal{R}}, \tag{17}$$

where N_p and N_c are the prediction and control horizon, respectively, $\hat{\boldsymbol{x}}_{SD_i}$ is the prediction of the oxygen mass in the cathode at time i, $\boldsymbol{u}_{SD_i}$ is the current that has to be optimised throughout the control horizon (decision variable) and $\mathcal{Q}$ and $\mathcal{R}$ are the state and input weighting matrices which determine the aggressiveness of the controller.
The vector of decision variables $\boldsymbol{U}$ is defined as:

$$\boldsymbol{U} = \begin{bmatrix} u_{SD_{k+1}} \\ u_{SD_{k+2}} \\ \vdots \\ u_{SD_{k+N_c}} \end{bmatrix}. \tag{18}$$

The optimal sequence of input variables $\boldsymbol{U}_{opt}$ is obtained by minimising the cost function 17:

$$\boldsymbol{U}_{opt} = \arg\min_{\boldsymbol{U}} \text{J}. \tag{19}$$

According to the receding horizon principle, only the first element $u_{SD,i+1}$ is used. Therefore, during shut down, the input vector consisting of the inlet air flow W_{in}^{ca}, anode supply manifold pressure p_{sm}^{an}, current I and backpressure valve position α_{ca} fed into the plant at the next time step $k+1$ is

$$\boldsymbol{u}_{k+1} = \begin{bmatrix} 0 \\ 1.35bar \\ u_{SD,k+1} \\ 0 \end{bmatrix} \tag{20}$$

C. Start up procedure

For start up, the controller does not use the MPC, instead, it is switched on or off depending on the system state. When the power demand is different from zero and the operating state is 'OFF', start up happens. The inlet air flow and backpressure valve position are ramped up until the oxygen is restored in the cathode. Then, the controller is switched to normal operation again.

IV. Results and discussion

In this section, a simulation scenario is analysed, where the fuel cell system is required to fulfill a power demand trajectory as seen in Fig. 2a. The system is controlled by the SLMPC up until the moment $t = 37s$ where the power demand becomes zero, meaning that it requires to shut down. At that moment, the controller switches from the SLMPC to the shut down linear MPC (20) which ramps down the air inlet flow (see Fig. 2d), sets the anode inlet pressure to 1.35 bar (see Fig. 2e) and closes the backpressure valve (see Fig. 2g). The shut down MPC then uses the current to deplete the oxygen mass in the cathode as seen in Figs. 2f and 2c, respectively. One can see in Fig. 2a that the power does not immediately decrease when shut down is commanded, but rather, it drops with a delay. This is due to the shut down controller's goal of removing the oxygen from the system; it has to use the current and in doing so, the stack power is not zero until the current and/or the voltage drop to zero. The voltage, shown in Fig. 2b starts to decrease when shut down begins because there are less reactants, but then increases when the current starts to decrease

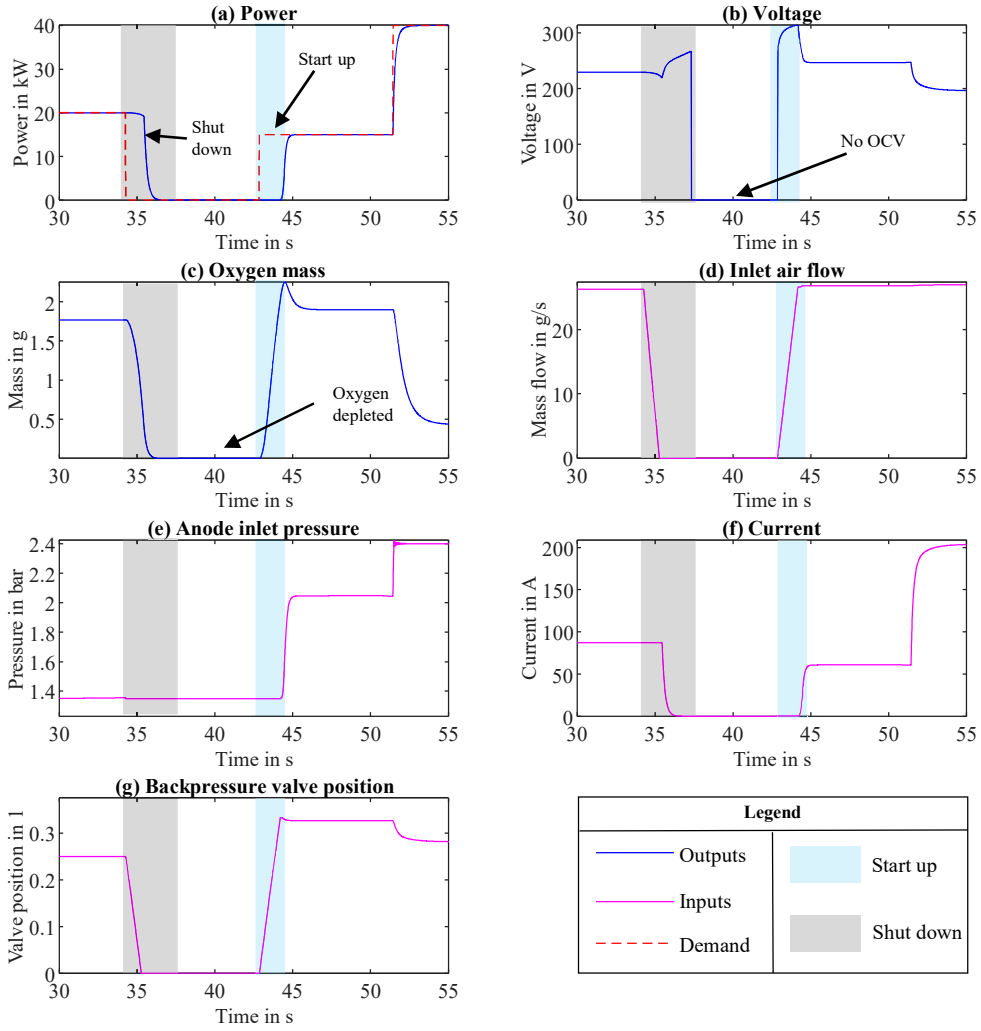

Fig. 2. Illustration of the effects of the start up and shut down controller. The plots (a),(b) and (c) show the stack power, voltage and oxygen mass in cathode. The other four plots show the actuation variables: inlet air flow, anode inlet pressure, current and cathode backpressure valve position which are used to fulfill the control goals (power demand tracking, shut down and start up). The grey shade marks the time the fuel cell was controlled by the shut down model and conversely, the light blue shade marks the time the fuel cell spent in start up before the SLMPC took over.

because the ohmic losses are then lower until it drops again, this time completely when the oxygen is depleted. The voltage model used in this work [16] does not really perform well in region of very low reactants' concentrations because of the Nernst potential part of the equation which requires to compute the logarithm of the oxygen/hydrogen concentration which is undefined when the mentioned variables are zero, so in this case, it is manually set to zero when the mass of one (or both) of the reactants becomes zero. Further investigation in the field of fuel cell voltage model at boundary conditions such as these is needed. From $t = 37s$ until $t = 43s$, the fuel cell system is off. At $t = 43s$, the power demand becomes nonzero again and the start up procedure begins. The inlet air flow of air is increased and the backpressure valve is open for 1 second as seen in Figs. 2d and 2g, respectively, causing the cathode channel to be replenished with oxygen. At $t = 44s$, the start up is complete and the controller switches back to the SLMPC responsible for delivering the required power demand during fuel cell operation. With this approach, a model can be used to guide the system to a protected shut down avoiding OCV by depleting the oxygen from the cathode as well as not causing an air/hydrogen front during start up in the anode.

V. Conclusions

In this paper, a framework of MPC based controllers was designed for fuel cell degradation conscious shut down / start up control. Based on the power demand and fuel cell operating mode, a controller is chosen to perform shut down, start up, or normal operation. Open circuit voltage and anode air/hydrogen front avoidance was embedded into the control design. A simulation scenario was presented to showcase the mentioned principle. Future work includes the consideration of additional safety constraints as well as validation against measurement data.

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References

[1] R. Lin, X. Cui, J. Shan, L. Técher, F. Xiong, Q. Zhang, Investigating the effect of start-up and shut-down cycles on the performance of the proton exchange membrane fuel cell by segmented cell technology, Int. J. Hydrogen Energy. 40 (2015) 14952–14962. https://doi.org/10.1016/j.ijhydene.2015.09.042.

[2] T. Mittermeier, A. Weiß, F. Hasché, G. Hübner, H.A. Gasteiger, PEM Fuel Cell Start-up/Shut-down Losses vs Temperature for Non-Graphitized and Graphitized Cathode Carbon Supports, J. Electrochem. Soc. 164 (2017) F127–F137. https://doi.org/10.1149/2.1061702jes.

[3] H. Tang, Z. Qi, M. Ramani, J.F. Elter, PEM fuel cell cathode carbon corrosion due to the formation of air/fuel boundary at the anode, J. Power Sources. 158 (2006) 1306–1312. https://doi.org/10.1016/j.jpowsour.2005.10.059.

[4] S. Zhang, X.Z. Yuan, R. Hiesgen, K.A. Friedrich, H. Wang, M. Schulze, A. Haug, H. Li, Effect of open circuit voltage on degradation of a short proton exchange membrane fuel cell stack with bilayer membrane configurations, J. Power Sources. 205 (2012) 290–300. https://doi.org/10.1016/j.jpowsour.2012.01.031.

[5] S. Zhang, X.Z. Yuan, J.N.C. Hin, H. Wang, K.A. Friedrich, M. Schulze, A review of platinum-based catalyst layer degradation in proton exchange membrane fuel cells, J. Power Sources. 194 (2009) 588–600. https://doi.org/10.1016/j.jpowsour.2009.06.073.

[6] A. Collier, H. Wang, X. Zi Yuan, J. Zhang, D.P. Wilkinson, Degradation of polymer electrolyte membranes, Int. J. Hydrogen Energy. 31 (2006) 1838–1854. https://doi.org/10.1016/j.ijhydene.2006.05.006.

[7] C.A. Reiser, L. Bregoli, T.W. Patterson, J.S. Yi, J.D. Yang, M.L. Perry, T.D. Jarvi, A reverse-current decay mechanism for fuel cells, Electrochem. Solid-State Lett. 8 (2005). https://doi.org/10.1149/1.1896466.

[8] J.N. Schwämmlein, P.J. Rheinländer, Y. Chen, K.T. Freyer, H.A. Gasteiger, Anode Aging during PEMFC Start-Up and Shut-Down: H 2 -Air Fronts vs Voltage Cycles , J. Electrochem. Soc. 165 (2018) F1312–F1322. https://doi.org/10.1149/2.0611816jes.

[9] R. Borup, J. Meyers, B. Pivovar, Y.S. Kim, R. Mukundan, N. Garland, D. Myers, M. Wilson, F. Garzon, D. Wood, P. Zelenay, K. More, K. Stroh, T. Zawodzinski, J. Boncella, J.E. McGrath, M. Inaba, K. Miyatake, M. Hori, K. Ota, Z. Ogumi, S. Miyata, A. Nishikata, Z. Siroma, Y. Uchimoto, K. Yasuda, K.I. Kimijima, N. Iwashita, Scientific aspects of polymer electrolyte fuel cell durability and degradation, Chem. Rev. 107 (2007) 3904–3951. https://doi.org/10.1021/cr0501821.

[10] H.J. Kim, S.J. Lim, J.W. Lee, I.G. Min, S.Y. Lee, E.A. Cho, I.H. Oh, J.H. Lee, S.C. Oh, T.W. Lim, T.H. Lim, Development of shut-down process for a proton exchange membrane fuel cell, J. Power Sources. 180 (2008) 814–820. https://doi.org/10.1016/j.jpowsour.2007.12.112.

[11] Y. Yu, X.Z. Yuan, H. Li, E. Gu, H. Wang, G. Wang, M. Pan, Current mapping of a proton exchange membrane fuel cell with a segmented current collector during the gas starvation and shut-down processes, Int. J. Hydrogen Energy. 37 (2012) 15288–15300. https://doi.org/10.1016/j.ijhydene.2012.07.023.

[12] Q. Shen, M. Hou, D. Liang, Z. Zhou, X. Li, Z. Shao, B. Yi, Study on the processes of start-up and shutdown in proton exchange membrane fuel cells, J. Power Sources. 189 (2009) 1114–1119. https://doi.org/10.1016/j.jpowsour.2008.12.075.

[13] D. Ritzberger, C. Hametner, S. Jakubek, A real-time dynamic fuel cell system simulation for model-based diagnostics and control: Validation on real driving data, Energies. 13 (2020). https://doi.org/10.3390/en13123148.

[14] M. Vrlic, D. Ritzberger, S. Jakubek, Safe and Efficient Polymer Electrolyte Membrane Fuel Cell Control Using Successive Linearization Based Model Predictive Control Validated on Real Vehicle Data, Energies. 13 (2020). https://doi.org/10.3390/en13205353.

[15] M. Vrlic, D. Ritzberger, S. Jakubek, Model-Predictive-Control-Based Reference Governor for Fuel Cells in Automotive Application Compared with Performance from a Real Vehicle, Energies. 14 (2021). https://doi.org/10.3390/en14082206

[16] A. Kravos, D. Ritzberger, G. Tavcar, C. Hametner, S. Jakubek, T. Katrasnik, Thermodynamically consistent reduced dimensionality electrochemical model for proton exchange membrane fuel cell performance modelling and control, J. Power Sources. 454 (2020) 227930. https://doi.org/10.1016/j.jpowsour.2020.227930.

[17] M. Ławryńczuk, Nonlinear predictive control of a boiler-turbine unit: A state-space approach with successive on-line model linearisation and quadratic optimisation, ISA Trans. 67 (2017) 476–495. https://doi.org/10.1016/j.isatra.2017.01.016.