

Fault-Tolerant MPC Control of PEM Fuel Cells

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Abstract: In this paper, fault-tolerant MPC control of PEM fuel cells is addressed. MPC is a suitable control methodology to control fuel cell systems because of their multivariable and complex behaviour. Additionally, MPC is one of the control methodologies that can introduce more easily fault-tolerance. However, the problem of including actuator fault-tolerance in the control loops of these systems has not already been addressed in the literature. This work is focused on the air feeding control. A new control structure that not only uses the compressor voltage as a control variable but also the air valve opening area at the cathode output is considered to improve the fault-tolerance of the air feeding subsystem. It is shown that using this additional control permits to introduce fault-tolerance against compressor faults at the same time that allows to improve control performance. Finally, the proposed approach is assessed on a known test bench PEM fuel cell through simulation.

Keywords: Fault tolerant control, model predictive control, fuel cells, fault

1. INTRODUCTION

PEM fuel cells have been developed considerably in the last years. Although they were invented more than a century ago, they have received much attention in the last decade as good candidates for clean electricity generation both in stationary and automotive applications. There are many open issues related to fields such as materials, manufacturing or maintenance, being automatic control one of the most important. There exist many types of fuel cells (Larminie, 2005), but this work is devoted to PEM (Polymer Electrolyte Membrane) fuel cells. These fuel cells run at low temperature and show fast dynamical response, which make them suitable for mobile applications. It is clear that good performance of these devices is closely related to the kind of control that is used, so a study of different control alternatives is justified (Pukrushpan, 2004a) (Serra, 2005). A fuel cell system, which supplies electricity to an electric load or to the grid, is not composed of the fuel cell alone but it integrates many components. Several devices such as DC/DC or DC/AC converters, batteries or ultracapacitors are included in the system and, in case the fuel cell is not fed directly with hydrogen, a reformer must also be used. Therefore, there are many control loops schemes, depending on the devices that must be controlled. The lower control level takes care of the main control loops inside the fuel cell, which are basically fuel/air feeding, humidity, pressure and temperature. The upper control level is in charge of the whole system, integrating the electrical conditioning, storage and reformer

(if necessary). Many control strategies have been proposed in the literature, ranging from feedforward control (Pukrushpan, 2004a), LQR (Pukrushpan, 2004b)(Rodatz, 2005), Neural Networks (Almeida, 2005) (El-Sharkh, 2004) or Model Predictive Control (Bordons, 2006)(Feroldi, 2007).

This paper is focused on the control of the fuel cell using Model Predictive Control (MPC) to fulfil “oxygen starvation” prevention. Two controller architectures will be compared. The first one uses only one actuator (the compressor) and the air feeding subsystem is controlled manipulating the compressor voltage. The second one uses two actuators (the compressor and the outlet air valve area) so additionally to the compressor voltage, the controller has an extra control variable based on the opening of the outlet air valve at the cathode (Feroldi, 2007). The advantages and disadvantages of using this extra actuator are in study within the PEMFC community.

The main control objective is to avoid lack of oxygen (oxygen starvation) by maintaining the oxygen excess ratio close to a pre-established set-point, in spite of the disturbance introduced by the current load. Notice that air feeding has crucial importance on fuel cell behaviour, as shown in (Pukrushpan, 2004a). However, due to the complexity of the fuel cell system, it is prone to suffer from faults in its operation time (Fouquet, 2006). So, some fault tolerant capabilities should be added to the control system in order to maintain the fuel cell system under control even in the presence of faults. This paper explores the possibility of making use of the known inherent fault-tolerant capabilities

of MPC control applied to PEMFC. In particular, it will be shown that the controller architecture based on manipulating two actuators (the compressor and the outlet air valve) offers better fault tolerant capabilities and improves the system performance. Effectively, in a previous work (Feroldi, 2007), it was demonstrated that with this control structure it is possible to increase the system efficiency and, at the same time, to improve the transient response. The fault tolerant MPC controller is tested on a full nonlinear model of a PEM fuel cell, showing that good results can be obtained.

The remainder of paper is organized as follows: in *Section 2*, constrained MPC principles and how fault-tolerant capabilities can be added are recalled. In *Section 3*, the two actuator MPC architecture is compared with the one actuator MPC architecture regarding control performance when applied to a test bench fuel cell. In *Section 4*, the fault tolerance capabilities of both MPC architectures are discussed. Finally, the major conclusions are drawn in *Section 5*.

2. FAULT TOLERANT MPC

2.1 MPC background

Model Predictive Control (MPC) has become the accepted standard for complex constrained multivariable control problems in the process industries. At each sampling time, starting at the current state, an open-loop optimal control problem is solved over a finite horizon N :

$$\min_{u(0), \dots, u(N-1)} \sum_{k=0}^{N-1} [x^T(k)Qx(k) + u^T(k)Ru(k)] + x^T(N)Px(N)$$

subject to :

$$x(k+1) = Ax(k) + B(u) \quad k = 0, \dots, N-1$$

$$u(k) \in [u, \bar{u}] \quad k = 0, \dots, N-1$$

$$x(k) \in [\underline{x}, \bar{x}] \quad k = 0, \dots, N$$

At the next time step, the computation is repeated starting from the new state and over a shifted horizon, leading to a moving horizon policy. The solution relies on a linear dynamic model, respects all input and output constraints, and optimizes a quadratic performance index. Thus, as much as a quadratic performance index together with various constraints can be used to express true performance objectives, the performance of MPC is excellent. Over the last decade a solid theoretical foundation for MPC has emerged so that in real-life large-scale MIMO applications controllers with non-conservative stability guarantees can be designed routinely and with ease (Qin, 2003)(Rawlings, 2000).

2.2 Fault-tolerant MPC

Fault-tolerant control is an incipient research area in the automatic control field (Blanke, 2003). One way of achieving fault-tolerance is to employ a fault detection and isolation

(FDI) scheme on-line. This system will generate a discrete event signal to a supervisor system when a fault is detected and isolated. The supervisor, in turn will activate some accommodation action in response, which can be pre-determined for each fault or obtained from real-time analysis and optimization. Due to this discrete-event nature of fault occurrence and the reconfiguration/accommodation, a FTC system is hybrid system by nature. Therefore, the analysis and design of FTC systems is not trivial. For design purposes of these systems, traditionally the hybrid nature has been neglected in order to facilitate a simple design, reliable implementation, and systematic testing. In particular, the whole FTC scheme can be expressed using the three-level architecture for FTC systems proposed by Blanke (2003) (see Fig. 1):

- Level 1: “**Control Loop**”. This level comprises a traditional control loop with sensor and actuator interfaces, signal conditioning and filtering and the controller.
- Level 2: “**Fault Diagnosis and Accommodation**”. The second level comprises a given amount of detectors, usually one per each fault effect which will be detected, and effectors that implement the desired reconfiguration or other remedial actions given by the autonomous supervisor.
- Level 3: “**Supervision**”. The supervisor is a discrete-event dynamical system (DEDS) which comprises state-event logic to describe the logical state of the controlled object. The supervisor functionality includes an interface to detectors for fault detection and demands remedial actions to accommodate a fault.

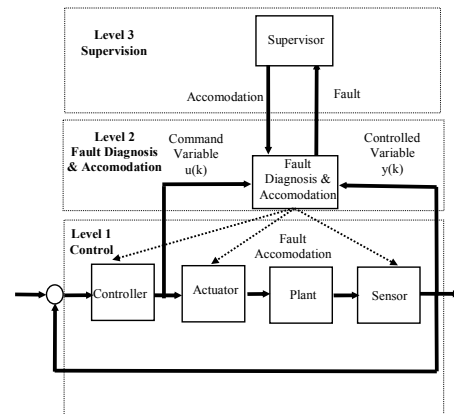


Fig. 1 Fault-tolerant architecture

2.3 Inclusion of fault tolerance in MPC

Fault-tolerance against faults can be embedded in MPC it relatively easily (Maciejowski, 2002). This can be done in several ways:

- (a) Changing the constraints in order to represent certain kinds of fault, being specially “easy” to adapt the algorithms for faults in actuators, assuming that the fault can be located and their effects can be estimated using an FDI module.

- (b) Modifying the internal plant model used by the MPC in order to reflect the fault influence over the plant using the information provided by an FDI module.
- (c) Relaxing the initial control objectives in order to reflect the system limitations under fault conditions.

3. ONE ACTUATOR vs TWO ACTUATOR MPC CONTROL ARCHITECTURE FOR FUEL CELL CONTROL

3.1 One actuator MPC fuel cell control architecture

A common practice in the PEM fuel cell control is to control the hydrogen supply using the anode inlet valve in such a way that the anode pressure tracks the cathode pressure. This is done by a simple proportional controller in order to avoid high differential inlet pressure at both sides, which could tear the membrane. The control of oxygen (or air) flow is achieved by acting on the compressor voltage, as shown in Figure 2. The controlled variable chosen is the oxygen excess ratio. This variable is controlled to avoid the so-called "oxygen starvation" phenomenon that can deteriorate or even spoil the catalyst and provokes voltage and efficiency degradation.

To test the proposed approach, a known test-bench based on the model proposed by (Pukrushpan, 2004b) is used. This model is widely accepted in the PEM fuel cell community as a good representation of the behaviour of an actual PEM fuel cell for control purposes. It is a lumped parameter model that describes quite well the system dynamics. This model considers that the operating temperature inside the cells and the humidity of the reactants are perfectly controlled and, because of that, these variables are treated as parameters. The main characteristics of the fuel cell used in this work are: Number of cells=381, Material of the membrane=Nafion 117, Active area=280cm² and Maximum Power= 75kW.

The oxygen excess ratio control is implemented using MATLAB MPC Toolbox. The Fuel Cell System linear model used to implement the MPC is derived through a linearization at the selected operating point: 40kW of net power, an oxygen excess ratio of 2.3 and a stack voltage of 235V as measured variables; 191A of load current as measured input disturbances; and 164V of stack voltage as manipulated variable. MPC weights are tuned to achieve the desired control goal, that is to maintain the oxygen excess ratio. In the model proposed by (Pukrushpan, 2004a), there are three measured outputs (Stack Net Power, Oxygen Excess Ratio and Stack Voltage), but only the oxygen excess ratio measurement is controlled by the implemented MPC controller. The weight associated to this variable has been selected to have a value of 5 while the weight associated to the control input variation has been selected to have a value of 0.1 for a good performance control, after some "trial and error" experimentation. The air compressor voltage is modelled as a constrained input due to physical limits (maximum compressor voltage cannot exceed 230V, and voltage value is never negative). The oxygen excess ratio is modelled using a constrained output (the operating range is between 1.5 and 3) in order to avoid starvation and to obtain

near optimal operation (Pukrushpan, 2004a). Notice that this output constraint is implemented as a soft constraint in the MPC toolbox in order to prevent the infeasible solution. Figure 3 shows the evolution of the oxygen excess ratio when the designed MPC controller is used in front of an applied series of step changes in the stack current. This current is considered a measured disturbance for MPC controller. The compressor voltage is the control action computed by MPC. Notice that the control goal is achieved, providing a maintained value (2.3) of oxygen excess ratio.

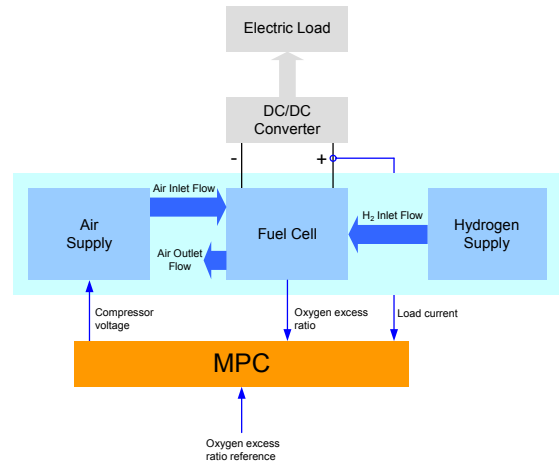


Fig. 2 First MPC fuel cell control architecture

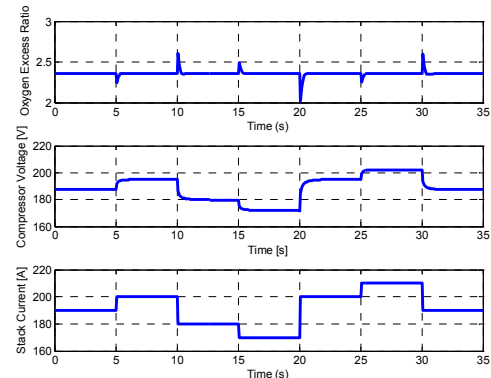


Fig. 3. Control results using the one actuator architecture

3.2 Two actuators MPC fuel cell control architecture

The two actuator MPC fuel cell control architecture presented in Figure 4 is proposed. The difference of this architecture with respect to the one presented in Figure 2 is that additionally to the compressor voltage, the opening area in the cathode outlet valve is controlled. In Feroldi (2007), it was shown that the use of these two actuators offers better control performance and efficiency improvement in the case of regulation of the stack voltage and the oxygen excess ratio at the same time. In this section, control structures of Figures 2 and 4, that have only one regulated variable, are compared. It is found that the compressor voltage variations from the steady-state value to obtain the same control performance regarding the control of the oxygen excess ratio are smaller in the two actuator case than in the one actuator case. These smaller compressor voltage variations are compensated by the control of the outlet valve area. This can be seen in Figure

5. Figure 6(a) shows in detail the comparison of the oxygen excess ratio and the compressor voltage in case of using one actuator and two actuator control architectures. From this figure it can be clearly seen that for the same quality of regulation of the oxygen excess ratio, the two actuator architecture requires smaller voltage variations in the compressor. In Figure 6(b), two basic variables of the fuel cell performance are shown: the stack voltage and the oxygen partial pressure in the cathode. Even though these variables are not controlled, their behaviour must be checked in order to avoid inefficiencies or dangerous responses. The simulation results show different trade-offs. The control architecture with one actuator maintains the stack voltage close to the nominal value and drives the oxygen partial pressure to higher variations while the control structure with two actuators maintains the oxygen partial pressure closer to the nominal value and drives the stack voltage to higher variations.

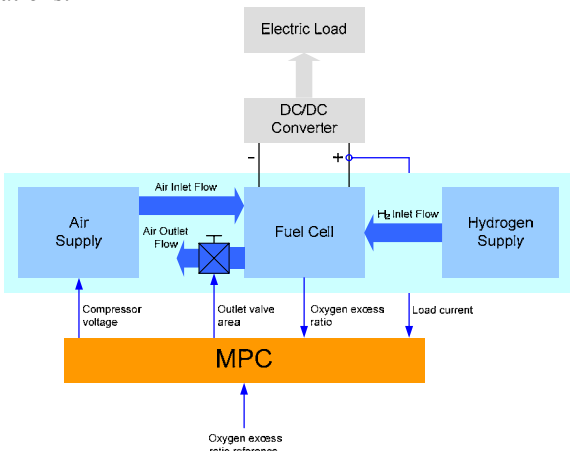


Fig. 4 Two actuators MPC fuel cell control architecture

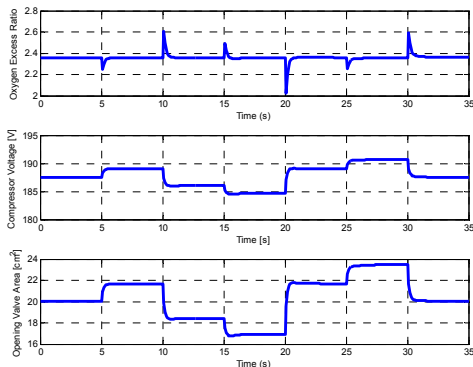


Fig. 5. Control results using the two actuators architecture

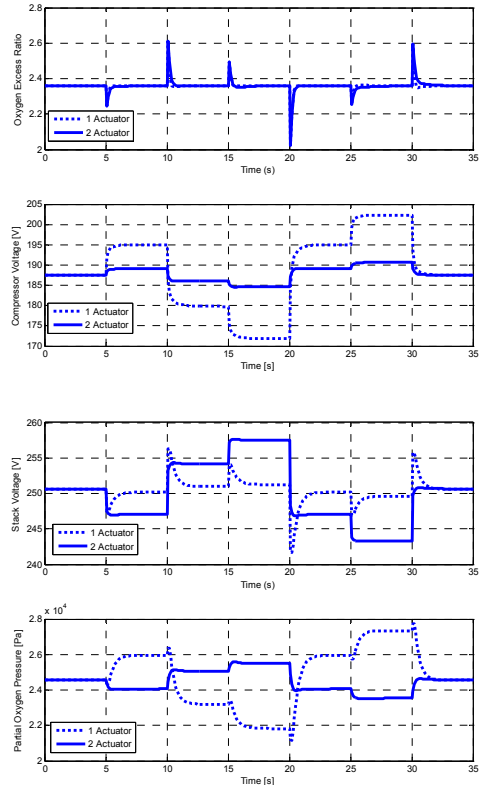


Fig. 6 Comparison of control results using both architectures

4. FAULT-TOLERANCE OF THE TWO CONSIDERED MPC CONTROL ARCHITECTURES

4.1 Active fault-tolerance inclusion

In this section, the advisability of implementing an active fault-tolerance scheme using the two actuators MPC control architecture is shown. As explained in previous sections, the MPC formulation allows to easily include active fault-tolerant control capabilities in the control law. In this paper, the case of actuator faults in the PEM fuel cell system is addressed. In a preliminary manner, the compressor faults are modelled through a reduction of the compressor voltage range. However, in future work not only this limitation but also other compressor malfunctions and other fuel cell faults will be addressed. According to Section 3, the FDI module should provide the MPC controller the new limits of compressor voltage range, once the fault has been detected, isolated and estimated. The active FTC control architecture is shown in Figure 7, where the actuator operating range limits are estimated by FDI module.

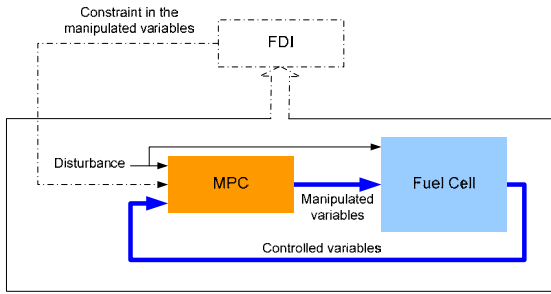


Fig. 7 Fault Tolerant MPC schema for air compressor faults.

The FDI module (drawn in dashed line) is not implemented in this paper and it is assumed that it is available and working perfectly. In order to take into account changes in the compressor voltage range due to the fault (actuator limits), the linear model for MPC design is modified by including the actuator limits as new states that will be estimated by the FDI module:

$$\begin{aligned} \begin{bmatrix} \dot{x}_{1..n} \\ \dot{x}_{n+1} \\ \dot{x}_{n+2} \end{bmatrix} &= \begin{bmatrix} A & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{1..n} \\ x_{n+1} \\ x_{n+2} \end{bmatrix} + \begin{bmatrix} B \\ 0 \\ 0 \end{bmatrix} u \\ \begin{bmatrix} y_{1..m} \\ y_{m+1} \\ y_{m+2} \end{bmatrix} &= \begin{bmatrix} C & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{1..n} \\ x_{n+1} \\ x_{n+2} \end{bmatrix} + \begin{bmatrix} D \\ -1 \\ -1 \end{bmatrix} u \end{aligned} \quad (2)$$

where A, B, C, D are the original fuel cell system matrices. In (2), x_{n+1} corresponds to the current upper limit while x_{n+2} corresponds to lower limit role. Besides, additional output constraints have been added to the MPC controller: $y_{m+1} \geq 0$ and $y_{m+2} \leq 0$, that ensures that the computed control variable u will be into the range estimated by FDI module. Notice that from the controller point of view, $y_{m+1} = x_{n+1}$ and $y_{m+2} = x_{n+2}$. Thus, the only way to respect these constrains is by modifying the control variable u .

4.3 Control results in several fault scenarios

Figures 8, 9 and 10 show the simulation results of FTC scheme considering several fault actuator scenarios considering the two control structures presented in Section 3. The current applied to the stack is the same than in the non-faulty scenario presented in Figure 3. In Figure 8, the control action is shown when the actuator (air compressor) fault causes a limit range reduction such that the upper limit of the range is reduced to 75% of the original one. In this case, there is no control degradation since the compressor voltage does not reach the upper range limit in any of the two considered controller architectures. Figure 9 shows the case corresponding to a reduction of the upper limit range of 50% with respect to the original one. Now, the control degradation is visible in case of the controller architecture that uses only one actuator (the compressor) when the values of stack current are high. In the case of the two actuator architecture, since the voltage excursion of the controller does not reach the upper limit of the operating range, the controlled variable is not affected. Finally, in Figure 10 the upper limit range is reduced to be 25% of the original one. In this case, the control goal is highly affected in the case of using the one

actuator architecture while in the case of the two actuators architecture the control results are still unaffected.

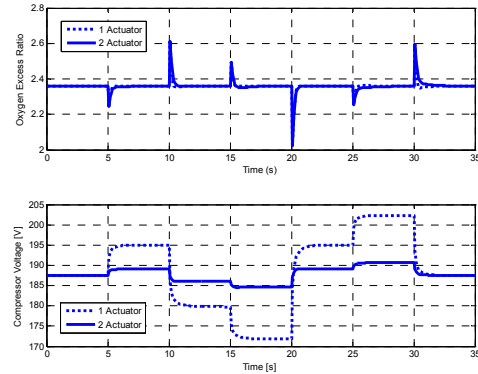


Fig. 8. Fault-tolerant MPC results in case of an actuator fault that limits the operating range to 0-75%.

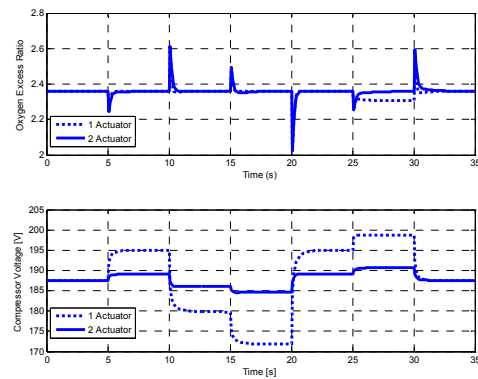


Fig. 9. Fault-tolerant MPC results in case of an actuator fault that limits the operating range to 0-50%.

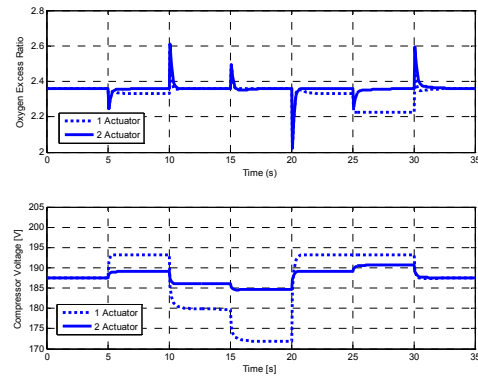


Fig. 10. Fault-tolerant MPC results in case of an actuator fault that limits the operating range to 0-25%.

4.4 Discussion

The results presented in the previous section show that the control architecture that uses two actuators offers a better fault tolerance against compressor faults. This is due to the fact that to achieve the same control results the compressor voltage changes are smaller. The inclusion of the cathode outlet valve opening adds additional redundancy to the system that can be exploited in case of non-severe faults in the compressor.

This fault-tolerance superiority of the two actuators configuration is further presented in Figure 11. This figure compares the control results corresponding to a fault scenario where the compressor voltage is fixed to 187.5 V in two cases. The first case corresponds to the case that MPC controller is informed about the existence of the fault through the FDI module and accommodated as will be explained in Section 4.2 (active FTC). The second case corresponds to the case that MPC controller is not informed (passive FTC). From Figure 11, it can be seen that control results regarding the controlled objective (oxygen excess ratio) are better in case of the active FTC. However, performance degradation in the control objective (oxygen excess ratio) for the passive case appears but it is not as severe as it would have been in case of the one actuator configuration. Figure 11 also shows how the MPC in the active FTC case compensates the effect of the fault in the first actuator (compressor) using the second actuator (cathode valve). In the passive FTC case this is not the case since the MPC controller uses the compressor as it was operating normally, but because of the fault the compressor does not respond as the MPC controller has ordered. This further motivates the inclusion of an active FTC scheme.

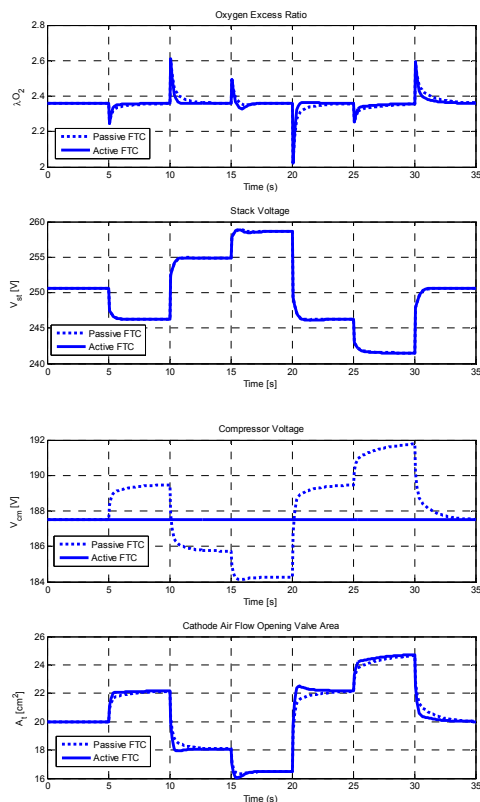


Fig. 11. Active vs. passive MPC fault-tolerant control

5. CONCLUSIONS AND FUTURE WORK

In this paper, fault-tolerance of MPC control for fuel cell systems has been addressed. MPC is a suitable control methodology to control fuel cell systems because of their multivariable and complex behaviour. MPC is one of the control methodologies that can introduce more easily fault-tolerance. However, the problem of including actuator fault-

tolerance in the control loop has not been already addressed in the literature for those systems. Here, a new control structure that not only uses the compressor voltage as a control variable but also the cathode outlet valve area output has been proposed. It is shown that using this new control allows improving the control performance and at the same time allows introducing fault-tolerance against compressor faults. This gives arguments for the inclusion of the cathode output valve, which is a debatable aspect in the design of PEMFC. Finally, the proposed approach has been assessed on a known PEM fuel cell test bench. As future work, not only compressor faults modelled as a reduction of the limits of the operating range, but also other type of compressor faults will be addressed.

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