State Machine-Based Architecture to Control PEMFC System Processes in a Fuel Cell Electric Vehicle

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In this paper, a state machine-based control architecture for a Fuel Cell Electric Vehicle (FCEV) is proposed. The considered Fuel Cell System (FCS) is a complex system with multiple different states of operation. This includes the start-up, run, shut-down and idle states, which have been identified as the states of a State Machine (SM). Furthermore, the FCS incorporates several subsystems; namely, as the cathode, anode and thermal subsystems and the DC/DC converter that all have different modes of operation. In each specific state of the FCS, the subsystems should operate in a specific predefined mode. A control structure is therefore necessary to coordinate these subsystems and the stack in the different FCS operation states and the operation modes of the different subsystems. This work describes in detail the SM designed for the fuel cell system of the FCEV of the INN-BALANCE project [1]. The SM combines time and event-triggered actions based on "if-then-else" logic and issues messages indicating the current state [2]. It has been programmed in State-Flow/Matlab and has several advantages, including being 1) Clear in structure: which is explicitly readable, so that the FCS states can be relatively easily identified and 2) Easy to calibrate: the SM has a finite number of parameters that can be easily modified [3]. The proposed state machine gives the following abilities to a fuel cell system in a vehicle application.

- Ensures the orderly flow of events and prevents the occurrence of undesired chains of events in the system
- Normal and freeze startup ability for the fuel cell system
- Normal shutdown ability for the fuel cell system
- Galvanostatic and potentionstatic operation
- Prevents ice formation inside the stack in the shutdown state
- Allows fast shutdown when neccessary

The operation states of the fuel cell system in this automotive application are: Initial, Failsafe, Standby, Refueling, Service mode, Start-up, Run, Min Power, Normal shutdown, Fast shutdown. The overall scheme of the proposed SM is shown in **Figure 1**. In each operation state, the SM manages the activation of the different subsystems in their various modes of operation. It uses communication protocol numbers and status numbers to have communication with the subsystems to activate their modes of operation and be informed about their status, respectively. The different operation modes of the four subsystems and the assigned protocol numbers to their different operation modes are listed in **Table 1.** The proposed SM is integrated into a supervisory controller to control the PEMFC system processes. The designed supervisory controller consists of an optimal setpoint generator unit in addition to the SM. It generates the balance of plant subsystem setpoints based on the requested power from the vehicle side and the SM sends these setpoints to the subsystem's local controllers corresponding to the states of operation. The fuel cell supervisory control unit is turned on when the vehicle is started and the onboard computer turns on. The SM starts in the initial state named 'Initialization'. All the subsystems are not still activated. If the different subsystems report their successful initialization, the SM moves to the 'Standby' state and waits until the 'Run-Requested' is activated by the Vehicle Control Unit. Once the 'Run-Requested' is activated, the state-machine goes into the next state where the 'Start-up' procedure starts. During the 'Start-up' procedure, the state machine sends the protocol numbers and setpoints to the subsystem controllers to start the different subsystems. The state machine get feedback from the subsystems with the sensors and the status variables. At the end of the 'Start-up' procedure, the subsystems and the fuel cell are ready to operate in 'Run' state. During 'Run' state, the SM receives setpoints of the different subsystem from the optimal setpoint generator unit and sets them for the different subsystem and the DC/DC converter. When necessary, the driver stops the car and the system goes to 'Min Power'. From this state, the system can go to the 'Start-up' procedure again or to the 'Normal Shutdown'. If the system goes to 'Normal Shutdown', the subsystems have to be turned off in an orchestrated manner by receiving ordered protocol numbers to avoid damage to the fuel cell stack. After the Shutdown is finished, the state machine goes to 'Standby'. In the case of a malfunction in one of the subsystems or components, the 'Failsafe' state is triggered and the whole system is depowered. The 'Failsafe' state has the highest priority among the other states of operation.

The startup procedure is shown in **Figure 2.** It shows how the different modes of operation of the subsystems are activated. The condition to transit from one substate for example 'start compressor bypass' to the next substates, 'cathode min flow' and 'anode startup', is to receive a status number from the cathode subsystem that verifies the compressor started successfully; otherwise, the SM remains in the previous substate until a timeout is reached and the 'Failsafe' is activated. **Figure 3** shows the activation signals for the first 40 seconds of a 'Normal Startup'. The data shown in **Figure 3** are corresponding to the fuel cell in the real vehicle of the INN-BALANCE project. It shows the change in the protocol numbers of the different subsystems to do a successful startup. It also shows two of the locally controlled variables measurements: the mass flow of air and inlet coolant temperature. The mass flow of the compressor increases when the protocol number of cathode changes from 0, then decreases to a setpoint value for protocol number=4 at second 14. In this test, the stack temperature is Tstack>33°C and the 'heating loop without heater' is activated in the thermal subsystem with protocol number 1 and then at second 14 the 'cooling loop' is activated and the temperature of the coolant decreases due to the volume of water inside the radiator and then increases, due to reaction inside the stack, to reach a defined temperature setpoint. Results of the tests in the real prototype car showed that the proposed SM structure can successfully perform the fuel cell system processes for an automotive application.

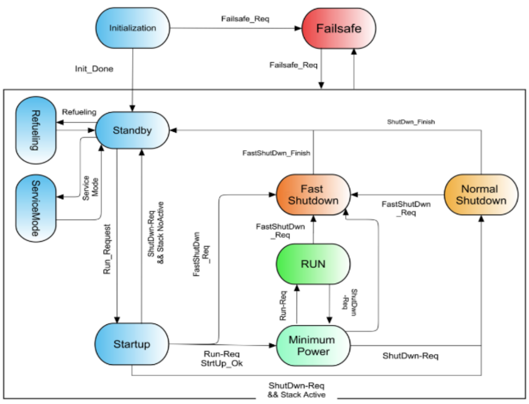

Figure 1. Overall scheme of state machine

Table 1. Subsystems modes of operation

Cathode SS		Thermal SS		Anode SS		DC/DC SS	
Off	0	Off	0	Off	0	Standby	0
Bypass Humidification	1	Heating loop without heater	1	Startup	1	Galvanostatic	1
Start Compressor Bypass air	2	Heating loop with heater	2	Run	2	Potentiostatic	2
Min flow	3	Cooling loop	3	Shutdown	3	Passive	5
Run	4	Cooling Loop for isolation	4			Error	15
Max flow	5						

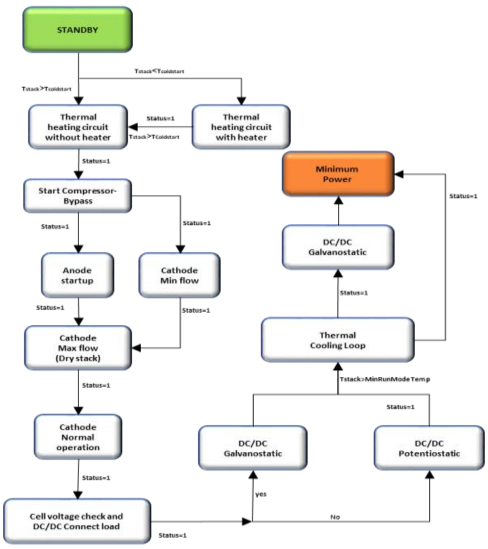

Figure 2. Startup procedure

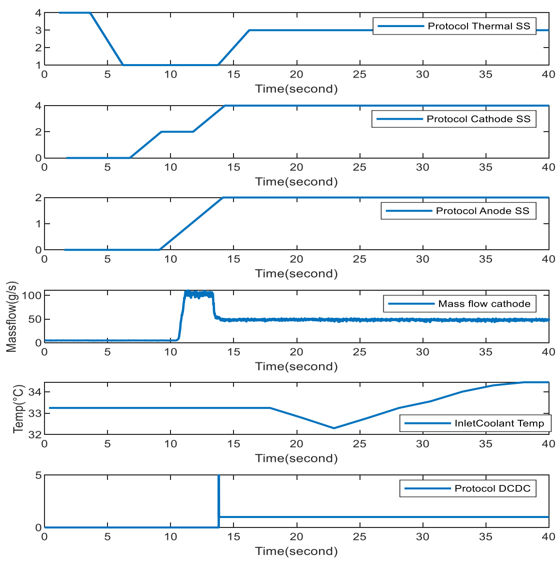

Figure 3. Activation of the subsystems in the startup procedure

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