DESIGN, IMPLEMENTATION AND TESTING OF AN AUTOMATIC POWER MANAGEMENT SYSTEM FOR RESIDENTIAL STAND-ALONE MICROGRIDS WITH HYBRID POWER SUPPLY

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Outline

- Description of the system
- Functions of the automatic power management system
  - battery state of charge estimation
  - experimental validation of the SOC estimation
  - control strategy and limiters of the battery voltage
  - PMS implementation into an embedded microcontroller
- Experimental investigation of the stand-alone operation
- Load rejection maneuver
Description of the system
PEM fuel cell stack

Characteristics:

- $P_{\text{stack}} \rightarrow 6 \text{ kW}$
- $V_{\text{stack}} \rightarrow 50 \div 70 \text{ V}$
- Temp $\rightarrow 65 \degree \text{C}$
- $p_{\text{H}_2} \rightarrow 1.7 \text{ bar}$
- plates $\rightarrow$ graphite
- $n$° of plates 80
- dead end pulsing
PEM fuel cell layout

- Stack
- H2 inlet valve
- Humidifier
- Water tank
- Water pump
- Blower
- Heat Exchanger
- Water pump
- Fan
- Radiator
- Water tank
- Water pump
- Electro valve 2
- Electro valve 1
- Pressure reducing valve
- Gas to gas humidifier
- Filter
- Air outlet
- Air inlet
- Water outlet
- Water inlet
- Air outlet
PEM fuel cell electric scheme
Battery

Bidirectional voltage-source converter

Characteristics:

- $P_{net} \rightarrow 4200 \text{ W}$
- freq $\rightarrow 50 \text{ Hz}$
- Range $V_{DC} \rightarrow 41 \div 63 \text{ V}$
- Range $V_{AC} \rightarrow 172 \div 250 \text{ V}$

Battery storage system

Characteristics:

- 4 lead-acid unit in series
- Voltage $\rightarrow 12 \text{ V per unit}$
- Capacity $\rightarrow 100 \text{ Ah}$
PV emulator

Typical Curve

Points under dashed line are invalid

Maximum Power

Maximum Voltage

80V = E4361A
85V = E4381A
120V = E4362A
130V = E4382A

510W = E4361A
600W = E4382A
Monitoring and control

PV array emulator

Battery source

Fuel Cell

Active Load

Reactive Load

OLTC

Trans.

Load and PV profile emulator

Electric Board

Microcontroller

PV array current

Battery source current

Electric board current

Battery source DC current

Battery source temperature

FC hydrogen mass flow

FC auxiliaries AC current

FC auxiliaries AC voltage

FC active power set point

Active load set point

Load current

Battery source current

PV array current

AC node voltage

FC current

FC stack DC current

FC stack DC voltage

DSP-FPGA National Instrument CompactRio
Functions of the power management system

1. Grid connected operating mode

2. Islanded operating mode
   2.1 FC in operation
      2.1.1 battery charging
      2.1.2 battery discharging
      2.1.3 load reduction
      2.1.4 Intentional FC shut-down
   2.2 FC not operating
      2.2.1 battery discharging
      2.2.2 FC start-up when $SOC < SOC_{\text{start}}$
      2.2.3 load reduction
      2.2.4 Intentional FC start-up
Battery state of charge estimation

\[
SOC(t) = \frac{C(t_0) - \alpha(I, \theta) \int_{t_0}^{t} i(t)dt}{C(I, \theta)}
\]

where:
- \(C(I, \theta)\) is the battery capacity for a constant discharge rate \(I\) of the battery at electrolyte temperature \(\theta\)
- \(C(t_0)\) is the battery capacity at time \(t_0\)
- \(i(t)\) is the instantaneous value of the battery current
- \(\alpha\) is the efficiency coefficient associated to battery charge and discharge (for small SOC variations \(\alpha \approx 1\)).
Temperature correction

\[ C(t_0) = C / 20 \left( 1 + \beta (\theta - \theta^*) \right) \]

\[ \beta = 0.006 \text{ Ah/°C} \]

\[ \theta^* = 20 \text{ °C} \]
\[
SOC(t) = \frac{C(t - \Delta t) - \left(\tilde{I}_{T, f_s} (t - \Delta t) + \tilde{I}_{T, f_s} (t)\right) \Delta t}{2C(\tilde{I}_{T, f_s}, \theta)}
\]

where

\[
C(\tilde{I}_{T, f_s}, \theta) = \frac{C(I^*_k) + C(I^*_{k+1})}{2}
\]

\[
C(\tilde{I}_{T, f_s}, \theta) = C(\tilde{I}_{T, f_s}, \theta^*)(1 + \beta(\theta - \theta^*))
\]

\(\tilde{I}_{T, f_s} \in [I^*_k, I^*_{k+1}]\)

\(f_s = 5\) Hz, and \(T = 2\) s

Temperature correction

![Graph showing battery capacity vs. constant current discharge rate](image-url)
\[
SOC(t) = \frac{C(t - \Delta t) - (\tilde{I}_{T,f_s}(t - \Delta t) + \tilde{I}_{T,f_s}(t)) \frac{\Delta t}{2}}{C(\tilde{I}_{T,f_s}, \theta)}
\]

In order to avoid discontinuity

\[\tilde{I}_{T,f_s} \in [I_j^*, I_{j+1}^*] \quad j \neq k\]

\[C(t - \Delta t) = C(\tilde{I}_{T,f_s}, \theta) SOC(t - \Delta t)\]
Experimental validation of the SOC estimation

- The initial battery SOC is adjusted to be equal to 50%

- The microgrid is operated islanded with variable load profiles in order to simulate realistic operating conditions

- The test is stopped when the estimated SOC reaches a predefined value (namely 30%, 40%, 50% and 60%).

- The battery is disconnected from the microgrid and discharged with a constant current, corresponding to the given discharge rate and corrected with the battery temperature ("true SOC").
True SOC (%) vs. Estimated SOC (%)
Control strategy and limiters of the battery voltage

The FC output reference value is controlled each 5s in order to track a target SOC value, $SOC^*$ which is pre-determined as an average SOC level.

Limits:

$$P_{FC}^{\text{min}} \leq P_{FC,\text{ref}} \leq P_{FC}^{\text{max}}$$

$$V_{batt}^{\text{min}} \leq V_{batt} \leq V_{batt}^{\text{max}}$$
\[
SOC_{\text{max}} \leq SOC \\
p_{\text{FC,ref}} = -P_{\text{PV-load}} + \left( p_{\text{FC}}^{\text{min}} + P_{\text{PV-load}} \right) \cdot \left( 1 - u_{\text{min}} \right)
\]

\[
SOC^* \leq SOC < SOC_{\text{max}} \\
p_{\text{FC,ref}} = -P_{\text{PV-load}} + \\
\quad + \left( p_{\text{FC}}^{\text{min}} + P_{\text{PV-load}} \right) \cdot \frac{SOC - SOC^*}{SOC_{\text{max}}^* - SOC^*} \cdot \left( 1 - u_{\text{min}} \right)
\]

\[
SOC_{\text{min}}^* < SOC < SOC^* \\
p_{\text{FC,ref}} = -P_{\text{PV-load}} + \\
\quad \left( p_{\text{FC}}^{\text{max}} + P_{\text{PV-load}} \right) \cdot \frac{SOC^* - SOC}{SOC^* - SOC_{\text{min}}^*)} \cdot \left( 1 - u_{\text{max}} \right)
\]

\[
SOC \leq SOC_{\text{min}}^* \\
p_{\text{FC,ref}} = -P_{\text{PV-load}} + \left( p_{\text{FC}}^{\text{max}} + P_{\text{PV-load}} \right) \cdot \left( 1 - u_{\text{max}} \right)
\]
\[ K_p = 1 \]
\[ T_i = 30 \text{ s} \]
\[ T_d = 0.06 \text{ s} \]
Tests

Test a) initially $SOC < SOC^*$
Test b) initially $SOC > SOC^*$

$SOC^* = 50\%$, $SOC^*_{\text{min}} = 47.5\%$, $SOC^*_{\text{max}} = 52.5\%$, $SOC_{\text{start}} = 45\%$,

$V_{\text{min}}^{\text{batt, nom}} = 44\ V$

$V_{\text{max}}^{\text{batt, nom}} = 54\ V$
### Set Points of the PV-Array Emulator

<table>
<thead>
<tr>
<th>Changing time (s)</th>
<th>$V_{oc}$ (V)</th>
<th>$I_{sc}$ (A)</th>
<th>$V_{mp}$ (V)</th>
<th>$I_{mp}$ (A)</th>
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<tbody>
<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>10</td>
<td>60</td>
<td>6.4</td>
<td>51.5</td>
<td>5.6</td>
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<td>40</td>
<td>60</td>
<td>5.6</td>
<td>51.0</td>
<td>4.9</td>
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<td>130</td>
<td>60</td>
<td>7.2</td>
<td>52.0</td>
<td>6.3</td>
</tr>
<tr>
<td>210</td>
<td>60</td>
<td>8.0</td>
<td>52.5</td>
<td>7.0</td>
</tr>
<tr>
<td>900</td>
<td>60</td>
<td>4.0</td>
<td>50.0</td>
<td>3.5</td>
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</table>

### Set Points of the Load Emulator

<table>
<thead>
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<th>Changing time (s)</th>
<th>$P_{load}$ (W)</th>
<th>$P_{load}$ (W)</th>
</tr>
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<td>0</td>
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<td>5000</td>
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<tr>
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<td>3000</td>
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<td>590</td>
<td>1200</td>
<td>3500</td>
</tr>
<tr>
<td>690</td>
<td>500</td>
<td>5000</td>
</tr>
<tr>
<td>940</td>
<td>1500</td>
<td>3000</td>
</tr>
</tbody>
</table>

Power factor = 0.85
Test a)
Test a)

total energy request by the loads (taking into account also the PV production) = 0.414 kWh

FC production = 0.844 kWh

its net electric efficiency = 37.4%

(stack production = 1.123 kWh,
auxiliaries’ energy consumption = 0.131 kWh
hydrogen consumption = 0.758 Nm$^3$)

energy accumulated in the battery = 0.358 kWh
(0.427 kWh is the net energy absorbed by the battery storage system from the microgrid)
Test b)
Test b)

total energy request by the loads (taking into account also the PV production) = 1.386 kWh

FC production = 1.376 kWh

net electric efficiency = 37.6%

(stack production = 1.807 kWh
auxiliaries’ energy consumption = 0.182 kWh
hydrogen consumption = 1.231 Nm$^3$)

energy provided by the battery = 0.108 kWh (0.013 kWh is the net energy provided by the battery storage system to the microgrid).
Load rejection
Conclusions

The realized PMS allows the reliable stand-alone operation of a kW-class residential microgrid fed by a controllable FC and a PV unit.

The estimation of the battery $SOC$ represents a key parameter for the management of the energy flows.

The described PMS does not include a load forecast tool.