Testing of a Predictive Control Strategy for Balancing Renewable Sources in a Microgrid

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Outline – I part (storage control strategy and experimental validation)

I. Introduction

II. Microgrid and energy management details
   ✓ Problem definition
   ✓ System layout and forecast input
   ✓ Energy management strategy and microgrid components
   ✓ Storage sizing and controller sensitivity

III. Experimental testing results and procedures
   ✓ Experimental results on 3rd July
   ✓ Experimental results on 7th July

IV. Conclusions and future developments
Introduction

• In several member countries of the European Union, small scale feed-in systems have increased in popularity due to favorable regulations.

• Due to the fact that the conventional power plants are displaced and thus eventually shut down, DER plants (including PV and wind) will be required to provide a predictable production plan and to be able to grant it, even if the meteorological conditions differ from the forecasted ones.

• It means that every producer will have to provide a day-ahead production plan with hourly resolution, which is supposed to be granted within a given confidence interval.

• In such setup energy storage (or demand response) can help in meeting the hourly production plan.
Microgrid and energy management details

Problem definition - hypothesis

- The day-ahead, an hourly energy production plan for the microgrid system is defined. This plan is calculated by knowing the PV module layout information, the WT power curve and the weather forecast.

- During the operation day the hourly production plan must be respected within ±1%.

- The storage system can be used to correct the deviations from the plan, but it is very crucial not to overuse it, because any charge/discharge cycle would lead to energy losses.
Microgrid and energy management details

System layout in SYSLAB facility

- SYSLAB facility and used subset of power components. SYSLAB is a small-scale power system consisting of real power components interconnected by a three phase 400V power grid, and some communication and control nodes interconnected by a dedicated network, all distributed over the Risø Campus.
Microgrid and energy management details

**Forecast input**

- Forecasts are given by the Wind Energy Dep. two times per day for the following 48 hours:
  - @ 9 am the 48 hourly series starting at 12 GMT
  - @ 9 pm the one starting at 24 GMT.

- 6 months of comparison between the forecasted values of wind speed and solar irradiance and the respective historical data are reported.

- The mean values are respectively equal to 1.0 m/s and 34 W/m²

- The standard deviations are 2.9 m/s and 258 W/m²
Microgrid and energy management details

*Microgrid components models*

- In order to evaluate the PV and the WT production, proper models have been developed in Simulink.
- The hourly weather data is used as input for the models

- The PV and WT estimated hourly productions are used for defining the energy production plan (the one that the microgrid owner is supposed to follow with a precision of ±1% during the day of operation).
Microgrid and energy management details

Energy Management Strategy

- The hourly energy plan is used by the energy manager to build the Energy Ref curve.
- **The red and the green dashed curves are the control band.** Whenever the energy profile exceeds the upper or the lower bound (red and green line) the battery is activated:
  - the more the distance from the objective value, the deeper the charge/discharge required.
  - the opening of the lines, that means the distance between the upper and the lower band with reference to the “Energy Ref” curve, determines the stiffness of the control.

[Energy Plan - Microgrid graph]

- Upper Band
- Lower Band
- Energy Ref
Microgrid and energy management details

* a possible way to address the storage control – power smoothing strategy*

- A storage (15 kW-190 kWh) plus wind turbine (11 kW) system aiming at smoothing the power output at the PCC with 1 second communication delay!
Microgrid and energy management details

*a possible way to address the storage control – power smoothing strategy*

- ...and now with 8 seconds communication delay!!! Very far from being smoothed!
Microgrid and energy management details

Concerning the power and the energy sizing of the storage

- The design of the control bands has an impact on both storage power and energy size. The two main variables that affect the sizing of the storage are the forecast precision and accuracy (i.e. if they have an offset and how much they span).

- **Power sizing:**
  - In the considered setup the control bands are set to 10%, meaning that the lower band (the green line) crosses at the 6th minute the time axis.
  - This means that a storage inverter of 5 kW should be able, in case of null production of the microgrid, to release full power for the remaining 54 minutes, leading to a maximum energy of 4.5 kWh.
  - Considering a microgrid maximum hourly production of 21 kWh, which means full power output from both PV and WT, with this control band setup, the storage is able to compensate production errors up to 21% of the microgrid hourly production.

- **Energy sizing:**
  - The sizing of the storage capacity depends on the coherence of the forecast errors. It can be noted that in case of alternate hourly errors, the storage alternatively charges and discharges so that the depletion of the state of charge depends mainly on the storage internal inefficiencies.
  - Therefore the storage energy rating could be relative small. If the error has the same sign for the whole day, then the storage energy sizing criteria needs to be revisited.
Microgrid and energy management details

Controller sensitivity

- The relative energy error is the difference between the system energy state and the control bands. Two energy errors can be identified depending on the crossing of the upper or the lower band.
  - $e_{\text{up}}$ is the difference between the system energy state and the upper control band, divided by the upper control band value. This error triggers a storage charge.
  - $e_{\text{down}}$ is the difference between the system energy state and the lower control band, divided by the lower control band value. This error triggers a storage discharge.

- The sensitivity of the controller is chosen in order to have the storage to store/release the maximum power, $P_{\text{max}}$, if the relative energy error, $e$, is equal or greater to 1%.

- If the error amplitude is within 0% and 1%, the storage power set-point is changed by five discrete steps 20% amplitude.

<table>
<thead>
<tr>
<th>Upper relative energy error %</th>
<th>Storage reference power</th>
<th>Lower relative energy error %</th>
<th>Storage reference power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_{\text{up}} \leq 0%$</td>
<td>0</td>
<td>$e_{\text{down}} \leq 0%$</td>
<td>0</td>
</tr>
<tr>
<td>$0 &lt; e_{\text{up}} \leq 0.2$</td>
<td>0</td>
<td>$0 &lt; e_{\text{down}} \leq 0.2$</td>
<td>0</td>
</tr>
<tr>
<td>$0.2 &lt; e_{\text{up}} \leq 0.4$</td>
<td>-20% $P_{\text{max}}$</td>
<td>$0.2 &lt; e_{\text{down}} \leq 0.4$</td>
<td>20% $P_{\text{max}}$</td>
</tr>
<tr>
<td>$0.4 &lt; e_{\text{up}} \leq 0.6$</td>
<td>-40% $P_{\text{max}}$</td>
<td>$0.4 &lt; e_{\text{down}} \leq 0.6$</td>
<td>40% $P_{\text{max}}$</td>
</tr>
<tr>
<td>$0.6 &lt; e_{\text{up}} \leq 0.8$</td>
<td>-60% $P_{\text{max}}$</td>
<td>$0.6 &lt; e_{\text{down}} \leq 0.8$</td>
<td>60% $P_{\text{max}}$</td>
</tr>
<tr>
<td>$0.8 &lt; e_{\text{up}} \leq 1$</td>
<td>-80% $P_{\text{max}}$</td>
<td>$0.8 &lt; e_{\text{down}} \leq 1$</td>
<td>80% $P_{\text{max}}$</td>
</tr>
<tr>
<td>$e_{\text{up}} \geq 1%$</td>
<td>-$P_{\text{max}}$</td>
<td>$e_{\text{down}} \geq 1%$</td>
<td>$P_{\text{max}}$</td>
</tr>
</tbody>
</table>
Experimental testing

Procedure

- The testing days reported are the 3rd July 2013, which was a windy day with frequent clouds passages and the 7th July, which was a sunny day with few wind.

- The experimental process is here explained:

  1. The meteorological forecast data (solar irradiance, wind speed, air temperature) of the studied day are used to evaluate the PV and WT output. The day-ahead forecasts that mean the forecasts given at the 9 am of the 2nd July 2013 (for the experiment run on the 3rd July) are taken in consideration.

  2. The PV and WT model outputs are used to build the forecasted energy plan for the studied day (3rd July).

  3. The microgrid setup is prepared and the pc with the Simulink controller, aimed at managing the storage system, is connected to the SYSLAB facility and the experiment runs.
Experimental testing
test on July 3rd

• The experiment starts at 13:00 GMT (15:00 local time) and lasts for 3 hours.

• The overall energy plan, that means the expected production for PV and WT, for the 3 hours experiment is shown in the first plot. The microgrid energy production can be also observed in this plot (black curve).

• The storage, whose output is depicted in the second plot, is able to compensate the deviations from the predicted production.

• The relative deviation from the expected production, which means the difference between the production and the forecasts, referred to the energy plan is reported in the third plot.
Experimental testing
test on July 3rd – detail
Experimental testing
test on July 3\textsuperscript{rd}

- The power profiles of the different components can be observed in the first plot.

- While the overall microgrid production, that means the power transit at the PCC, is reported in the second plot.
Experimental testing
test results on July 3rd

- PV+WT forecasted is the forecasted hourly production, it is the value of the energy plan at the end of the hour.
- PV+WT produced is the hourly energy produced by the renewable sources: photovoltaic and wind turbine.
- PV+WT error is the difference between energy produced and forecasted. The error is positive if there is an excess of production.
- Storage usage is the total work of the storage that means the sum of charge and discharge regardless of the sign.
- PCC energy transit is the hourly production of the whole microgrid, thus PV, WT and storage and including the cable losses (almost negligible due to their size).
- PCC energy absolute error is the difference between the production of the microgrid and the forecasted one.
- PCC energy relative error is the PCC energy error relative to PV+WT Forecasted.

*calculated as the sum of the hourly errors regardless of sign;
** calculated as the weighted average of the hourly errors regardless of sign

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PV+WT forecasted (kWh)</td>
<td>7.85</td>
<td>12.61</td>
<td>9.61</td>
<td>30.07</td>
</tr>
<tr>
<td>PV+WT produced (kWh)</td>
<td>8.49</td>
<td>10.75</td>
<td>11.35</td>
<td>30.58</td>
</tr>
<tr>
<td>PV+WT error (kWh)</td>
<td>0.64</td>
<td>-1.86</td>
<td>1.74</td>
<td>*4.24</td>
</tr>
<tr>
<td>Storage usage (kWh)</td>
<td>-0.51</td>
<td>2.48</td>
<td>-4.10</td>
<td>*7.09</td>
</tr>
<tr>
<td>PCC energy transit (kWh)</td>
<td>7.88</td>
<td>12.60</td>
<td>9.61</td>
<td>30.08</td>
</tr>
<tr>
<td>PCC energy absolute error (kWh)</td>
<td>0.027</td>
<td>-0.014</td>
<td>-0.003</td>
<td>*0.044</td>
</tr>
<tr>
<td>PCC energy relative error (%)</td>
<td>0.35</td>
<td>-0.11</td>
<td>-0.03</td>
<td>**0.15</td>
</tr>
</tbody>
</table>
Experimental testing
test on July 7th

- The experiment starts at 9:00 GMT (11:00 local time) and lasts for 6 h.

- The overall energy plan, that means the expected production for PV and WT, for the 3 hours experiment is shown in the first plot. The microgrid energy production can be also observed in this plot (black curve).

- The storage, whose output is depicted in the second plot, is able to compensate the deviations from the predicted production.

- The relative deviation from the expected production, which means the difference between the production and the forecasts, referred to the energy plan is reported in the third plot.
Experimental testing

test on July 7th

• It is straightforward to note that the forecasts were rather optimistic; however the storage succeeds in managing the microgrid energy production.

• the microgrid power output smoothing is not pursued.
Experimental testing

test results on July 7th

- **PV+WT forecasted** is the forecasted hourly production, it is the value of the energy plan at the end of the hour.
- **PV+WT produced** is the hourly energy produced by the renewable sources: photovoltaic and wind turbine.
- **PV+WT error** is the difference between energy produced and forecasted. The error is positive if there is an excess of production.
- **Storage usage** is the total work of the storage that means the sum of charge and discharge regardless of the sign.
- **PCC energy transit** is the hourly production of the whole microgrid, thus PV, WT and storage and including the cable losses (almost negligible due to their size).
- **PCC energy absolute error** is the difference between the production of the microgrid and the forecasted one.
- **PCC energy relative error** is the PCC energy error relative to PV+WT Forecasted.
- *calculated as the sum of the hourly errors regardless of sign;
- **calculated as the weighted average of the hourly errors regardless of sign

<table>
<thead>
<tr>
<th>GMT hours</th>
<th>9-10</th>
<th>10-11</th>
<th>11-12</th>
<th>12-13</th>
<th>13-14</th>
<th>14-15</th>
<th>9-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV+WT forecasted (kWh)</td>
<td>11.56</td>
<td>12.78</td>
<td>12.82</td>
<td>12.40</td>
<td>11.46</td>
<td>9.67</td>
<td>70.69</td>
</tr>
<tr>
<td>PV+WT produced (kWh)</td>
<td>8.90</td>
<td>9.78</td>
<td>9.41</td>
<td>9.42</td>
<td>9.58</td>
<td>6.93</td>
<td>54.02</td>
</tr>
<tr>
<td>PV+WT error (kWh)</td>
<td>-2.66</td>
<td>-3.00</td>
<td>-3.41</td>
<td>-2.98</td>
<td>-1.88</td>
<td>-2.73</td>
<td>*-16.66</td>
</tr>
<tr>
<td>Storage usage (kWh)</td>
<td>2.56</td>
<td>5.36</td>
<td>8.63</td>
<td>11.56</td>
<td>13.36</td>
<td>16.00</td>
<td>57.47</td>
</tr>
<tr>
<td>PCC energy transit (kWh)</td>
<td>11.48</td>
<td>12.60</td>
<td>12.70</td>
<td>12.38</td>
<td>11.38</td>
<td>9.57</td>
<td>70.11</td>
</tr>
<tr>
<td>PCC energy absolute error (kWh)</td>
<td>-0.08</td>
<td>-0.18</td>
<td>-0.12</td>
<td>-0.03</td>
<td>-0.07</td>
<td>-0.10</td>
<td>*-0.58</td>
</tr>
<tr>
<td>PCC energy relative error (%)</td>
<td>-0.71</td>
<td>-1.41</td>
<td>-0.90</td>
<td>-0.22</td>
<td>-0.60</td>
<td>-0.99</td>
<td>**0.80</td>
</tr>
</tbody>
</table>
Conclusions...

• The management of the energy production of energy systems with renewable generation sets will get more and more important in the near future and the correct prediction of the expected production will be crucial in order to be able to manage the overall system resources.

• Improving the forecast techniques is of great importance; however errors cannot be totally avoided. The compensation of these errors will be critical and a proper management of the controllable resources, such as storage systems or controllable loads, is essential.

• This presentation showed a management strategy capable of controlling a storage system (limited to 5 kW) in order to grant the forecasted energy production plan of a microgrid, formed by a 10 kW PV and an 11 kW WT.

• The overall idea consists in, by knowing the meteorological forecast for the next 24 h, controlling the storage system in order to compensate the hourly deviations from the day-ahead energy plan, minimizing the storage usage.
...and future developments

- A first evaluation of the correlation between the meteorological forecasts errors and the sizing in term of power and energy of the storage is analyzed even if deeper analyses are needed.

- The range of experiments will be extended across the days, taking also advantage of the fact that the whole system can be studied in the simulated environment.

- Finally, further analysis will aim at extending the described strategy in a larger microgrid setup, including building appliances, such as heating systems and water heaters, and electric vehicles.
Outline – II part (simulations over 1 day and storage sizing)

I. Introduction

II. Model Description
   – Problem definition
   – System layout and management strategy analysis

III. Simulation Results
   – Simulation procedure
   – Scenarios analysed (different storage power size)

IV. Conclusions and Future Developments
Model Description

System layout – components are simulated

10 kW PV Plant: TF & Poly

400 V 3p
Main Network

VRB storage system

Meteo Forecast:
Solar Irr; Temp; Wind

Estimated Production

Energy Manager

Energy Plan

Control System

Storage Power Ref

PCC
Power Transit

PV Plant Model

Hourly Data
Model Description

*Photovoltaic model*

- The DC power produced by the module mainly depends on the incident solar radiation and on the temperature, which for instance is function of air temperature, wind speed and radiation itself.

- The dependence of the panel output with different sunlight intensity and the dependence in function of the temperature have been evaluated in order to evaluate the reduction from the nominal efficiency, having taken in account that the nominal data are provided for standard meteorological conditions (1000 W/m² and 25 °C)
Model Description

storage model

- The modelled dynamics regard the State-of-Charge (SOC) behaviour, the electrochemical conversion and the thermal characterization.

- The main state variables are therefore the state of charge, the temperature and the voltage: all the characteristic elements of the storage system (as open circuit voltage, internal resistances, limitations and protections thresholds) present some kind of dependence from these state variables.
Model Description

Energy Management Strategy

• The input of the controller is the power measured at the PCC, which is not directly used in the control loop; but it is used to compute the correspondent energy reference within the hour.

![Energy Plan](image1)

- The red and the green lines form the control band: whenever the energy profile exceeds the upper or the lower bound (red and green line) the battery is activated:
  - the more the distance from the objective value, the deeper the charge/discharge required.
Simulation Results

Simulation Procedure

• The simulation day chosen is the 4\textsuperscript{th} May 2013, which was a sunny day with frequent clouds passages.

• The simulation process follows:

1. The forecast meteorological data (solar irradiation, wind speed, air temperature) are used to evaluate the PV output. The day-ahead forecasts (that mean the forecasts given at the 8 am of the 3\textsuperscript{rd} May 2013) are taken in consideration.

2. The PV model output is used to build the energy plan for the studied day

3. Since the sensitivity analysis aim at finding the suitable size of the storage system, several simulations are run using the historical production data of the PV installed in the SYSLAB and using the Simulink validated model of the storage.
Simulation Results
Simulation Procedure

PV Production 10 kW - 60 minute sampled

Forecast Output
Historical Data

PV Forecasted profile (red)
PV historical data (blue)

The total energy produced by the PV for the studied day was 64.6 kWh, while, according to the forecasts, it would have been 71.8 kWh (+11%).
Simulation Results

Base case – no storage

The relative average error is equal to 17.3% and the maximum one is greater than 50%.
Simulation Results

Different storage power size (with reference to the PV installed capacity)

Results with the storage size of 3 kW (30% scenario)
Simulation Results

Different storage power size (with reference to the PV installed capacity)

- It is interesting to observe the behavior of the power measure at the PCC (first plot) which for certain aspects is worsen because of the power steps which can be induced by the storage operation.

- However it has to be kept in mind that the objective of the control strategy proposed is driven from an energy perspective due to the need to respect the scheduled energy plan.
# Simulation Results

*Storage usage and system performances*

<table>
<thead>
<tr>
<th>Storage Size</th>
<th>Storage usage (kWh)</th>
<th>Energy released (kWh)</th>
<th>Average hourly error</th>
<th>Max hourly error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case size 0% PV</td>
<td>0</td>
<td>0</td>
<td>17.3%</td>
<td>&gt;50.0%</td>
</tr>
<tr>
<td>5%</td>
<td>2.64</td>
<td>1.90</td>
<td>10.3%</td>
<td>&gt;50.0%</td>
</tr>
<tr>
<td>10%</td>
<td>4.45</td>
<td>3.54</td>
<td>7.2%</td>
<td>41.2%</td>
</tr>
<tr>
<td>15%</td>
<td>6.03</td>
<td>5.07</td>
<td>4.1%</td>
<td>19.8%</td>
</tr>
<tr>
<td>20%</td>
<td>7.43</td>
<td>6.46</td>
<td>1.5%</td>
<td>6.1%</td>
</tr>
<tr>
<td>25%</td>
<td>7.99</td>
<td>6.99</td>
<td>0.7%</td>
<td>2.6%</td>
</tr>
<tr>
<td>30%</td>
<td>8.10</td>
<td>7.10</td>
<td>0.6%</td>
<td>2.2%</td>
</tr>
<tr>
<td>50%</td>
<td>8.28</td>
<td>7.27</td>
<td>0.5%</td>
<td>1.4%</td>
</tr>
</tbody>
</table>
Conclusions and future developments

• The proposed work describes an energy management strategy for a 10 kW PV plant coupled with a storage system.

• By knowing the meteorological forecast for the next 24h, the objective is to dispatch the PV system and to be able to grant the scheduled hourly energy profile by a proper management of the storage.

• The energy manager controls the storage in a predefined way in order to ensure that the hourly energy production plan is respected, compensating the forecast errors and minimizing the storage itself usage.

• The study is intended to provide also a methodology for the evaluation of the size of the storage system in terms of power and energy.

• Further analysis will aim at extending the study along the whole year and at evaluating the behaviour of the energy manager in case of different forecast horizons.
For further readings...


