Wind power and storage modeling and integrated control in electric distribution systems

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REPORT OF

TRANSNATIONAL ACCESS

FOR

ID 20100930-02

WIND POWER AND STORAGE MODELING
AND INTEGRATED CONTROL IN ELECTRIC
DISTRIBUTION SYSTEMS

01/05/2011-13/05/2011

AT

SYSLAB, RISØ DTU, DENMARK

UNDER THE PROJECT

DERRI – DISTRIBUTED ENERGY RESOURCES RESEARCH INFRASTRUCTURES

FP7 GRANT AGREEMENT NO 228449 DERRI

MAY 2011
This report documents the activities under the specified Transnational Access to the SYSLAB DER research infrastructure at Risø DTU, Denmark, under the DERri project and supported by the European Commission under FP7. The report is prepared by the Users.

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Organisation: University of Genova – IEES (Intelligent Electrical Energy Systems) laboratory
Users: Mattia Marinelli – Francesco Baccino
Organisation: University of Genova – IEES (Intelligent Electrical Energy Systems) laboratory
Report date: 17-05-2011
## Activities

<table>
<thead>
<tr>
<th>Date</th>
<th>Activities</th>
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</tr>
</thead>
<tbody>
<tr>
<td>02/05</td>
<td>Facilities presentation and activities scheduling</td>
<td>PN-FRIS-LM</td>
</tr>
<tr>
<td>03/05</td>
<td>Matlab-Simulink communication tuning with Syslab SCADA</td>
<td>FRIS</td>
</tr>
<tr>
<td>04/05</td>
<td>First VRB-Gaia turbine combined control system attempt</td>
<td>FRIS-LM</td>
</tr>
<tr>
<td>05/05</td>
<td>VRB full charge at nominal power (i.e. -15 kW AC)</td>
<td>FRIS-LM</td>
</tr>
<tr>
<td>06/05-07/05</td>
<td>VRB 1/3 nominal power discharge (i.e. 5 kW AC)</td>
<td>FRIS</td>
</tr>
<tr>
<td>08/05-09/05</td>
<td>VRB 1/3 nominal power charge (i.e. -5 kW AC)</td>
<td>FRIS</td>
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<tr>
<td>09/05</td>
<td>VRB-Gaia turbine combined control system</td>
<td>FRIS</td>
</tr>
<tr>
<td>09/05-10/05</td>
<td>VRB 1/3 nominal power charge (i.e. -5 kW AC)</td>
<td>FRIS</td>
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<tr>
<td>10/05</td>
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<tr>
<td>11/05</td>
<td>VRB nominal power discharge (i.e. 15 kW AC)</td>
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<tr>
<td>12/05</td>
<td>VRB-Gaia turbine combined control system</td>
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**Assistants**

<table>
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<th>Name</th>
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<td>PN</td>
<td>Per Norgaard</td>
</tr>
<tr>
<td>FRIS</td>
<td>Fridirik Rafn Isleifsson</td>
</tr>
<tr>
<td>LM</td>
<td>Lucian Mihe-Popa</td>
</tr>
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1   EXPERIMENT

1.1   CONTEXT
The modeling of wind parks and the relative control architectures are an important part for the introduction of relevant quantity of renewable energy in the future smartgrids. Therefore there is a strong necessity to have proper validated models to help operators to perform better studies and to be more confident with the results.

In order to fully exploit wind generation capabilities, there is a great attention to couple wind generation to storage systems. The storage model proposed below is suited for electrical studies and has a general validity. For this activity it has been tuned on the specification of a Vanadium Redox battery. The analyzed dynamic regards the SOC (State of Charge) behaviour, the electrochemical one and the thermal one.

The main aim of the project is to validate models of small wind turbines and storage systems and integrated control strategies of the whole resulting system thus describing and testing the benefits that the storage system can provide.

The storage system is coupled to the wind generation system in order to realize different tasks: to have the generation output power smoothed or to grant a certain energy value.

1.2   OBJECTIVE
The proposed project has the following objectives:

1. Validate models for VRB storage (15 kW – 260 kWh) system and relative controllers.
2. Implement and test control strategies for the combined VRB – Gaia Wind Turbine (11 kW) system.

Firstly a series of charge/discharge cycles at different power level (i.e. nominal power and 1/3 nominal power) are run with the aim of providing a deep characterization of the proper dynamic and static parameters of the realized Matlab-Simulink model (see Chapter 2).

After the VRB is coupled with the Gaia turbine and connected to the grid. The idea is to control the battery charging and discharging in order to control the whole system output. The controller sets the reference power that the VRB has to accomplish. Two controller typologies are studied: the first one that provides the control of the power output, the second one related to the control of the energy output in a given time window (see Chapter 3).
2 TEST #1 – VRB PARAMETERS CHARACTERIZATION

2.1 OBJECTIVE
The objective of this test is to characterize the VRB static and dynamic parameters by a sequence of charge/discharge cycles and step responses at different SOC levels and with different power set-points.

2.2 SET-UP
Four tests have been performed (2 charges and 2 discharges) at different power levels (15 kW AC and 5 kW AC). The cycles have been SOC-fractional (i.e. charge from 0% SOC to 10%, then from 10% to 20%, etc...) and after each step the storage power set-point has been set to zero for 10 minutes:

- Charge @ Nominal power (-15 kW AC → -13.6 kW DC) from 0% to 100% SOC level by 10% SOC steps. Total time required 20 hours.
- Discharge @ Nominal power (15 kW AC → 16.2 kW DC side) from 0% to 100% SOC level by 10% SOC steps. Total time required 12 hours.
- Charge @ 1/3 Nominal power (-5 kW AC → -4.4 kW DC side) from 0% to 100% SOC level by 10% SOC steps. Total time required 52 hours.
- Discharge @ 1/3 Nominal power (5 kW AC → 5.5 kW DC side) from 0% to 100% SOC level by 10% SOC steps. Total time required 35 hours.

The storage nominal capacity “should” be about 260 kWh. This value is estimated by the volume of the electrolyte. The two tanks, in fact, store about 6,500 litres of Vanadium solution each. From the literature the storable, theoretical, energy is about 20 Wh per litre (thus 20 Wh per 13,000 litres → 260 kWh).

2.3 MEASUREMENT
The measured variables have been: Battery Voltage, Reference Cell Voltage, Battery Current, measured SOC. The evaluated parameters: Rstatic, Rdynamic, Cdynamic, Max/Min Voltage thresholds, theoric SOC.

The measurements depicted in Fig. 1 are:

- V0: voltage @ t0 (t0 is the time when the voltage step happens, due to the power request),
- V1: voltage @ t0’ (in reality it requires 2 seconds, 1 due to the inverter time constant, 1 due to measurement delay),
- V2: voltage @ t1 (t1 is the time when the voltage step happens, due to the stopping),
- V3: voltage @ t1’ (in reality it requires 2 seconds, 1 due to the inverter time constant, 1 due to measurement delay),
- V4: voltage @ tinf (in reality is the voltage before the beginning of the next voltage step, it is equal to the V0 of the following cycle),
- I1: current @ t0’
- I2: current @ t1’
Fig. 1 – Voltage and Current measurements

With these measurements the parameters are determined as follows:

- \( R_{\text{static\_begin}} \): \( \frac{\text{abs}(V_0-V_1)}{I_1} \),
- \( R_{\text{static\_end}} \): \( \frac{\text{abs}(V_2-V_3)}{I_2} \),
- \( 3\text{Tau} \): the time required to the voltage to get inside the band \( V_4 \pm 5\% \cdot \text{abs}(V_4-V_3) \) (see Fig. 2),
- \( V_{1\text{dyn}} \) is the value the voltage reaches after \( t_0 + 3\text{Tau} \),
- \( R_{\text{dynamic}} \): \( \frac{\text{abs}(V_{1\text{dyn}}-V_1)}{I_1} \),
- \( C_{\text{dynamic}} \): \( \frac{\text{Tau}}{R_{\text{dynamic}}} \).

Fig. 2 – 3 Tau evaluation

Once all the parameters are evaluated, the electric circuit reported in Fig. 3 can be fully characterized.
It is worth to note that the pumps consumptions is about 1500 W when the battery is running at full power and 1400 W when the power is reduced (1/3 of the nominal). If the battery is in stand-by, but ready to enter in service, the consumption still remains high (about 1150 W).

Moreover the Battery Management System (BMS) is always on and requires about 400 W constant.

### 2.4 RESULTS DURING CHARGE AT NOMINAL POWER

The first test performed is the charge at nominal power (-15 kW AC side → -13.6 kW DC side). At each 10% measured SOC step the charge is stopped for 10 minutes in order to evaluate the dynamic parameters (internal RC chain). The test lasted 20 hours, thus leading to a supply energy equal to 258 kWh (AC side) and 234 kWh (DC side). Next figures report the main variable measured (Fig. 4, Fig. 5, Fig. 6, Fig. 7, Fig. 8) and the evaluated internal parameters (Fig. 9, Fig. 10, Fig. 11).
If the OCV values, given by the reference cell, are plotted in function of the measured SOC, it can be noted that the internal BMS gives information about a SOC that does not correspond to the theoretic OCV-SOC relationship described by the Nernst law, here reported and designed in Fig. 6 (blue line):

\[
V_{oc} = V^0 + \frac{R^*T}{F} \ln \left[ \frac{SOC^* (SOC + 6)}{1 - SOC} \right]
\]

Fig. 6 – OCV theoretic and measured in function of the SOC
A matching between the two SOCs has been performed in order to understand what level of the theoric SOC corresponds to the 0% SOC read by the BMS (see Fig. 7). Thus the non-linear characteristic that matches the two SOCs has been analyzed in Fig. 8 and an analytic expression has been found:

\[
SOC_{theoric} = -0.2157 \times SOC_{meas}^2 + 0.7211 \times SOC_{meas} + 0.3916
\]

![Fig. 7 – Matching between the two OCVs](image1)

![Fig. 8 – SOC measured vs SOC theoric characteristics (black line) and parabolic approximation (red line).](image2)

The evaluated parameters, Rstatic, Rdynamic, Time constant and thus Cdynamic are hereafter reported, both in function of the measured and the theoric SOCs:
Fig. 9 – $R_{\text{static}}$; $C_{\text{dynamic}}$ and $R_{\text{dynamic}}$ in function of the measured SOC. (note $R$ in Ohm, $C$ in 1e5 F)

Fig. 10 – $R_{\text{static}}$; $C_{\text{dynamic}}$ and $R_{\text{dynamic}}$ in function of the theoretic SOC. (note $R$ in Ohm, $C$ in 1e5 F)

Fig. 11 – Time constant ($RC$)

Apparently there is a mismatch between the supplied (and measured) DC energy (equal to 234 kWh) and the effective stored energy. Considering that the Joule losses account for about 22 kWh while the shunt losses, at first instance evaluated as 3% of the DC energy, account for 8 kWh; the effective stored energy
would be 202 kWh. However, if the measured SOC is effectively related with the theoretic SOC, as previously explained (see Fig. 7), then the battery would have to store just 132 kWh (from theoretic SOC 39% to 90% → 51% of 260 kWh). There is thus a huge difference between the effective energy pushed (i.e. stored) inside the battery equal to **202 kWh** and the energy stored according to the SOC measurement (ΔSOC*Enom → 51%*260 kWh= 132 kWh). 

It looks like that the usable energy stored in the battery is equal to around 202 kWh, thus corresponding to the 78% of the expected storable energy (i.e. 260 kWh) and not to just the 51%!

There is the need to better analyze the assumed matching between the measured OCV and the theoretical OCV provided by the Nernst equation (see Fig. 7). Moreover there is the need to know the transfer function, embedded in the internal BMS, which provides the SOC measurement (what kind of linkage with the OCV?).

### 2.5 RESULTS DURING DISCHARGE AT NOMINAL POWER

The second test performed is the discharge at nominal power (15 kW AC side → 16.2 kW DC side). Each 10% measured SOC step the charge is stopped for 10 minutes in order to evaluate the dynamic parameters (internal RC chain). The test lasted 12 hours, thus leading to a supply energy equal to 166 kWh (DC side) and 153 kWh (AC side). Next figures report the main variable measured (Fig. 12, Fig. 13) and the evaluated internal parameters (Fig. 14, Fig. 15, Fig. 16).

![VRB OCV and Battery Voltages](image)

**Fig. 12 – OCV and Battery voltage; Battery current**

The evaluated parameters, Rstatic, Rdynamic, Time constant and thus Cdynamic are hereafter reported, both in function of the measured and the theoretic SOCs:
Fig. 13 – AC and DC powers; SOC measured

Fig. 14 – Rstatic; Cdynamic and Rdynamic in function of the measured SOC. (note R in Ohm, C in 1e5 F)

Fig. 15 – Rstatic; Cdynamic and Rdynamic in function of the theoric SOC. (note R in Ohm, C in 1e5 F)
As a confirmation of the previous energy estimation, because the Joule losses weigh about 26 kWh and the estimated shunt losses around 6 kWh, if the DC released energy is 166 kWh, then the battery should have contained 198 kWh that is almost equal to the 202 kWh estimated at the end of the charge.

It is thus possible to make a rough evaluation of the round trip efficiencies:

- DC roundtrip: 166 discharged vs 234 charged → DCeff = 71%
- AC roundtrip: 153 discharged vs 258 charged → ACeff = 59% (due to DCeff, the inverter efficiency and the BMS losses)
- Full roundtrip: 150 kWh discharge – 15 kWh pumps vs 258 kWh charged + 27 kWh pumps → Full_eff = 48% (due to the previous efficiencies and the pumps consumption)

It has to be noted that these efficiencies do not take in account the fact that the BMS and the pumps run also when the battery is in stand-by, ready to work.

2.6 RESULTS DURING CHARGE AT 1/3 NOMINAL POWER

The third test performed is the charge at 1/3 nominal power (-5 kW AC side → -4.4 kW DC side). Each 10% measured SOC step the charge is stopped for 10 minutes in order to evaluate the dynamic parameters (internal RC chain). The test lasted 52 hours, thus leading to a supply energy equal to 225 kWh (DC side) and 255 kWh (AC side).

Next figures report the main variable measured (Fig. 17, Fig. 18) and the evaluated internal parameters (Fig. 19, Fig. 20, Fig. 21).
Fig. 17 – OCV and Battery voltage; Battery current

Fig. 18 – AC and DC powers; SOC measured
In this case the Joule losses weigh about 8.5 kWh, the estimated shunt losses around 7.4 kWh, the DC stored energy is 225 kWh (and the AC 255 kWh), thus the battery has taken around 209 kWh. This value is
higher than the one obtained with the full power charge (i.e. 202 kWh). This mismatch could be addressed to the Peukert law, which says that, for liquid electrolyte batteries, the storable energy depends on the charge/discharge intensity. A greater number of charges/discharges with different intensities has to be performed to correctly evaluate this phenomena.

2.7 RESULTS DURING DISCHARGE AT 1/3 NOMINAL POWER

The fourth test performed is the discharge at 1/3 nominal power (5 kW AC side \(\rightarrow\) 5.5 kW DC side). Each 10% measured SOC step the charge is stopped for 10 minutes in order to evaluate the dynamic parameters (internal RC chain). The test lasted 35 hours, thus leading to a supply energy equal to 179 kWh (DC side) and 163 kWh (AC side).

Next figures report the main variable measured (Fig. 17, Fig. 18) and the evaluated internal parameters (Fig. 19, Fig. 20, Fig. 21).

![VRB OCV and Battery Voltages](image)

![VRB Current](image)

Fig. 22 – OCV and Battery voltage; Battery current
Fig. 23 – AC and DC powers; SOC measured

Fig. 24 – Rstatic; Cdynamic and Rdynamic in function of the measured SOC. (note R in Ohm, C in 1e5 F)

Fig. 25 – Rstatic; Cdynamic and Rdynamic in function of the theorical SOC. (note R in Ohm, C in 1e5 F)
In this test the Joule losses account for about 8.3 kWh while the shunt for 5.6 kWh, the DC released energy is 179 kWh (and the AC 163 kWh), thus the battery had about 193 kWh.

The same efficiencies evaluation are also provided for the 5 kW charge/discharge:

- DC roundtrip: 179 discharged vs 225 kWh \( \rightarrow \) DCeff = 80%
- AC roundtrip: 163 discharged vs 255 kWh \( \rightarrow \) ACeff = 64% (due to DCeff, the inverter efficiency and the BMS losses)
- Full roundtrip: 163 kWh discharge \( - \) 45.6 kWh pumps vs 255 kWh charged + 71.5 kWh pumps \( \rightarrow \) Full_eff = 36% (due to the previous efficiencies and the pumps consumption)

It has to be noted that these efficiencies do not take in account the fact that the BMS and the pumps run also when the battery is in stand-by, ready to work.

### 2.8 COMMENTS

The tests have been useful to determine the internal parameters and the system efficiencies. However some questions arise about the SOC measurement and the SOC energy storable inside the battery.

The usable energy looks like to be 200 kWh compared to a theoretical energy of 260 kWh. This value however does not match with the 130 kWh estimated by the SOC theoric – SOC measurement relationship.

The internal resistance looks like to have a dependence from the versus and the intensity of the current. The higher values are achieved during the charge with low intensity, while the lower ones during the full power discharge. Moreover there is a slight reduction whenever the measured SOC is within the central area.

The RC time constant is quite variable and moreover difficult to evaluate with precision (due to the measurement errors), a first evaluation put it in the range of 30÷40 seconds.
An evaluation of the storage efficiencies has also been performed. Several efficiencies have been defined depending on the subsystem considered (just the battery, the battery and the inverter and the overall system included the pumps). An overview is reported in Table 1.

Further analysis can regard the characterization of the thermal behaviour, it means to have information on the cell temperature response, in order to build a thermal overload capability of the cell stack. The measurement can be performed by the insertion of a temperature probe on the liquid that flows out the cells and on the cell surface itself.

To reduce the measurement error, it would be better to have a separate measure of the DC current (now it has been calculated as the ratio of the DC power and the DC voltage).

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<td>DC power (kW)</td>
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<td>80%</td>
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<tr>
<td>Eta AC (Joule&amp;shunt&amp;inverter&amp;BMS)</td>
<td>59%</td>
<td>64%</td>
</tr>
<tr>
<td>Eta Full (aux&amp;Joule&amp;shunt&amp;inverter&amp;BMS&amp;pumps)</td>
<td>48%</td>
<td>36%</td>
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3 Test #2 – Combined VRB-Gaia System Control

3.1 Objective
The objective of this test is to analyze different control strategies for the combined control of the VRB plus Gaia wind turbine plant.

3.2 Set-Up
The controllers have been developed in the Matlab-Simulink environment and the software has been interfaced with the local SCADA system in order to set the reference power to the storage system and to read and thus control the power output at the PCC (see Fig. 27).

![VRB plus Gaia plant layout](image)

3.3 Measurement
The controller is designed in Matlab-Simulink. The notebook, on which the controller runs, is connected to the local SCADA system in order to take the power measurement of the network transit and of the devices. It moreover sets the reference power to the battery in order to accomplish the desired mission.

It has to be noted that 1 second (at least) is required to read the power measurement and another second is required to set the reference setpoint.

Two control strategies have been tested:
- Power Control whose aim is to have the desired power profile at the PCC
- Energy Control whose aim is to have the desired energy profile at the PCC
3.4 POWER CONTROL

The battery reference power and the battery AC effective power are reported in Fig. 28. The battery behaviour is very satisfactory because it is able to follow quite quickly the reference set. The 1 second delay is due to the SCADA intrinsic delay.

![Battery Power](image)

**Fig. 28 – Battery powers.**

The Gaia production is reported and compared with the battery output in the first diagram of Fig. 29. The PCC desired and real output are reported in the second diagram.

![Battery and Gaia Powers](image)

![PCC Power](image)

**Fig. 29 – Battery and Gaia outputs; PCC reference and effective power.**
Unfortunately the controlling action is not successful (the PCC power is very far from being smoothed) because the power transit at the PCC is sampled each 10 seconds as it can be better appreciated in Fig. 30. This introduces a great delay in the controlling loop that destabilizes the controller.

3.5 ENERGY CONTROL

In this scenario the controlling action is realized within a far more relaxed time frame. This time it is not required the control of the instantaneous power transit at the PCC but just the energy transit in 10 minutes.
A comparison between the desired energy output and the provided by the system is shown in Fig. 32 and in Fig. 33. The error at the end of the controlling window is within 2%.

![Battery Power](image)

**Fig. 32** – Battery reference power (red line) and battery power (black line).

![Energy Error](image)

**Fig. 33** – Energy errors.

It can be appreciated how the controller is able to regulate the discharging action of the storage in order to have the desired energy amount at the end of the period (i.e. 2 kWh in 10 minutes). The PCC power profile is not smoothed as it can be appreciated in the first diagram of Fig. 31.

This control strategy has been tested also for a longer period (30 minutes) but with the same controlling window (10 minutes). This time the desired energy output has been reduced due to light wind conditions.
The controlling action is fully realized, the energy errors are below 2% as it can be seen in Fig. 35, in Fig. 36.

Fig. 34 – Battery and Gaia outputs; PCC reference and effective power.

Fig. 35 – Second diagram: battery reference power (red line) and battery power (black line).

Fig. 36 – Energy errors.
3.6 COMMENTS

The controller testing has been successful for what concerns the dynamic response of the battery. Note that for the Power Control no limitation on the ramp rate of the battery power output has been set. The battery has proved to be able to pass from full charge to full discharge mode within 1 second, due mainly to the communication time lag. Unfortunately the 10 seconds lag on the feedback of the PCC power transit did not allow the success of this control strategy. Further tests will require an improvement of this aspect.

Regarding the Energy Control, because of its slow nature, the ramp rate has been set to 1 kW/sec, in order to avoid rapid charge/discharge action. This control strategy has been successfully tested and the desired energy profile has been achieved.

Keep in mind that the circulating pumps are fed externally from the battery system but are within the balance of the system. Thus if the Gaia is producing an average power of 12 kW, the desired energy at the end of the 10 minutes window will not be 2 kWh (i.e. 12 kW *1/6h) but will be no greater than 1.8 kWh merely due to 1200 W *1/6h required by the pumps.
4 CONCLUSION

The present project focused on the characterization of model for storage systems, in Matlab-Simulink environment, useful for implementing integrated control strategies of the combined system turbine-battery in order to describe the benefits that storage can provide to renewable generation. The main purpose was the facilitation of the integration of distributed, intrinsically not dispatchable, generation in the electric grid.

The storage model validation provided an evaluation of the different parameters in function of the SOC and of the charge/discharge intensity. However some incoherencies on the storable energy have arisen.

The battery internal DC roundtrip efficiency resulted to be quite good (between 71% to 80%), but the huge amount of energy required by the auxiliary system resulted very high, reducing thus the overall roundtrip efficiency (between 48% to 36%). That could threaten the economic effectiveness of this storage typology. A better modulation of the pumps (i.e. inverter driven pumps) could improve the overall efficiency.

A further step of characterization could provide the thermal description of the cell stacks in order to evaluate a possible degree of overload capability.

Two control strategies have been envisaged, the first one named Power Control and the second one Energy Control, with the aim of setting the battery charging and discharging phases in order to control the whole Gaia plus VRB system.

The battery proved to be a very fast respondent battery, since the only limits are due to the communication delays and to the inverter ramping rate, however the great delay in the feedback of the PCC measure had the effect to destabilizes the Power Control.

Concerning the Energy Control, the tests have proved the effectiveness of this slow type control even with some bounds on the power ramp rate of the battery.