Design and Implementation of a Hybrid Power Plant Controller

Alin George Raducu, Nikolaos Styliaras, Jonas Funkquist, Claudiu Ionita
Research and Development
Vattenfall AB
Stockholm, Sweden
alingeorge.raducu@vattenfall.com

***Abstract*— This paper presents the development of a controller, used to steer renewable hybrid power plants, consisting of wind power plants (WPP), solar power plants (SPP) and battery energy storage systems (BESS) with the aim to facilitate the integration of new generating/storage units to existing sites. A simulation environment in Matlab/Simulink is used to show how the controller distributes external commands for curtailments to the different components through a dispatch function.**

Keywords - Control of renewable energy sources, Hybrid power plant control and optimization, Hybrid power plant integration, Battery energy storage system.

I. INTRODUCTION

The decreasing cost of photovoltaic (PV) systems and batteries during the last years is rendering a number of business cases profitable, giving the green light for implementation. A common trend is the installation of batteries and PV power generation in already existing onshore Wind Power Plants (WPP). In that way, the cost of developing new infrastructure is avoided and the fast dynamics of the battery can be used to support the facility in different ways. However, when adding new generation or storage units connected in the existing point of connection it is crucial that the new units will be synchronized with the operation of the wind farm and that the power quality will satisfy the requirements imposed by the grid codes. Another important challenge will be to ensure that the point of common connection will never be overloaded due to these extra production/storage units. All of the above can be achieved by means of a controller.

The controller proposed to this work, referred to as Renewable Park Controller (RPC), will be on a level above the controllers of the individual components of the hybrid plant. The RPC will only communicate with the individual park controllers via their set-point commands and not directly with the lower level components, such as the wind turbines, solar inverters or battery cells. The development of such a controller is expected to facilitate the integration of new units (generation and/or storage) to already existing sites and also enable the use of online optimization functions based on market-related inputs. The exact functionality of this controller can vary depending on the requirements for the specific site, e.g. primary frequency control, power ramp limitation, power limitation, increased renewable energy utilization, etc. Some scientific publications regarding optimization-based control can be found in the literature, but they mostly concern offline optimization [1] [2] [7] [8]. Some work has also been done within control of hybrid wind-solar-battery plants but they deal with control based on given weather and load conditions within a specific period [4] [5]. This is more important when examining island operation [6]. A real-time control algorithm is presented in [3], but the purpose there is to reduce the fluctuations in the output power at the connection point, utilizing the battery. Basic questions regarding the integration of new units to existing sites have not been addressed often.

A proof of concept of such hybrid power plant controller is developed first in a simulation environment and will then be deployed in an existing power plant. It concerns a wind power plant where a battery is installed and there are plans for a solar farm to be installed as well. However, there is a grid limitation regarding the injected power at the point of connection that may not be exceeded. The desired functionality of the RPC will consist of optimized active/reactive power generation and curtailment of the generating/storage units function of grid limitation. The curtailment of each component has different priorities which is performed through a dispatch function. The RPC architecture, the plant models used to simulate the controller, the dispatch function and simulation results are presented in this work.

II. ARCHITECTURE DESIGN

A. *System Description*

A schematic diagram of the examined system is shown in Fig. 1. The RPC consists of two main parts as shown in the diagram: the controller and the dispatch function. The inputs of the controller component are the total active power production measured in the point of common connection (PCC) of the hybrid power plant and a reference value for the production. This reference may come from different sources: as a curtailment setpoint, as a constraint, e.g. a grid limitation, or as a calculated value based on an optimization algorithm. The advantage of this setup is that the future optimization algorithm can be chosen based on the site requirements. Forecasted values for electricity spot price or other cost functions can be input to the optimization to ensure

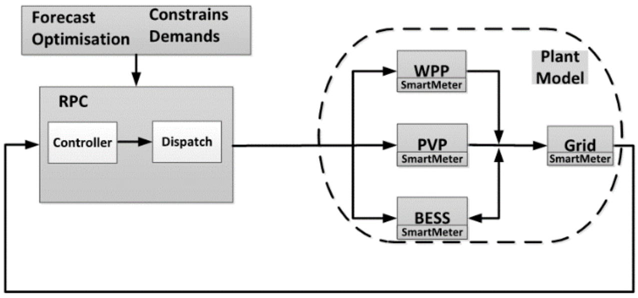

Figure 1. Renewable park controller simulation architecture.

that the battery contributes to a more cost-effective operation of the hybrid power plant.

The output of the controller is a setpoint command for the total production of the hybrid plant. It is then passed to the dispatch function that decides how to distribute this setpoint to the individual components.

In order to test the RPC, a plant model is required to simulate the closed loop performance. The plant consists of models for the wind power plant (WPP), the solar power plant (SPP), the BESS and the electric grid. Fed by the setpoints from the dispatcher, the plant model will calculate the values representing the measurements that is consumed by the controller. The controller and dispatch function are described in the following sections and the plant model is presented in section III.

B. Controller

The main functionality of the controller is to ensure that the setpoint in the PCC, provided by the TSO or the operators in the control room is tracked as accurate as possible.

The connections between the power production plants and the PCC are made with cables/OHL, which in turn will result in active and reactive power losses. Furthermore, there might be cases when the plants are not able to provide the expected output. The controller must therefore compensate for the error, based on measurements. The output of the controller must then be dispatched accordingly to the individual power plants (i.e. the WPP, SPP and BESS).

The controller requirements are:

- No steady-state error
- No overshoot
- Stable system
- Settling time < 30 s
- Sampling time of 100 ms

One of the grid services that can be provided by the RPC is the primary frequency response. The settling time requirement of < 30 s is therefore chosen based on the Danish tender conditions for provision of ancillary services, which states that the generation unit should be able to provide half of the agreed power in 15 s and full power in 30 s [9].

A controller which is able to fulfil the requirements presented above is the PI-controller (proportional-integral), a standard controller with well-known discretization methods. The design of the controller is done in s-domain and then a suitable discretization method is chosen together with an appropriate sampling-time. The transfer function of the PI in the s-domain is:

$$G_{PI}(s) = K_p \frac{T_i s+1}{T_i s} \tag{1}$$

The Modulus Optimum design criteria has been applied here to determine the parameters K_P and T_i. This means that the pole with the highest time constant is replaced with a pole in the origin. Using this method the resulted response of the closed loop is similar to the response of open loop. In this case, the plant with the slowest response time is the WPP. Based on this knowledge T_i is chosen as the response time of the WPP (i.e. $T_i = \tau_P$). K_P can then be adjusted to yield the desired bandwidth and settling time (chosen value $K_P = 0.4$). According to a previous study [10], Tustin provides the fastest response and it yields a more accurate mapping into the z-plane, therefore this is the selected method.

Anti-windup is needed to ensure that the output of the controller is not higher than the maximum power than can be delivered by the power plants. Since the possible power of the plants is fluctuating, the limits of the antiwind-up loop must change dynamically. Assuming a generator sign convention (i.e. positive value means power is injected into the grid and negative value means power is consumed from the grid), the following limits can be applied:

$$P_{dmd,max} = P_{poss,WPP} + P_{poss,SPP} + P_{poss,BESS-} \tag{2}$$

$$P_{dmd,max} = P_{poss,BESS+} \tag{3}$$

which are the upper and the lower saturation limit respectively and $P_{poss,BESS-}$ and $P_{poss,BESS+}$ are battery discharging and charging possible power, respectively.

C. Dispatch Function

The purpose with the dispatch function is to distribute the demanded power from the controller between the generation and storage units. The following notation is used in the mathematical description of the dispatch function:

GU:	Generation unit, $GU \in \{WPP, SPP, BESS\}$
P_{dmd}:	Demanded power from the controller
$P_{spt,GU}$:	Power setpoint to unit GU
$P_{poss,GU}$:	Possible power in unit GU
$P_{meas,GU}$:	Measured power in unit GU
$P_{min,GU}$:	Min power in unit GU
$P_{rated,GU}$:	Rated power of unit GU
$P_{surplus}$:	Surplus power from WPP and SPP

The dispatch function has two main states:

MP – power maximization with the scope to maximize the output power

LP – output power limitation due to curtailment commands or due to that the possible power exceeds the limit in the PCC.

Mathematically these states can be expressed as:

$$(MP):\ P_{dmd} \geq P_{poss,WPP} + P_{poss,SPP} \tag{4}$$

$$(LP): \;\; P_{dmd} < P_{poss,WPP} + P_{poss,SPP} \tag{5}$$

The MP state represents the cases of no curtailment and "passive" curtailment where the possible power is below the curtailment setpoint. The dispatch will then command to maximize the output power of the WPP and SPP, and to operate the BESS (charge or discharge) if such system is available and enabled:

$$P_{spt,SPP} = 1.1 \cdot P_{rated,SPP} \tag{6}$$

$$P_{spt,WPP} = 1.1 \cdot P_{rated,WPP} \tag{7}$$

$$P_{spt,BESS} = P_{dmd} - P_{meas,SPP} - P_{meas,WPP} \tag{8}$$

The LP state represents the situation where production could be higher than allowed in the PCC as well as an active curtailment command when the possible power is above the curtailment setpoint. The dispatch function then use as much as possible of the surplus power to charge the battery. The remaining part of the surplus is then curtailed, first from the SPP and, if needed, second from the WPP, respecting also the requirement on minimum production by the generation units. The equations read as follows:

$$P_{surplus} = P_{dmd} - P_{poss,WPP} - P_{poss,SPP} \tag{9}$$

$$P_{spt,\mathrm{BESS}} = \max\left(P_{surplus}, P_{min,BESS}\right) \tag{10}$$

$$P_{spt,SPP} = \max\left(P_{dmd} - P_{poss,WPP} - P_{meas,BESS}, P_{min,SPP}\right) \tag{11}$$

$$P_{spt,\mathrm{WPP}} = \max\left(P_{dmd} - P_{spt,SPP} - P_{meas,BESS}, P_{min,WPP}\right) \tag{12}$$

The dispatch strategy presented above can be considered a base for further optimization functions in terms of grid ancillary services (primary frequency control, reactive power operation etc.), different market functionalities (arbitrage market, power generation peak shaving etc.) or different grid demands.

III. PLANT MODEL

In order to assess the functionality of the RPC by simulation, appropriate models of the plant components that are controlled were developed. Since the main controller and dispatcher will send references to the WPP, SPP and BESS it is necessary to reproduce the dynamic behavior at power plant level. This means that the models need only to capture the main dynamics of the plant and provide the available information that is also accessible in the field. The following sections describe the models used for verification of the controller.

A. The Wind & Solar Power Plant Models

The model presented in Fig. 2 is used to describe both the WPP and SPP behaviour. The only differences are in terms of the parameters chosen, such as the rated power of the plants. Since this paper only focuses on the control of active power, the reactive power loop is not presented here and the interactions between the active and reactive power are not taken into consideration.

Modern WPPs and SPPs are able to provide an estimation of the possible power that can be generated with high accuracy. The power that is calculated by the model, P_{meas} cannot be higher than the possible power of the plant, P_{poss}. A function that takes the minimum between the P_{poss} and the setpoint, P_{spt}, ensures that. The saturation block limits the output between zero and the rated power. The rate of change limits the ramp of the power production, which is either specified by the TSO or set at the standard value. Dynamic repose of the plant and the delay introduced by communication and filtering of the measured signal are modelled using first order transfer functions with the time constants t_P and t_M, respectively.

B. The Battery Energy Storage System Model

The BESS model is shown in Fig. 3. It has an active power setpoint, P_{spt}, as input and the measured power, P_{meas}, and state of charge (SOC) as outputs. The block *Check Battery Charge* contains the logic that ensures the limitation of the setpoint depending on the SOC (i.e. if $SOC = 1$, the minimum setpoint is limited to 0 and if the $SOC = 0$, the maximum setpoint is set to 0) . The rate limiter, plant transfer function and grid meter transfer function have the same functionality as for the WPP and SPP.

The state of charge is calculated using the following equation:

$$SOC = \frac{E}{E_{max}} \cdot 100 \tag{13}$$

where E is the current energy level in the battery and E_{max} is the rated energy capacity of the battery.

The energy level in the battery is calculated integrating the output power of the battery:

$$E = E_{init} - a \cdot \int P_{out} dt \tag{14}$$

where a is a gain that takes into account the charging/discharging efficiency [12] and is expressed according to the following:

$$a = \frac{1}{\eta_{discharge}}, \; P_{out} \geq 0 \tag{15}$$

$$a = \frac{1}{\eta_{charge}}, \; P_{out} \leq 0 \tag{16}$$

The initial energy in the battery is specified using E_{init}.

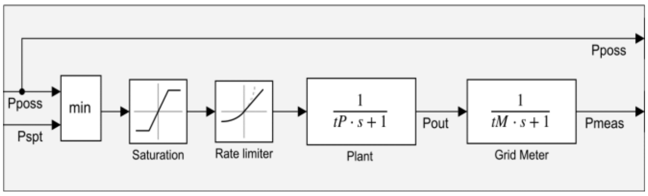

Figure 2. WPP and SPP implementation

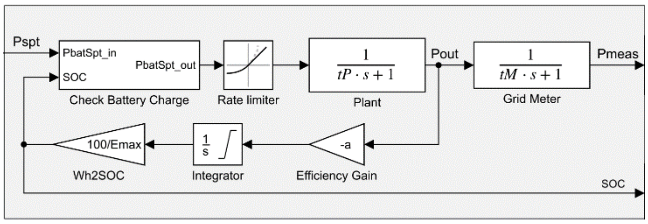

Figure 3. The BESS model implementation.

C. The Grid Model

The electric grid model aggregates the power flows from the different components to a single PCC. The measurements are then fed to the controller through a simulated grid meter. The current inputs for the grid model are the active and reactive power flows from each of the electrical components (WPP, SPP and BESS).

The connection losses for each component from the point of production to the point of connection can be set as percentages of the power before they are aggregated in total active and reactive power flow.

There are some functions that are not used right now but are needed in case voltage and frequency control are implemented. For example, there is a voltage variation calculation as follows:

$$V_2 = \frac{PR+QX}{V_1} + V_1 \tag{17}$$

where P and Q are the aggregated active and reactive power flows respectively, R and X are the resistance and reactance of the equivalent network impedance respectively and $V_1 - V_2$ is the voltage variation between the impedance $R + jX$.

The power factor at the PCC is sent to the grid meter and is estimated as:

$$PF_{PCC} = \frac{|P|}{\sqrt{P^2+Q^2}} sign(Q) \tag{18}$$

where P and Q are the aggregated power flows and sign(Q) is 1 if Q is positive, -1 if Q is negative and 0 if Q is 0.

The last output of the grid model is the grid frequency, which is currently fixed to 50 Hz, but in case a frequency control function is included, this output may be calculated as a function of active power.

IV. SIMULATION RESULTS

This section presents three simulation scenarios using the plant model and controller described in the previous sections. The hybrid power plant in this case consists of a 122.4 MW WPP, a 40 MW SPP and a 12 MW BESS. Note, however, that all results presented in this section are given in per unit (p.u.). The first scenario is a curtailment where the possible powers of the WPP and SPP are constant and where the hybrid active power setpoint is reduced in two steps and then brought back to its initial value. Fig. 4 shows the simulated measured active power in the PCC, the WPP, the SPP and the BESS, respectively. From the figure, it is clear that the initial setpoint cannot be reached since the sum of the possible power from the three power generation units is below the desired value (0.86 p.u.). At time 50 sec., the setpoint is reduced down to 0.6 and first the BESS responds by changing from maximum discharge to maximum charge. At about time 60 sec. also the SPP is curtailed such that the overall setpoint can be reached at around time 80 sec. The next setpoint reduction at time 100 sec. requires that the WPP is curtailed after the SPP has been curtailed to the minimum value. When the setpoint is increased again at time 150 s, both the WPP and the SPP respond, however, the SPP stays curtailed until the setpoint is further increased back to its initial value at which point also the BESS switches back from charging to discharging.

In the second scenario, the hybrid power plant setpoint is constant at a highly curtailed value (0.3 p.u.) whereas the possible power varies according to actual measurements as seen in Fig. 5. In Fig. 6, we see that we can keep the setpoint until about time 75 min. where we get a dip for about 10 min. The total possible then gets below 0.3 p.u. when the WPP production has reduced to 0.2 p.u. and the SPP production gets below 0.1 p.u. Also between time 175 to 225 and after 275 min., the setpoint cannot be reached.

In the third scenario, the BESS is activated for the same input scenario as shown in Fig. 5. The two dips in power production at time 75 min. and 175 min. can then be decreased or completely avoided as shown in Fig. 7. This is also more clearly seen in the plot in Fig. 8. How the BESS is utilized to achieve this is seen in Fig. 9. It is clear that short dips in possible power as at time 75 min. are easily handled by the BESS but for longer reductions the BESS can only help for a certain time period (in this case about an hour) before the battery is completely discharged.

V. CONCLUSIONS AND FUTURE WORK

The development of a controller used to optimally steer renewable hybrid power plants, composed by wind power plants, solar power plants and/or battery energy storage systems is presented in this paper. Such hybrid power plant controller enables and facilitates the integration of new generating/storage units to existing sites. A simulation environment in Matlab/Simulink was built and used to illustrate how the controller makes the system follow the overall hybrid power plant setpoint and how the commands for curtailments are distributed to the different components through a dispatch function.

Three test scenarios were used as verification of the controller. From these scenarios it may be concluded that the RPC utilizes the BESS as desired and distributes curtailments according to the desired priorities where surplus power is first used to charge the BESS, then the SPP is curtailed and finally, if required, also the WPP is curtailed.

Once that the hybrid power plant controller is verified in simulation environment a Hardware-In-the-Loop (HIL) test will be performed prior to the field deployment. The test results will be gathered and presented in future publications.

The controller presented in this article will facilitate future enhanced optimization functions based on forecasted energy production from different sources (wind and solar), market related functions and requirements (primary frequency control, arbitrage market etc.) or grid demands.

TABLE OF ABBREVIATIONS

BESS	Battery Energy Storage System
GU	Generation Unit
HIL	Hardware-In-The-Loop
LP	Limit Power State (dispatch function)
OHL	Overhead Line
MP	Maximize Power State (dispatch function)
PCC	Point of Common Connection
PI	Proportional-Integral
p.u.	Per-unit
PV	Photovoltaics
RPC	Renewable Park Controller
SOC	State of Charge
SPP	Solar Power Plant
TSO	Transmission System Operator
WPP	Wind Power Plant

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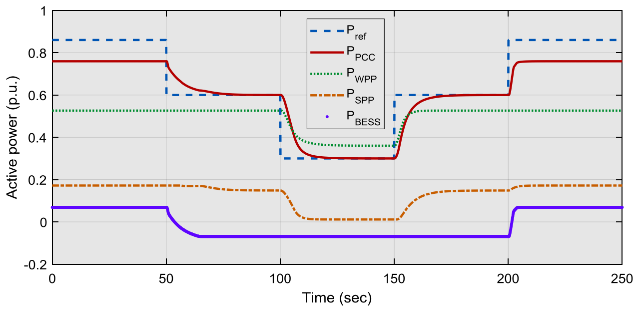

Figure 4. Curtailment scenario with constant possible power ($P_{possWPP} = 0.53$ p.u., $P_{possSPP} = 0.17$ p.u., $P_{possBESS} = 0.07$ p.u.).

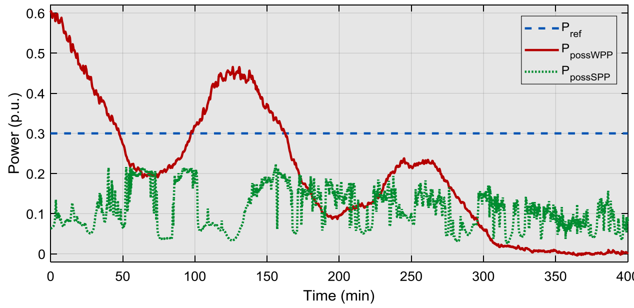

Figure 5. Varying possible power scenario.

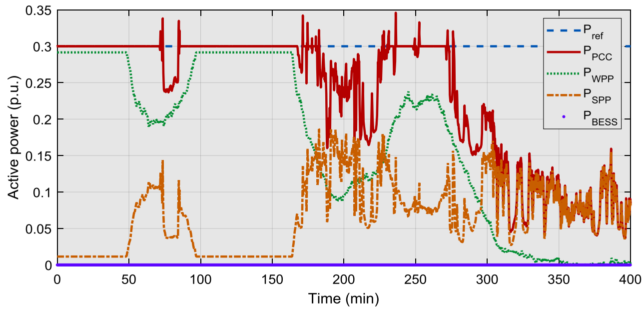

Figure 6. Scenario with constant curtailment but varying possible power and battery deactivated.

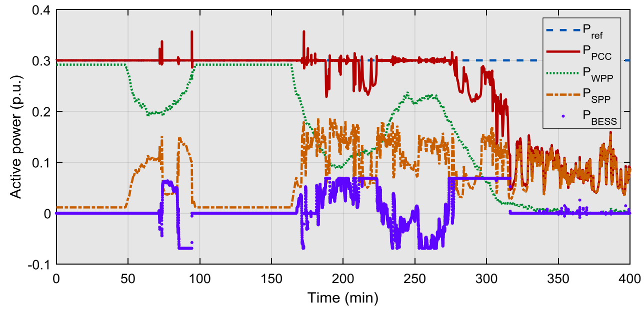

Figure 7. Scenario with constant curtailment but varying possible power and battery activated.

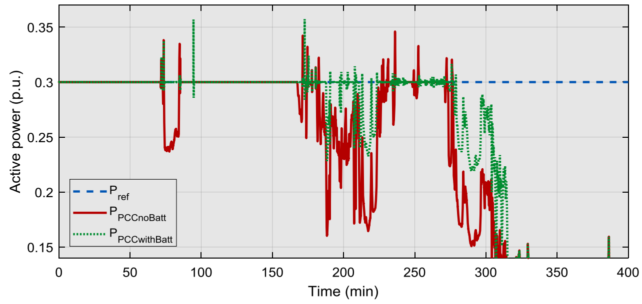

Figure 8. Comparison between scenario #2 and #3 where the latter is with battery activated.

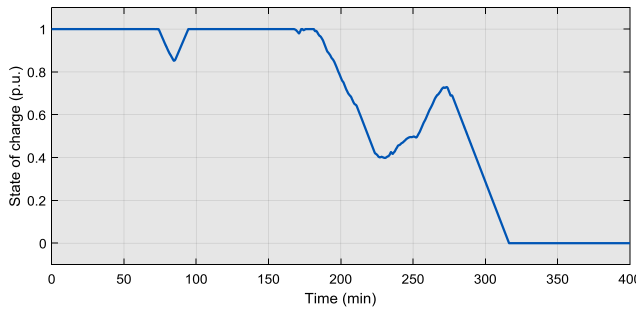

Figure 9. Battery state-of-charge for scenario #3.

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