Market participation of large-scale Hybrid power plant

Sharan Satheesh
Energy Technology, EPSH4-1039, 2020-05

Master′s Thesis

STUDENT REPORT
AALBORG UNIVERSITY

This report has been written with LATEX using Overleaf. During the project a hybrid power plant was modelled in MATLAB and PowerFactory. A market participation algorithm and hybrid plant control system for the same was developed using MATLAB.

DEPARTMENT OF ENERGY TECHNOLOGY
Aalborg University
http://www.aau.dk

AALBORG UNIVERSITY
STUDENT REPORT

Title:
Market participation of large-scale Hybrid power plant

Theme:
Hybrid power plant control

Project Period:
Spring Semester 2020

Project Group:
EPSH4-1039

Participant(s):
Sharan Satheesh

Supervisor(s):
Florin Iov
Mads Rajczyk Skjelmose

Copies: 1

Page Numbers: 51

Date of Completion:
May 29, 2020

Abstract:

With the increasing demand for electricity all across the world it has become very important for renewable energy sources to be cost competitive with convention energy sources. Participating in multiple energy markets like day-ahead and intraday markets effectively can help generate maximum revenues for the renewable plant operators. In this work a large-scale Hybrid plant with wind, solar and battery is used for developing a market participation algorithm for day-ahead and intraday market. The algorithm worked well with the proposed hybrid plant control system to fulfil the market commitments by the algorithm for each trading interval. The algorithm was then tested in simulation for the Australian energy market. The plant was able to balance any over commitment in the day-ahead market by participating in the intraday/balancing market and also sell the excess available energy in the intraday market.

Contents

Preface

This thesis report is part of masters of energy engineering with specialization in Electrical power systems and high voltage. As my specialization is on power systems, Hybrid power systems was of great interest, as I would be able to work with two types of power system and expand my knowledge about hybrid power systems.
Effective Market participation of renewable power plants is of growing important due to growing energy demands. The control system design needed for having a stable power output proved to be a complicated design due to response characteristics of the wind turbines, batteries and PV generators.
A hybrid power plant was modelled in Matlab Simulink, then the market algorithm along with control system was implemented on this model, to see the effectiveness of the algorithm. I was able to get a good understanding on designing of a control system of Hybrid power plant.
I would like to thank Vestas for providing me with the opportunity for doing this thesis in collaboration with them. I would like to thank my Vestas supervisor, Mads Rajczyk Skjelmose for the timely guidance and advice, during meetings.
Finally, I would like to express my gratitude to my University supervisor Florin Iov for all the support and help for the development of this Thesis. The input from academia and industry was very helpful in developing this project accurately. The coordination helped in completing the project and delivering the thesis report on time.

Aalborg University, May 29, 2020

Sharan Satheesh
<ssathe18@student.aau.dk>

Chapter 1

Introduction

1.1 Background

Electricity demand has been increasing with the increase in population and economic growth, especially in developing economies. In developing countries India and China the demand growth is predicted to be higher compared to developed countries like USA and Japan, where there is much slower growth [1]. Even though in developed countries the growth of demand is slow, due to the new energy policies for climate change, developed nations will be decarbonizing their grids by installing more renewable sources of energy. In the New policies scenario by the IEA, installed wind and solar is set to grow at a high rate (Figure 1.1) [1]. Solar PV is predicted to have the second largest installed capacity by 2040.

With the increase in renewable energy connected to the grid, the supply and demand will not be balanced due to the intermittent nature of renewable energy. This would reduce the reliability and stability of power grids. The complementarity of solar and wind generation [2], would reduce the variability of power output of hybrid power plant with both solar PV and wind farm. With the reducing cost of batteries [3] [4], Battery energy storage system (BESS) is good storage option which has a fast response and can be used for different applications like frequency control, voltage control and energy arbitrage [5][6][7]. Thus, a hybrid power plant with wind farm, PV plant and BESS is a very attractive solution for markets with abundant solar and wind.

1.2 Problem formulation

The wholesale electricity pricing in competitive market has been on a decline in the last 10 years [1]. Power plant have high capitals cost of construction. The

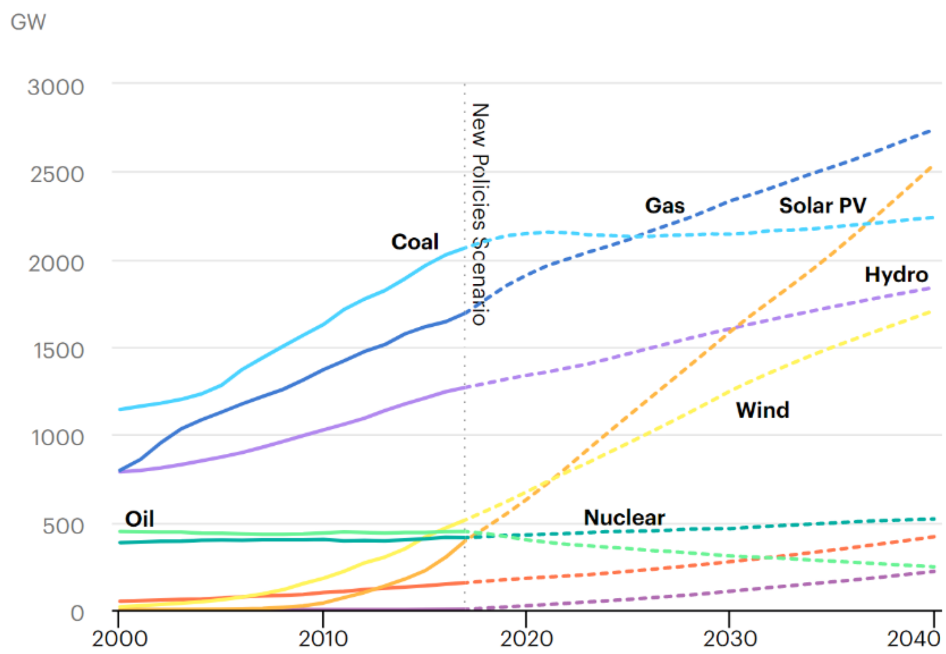

Figure 1.1: Installed power capacity in the New Policies Scenario, 2000-2040 [1]

operating cost of renewables is negligible compared to conventional sources. In order to recover the capital investment on the renewable based hybrid power plant, the plant can participate in multiple electricity markets (day-ahead, intraday) and provide ancillary services.
Providing a stable power output by the hybrid power plant can impact the lifetime of the plant assets. Due to the variability of Wind and PV output the Battery system will have to go through a lot of discharge cycles to provide a stable output at the Point of common coupling which can deteriorate the lifetime of the battery system. This will further increase the investments needed to replace the deteriorated plant assets.

1.3 Objectives

- Objective 1: To develop, verify and validate control algorithms that enables large-scale Hybrid power plant to participate on (multiple) energy markets
- Objective 2: To study a suitable electricity market to understand the rules, regulation and settlement process of that market.
- Objective 3: Measure the economic impact on such a hybrid plant with proposed control algorithm

1.4 Expected outcomes

- Working control algorithm for hybrid plant which can participate in both day-ahead market and balancing markets.
- The proposed algorithm can make maximum profits by participating in multiple markets for the plant owner.
- Understanding of the chosen electricity market on their compatibility towards renewable energy hybrid power plants.

1.5 Methodology

In order to meet the objectives of this project certain task need to be carried out to meet each of the objectives. The tasks are divided for each objective below
For objective 1:

- Carry out a literature review on the control of renewable energy hybrid plant, Wind farms and PV plants.
- Carry out a literature review on renewable energy plants participation in multiple electricity markets
- Develop the market participation algorithm for hybrid power plant for participation in multiple energy markets considering forecast uncertainties of wind and solar energy
- Design a control system for hybrid power plant to implement the proposed market algorithm
- Verify the algorithm with simulations

For objective 2:

- Study the rules and regulation for a renewable energy hybrid power plant to participate in the chosen market.
- Identify the possible restriction on renewable energy hybrid power plant for participation in multiple energy markets
- Understand the settlement process for each of the market the hybrid power plant participates in the chosen market region

For objective 3:

- Calculate the income made by the power plant from the markets it participated in as per the settlement process of the chosen market

- Evaluate the degradation on the Battery energy storage systems with such a control algorithm

1.6 Scope and limitations

- Auxiliary services (frequency control and voltage control) in the energy market will out of scope of the developed control algorithm
- Reactive power control will out of the scope for the control algorithm
- • Battery energy storage systems are considered for the energy storage of hybrid plant design

1.7 Contents of report

The chapters of this report contain the following content:
Chapter 2: State of the art in this chapter the literature review of the control of renewable energy power plants is done. The state of art on hybrid plant operating in multiple markets are also reviewed.
Chapter 3: Electricity market in this chapter describes what an electricity market is and how it functions. Then the Australian energy market is studied to understand it rules and regulation, and how the different markets work i.e. day ahead, and balancing market.
Chapter 4: System design in this chapter the design of hybrid plant to be used in the project will be proposed.
Chapter 5: Market participation algorithm in this chapter a market participation algorithm will be proposed for the hybrid power plant which will determine the market commitment of the hybrid power plant for the day ahead and intraday electricity market.
Chapter 6: Hybrid power plant control in this chapter a control system will be designed for the hybrid power plant which will be able to control the hybrid power plant to deliver the energy to the market, as per the commitment by the proposed market algorithm.
Chapter 7: Simulation and Analysis in order to test the market participation algorithm, simulations will be carried out to see the effectiveness of the algorithm. Economic evaluation of the simulations will be carried out to how much income the plant operator was able to generate by participating in multiple markets for the simulation period.
Chapter 9: Conclusion this chapter provide the conclusions the author has made from this report.

Chapter 2

State of the art

In order to develop a control algorithm for participation of renewable hybrid plant in multiple energy markets, the state of the art in market participation of renewable and control of large-scale renewable energy plants need to be reviewed. In the following paragraphs, firstly the literature review of market participation of renewable energy plants will be done. Followed by the review of control systems of large-scale renewable energy (Wind and PV plant) power plants.

2.1 Market participation of renewables

In the literature review of market participation renewables, wind farm participation [8][9] as well as solar PV plant participation [10][11] was found. Except in [8], all the proposed renewable energy systems had storage system. Storage systems helped in providing a firm power output [11] at the PCC and in some cases also provided energy arbitrage[10].

In [8], intraday and day ahead market participation of wind farm without any storage system was proposed. The proposed control algorithm did not include any optimization technique, instead relied on the forecast of wind power and forecast of prices in the intraday markets. Authors found that bigger wind farms (above 5 MW) benefited more from participation in intra-day market, but as the capacity of plant increased (above 500MW) the profits from trading starts reducing. In [9], the authors proposed market participation in day ahead market and the frequency control reserve market of a wind farm along with storage. The authors found that participating in frequency reserve market provided high profits, but this profit could be offset if the grid has very high wind energy penetration. The authors do not discuss the effects of forecast uncertainties in the day ahead market participation and the effects on the battery lifetime due to market participation. In [12], the authors discuss the possibilities of participation of Wind farms in day ahead market in the Indian energy exchange market (IEX). The main idea was to have

an accurate price forecast and wind power forecast in place to optimally bid in the day ahead market. Short term price forecast was used to optimize the battery usage to fulfill the day ahead market needs. The proposed wavelet based neural network price forecast was accurate for the Indian energy market.
In [11], a solar plant with storage market participation in both day-ahead and intraday was proposed by the authors. Optimization was carried for sizing the storage system with the help of PV forecast data and market data to maximize the revenue of the plant. The same optimization framework was used for the control of the plant as well which included the optimally sized storage system. The proposed optimization considered the battery lifetime degradation which was not considered by other works presented above. The authors found that the revenue of such a plant could be increased by energy arbitrage during the evening hours. In [10], the same authors added an ancillary service of providing secondary frequency reserve to the existing day-ahead and intraday participation of solar plant with storage. This control worked effectively on a sunny day, where the plant participated in all the markets and provided frequency service the whole day. On a cloudy day, the frequency service was not provided during all periods of the day, as the battery was trying to smoothen the variations of PV generation, and did have enough power to provide for the frequency response. Thus, on cloudy day it is preferable to participate in the frequency service during the nighttime when there is no PV generation.

From the review of market participation of renewable, both solar and wind plant could effectively participate in the day-ahead and intraday markets. The battery degradation and lifetime assessment is an important aspect, which was considered in [10][11]. Frequency regulation service could be difficult to achieve in a hybrid power plant with both solar and wind as the battery would be required to balance the variations of wind and PV plant outputs. In this review, there was no research on wind + PV + BESS Hybrid power plant market participation in the current literature.

2.2 Control of renewable power plants

Hybrid plant with renewable generators like PV plant and wind farms also need to have control systems to have controllable active power output with smooth output. In [13]], an optimization strategy was proposed to provide a smooth power out with the help of storage system. A low pass filter was used on the power input from the renewable generators to get the power signal for the storage system. They found a way to size the storage system for smoothening of the power output at the PCC from the hybrid plant. Another smoothen control was proposed by [14], where ultracapacitors where used for the smoothening of the output. The hybrid plant proposed by the author had a DC plant network which was connected to a common grid side converter to convert to AC before being connected to PCC. The authors did not discuss the effects of discharge cycles of the storage system on its lifetime to provide the smooth output. In [15][15], an active power control for hybrid power plant with wind and PV plant was proposed which stabilized the frequency at the PCC. In [16], another hybrid plant with only wind and PV plant, a fast frequency control was proposed. In this control inertia form wind turbines and virtual inertia from PV plant from curtailed reserve power was utilized to provide the frequency response.

In small PV power plants, the plant produces maximum available power in the plant, and different types of MPPT algorithms (Perturb and observe, Incremental conductance) are used to achieve the Maximum power point. Whereas in large scale power plants (MW to GW scale) (LPVPP) need an effective active power control in place, in order to provide stable power to the grid. The grid requirements for LPVPP's include the curtailment of power output, reserve power and ramp rate levels for increasing and decreasing the power output [17]. In [17]], active power control is proposed for a LPVPP without energy storage. In this control scheme the MPPT algorithm is modified to follow a reference point of power flow rather than maximum power point, this control was not able to follow the reference on cloudy days when the output varied a lot. This proposed control was only for individual PV generators in a large-scale PV plant, the authors did not discuss about the higher-level control on the power plant level and on ramp rate limit control. In [18], a control for limiting the ramp rate for LPVPP with reserve power from both PV plant and external storage was proposed. The authors found the capacity of reserve power requirement is dependent on the size of the plant and the PV penetration in the selected grid. It was found that the storage was required for smaller plants (<100MW) whereas bigger plants could cover the reserve requirement just by 10% curtailment of plant output to satisfy the ramp rate limits, as bigger plant had larger spatial distribution this reducing the overall fluctuation in plant outputs. In [19], the LPVPP control at the plant level is proposed. Here the PV generators (PV arrays + inverter) have their own control to follow the reference powers, the proposed control is at the plant level which sent out the set points to the generators to get the required power output at the PCC. The control takes into consideration the ramp rate limits as per TSO requirements and compensate the power losses in the power plant.

In large scale wind farms as well, it has become essential to control the active power output with the increased penetration of renewable energy sources. In some markets the wind turbines can produce the maximum amount the available power, the demand and supply are then balanced by the operator with conventional generation sources. But with increasing penetration of renewable energy to the grid, large scale wind farms need to be curtailed in its operation and maintain it ramp rate limit like with LPVPP's. In [20], control of wind farm was proposed, which could curtail the power output or provide constant power output. The authors had also formulated ramp rate limiter control into the control algorithm. The authors did not consider compensation of the power losses in the network which meant the power output did not meet the reference power accurately. In [21], another active power control for wind farms was proposed. The authors had considered forecasting errors of wind for different time steps and multiple time step dispatch instructions for the wind turbines in the wind farm. In [22], active power control based on a optimization technique is proposed, the number of running and stopping of turbines in a large scale wind farm was optimized. This control used only ultra-short-term wind forecast for its control thus the control was of wind farm was done in real time according the to the available power which would not allow the wind farm to participate in the day ahead market.

Chapter 3

Electricity market

Electricity market is a system where producers and consumers can trade electricity. Electricity markets are complex in nature as electricity is not easy to store and the demand and supply can vary continuously throughout the day. Imbalance between generation and supply can cause reliability issues in the power grid. Generally, Electricity market are divided into day-ahead, intra-day/balancing markets. The electricity is sold in units of Power (MW) or energy (MWh) to the consumers. The suppliers can participate in day-ahead, intraday/balancing markets depending on the demand and supply of power in the grid. The pricing of the electricity in the market is dependent on the electricity demand and supply. In order to develop a market participation algorithm, we study real electricity markets to understand more about how the day-ahead and intraday market works and how the settlement process is carried out to calculate the revenues generated. In this work the Australian energy market is chosen as Australia as good resources of both wind and solar.

3.1 Australian energy market

National Electricity market in Australia is the electricity market for the eastern and southern regions, which facilitates wholesale trading of electricity between the regions [23]. The western and northern regions have independent markets [23]. The South west interconnected system (SWIS) has made the Wholesale electricity market (WEM) for the western region of Australia [24]. In SWIS the electricity market is managed by the Australian energy market operator (AEMO) [24].
The WEM is broadly divided into reserve capacity market and the energy market. The reserve capacity mechanism is in place the ensure that demand for the year is met by the supply in the market. The retailers can buy reserve capacity as per the forecasted peak demand, bilaterally from the producers or from AEMO. The retailers must pay fixed hourly price per MW for the reserve capacity they have

purchased for the whole year whether they use it or not. The WEM energy market consists of three trading means, bilateral trade, short term energy market (STEM) and the balancing mechanism market [24]. Bilateral trade agreement is made between the producers and consumers well in advance for the energy to be supplied. Then the consumers can buy or sell the variations from the contracted energy from STEM on the day before or trading day market (Figure 3.1). The balancing market is in the real time market where there will be deviations from the contracted energy from the bilateral trade and the STEM trade, the balancing market thus can be used to trade these deviations in energy. The balancing market closes 2 hours prior to the trading interval.
Intermittent generators like wind and PV plants are better suited to be in the energy market than the reserve capacity market. Wind plant can participate in the reserve capacity market, the capacity is calculated based on the average wind power output in the last three years. As per the rules and regulation in WEM, intermittent generators are classified as non-scheduled generators, the rules do not allow non-scheduled generators to increase its generation in the balancing market, instead only curtailment is allowed [25]. The non-scheduled generators are exempt from funding for spinning reserve, if the operator can guarantee a gradual shutdown of the generator at a ramp rate of installed capacity (MW)/15 (MW/min)[25]. Multiple non-scheduled generators can be aggregated as one non-scheduled generator, if they are located in the same area or have the same loss factor, and the generators should not be part of an ancillary service[25].

In the bilateral market the energy producers need to submit their contract po-

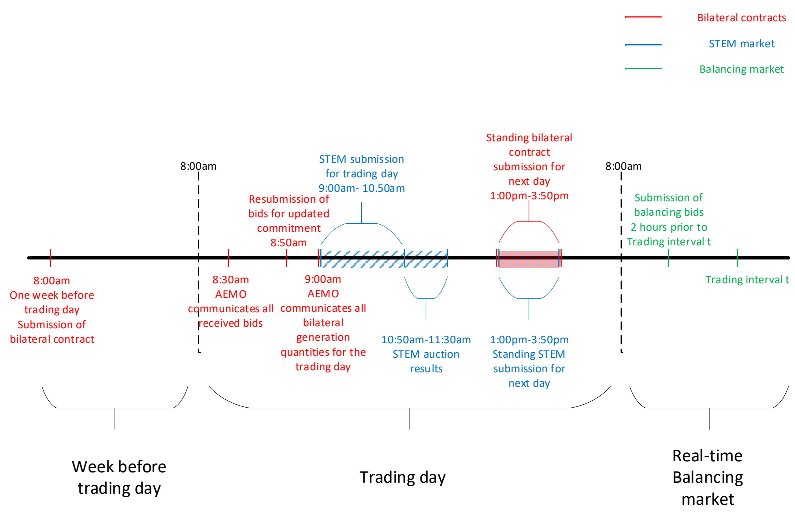

Figure 3.1: Wholesale electricity market trading timeline of different markets

sition one week in advance to the trading day (Figure 3.1) [25]. This contract in then revised on the trading day according to the demand and supply. The bilateral market is closed by 9 am on the trading day, after which the STEM market submission begins, which closes at 10:50am. Both in bilateral contract and STEM market, the participant can resubmit a standing bid for the next day and make changes to the previously submitted bids (1pm-3:50pm Figure 3.1). In case of the balancing market, the participant must bid two hours prior to the trading interval in which they are participating (Figure 3.1).

3.1.1 Settlement process

In bilateral contract the settlement is done directly between the participants who are involved in the contract. The settlement for STEM is done for the trading week which commences from Thursday and ends on Thursday of the next week. The settlement process for balancing market participation is done for the trading day which is from 8am to 8am next day. The settlement calculation for STEM market for the trading week w for participant p is as given below[18]:

$$\begin{aligned} STEMSA(p,w) \ &= \ Sum(d \in D,\ t \in T,\ STEM_{price}(d,t) \\ &\quad \times STEM_{Quantity}(d,t) \times \ SSF(d,t) \end{aligned} \tag{3.1}$$

- $STEM_{price}$ – the STEM price for the interval ($/MWh)
- $STEM_{Quantity}$ – the quantity of energy produced during the interval in MWh
- SSF – STEM suspension flag which is set to zero if STEM market is suspended and set to one otherwise

The settlement calculation for balancing market for the trading day t for participant p is as given below[18]:

$$\begin{aligned} BSA(p,d,w) \ &= \ Balancing_{price}(d,t) \times MBQ(p,d,t) \times \ CONC(p,d,t) \\ &\quad \times COFFC(p,d,t) \ \times DIP(p,d,t) \end{aligned} \tag{3.2}$$

- $Balancing_{price}$ – Balancing market price
- MBQ – metered balancing quantity in MWh
- $CONC$ – Constrained On Compensation for Market Participant
- $COFFC$ – Constrained Off Compensation for Market Participant
- DIP – Non-Balancing Facility Dispatch Instruction Payment

From the review of the Australian energy market, there is an understanding on the market operation of day-ahead and intraday market (balancing market). The settlement process described above will help to compute the economic performance of the hybrid power plant with the market participation algorithm. In Australian energy market intermittent generators like solar and wind are not allowed to upregulate in the power in the balancing market, this rule can put strain on the plant operators and they need to rely a lot on the day ahead forecast to bid for the maximum amount of energy possible, this would be risky if the plant is not able to produce the required energy. If intermittent plant can upregulate in the balancing market this would make plants efficiently participation in both the markets and increase the profits.

Chapter 4

System design

In this chapter the hybrid power plant required for the study of market participation algorithm is developed. The plant model design considered here is for large scale hybrid plant models. The hybrid power plant is designed such that the plant components like wind farm, PV plant and BESS are connected at the hybrid plant substation (Figure 4.1).

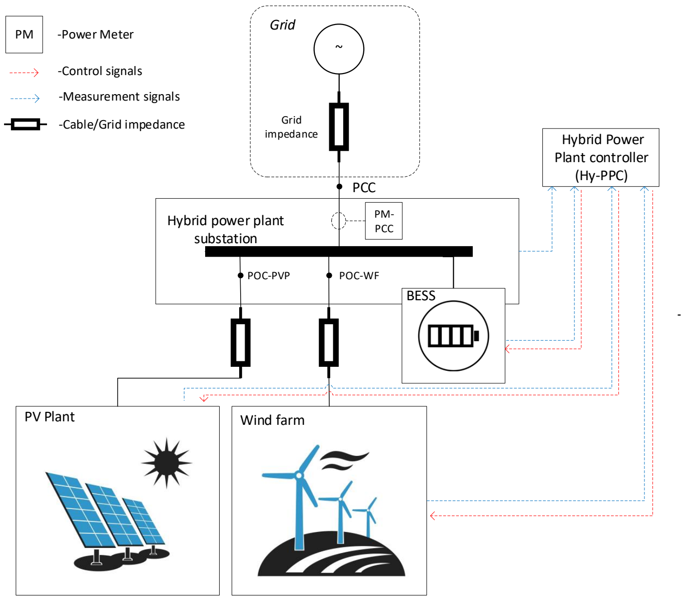

Figure 4.1: Hybrid power plant layout

They are connected via medium voltage AC plant network. The hybrid plant substation is then connected to the grid via point of common coupling (PCC). The

Plant assets can be situated from a few hundred meters to a few kilometers away from the hybrid power plant substation. The Point of connection (POC) of the plant assets are at the substation of the Hybrid power plant, therefore the plant assets must produce the allocated reference power at that point such that all the transmission losses until the POC are considered. The Hybrid plant controller (Hy-PPC) controls the output power at the PCC. In this design there is only one power meter used which is at the PCC to measure the output power of the hybrid power plant. In the following sections, the design of individual plant assets, sizing of the hybrid power plant and simulation modelling will be discussed.

4.1 Wind farm

A wind farm consists of Wind turbine generators (WTG), substation transformers and power plant controller. The Wind farm design for this project has m number of parallel strings with each string having n WTG's. For the hybrid power system proposed here, there is common power plant controller (Hy-PPC) to control the power output for the entire power plant, thus there is no individual power plant controller for the wind farm. Instead there is a wind farm dispatcher which dispatches the reference power of the wind farm between all the turbines based on the available power at each wind turbine. In general, the distance between each turbine is around 1 km so the cable length between each turbine can be assumed as 1 km.

4.2 PV plant

Photovoltaic plant is made up of PV modules. PV modules convert sunlight to electricity. Many PV modules are connected in series and parallel to form PV array. The PV arrays are connected to a PV plant converter (PVP-C) to convert from DC to AC (Figure 4.3). Each of these PVP-C's can be considered as a PV generator which produce the required reference power (Figure 4.3). In a large-scale PV plant, there would be multiple such PVP-C's connected to the PV plant substation. The PV plant design for this hybrid power plant consists of n PVP-C's and each of the PVP-C has a n number of arrays (Figure 4.3). For simplicity each array is assumed to have same number of modules so that all the PVP-C have the same rated power output. The PV plant also has a dispatcher to dispatch the reference power between the PVP-C's based on the available power on each of the units.

To design the PV plant, n number of PV generators will be connected to the PV plant substation. Such a design is shown below in the figure where each PV generator is of the same rating and area (l x b). The length and breadth of the PV

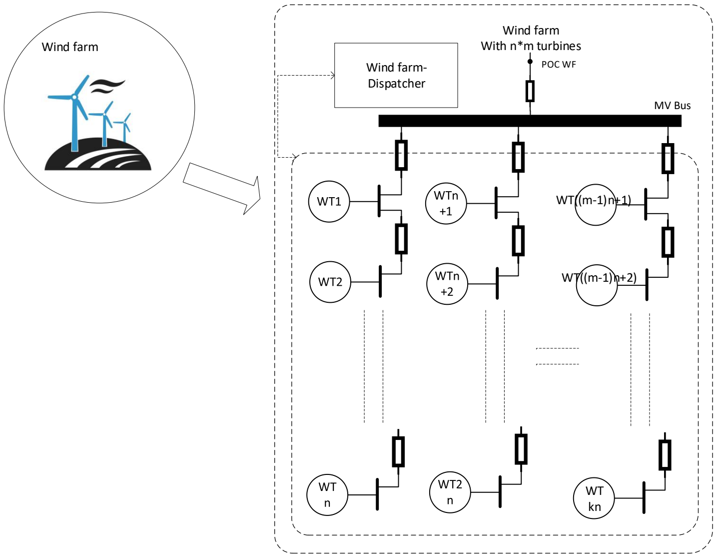

Figure 4.2: Wind farm layout

generators can help to calculate the lengths of the cables in the PV plant network.

4.3 BESS

Battery energy storage systems consists of batteries, converter, inverter, DC-link and transformers (figure 4.4). The converter and inverter together can control the power generation and absorption of the BESS. The transformer steps up the voltage to MV level to comply with plant grid voltage.

4.4 Hybrid plant sizing

Sizing of hybrid plants with wind farm, PV plant and BESS can be very complicated task. It depends of many factors like geographical location, available area, cost, plant operation and market participation. For this thesis work the focus is on developing hybrid power plant control system which can effectively participate in multiple markets. For effective market participation of a hybrid power plant, Battery sizing becomes an important aspect due to the variable nature of wind and PV output. The battery would help to provide and constant power output during each time interval in the electricity market. So, for this thesis work it is assumed that the wind farm and PV plant size is provided, and the BESS need to be sized

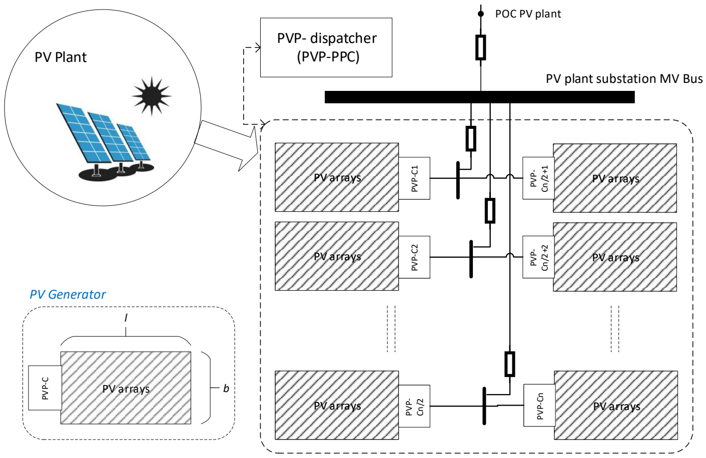

Figure 4.3: PV plant layout

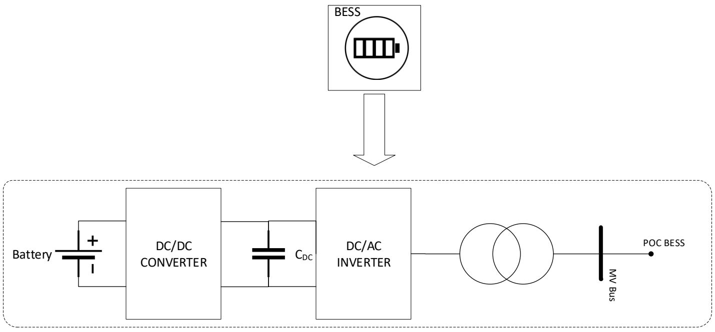

Figure 4.4: BESS design

for the hybrid power plant. A simple way of sizing a BESS in hybrid power plant was introduced in [26], where they operated a hybrid power plant with min-max dispatch strategy, where the battery was used to store energy during low demand time and discharge during high demand time. This type of sizing is would be a simple solution for sizing the battery. As it makes sense to sell less energy during low demand as the energy price would be low during which BESS can be charged and then sell the stored energy when the prices are high during peak demand periods.

The day is divided into peak demand interval and low demand intervals. The min-max dispatch strategy dispatches the minimum available power for low demand interval and maximum available power for peak demand interval. Then for a given wind and solar power profile for a day BESS power can be sized as the maximum discharge power and maximum charge for peak and off-peak periods. For energy

rating of the BESS, it is selected as per the number of peak demand period and low demand period as this would determine the discharge cycles of the BESS in one day.
In this thesis work the author has selected a 30 MW Wind farm and 10MW PV plant, hybrid plant. The BESS needs be sized using the above technique for this plant. The wind and solar irradiance data are chosen such that there are high variations in the PV and Wind farm output. This kind of data would allow for BESS to be sized for the worst-case scenarios. The chosen hybrid power plant min-max strategy power dispatch is calculated, based on the selected peak demand periods from 05:30-10:30 and 16:00-21:00. As seen in Figure 4.5 the Hypp dispatches max power during peak demand periods and min power during low demand periods.
From this data it was found that the maximum discharge power required for the

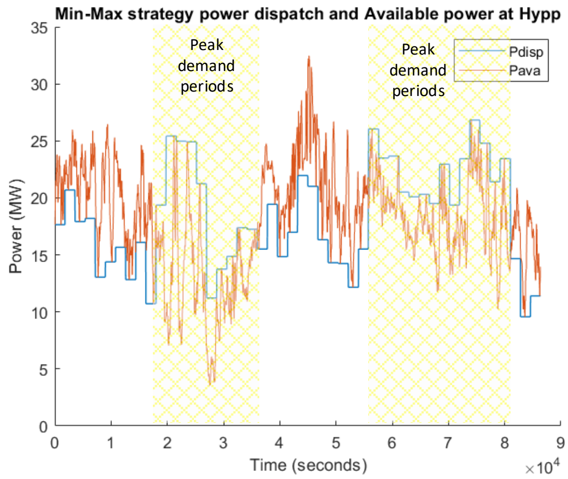

Figure 4.5: Min-max dispatch strategy power for HyPP

BESS was 19.4MW and maximum charge rate required was 14.06MW. The higher value among the two is close to 20 MW , so the rated power of the BESS is chosen as 20MW. Now for the energy capacity of BESS, maximum charge and discharge energy during the charging and discharging periods are calculated from the below graph (Figure 4.6) From this graph it clear that the maximum energy is required during discharge rate (-5.80MWh), now considering a BESS efficiency of 80% the required energy capacity of the BESS is -7.25MWh. Thus, considered a standard rating we can round this figure to 10MWh which gives a BESS of 20MW @10MWh capacity. This may not be an optimal way of sizing the BESS for this hybrid power plant but could be reference point after analyzing how well the market participation algorithm works for the hybrid power plant by using a simple BESS sizing

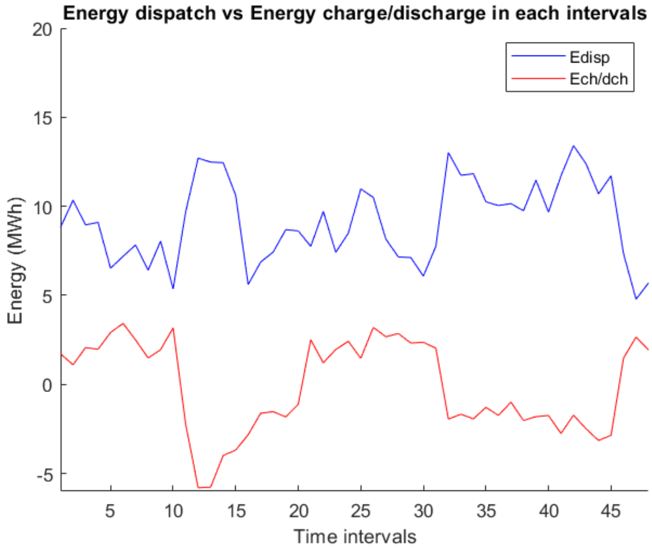

Figure 4.6: Dispatched energy vs BESS charge and discharge energy

technique. Further research can be carried out in the future to find a more optimal sizing method.

4.5 Modelling of Hybrid power plant

In this work the hybrid power plant model needs to run the active power control system of the plant to calculate accurately the power output at the PCC, thus help evaluate the market participation algorithms effectiveness. The performance models of wind turbines, PV plants and BESS in [27] are perfect for this application as it very simple lower order models which depict the real generators behavior and very less computational effort. It is advantageous for the model to have low computational effort as the model need to simulate minimum of one day. The only power measurement point of the hybrid power plant is at the PCC of the hybrid power plant. The simulation model needs to compute accurately the power output at the PCC. A simple summation model of wind farm, PV plant and BESS can be used to calculate at the active power PCC (Figure 4.7).

In order to compute active power at the PCC accurately with this model, the loss factor of the wind farm and PV plant needs to be calculated to account for the transmission losses in the plant network. The loss factor for BESS is ignored as the it is situated very close to plant substation.

This loss factor calculation was done by forming quadratic equations of power loss with respect to plant output [28]. The power loss equation using the curve fitting technique is done for a Wind farm and PV plant for the proposed hybrid power

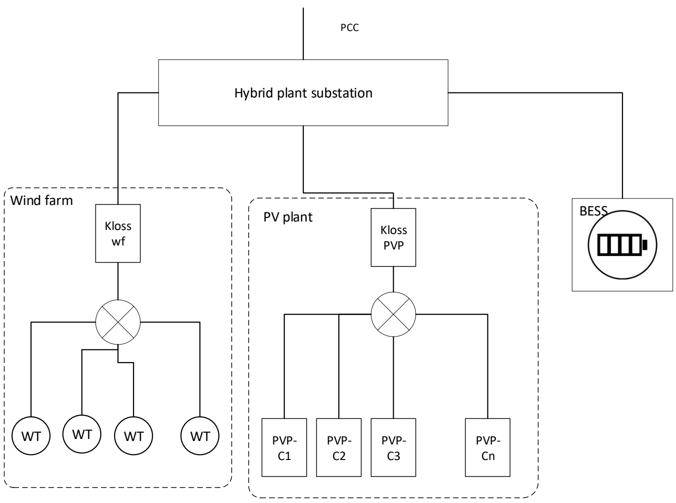

Figure 4.7: Summation model

plant.
The Hybrid power plant used for this project was first modelled in Powerfactory, to calculate the power losses on wind farm and PV plant at until the POC of each. To calculate the Kloss we assume the grid voltage as 1pu, SCR=15 and the X/R ratio of the external grid as 5. Using these assumptions, a polynomial function is derived for the kloss factor using the curve fitting toolbox from Matlab.

4.5.1 Power loss for 30MW Wind farm

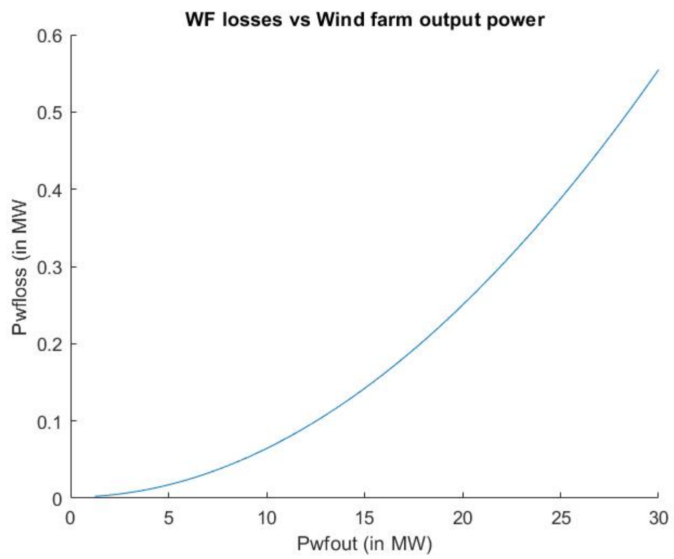

Figure 4.8: Power loss vs Power output for 30MW wind farm (Powerfactory)

Using curve fitting we get a third order and second order polynomial function for the losses which fit the curve, the third order polynomial function is a closer fit the curve hence third order equation is selected. Linear model Poly3:

$$Ploss_{WF}(P_{WF}) = \; p1 * (P_{WF})^3 + p2 * (P_{WF})^2 + p3 * P_{WF} + p4 \tag{4.1}$$

- $p1$ = -6.437e-07 (-6.447e-07, -6.427e-07)
- $p2$ = 0.0006331 (0.000633, 0.0006331)
- $p3$ = 2.84e-05 (2.774e-05, 2.906e-05)
- $p4$ = 0.001435 (0.001433, 0.001438)

4.5.2 Power loss for 10MW PV plant

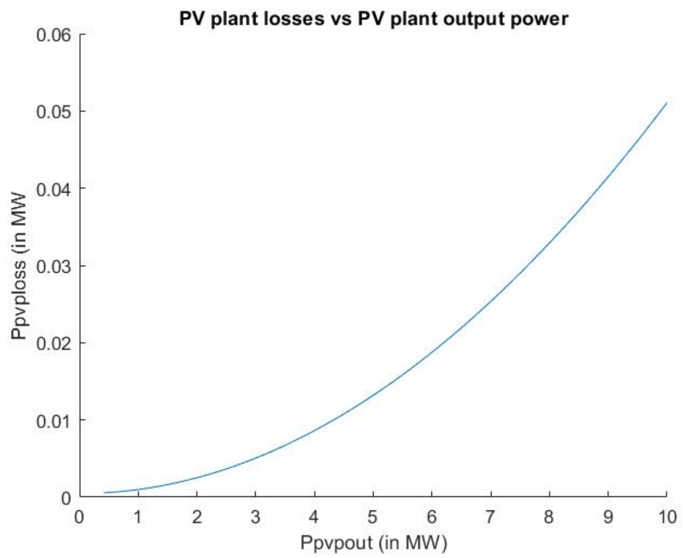

Figure 4.9: Power loss vs Power output for 30MW wind farm (Powerfactory)

Using curve fitting we get a third order and second order polynomial function for the losses which fit the curve, the third order polynomial function is a closer fit the curve hence third order equation is selected. Linear model Poly3:

$$Ploss_{PVP}(P_{PVP}) = \ p1 * (P_{PVP})^3 + p2 * (P_{PVP})^2 + p3 * P_{PVP} + p4 \tag{4.2}$$

- $p1$ = -4.814e-07 (-4.824e-07, -4.805e-07)
- $p2$ = 0.0005107 (0.0005107, 0.0005107)
- $p3$ = 1.2e-06 (1.132e-06, 1.269e-06)
- $p4$ = 0.0004789 (0.0004788, 0.000479)

Once power loss equation is obtained, then the Kloss factor can be calculated as per below equation for each of the plant assets.

$$K_{loss} = \frac{P_{output} - P_{loss}}{P_{output}} \tag{4.3}$$

This would help in modelling the hybrid plant for simulation as well as help with power loss compensation of the Hybrid plant control system.
The Hybrid plant layout and the simulation model for the hybrid power plant have been proposed in this chapter. This model is now suitable to run the market participation algorithms and hybrid plant control systems.

Chapter 5

Market participation Algorithm

The market participation algorithm allocates the energy to be generated by the hybrid power plant in the day ahead and intraday markets are per the forecasts of wind and solar energy. The proposed algorithm is required to participate in both day-ahead and intraday/balancing market. It is important to generate all the renewable energy available in the plant as would increase the revenue generated by the plant, but this would affect the battery lifetime. A trading day d is divided into n number of trading intervals.

$$d = \ [1,\ 2{,}3,\ \ldots,\ n] \tag{5.1}$$

As the trading day will have peak demand and low demand periods, this can be defined by peak demand interval Pdi and low demand intervals Ldi,

$$Pdi = p_1, p_2, \ldots .p_m \tag{5.2}$$

$$Ldi = ld_1, ld_2, \ldots .ld_l \tag{5.3}$$

$$m < n \tag{5.4}$$

$$l < n \tag{5.5}$$

$$m + l = n \tag{5.6}$$

Where p_m is the peak demand trading interval and ld_l is the low demand trading interval during the trading day. m and l are the number of peak demand trading intervals and low demand trading interval in a trading day The trading day (d) in Australia is divided into 30 minutes trading intervals (t). So, in a day there are 48 trading intervals.

5.1 Forecast Variables

The wind energy forecast for the trading day on the day of bidding is given by $WF_{dayahead}$, for each trading interval

$$WF_{dayahead} = [wf_1, wf_2, wf_3, \ldots, wf_n] \tag{5.7}$$

The wind energy forecast uncertainty for the day ahead forecast is given by $WFun_{dayahead}$, this value can be anywhere from 10-30% depending on the quality of the forecasted data and the forecast technique used.

$$WFun_{dayahead} = 20 \tag{5.8}$$

The hourly wind energy forecast which update the forecast every interval for the trading day d is given by $WF_{Intraday}$, for each trading interval

$$WF_{Intraday} = [iwf_1, iwf_2, iwf_3, \ldots, iwf_n] \tag{5.9}$$

The wind energy forecast uncertainty for the hourly forecast is given by $WFun_{Intraday}$,

$$WFun_{Intraday} = 10 \tag{5.10}$$

Similarly, for PV day-ahead and hourly forecast and its uncertainties are given below,

$$\begin{aligned} PVF_{dayahead} &= [pvf_1, pvf_2, pvf_3, \ldots, pvf_n] \\ PVFun_{dayahead} &= 20\% \\ PVF_{Intraday} &= [ipvf_1, ipvf_2, ipvf_3, \ldots, ipvf_n] \\ PVFun_{Intraday} &= 5\% \end{aligned} \tag{5.11}$$

The forecast uncertainty depends on the quality of the forecast and the technique used. In this market participation algorithm, the plant operator can choose how much risk they want to take when bidding in the day ahead market. The risk levels are described as high, medium and low. The risk rate (rr) is added to the uncertainty depending on the chosen risk level as shown in the below equation.

$$Risk\ level = \begin{cases} high & rr = +x \\ medium & rr = 0 \\ low & rr = -x \end{cases} \tag{5.12}$$

Where x is the risk rate the plant take at high or low risk levels.

The BESS operation also needs to be considered for the market participation algorithm as the batteries need to charge during the off-peak hours and discharge during peak hours. This can be done by the introducing a demand period offset (Dpoff) for each time interval. Where,

$$Dp_{offset} = [\, dpo_1,\ dpo_2,\ dpo_3,\ \ldots,\ dpo_n] \tag{5.13}$$

$$Dp_{offset}(t) = \begin{cases} if\ t\ \in Pdi & -y\% \\ if\ t\ \in Ldi & +y\% \end{cases} \tag{5.14}$$

The Dp_{offset} is the offset level which will be added to the market bids such that that BESS can discharge and charge through the trading day, this offset to y for peak demand and low demand periods as per the above equations.

5.2 Day Ahead Electricity Market

As the day-ahead wind and solar forecast have a high uncertainty, the plant bids for day-ahead market considering the uncertainties of both solar wind, the risk rate and the demand periods offset levels.

$$\begin{aligned} M_{DA}(t) \ = \ &(100 \ - \ (WFun_{dayahead} + rr/2 \ + \ Dp_{offset}(t)/2)) \ * \ WF_{dayahead} + \\ &(100 \ - \ (PVFun_{dayahead} + rr/2 \ + \ Dp_{offset}(t)/2)) * \ PVF_{dayahead} \end{aligned} \tag{5.15}$$

Here for the day-ahead bidding the lower limit for forecast after uncertainty, risk rate and demand period offset is considered. The actual available power at the plant can be higher lower from the day ahead forecast.

5.3 Balancing Market / Intraday Market

In the intraday or balancing market, the plant can increase or decrease its generation. In the intraday market the plant has a more accurate forecast for power generation. Depending on this forecast the plant can participate in the intraday market. The bid for each intraday market trading interval is usually done from one to few hours prior. In the Australian energy market, the balancing market closes two hours prior to the trading interval. Even with this hourly forecast of wind and solar there is still some level of uncertainty in the available power. Let's consider that the two hours prior forecast of wind and solar has uncertainty level of $WFun_{Hourly}$ and $PVFun_{Hourly}$. The energy forecast for interval t considering the forecast uncertainty is given by $E(t)_{intraday}$,

$$\begin{aligned} E(t)_{intraday} = \ &(100 \ - \ (WFun_{Hourly} \ + Dp_{offset}(t)/2)) \ * \ WF(t)_{Intraday} \ + \\ &(100 \ - \ (PVFun_{Hourly} \ + \ Dp_{offset}(t)/2)) \ * \ PVF_{Intraday} \end{aligned} \tag{5.16}$$

Then the decision of participation in the intraday market is based on the amount of energy required to be sold in that interval for the day ahead market.

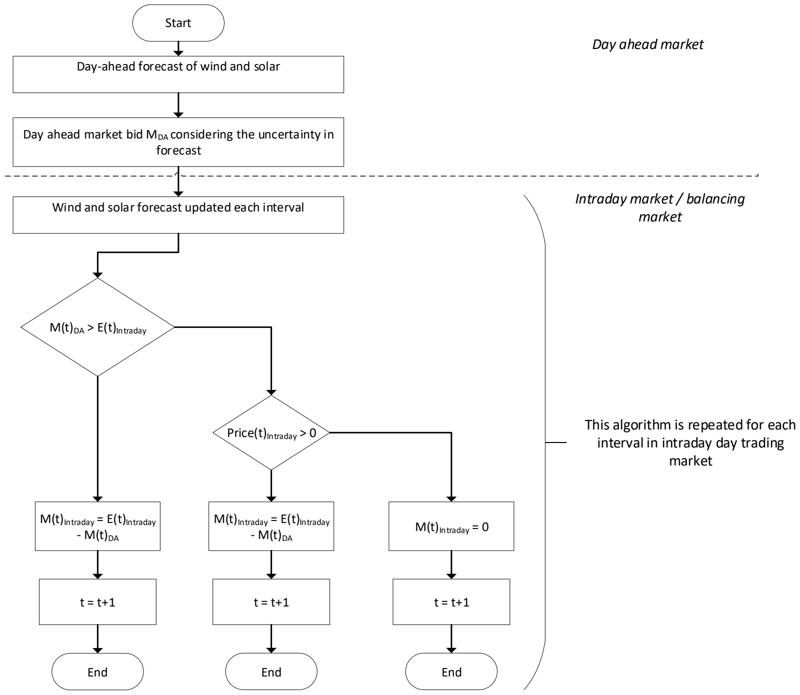

Figure 5.1: Market participation algorithm

If $M(t)_{DA} > E(t)_{intraday}$, then the hybrid plant does not have enough energy to meet the day ahead market bid.
But if there is more generation in the intraday market interval than the demand then the plant can reduce its generation by buying energy during that interval, thus reducing the output of the hybrid power plant. This market imbalance can be identified in the intraday market when the intraday market price $Price(t)_{intraday}$ for the trading interval t for generation is negative.
Other case is when $M(t)_{DA} <= E(t)_{intraday}$, then the hybrid plant has the opportunity to sell more energy in the intraday market, provided there is a need for more generation in the market i.e. the intraday market price is greater than zero.
Considering the forecast uncertainty of both the markets, in Figure 5.1 , the market forecast algorithm selects the appropriate energy commitment for each interval in both day-ahead and intraday market. The first part of the algorithm allocates the day ahead market commitment for the plant. The second part of the algorithm run before each interval in order to decide the plant commitment in the intraday market which is two later from the current interval. In the second part the algorithm

first checks if the plant is able to meet the day ahead market commitment and then proceeds to commit the excess energy to the balancing market or buy energy from the market the plant is not able to meet the day ahead energy commitment.
The proposed market participation algorithm in this chapter will provide a power reference to the Hybrid plant control system to generate the required in energy in each market interval.

Chapter 6

Hybrid power plant control

The Hybrid power plant control system controls the power output of the hybrid power plant to achieve the energy commitments in each market interval considering ramp rate limitations and firm power output at the Point of common coupling (PCC).
The main aspect of active power control of the hybrid power plant is firm power output, ramp limiting during increasing or decreasing the plant generation and finally power loss compensation to achieve the desired reference output power at the PCC.

6.1 Hybrid power plant design

The Hy-PPC receives available power measurements from wind and PV plants, and the SOC level in the case for BESS. The output power measurement at the PCC is sent to the Hy-PCC. Using these inputs and the reference power input of the plant the Hy-PPC is able to control the Hybrid power plant to produce the required power by sending the reference power control signals (red line in fig) to each of plant components (Wind farm, PV plant, BESS). The total sum rated power of wind farm and PV plant is considered as the base of the per unit of the system. The available power at each of the plant assets is provided based on this per unit base.

6.2 Hybrid power plant controller (Hy-PPC)

The Hy-PPC has three main objectives - ramp limiting, firm power output and power loss compensation. Ramp rate limiting can be achieved by using a ramp rate limiter as shown in the control diagram (Figure 5). The power measurement at

PCC provides feedback to the control system, the PI control thus can compensate the power losses in the system network to meet the required reference power at the PCC. The hybrid plant dispatcher divides the power references between the different plant assets depending on the available powers at each of these assets. The Hybrid plant dispatcher used here is a very simple dispatcher, where maximum amount of wind and solar energy is used for generation, and the battery system charges or discharges depending on the reference power required and the SOC level of BESS.

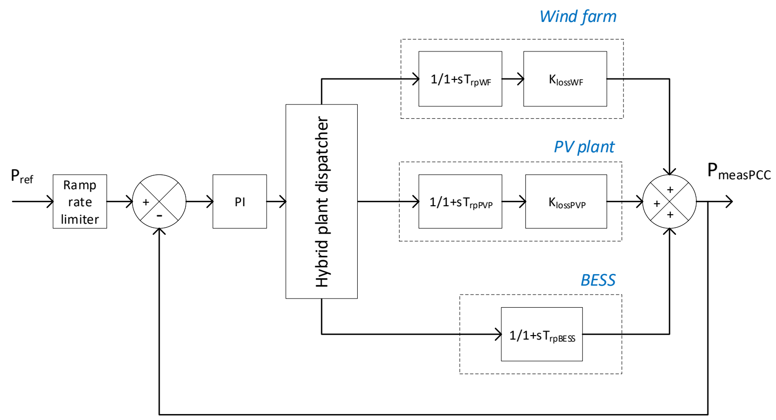

Figure 6.1: Hy-PPC control diagram

6.3 Controller design

The Proportional integral controller needs to be tuned carefully to have a stable control system which can provide a stable power output at the PCC. Due to the complexity of the control system, the control system needs to simplify in order perform stability analysis and tune the PI controller.

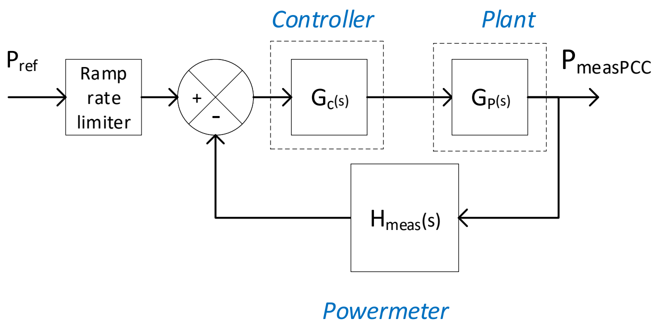

Figure 6.2: Plant control loop

The plant needs to be simplified into $G_p(s)$ in order to design the controller $G_c(s)$ [figure 6.2]. $H_{meas}(s)$ here is the measurement delay of the power meter, as per [] this is a first order delay of,

$$H_{meas}(s) = \frac{1}{1 + sT_m} \tag{6.1}$$

Typically, T_m has a value of 15ms [28]. The closed loop transfer function for the system will be,

$$G_{cl}(s) = \frac{G_p(s)\ G_c(s)}{1 + \ G_p(s)\ G_c(s)\ H_{meas}(s)} \tag{6.2}$$

The Hybrid power plant dispatcher is simplified here further, by replacing it with gains based on the available of power at each plant asset [fig], this would help in finding the Gp(s) for this plant. Now that the response time of Wind turbines, PV plant and BESS are not the same, this would affect the design of the PI Controller. Thus, it is necessary to tune the PI controller considering the different scenarios of operations of the hybrid power plant. The scenarios of the operation of hybrid plant can be classified as the following 1. Wind farm only 2. Wind farm + BESS 3. PV plant only 4. PV plant + BESS 5. Wind farm + PV plant 6. Wind farm + PV plant + BESS The Control diagrams of each of the above scenarios are given in Figure 6.3 and Figure 6.4.

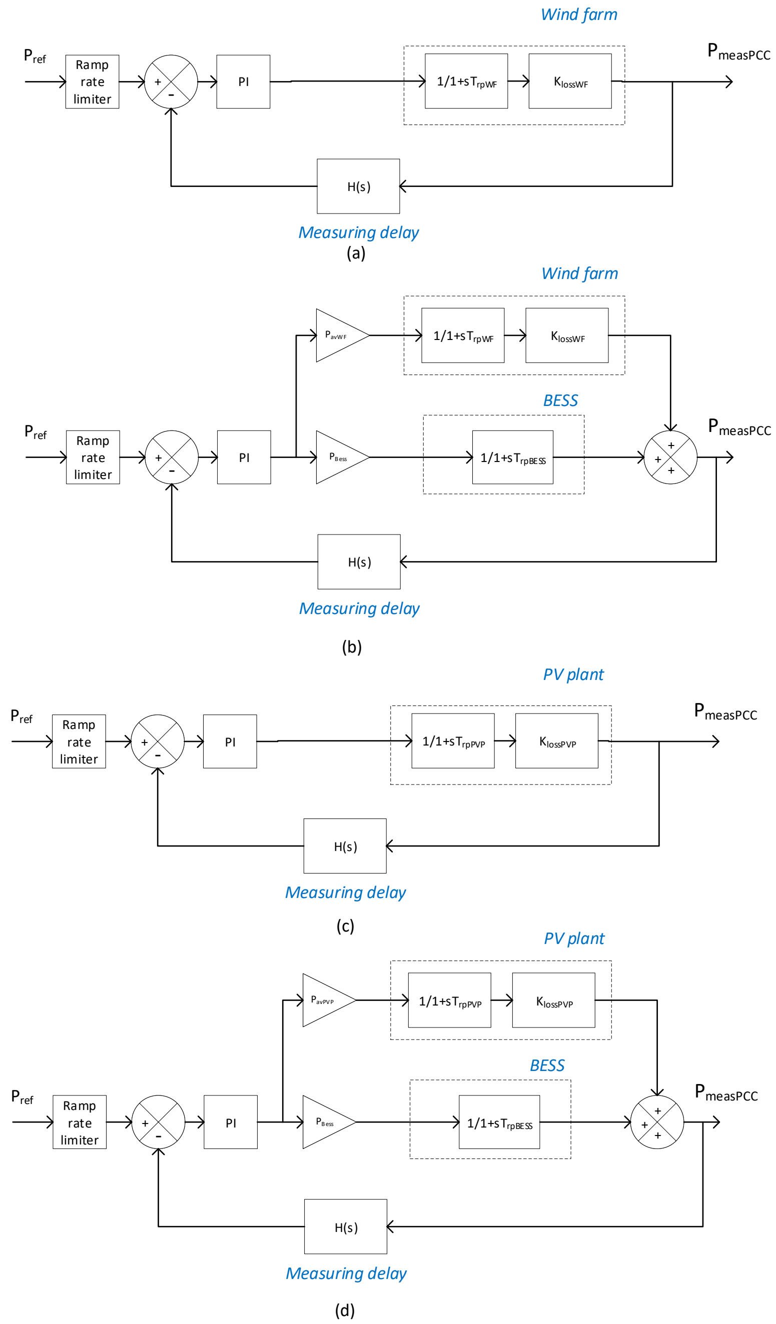

Figure 6.3: Plant control system for scenarios 1-4 (a)-(d)

In Figure 6.3, scenario 1 and 3 where only Wind farm or PV plant operates in the hybrid plant, there is no gain in the system as all the power is provided by the respective plants.

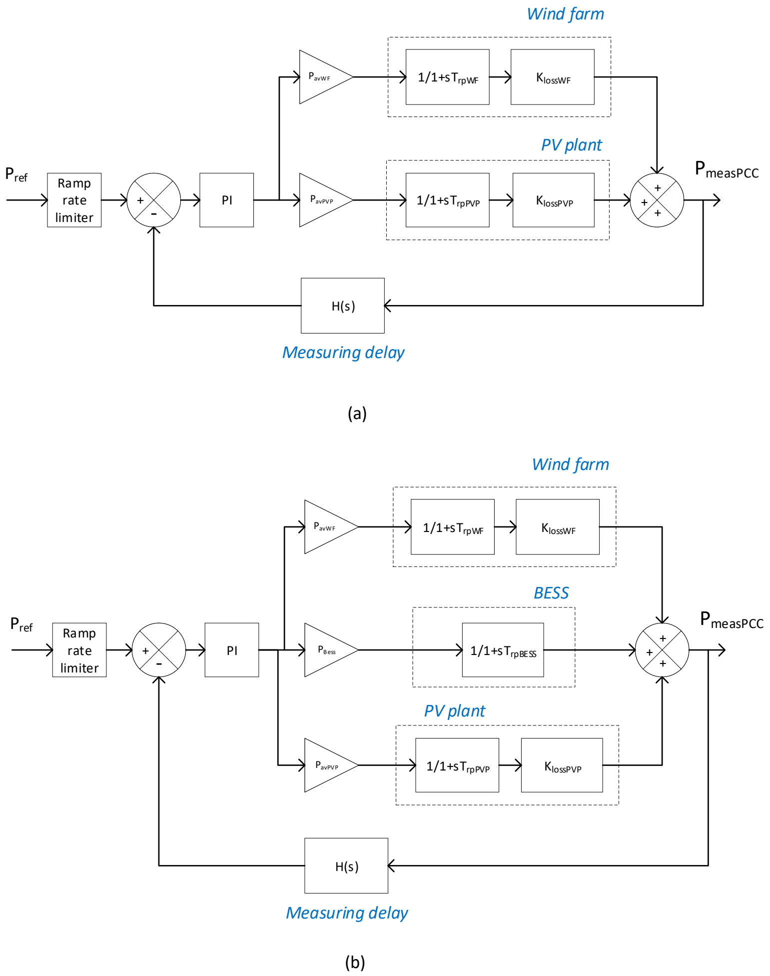

Figure 6.4: Plant control system for scenarios (a) 5 (b) 6

Now by generalizing the control systems we get $Gp(s)$ as,

$$G_p(s) = P_{avWF} \times \frac{K_{lossWF}}{1 + sT_{rpWF}} + P_{avPVP} \times \frac{K_{lossPVP}}{1 + sT_{rpPVP}} + P_{BESS} \times \frac{1}{1 + sT_{rpBESS}} \quad (6.3)$$

This equation can be applied all the scenarios, by adjusting the available power gains. For scenario 1 and 4 this available power gain would be set to 1.
Now this is a very complex transfer function, as available powers P_{avWF} and P_{avPVP} are variables. T_{rpWF}, T_{rpPVP}, T_{rpBESS} are the time constants of each of the plant assets.

In [27], the response time constant for wind turbine and BESS are given as per the values below,

$$T_{rpWF} = 1\ sT_{rpBESS} = 1.388\ s \tag{6.4}$$

The response time constant for PV plant is much lower than that of wind turbines or BESS. Thus, the value for it assumed as,

$$T_{rpPVP} = 0.05\ s \tag{6.5}$$

Considering equation (3) as the plant transfer function $G_p(s)$, the controller for the hybrid plant can be designed for the 6 scenarios mentioned in this section.
The transfer function of PI controller $G_c(s)$ is,

$$G_c(s) = P(1 + I/s) \tag{6.6}$$

Where P is the proportional gain value and I is the integral gain value.
Considering that the open loop transfer function of the plant is the product of plant transfer function $G_p(s)$ and measuring delay function $H_{meas}(s)$

$$G_{ol}(s) = \quad G_p(s)\ \times\ H_{meas}(s) \tag{6.7}$$

The hybrid plant used for this work has a 30 MW wind farm and 10 MW PV plant, thus the total rating of the hybrid power plant is 40MW which would be considered as the base of the per unit system. Thus, the Wind farm has a pu rating of 0.75pu and PV plant is 0.25pu.
In order to design this PI controller, the controller needs to be designed for different output of plant assets. The available powers of each of the assets are set specific values and then the PI controller is designed for each of the cases. The set points for each asset is mentioned below.

$$\begin{aligned} P_{avWFset} &= [0\ 0.3\ 0.5\ 0.7] \\ P_{avPVPset} &= [0\ 0.1\ 0.2] \\ P_{BESSset} &= [0\ 0.1\ 0.3\ 0.5] \end{aligned} \tag{6.8}$$

Using the SISOTOOL from Matlab we can tune the PI controller for various operating points of the Hybrid power plant. The operating points of the hybrid power plant will be varied according to the different available power set points of each of the assets. The design characteristic of the PI controller is that it has a response time of 1 sec and Phase margin of 90 degree such that the overshoot is limited.

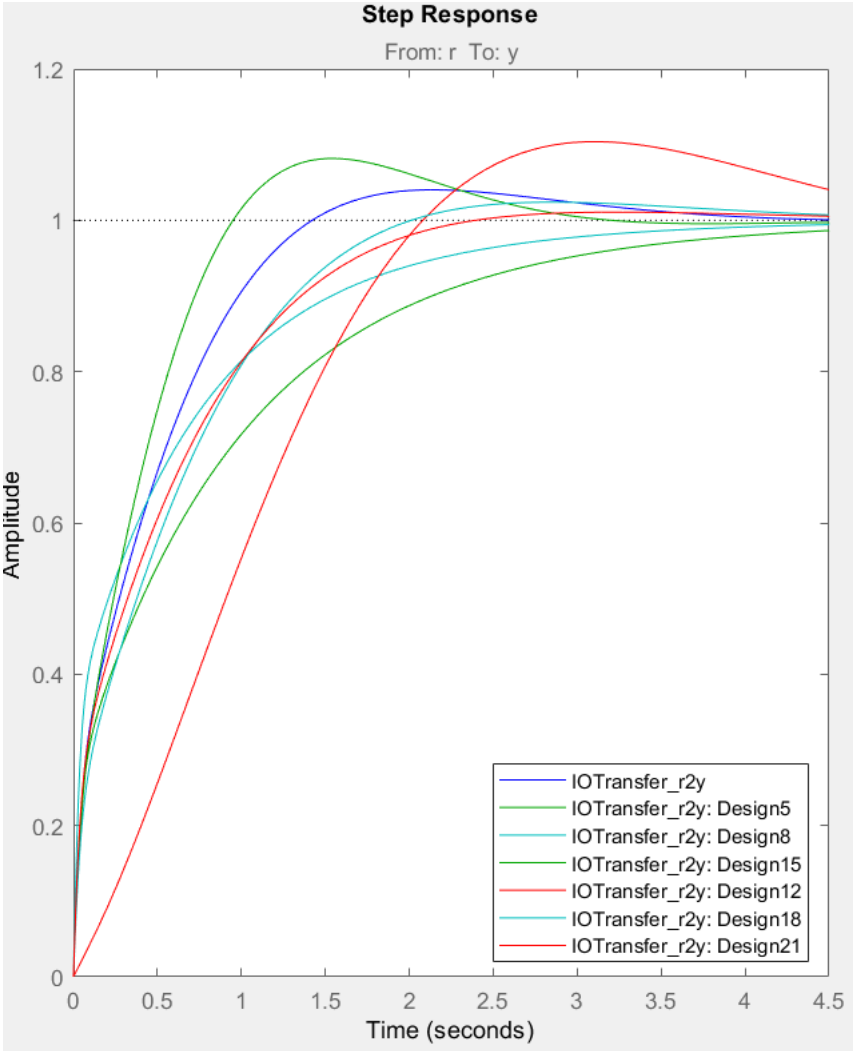

Figure 6.5: Step response of 6 Scenarios of hybrid plant operation

In the following tables the gain values (P, I) have been calculated for 48 different cases dependent on the operating points of the plant assets. These cases include all the scenarios discussed earlier in the section.

P value		Wind farm output	PV plant output		BESS output			
0	0	0.1	0.2		0.1	0	0.1	0.2
0	0	0.13028	0.13054		0	2.8078	3.241	1.252
0.3	2.0457	3.2064	1.7199		0.3	5.5008	3.0333	1.7683
0.5	2.0557	2.6003	1.6776		0.5	3.5929	2.4326	1.65
0.7	2.0657	2.1305	1.532		0.7	2.6742	2.0039	1.4874
0.3	0	0.1	0.2		0.5	0	0.1	0.2
0	2.8078	3.7918	1.8264		0	2.8078	3.2799	1.532
0.3	3.9604	2.63	1.7402		0.3	3.0918	2.2737	1.6399
0.5	2.8665	2.1286	1.5591		0.5	2.5207	1.8769	1.452
0.7	2.2504	1.7816	1.3905		0.7	1.9416	1.5971	1.2941

Table 6.1: Proportional gain values for different cases (48 cases) of wind farm, PV plant and BESS outputs

P value		Wind farm output	PV plant output		BESS output			
0	0	0.1	0.2		0.1	0	0.1	0.2
0	0	15.34	15.34		0	0.6529	4.839	7.161
0.3	0.9261	2.31	3.448		0.3	0.8686	1.989	2.944
0.5	0.9261	1.794	2.56		0.5	0.8883	1.644	2.322
0.7	0.9261	1.56	2.138		0.7	0.8979	1.47	1.996
0.3	0	0.1			0.5	0	0.1	0.2
0	0.6529	2.376	1.8264		0	0.6529	1.737	3.088
0.3	0.8047	1.615	2.337		0.3	0.7701	1.405	1.984
0.5	0.8373	1.438	1.989		0.5	0.8477	1.303	1.767
0.7	0.8559	1.334	1.78		0.7	0.8262	1.237	1.625

Table 6.2: Integral gain values for different cases (48 cases) of wind farm, PV plant and BESS outputs

I can be seen from the tables above that the gain values different for the various operating points of each of the assets. This was expected as the wind turbine, PV generator and BESS have different response time constants, thus altering the design variables in each of the case. The Integral gain (I) increases a lot when the PV plant is in operation.

To implement this a gain scheduled PI controller [29](figure 6.6(Bett, 2005) (Figure 17) is required, where the gains are dependent of Power output at wind farm, PV plant and BESS.

The gain schedule can be done with the help of a 3-dimensional lookup table

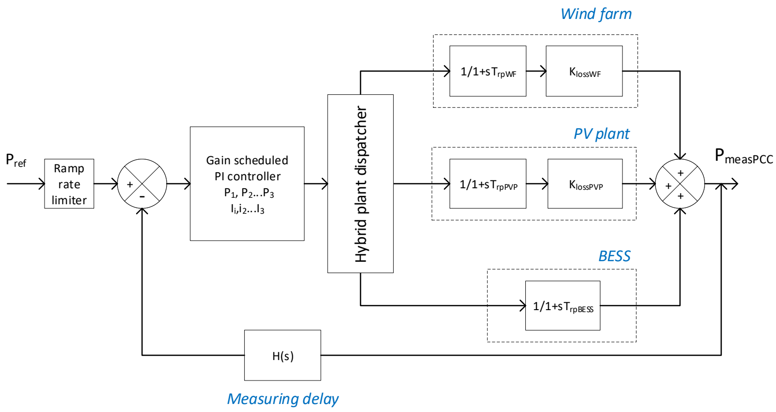

Figure 6.6: Hybrid plant controller with gain scheduled PI

(Figure 6.6), as there are 3 inputs here (Power output of Wind farm, PV plant and BESS). This lookup table will lookup the value from the tables above and predict the gains required for operation of the Hybrid plant control system. The lookup table gain prediction accuracy can be increased if more cases are included in the table.

The Hybrid plant control system required to implement the market participation algorithm is designed in this chapter. The ramp limited will limit the ramp rate of the Hybrid power plant, and the PI controller will help to compensate the power losses in the system. It is yet to be seen how this gain scheduled PI controller perform in the real power system, on how well the lookup tables perform in approximating the controller's gains. This would be further explored in the next chapter.

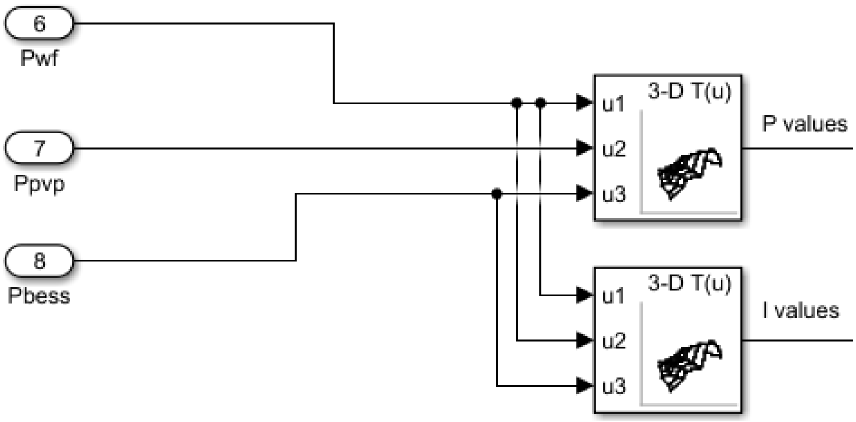

Figure 6.7: 3 dimensional lookup table for PI gain schedule

Chapter 7

Simulation and Analysis

With the Hybrid plant model proposed in chapter 4, the market participation algorithm along with the control system proposed in the previous chapter can be simulated in this Hybrid plant model. One day simulation of the hybrid power plant is carried out to obtain the revenues generated by the Hybrid power plant with the proposed market participation algorithm. The data for solar irradiance and PV panel temperature was obtained from installed PV system in Aalborg university [30]. The wind data from a 2MW wind turbine was provided by Vestas. The simulations were carried out for Australian energy market

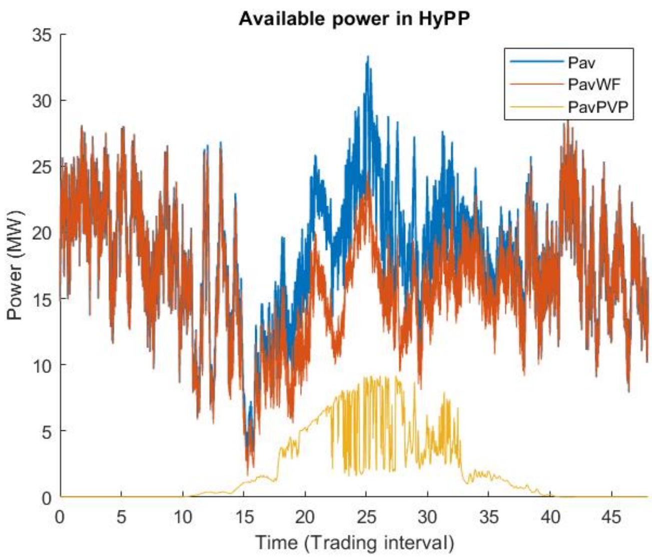

Figure 7.1: Available powers at HyPP

7.1 Market participation algorithm and forecast

The market algorithm requires day ahead and intraday forecast of both wind and solar. The available real data of wind and solar was used to make an approximation of the solar and wind forecast. From the data, wind and solar energy was calculated for each interval then a white gaussian noise was added to this value to introduce some uncertainty to the forecasted energy. The variance of this noise was adjusted as per the and type of forecast (day-ahead/intraday). For example, the variance for wind on day-ahead forecast has higher value compared to the intraday forecast.

The day-ahead forecast of wind and solar can generate the market participation for the all interval on the next day. As seen in Figure 7.1 market participation algorithm keeps some margin for uncertainty and bids lower that day-ahead forecasted power. This example is for medium case of risk, when the risk levels are increased then the day-ahead market commitment is also increased as per the *rr* value associated with the risk level.

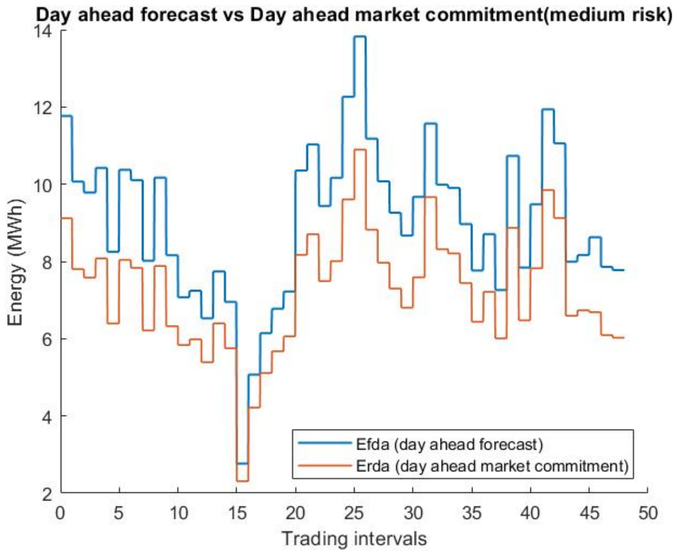

Figure 7.2: Day-ahead forecast and market commitment (medium risk)

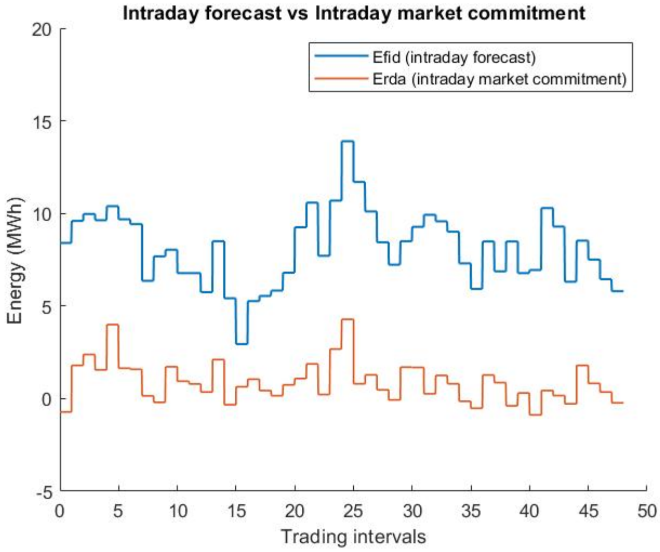

Figure 7.3: Intraday forecast and market commitment (medium risk)

During the trading day (during simulation) the intraday forecast is calculated before each interval, this forecast is used to calculate the intraday market commitment (Figure 7.2). In Figure 7.2, the intraday market commitment is shown in red, where in few intervals the commitment is negative, as the intraday forecast turnout to be less than that of the day-ahead commitment (Figure 7.3), thus the plant purchase the energy from the intraday market to make up for this mismatch.

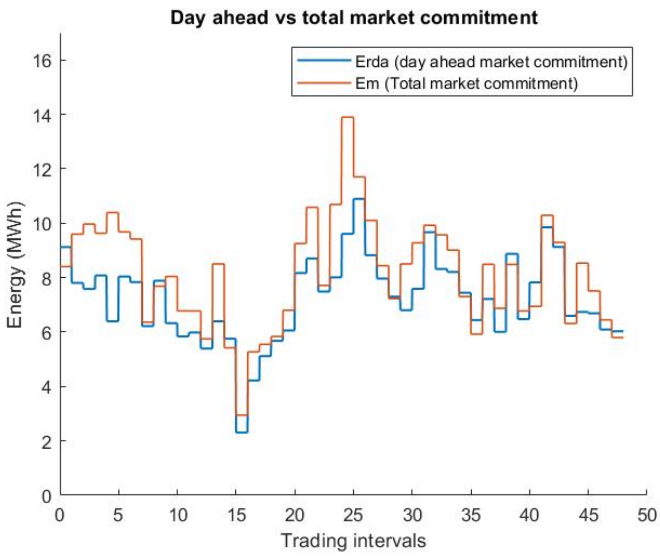

Figure 7.4: Day-ahead and total market commitment of HyPP

Once the intraday market commitment is calculated for the interval the then total market commitment is provided to the Hybrid plant control system to generate the required energy during that interval.

7.2 Hybrid plant control system performance

The hybrid plant control system converts the total market energy commitment for the interval into a reference power point of the interval, this reference power is then generated by the Hybrid power plant for that interval. In Figure 7.4, the medium risk market participation algorithm is applied and the Hybrid power plant control is able to provide output around the value of reference power for most of the intervals. The gain scheduler in some interval does not approximate the gain for the PI controller accurately thus there are some oscillations as seen in the end of simulation in interval 47 and 48.

Zooming into the power output in Figure 7.6, it can be seen that the power out-

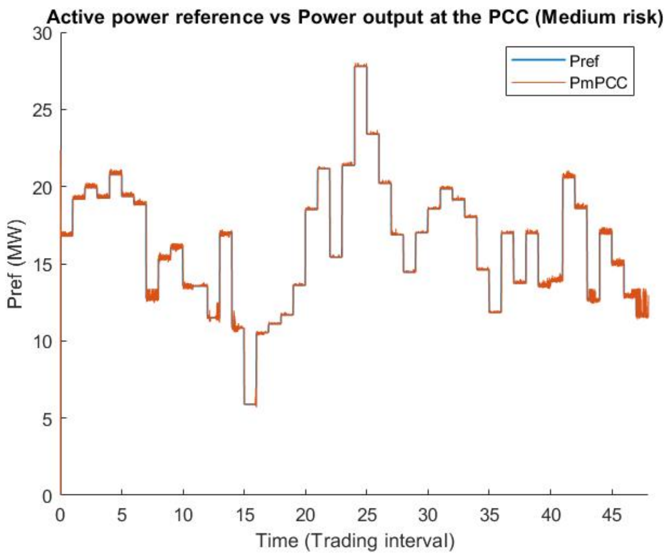

Figure 7.5: Power output at PCC with medium risk market participation algorithm

put ramps up smoothly as per the ramp rate limit (0.02pu), and the power output has small deviations from the reference power signal which can be expected for a complicated control system. The deviations are generally around the +-0.25% of the plant rating.

The energy generated at the PCC is compared with the total energy commitment for the Hybrid power plant during each interval. Ediff is the energy difference between market commitment and the energy produced, as seen in the graph in

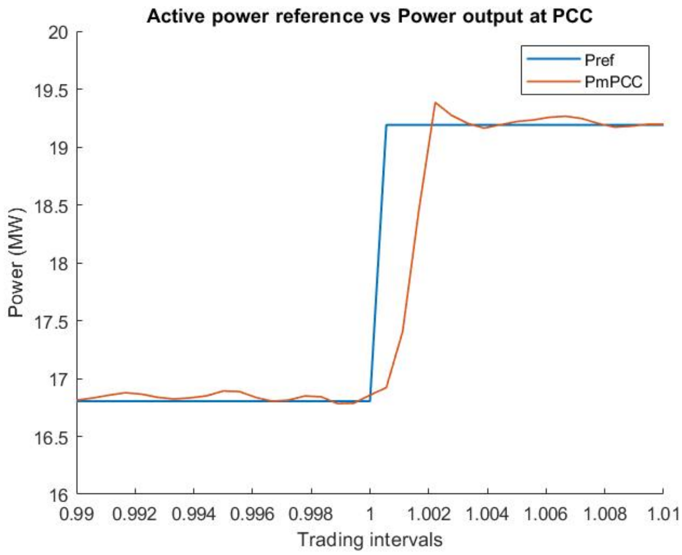

Figure 7.6: Power output response for each interval

Figure 7.7. In most interval this value is very low, but in case where the controller oscillates Ediff values are high, especially in the final intervals.

Although the Hybrid plant control system performs will, in some cases it is not able to keep up with the reference power. This could be improved by including more design cases in the lookup table for gain scheduler.

7.3 Revenues of Hybrid power plant

Three case studies where carried out on the model with the three risk levels (high, medium, low). The proposed algorithm was able to participate in both day-ahead and intra-day markets. The plant mainly participated in the day-ahead market and used the intraday market as means of balancing out is day-ahead market commitment errors. The revenues generated by the Hybrid power plant is calculated as per the equations in chapter 3. The revenues generated in each case for one day is shown in the table below. The calculation of intraday market or balancing market, the values for CONC and COFFC as per equation (2) is ignored as hybrid plant increase or decrease the output for the entire duration of the interval, which is not the case in a real system as the grid operator can ask to increase or decrease as per the balancing needs of the market.

From the table 7.1 it can be seen that higher risk levels of market participation algorithm yields higher rewards, this is partly because the market participation algorithm considers enough uncertainty in the Wind and PV forecast, so there is

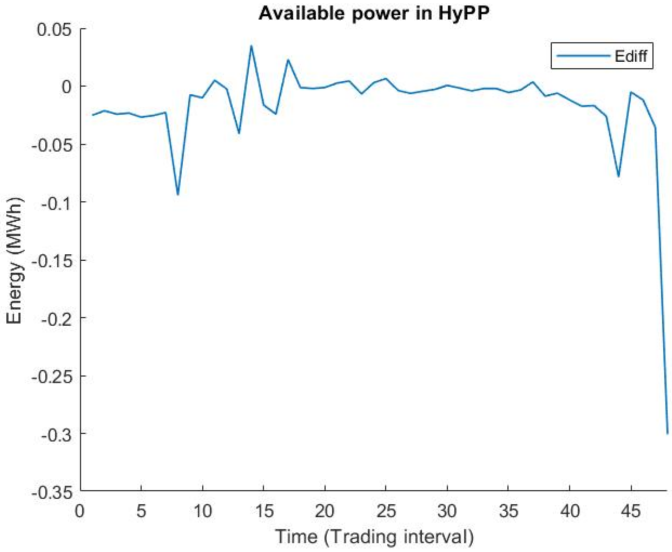

Figure 7.7: Energy difference between market commitment and output energy

Risk Level	Revenue generated (AUS$)
High	15516
Medium	15376
Low	15238

Table 7.1: Revenues generated by market algorithm for different levels of risk

enough excess energy available at the plant to take the risk. Main reason for this increased revenue at higher risk is because of the sizing of the BESS. The BESS size is oversized for this application of multiple market participation. Maybe if the Hybrid plant is more aggressively participating in the balancing market this BESS could be strained more. Currently the SOC limits of the battery increases by the end of the day and the state of charge does not cycle too much (Figure 7.8) even in high risk scenario.

Even though there are few discharge cycles, the depth of discharge of the cycle are very low, thus this operation would not affect the battery lifetime severely.
The market participation algorithm can generate power for both the electricity markets, participating in the intraday market allow the plant operators to take more risks while bidding in the day-ahead. As discussed in chapter-3 the Australian energy market currently does not allow renewable generation sources to upregulate power in the intraday market, only down regulation is allowed. The simulation carried out has proved that upregulation of energy in balancing market can be done effectively by Hybrid renewable energy plants, which can increase the profits for the plant operators.

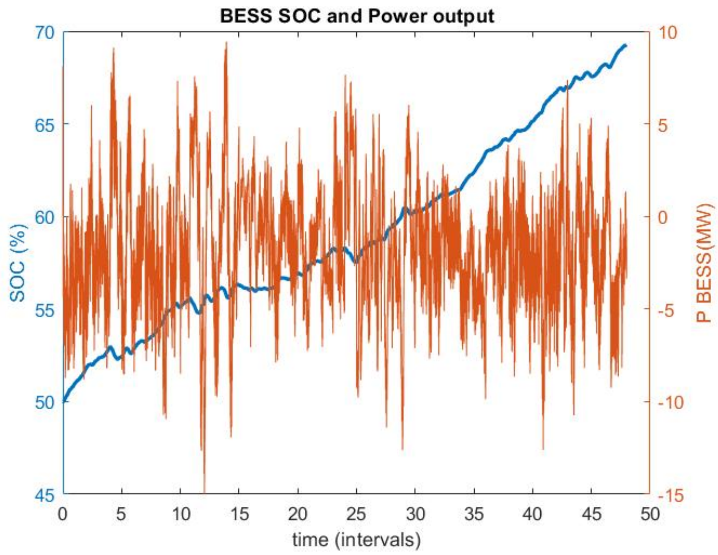

Figure 7.8: BESS SOC and Power output (High risk case)

Chapter 8

Conclusion

The declining electricity prices in market, growing electricity demand has put immense pressure on grids which are trying to decarbonize (IEA, 2018). Many countries in Europe like Germany, Denmark and Netherlands have removed the subsidies from the renewable power plants, which means that renewable power plants need to compete with conventional energy source to gain the market share. Advantageous aspect of renewable generation plants is it has very low capital cost when compared to conventional sources. Effective market participation becomes a key aspect for renewable power plants in order be cost effective and thus prove attractive to investors to invest in renewable energy project.
Wind and PV generation have been growing all over the world, and it is set to grow more in the coming year. Hybrid plant with wind, PV and BESS becomes a very attractive solution, as BESS would be able to support the plant to give stable output and participate more effectively in electricity markets. The market participation algorithm proposed in this thesis work was able to effectively participate in day-ahead and intraday markets. The algorithm's risk level gives plant operators an option of how much risk they are willing to take, as this can depend on many aspects like forecast data quality, geographic location etc.
Although the control system implemented was not able to fully keep up with the power references in the simulation, this can easily be solved by increasing the number of design samples for the gain scheduler. Electricity markets around the world are still adapting to increasing the renewable energy generation share, the regulation in place can sometimes halt this increase market share of renewables. Providing the capability of ramping up power of renewable generation plant in intraday markets not only helps in increasing the revenues by plants, but also gives the plant operators to avert some the risk taken in the day-ahead market.
BESS is a very important component in implementing such an algorithm in a hybrid power plant. The deterioration of BESS can increase the replacement cost for the plant operator. In the proposed plant the BESS was sized using a simple sizing

method, thus the BESS size proposed for the plant was very big. The proposed BESS, the lifetime was not deteriorated that much as the depth of discharge of the charge cycles where very small. Future work could be done on sizing of BESS, which is suitable with the market algorithm used, as the BESS sizing is correlated with applications it is used for. The control system proposed can be tested in a real system, to validate it control capabilities.

Bibliography

[1] IEA. *Electricity – World Energy Outlook 2018*. 2018. URL: https://www.iea.org/reports/world-energy-outlook-2018.

[2] Rafael A. Campos et al. "Performance Assessment of PV Technologies and Complementarity of Utility-Scale PV and Wind Power Plants in Brazil". In: *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion, WCPEC 2018 - A Joint Conference of 45th IEEE PVSC, 28th PVSEC and 34th EU PVSEC* (2018), pp. 1173–1178. DOI: 10.1109/PVSC.2018.8547259.

[3] C. Christiansen et al. "Energy Storage Study: A storage market review and recommendations for funding and knowledge sharing priorities". In: *Australian Renewable Energy Agency and AECOM Australia Pty Ltd, Sydney* (2015).

[4] Napat Chatrung. "Battery Energy Storage System (BESS) and Development of Grid Scale BESS in EGAT". In: *2019 IEEE PES GTD Grand International Conference and Exposition Asia, GTD Asia 2019* 1 (2019), pp. 589–593. DOI: 10.1109/GTDAsia.2019.8715953.

[5] Jamie C. Beardsall, Christopher A. Gould, and Moofik Al-Tai. "Energy storage systems: A review of the technology and its application in power systems". In: *Proceedings of the Universities Power Engineering Conference* 2015-Novem (2015), pp. 1–6. DOI: 10.1109/UPEC.2015.7339794.

[6] Nadezda Belonogova et al. "Multi-objective role of battery energy storages in an energy system". In: *LUT Scientific and Expertise Publications/Tutkimusraportit–Research Reports* 0494 (2018), pp. 7–8.

[7] Sahar Zafar et al. "On PQ control of BESS in grid-connected mode and frequency control in Islanded-mode for micro-grid application". In: *2018 International Conference on Computing, Electronic and Electrical Engineering, ICE Cube 2018* (2019), pp. 1–6. DOI: 10.1109/ICECUBE.2018.8610962.

[8] Anders Skajaa, Kristian Edlund, and Juan M. Morales. "Intraday Trading of Wind Energy". In: *IEEE Transactions on Power Systems* 30.6 (2015), pp. 3181–3189. ISSN: 08858950. DOI: 10.1109/TPWRS.2014.2377219.

[9] Peng Hou et al. "Cooperation of Offshore Wind Farm with Battery Storage in Multiple Electricity Markets". In: *Proceedings - 2018 53rd International Universities Power Engineering Conference, UPEC 2018* (2018), pp. 1–6. DOI: 10.1109/UPEC.2018.8541864.

[10] Amaia Gonzalez-Garrido et al. "Comparison of market operation strategies for photovoltaic power plants with storage systems providing frequency ancillary services". In: *2018 13th International Conference on Ecological Vehicles and Renewable Energies, EVER 2018* (2018), pp. 1–8. DOI: 10.1109/EVER.2018.8362386.

[11] Andoni Saez-De-Ibarra et al. "Co-Optimization of Storage System Sizing and Control Strategy for Intelligent Photovoltaic Power Plants Market Integration". In: *IEEE Transactions on Sustainable Energy* 7.4 (2016), pp. 1749–1761. ISSN: 19493029. DOI: 10.1109/TSTE.2016.2555704.

[12] Rishabh Abhinav and Naran M. Pindoriya. "Electricity Price Forecast for Optimal Energy Management for Wind Power Producers: A Case Study in Indian Power Market". In: *International Conference on Innovative Smart Grid Technologies, ISGT Asia 2018* (2018), pp. 1233–1238. DOI: 10.1109/ISGT-Asia.2018.8467870.

[13] Yi Liao et al. "An optimization strategy of smoothing control of HPWS active power output". In: *APAP 2011 - Proceedings: 2011 International Conference on Advanced Power System Automation and Protection* 2 (2011), pp. 1182–1187. DOI: 10.1109/APAP.2011.6180557.

[14] Rupesh G. Wandhare and Vivek Agarwal. "A control strategy to reduce the effect of intermittent solar radiation and wind velocity in the hybrid photovoltaic/wind SCIG system without losing MPPT". In: *Conference Record of the IEEE Photovoltaic Specialists Conference* (2012), pp. 1399–1404. ISSN: 01608371. DOI: 10.1109/PVSC.2012.6317860.

[15] Zhongyang Wang, Di Luo, and Lu Zhang. "Research on the active power coordination control system for wind/photovoltaic/energy storage". In: *IEEE Conference on Energy Internet and Energy System Integration (EI2)* (2017).

[16] Rakesh Reddy Vattigunta, Zakir H. Rather, and Ramakrishna Gokaraju. "Fast frequency support from hybrid solar PV and wind power plant". In: *Proceedings of 2018 IEEE International Conference on Power Electronics, Drives and Energy Systems, PEDES 2018* (2018). DOI: 10.1109/PEDES.2018.8707879.

[17] Ana Cabrera-Tobar et al. "Active power control of a PV generator for large scale photovoltaic power plant without energy storage". In: *2019 IEEE PES Conference on Innovative Smart Grid Technologies, ISGT Latin America 2019* (2019). DOI: 10.1109/ISGT-LA.2019.8895469.

[18] Bogdan Ionuţ Crăciun et al. "Power Ramp Limitation Capabilities of Large PV Power Plants With Active Power Reserves". In: *IEEE Transactions on Sustainable Energy* 8.2 (2017), pp. 573–581. ISSN: 19493029. DOI: 10.1109/TSTE.2016.2612121.

[19] Eduard Bullich-Massagué et al. "Power plant control in large-scale photovoltaic plants: Design, implementation and validation in a 9.4 MW photovoltaic plant". In: *IET Renewable Power Generation* 10.1 (2016), pp. 50–62. ISSN: 17521424. DOI: 10.1049/iet-rpg.2015.0113.

[20] Shiyu Xu et al. "Study on active power control in DFIG-based wind farm". In: *PEAM 2011 - Proceedings: 2011 IEEE Power Engineering and Automation Conference* 1 (2011), pp. 192–195. DOI: 10.1109/PEAM.2011.6134833.

[21] Li Lin et al. "An active power control application in a utility wind farm cluster". In: *IEEE Power and Energy Society General Meeting* 2014-Octob.October (2014), pp. 1–5. ISSN: 19449933. DOI: 10.1109/PESGM.2014.6939467.

[22] Jianxiao Zou et al. "A multi-objective optimization approach to active power control of wind farms". In: *Proceedings of the American Control Conference* (2012), pp. 4381–4386. ISSN: 07431619. DOI: 10.1109/acc.2012.6315415.

[23] Shu Fan, Senior Member, and Rob J Hyndman. *National Electricity Market*. 2012.

[24] South West Interconnected System Wholesale Electricity Market. "the South West Interconnected System Wholesale Electricity Market :" in: (2006).

[25] AEMO. "Electricity Industry (Wholesale Electricity Market) Regulations 2004: Wholesale Electricity Market Rules". In: 8.October (2004), pp. 1–17.

[26] A. Hina Fathima, N. Prabaharan, and K. Palanisamy. "Sizing of a VRB battery based on max-min method of power dispatch in a wind-PV hybrid system". In: *2015 IEEE Conference on Energy Conversion, CENCON 2015* (2015), pp. 221–226. DOI: 10.1109/CENCON.2015.7409543.

[27] Lennart Petersen et al. "Validating performance models for hybrid power plant control assessment". In: *Energies* 12.22 (2019). ISSN: 19961073. DOI: 10.3390/en12224330.

[28] Claudiu Ionita. "Advanced Active Power and Frequency Control of Wind Power Plants". In: (2017).

[29] Christopher J. Bett. *Gain-Scheduled Controllers*. Elsevier Inc., 2005, pp. 1107–1114. ISBN: 9780121709600. DOI: 10.1016/B978-012170960-0/50086-4. URL: http://dx.doi.org/10.1016/B978-012170960-0/50086-4.

[30] *Aalborg university Photovoltiac systems*. URL: url:https://www.et.aau.dk/researchprogrammes/photovoltaic-systems/.