DEPARTMENT OF ENERGY TECHNOLOGY

Added Value Assessment of Energy Storage for Wind Power Plants

Conducted by Group WPS4-1053

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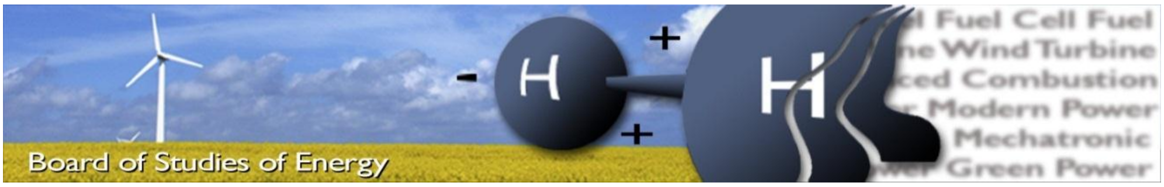

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Abstract

Increasing the penetration of Wind Power Plants (WPP) into the electric system brings about problems related to wind's inherent variability. Energy Storage Systems (ESS) are explored as a potential solution for addressing these problems, by providing WPPs with increased versatility and reliability without reduced production. The current needs of WPPs for participating in the electric grid are evaluated, and possible services that ESSs could provide are selected, as well as evaluated for their potential profitability. The ability of battery energy storage (BES) to provide these services is verified by using a Real-Time Digital Simulator (RTDS). Finally, real wind production and market data is analyzed and used to estimate benefits from providing services for the WPP, calculations which include the cost and lifetime of the BES.

Copies: 3
Pages, total: 71
Appendix: Annexes
Supplements: CD

By signing this document, each member of the group confirms that all participated in the project work and thereby that all members are collectively liable for the content of the report.

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Table of Abreviations

BES	Battery Energy Storage	**LFP**	Lithium Iron Phosphate
BMS	Battery Management System	**NPV**	Net Present Value
CAES	Compressed Air Energy Storage	**OpEx**	Operational Expenditures
CapEx	Capital Expenditures	**PCC**	Point of Common Coupling
CP	Control Power	**PCP**	Primary Control Power
CHP	Combined Heat and Power	**PHES**	Pumped Hydro-Electric Storage
DFIG	Doubly Fed Induction Generator	**RTDS**	Real Time Digital Simulator
DoD	Depth of Discharge	**SMES**	Superconducting Magnetic ES
EA	Energy Arbitrage	**SOC**	State of Charge
ESS	Energy Storage System	**SCP**	Secondary Control Power
EMS	Energy Management System	**TCP**	Tertiary Control Power
FRT	Fault Ride Through	**VSC**	Voltage Source Converter
FES	Flywheel Energy Storage	**WPO**	Wind Power Operator
GPC	Giga Processor Card	**WPP**	Wind Power Plant

Chapter I. Wind Energy in Denmark

In order to understand the problems of large-scale wind power integration to the electrical grid, it is necessary to first explain the nature of wind energy and the technologies employed to harvest it. Afterwards, the demands that grid operators are imposing on the operation of wind parks can be better understood, as well as the needs of the wind farm owners themselves. Finally, a possible solution is presented to face these necessities.

1. The Nature of Wind Energy

There are environmental, economic and social pressures for the development and installation of wind power plants, in Europe and worldwide. Attention brought to the emission of CO_2 by traditional power sources has pushed for a shift towards more eco-friendly alternatives. National policies now reflect this desire, with aims of up to 50% renewable energy by 2020 [1] in the case of Denmark. These policies reflect themselves in subsidies for green energy. These subsidies, together with the fact that no fees need to be paid on CO_2 emissions, make renewable sources economically attractive. In the case of Denmark, where the flat terrain and lack of rivers makes hydro power impossible and social opposition takes nuclear power out of the picture, wind energy has especially flourished. Penetration of wind power into the national grid now reaches 20%, and it is expected that much of the new capacity to be installed to meet the 15-year goal will come in the form of wind turbines [2].

There are a number of issues associated with the increasing penetration of wind power into the electrical grid, mostly related to wind's inherent variability. As the power output of a turbine is heavily reliant on the wind resource available, changes in the magnitude of the wind will also bring about changes in the power output. While mechanical pitching of the blades can help to ameliorate some of the gradients, a single wind turbine cannot be trusted to provide a steady output, all of the time. From the grid's perspective, a single wind turbine could be seen as a wildly variant negative load. As the proportion of energy coming from wind turbines in the grid increases, these variations become more important, until their presence cannot be ignored.

As mentioned above, the magnitude and variations in the output of a wind turbine are directly connected to the magnitude and variations of the wind itself. The power available in a laminar, tube-shaped constant flow of air can be expressed as

$$P_{AW} = \frac{1}{2} A \rho v^3$$

where A is the area of the base of the cylinder, ρ is the density of the air (around 1.225 kg/m3, at sea level), and v is the velocity of the wind in the direction of the axis of the cylinder. This is the airflow that passes through a wind turbine's rotor, in which case the extracted power is

$$P_W = C_P \cdot P_{AW}$$

where C_P is the power coefficient, or the proportion of wind power that is transferred into rotational energy by the turbine [3]. The theoretical upper limit for C_P is 0.593, called Betz' limit after the German physicist Albert Betz. Given that the power is related to the cube of the wind speed, even small variations in the magnitude of the wind can be reflected in large variations in the output of the wind turbine. Furthermore, variations in the wind are a given, and exist in different magnitudes and for different time scales.

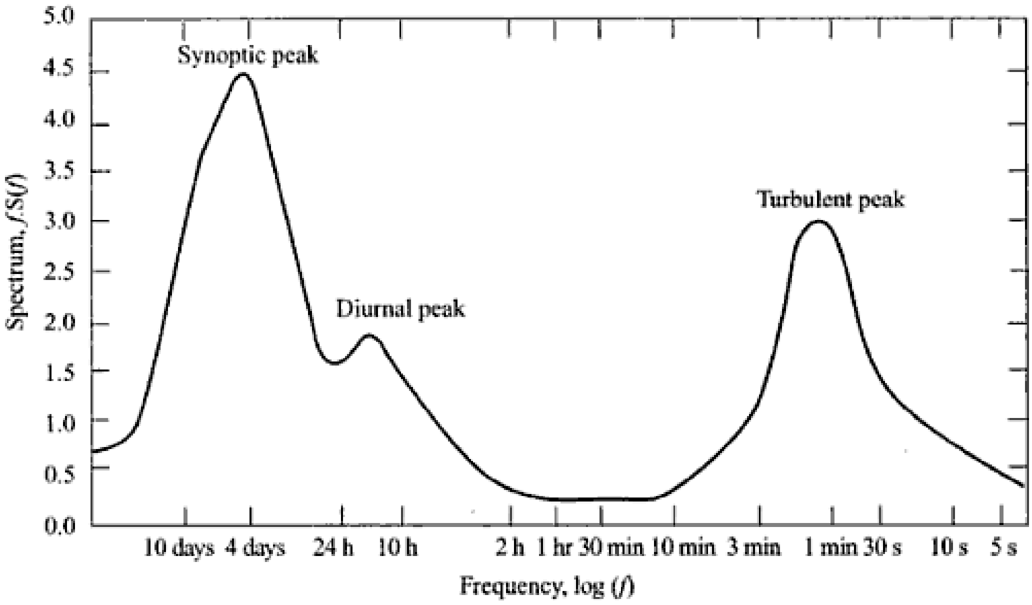

Fig. 1.1. *Wind Speed variation spectrum. [3]*

In addition to the scales shown above, the wind suffers from seasonal and even yearly variations. Very large turbines have enough mass in their rotors so that, thanks to their inertia, they can in greater or lesser measure ignore variations in the very fast scale. The variations shown above expose the central flaw of electric energy coming from wind turbines. Within the electric grid, energy must be consumed at the same time it is generated. The fact that the output of a wind farm cannot be precisely known in advance means that it cannot be relied upon to provide the base load. Even to provide the intermittent load, other sources of energy must be present to be able to make up for the difference between the expected and actual output. While mechanical pitching of the blades can help to ameliorate some of the gradients, a single wind turbine cannot be trusted to provide a steady output, all of the time. From the grid's perspective, a single wind turbine could be seen as a wildly variant negative load. As the proportion of energy coming from wind turbines in the grid increases, these variations become more important, until their presence cannot be ignored.

If the aggregated effort of several wind turbines, distributed across a sufficiently large geographical area, is taken into account, variations seem to become less of an issue. [1] A surplus of wind in one region will compensate a lack of it in another, given that the transmission system between them is strong enough. A large, strong grid with enough wind turbines will have a more steady contribution of wind power. This does not completely solve the problem of wind variations, though, for two reasons. The first one has to do with the time scale of the variations. A large geographical distribution can help cancel variations in the minute or hour time-scales, but larger variations, such as daily or seasonal, cannot be met for any practical purposes. In many places, there tends to be more wind during the night than during the day, and more during winter than summer [4]. The grid must still be prepared to carry for the whole of the wind capacity, in case there is no production at all during some time period. The second reason has to do with the transmission capabilities of the grid. A single line is limited in the amount of power it is able to carry. Supposing that a large enough distribution of wind turbines can simply compensate each other also necessitates the existence of a strong enough – and expensive –

transmission system. The reliability of a wind farm is a necessity for its large-scale participation in the electric grid.

These reasons constitute the source of wind energy's shortcomings. Despite the fact that wind turbines deliver clean and CO_2-free energy, the growth of wind energy in Denmark does not imply a decommissioning of traditional power sources in the country. It is often considered that a large spinning reserve, "almost equivalent to the installed capacity"[5] is required to provide adequate balancing services. In Denmark, conventional gas and oil plants must still be run for local heating, and CEPOS's controversial 2009 report on wind energy claims that they are also run to account for all the capacity of the unreliable wind power. In spite of the report's flaws and biases, it was correct in pointing out that wind production in Denmark has a strong correlation with energy exports and imports with its neighboring countries, although this does not imply that the energy exported is actually coming from wind turbines [6]. If not for the sake of economics, the grid must be strengthened in order to accommodate the growing wind fraction. Presently, Denmark relies heavily on its strong ties with Norway, Sweden and Germany to accommodate its large penetration of wind power. The excess wind energy in Jutland goes to reduce the amount of hydropower consumed in Norway and, in an ironic twist, traditionally anti-nuclear Zealand uses some of Sweden's nuclear power, when its own wind power fails [2]. If wind energy is to remain a competitive alternative to other energy sources without incurring in great balancing costs at higher penetration, wind farms must become virtual wind power plants, providing steady, controllable, and reliable energy.

1.1 Wind Park Technology

Despite the many challenges that must be faced in harvesting usable energy from the wind, those who try are not completely disarmed. Modern wind turbine technology has evolved to better be able to fulfill these services. The following section deals with explaining the main technologies used today, and how each is able to cope with demands given to it.

Rotor Technology

The rotor's job is to transform the kinetic energy present in the wind into rotational energy. Unlike traditional wind turbines, which used the drag properties of the wind, like sail ships, the blades of a modern wind turbines use the lift properties, like planes. This allows the blades to perform the same functions as the wings on a plane can, such as pitching and stalling. Pitching means to change the angle with which the profile of the blades meets the incoming wind. This can be used to optimize the power extracted, as the relative motion of the blades means that the perceived wind will gain a tangential component, or to limit the output under high wind conditions. If the wind becomes too strong, or the rotor must be stopped for maintenance, the blades can be pitched so much that the rotor goes into stall, and rotations cease. Additionally, yaw control can change the orientation of the nacelle itself, so that the blades do not directly face the wind.

Changing the pitch angle of the blade β effectively changes the power coefficient C_P, changing the operational point of the turbine. The image below shows the relationship between C_P , β and the tip speed ratio λ, where this last one is defined as the ratio of the rotational speed of the blades divided by the actual wind speed at the hub. [7]

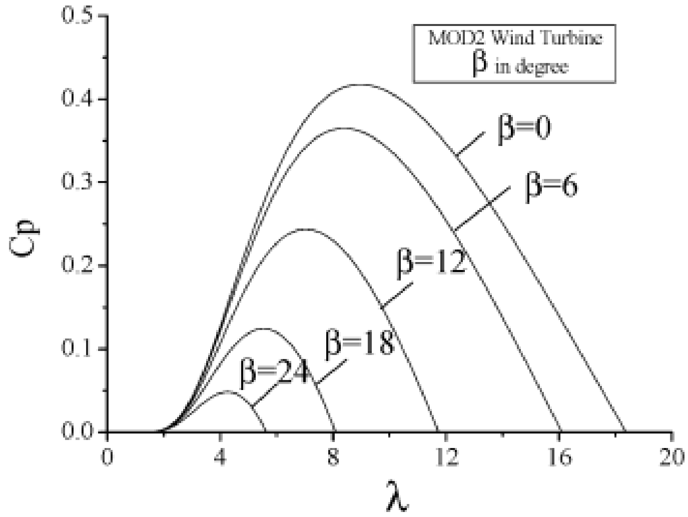

Fig. 1.2. *The power coefficient C_P as a function of the tip speed ratio λ and the pitch angle β. [7]*

In practice, pitching the blades can only reduce the power output of a turbine. However, if the turbines are constantly kept pitched so that the turbine is operating at a suboptimal point, both downwards and upwards regulation are possible. The image below shows the power output for a given turbine, operating at different pitch angles. If β is kept at a suboptimal point, so that the output is less than what is possible under those wind conditions, the power output can be increased by modifying the pitch angle. The upwards regulation is limited by the margin of available power that is kept. This margin is often known simply as a delta, δ, and implies a reduced production from the wind turbine. Current control strategies, as expressed in the Danish Grid Codes [8], demand that wind parks be able to limit their output in such a way, in case it is asked for by the Transmission System Operator.

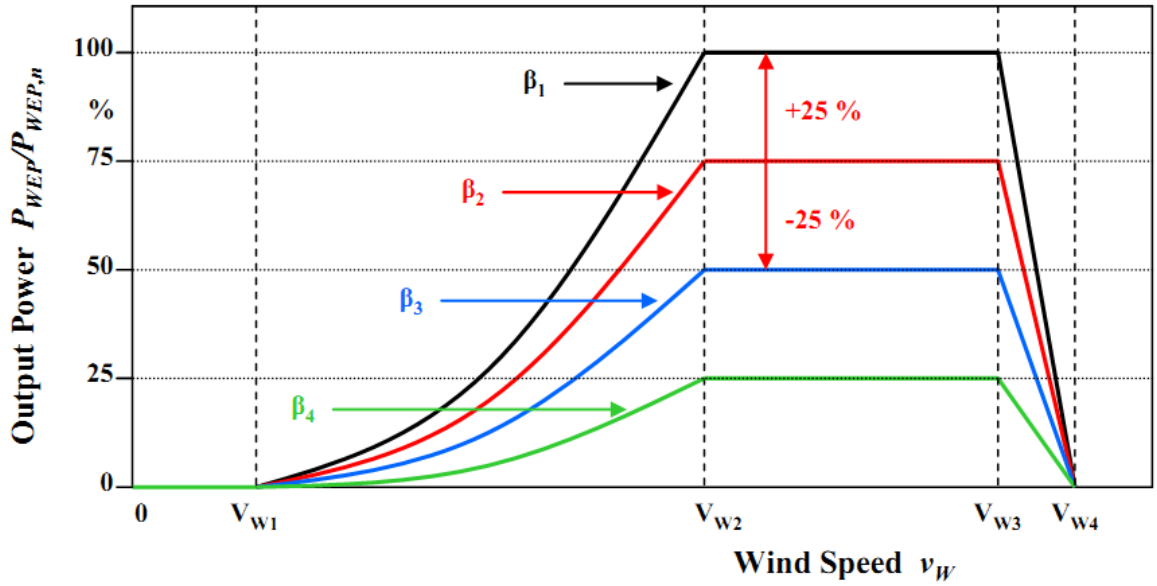

Fig. 1.3. *Upwards and downwards control of the output power through the pitch* angle β. [9]

Generator Topologies

Once the rotor has extracted the kinetic energy from the wind, and stored it in itself in the form of rotational energy, it is up to the generator to transform it into electrical energy. Many variations of generator topologies have been implemented: with and without gearboxes or permanent magnets, or using synchronous instead of induction generators. Each model presents its own advantages and disadvantages, the more complex variations being capable of performing more advance functions. Three common constructions will be briefly presented, as explained by [5] and [9], among others.

Constant Speed Induction Generator

Though rapidly being outplaced by variable speed generators, constant speed generators are still present to in older turbines. Their relatively simple setup offers low complexity at the cost of limited control possibilities.

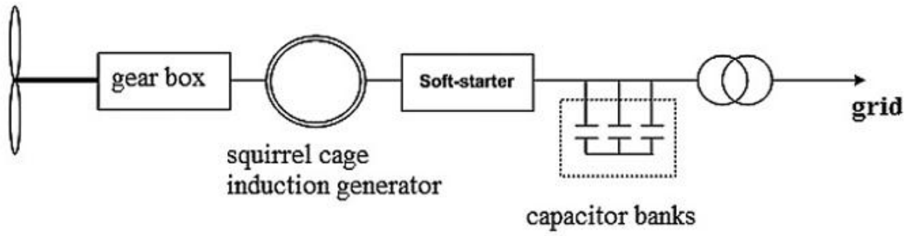

Fig. 1.4. *Topology of a constant speed induction generator [10]*

Constant speed generators operate, as their name indicates, at a constant rotational speed, as the slip of the generator is fixed at 1% [10]. The consumption of reactive power by the rotor´s windings must be compensated by the installation of additional capacitor banks. The simple construction means that the only mechanisms available to the operator are through the yaw and pitch control for active power and the connection of the compensating capacitors for reactive power. Some additional control can be achieved by the installation of variable resistances on the stator excitation circuit.

Overall, this topology is inadequate to meet the demands that modern grid operation requires, as very little reactive and active power control is possible without additional equipment [9].

Doubly-Fed Induction Generator

An improvement on the constant speed topology can be made by interfacing the rotor excitation circuit to the grid by means of back-to-back Voltage Source Converters. While the stator still operates synchronously with the grid, the rotor excitation frequency can now be controlled, permitting a variable speed operation.

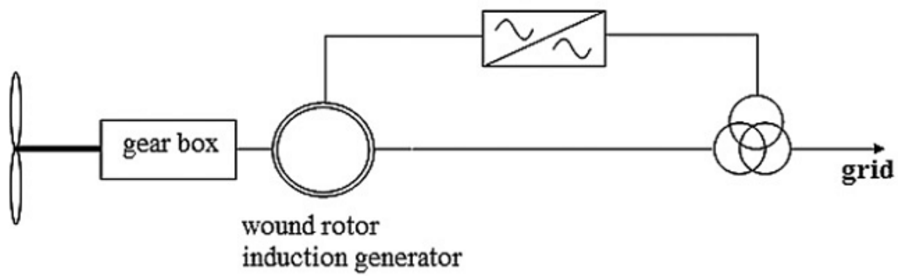

Fig. 1.5. *Topology of a Doubly-Fed Induction Generator [10]*

Doubly-fed induction generators (DFIG) now represent a large percentage of existing wind turbines. They provide more control than constant speed generators, even without added power electronic devices. Purely by varying the rotor current, it is possible to provide some reactive power control, and by overspinning the generator some degree of active power control is also possible. [5]

Synchronous or Asynchronous generator with full power converter

More flexibility can be achieved if both stator and rotor excitation currents are fed through a back-to-back VSC. In this case, the frequency of the generator can be independent of the frequency of the grid, providing maximum power control. The converter must be able to handle the full of the generator's capacity.

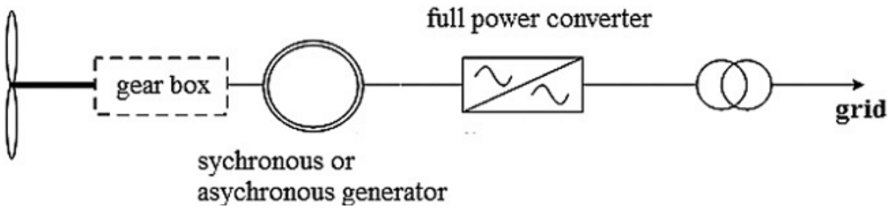

Fig. 1.6. *Topology of a Synchronous or Asynchronous generator with full power converter [10]*

Variable speed wind turbines, such as this topology and the DFIG, offer much higher control for active and reactive power. It is considered, by [10] and [5], that these technologies, together with some support from power electronics devices, can comply with all the demands issued by national grid codes.

2. Needs and Demands in the Wind Sector

There are many actors involved in the development of wind energy. Wind farm owners or operators, wind turbine manufacturers, and the transmission system operators are just some of the stakeholders. Some of the others will now be shorty presented.

The Transmission System Operator (TSO) is represented, in Denmark, by Energinet. This is a public enterprise, owner of the electrical transmission distribution system, as well as the gas system. It is the regulating body for energy producing units, and the enforcer of grid codes.

The Market Regulator can be an actual entity or just the competing supplies and demands, in countries where electrical production is privatized. Nordpool is the common market for the Scandinavian countries, Finland, and Estonia. Here, electric energy producers offer their bids based on production expectations.

Wind Power Owners or Operators (WPOs) were, in Denmark, often collectives or neighbours. As the scales of wind farms grew, they became more usually companies. They must produce energy that is cheap and reliable enough to participate in the market, at the same time as they comply with the TSO's codes.

Other important participants are

Conventional Power Generation units are vital in Denmark, where Combined Heat and Power (CHP) units are used both for electricity and district heating. For the same reason, it is difficult to curtail their use and have a much lower ramp rate.

Balancing Responsible Parties offer generative power that is faster than larger, traditional power generators. In Denmark, smaller gas-fed power plants are used to quickly compensate for grid instability. They are often managed by third-party companies that buy electricity from independent producers and WPOs. They can also offer their balancing power in the Elbas market.

Transmission Partners can be used to quickly procure additional energy or sell a surplus. Denmark has strong ties with Sweden, Norway and Germany, ties which have allowed it to have a large penetration of wind energy without a need for storage.

Wind Power Systems Manufacturers are, finally, also important participants, as they must produce effective machines that satisfy the TSO's demands, while participating in a common market with conventional power systems. It is in the manufacturer's interest to build not only a wind turbine, but a virtual wind power plant.

From these stakeholders, one must understand that each expects different things from wind power systems. The TSO sees WPS as a variable and unreliable source, whose weaknesses become more important as the share of wind energy in the system increases. For this reason, grid codes are published in each country, detailing the way that plants must be run and the kind of hardships that they must be able to withstand. Wind power owners are participants in the energy markets, where prices for electricity are negotiated based on the generation offers and consumption demands, as well as the capability of the grid to manage the energy flow. In order to participate in this market, WPOs must enter in a contract with a balancing service, often provided by a third party which also buys their energy and makes biddings in the market for them.

2.1 Technical Demands for Wind Power Systems in Denmark

As the penetration of wind turbines in the capacity of an electric grid increases, it becomes more and more vital for each one of them to be a reliable part of the network. If turbines disconnect under any given fault condition, the severity of the fault will only be increased with the sudden disappearance of the wind turbines. For this reason, it is demanded from connected turbines that they are able to operate under significant deviations of nominal grid voltage, fluctuations of grid frequency, and to be able to withstand faults, as well as other requirements for power control and power quality.

Energinet issued the 30th of September 2010 their latest version of the Danish grid codes, pertaining to wind turbines larger than 11 kW [8]. These codes specify a series of demands that wind turbines and wind farms must comply with if they wish to be connected to the Danish network.

Tolerance for frequency and voltage deviations

The Danish grid codes define a point of normal operation, as well as regions of abnormal operation and required times for turbines to remain connected to the grid. Normal Operating conditions are defined as any situation in which the voltage at the point of common connection finds itself between 110% U_{NOM} and 90% U_{NOM}, where U_{NOM} is the rated voltage for that given connection, and the frequency finds itself between 49.50 Hz and 50.20 Hz. In the event that the generated power does not match the consumed power, which is the case in the loss of a generating unit, a fault in a line or sudden changes in the load, the frequency will rise – if production exceeds consumption—or fall – if the opposite is true. Under these conditions, further changes in the grid, such as the disconnection of a wind turbine, will only exacerbate the problem. Therefore, the grid codes demand that turbines remain connected to the grid under different conditions, as explained in the image below.

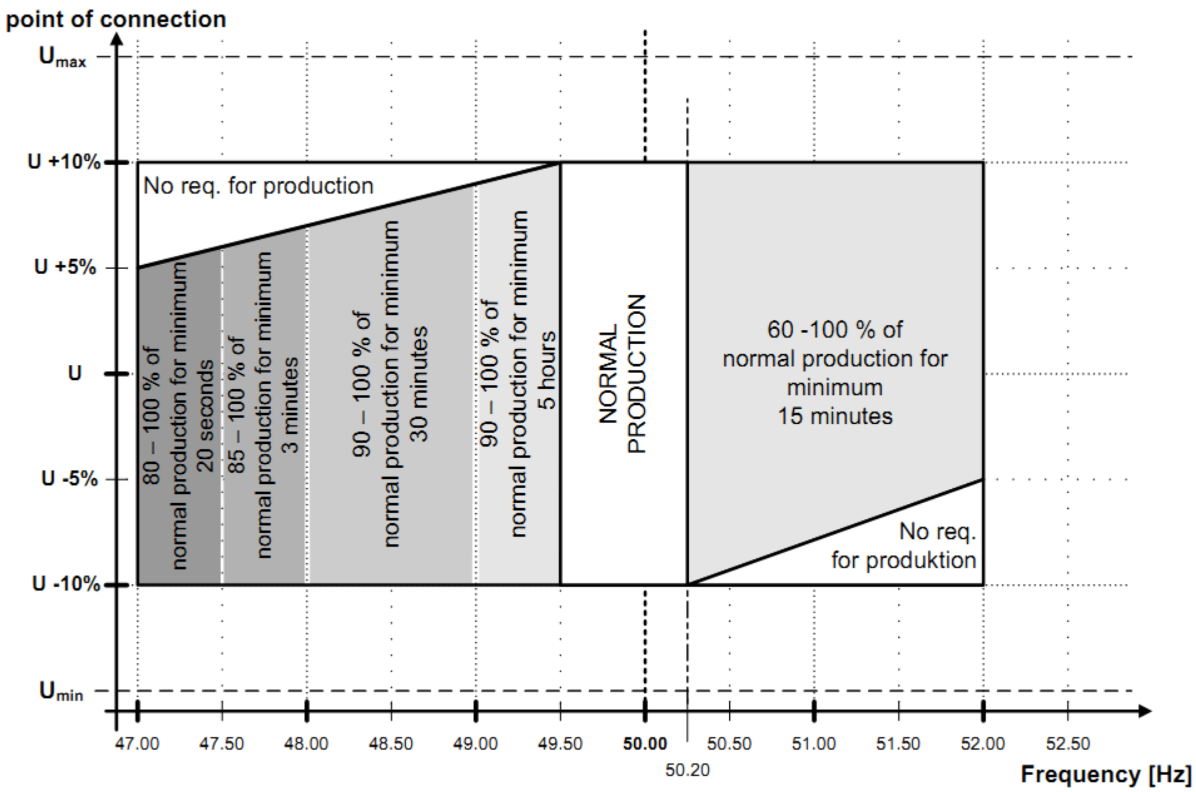

Fig. 1.7. *Tolerance for Frequency and Voltage deviations, for turbines over 25 kW [8]*

Low Voltage Ride Through

Faults in the grid, such as a line to line or line to ground fault, result in a sag in the grid voltage, near to the area where the fault occurs. Generating facilities near the fault must remain connected to ensure the supply of power to the area, and to make sure that the fault will not propagate once the error has been corrected or isolated with circuit breakers. The ability of a generating unit to cope with these disturbances is known as **Low Voltage Ride Through** or **Fault Ride Through** (**FRT**).

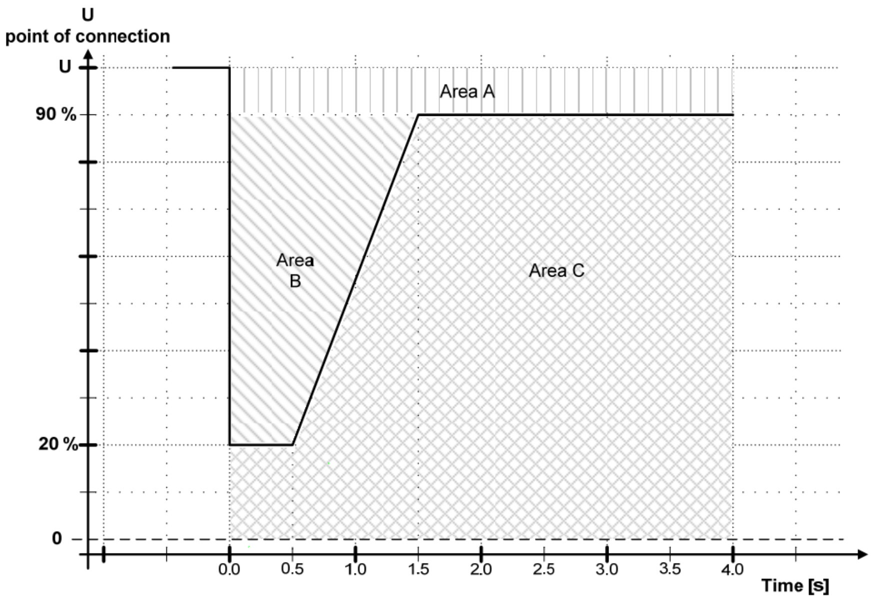

Fig. 1.8. *Low Voltage Ride Through demands, for turbines over 1.5 MW. [8]*

The above graph shows the demands for turbines above 1.5 MW. As expressed in [8], in Area A, turbines must remain connected. In Area B, turbines must remain connected and provide reactive power, to make up for the loss in voltage. Decoupling is allowed in Area C.

Active Power and Frequency Control

The balance between energy consumed and produced in an electric grid must be carefully kept even at all times. Excesses in production will reflect themselves in an increase in grid frequency, while deficits will bring a drop in it [11]. User devices and industrial machinery are designed to be used with a specific frequency, 50 Hz in Denmark. Deviations from this value can cause damage to components in these devices, as well as in the generating units. For this reason, the Danish grid codes have established as safe operating limits 50.20 Hz and 49.50 Hz. [8]

Maintaining the frequency within these limits is achieved through the use of regulatory power or control power (CP). Primary Control Power (PCP) is based on the spinning reserve of large generators. It should start acting at the most 5 seconds after a change in the frequency and must be able to provide the control for at least 15 minutes. PCP can be seen as a droop controller, in that it seeks to deliver the required energy to stabilize the frequency, but not to establish a new operating set point for the system [11]. Secondary Control Power (SPC) consists of fast-acting reserve generators, such as gas turbines in Denmark. It must start acting at the most 30 seconds after a change in frequency, and should take the load off the PCP before 15 minutes have passed. SPC can be seen as an integrative controller, in that it seeks to bring the frequency back to its optimal value by delivering the needed amount of energy. Tertiary Control Power (TCP) comes into action after fifteen minutes. It involves the establishment of a new operational set point for all the generators in the system, in order to accommodate the deficit in energy. [9]

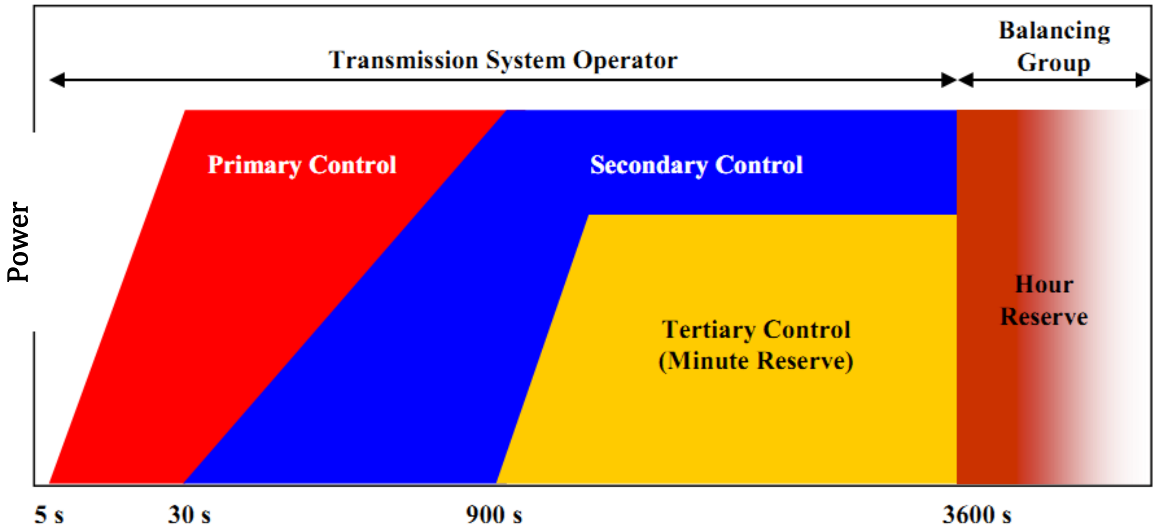

Fig. 1.9. *Temporal operational demands for different stages of Power Control. [9]*

In the case of a frequency drop, as shown in the image below, the PCP would come in effect before 5 seconds have passed, and would seek to stabilize the frequency to a point lower than the optimal operational one. This control power must be able to be delivered for at least 15 minutes. After 30 seconds, the SCP comes into action, acting as an integrative controller and seeking to restore the frequency to its original point.

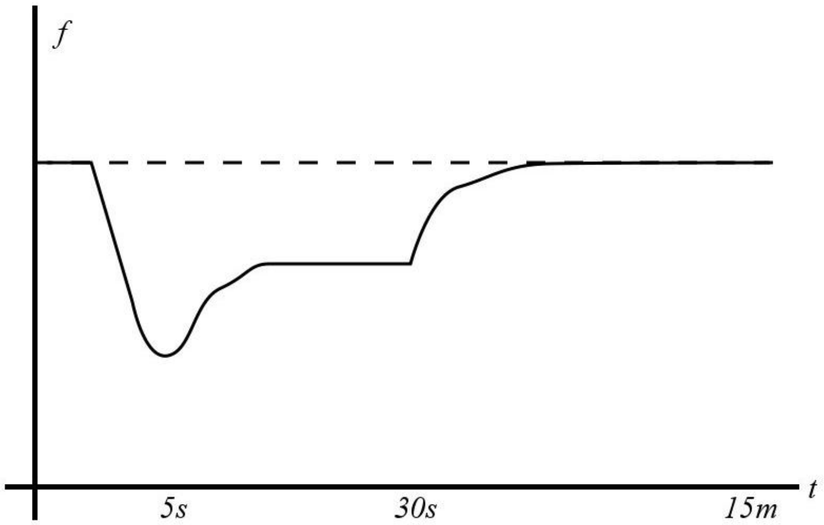

Fig. 1.10. *Primary and secondary control acting on a frequency drop.*

Participation of Wind Power Systems in Power Control

According to the Danish grid codes, Wind Power Plants larger than 1.5 MW must participate in the control of the grid power. WPPs are expected to be able to perform the following functions [8]:

Absolute production limitation, meaning that wind turbines must be able to stabilize themselves around their nominal power;

Delta production constraint, meaning that WPPs above 25 MW must be able to reduce their output down to 40% of their nominal power, if asked by the TSO;

Power Gradient Constraint, meaning that the output of the WPP must not rise or fall faster than a given limit, in MWs per minute. In Germany, for example, this limit is 10% of the WPP's nominal power [1].

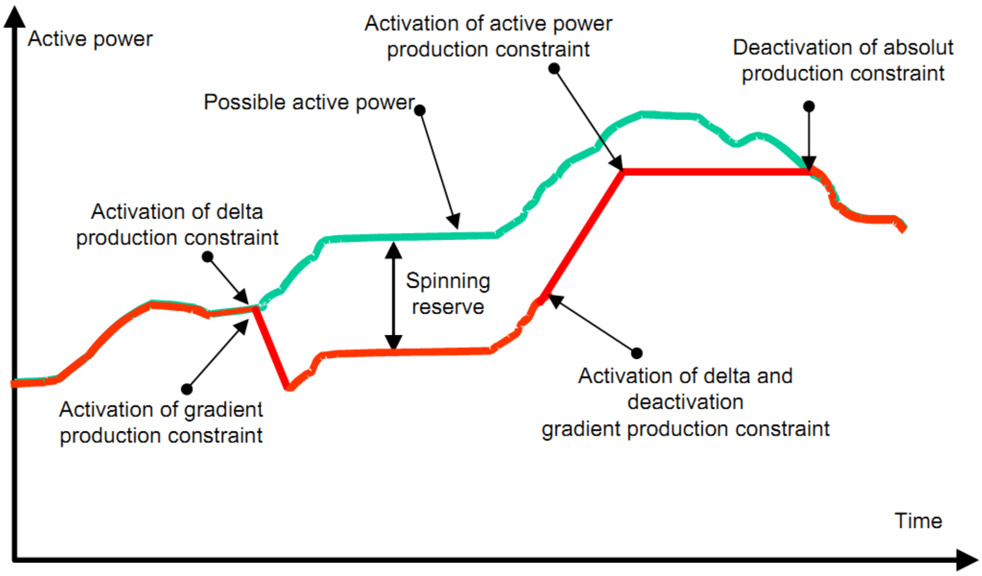

Fig. 1.11. *Example of the production constraints which WPPs must be able to enforce, according to [8].*

These limitations have different priorities, with the purpose of the delta production constraint demand to ensure that the gradient limitations are not exceeded, among others. As seen in the image above, the delta curtailment is enforced in anticipation of a rise in the wind, in order to be able to enforce the gradient limitation. The image above contains a mistranslation from the original document in Danish [12]: when the red signal begins to rise, it is the delta constraint which is deactivated and the gradient constraint which is maintained. The delta constraint can also be enforced under petition of the TSO, in order to allow the WPP to provide some Control Power by function of frequency control. The image below shows a WPP operating under this delta curtailment, and signals the droops which it should be able to perform under different changes of the grid frequency.

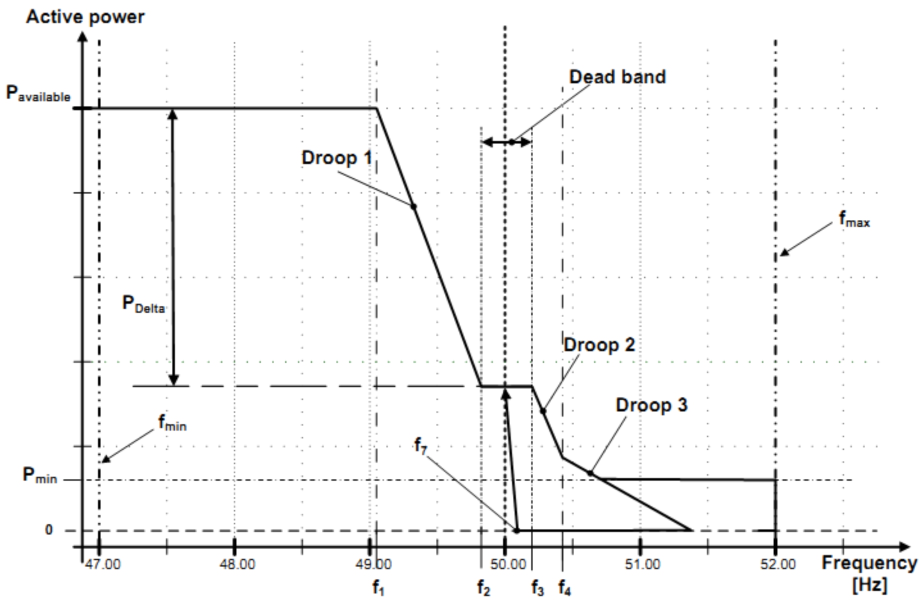

Fig. 1.12. *Frequency Control for Wind Power Plants above 25 MW. [8]*

The image above shows how a WPP is expected to be able to reduce its output as low as 40% of its available power, in order to participate in frequency control. A modern WPP is able to do this by pitch control, by disconnecting some of its turbines, or by overspinning its turbines [13], though possible pitch angles do not exist in a continuous series, and the rate of change of a pitch angle often has a limit of some 6° per second [14]. All of these actions, by necessity, involve a curtailment in the output of a wind turbine, and thus also in the production of a WPP. The TSO in Denmark is required by law to compensate the losses incurred by this curtailment, based on a calculation of what energy would have been delivered and the current Nordpool Spot prices [15]. This will be further explained in the following section.

Reactive Power and Voltage Control

In addition to the active power control requirements, there are also requirements for offering control for the reactive power of the system, as well as the voltage, which is linked to this. While this feat is unattainable for constant speed wind turbines without the help of power electronic devices, variable speed topologies, such as DFIG, have much greater control over the power factor of their production. The Danish grid codes demand that WPPs are able to control their reactive power output Q individually, as well as their power factor, as per the image below, in order to provide capacitive or inductive reactive power.

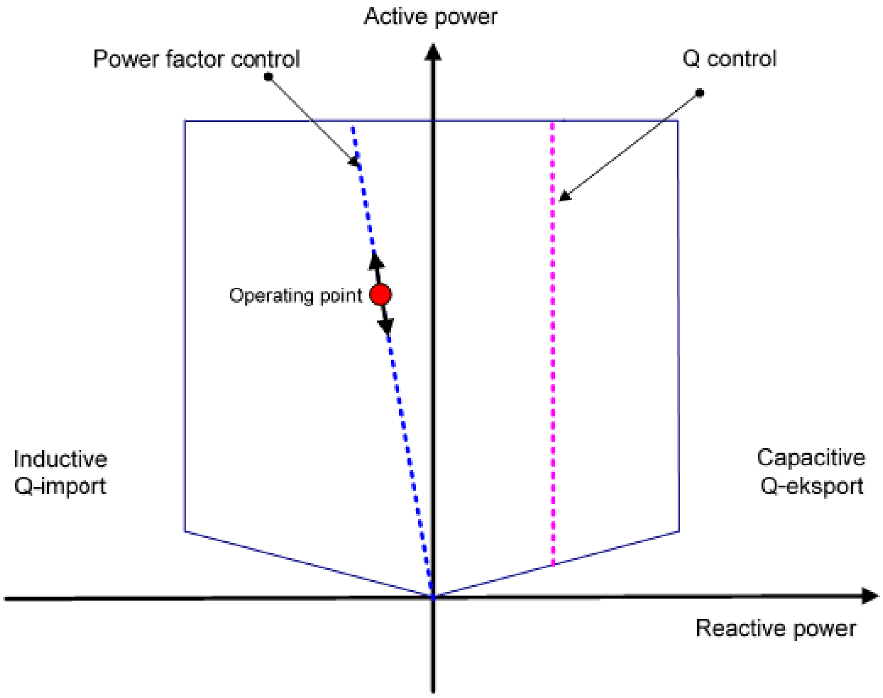

Fig. 1.13. *Reactive power demands for a Wind Power Plant. [8]*

Wind Power Plants must also be able to control the voltage of their output, and be able to operate at different voltage levels. The table below summarizes the different requirements that are imposed on WPP, according to whether they are larger or smaller than 25 MW in nominal power.

Control function	**1.5 MW < P < 25 MW**	**P > 25 MW**
Frequency control (5.2.1) *	-	X
Absolute production constraint (5.2.2.1)	X	X
Delta production constraint (5.2.2.2)	-	X
Power gradient constraint (5.2.2.3)	X	X
System protection (5.4)	X	X
Q control (5.3.1)	X	X
Power factor control (5.3.2)	X	X
Voltage control (5.3.3) *	-	X

Fig. 1.14. *Table showing different requirements, according to nominal power. [8]*

Additionally to the demands shown on the table, there are also demands concerning electric quality, like harmonic and flicker reduction, and system protection mechanisms, which will not be looked at in detail, but can be easily accessed in [8] and [12].

2.2 The Danish Energy Market

The above requirements permit the connection of a Wind Power Plant to the electric grid. It is now up to the optimal operation of the plant and a good market strategy to deliver a maximum profit to the owner. As long as the above cravings are met, the energy produced by the turbines can be sold to the consumers. In Denmark, this transaction is managed through Energinet, the national Transmission System Operator. Furthermore, the price for the transaction is determined by the market situation at Nordpool Spot, the Nordic countries' energy market, where the providers offer their energy and the TSOs post their customer's demands. An inter-daily market, called Elbas, opens when the biddings at Nordpool Spot have closed, with the purpose of trading balancing services. Furthermore, each TSO manages a pool of regulating power, which offers Primary Control Power to keep their individual systems balanced. [16]

In delivering the energy a WPP has produced, a Wind Power Operator must interact with all these markets before it can count its profits. Although changes are occurring to these markets in a push for market harmonization within northern Europe [17], the following can help understand the basic principles of their operation.

Elspot and Bids for Production

The Nordpool Elspot Energy Market manages all international energy transactions in Scandinavia, Finland and Estonia. Wind Power Operators offer at noon their forecasted productions for each hour of the next day, together with the bids of conventional power plants and the demands of each country, as forwarded by their respective TSOs. According to the level of demand, the amounts of power offered by each bidding agent and the prices in which they offer it, the system price for each hour of the following day is determined. It is according to this price that profits for a given operator will be counted.

In the event that a TSO asks a Wind Power Operator to curtail its production, the compensation it will receive will be equal to the production it would have achieved times the current Elspot price [15]. As mentioned in the grid code review above, WPPs larger than 11 kW are expected to either provide their own balancing capability or obtain it through a Balancing Responsible Party. These BRPs will manage a portfolio of different energy sources, in order to ensure that the total output of their clients remains balanced. A scheme from the Danish government in cooperation with the European parliament guarantees a compensation of 0.023 DKK/MWh of delivered energy in order to help with the balancing costs attached to wind energy [18]. Smaller WPOs often choose to interact with a BRP, like an energy company such as EnergiDanmark, which may end up charging less than what the compensation covers [19]. In such cases, the WPO has the option of entering a fixed price agreement, in which the BRP will pay them a fixed tariff for all their energy, independently of the Spot prices. Alternatively, they can choose to deal directly with the Spot prices, which provide greater risk, and simply paying a balancing fee.

Larger WPOs often deal directly with the Nordpool Spot market, and thus must secure their own balancing power.

Elbas and Bids for Balancing

Bids for participating in the Nordpool Spot market must be delivered at noon the day before the operations are scheduled. Wind operators rely on wind forecasts to estimate their production and thus their bids. An overly optimistic bid may leave an operator in the need of purchasing additional balancing power, which is more expensive than the actual price of electricity. An overly pessimistic bid might mean curtailment of wind production for the WPO, and thus a loss of profits. Negative prices for electricity were introduced last year, meaning that producers might actually be charged for producing electricity, in cases of overproduction [18].

The Elbas market opens up at 14:00, after the Elspot market closes, and allows for transactions within the operating day for balancing services. Errors in the forecasts of wind producers must be compensated by purchasing upwards and downwards balancing from third parties. From the grid stability point of view, these services offer Tertiary Control Power, as they operate within the hourly schedule and serve to balance out errors in production in the order of several MW.

The Danish Wholesale Market and Bids for Regulation

Balancing of the system in a smaller time scale is carried out by regulating agents. These players offer an amount of readily-available power to the TSO for primary control in order to ensure that the system frequency remains within ±200 mHz of 50 Hz, that is, between 49.80 Hz and 50.20 Hz. These agents must operate independently of the TSO, that is, no orders will be received from Energinet to start or stop their supply, but must instead rely on their own measurements of the system frequency [20]. Half of the power that they offer must be available within 15 s of a disturbance to the frequency, and the rest should be available within 30 s.

The bidding procedure is as follows. A private actor possesses an amount of fast-acting power that it is able to deliver to the grid instantly, as in spinning reserve. Energinet holds a daily auction to receive offerings for the next day, where actors offer the amount of power they are able to deliver, for up to 15 minutes, and the price at which they are willing to deliver it. The minimum bid is 0.3 Mw, and upwards and downwards regulation are treated separately and thus have different pricings. The price paid to all the participants is the price offered by the most expensive bidder that was accepted. Not all bidders are accepted, as Energinet determines a limited amount of power to be bought each day, and bidders enter starting from the cheapest [20].

Bidders offer an amount of power at a certain price for a different time of day. The day is divided into six blocks, as follows:

Block 1: from 00.00 to 04.00

Block 2: from 04.00 to 08.00

Block 3: from 08.00 to 12.00

Block 4: from 12.00 to 16.00

Block 5: from 16.00 to 20.00

Block 6: from 20.00 to 00.00

A given bid must be deliverable at for the entirety of the block, and the price must be issued for the whole block. The prices are stated in DKK/MW, but are paid hourly, and so may be expressed as DKK/MWh, despite the fact that no energy is being considered in reality. By being accepted for a bid, an actor is responsible for monitoring the frequency under its respective block, and reacting inversely-linearly to changes in the frequency, in order to maintain the frequency within the requested limits. The actor must be able to provide the stated power for 15 minutes, until secondary control power enters to relieve it. The task of primary control is to bring the frequency back to the boundary of 49.8 and 50.2 Hz. It is the secondary controller’s task of returning it to precisely 50 Hz. The performance of the regulating power control can be monitored by Energinet, to ensure the functioning of the controller and delivering of the power.

3. Problem Description

Now that an overview has been given of the wind energy scenario in Denmark, the challenges with wind integration in the future can be better appreciated. This allows for the presentation of the problems that will be addressed in this project.

The increasing penetration of wind energy into electric grids threatened the system's stability, due to the wind's inherent variability. For this reason, TSOs must increase the balancing and regulating reserves, and grid codes are becoming more demanding for the operation of wind parks. Such requirements might become chocking for the continuing development of wind energy, unless wind parks can provide their own balancing needs, at the same time as they deliver maximum profits to their owners. A possible solution to both problems could be found in the application of Energy Storage Systems (ESSs). These could allow wind production to go – to a certain extent – uncurtailed, while ensuring a regulated power output. Ideally, the usage of ESS could allow to eliminate the need for wind curtailment while providing the needs of a WPP for regulation – by providing its own primary control – and to reduce its dependence on the accuracy of wind forecasts – by providing balancing services. While under present conditions in Denmark, with the flexible market operations and the government balancing subsidies, such a storage might not seem necessary, wind energy must become a more solid and independent option, in order to be more easily introduced to other markets.

The main objective of this work is

To assess the technical and economic feasibility of services that an energy storage system could provide for a wind power plant.

In order to fulfill this objective, several intermediate steps must be taken, in terms of research, simulation, and benefit analysis. The following section describes the steps and milestones for this project.

3.1 Methodology

The first section of this work focused on describing the situation of wind in Denmark, from a technical perspective. Now that a possible solution to the needs of a Wind Power plant has been suggested in the form of energy storage, the different technologies available will be analyzed in Chapter 2. Potential services will also be reviewed. An important milestone is then

To identify the most adequate technologies and the most useful and needed services for Wind Power Plants in Denmark.

Afterwards, to ensure that such services can be provided by a given ESS, the interaction of a Wind Power System, the grid and the storage system will be modeled. Chapter three will address this task by modeling the system with the help of a Real Time Digital Simulator (RTDS). An important milestone in this stage is

To model the execution of these services, to ensure their technical feasibility.

Once the technical possibilities have been explored, the economic impact of each service will be assessed. This will take place both in terms of the size, cost and lifetime of the required ESS and the monetary gain that providing such a service would allow. The objective of chapter four will be

To identify the most profitable service or mix of services to be provided, with the most adequate technology, and to determine the expected benefit of performing said services.

Finally an optimal control for the BES will be determined, based on the findings of the previous sections, in order to maximize the benefit of its application.

3.2 Limitations

There are many aspects that, for practical reasons, will not be considered in this work. Likewise, many assumptions and simplifications must at some point or another be taken, in order to arrive to any concrete conclusions. The effects of these assumptions and limitations will of course affect the applicability of the conclusions. The different limitations, assumptions and their effect on the conclusions will each be discussed at greater length when they are more relevant to introduce, but will first be gathered here, for simplicity's sake.

Although different types of Energy Storage Systems are suited for different applications (as will be explained in Chapter 2), the focus of the work will be on Battery Energy Storage systems, specifically Lithium Ion cells. The services to be provided are therefore selected around the properties of this ESS technology. The benefits of different services will be discussed, but it is the point of view of the Wind Power Plant Operator which is mainly considered to decide whether a service is beneficial or not.

When modeling in the RTDS, a system must be assumed. The size and characteristics of the Wind Power Plant, the size of the grid and loads and the transmission capabilities of the lines must be defined. These values were chosen to be as realistic as possible, but their possible influence on the results must be taken into account.

In designing the controller and defining the services, only active power control was considered. Although a BES could provide some reactive power control with an adequate power electronics setup, it is in active power where its main strength lies, and thus the only one considered.

When researching the benefits of a particular service, the cost of the ESS and its Operation and Maintenance costs must first be calculated. A cycle-counting algorithm was combined with manufacturer data to estimate the approximate life expectancy of the cells. Likewise, when calculating the profit achievable from a given service, it was necessary to rely on the available data. A year-long wind power signal with a resolution of 1 minute was available. In the case of forecast signals, and electricity price signals, the resolution is, for reasons related into how these signals are provided, of one hour. The price signals come from the year 2010; the wind signal is from an unknown year. Both years are assumed to be typical.

Chapter II. Energy Storage Technologies and Applications

In the previous section, Energy Storage Systems were proposed as a possible aid in increasing the reliability of Wind Power Plants. In this section, an overview of the different technologies of ESS will be presented, as well as of the possible services they could provide to a network. The last part of this chapter summarizes the selected services to be considered, as well as the specific technology that will be modeled for the benefit analysis.

1. ESS Technologies

There exist many different techniques for storing and delivering energy, and their different properties allow for different applications and demand different restrictions. Fast acting technologies often offer low energy capacities, but are able to provide quick bursts of high power. Some technologies are easily scalable and some require very specific geological conditions. Technologies can usually be classified as power applications (providing large amounts of energy for a short time) or energy applications (providing scalable amounts of energy for longer periods of time). The classification to be followed in this section will instead focus on the mechanisms behind their operation, that is, mechanical, electromagnetic or electrochemical. Overviews of this kind are common in the literature, as in [21], [22], [23], [24] and [25]. The operational basics of the technologies have not changed, but price approximations have been taken from the newest sources, and must be taken as an estimate.

1.1 Mechanical Energy Storage

Devices which use kinetic, potential or rotational energy to store and deliver power are classified in this section.

Flywheel Energy Storage (FES)

A motor adds rotational energy to masses in a shaft with precautions taken to reduce friction, such as operating in a vacuum or using levitating magnetic bearings. This allows a high round trip efficiency, of around 90% [23]. Larger masses and speeds allow for larger amounts of energy, but in any case the delivery time, where the energy is used to drive a generator, is highly limited to short durations. In a large scale, this technology could be very useful in applications like frequency control and output smoothing, thanks to its fast response time. FES with 20MW have already been proposed for frequency regulation [24]. The price of this technology is around 350 €/kW for power, but the price of energy capacity can vary between 200€/kWh and 3100€/kWh, depending on the technology being used. [21]

Compressed Air Energy Storage (CAES)

With this technology, air is compressed into underground caverns (or, potentially, storage tanks) when charging. The pressurized air can make the combustion of a natural gas turbine much more efficient, increasing its power output, as no extra energy is needed to compress the air. The output of the turbine is three times what it would be without the CAES support [26], leaving the overall efficiency of the process at around 70% [27]. In this way, it can be seen as a kind of energy storage. Although the technology is not new, there exist only two such installations so far, though some others are under development. The existing plants (a 110 MW plant in the US and a 290 MW plant in Germany) pump air into underground caverns during off-peak hours, mainly to support slow-acting nuclear power plants in the network [26].

Operating in the same manner as a natural gas turbine, the applications most suited for this technology are load following, time shifting intra-hour balancing (such as secondary power control). The output power of the plant depends on the size of the gas turbine, while the capacity depends on the attainable pressures and amounts of air stored. As few examples of this technology have been constructed, and the construction possibilities and costs depend greatly on geological locations, the price estimates give little information. The price of power is around 480 €/kW, while the price of energy is around 160 €/kWh [21].

Pumped Hydro Energy Storage (PHES)

Pumped Hydro Energy Storage relies on using a pump to increase the potential energy of a body of water, by moving it up to a reservoir, a dam or a water tower. During discharge, the water is fed down to a hydro-turbine, generating electricity. As this technology relies very heavily on the availability of such a reservoir, it is only practical where such a condition already exists, or else the installation costs would be exorbitantly high. On the other hand, with the low price of water, the capacity is limited by the size of the reservoir, and the larger this one is, the lower the capacity price will be. The efficiency of this technology is around 80%. [25]

Price estimates are around 480 €/kW for power and 6 €/kWh for energy. The response time of less than 15 minutes, the high possible power levels and the very long delivery time makes it ideal for intra-hour balancing, load following, time shifting and providing a base load. [21] [25]

1.2 Electromagnetic Energy Storage

These technologies make use of the electromagnetic properties of current flows, relying heavily on solid state technology to hold or delay power flows.

Supercapacitors

Using the same principle as a normal capacitor, two parallel plates accumulate charge and then discharge when needed. The charge captured can be increased by adding liquid electrolytes or polymer membranes at the interface. Supercapacitors have a long operational lifetime, with more than 300,000 cycles, and a high efficiency of 80-90% [21]. Very low energy density and short delivery times means that they are most useful in reducing transcient imbalances, or for delivering short bursts of energy – like when starting up a diesel vehicle [27]. Costs are around 190 €/kW for power and 9,400 €/kWh for energy. [21]

Superconducting Magnetic Energy Storage (SMES)

Analogous to the supercapacitor, the SMES uses a superconducting coil and the properties of current to create a strong magnetic field. This field can then be used to discharge current off of the coil. Refrigeration techniques are used to keep the temperature low, increasing the already long lifetime of the system [22]. This technology has very high efficiency (above 90%), lifetime and reaction times, but, like the supercapacitor energy storage, low energy density and high energy costs. Its properties make it ideal for industrial power quality and short-time scale voltage sags. [21]

1.3 Electrochemical Energy Storage

These technologies make use of the Gibbs free energy of a chemical reaction to generate an electric current. The reaction must be reversible, or the reactants must be easily produced, in order to "charge" the storage system.

Hydrogen Fuel Cells

An electric current can be used to drive an electrolytic process, and dissociate hydrogen from water. The stored hydrogen can then be processed through a fuel cell, which makes use of a special membrane (called Proton Exchange Membrane or PEM) to cause a current during the recombination of hydrogen and air into water and other compounds [21]. Recent interests in fuel cells have driven the prices down, especially as interest grows in small, mobile fuel cell systems for automotive purposes. The US Department of Energy estimates the cost of power at 42 €/kW, with the capacity depending on the hydrogen storage tanks available [28]. However, for consideration as an ESS, the plant must also be able to produce its own hydrogen from an electric current, which implies a higher cost per kW, not counting the cost of storage tanks.

Fuel cells have fast response times, but not very high power or energy densities. Both the fuel cell and the electrolytic process to extract hydrogen from water have low efficiencies in comparison to the other technologies. Scaled up systems could provide secondary frequency control and time shifting [21].

Flow Batteries

Flow Batteries are the interface between a fuel cell and an ordinary electrochemical cell. The two compounds whose transformation releases or absorbs energy are stored in liquid form in tanks, the formation of one into the other consuming energy, and the recombination releasing it. Like fuel cells, they suffer from low efficiencies and energy densities. Like fuel cells, they have the advantage of a very large storage capacity, limited only by the size of the containing tank. They have a much longer lifetime than normal electrochemical cells, with up to 10,000 full charge and discharge cycles. Different technologies exist, with different power prices, ranging from 500 €/kW for Zinc Bromide flow batteries to 1,400 €/kW for those that use Vanadium Redox. Their applications are similar to fuel cells, able to cover a variety of time ranges and power demands depending on their scale.

Electrochemical Cells

There exist many different technologies of electrochemical cells, all functioning on the basic principle: the flow of electrons due to a chemical potential unbalance. A cell consists of two electrodes separated by an oxidizing electrolyte. Ions of the reacting metal travel through the electrolyte, while electrons flow through the terminals, creating a voltage difference. Cells in which the reaction cannot be reversed are called primary cells, while cells in which reaction can be reversed are called secondary, or rechargeable, cells [29]. A number of technologies has been developed throughout the past, including lead acid, nickel-cadmium, sodium-sulphur and many variations of lithium ion. These technologies vary in cost, cycle life, energy density, operational temperature and environmental impact.

Lithium ion is a current favorite for development in electric vehicles, as it offers a long lifetime and steady output, at the same time as it has a smaller environmental footprint than cells with lead or cadmium. Especially cells build with Lithium Iron Phosphate and Lithium Titanate present a particularly good prospect, as they have a long life and are relatively safe from fire and explosions [30]. These technologies possess an energy density sufficiently high for use in automotive purposes, as well as a fast response time. Further development into electric vehicles could drive the costs of this technology further down. In the meantime, prices can be as high as 567 €/kW for power and 3,400 €/kWh for energy, in the case of high-quality lithium iron phosphate cells, as estimated from the available model.[31][32]

2. ESS applications

There exist two basic actions that an energy storage system can perform: charging and discharging. The time scale, pattern and purpose of these charges and discharges are what differentiate a service from another. Furthermore, these services are also called by different names when performed by different actors. Previous reports, such as [24] and [33], offer very detailed analyses of potential services, categorizing them differently if they are from the different actors' perspective. This work will instead attempt to categorize the services according to the charging and discharging patterns, the magnitudes and the response time required, and then explaining how different actors can use them to their advantage, with a focus on Wind Power Operators.

Services can be power-based (demanding high power for short times) or energy-based (demanding long times at steady power). Services can also call for fast response times, or a large capacity without much actual energy usage [33].

2.1 Time Shift

In a market-based electrical grid, system prices vary hour to hour to reflect changes in demand and supply. Prices are directly proportional to demand and inversely proportional to supply. From the WPOs' point of view, production is not always matched up with demand, and may take place when prices are low, as can be seen in the image below.

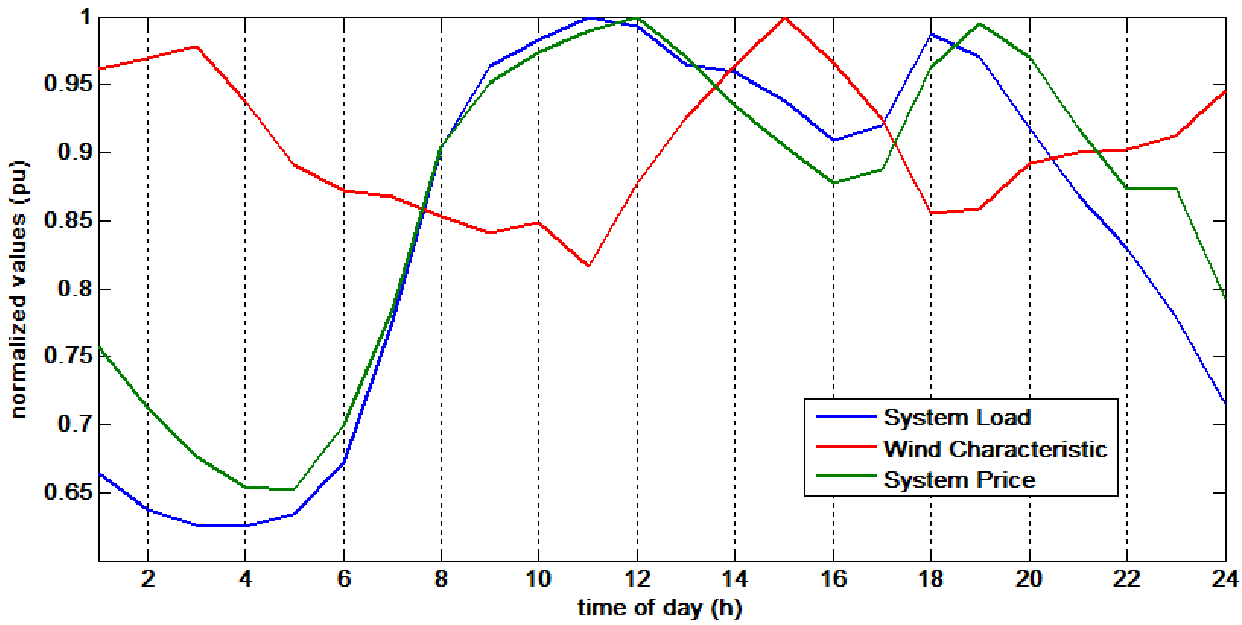

Fig 2.1. *Daily system load, price and production for a wind farm, normalized to mean values. Data from [16]*

An ESS could potentially exploit this price difference. The system could charge during the hours of low demand and low prices and discharge during the hours of peak prices. This application will be successful in proportion to the scale of the ESS power, starting from a few MW. The delivery time must be at least of one hour and be reported the day before, in order to be able to enter the bidding at Nordpool Spot [34]. When done with this purpose, time shifting is known as Energy Arbitrage (EA).

The ESS can perform a similar service for the end-user, by charging during the nights and discharging during the day for private usage. This will reduce the need to buy electricity at the hours when it's most expensive. In this case, the scale of the ESS depends simply on the needs of the end-user: industrial users might still need power in the scale of MW, while private persons probably require a lot less. Residential consumption has the added advantage of not having to report their expected consumption, and thus offers more flexibility on deciding whether to charge or not. When done by the end-user, time shifting is known as Time-of-Use energy cost management [33].

From the perspective of the WPO, would be performed in the same way as Energy Arbitrage, as described above. During times of low system prices, when wind production is ostensibly high, charging can take place. It could be argued that the cost of charging would be lesser if the WPO had purposefully reported a lower production for the following market day, knowing that the ESS would charge a given amount at a given time. However, the energy that would be diverged from the WPP to the ESS could have also been sold to the system. From the point of view of the WPO, the cost of charging the ESS is the profit lost from not selling that same energy to the system, and thus indistinguishable from the system price. In this way, the service is basically a way of EA. The ESS size requirements then need not be attached to the size of the WPP, apart from considerations related to plant's transmission capabilities.

The long delivery time and the potentially large power scales limit the technologies that could effectively provide this service. Energy-based technologies, like CAES and PHES are ideal for this purpose, but flow batteries, large fuel cell plants and battery energy storage systems could also provide this service, albeit at the cost of deep cycling, which greatly affects their expected lifetime and therefore the potential profit of this activity [27]. It is also important to consider the efficiency of the technology being used, as it greatly affects the profits attainable.

2.2 Expansion Deferral

Energy Storage Systems have also the potential of becoming intrinsic parts of the distribution grid, as necessary as transformers and lines. Given a weak section of the grid, with few generating units and poor transmission capabilities, an ESS could strengthen the area, and defer costs of expanding the grid or installing new generation units. From the point of view of the TSO, an ESS could be used as Transmission Expansion Deferral, if its installation saves the TSO from having to install new (or replace the existing) lines.

If an area's peak demands begin to approach the transmission system's limitations, an ESS could be installed on the area's side. The system could charge during off-peak demand times, and provide the area with energy during peak times, when the transmission system is already at its maximum capacity. Alternatively, if a generating unit was being considered for the same purposes, an ESS could be used for Generating Capacity Deferral. The ESS would charge during off times and help when the power demands reach existing generating units' limits. The size of such ESS would be defined by the needs of the grid in that area, but would probably be in sizes >1 MW, with delivery times in the scale of 3 to 6 hours [33].

Large industrial end-users are often charged fees according to their peak demands. Using an ESS in a similar way could reduce their peak needs, and thus their electric bills. While this might not seem an identical service to the ones above, it is very much related, at least form the point of view of the TSO. Expanding a grid area's transmission or production capabilities is required when the demands of the area cannot be met by the current supply. In all these cases, an ESS is being used to secure the supply of the area, either by increasing energy reserves in the area for times of peak demand, or by reducing the peak demands of the area. The purposes and benefits from providing this service makes it of interest only to TSOs, and so will not be included in further analysis.

Like in Time Shifting, the long delivery times make CAES and PHES ideal for this situation. However, the nature of the problem implies that the area is already not strongly connected. Therefore, small BES, flow batteries and hydrogen fuel cells can prove to be more useful, as their small scales and high energy densities allow for smaller installations [25].

2.3 Load following

The bulk of power delivered in a grid comes from large power plants catering to the base load, CHP units, in Denmark. The variability of these plants is limited both by the technical parameters of the generators and by the fact that they are used both to provide heat and electricity, and as such cannot simply be turned off. In addition to these units, smaller gas turbines are used to supply the peak load, performing what is known as load following. As the day starts and demand grows, these units ramp up to keep up with the load. During the late evening, as demand drops, they lower their output. The fact that wind energy often has a very different profile – that is, falling throughout the day and rising in the afternoon – means that the gradient that must be followed by ramping generators is even steeper, which can cause increased wear and tear [33].

Energy storage could help reduce this mismatch, by discharging or charging in order to counteract the gradients between wind energy and load. The approach is the same, whether the ESS is owned and managed by the WPO (for the purpose of making its energy output more valuable) or by a Balancing Responsible Party, as part of their balancing portfolio. The size of the storage required for such an activity implies a storage time of between 2 and 4 hours, in reference of the time it takes for the load to fall and rise to its maximum every day [33]. The size of the storage depends, again, on the system and the properties of the grid, but some estimate place it around 25% of the installed wind capacity, in case it is being operated to counteract wind variations. [22] [27]

2.4 Power Reliability and Quality

Many services fall within the category of power reliability and quality. Already, industrial consumers who require very high quality current, such as steel mills, make use of fast acting energy storage to secure that their electricity is free of flicker and has low harmonic distortion. Supercapacitors and flywheels are used to ensure that the power supply remains constant, with voltage and frequency levels within the optimal operational points. Longer acting ESS technologies can provide Uninterruptable Power Supply, which guarantees some continued operation in the event of a shortage or a fault. In these cases, the ESSs are serving the end-user keep a stable and high-quality power supply.

Wind Power Plants should strive to be able to provide just such a service, and the application of similar energy storage techniques could be a vital step in this direction. Fast acting energy storage could help smooth out fast variations in the power output. As the variations move in the time spectrum from a few seconds to days or seasons, they move as well in their magnitude, becoming more and more oscillating until they span the whole of the wind plant's capacity [4]. As part of an interconnected grid, power reliability means an UPS for 15 minutes to 1 hour [33]. In islanded situations, the UPS should be able to operate ceaselessly.

2.5 Active Power Capacity firming

What is meant by capacity firming is any action which stabilizes the output of a Wind Power Plant. From the perspective of the TSO, a lone wind turbine is seen more as a negative load than an actual generating unit, as its power capacity is too variable and volatile. For the purposes of this work, volatility will be understood as changes within a time scale of a minute or a couple of minutes, while variability will be understood as changes within an hour or a couple of hours, as defined by [33]. There is not much that can be done about the variability in the wind, but this is not an insurmountable obstacle for its integration in the grid. As has been explained in the previous chapter, the energy market Nordpool Spot accepts hourly bids for wind power production, which WPOs deliver 36 hours in advance based on weather forecasts. As long as a WPP can keep its hourly production within the values forecasted, there will be little problem within the perspective of daily variability. Misestimations of wind production can be complemented with the inter-hour market, Elbas, where upwards and downwards balancing services are negotiated by Balancing Responsible Parties, albeit at higher prices than the system price of electricity [35].

An ESS could provide the same services as these BRP do, Active Power Balancing, without the need of operating as a profit. Modern forecasting methods have accuracies with less than 10% of the nominal power as error, even 36 hours after the forecast was performed [36]. Individual mistakes can, of course, be much higher, but the precision of the forecast limits the required energy capacity of the ESS. Previous estimates place this at around 25% of the nominal WPP capacity with a discharge time of 1 hour [27]. ESS technologies able to deliver this service include fuel cell plants, flow batteries and BES.

Regarding the volatility of wind power, it must be said that the greatest part of variations that are faster than a few seconds, and which are present in the wind, can be eliminated if one accounts for the large mechanical inertia present in the massive modern wind turbines. Volatility is further reduced if a wind park is considered, as the distribution of turbines within the park means that variations cannot affect them all simultaneously. Even so, the operation of a grid, with or without a high penetration of wind power, necessitates the presence of regulating capacity. In Denmark, this is achieved with the help of the Danish Wholesale Ancillary Market, where Energinet manages its regulating need. Every day, Energinet publishes the amount of Control Power (CP) it has estimated it will need for the next day, as a *Reserveauktion*. Providers of spinning reserve, power that is connected but unloaded, submit bids to supply this CP and are taken in starting from the cheapest, until the need is met. Generating actors then pay Energinet a fee for the balancing power that their production necessitates [20].

Wind Power plants could become more attractive options, easier to integrate into the grid, if they could take care of their own balancing and regulation. In this time scale supercapacitors, flywheels or BES could provide the primary control needed, acting as a sort of spinning reserve [37]. In volatile times the ESS could service the WPP, providing Active Power Regulation, and in calmer times offer its regulation to the grid or other actors. Energy needs would be around one minute, and no longer than 15 minutes, which is the boundary for secondary control. Integrating secondary control into the requirements would imply higher powers and up to an hour of delivery time [20].

3. Selection and justification

It is clear that, due to different characteristics of power demands and delivery time, not all technologies can satisfy the needs of all services. In this section, a specific technology to be examined and simulated will be selected, together with the services which it would be able to provide for a WPP. Afterwards, the ability of the selected ESS to fulfill these services will be examined, before assessing the potential benefit of providing them.

3.1 Technology selection

Energy storage is already a reality, embodied in several installations throughout the world. As mentioned before, two CAES plants exist already for load following, though they mostly cater to nuclear stations. In Norway, pumped hydro is already used for balancing long-time scale variations of wind production, transmitted from Denmark [2]. However, it is nonsensical to contemplate a PHES for every WPP. A sort of fuel cell plant operation exists in California, where power from wind turbines is used to produce hydrogen, which then goes on to power an experimental fleet of buses [38], though the only actual service this system provides for the WPP is downwards regulation, as no energy can be delivered back into the grid.

An Energy Storage System that does interact with the grid is being planned in the US-Mexico border, south of California. A massive 1 GW BES system, based on sodium-sulphur (NaS) technology would provide regulation and balancing for the renewables in the area [38]. However, NaS technology is not as environmentally friendly as other technologies, such as lithium ion [30]. This last kind of cells has a bright future ahead of it, if development into electric vehicles equipped with this technology continues. Lithium iron phosphate technology (LFP) in particular shows promise, as it has a longer cycle life than other lithium cells, as well as decreased risk of accidents [31]. It is therefore this technology which will be selected for modeling, as well as for cost and lifetime calculations.

3.2 Service Selection

The possibility of services to be offered is now limited by the selected technology. Based on the characteristics of each service presented in the previous section, as well as on the needs of Wind Power Plants explained in the first chapter, the following services will be assessed for their potential benefit.

Active Power Balancing

The service of Power Balancing for Wind Power Plants implies using an ESS for the purpose of reducing or eliminating the need for external balancing power due to forecast errors. At present, WPPs incur in costs when they must purchase upwards balancing power or from lost profits when they exceed their planned output and must curtail their production. Curtailment under command of the TSO for system balancing reasons would still be effectuated and compensated as the regulation directs it [15], even though the ESS would be charging at the time. Using an ESS for Power Balancing might reduce the need for external balancing power purchase, and the power that would have been curtailed can instead be used to charge the system and delivered at another time. The expected benefit will come in the form of reduced operating costs and reduced loss of profits.

Active Power Regulation

An ESS could act as part of the Danish Wholesale Market, by offering its regulating capabilities. In this way, the WPP could become a self-standing generating unit, with no need for external power regulation. In performing this service, the ESS would act as a spinning reserve, changing its output to match changes in frequency. Only primary frequency control is required to participate in the regulating market, that is, an inversely linear control. Larger ESS could also provide secondary control by incorporating an integrative controller, though this might seem more appropriate where no other balancing units exist, such as in microgrids or islanded grids. It is assumed that the above "Active Power Balancing" service incorporates, in larger or smaller degree, active power regulation. The purpose of the separation is to examine the individual benefit of offering this service to the Danish Wholesale Market, instead of purely for regulating a WPP's output. The expected benefit would come in the form of paid bids, from participating in Energinet's regulation market.

Time Shifting

As explained above, whether a WPP uses its own energy to charge a ESS or whether the ESS purchases this power form the grid is irrelevant, as any energy that the WPP devotes to this activity could have instead been sold for the same cost of charging it. Therefore, time shifting done for the purpose of delivering wind energy at times where it is more profitable is undistinguishable from energy arbitrage, which is merely the charging at low system prices and discharging at higher ones. The expected benefits from this service would come as profits from the trading of electricity in the temporal dimension.

Chapter III. Modeling and Simulation

In this chapter, the system to be simulated is explained. Simplified models for each component are introduced and explained, as well as the controller for the energy storage. Results of the simulation are also shown, to examine the ability of the energy storage to respond to changes in grid frequency.

1. System Description

Of all the services that were chosen for consideration in the previous chapter, there is only one that warrants a detailed modeling. In cases where the response time of the energy storage is counted in minutes, or where the delivery time is considered in hours, it is only a matter of examining the size of the ESS (its power and energy capacity) in order to determine whether or not it would be able to provide such a service. Among the services selected, which are suitable for a battery energy storage, whether one is considering forecast improvement, time shifting, energy arbitrage, or primary control, the principle is always the same: the BES can either charge or discharge, in different magnitudes and for different periods of time. It is only in this last case, primary frequency control, where the response of the controller exhibits characteristics interesting for studying. It can be taken for granted that, if a BES is fast enough to perform primary control, then the only limitations it could face in performing other services are related to the amount of cells available.

In order to explore the ability of a BES in performing the services selected in the previous chapter, it is only required to test its ability to provide primary control. In order to do this, a hypothetical system must be first devised.

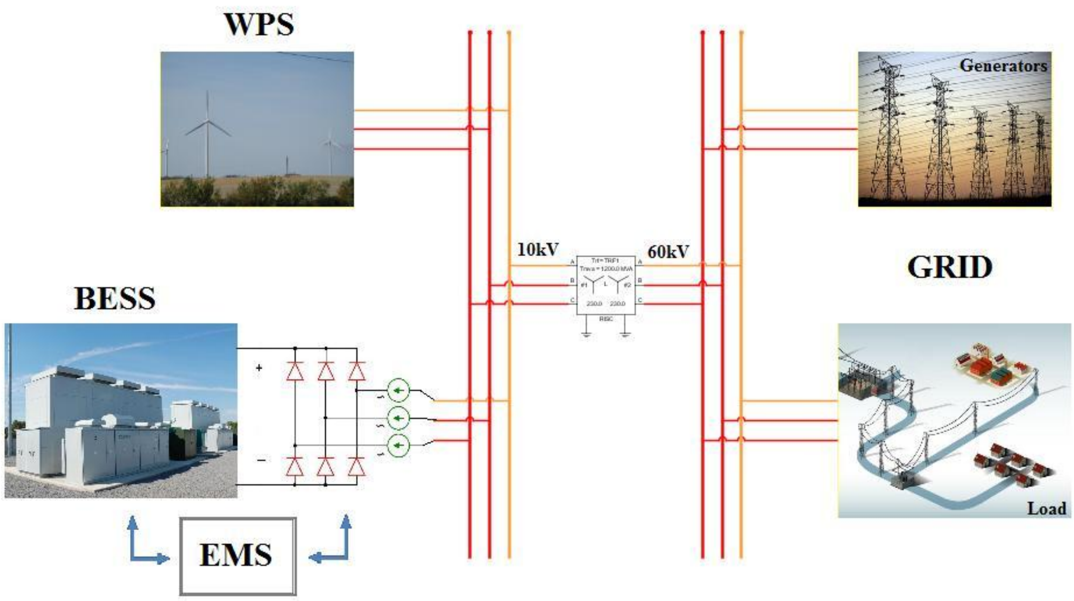

Fig. 3.1. *Block representation of the system under study.*

The system modeled consists of a Wind Power Plant with a Battery Energy Storage. These two components share a Point of Common Coupling, at their end of a 10/60 kV transformer that connects them to the rest of the grid. The scales chosen for the WPP capacity in relation to the grid and to the ESS where done so with the objective of making a disturbance of the WPP noticeable in the frequency of the grid. Likewise, the size of the ESS must be so that it is able to compensate, at least partially, for sudden changes in the WPP. A value of ¼ of the WPP nominal power has been suggested and explored before, in [22], [27] and [39], as being more than adequate even for more demanding services than primary control. Therefore, the WPP is scaled at 100 MW, representing a large collection of wind turbines, and the ESS has a maximum value of 25 MW, though it is scalable by changing the number of cells and the maximum current allowed. The grid operates at a load of 1000 MW, delivered by generators operating below their maximum capacity. The load, as well as the reference for the WPP, is modifiable to simulate imbalances in generation/demand. The voltage levels of the buses were chosen to be 1 kV within the WPP, 10 kV in the collecting bus of the WPP and the ESS, and 60 kV in the grid, corresponding to a mid-level distribution system in Western Denmark.

The platform chosen to perform the modeling is RSCAD, an EMTDC related software developed by RTDS technologies, for use with their RTDS (Real Time Digital Simulator) computing system. The RTDS technology was developed by the Manitoba HVDC Research Centre, as a way of simulating power systems and machines in real time. RSCAD uses a very similar method of building the system as its sister PSCAD, but all of the actual simulation is performed by the RTDS machine, equipped with up to 6 GPCs (Giga Processor Card) per rack. The real power of the RTDS is the ability of allowing input and output signals of the system to interact with real life equipment.

Fig 3.2. *Image of an RTDS rack system.*

In the system to be modeled, for example, one could output signals representing the grid frequency, or the current passing through the BES. These signals could then be processed through an external controller, or fed directly into a real cell (provided an adequate amplifier and load were present). The developed model is thus a first step, in a potential simulation system for subjecting batteries to actual current flows, resulting from providing a given service.

2. Modeling

It is a necessary step in any engineering endeavor to simplify a complex problem into a more manageable situation, while maintaining all the properties of the original one so that conclusions can retain their validity. The RTDS is powerful enough to simulate very large systems with little or no need for simplification, and the prebuilt machine and line models are very detailed. The main limitation is then the detail that the simulator requires and the number of GPCs. The time resolution is also a relevant aspect. In order to model very fast phenomena, such as switching in a converter and pulse width modulation, the RSCAD divides the system into “large” and “small” time steps, consisting of around 50μs and 2μs, respectively. This will become important when choosing whether to model an actual converter or just a simplification of the same.

2.1 The Wind Power Plant

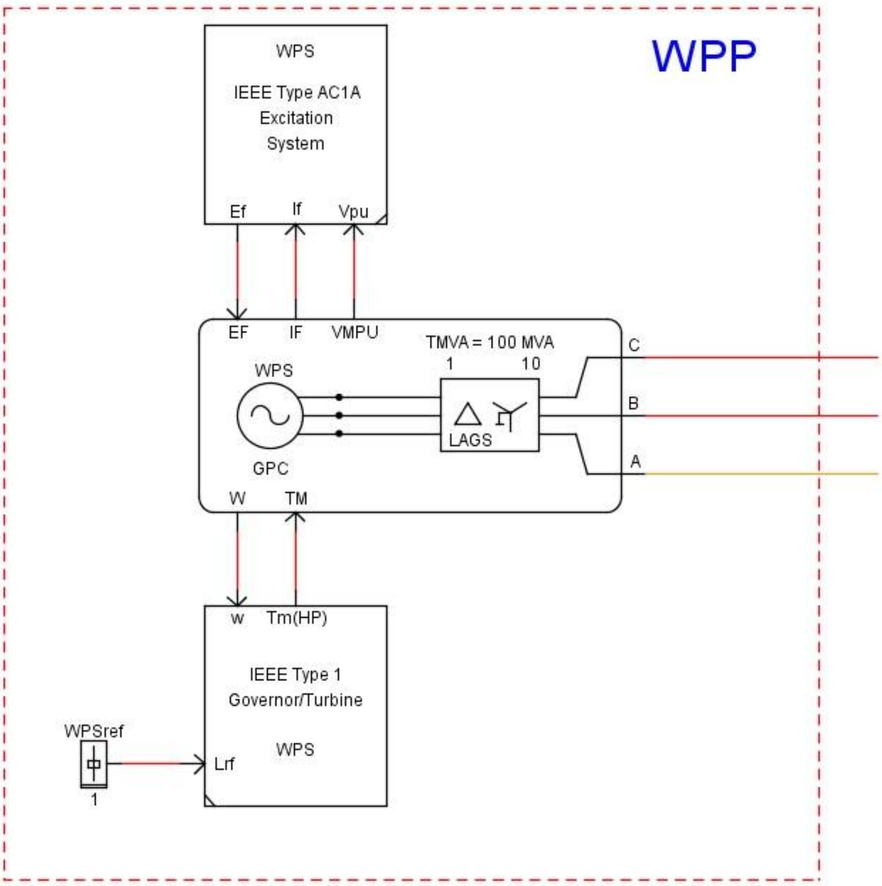

Fig. 3.3. *Block system representation in RSCAD of the Wind Power Plant*

With a size of 100 MW, the Wind Power Plant is very obviously not a single wind turbine, but a large wind farm. Although the output power from a turbine differs from that of a wind park, not only in magnitude but in the distribution of variations, for the purposes of this simulation, the aggregate signal of the wind park will be modeled by a single very large turbine. As the model permits controlling the inertia, power output, and response times of an individual generator, it can be assumed that the output of a synchronous generator with a variable load reference can be used to model such a park.

The uppermost block controls the excitation current for the generator, as well as offering voltage control. As this is of no interest to the work at hand, due to the limitations of the project, it was left to act in the automatic setting, with no control or customization from the user. The middle block receives the excitation current from the upper one, as well as the mechanical torque from the lower block. It outputs a three phase signal, at a voltage level of 1 kV. The block has an integrated transformer, which raises the voltage to 10 kV, which is the level that the collecting bus has. The lowermost block represents the governor for the system. It receives the rotational speed of the generator and compares it to the reference of 50 Hz. The block was customized so that it receives a load reference in pu from an outer source. In the model, this is merely a slider which allows the user to set the operational point for the WPP, but it could also be controlled externally from an input signal to the RTDS.

2.2. The Grid

While from the point of view of the WPP and the ESS, all that is perceivable is a connection to the grid with a given voltage, frequency, power and power factor, it is necessary to model an actual pseudo-grid. This is achieved by means of two generators and a variable load. The load is modeled as a three-phase variable resistance. The value of this resistance is calculated so that the consumption is easily modifiable by the user. The default value is 3.81 ohms, which at 60 kV corresponds to a demand of 945 MW.

The bottommost generator functions with the same components as the WPP, with the difference that the controller in the governor has been modified to act as a simple droop control. This generator represents the peak generator, and is therefore smaller than the base generator at 200 MW. Its operational set-point is 100 MW. Being droop-controlled, in event of a change in system characteristics, such as a change in frequency, it will either increase or decrease its output inversely linearly to the change in frequency, but will not attempt to set a new operational point.

The topmost generator takes care of the base load, and is scaled at 800 MW, though its default operational set-point is 750 MW. The governor and generator parameters have been modified to reduce the response time, increase the inertia, and add the possibility of externally controlling the load reference. This is required because, being that all the other generators are acting either on droop control or on a fixed load reference, an integrative controller is required to balance the system, in case of a change in the load. If the user wishes to model such a case, the load reference for at least one of the generators must include an integrative controller.

These three elements are gathered in a 60 kV network, equivalent to that of a distribution system in western Denmark. This bus is connected through a wye-wye transformer to a 10 kV bus, which contains the WPP and the ESS.

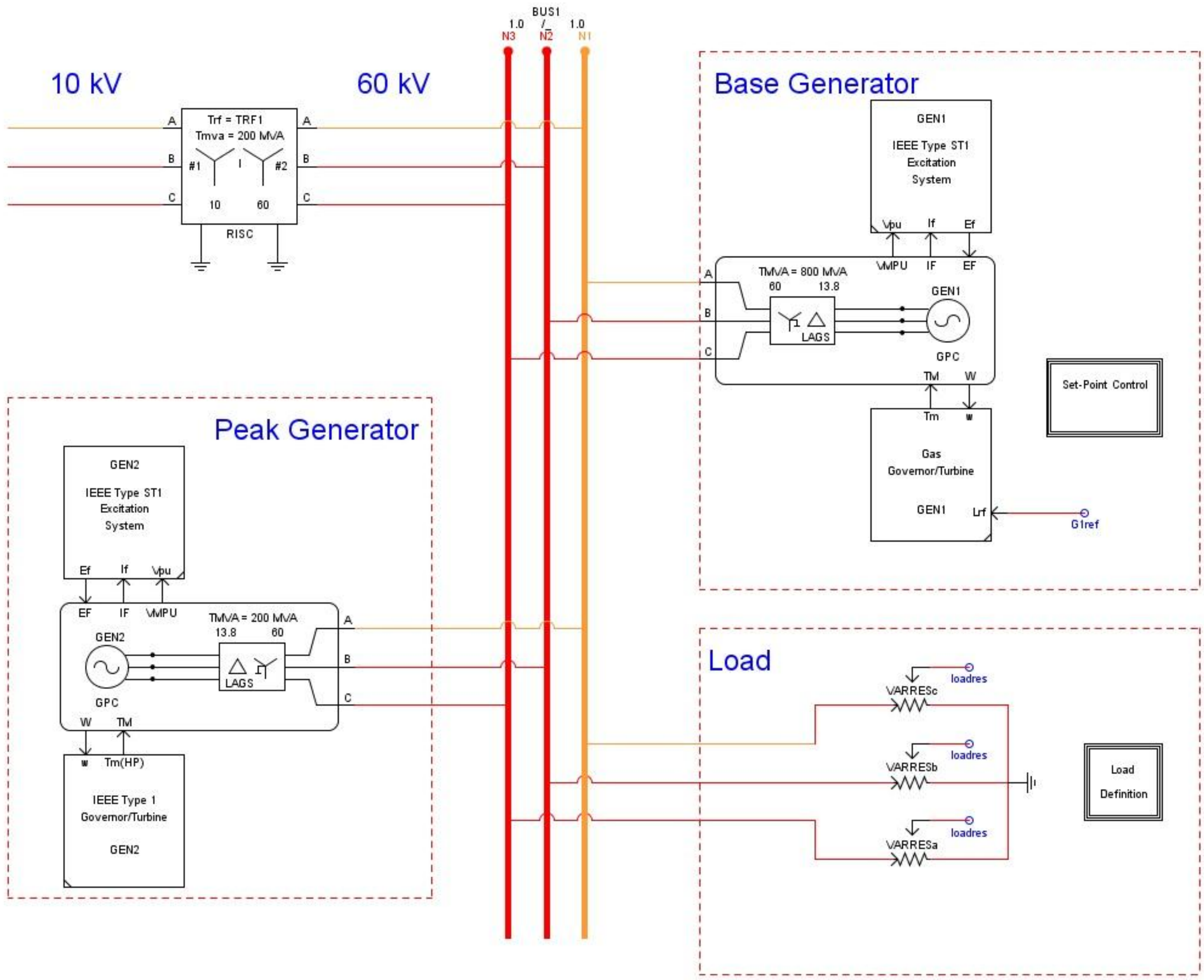

Fig. 3.4. *Block system representation in RSCAD of the modeled Grid*

2.3 The Battery Energy Storage System

In the real system, as in the model, this section consists of three separate parts. In the real system, these are the converter and transformer, the cells themselves and the energy management system. The three blocks used to represent these roughly correspond to their counterparts in the real system; at least insofar as the end result of each is the same as those that they model.

Battery Model

The basic electrochemical cell model, as used by [27] and [40], is implemented. A single cell is modeled, and the output voltage is simply multiplied by the user-defined number of cells. The modeled cell has a nominal voltage of 3.6 V and a capacity of 50 Ah, with a maximum discharge current of 6 times the capacity, or 300 A. As the assumption is made that all the cells are connected in series, the current flowing through them is the same.

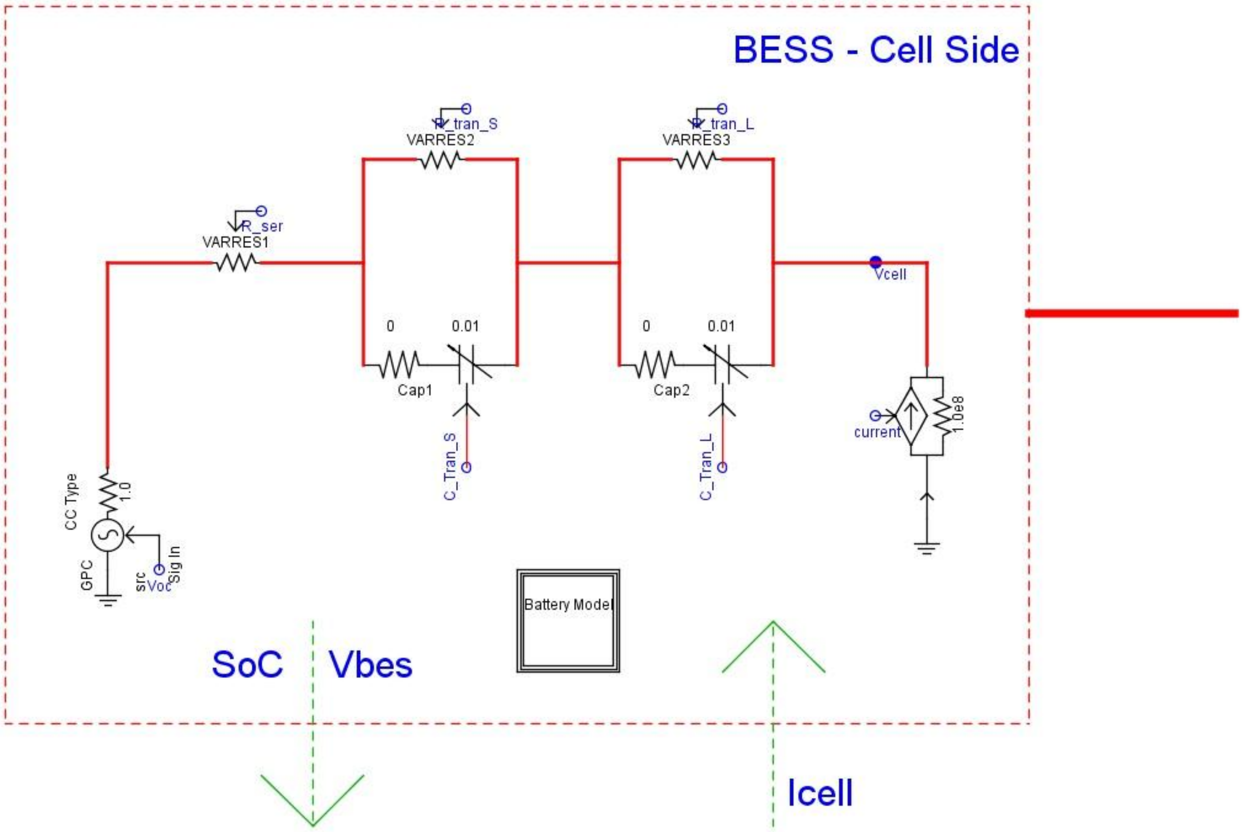

Fig. 3.5. *Modeling of an electrochemical cell in RSCAD*

The output voltage of the cell, V_{CELL}, is the sum of the open circuit voltage (V_{OC}) and the equivalent circuit voltage (V_{EQ}). The first one is a function of the State of Charge (SoC) of the battery, while the other depends on the direction of the current. When the cell is discharging, the V_{EQ} reduces the output voltage V_{CELL} of the cell. When the cell is charging, it adds to the voltage that must be defeated in order to charge the cell. In this way, losses are modeled. The equivalent impedance, Z_{EQ}, which is formed of a resistive element and two RC circuits in series, is in itself a function of the SoC of the battery. The open circuit voltage V_{OC}, to the state of charge are shown in the following images.

The cell's modeling includes two capacitive elements. Although the effect of these on the outcome is negligible, as the cell operates in dc, they are still included for the sake of completeness of the model, and to permit the work to be picked up in a different direction which might make use of them. The values of V_{OC} were obtained experimentally for this particular cell in the past, and are repeated from [27], while the values for the individual parameters of Z_{EQ} were obtained theoretically from [40]. A sub-block calculates the SoC based on the current flowing in and out of the battery, and modifies the values of the parameters accordingly. More details on both the battery model and the following converter model can be found in [41].

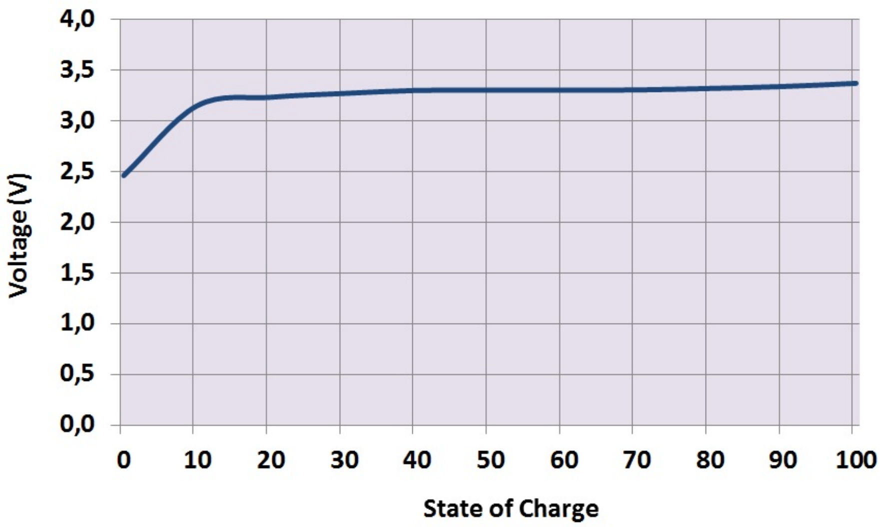

Fig. 3.6. *Relationship between the modelled cell's voltage and its State of Charge*

Converter Model

The real system would probably employ some Voltage Source Converter in order to invert, rectify, and modulate the power being delivered or absorbed by the battery. As explained earlier, such devices operate under the "small time step" of the RTDS, a resolution corresponding to around 2 µs. The rest of the system operates at the "large time step" of 50 µs [42]. In order to model a service such as frequency control, where a single period in voltage at 50 Hz is equal to 20,000 µs, it is absurd to model with a resolution of 2 µs. The elements that have been arranged within the dotted area of the model instead replicate the functioning of an actual converter; they function in a simplified manner, yet maintain the exact inputs and outputs as an actual converter would have.

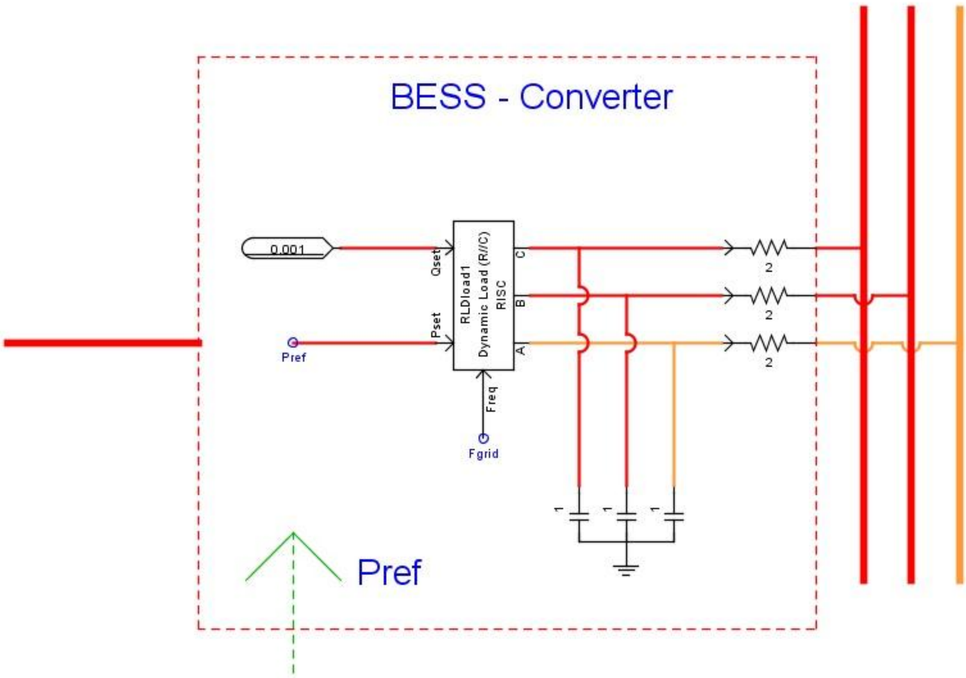

Fig. 3.7. *Block system representation of the modeled converter.*

The central piece is a dynamic load, which was modified in RSCAD's component builder, in order to be able to "consume" negative power, and thus deliver it to the grid. The resistance was added in order to monitor the power output from the block and to keep the bus from shorting to ground, as the dynamic load does not act as a simple resistance. The block contains a sub-block, which calculates the power the dynamic load should consume or produce, accounting for losses in the added resistance. The block itself receives from the Energy Management System (EMS) a power reference, P_{REF}, which it should deliver. The sub-block ensures that this is the power that is actually being consumed, and then relays the net energy delivered to the cells, to ensure that they are charging and discharging according to the magnitude of the power that they are actually delivering or absorbing. In this manner, the converter acts as an ideal component, in that no losses are modeled within it.

Energy Management System (EMS)

Like its real life counterpart, the EMS takes decisions as to whether the ESS should charge or discharge and with what magnitude. As the service being modeled is primary frequency control, the EMS duties are limited to offering a PID controller to changes in the grid frequency. This frequency is the only input that the controller has, as per the request of the Danish grid codes [20], which explain the way in which such devises must operate. The controller can be operated as a simple PD controller, offering droop control and true primary control (without attempting to establish a new operating set-point), or as a full PID controller, which accounts for the error with the integral component and attempts to bring the frequency back to 50 Hz.

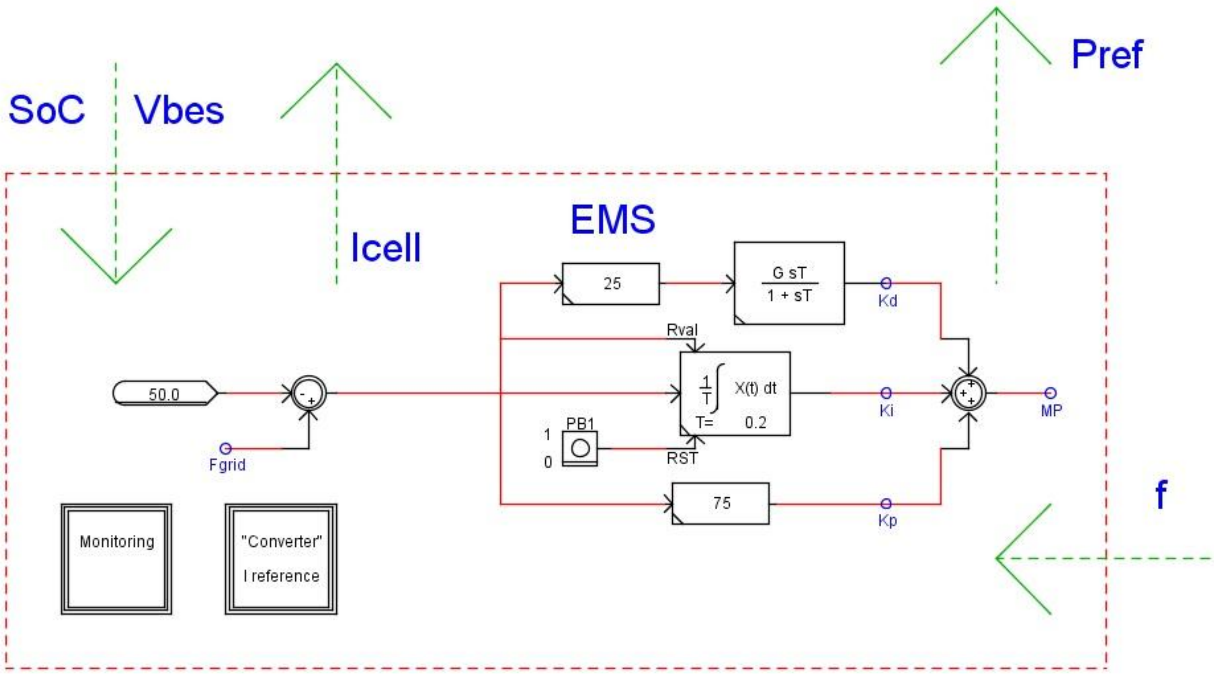

Fig. 3.8. *Block diagram of the Energy Management System controller.*

The three constants of the controller where tuned to best respond to the demands of this same document, which say that half of the nominal power should be available before 15 s have passed, and the full amount before 30 s. They have also been tuned to reduce the transient to a minimum, and – if the integrative part is present – to bring the frequency back to normal as soon as possible. The image below simulates a drop in frequency, and shows the performance of the three components of the controller.

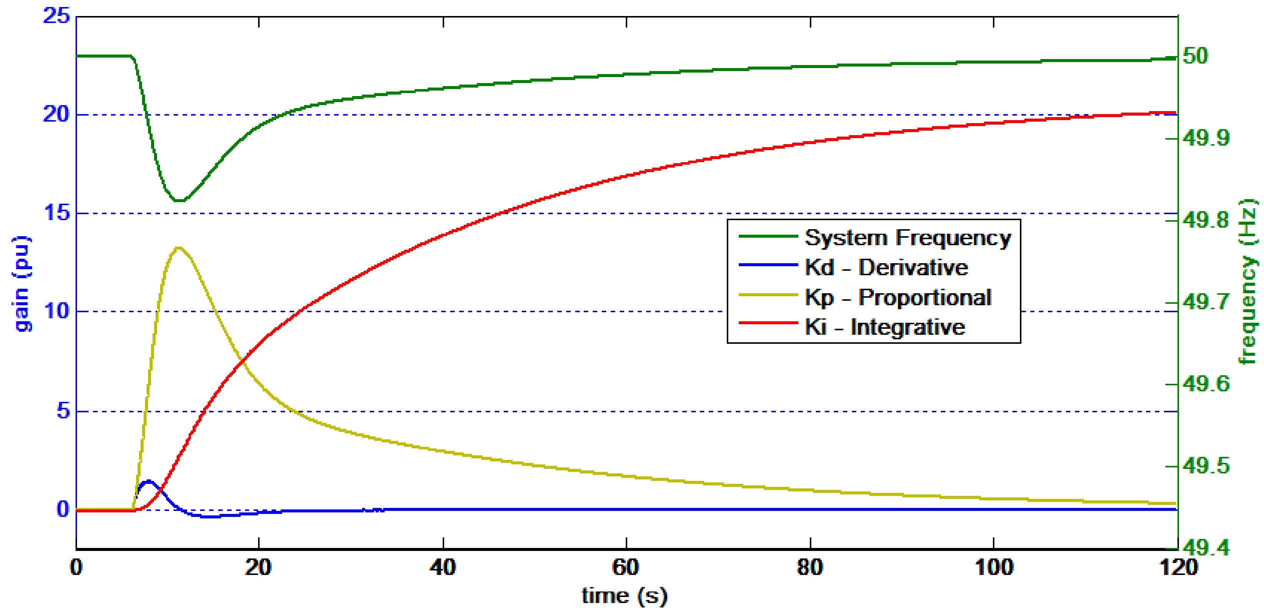

Fig. 3.9. *Components of the controller, reacting to a change in frequency.*

3. Simulation Results

The simulation environment within RSCAD allows for both the visualization of any runtime variable, as well as for the control of many parameters, in real time. The highly customizable interface allows for the plotting of any variable or combination of variables, albeit not in real time, but in a predefined measurement period, which can be refreshed at any time. Some of the important controllable variables for the operation of the built model will now be explained, before continuing on to the simulated cases.

3.1 Simulation Environment

In the modeled system, one can find five main elements: three generators and two variable loads, one of which acts as the ESS. The three generators can be operated in either “free” or “locked” mode, where locked mode means that the governor is not interacting with the generator and this last one if simply spinning at the rated frequency of 50 Hz. For any realistic simulation, the generators must be acting in “free” mode, so that changes in the system variables (voltage, frequency) will cause a response in their performance. The generators start the simulation in “locked” mode, and must be released by flipping their corresponding switches, as shown in figure 3.10, allowing for the other generators to adjust before releasing the next one.

In case a drop in WPP production is to be simulated, the load reference for the wind plant generators can be controlled by the slider label “WPP Reference”, in per unit values. This slider works only when the generator is operating in the “free” mode, of course, as the load reference is a variable within the governor’s controller.

In case a change in the system load is to be simulated, the load’s demand can be changed using the provided slider, label “Load Demand”, in MW. The user should be aware that changes in the model itself must be effectuated in order to model one case or the other, as will be explained in following sections.

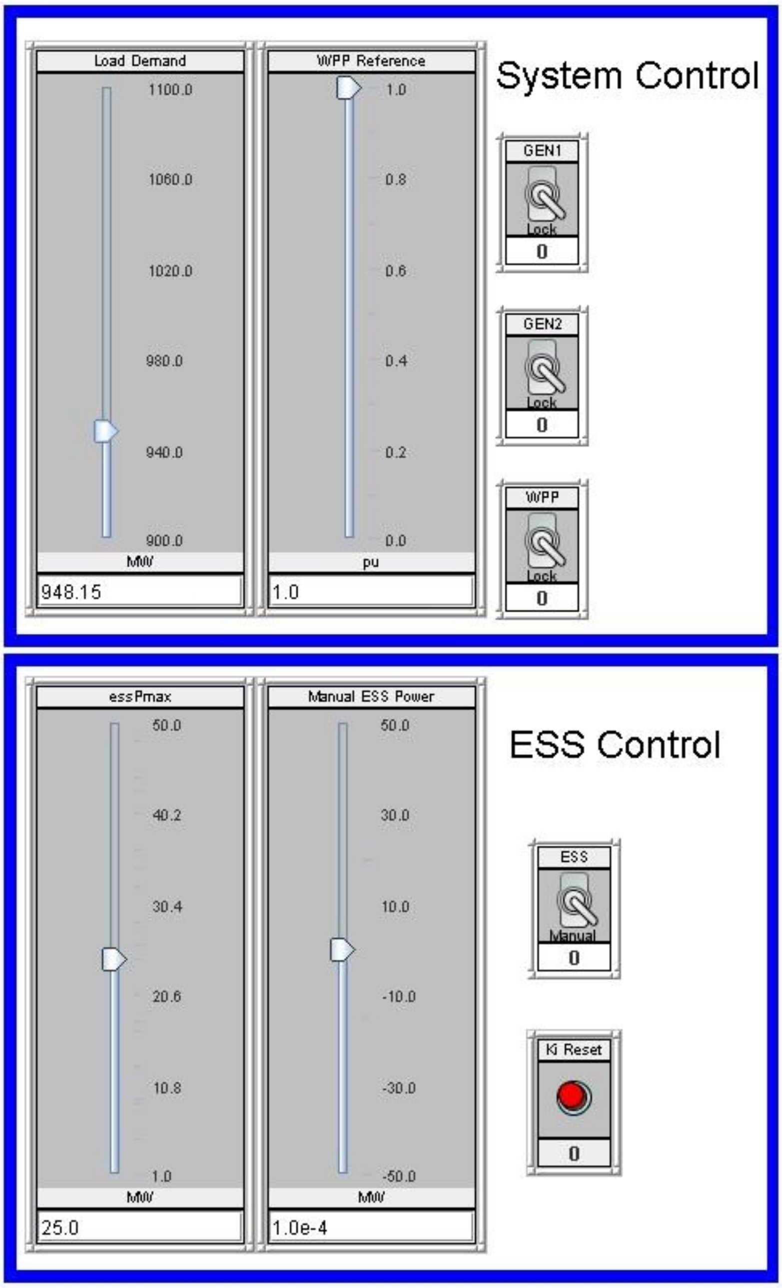

Fig 3.10. *Simulation environment, showing the system controls.*

There is a fourth switch, which determines whether the ESS will operate in “Manual” mode (where the ESS’s output or input is a fixed constant value) or in “Automatic” mode, where the ESS operates as the integrated frequency controller dictates, in order to maintain system frequency. The default setting is Manual, which enables simulation of cases with no ESS. While in Manual mode, the load reference for the ESS can be changed by means of the provider slider, labeled “Manual ESS Power”, in MW, which determines the power to be supplied by the storage. A positive value in this slider implies a discharge, while a negative one implies a charge.

Flipping the switch into "Automatic" mode engages the designed frequency controller. The variables of the three components of the controller (proportional, integrative and derivative) can be separately monitored. This controller monitors the errors in the frequency even if the ESS is disengaged. In case the simulation has been left to run for a long time and the integrative component is too large for ESS connection, it can be reset to zero by pressing the "Ki Reset" button.

Finally, the "Max ESS Power" slider allows the user to limit the output of the ESS even below the limitations that its size and capacity should allow. This is useful when simulating several cases with varying sizes of ESS, without having to alter the modeled number of cells or the allowed current.

A large number of monitors can be kept at any time, their number being limited only by the number of variables in the system. There's a possibility of monitoring for every node voltage, the grid frequency, machine variable, power outputs, cell voltage, and BES State-of-Charge. A number of these have been included in the environment and have been grouped and labeled for convenience.

3.2 Variations in the Wind Power Output

Sudden changes in the power output of the WPP can be easily modeled by readjusting the "WPP Reference" slider in the simulation runtime. However, the system must be tweaked for this function. The governor of the WPP block must be controlled by an external Load Reference signal, while the other generators must be operating with an internal load reference, that is, a pure droop control, to allow the ESS to perform all the control by itself. Two separate controller modes where modeled. The first is a PD controller, that is, a "pure" primary controller, which supplies power until the frequency becomes stabilized, but does not attempt to bring the frequency back to 50 Hz, leaving that instead to an un-simulated secondary control. The second is a PID controller, which attempts to compensate perfectly for drops in the WPP output, and uses its integrative component to reduce the steady-state error and bring the frequency back to 50 Hz. Both of these cases were simulated for cases in which the WPP is operating at maximum capacity and drops to 80% and 60%.

PD-Controlled ESS

The first case simulated is a drop to 80%, and the response of the ESS with different maximum power outputs. The integrative component of the controller is deactivated, and the load reference of the WPP is controlled with a slider. After allowing the system to reach a steady state, after the transients caused by releasing the generators, the WPP reference is lowered from 100% to 80%. The response of a 25 MW ESS is shown in figure 3.11.

The following figures show that, in the case of the PD controller, even though more energy was available, the ESS delivers only what is needed to stabilize the frequency as fast as possible. This is characteristic of primary control, which in this case is a simple droop controller. In the following section, an integrative element is included to simulate the intervention of secondary control. Smaller ESS sizes attempt to follow the same curve, but are limited by their maximum power output. The image below shows the variations in frequency that the system experiences as a result of this drop. For sizes above 20 MW, the response is the same, even if the frequency does never reach 50 Hz. This, again, is a result of the type of controller modeled.

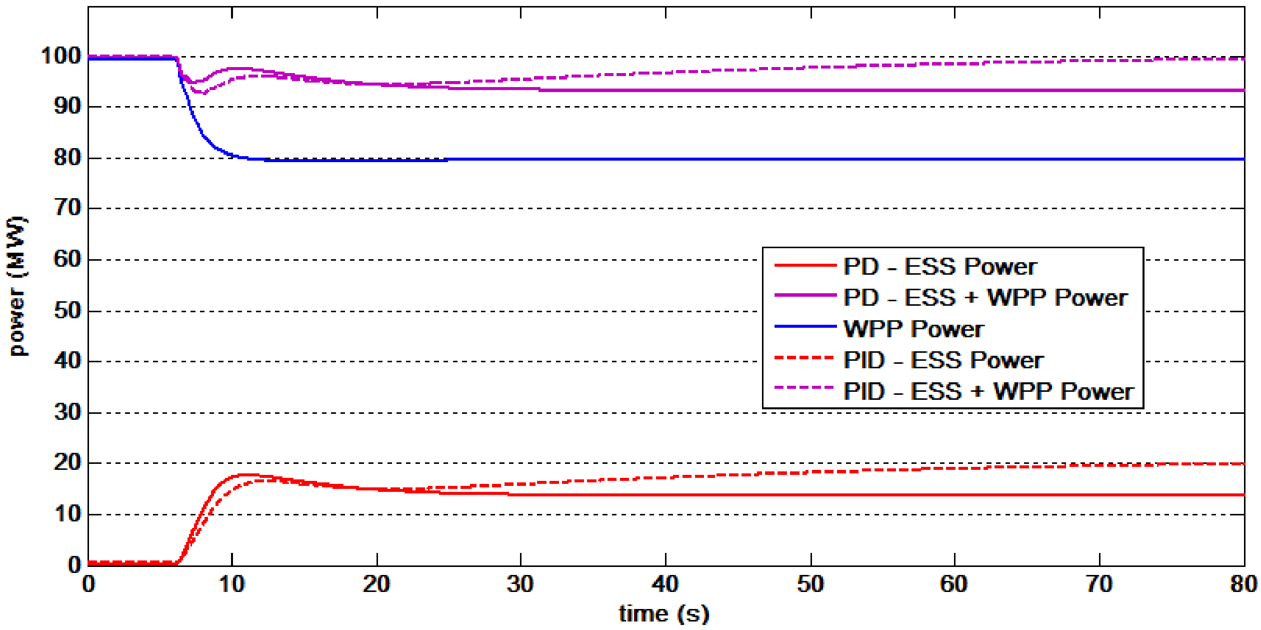

Fig. 3.11. Output powers for the Wind Park, the 25 MW Energy Storage, and the combined flow at the PCC

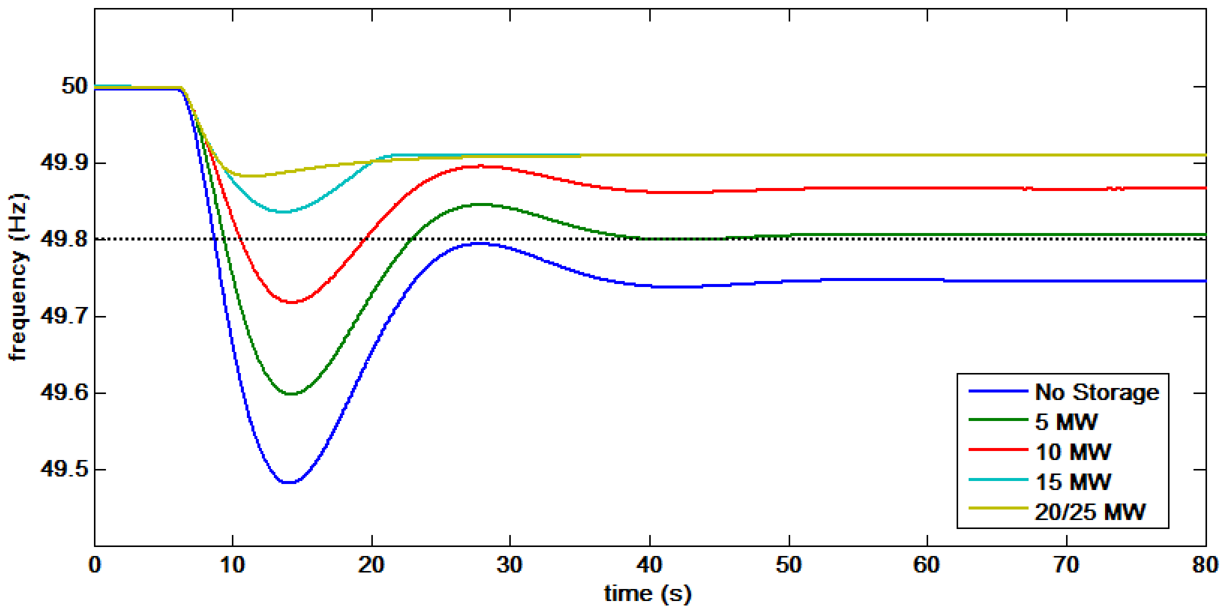

Fig. 3.12. Frequency variations with the intervention of different sizes of ESS, for a drop of 20% of the WPP

PID-Controlled ESS

Again, a drop to 80% the WPP nominal power is simulated; only that in this scenario the ESS controller includes an integrative element. This controller produces a result more like what one would expect to see in real life frequency variations. However, a true primary controller does not include this integrative component. Instead, in the real grid, secondary reserves and balancing units take care of reducing steady state error, and it is their effect that would act upon the system. This can be seen back in figure 3.11, together with the PD-only controller. Now that the PID controller can detect the steady state error, the ESS slowly increases its output to match the WPP's deficit. Smaller sizes cap at their output maximum. As could be expected, frequency variations follow a similar trend, when the integrator is included.

It is important to note that these frequencies are purely the result of the specific set-up of the particular system modeled. In reality, the input from a single actor of spinning reserve is not enough to completely counteract drops in frequency, all by itself. The response is in fact the conjunction of all the other actors put together, and the expected curve will look most like the 20/25 MW curve in figure 3.12 [20]. That response is the expected response of a primary controller operating in the grid.

The response of smaller sizes of ESS is basically identical to the one they had without the PID controller (compare to figure 3.12). However, for larger sizes the frequency approaches 50 Hz as the simulation time progresses. A similar effect occurs with larger modeled drops, with the exception that ESS power is capped at the maximum, and thus the 49.8 Hz minimum line cannot be approached.

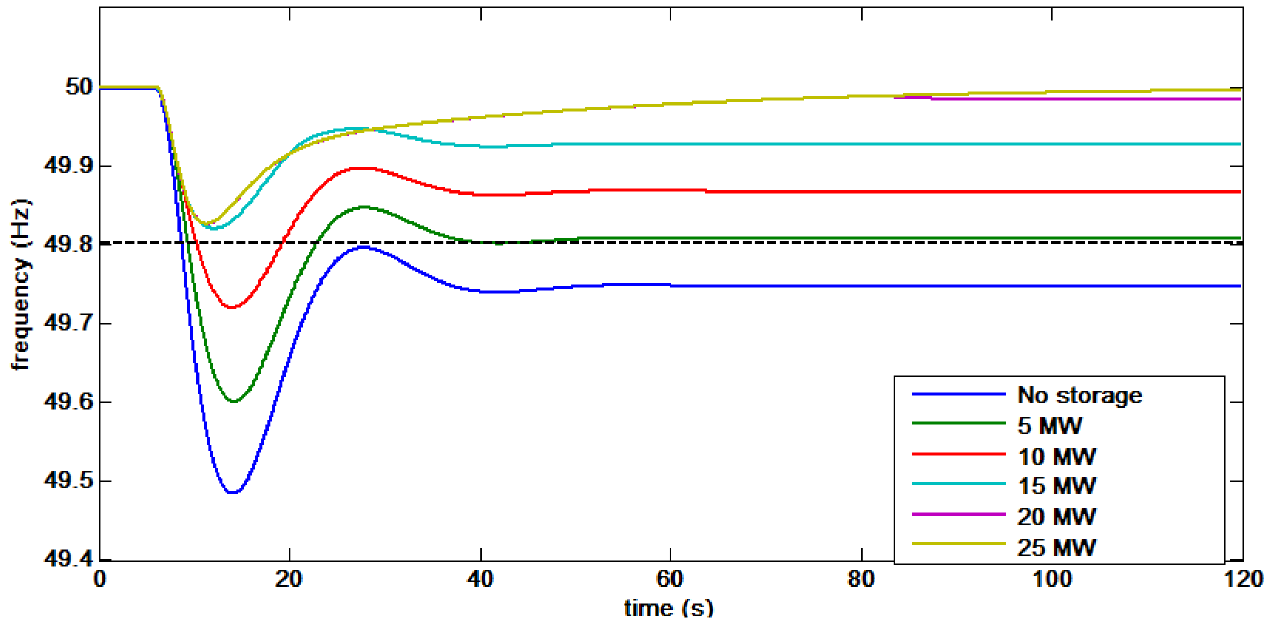

Fig. 3.13. *Frequency response, for different sizes of PID-controlled ESS, after a drop of 20% of the WPP*

These results are satisfactory with what is required in providing a primary reserve service in Denmark. As can be seen in figure 3.11, the maximum output power is deliverable within instants of the frequency drop, well within the 30 second limit imposed in [20]. Furthermore, the results show that purely by observing changes in frequency, a PD or PID controlled ESS will move towards complementing drops in the power output of a WPP.

3.3 Variations in the Load Demand

When modeling changes in the WPP output power, the rest of the generators are left on their standard droop control. However, if one wishes to model changes in the general load of the system, a mechanism to change the operational set-point of the rest of the generators must be active. In such a system, there must be an integrative controller, while the rest of them operate in droop mode. Being that it is now desired to keep the WPP from making any variations to its output, we are left with making the main source, the Base generator, the one to set the new reference point.

As in the WPP block, and as explained in previous sections, the Base Generator is capable of having its governor’s load reference externally controlled. In this way, a secondary PI controller can be implemented purely for the purpose of changing the operational set-point of the system. Load reference changes for the main generator have a rate limitation of 0.0025 per unit per second, which is equal to 15% per unit per minute. Furthermore, although the Base Generator is too slow to adapt to this changes by itself, the setting of a new operational point allows the other generators to use their inertia to adapt to the new load.

Variations of load demand have a similar effect on grid stability, but due to the abovementioned necessity of adding an integrative controller to the other generators, a small oscillation exists after the frequency is reestablished. This oscillation can be completely eliminated, even with amounts of storage smaller than the changes in load, thanks to the stability which the additional controller provides to the system. Readers are referred to [41] for more information on these tests.

Chapter IV. Benefit Analysis

After having shown the technical feasibility of providing the services described in chapter 2, these services will now be evaluated, with the objective of determining their potential benefit when used in conjunction with a Wind Power Plant. The associated costs of the Energy Storage System will be calculated, followed by the profits obtainable in each of the evaluated services.

1. System Lifetime and Cost Evaluation

The three services described at the end of chapter 2, time shifting for energy arbitrage, active power balancing and active power regulation, each carry a different benefit. These benefits arise from the profit or losses avoided that each service has to offer and the cost of the Energy Storage System that the service requires. While it is understood that, in each case, a larger storage will provide greater possibility of income or costs avoided, the Capital Expenditure (CapEx) and Operational Expenditure (OpEx) of the system will not be the same in every case. A service that requires many deep cycles will shorten the cycle life of the Battery Energy Storage much more than one who requires merely a stand-by condition. Holding the BES in a discharged state for long periods of time further shortens the calendar life [27].

For the scenarios being assessed, a project lifetime of 10 years will be explored, with a discount rate of 5% in order to calculate the Net Present Value of CapEx, OpEx, incomes and costs avoided. A Rainflow Cycle Counting method, as described in [43] and [44], in order to count the SoC cycles of the BES and thus estimate its expected lifetime, using manufacturer's data, following the method of a previous work in [27]. The Rainflow method not only counts the total number of charging and discharging cycles, but categorizes them according to the Depth of Discharge that they incur on the BES. As explained in [27], deeper cycles cause a much larger effect on cell lifetime than shallow cycles. The cells being modeled, for example, should last up to 1,000 cycles at 100% DoD, but some estimated 2,500 cycles at 60% DoD [31].

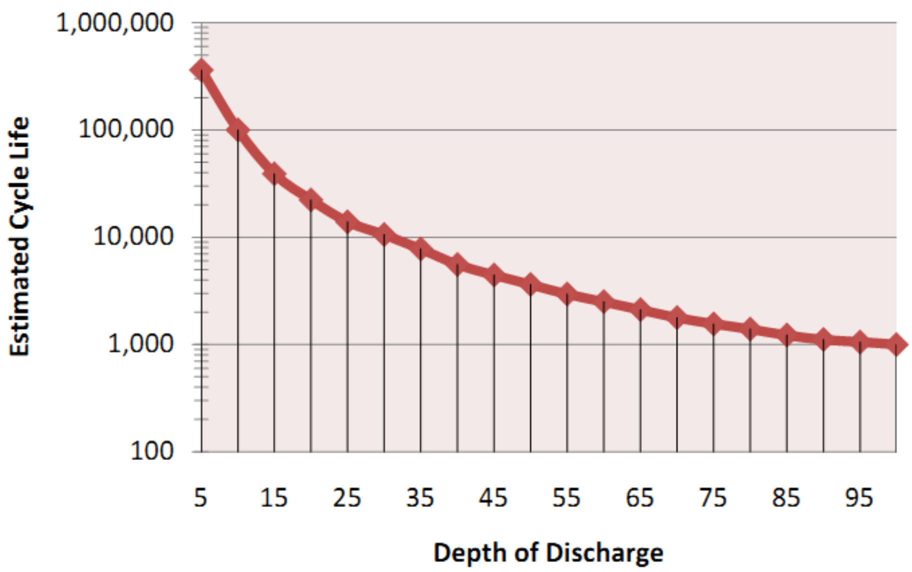

Fig. 4.1. *Estimated cell cycle life as a function of the Depth of Discharge [27].*

During the 10-year project lifetime, the entire BES would be replaced according to the lifetime expectancy, incurring in an occasional CapEx. The number of cycles shown in the figure above represents that time when cell capacity drops to 70% of the initial capacity, and are thus considered spent. The yearly OpEx costs have been estimated at 3.50 €/kW, according to a report from [45], for a cell technology with similar requirements. However, costs for the Balance-of-Plant (all CapEx costs related to the ESS apart from the cells themselves, including converters, computers, and storage housing and other components) have not been included, but can be expected to be incurred at the beginning of the project.

In order to calculate the NPV of the costs associated with providing a given service, the following process will be followed. First, a BES size will be selected, and a Simulink simulation will be performed using the available data, in order to estimate the yearly charging and discharging patterns. Using the Rainflow algorithm, this SoC signal will be analyzed to extract the number of cycles. Using the information displayed in figure 4.1, each cycle depth is assigned a weight, and the expected lifetime of the BES, in years, can be obtained. Finally, this information is used in a balancing sheet, and compounded using a 5% discount rate, to find the present value.

Calculating the cost of a given system will follow from the data available for the cells and their estimated costs in €/kW and €/kWh. The maximum power is estimated from the worst case scenario, a nearly discharged cell at 2.3 V, and the maximum discharge current, 300 A. The maximum energy and delivery time is estimated from the average voltage, 3.2 V, and the cell capacity, 50 Ah. If, for example, a 10 MW storage is desired, with a delivery time of 1 hour, then the maximum current has to be 50 A, in order to ensure the availability for the whole hour. Demanding a 1 hour delivery time therefore limits the maximum current and increases the cost in €/kW. The number of cells can be calculated as follows.

$$N_{CELLS} = \frac{P_{ESS}}{v_{MIN} \cdot i_{LIM}} \qquad \text{where} \qquad i_{LIM} = \frac{Cap_{CELL}}{T_{delivery}}$$

And from this number, the BES cost can be calculated. If, in performing the service, in is found that the cell goes through the equivalent of 250 full cycles each year, then the expected lifetime can be estimated at 4 years, as the cell is modeled to survive 1,000 full cycles. The table below shows the compounding plan for this CapEx. The present cost of the cells in the table below is represented by X. At the end of the 10^{th} year, given that the cells are half spent, they are assumed to be salvaged for half of their value.

Year	0	1	2	3	4	5	6	7	8	9	10
Compound factor		1,05	1,10	1,157	1,215	1,276	1,340	1,407	1,477	1,551	1,628
CapEx	X				X				X		
NPV	X				0,82X				0,67X		

Table 4.1. *Example of CapEx compounding, over 10 year lifetime.*

1.1 Data Available

Though many manufacturers, of cells and wind turbines, keep their data as confidential, many data can be obtained directly from the Transmission System Operators and the Nordpool Spot market. Limiting the working period to one year, signals were obtained for system prices, balancing costs, regulating prices, total demand and total wind production for western Denmark for the year 2010, with a 1 hour resolution. Additionally, the power production data for a 100 MW Wind Power Plant was available, for an unnamed year, with a 1 minute resolution.

There is basically unlimited potential to analyze and discuss the data available, as it shows trends and correlations between different system variables. This will now be discussed, insofar as it concerns the evaluation of the selected services.

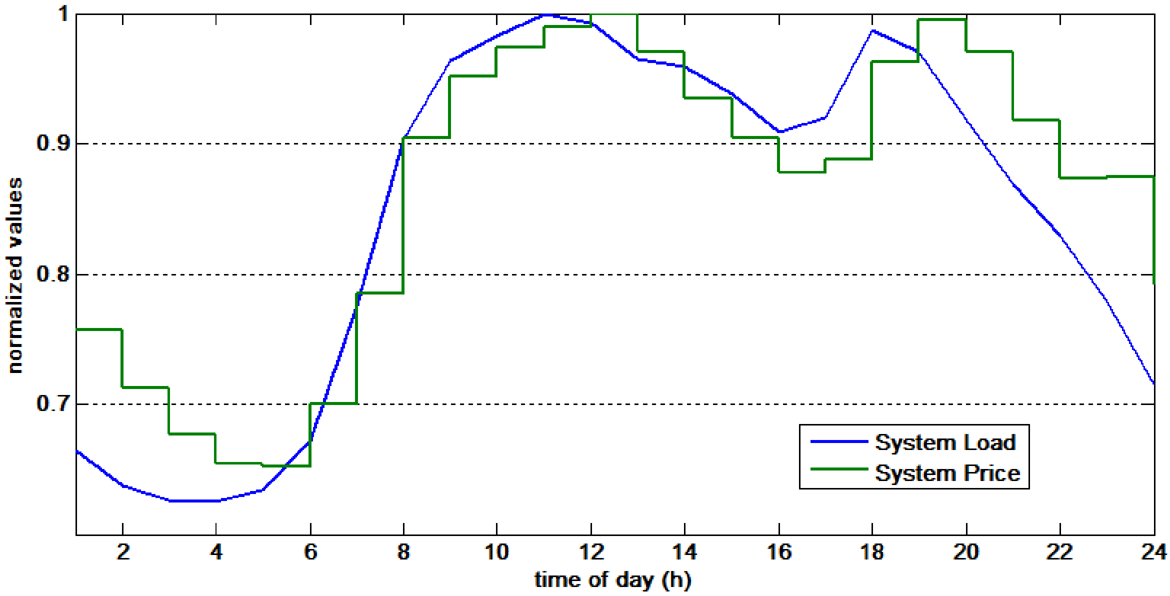

Fig. 4.2. Normalized daily variation of system load and price in western Denmark.

The values in the image above are normalized to the maximum value of each averaged signal, that is, 2,860 MW for the load and 53.84 €/MWh for the spot price. As can be seen in the image, system load is the main factor in determining the spot price. This is simply because most generating facilities are able to regulate themselves precisely for many hours, which in a demand and supply perspective, means that it is the changing demand which sets the price for energy, for the most part. Wind energy is also monitored by Energinet, though they show purely the aggregate amount.

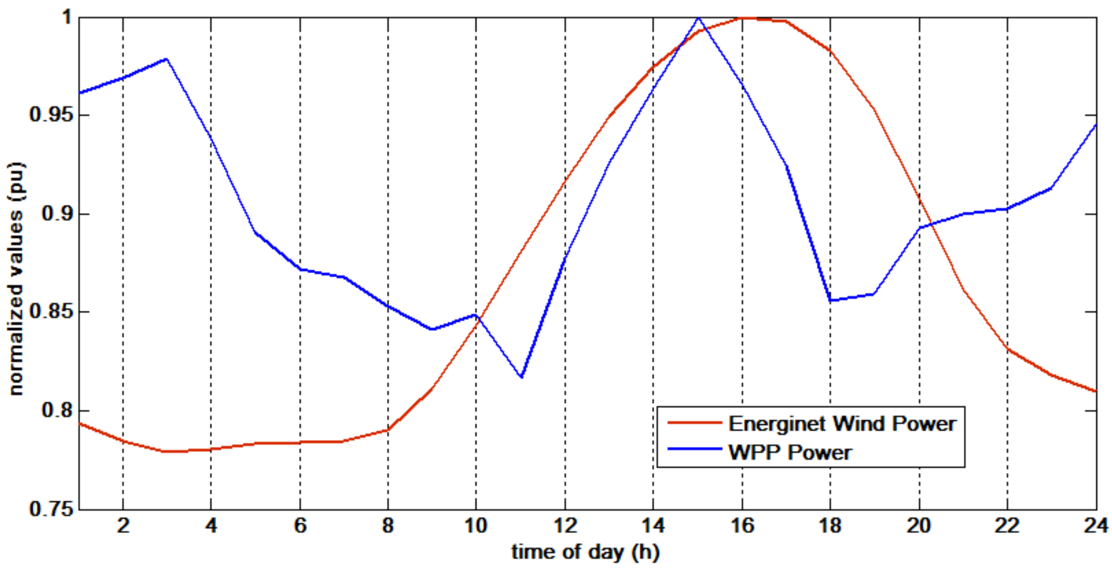

Fig. 4.3. Normalized average daily signals, data from Energinet and a 100 MW Wind Power Plant.

Note that the signals above have been normalized to the maximum value of the average signal, not the installed capacity. There is a very noticeable difference between these signals, which leads to the conclusion that the red signal, that which is reported by Energinet, is heavily curtailed and balanced in order to fit with the demand curve (see Figure 4.2). The blue signal, which was built out of raw wind production, minute to minute, contains two daily peaks, at 03.00 and at 15.00.

For this reason, it is the production signal for the 100 MW wind plant which will be used for comparison against Spot, balancing and regulation prices. The wind data provided by Energinet shows signs of curtailment, and thus could be unreliable when calculating needs for balancing. A new problem arises, as the data from the 100 MW wind park is not accompanied by a forecast data of any kind. An artificial forecast was therefore generated, based on data and theories from [36] and [46]. The generated forecast is produced up to 36 hours in advance, and updated every 24 hours. It follows the average hourly production of the wind, with a systematic error of increasing magnitude which follows the error profile of [46], leading to an average error, after 36 hours, of 10% of the nominal capacity.

2. Time Shifting

The first service to be examined will be Time Shifting, in the form of Energy Arbitrage (EA). The signals required for assessing this service are mainly the Elspot system price signal and the WPP output signal. The objective, as expressed in chapter 2, is to maximize the value of the energy output of the WPP by making it available at points of higher value than when it was originally produced.

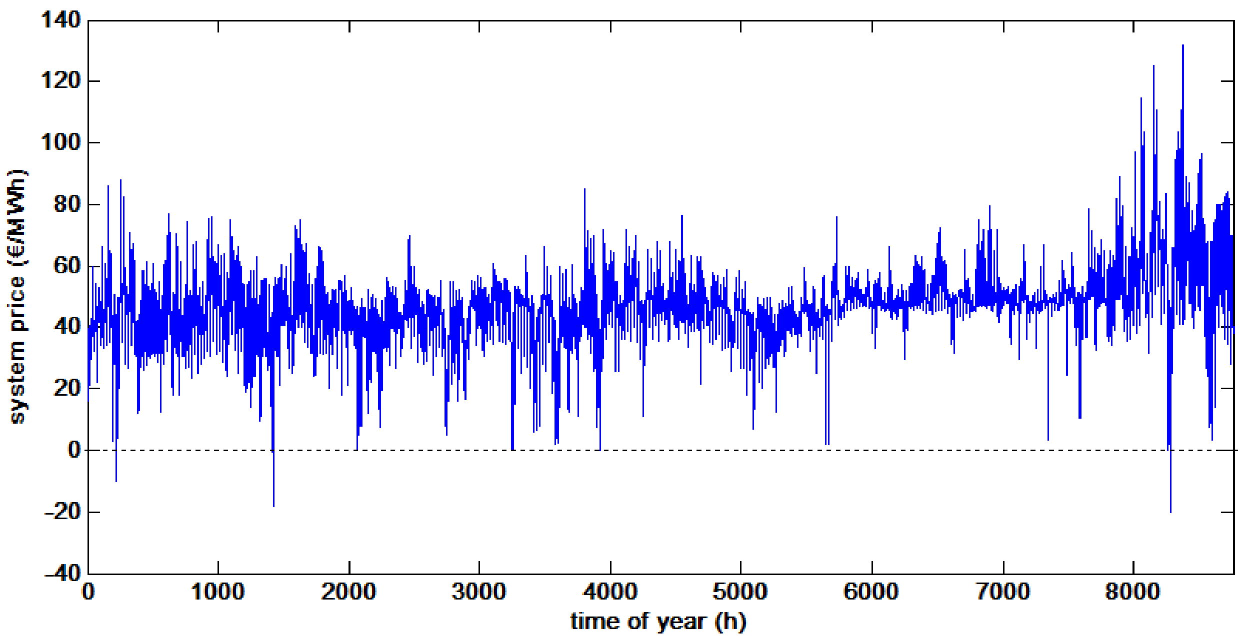

Fig. 4.4. *Yearly variation of system prices, for western Denmark, in €/MWh.*

It is not hard to see, from figure 4.4, that there exists great potential profit to be made from Energy Arbitrage (EA) in the Danish system, with these seemingly unpredictable variations. Even if one were not able to know in advance when such drops would take place, there must be a stable enough patter in the daily or weekly interactions. The figure below shows such variations.

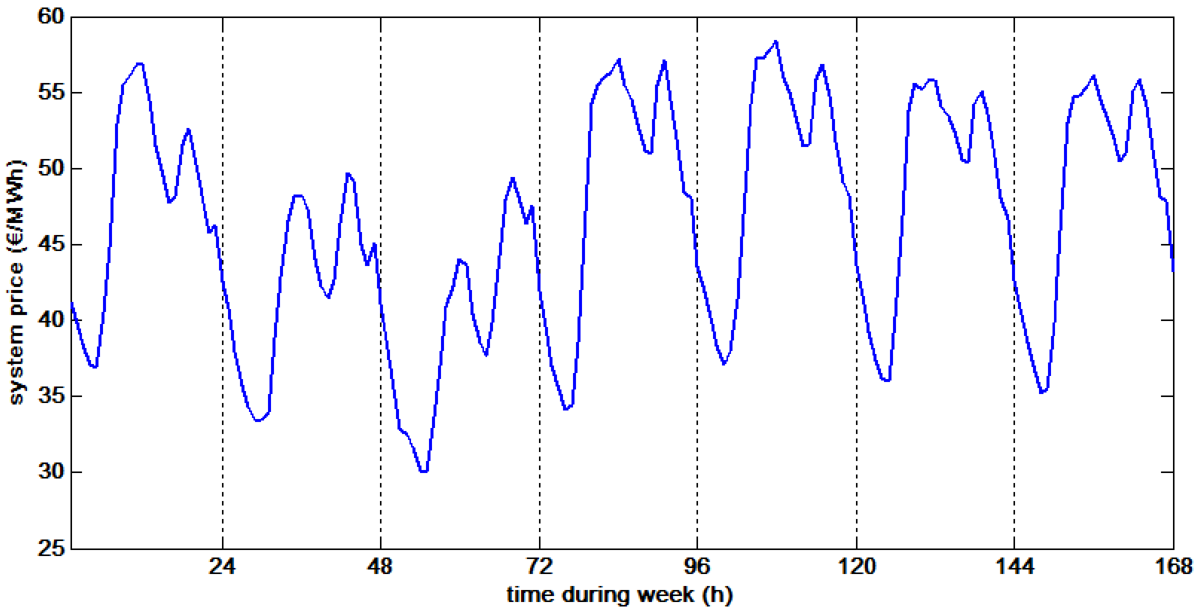

Fig. 4.5. *Weekly system prices, starting on a Friday, averaged throughout the year.*

The tempting approach would be simply to constantly monitor the system prices, perhaps combined with expected values, historical values and actual wind production, in order to decide the cheapest moment to charge, and then repeat the operation for discharge. However, examining the rules that a strategy for EA requires will prove that this is not a viable approach.

2.1 ESS Strategy

The rules for performing EA limit the way the control of the ESS may perform. One must remember that the ESS is acting in combination with a WPP, and so the output of both of these two components is the one being measured at the PCC, before being fed into the grid. Charging or discharging performed by the ESS will affect the output of the system as a whole, making the forecast unattainable. Instead, any interaction by the ESS on the system must be planned up to 36 hours in advance, when the production forecast for the next day is being delivered. Moreover, the system prices for the next day are not disclosed until after all bids for production have been received.

All decisions regarding the strategy for the next day must then be based on historical information. From figures 4.2, 4.4 and 4.5, one can see daily, yearly and weekly variations, respectively. Seasonal variations exist, with the summer months offering the lowest average prices. However, variations in price are greater within an individual day than within seasons. From figure 4.2, which shows the daily variations, one might think that the most beneficial strategy would be to charge in the hours from 04.00 to 05.00 in the morning, when the prices are lowest, and then discharge either at noon or at dinner time, when the prices are highest. This does not consider variations within weekdays. Inspecting figure 4.4, one can see that the lowest price tends to happen in the early hours of Sunday morning. Charging at this time and delivering the energy in the high priced hours of Monday might maximize the income per MW of power, as well as the lifetime of the ESS, as only 52 full cycles would occur throughout the year. A downside of this 1-cycle strategy is that the battery would spend most of its time in a discharged state, which [27] and [32] report lowers the calendar life of the cell. A more sensible alternative would be to discharge Friday at noon, spend only Saturday discharged, and charge again in the early hours of Sunday.

A second approach, which offers more profit at the cost of more cycling, would be to charge during each day's historic low point and discharge during each day's historic peak. This 7-cycle strategy would produce roughly seven times more profit at the cost of having a lifetime seven times shorter.

A third option would be a compromise between the two above. From the first case, the one with a single weekly cycle, a rough estimate leads to 52 cycles a year. That leads to 520 cycles in the 10 year project lifetime. A 2-cycle strategy that incorporates two weekly cycles would last the 10 years required of the project. These alternative strategies are shown in the figure below. They will all be assessed.

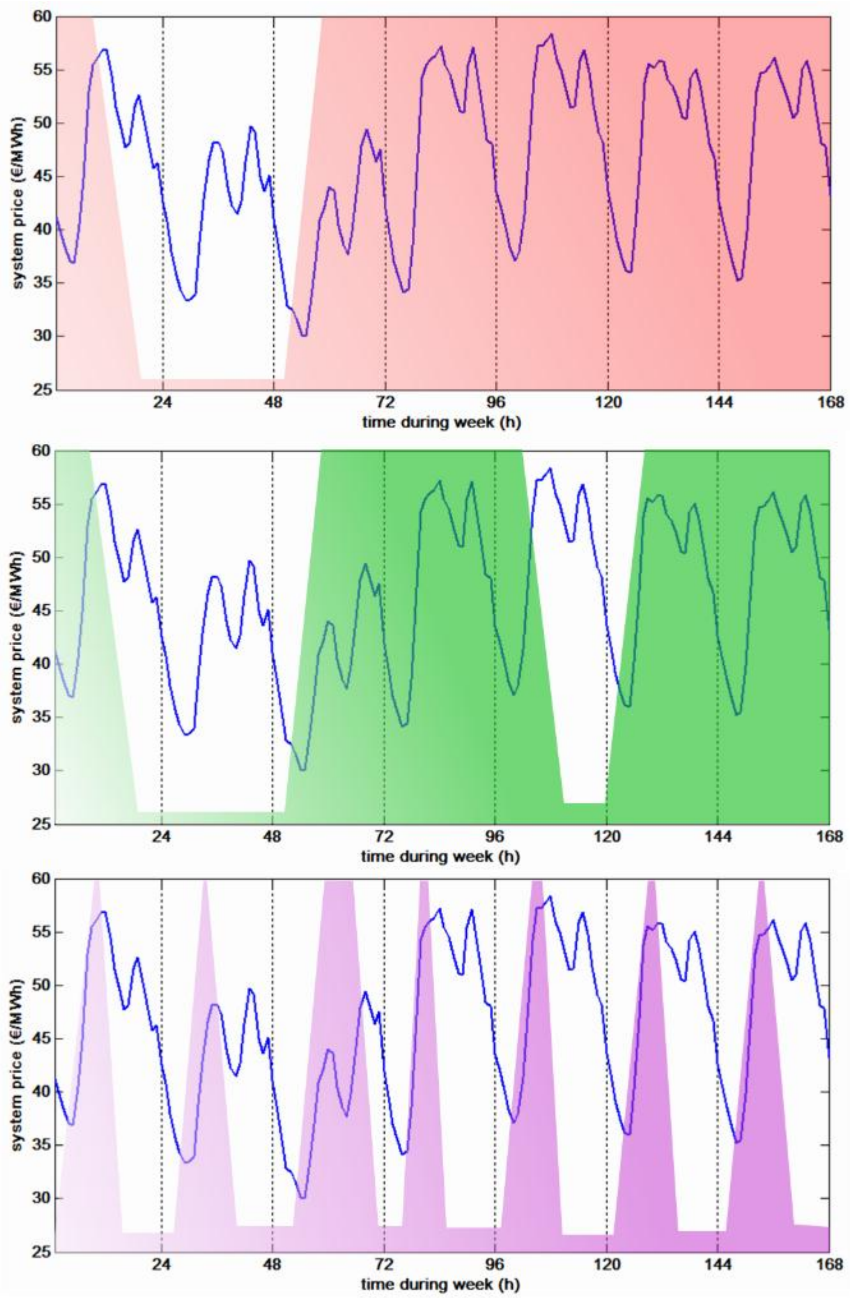

Fig. 4.6. *1-cycle, 2-cycle and 7-cycle strategies for Energy Arbitrage*

2.2 Income Calculation

From the fact that the ESS and the WPP must operate in conjunction, and that all energy that is charged from the ESS is energy that the WPP is not selling to the grid, and that all discharging from the ESS is energy that the WPP is selling to the grid, it is possible to skip to the assumption that the only information needed to make calculations on EA is the Nordpool System Prices. The profit from the EA is therefore completely independent from the WPP production. From this and the above-mentioned strategies, which revolve around fixed weekly transactions, it is simple to estimate the yearly income that each of the activities would generate.

Being that the charging patterns are specified for hour to hour intervals, the delivery time is set at 1h, and it is only the ESS power that is altered. Growing amounts of ESS power produce different amounts of yearly income, calculated by subtracting the total costs of charging from the total income from discharging and multiplying it by the number of periods repeated in a year, which in this case is 52 weeks.

$$Income = P_{ESS} \cdot N \cdot \epsilon \cdot \left[\sum_{i=1}^{x} (D_i) - \sum_{j=i}^{y} (C_j) \right]$$

Where P_{ESS} is the power of the modeled ESS, N is the number of periods in a year, D_i is the income per MW for fully discharging in cycle i, x is the number of discharge episodes, C_j is the cost per MW of charging during cycle j, y is the number of discharge episodes, and η is the round-trip efficiency of the ESS, estimated at 90%, according to [30].

The NPV of the yearly income for these three strategies is shown below, for increasing amounts of storage, for the lifespan of the 10 years of the project.

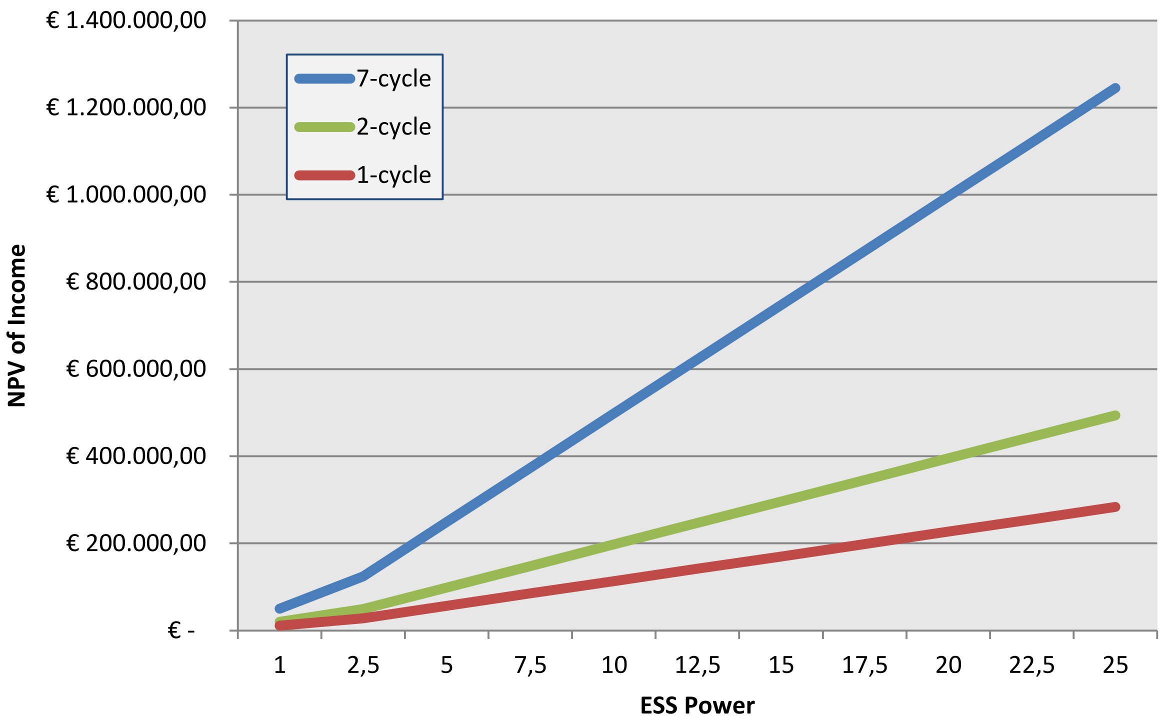

Fig. 4.7. *Net Present Value for different strategies of ESS providing EA, over 10 years.*

The proportion between these different strategies is not, as one might think, 1/7 for the 1-cycle against the 7-cycle and 1/2 for the 1-cycle against the 2-cycle. Instead, as the 1-cycle strategy already takes place in the most profitable exchange, and the other two strategies spend some of their cycles in less profitable interactions, leaving the proportions in the range of 1/4.7 and 1/1.7, respectively.

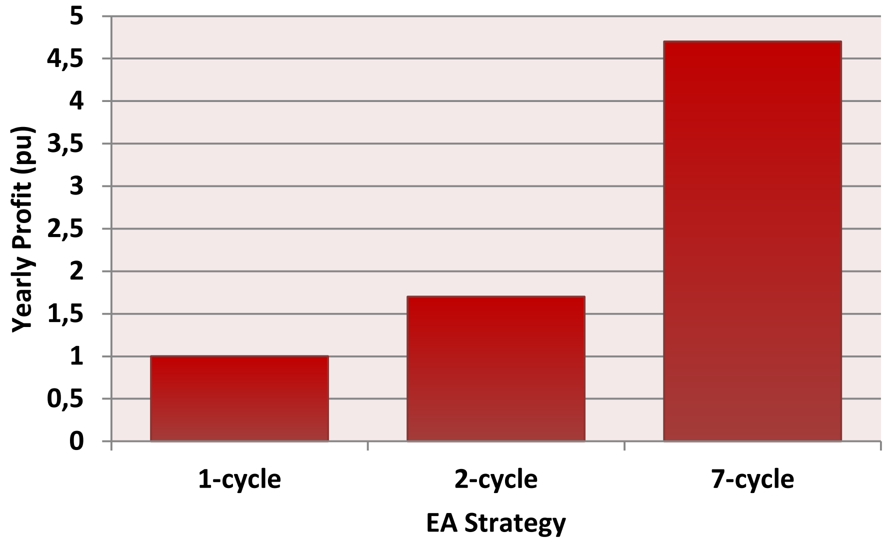

Fig. 4.8. *Yearly profit in pu of the 1-cycle strategy profit.*

Moreover, the 7-cycle strategy would leave the BES with an operating lifetime of 2.74 years, and the batteries would need to be replaced three times during the project's 10 years span. The 1-cycle leaves the BES with the possibility of being salvaged after the project, and the 2-cycle strategy makes the BES last barely the same span as the project itself.

2.3 Benefit Assessment

While the numbers in figure 4.7 might seem encouraging, the enormous cost that BES implies in providing long lasting power supply might change the final result. What's more important, the strategy that delivers the most income is also the one that more quickly diminishes the cell's lifetime, implying multiple CapEx costs during the project span. The cell cost associated with delivering 1 MW of power for 1 hour is, according to the available data and calculations, over 2,400,000 €, not including an estimated 3,500 € yearly on OpEx. Like a wind farm, BES is very capital intensive, with few OpEx costs. The need to replace all of the cells during the project's lifetime makes the prospect unprofitable. Even in the case of the 2-cycle strategy, where no CapEx costs need be considered beyond the start of the project, the NPV of applying a 5-MW storage barely reaches 99,000 €. The CapEx for the cells alone, for 5 MW and 1 hour, is over 12,000,000 €, making this service completely out of reach for this kind of technology.

Other ESSs, like PHES, CAES, or even a large flow battery, could be considered to deliver this kind of service. The low energy cost associated with these technologies might make the project more profitable. If a WPP will ever include an ESS to deliver time-shifting in these magnitudes, it will by necessity need lower costs on the cells. The service does provide some income, but it is not enough to even outweigh this initial expenditure.

3. Active Power Balancing

The second service that will be assessed is Active Power Balancing. This is the most complicated service to explore, as it requires information from the WPP output power signal, a forecast signal for it, the Elspot prices for every hour of the year and the Upwards Balancing cost signal, from the Elbas Balancing market. Wind Power Operators are paid for supplying power as close to their forecast as possible. Deviations caused by errors in the forecast and the inherent variation of the wind must be compensated by purchasing upwards balancing power or by curtailing production, so that the hourly average values stay within the previously reported expected production.

3.1 ESS Strategy

Figure 4.9 shows an example of this interaction, in a one hour resolution. At the times when the average wind production is above what was forecasted, WPOs need to curtail their production, incurring in lost profits. When the green forecast signal is above the blue wind signal, production did not meet the expectations, and balancing power must be bought in the intra-day Elbas balancing market, with prices above the Elspot power market. The objective of this service is then to minimize the amount of balancing power that must be acquired through the Elbas market, a corollary of which is to reduce the curtailed power, as this will be used to charge the ESS. The benefit of this service is not measured in profits, but rather in costs avoided.

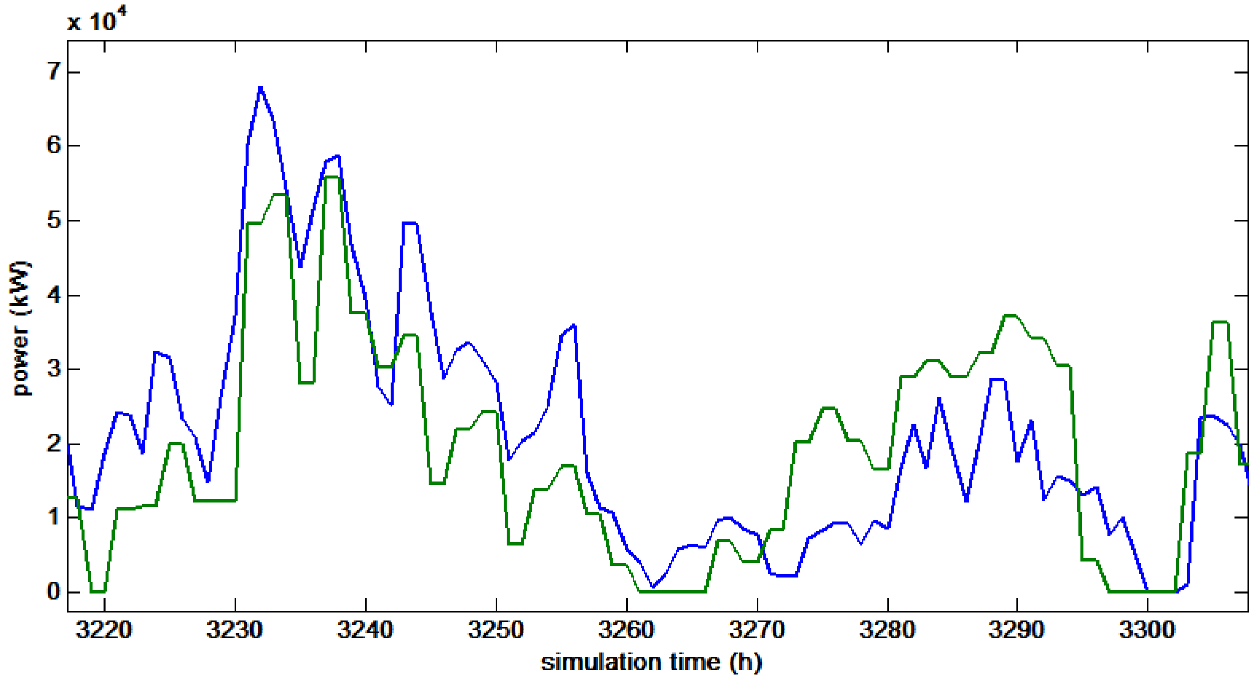

Fig 4.9. *Example of a WPP output signal (in blue) and its associated forecast signal (in green)*

Unlike time shifting, active power balancing allows the taking of actions based on current developments, and without previous planning. This permits a flexible strategy that can simply monitor the delivered power and the forecasted power. In case there is an excess production, it can charge itself in order to reduce the amount of profits lost. In case there is a deficit, it can discharge to reduce the amount of external balancing power purchase required.

3.2 Income Calculation

As mentioned earlier, there is no true income from providing this service, but rather a set of avoided costs. In order to calculate the added benefit of using an ESS, the performance of the WPP must first be analyzed, and then compared to scenarios with growing amounts of storage power.

$$Income = [P_{WPP} - P_{WPP>FORE}] \cdot Price_{system} - P_{WPP<FORE} \cdot Price_{balancing}$$

Where P_{WPP} is the potential production, $P_{WPP>FORE}$ is the portion of production above forecast, which must be curtailed and $P_{WPP<FORE}$ is the portion of production below forecast, which must be balanced. The total income can be calculated by the portion of the production that fell below the forecast curve (that is, all the production which did not have to be curtailed), time the system price at each hour, minus the cost of obtaining upwards regulation for the energy deficit. A simple algorithm was used to calculate this using a Simulink model, first developed for [27]. The model also allows using the same cell model developed in chapter 3, in order to simulate charging and discharging of an ESS, as well as its contribution to the energy balance in the system.

Simulating a 100 MW WPP, with no storage capabilities, and using its generated forecast function to evaluate its accuracy, the following numbers are obtained for a yearly operation.

Potential Income	Curtailed Power $P_{WPP>FORE}$*$Price_{System}$	Gross Income Potential - Curtailed	Balancing Cost $P_{WPP<FORE}$*$Price_{balancing}$	Net Income Gross - Balancing
9,295,700.00 €	- 1,738,400.00 €	7,557,300.00 €	-1,816,300.00 €	5,741,000.00 €

Table 4.2. *Incurring yearly costs for production deviating from forecasted values, for a 100 MW WPP*

One by one, different sizes of ESS are modeled, with different delivery times. In the end, it is more the number of cells which affects the results, but the following cases where all modeled with 1 and 4 hours of delivery time, for ease of comparison. The graph below shows the yearly net Income of the project with different storage sizes minus the yearly net income of the project with no storage at all.

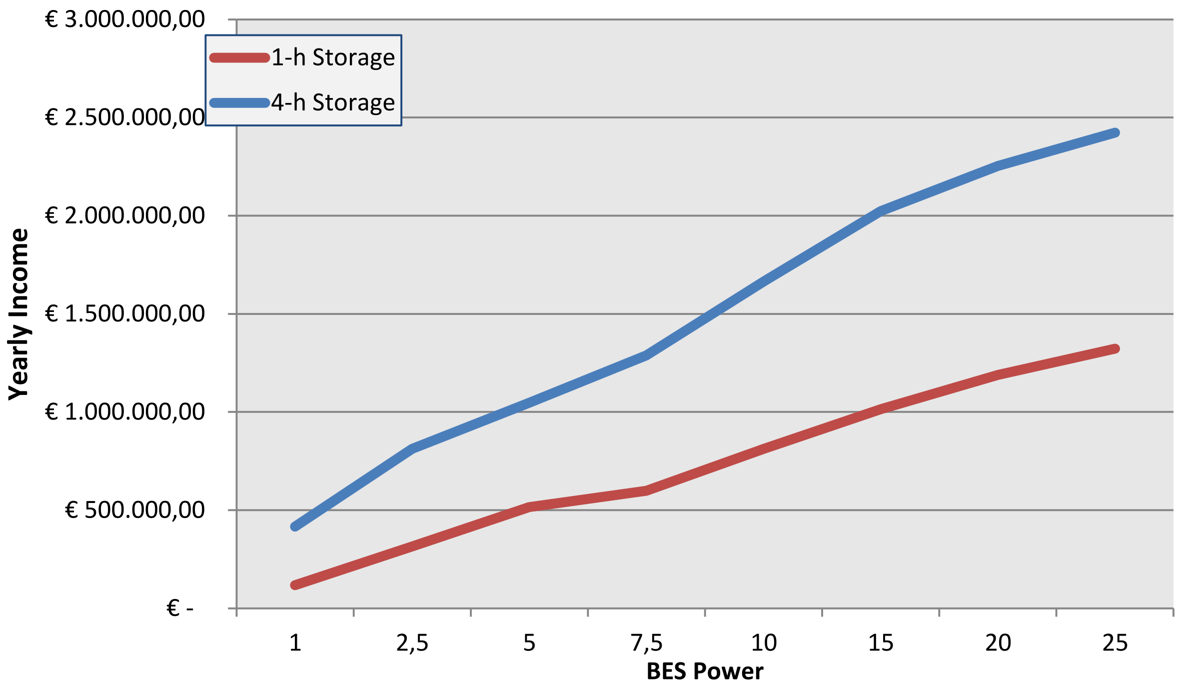

Fig. 4.10. *Yearly avoided cost for performing Active Power Balancing, according to ESS size*

Comparing this graph to figure 4.7, one can see that Active Power Balancing, while providing no actual income, reduces expenses at a larger rate than other services such as EA. The figure above represents the yearly estimated avoided cost, not the NPV of providing this service for 10 years. Even with small amounts of storage, there are large amounts of savings related to avoided balancing costs.

3.3. Benefit Assessment

Still, no consideration had been given to the expected lifetime of a BES providing this service. The cost per cell or per MW of available power is no different than in EA, but the lifetime of the cells is. The Simulink model also keeps track of the SoC of the BES, and using the Rainflow cycle counting algorithm, the expected lifetime for each storage size can be determined. Larger sizes take longer to charge and discharge, and thus age less within a year. Oversizing of the equipment is recommended for increasing lifetime, but this happens only after a BES is able to fully satisfy the needs of the service it is providing. This does not happen, for sizes below 25 MW.

From the image below, and the data that was required to form it, it is possible to deduce that it is the number of cells which mainly determines the lifetime of the system. It is also the number of cells which incurs in the heaviest CapEx. For the case of a 10 MW BES, for example, the cost of the cells is around 12,500,000 €. The yearly avoided costs by providing the service – that is, the income from the service – is 1,665,540 €, which amounts to a NPV of 12,860,820 €. However, the BES has an expected lifetime of 5.18 years, which means the CapEx cost must be repeated halfway through the project's lifetime.

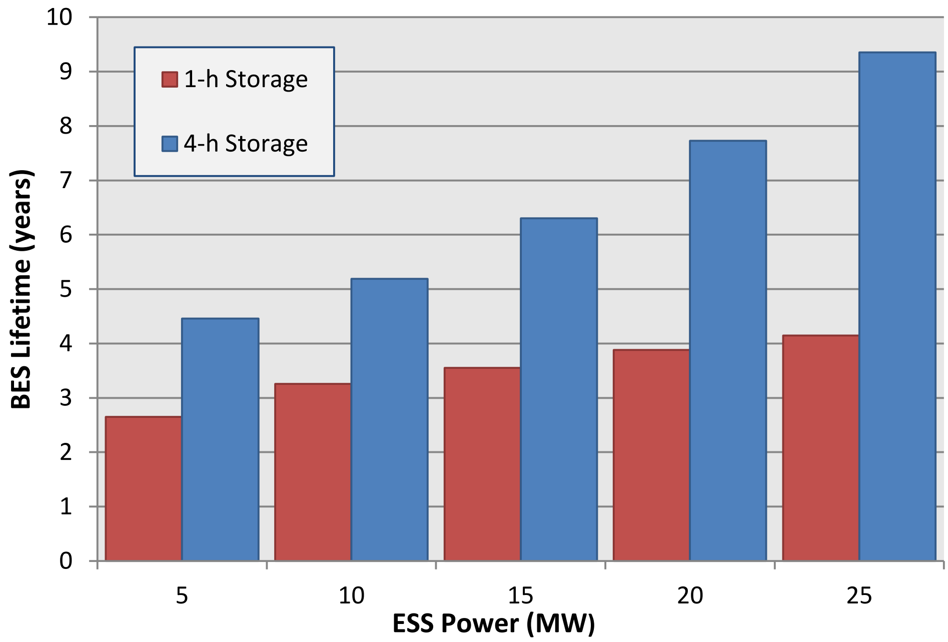

Fig. 4.11. *Expected BES lifetime, according to BES power*

Unlike EA, where the technology proved to be simply unsuitable due to its energy related costs, the modeled lithium ion BES seems almost able to provide this service, but is limited only by the specific costs used to assess the benefits. With the availability of additional data, or modeling cells with a slightly lower cost or a slightly longer lifetime, the results might be different. Or, if the service provision is desired no matter the cost, in order to guarantee increased reliability of the WPP, external funds must be provided.

4. Active Power Regulation

The last service that will be assessed is Active Power Regulation. This involves providing primary frequency control, on a contract with Energinet. Despite the fact that it is a very fast action and requires no human intervention, all interactions have been arranged, 24 hours prior, in the Danish Regulation Market, managed by Energinet. Participants are paid for their availability, and their interaction can be monitored by Energinet to ensure that they are actually performing as requested, per the mechanics explained in chapters 1 and 2. The objective of this service is to provide primary control to reduce changes in the frequency, and keep it within the values of 49.8 and 50.2 Hz, until secondary balancing control can enter and restore balance to the system. The ability of the BES to perform such a service has already been evaluated in chapter 3.

4.1 ESS Strategy

Despite being a very fast operation, all interactions have been decided the day prior, as the income from this activity come in the form of payments by Energinet for bids of availability. As explained in the first chapter of this work, participants are paid the same price, no matter their bid, this price being decided by the most expensive bid that was accepted. The historic payments that Energinet has delivered are available as a signal, and decomposed into payments for upwards regulation and downwards regulation. These fees have a strong variance, with a mean value of 44.45 €/MW per hour of standby for upwards regulation, and 21.81€/MW per hour of standby for downwards regulation. During some particular cases, which were common in 2010 but rarer in the present year, fees have even reached 500 €.

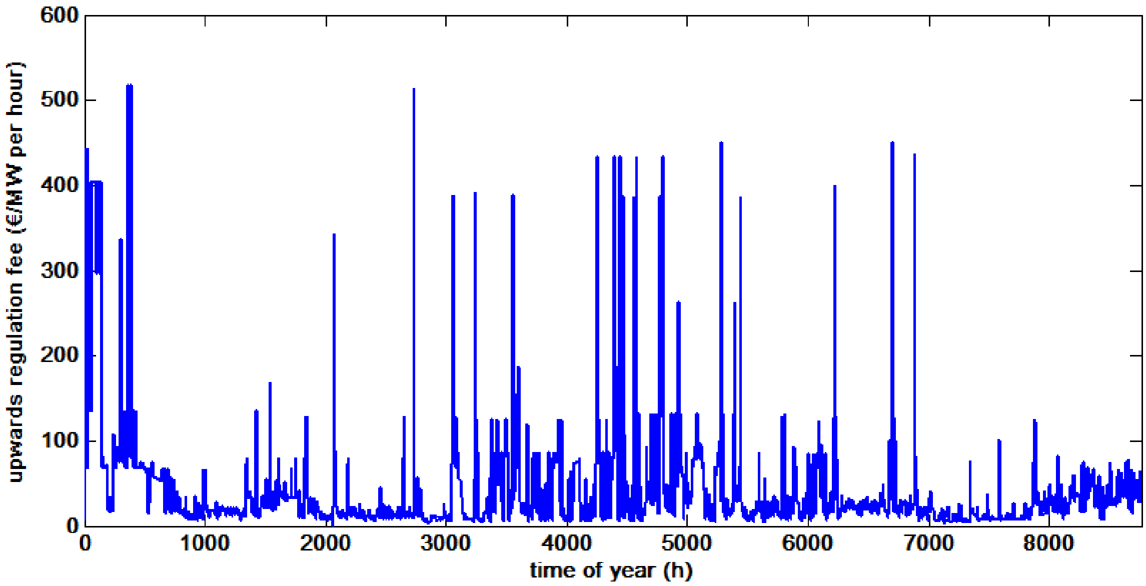

Fig. 4.12. *Upwards Regulation fees, for 2010, for western Denmark.*

Downwards regulation payments follow a similar trend, though with lower values and less variations. At this point, it might be tempting to attempt to find a correlation between wind production and the price of upwards regulation, or the requested amount of standby power and the price, or the load and the price. However, in all these events, a simple statistical analysis shows little if any correlation. A value of 1 in the correlation factor indicates that the signals might be proportional (or at least dependent) one on the other. A value of -1 indicates inverse dependence. A value of 0 indicates no correlation at all. The correlation between the upwards regulation fee and the wind supply -0.0331, indicating a very weak negative correlation.

This correlation is still too weak to warrant a close attention, and the rest of the dependency must rest on external factors, such as spinning reserve availability, transmission capabilities and usage patterns. In any case, the strategy is reduced to that of EA: to examine recurring patterns and determine the best times for performing the service. Unlike EA, however, the simple possession of a BES pushes towards always bidding, at all times, as no losses are suffered by remaining in standby, other than the inability of using the promised energy.

Before proceeding to a temporal analysis, there are some pertinent "rules" for this strategy. The minimum bidding power is 0,3 MW, and bids larger than 5 MW might be rejected in favour of more expensive ones, if accepting the 5 MW bid would exceed the amount requested by Energinet. Furthermore, bids and fees are paid in blocks of 4 hours. The ESS must remain available throughout the four hours, and the fee paid is the same during these four hours, though is only expected to last for up to 15 minutes at a time. Refer to chapter 1 for more information on these requirements.

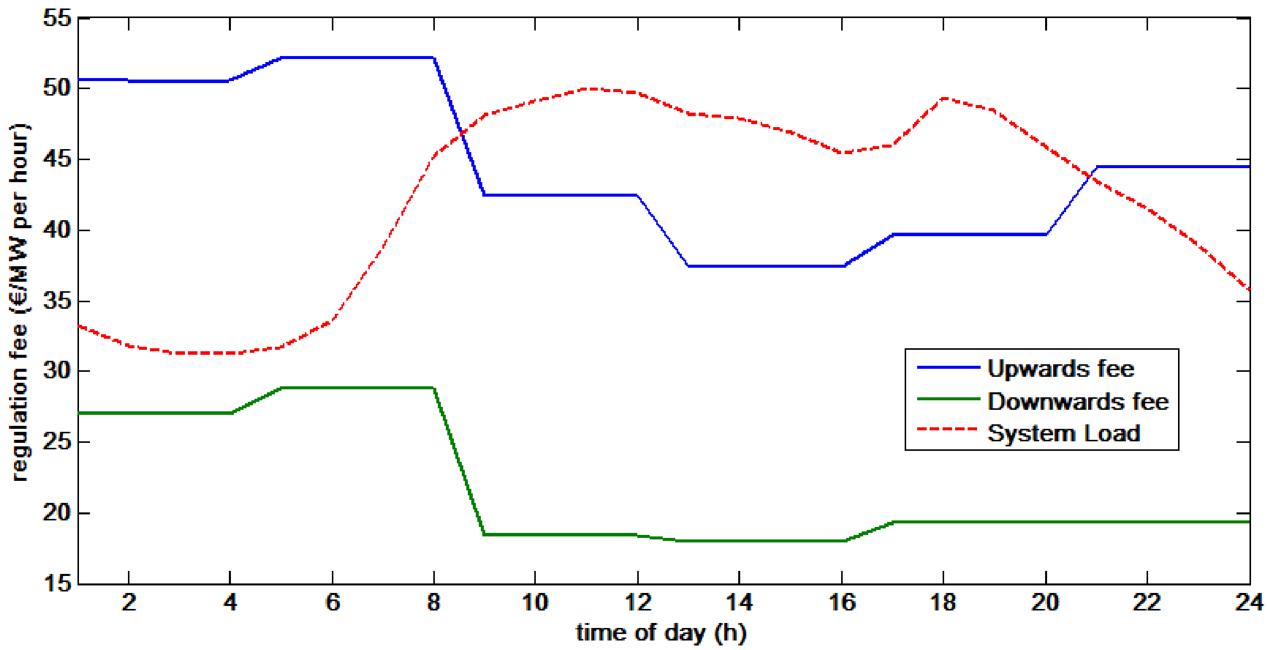

Fig. 4.13. *Average regulation fees throughout the day, compared with the system load.*

From the image above, it is simple to point out the most profitable hours, which don't match with the hours of highest demands. This is even more visible within a weekly scale.

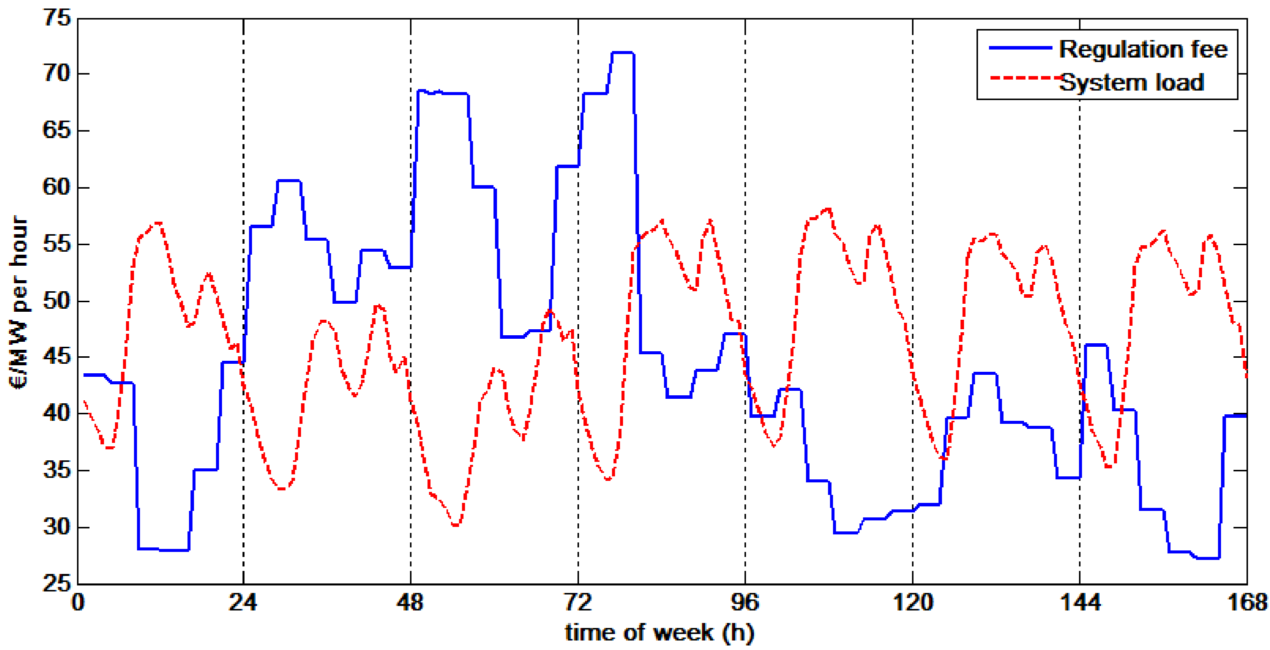

Fig 4.14. *Average upwards regulation fees throughout the week, compared to system spot price*

The image shows a strong correlation with the system load, and therefore, the system price. Indeed, the factor is of -0.61, meaning that at lower load, higher regulation prices. In any case, the best strategy keeps being to offer the service at all hours, perhaps shifting the proportion of the battery that is dedicated to upwards and downwards regulation.

4.2 Income Calculation

Being that the BES can offer its services at all times (as long as it is able to deliver what is promised), the only thing left to calculate is the proportion in which these two services – upwards and downwards regulation – are offered. Limiting the operation to purely upwards or downwards regulation means that any usage during one block will reduce the ability to perform the service during the next one. Instead, this strategy proposes to distribute the BES's resources according to the prices paid for each service.

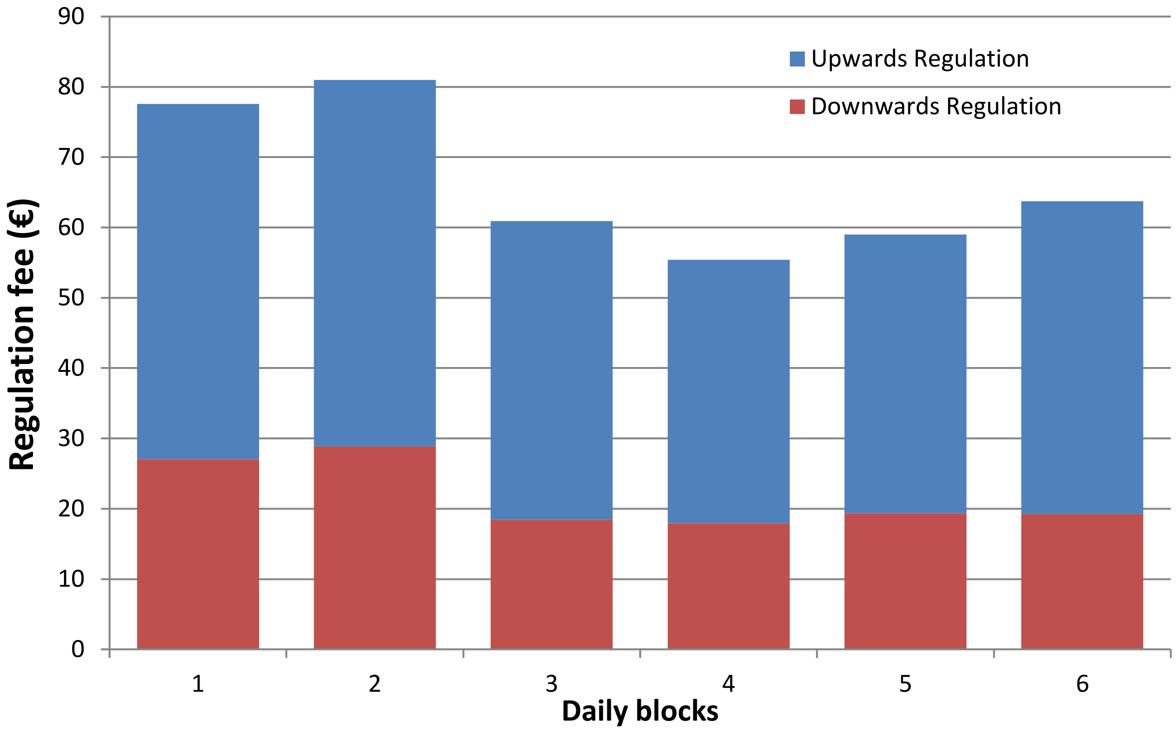

Fig. 4.15. *Yearly average of payments for upwards and downwards regulation, during the day's blocks.*

From the above information, it is possible to determine in which proportion the two services will be provided during the day, so that the following ratio will be maintained.

$$\frac{Pu(i)}{Pd(i)} = \frac{Fu(i)}{Fd(i)}$$

Where Pu and Pd are the power being offered for upwards and downwards regulation, respectively, and Fu and Fd are the payments paid for the services, during each block i. This comes from the separation of each part based on the percentage that its service provides for each block's total income.

$Pu(i) = \frac{Fu(i)}{Fd(i)+Fu(i)} \cdot P_{ESS}$ and $Pd(i) = \frac{Fd(i)}{Fd(i)+Fu(i)} \cdot P_{ESS}$, respectively.

The total yearly income can be calculated as follows.

$$Income = 365 \cdot 4 \cdot \left[\sum_{i=1}^{6} Fu(i) \cdot Pu(i) + Fd(i) \cdot Pd(i) \right]$$

Which, using the abovementioned properties, can be reduced to

$$Income = 365 \cdot 4 \cdot P_{ESS} \cdot \left[\sum_{i=1}^{6} \frac{Fu(i)^2 + Fd(i)^2}{Fu(i) + Fd(i)} \right]$$

Leading to a simple linear relationship, where the yearly income can be stated as

$$Income = P_{ESS} \cdot 324{,}641.75 \text{ €}\, MW^{-1}$$

This implies very high yearly incomes, even for small sizes of BES. This is even more significant, when the fact that only 15 minutes of power at a time are needed, and so the maximum current can be set to 4 times the nominal current of 50 A. This allows more power to be delivered by fewer cells.

4.3 Benefit Assessment

The low amounts of storage time required for this activity, connected with the low prices for power associated with lithium ion technology in BES, makes this service quite profitable, for all scales of ESS.

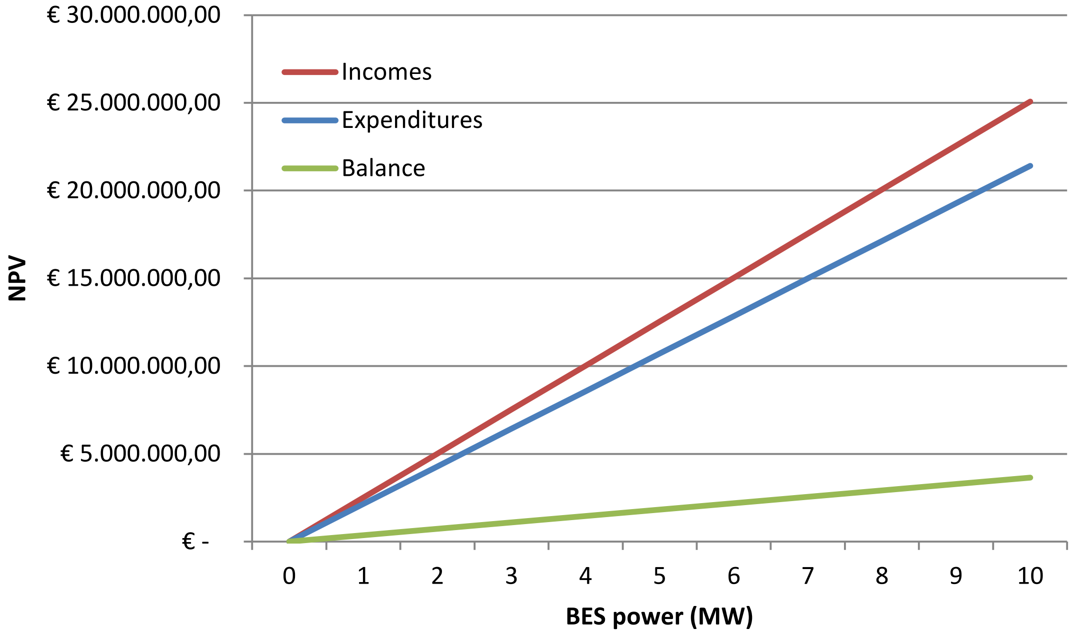

Fig 4.16. *Net Present Value of income and expenditures for a 10 year project, for different ESSs.*

An important detail that had to be estimated in order to make these calculations was the expected lifetime of the BES. As actual second-to-second frequency measurements would be required in order to estimate the required cycles that such a system would have to go through, an approximation of a full cycle a day was used. This is in fact a pessimistic view, as even if there was a low frequency demand every day, the delivered power would not necessarily reach the maximum power allowed, and this power is reduced constantly as the 15 minutes go by and secondary reserves go in effect. An approximation of some 33 cycles a month was used, which means that the estimated lifetime was of 2.5 years. Actual measurements might change this result, but until further information is obtained, this number is used in the following calculations.

Year	0	1	2	3	4	5	6	7	8	9	10
Income	€ 0	€ 325	€ 325	€ 325	€ 325	€ 325	€ 325	€ 325	€ 325	€ 325	€ 325
Expenditure	€ 652	€ 4	€ 4	€ 655	€ 4	€ 655	€ 4	€ 4	€ 655	€ 4	€ 4
Balance	€ -652	€ 321	€ 321	€ -331	€ 321	€ -331	€ 321	€ 321	€ -331	€ 321	€ 321
NPV	€ -652	€ 306	€ 291	€ -286	€ 264	€ -259	€ 240	€ 228	€ -224	€ 207	€ 197
Total NPV	€ 314										

Table 4.3. *NPV of a 1 MW, 15 m BESS, providing active power regulation for 10 years, in thousands of Euros.*

The technology being modeled is well-suited to provide this service, not only due to its scale, its ability to be easily controllable or its fast response time, but for the price and lifetime capabilities which it possesses. The limited amount of power that Energinet asks every day for regulation is the limiting factor in providing this service.

5. Optimal Control Strategies

In light of the previous sections' findings, Active Power Regulation far outdoes Energy Arbitrage as a profit-generating service, apart from providing the WPP with its own short-scale regulating capabilities. However, it would still be desirable to be able to offer Active Power Balancing, in the form of forecast error reduction, as a profitable service. Having each WPP possess the ability to produce their exact predicted output with little or no external balancing would greatly increase the easiness of having wind energy take a more important role, with increased penetration.

Despite BES's high energy costs, the possibility of using the revenue generated from providing regulating power to fund forecast reduction activities will first be explored. A general "optimal" control strategy, that is able to secure both balancing and regulating needs, will then be explained, without specifying the ESS technology required.

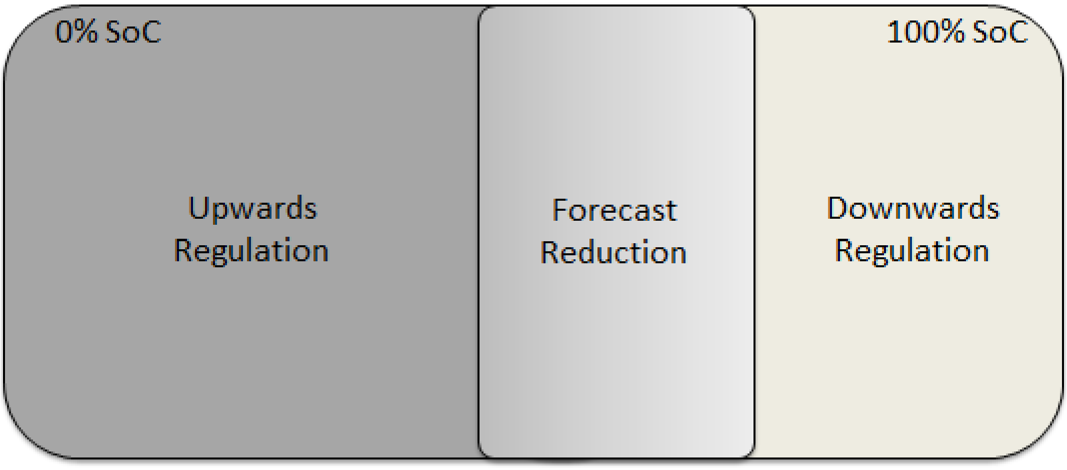

Fig 4.17. *Possible SoC distribution, for providing power balancing and regulation.*

One of the factors which enables BES to provide active power regulation in a profitable way is the short time span required. Only fifteen minutes are needed to fulfill the requirements posted in [20], which means that fewer cells can be used for the same amount of power at a lower price. When dealing with a service like forecast error reduction, longer delivery times are needed, as shown in figure 4.9. It is possible to use the profit generated from active power regulation to fund some less productive power performing forecast error reduction. Both services can be performed simultaneously and with the same BES, simply by limiting the share of SoC that they are able to affect.

The image above shows a possible allocation of resources, in order to be able to provide different services. The power distribution is, of course, the same in essence, but by administrating different amounts of delivery time, and defining different discharge currents, different amounts of the global BES power capacity can be divided by the services.

If, for example, a 10 MW BES with a delivery time of 1 h is divided among three services: 20 MW for 15 minutes of Upwards Regulation, 10 MW for 15 minutes of Downwards Regulation, and the remaining for Forecast Improvement, the following distributions would go into effect. The whole BES is able to provide 10 MW for 1 hour. If capacity is at half, it is able to provide either 5 MW for 1 h or 10 MW for 30 minutes. The 10 MW can then be delivered as 40 MW during 15 minutes, thanks to the technologies capacity of delivering up to 6 times its capacity current. As long as capacity is at 50%, the

BES will be able to deliver 20 MW for 15 minutes, as required by upwards regulation. As long as capacity is below 75%, the BES will be able to charge up to 10 MW for 15 minutes. The remaining 25% of the cell can be used by the forecast improvement service, as long as it does not move the SoC beyond the limits imposed by the other services.

Calculations were performed as to exactly how much power can be funded by the rest of cell operating for active power regulation. The high cost of cells means that 10 MW of ESS power performing frequency regulation allows only for 1.5 MW of "free" power, to be used in forecast error reduction. Increasing the amount of power dedicated to regulation can only work up to certain point, as Energinet's needs for regulation are not infinite, and in fact tend to average 27 MW.

If profits are not of concern, or if a cheaper technology is being employed, larger amounts of ESS could be dedicated to forecast reduction, while frequency control is kept to keep the operation profitable.

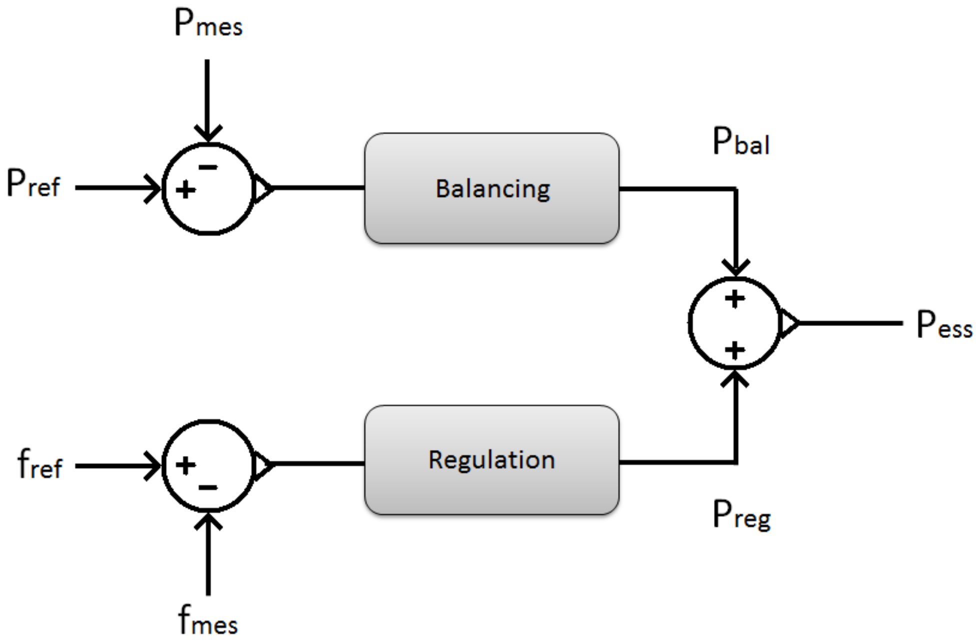

Fig 4.18. *Signal treatment for performing both Active Power Balancing and Regulation*

Remembering that the ESS and the WPP operate in conjunction, and as part of the network, it is possible to simply add the signals for delivering services with seemingly conflicting orders, as changes in the total output of the WPP, caused by the ESS, will produce the desired outcome of the services. The orders for regulating power Preg and for balancing power Pbal, exist in different time scales, the first taking place within the minute and the second within the hour.

Chapter V. Conclusions

This chapter brings the project to a close, answering the questions first posed at the beginning, as well as addressing the limitations of the project and proposing future work.

1. Wind Power and Energy Storage

The wind energy industry, like the oil industry, is concerned in the attempt to refine their prime matter into a more practical and profitable form. Decades of research in chemical processes gave the oil industry the capability of turning crude oil into useful fuel for the world. Similarly, a well carried out development of turbine technology, control strategies and energy storage is vital to secure the role of Wind Power Plants (WPP) as a reliable energy source. The main problem that this development faces is the variability of the wind, in different time scales. While long seasonal variations are still out of reach for improvement, WPPs are already equipped to offer increased control in shorter time scales. Pitch control, advanced generator topologies and power electronics allow limited regulation of the output, both in the active and reactive components. Active power can easily be regulated downwards by the use of pitch control and set-points, at the cost of losses of potential wind energy caused by the production curtailment. Upwards regulation is also possible in a limited amount, but again, by operating at a less-than-optimal set-point. Energy storage offers a possible alleviation of this problem, by allowing the WPP to operate at its full potential, instead of having to keep its production in check.

As parts of the electric grid, it is important for WPP to be able to contribute to the stability of the system. In regards to active power, it is critical for them to be able to perform in ways similar to conventional power plants and to be, if not fully controllable, at least accurately predictable. To be able to control their output, to provide upwards and downwards regulation, to follow their forecasted production closely and to help the grid in case of faults and sags means, to the WPP, to be a strong and reliable energy source. Different technologies of Energy Storage Systems (ESS) allow for the control of these variations in different time scales. While seasonal variations can only be faced with large scale storage such as pumped hydro, Battery Energy Storage (BES) offers the possibility of controlling shorter time scale variations, potentially offering upwards and downwards balancing services within the daily operation and providing some regulation capabilities without having to operate at sub-optimal set-point. That answers the first driving question of this work: "To identify the most adequate technologies and the most useful and needed services for WPPs in Denmark".

While lithium ion cells are still amongst the more expensive ESS technologies, interest by the automotive industry is helping in their development, increasing their lifetime and their safety of usage. Widespread adoption by a fleet of electric vehicles could further drive the costs down. Evaluating the ability of BES to provide these services is of great interest, and making sure that it can form a synergetic unit with wind parks and also to ensure the reliability of WPPs. This presents the second driving question of this work: "To model the execution of these services, to ensure their technical feasibility." Technologies like supercapacitors and flywheels, though more expensive in larger scales, could offer even faster response times, but simulations performed with the Real-Time Digital Simulator (RTDS) environment were able to replicate a BES providing these services, and show that such a system is able to complement the deficits of wind power.

Increasing the reliability of wind power plants will not alone secure their continued usage. Wind power must be cost efficient in itself, without incentives or government support, in order for the technology to prosper and have a wider adoption. Evaluating the benefits that an ESS can provide to a WPP is vital to see what exactly the added value of having such a system is. This was achieved by answering the last driving question: “to identify the most profitable service or mix of services to be provided, with the most adequate technology, and to determine the expected benefit of performing said services.” Expected earnings for energy arbitrage, power balancing and power regulation were obtained, these services being relevant given the explored time scale and the technology being considered. The high costs of the modeled BES technology showed pure energy arbitrage as unprofitable and power balancing barely financeable, though power regulation with lithium cells seems to be quite attainable. If profits are not the main objective, or if the service must be provided, independently of the cost it might bring, then having a BES give power balancing for forecast error reduction greatly improves the predictability of WPP power output and could thus ensure their increased penetration in the electric system.

Regarding the actual findings of the profitability of the selected services: the high cost of the modeled BES and the strong effect that cycling has on its expected lifetime limit its use in services such as Energy Arbitrage, where profit is directly related to the number and depth of cycles. While there is a potential source of income in trading with the temporal dimension of energy usage, the high cost of each individual cycle of the BES means that such a service would not be profitable under the current technology, or at least not with the available data. Given that a service like forecast error reduction is done not only with the purpose of increasing the profitability of the WPP but also to increase its reliability, the work found the net cost of providing the service, accounting for the costs avoided from balancing power resulting from the increased accuracy.

In a broader perspective, the seasonal, synoptic and daily variations, as well as the deviations within hourly expected values, must all be addressed in one way or another. While geographical distribution can help with wind volatility in the small time scale, the matter of WPP reliability in longer time scales remains. Energy storage can help increase the stability and predictability of wind power production, making WPP more suitable for operating in larger penetrations.

2. Future Work

While the work at hand has covered its aims in providing a good estimation of the added value of energy storage in providing services to wind power plants, it leaves many new questions and areas of possible research.

The defining advantage that the RTDS system offers is the possibility of interfacing with the real world. This sets the stage for much further work. The cell current could be output from the system into a real electrochemical cell, to test the response time of the cell and verify the accuracy of the cell model. The energy management system controller could also be taken out of the simulated environment, and implemented in actual hardware. This would permit the verification that the designed control algorithm is functioning correctly. Commands for the operation of the simulated WPP could also be delivered via external input, so that a real wind signal could be simulated in the RTDS’s grid, and the effects on the storage state of charge monitored over several days. The built model can easily be expanded to accommodate all of these changes.

On the side of the benefit assessment, the results obtained were limited to the data available. More concise information regarding actual BES costs might provide more accurate results. Furthermore, the active power balancing benefit estimation requires signals for both wind production prognosis and actual wind production. In the present work, the forecast signal was generated by using a production signal for an unknown WPP. More accurate results would follow using an actual forecast signal.

Finally, in order to more effectively cover the variations of the wind in different time scales, a hybrid energy storage system could be applied. Such a system would count with two or more different technologies, each used to respond to changes in a different time scale. In that way, the faster, but more expensive, technology could be used for quick and small variations, while larger storage takes charge after a certain time or magnitude has passed. This would both increase the versatility of the system while driving the costs of providing a service down, thus increasing the potential benefit of the services. A study into the working of such a system would have to follow a similar route to the one in this project, first selecting a variety of services, and then exploring different technologies and their ability to fulfill these services. A control system would be more complicated than the one implemented in this work, as it would also have to decide which storage technology to use, but the potential benefit of the system could well prove to be greater than the ones reported in this project.

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Appendix

The attached CD contains:

- A PDF version of this text
- A folder labeled “Sources” with a selection of sources from the reference list
- A folder labeled “Simulink Model” with the .mdl and .m files required to calculate the benefits of each service, as well as an .xls file containing the market data from Energinet, used in the calculations.
- A folder labeled “RSCAD Model” with the .dft and .sib files required to execute the simulation in an RTDS and visualize the simulation environment.