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DIVISION OF ELECTRIC POWER ENGINEERING

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Grid stability benefits with Seatwirl vs. horizontal shaft windpower plant

MASTER THESIS

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Abstract

In an ac power system the generated power should be equal to the consumed power in addition to the system losses. In case of any steady state imbalance between generation and consumption, the system frequency will deviate from its rated value. To keep the frequency stable, control power plants have to intervene. This intervention will not be immediate, which highlights the increasing importance of the instantaneous inertial response. In this thesis it is discussed how the inertia reduction in the power system due to large penetration of renewable energy sources that will effect the power system stability; non-inherent inertia generation consisting of fast-responding energy storage is proposed and financially compared with each other and with the synthetic inertia technology in the wind turbines. Seatwirl technology - A new floating wind turbines design with the ability of providing synthetic inertia- is introduced and simulated showing its ability to generate synthetic inertia, a technical comparison is made between Seatwirl and the previously suggested inertia generation methods. This thesis also highlights the benefits of using Seatwirl technology on the stability of electrical networks.

Acknowledgement

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Contents

List of Figures

List of Tables

1 Introduction

Rising awareness on climate change, unreliable fossil fuel supplies and prices in addition to the Environmental impact of nuclear power are some of the driving forces behind the spike in renewable energy sources(RES) generation. All over the world targets have been made towards a transition to RES, the European Union has its own 2020 climate and energy package setting three key targets to be met by the year 2020, this includes a RES generation percentage of 20% in the EU [1]. These legislation's resulted in an increment of investments towards RES to meet with the expected RES generation percentage required by 2020 and as a result, power system dependency on such generations is increasing. Due to the nature of RES, increasing network dependability on such generation means new challenges to the power system stability as system frequency should be between acceptable limits at all operation times. Contrary to the conventional power plants, some types of RES does not change their power output with changing system frequency as they are decoupled from the system frequency and do not utilize any meaningful inertia such as the synchronous generators instantaneous inertial reaction [2], in another words, they can be considered as power sources with zero inertia constant. System inertia plays a main role limiting frequency deviations and keeping the rate of change of frequency (ROCOF) in the designated grid normal operational limits. The possible negative result of insufficient system inertia is the split of the grid into islands and blackouts such as the famous incident occurred in September 2003 when Italy was disconnected from the former Union for the Coordination of the Transmission of Electricity (UCTE) and other similar events that resulted in dividing the UCTE into island grids similar to what happened in November 2006 resulting in three divided power grids [3]. As grid codes are requiring RES to contribute to the frequency stability now that they have a bigger share in energy generating and increasingly in the future as they increase their grid power penetration, synthetic inertia functions are being added to the various RES so it can mimic the inertia reaction of an actual synchronous generator. Implementing synthetic inertia on RES requires a way to sense the system frequency deviation and utilize the kinetic energy available in the turbine. By definition, the more kinetic energy in the turbine the more power contribution it can make to the frequency stability, with a bigger mass and improved wind turbine designs having more kinetic energy than the regular horizontal turbine it is expected that the synthetic inertia function generated from it will have more effect on the ROCOF and system frequency stability than traditional horizontal turbines, this will be demonstrated clearly along the thesis. Sections of the thesis,

- Section 1 Is a short introduction to the thesis.
- Section 2 Reviews basic definitions and concepts related to the thesis.
- Section 3 Discusses system Inertia importance and availability
- Section 4 Discuses variable speed wind turbines that are now available due to the advances in electronic inverter systems.
- Section 5 Introduction into vertical axis wind turbines and Seatwirl concept and technology.
- Section 6 Storage systems and inertia estimation.
- Section 7 Seatwirl financial evaluation.
- Section 8 Turbine modeling.
- Section 9 Simulations results.
- Section 10 Discussion and analyses.
- Section 11 Ethical and sustainable development aspects.

2 Related basic definitions and concepts

2.1 Frequency Control

Measures used to keep the energy demand and supply equal to a system frequency of (50Hz or 60Hz) during operating times.
There are different kinds of frequency control based on the interaction time:

2.1.1 Primary frequency control:

Primary control is the first response to a frequency change which is activated through automatic governors within some few seconds from the appearance of the disturbance. This service will be usually delivered by traditional power plants operating at a lower output than their rated in order to be able to ramp the power up and down when needed.

2.1.2 Secondary frequency control:

After a certain time secondary replaces primary frequency control as it is usually cheaper or more stable. Secondary control is applied by changing the base generation of the system, such as changing generation in a power plant that is not contributing to the primary control or using energy storage systems like batteries as they are considered in Holland to keep up with the future power regulations as higher penetration of wind power is expected [4].

2.1.3 Tertiary control:

Tertiary frequency control is requested through the operators from the supplier. Hydro pumped storage systems or gas power plants are what is usually used, tertiary control is slower in acting that the primary and the secondary.

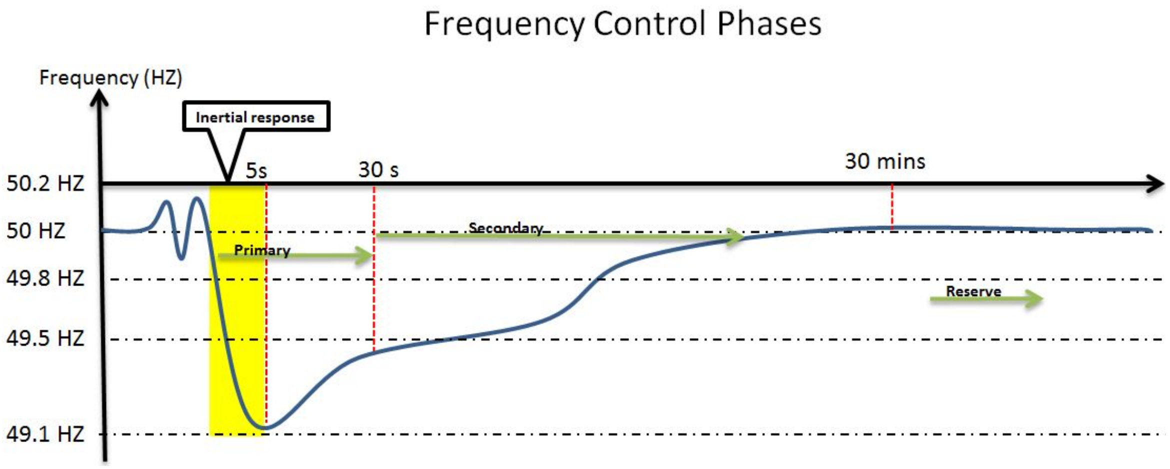

Figure 1: Time scale of frequency control

2.2 Voltage Control

The voltage on transmission and distribution lines must be controlled within certain limits. This can be achieved by controlling reactive power levels injected into the power system. Synchronous generators are usually used for this mean, SVC (Static Var Compensator) and STATCOM are used where the generators in the system are not able to regulate the voltage.

2.3 Load leveling

The process of storing energy during low energy demand time so it can be used later on when high demand occurs. In power systems with high wind penetration, the generated power at low demand night time will be used during peak load times at day time with the help of storage utilities such as pumped hydro storage's.

2.4 Island Grids

When a connection to the main power network is not feasible due to economical or technical reasons, a stand alone grid for this area can be initiated. When island grid is dependant on diesel generators, it will cause high cost and increased emissions due to fuel consumption, frequent fluctuation in power and high maintenance because of the constant ramp up and down.
One solution to the high cost/emissions of the island grid is a combination of using energy storage systems that can reduce load peaks and RES to reduce or eliminate the fuel cost. Storage systems can be tuned to work with the fluctuating energy supply of the RES to the demand and adapting to the frequency regulation.

2.5 Frequency nadir

A term indicates the minimum post disturbance frequency.

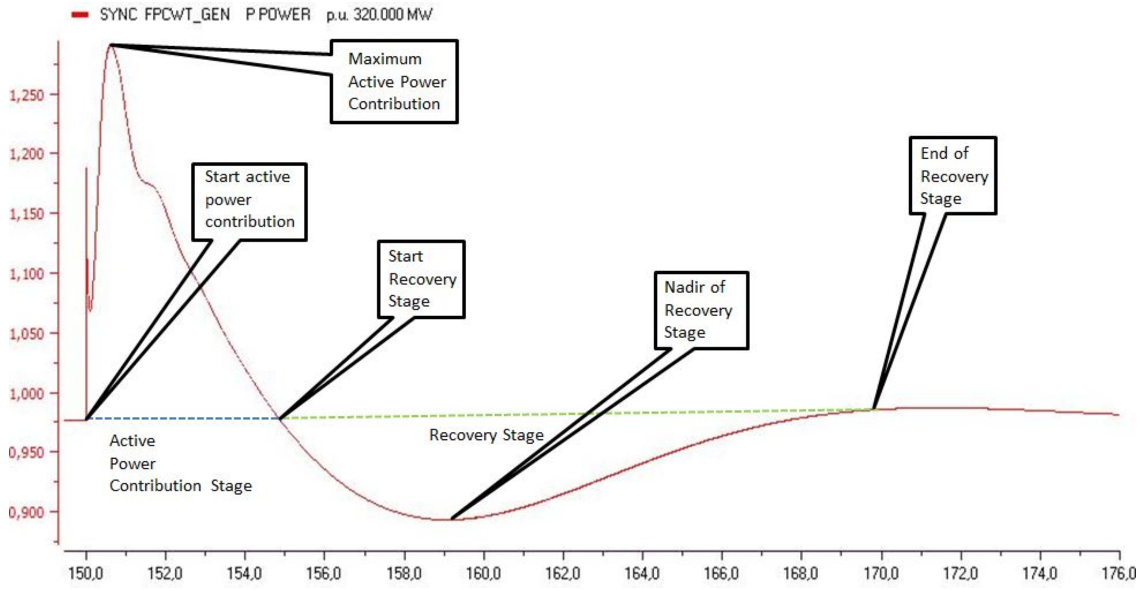

Figure 2: Power contribution and recovery stages

3 System Inertia importance and availability

Grid frequency f can be considered as an indicator for system generation and consumption power balance, when an imbalance occurs the power system frequency will change accordingly. One of the responsibility's of a transmission system operators is to operate the electric grid at a certain system frequency which is the nominal grid frequency f_0, 50 Hz in Europe, where the torque is continually adjusted to keep the system frequency at the nominal grid frequency. in equation (1)

$$\delta\omega/\delta t = \frac{T_{gen} - T_{load}}{J_{sys}} \tag{1}$$

Where $Tgen$ is the generated torque, $Tload$ is the consumed torque including grid losses torque and $JSys$ is the total moments of inertia in the system representing the coupled synchronous machines response in case of any power imbalance. $\delta\omega/\delta t$ is equal to $\delta(2\pi f)/\delta t$ indicating change in grid frequency/machine rotational speed, a negative torque in the power system means a case of generation loss which will lead to a decrease in frequency while a positive torque means a load decrease and an increase in grid frequency. Inertial response comes instantaneously from synchronous machines damping the system frequency deviation, this can be done by injecting kinetic energy while the rotational speed of the machine decreases in case of a decrease in frequency and storing that energy in case of an increase in the system frequency while the rotational speed increases. The below equation shows the relationship between kinetic energy, rotational speed ω and the inertia of the machine J.

$$E_{kin} = \frac{1}{2} * J * \omega^2 \tag{2}$$

The inertia constant H is the ratio of kinetic energy of a synchronous machine rotor to the rating of the machine, this can be interpreted as how long a generating machine can provide its rated power depending on its own stored kinetic energy[5], See Equation (3):

$$H = \frac{E_{kin}}{S_B} = \frac{J\omega^2}{2S_B} \tag{3}$$

S_B is the machine rated power and H is measured in seconds. The link between power generation imbalance and inertial response can be given by:

$$\delta(\frac{1}{2} * J * \omega^2)/\delta t = Pg - Pl \tag{4}$$

Where the left part of the equation is the derivative of the power system aggregated generators kinetic energy. As PCR does not get activated till seconds after the frequency deviation starts, this means that the frequency is solely affected by the inertial response in the first seconds after a frequency deviation which highlights the importance of system inertia and how lacking sufficient inertia due to the increase of inverter based RES could lead to serious network errors. In the recent situation of the connected power grid for the ECSA, the amount of residual inertia J_{res} needed to prevent a blackout is decided by ROCOF limits regulations which is in our case $\delta f/\delta t$=2 Hz/s, using related equations(1)(2) and by using an inertia constant similar to that of already available biomass and hydro units which is between /1.5s-4s/ [6], we get a maximum rated power in the magnitude of 20GW which is to put in context Significantly lower than the total installed hydro power capacity of 136 GW in the EU-27, with an additional 62 GW in Norway, Switzerland, Turkey, Croatia and Iceland combined [7], so it is clear that hydro along with other RES such as biomass can generate the needed J_{res} for the scenario discussed without calculating existing synchronous generators inertia nor calculating the inertia generated from synchronous loads, in other words even by the continuous decrease in synchronous generation inertia it won‘t be expected to not have enough inertia in the EU-27 power system to cover a blackout scenario in case of a single fault with a load generation of 3 GW in the near future.

Keeping the ROCOF between limits in addition to support keeping frequency within the limits of 47.5 Hz and 51.5 Hz as exceeding these limits will activate load shedding and a blackout will probably occur[8] will be the synthetic inertia main task in smaller connected grids, also in future scenarios with increased power demand/increased RES penetration to the power grid and in island grids situation. Synthetic inertia will have to cover the reduced power system inertia due to less synchronous generators and due to less coupled from the grid synchronous loads, providing synthetic inertia could be through very fast acting storage units as we will discuss later in chapter 6 or through a very fast acting generation that emulates the actual synchronous inertia such as the method used later on in our wind turbines models used in this thesis to sense any variation in frequency and injecting kinetic energy in response. When considering dedicated methods and technologies to generate synthetic inertia it is relevant to consider financial rewards/benefits to encourage such generation and to consider quantifying such generation, both aspects will be further discussed in chapter 7.

4 Variable speed wind turbines

Wind turbines now days usually are variable speed wind turbines, this allows them to efficiently capture wind. This also means the output in terms of voltage and frequency will be variable, to over come this issue power electronics will be between the generator and the grid converting the output of the generator to match the grid frequency and voltage. We will discuss both the doubly fed induction generator where just a part of the power output will be fed throw the power electronics and the full power converter generator were all the power get to the grid through the power electronics.

1. Doubly fed induction generator (DFIG): A variable speed generator that can collect energy from a wide range of wind and with low mechanical complexity. However, more complexity when it comes to electronics and electrical wiring used. Only the rotor power(30% of the total power) is converted in the case of DFIG, which means a smaller, less losses, more efficiency and cheaper power converter compared to other kind of variable speed generator. However, having to transfer power in both direction and having the ability to control power factor and generate reactive power increases the converter complexity. Having an overall look on the DFIG system considering equipment cost, maintenance and installation shows that there is a lower cost compared to other variable speed systems in some power levels range. The disadvantage of the DFIG system compared to the full power converter system is the need for a gearbox between the turbine and the generator needing extra space and resulting in additional maintenance costs and reducing reliability. From an inertia point of view, Although part of the power generated is directly connected to the grid, the DFIG delivered inertia is small and do not effectively influence frequency quality [9].

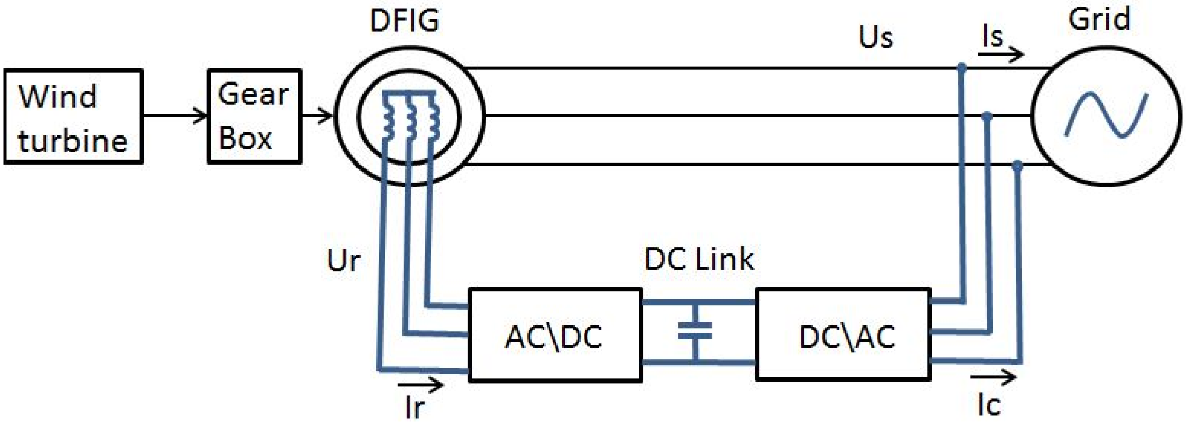

Figure 3: Variable-speed wind turbine with a doubly-fed induction generator (DFIG)

2. Full Power Converter generator: Unlike previous DFIG, a full power converter is used as all the generated power pass through the power converter. Multiple poles full power converter wind turbine can be designed which implies that the elimination of a gearbox is possible. In case a gearbox is used, it should be designed so that maximum rotor speed and the rated generator speed are corresponding. This system is well developed and robust, fully decoupled from the grid due to the usage of full power converter and no direct connection with the grid, so no inertial response in expected.

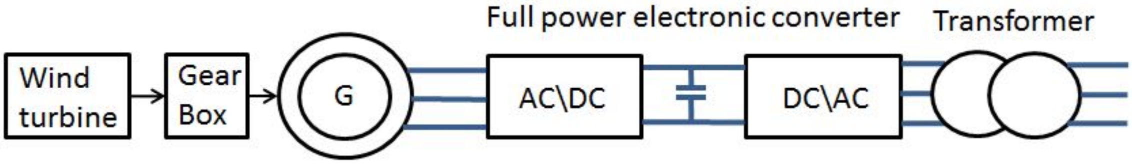

Figure 4: Variable-speed wind turbine with a synchronous/induction generator

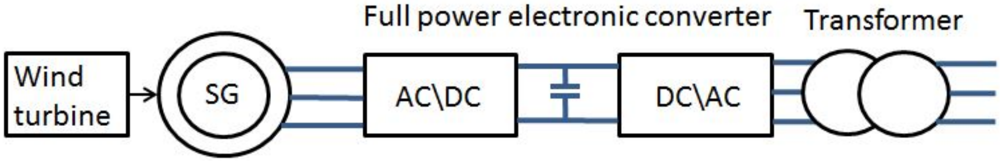

Figure 5: Variable-speed direct-driven (gear-less) wind turbine with a synchronous generator (SG)

What is going to be used as the generator in our horizontal and vertical(Seatwirl) model and simulations later on in the thesis is the full power converter generator due to the fact that it is totally decoupled from the grid so generated synthetic inertia can be observed more clearly.

5 Introduction into vertical axis wind turbines and Seatwirl concept and technology

5.1 HAWT and VAWT comparison

Horizontal axis wind turbines (HAWT) and Vertical axis wind turbines (VAWT) have some similarities and common parts but they differ in configurations and properties. A main advantage in VAWT is that they are cross-flow devices meaning that they can harness wind power from any direction eliminating the need of expensive yaw drive mechanism existing in HAWT, another advantage is that the VAWT generator, gearbox and brakes can be positioned near the tower base, resulting in safer and easier maintenance[10]. blades wise, they can have a straight bladed simplified geometry, making it easier and cheaper to manufacture, also they can be located nearer to ground making them more stable and easier to blend with the surrounding environment. Disadvantages includes VAWT stalling due to gusty wind, different applied forces during rotations affecting the blades structure and having a low starting torque compared to HAWT‘s. Common HAWT and VAWT components includes the rotor that converts wind power into mechanical power, tower that provide the support to the rotor, in most cases a gearbox to adjust the rotational shaft speed with the generator speed and a control system. Both tower needs a foundation that can withhold a certain stress. VAWTs can be divided into three main categories based on their aerodynamic shape and mechanical characteristics:

- The Savonius rotor
- The Darrieus rotor
- The H-Darrieus rotor

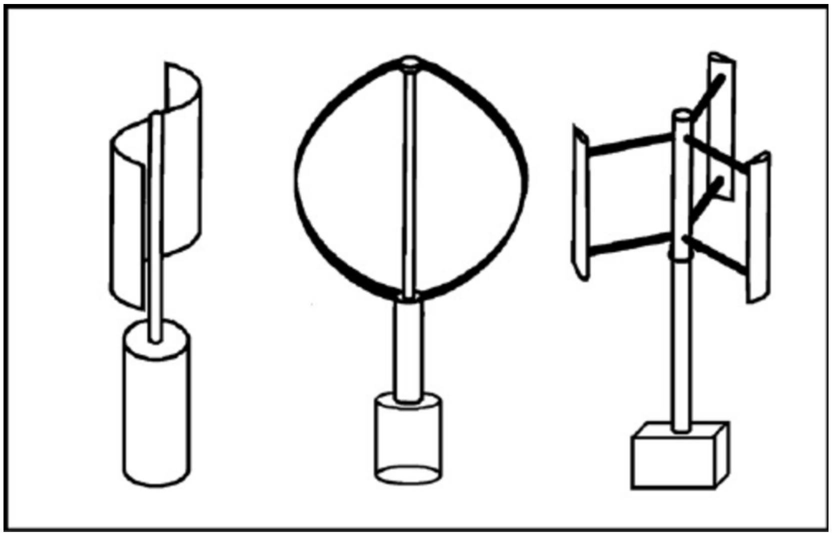

Figure 6: To the left is a Savonius rotor, in the middle a Darrieus turbine and to the right an H-rotor

Comparing different VAWT‘s categories it is found that.
The Savonius rotor:

- Poor efficiency and low power outputs, power coefficient about 0.3 and needed blade tip speed ratio to operate between 0.8 to 0.85
- Reliable

- Easy Maintenance
- High material need to manufacture, not cost-effective[11]

The Darrieus rotor:

- Not self starting
- Simpler control system[11]

The H-Darrieus rotor:

- Improved design of the Darrieus rotor
- Controlled by stall or pitch control
- Optimal rotational speed reached near after the cut in wind speed
- Less blades stress loading than other VAWTs, more suitable for large scale electricity production[11]

5.1.1 Offshore wind turbines

Wind turbine are designed considering a certain speed which is called "rated speed", this speed is usually a low wind speed as it is the most common winds inland. Any variations from the rated speed will negatively effect the efficiency of the wind turbine. In the current commercial wind turbines, when high energy high wind blow up, it is more effective to shut down the turbines reducing wear and tear and minimizing different hazards. To over come the above issue, the idea of offshore wind turbine came up as the most common offshore winds are high speed consistent wind, which means that the rated wind speed which is used to optimize the turbine power output is much higher leading to higher efficiency. Other upsides such as matching offshore wind peaks with power demand time pattern (contrary to onshore winds) reducing cost and needed ancillary services, positioning wind turbines out of public eyes as they are considered unattractive and reducing transmission installation costs as usually large cities are situated near the coastlines. On the down side, Offshore wind turbine are considerably more expensive due to:

- More complicated installation, usually base structures must be secured to the ocean floor providing needed support to overcome the ocean environment.
- Increased maintenance, more wear and tear because of the higher winds and corrosion effect due to the ocean water, performing regular maintenance operations is also more expensive due to the location.
- Integration issues, such as new offshore wind variations assessment methodologies, power transmission from offshore to grid, high production cost...etc.

Various studies have been conducted on the financial comparison between offshore and onshore turbines which concludes to a lower($/kw-hour) for onshore wind turbines than offshore. however, this cost difference is reducing as new inventions are decreasing the offshore turbine base construction cost as the later discussed Seatwirl and new technologies in power transmission is getting cheaper.

5.2 Seatwirl

Seatwirl is an offshore floating vertical wind turbine, the turbine tower is connected with a floating element and a keel that reaches into deep water depth. The tower, floating element and keel are attached to each other and rotates as a one piece structure while the keel acting as a stabilizing mass when capturing wind energy and the whole weight of the turbine is carried out by the water. The turbine generator can be seen underneath the blades surrounding the rotating central turbine mass, having the generator housing situated near to water surface will increase the turbine structure stability and provide an easy access to the maintenance personnel rather than climbing till the top of the turbine as in a regular horizontal turbine. Seatwirl manufacturers claims that it can be placed in deeper waters because of its floating capabilities contrary to the bottom fixed offshore turbines. In addition to the vertical turbines benefits and properties discussed earlier such as not needing a yaw system for aligning with the wind or a pitching mechanism and a lower maintenance cost due to less moving parts, the Seatwirl inventors claim that the bearings don't need to carry the weight of the turbine which means less stress on the bearings.

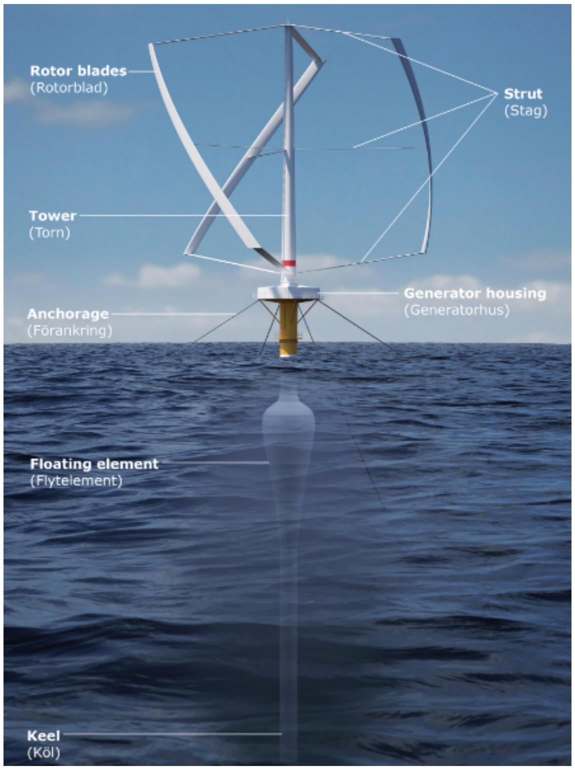

Figure 7: Seatwirl

6 Storage systems and inertia estimation

As the RES penetration continue to grow in the power grid system, several sources for inertia to cover up the decrease in synchronous generator inertia is discussed. In this thesis we are going to discuss how some types of storage systems can work out to be very similar to synchronous inertia response (mainly depends on utilizing time), these are the storage systems technologies that are most applicable in inertia generating/Emulating application from the thesis point of view as other storage technologies are either not technologically mature enough or they have expansion capabilities limitations due to environmental and geographical reasons such as pumped hydro. We can generate synthetic inertia from some types of decoupled RES such as wind turbines using controllers that extract kinetic energy from the turbine blades and the rotor of the non-synchronous wind turbine generators, this can be achieved by continuous measuring of the frequency rate of change for the system and applying an appropriate electrical torque on the rotor of the wind turbine which slows the rotor down releasing kinetic energy from the blades and rotor (Similar to how actual synchronous generator inertia works), how the actual synthetic inertia for the wind turbines controller works will be discussed later on in this thesis where resulting inertia will be considered as synthetic, artificial or emulated. Assuming a point where no inertia is available in the power grid, not even the residual inertia J_{res} previously discussed, it can be expected that the grid frequency will change instantaneously and sharply steep, this means all frequency control types won´t be able to react due to not having enough time. The storage capabilities that will be considered in this thesis are three types of battery based storage systems, flywheel storage systems and super capacitors.

6.0.1 Flywheel

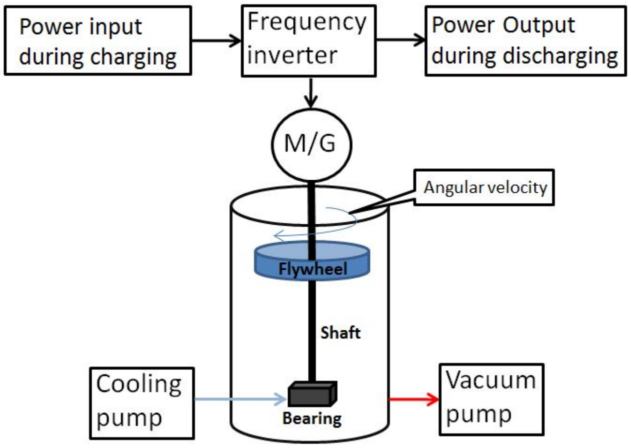

Figure 8: Schematic diagram of flywheel energy storage system

During charging time a motor accelerates a rotating mass which called flywheel so it can store kinetic energy that we can use later on when the energy is needed. The spinning of the wheel is made easier by putting the wheel in a vacuumed environment and using magnetic bearings to keep the rotational resistance as minimum as possible. Kinetic energy is extracted by a generator during discharge which is driven by the inertia of the flywheel resulting in the deceleration of the flywheel. flywheels properties are:

- Very high cycle life
- Very high power density
- Average energy density

- Very high self-discharge rate
- High number of charging-discharging cycles and only short storing periods (neither charging nor discharging)
- They absorb energy during the regenerative braking phases and feed power back during acceleration phases

And they have the below parameters: Round-trip efficiency equals to 80% - 95%, Depth of discharge equals to 75%, Self-discharge equals to 5 to 15%/hour, Power installation cost equals to 300 €/kW, Energy installation cost (high speed flywheel) equals to 1,000 €/kWh, Deployment time is about 10 ms [12]. This makes flywheel very suitable for high power short period application as in emulating inertia.

6.0.2 Super capacitors

Examining the power density and energy density compared to batteries we will find a much higher cycle life and power density capabilities and a much lower energy density. It is acceptable to say that comparing power density and energy density super capacitors is located between classical capacitors and batteries. Important parameters for our study: Round-trip efficiency equals to 90% - 94%, Depth of discharge equals to 75%, Self-discharge is up to 25%/hour in the first 48 hours, Power installation cost equals to 10 to 20 €/kW, Energy installation cost equals to 10,000 to 20,000 €/kWh, Deployment time is about 10 ms.

6.0.3 Batteries

The included batteries types in this thesis(Lead Acid, LI-ION, Sodium Sulphur) have a deployment time less than 5 ms, important parameters to our study for different battery types are mentioned in table 1.
Choosing the above power storage units came from the fact that power is provided semi-instantaneously with utilization time of 10 ms for both flywheels and super capacitors and 5 ms for battery based storage systems(after the detection of the imbalance in grid frequency), response time with the magnitude of 5ms and 10 ms are very near to the inertial instantaneous response and can serve to some extent as a synchronous generator inertia emulator. Because of the 5ms response time difference between batteries and other storage units types we can expect a higher power feed from batteries during the inertial response time frame which is in few seconds magnitude. In theory, storage systems can be installed and controlled at high voltage levels taking in mind that a detailed power flow assessment should be performed to minimize system losses as the traditional power plants that are providing synchronous inertia are connected to high voltage levels [13].

7 Seatwirl financial evaluation

When choosing a unit to trade synthetic inertia all factors that can effect the synchronous inertia should be considered, Checking the relation between inertia and both power and energy, energy output is equal to the machine rotating parts kinetic energy change. From Equation (2) taking the case of changing frequency, the energy output can be described as in equation (5):

$$E_{inertia} = E_{kin} = \frac{1}{2} * J_{sys} * (\omega_1^2 - \omega_2^2) \tag{5}$$

While Power output is the gradient of rotating parts stored kinetic energy. From Equation (2) after time differentiating:

$$P_{inertia} = \frac{\delta E_{kin}}{\delta t} = J_{sys} * \omega * \frac{\delta \omega}{\delta t} \tag{6}$$

Comparing equation (5) and (6) shows that while power depends on frequency and ROCOF, kinetic energy is affected by the frequency change. In another words inertia can't be considered as power so that the effect of kinetic energy limiting the frequency change is taken into consideration and at the same time can't be considered as energy so ROCOF limits won't be neglected. From above argument, it is concluded that energy and power units won't be a proper units to be used for inertia economical evaluation.

This section will determine the environmental and economical cost for the production of synthetic inertia produced by energy storage units. The power storage units examined are three types of battery based storage systems, flywheel storage systems and super capacitors. For the cost of storage systems different units will be used for power and energy, cost per unit power will be (\$/kW) and the cost per unit energy will be(\$/kWh). The storage systems are financially and environmentally evaluated from an inertia point of view using three ways:

1. Net present value (NPV) method and value per inertia unit.
2. Environmental risk and various other parameters.
3. Utilization time.

7.1 Net present value

Present value (PV) is the worth or value of a future sum of money given a specific rate of return on an investment. It reflects the discounted value of money into the future. The net present value (NPV) method will only consider financial evaluation, given in equation (8):

$$NPV = -Capital_0 + \sum_{y=1}^{30} \frac{F_y}{(1 + r_D)^y} \tag{7}$$

Where $Capital_0$ is the initial capital investment, 30 is the lifetime frame we are conducting the study in, F_y is the net cash flow at the end of year, and $r_D$is the appropriate discount rate. F_y is assessed for each year by the following relationship:

$$F_y = Savings(y) - (OM(y) + Capital(y) + PCS(y) \tag{8}$$

Note that these capital costs do not include the PCS or fixed operation and maintenance(O&M) costs, these will be added separately in the excel calculations(Appendix 1). power conversion system (PCS) required for many storage devices to convert the dc output to ac before interfacing with the load, By using power electronics and advanced control, the PCS looks like a traditional synchronous machine to the power system even when there are no spinning masses. Even inertia can be modeled within the system, enabling it to deliver or draw power to and from the grid, dependent on the system frequency

and rate of change.
An important distinction in storage system architectures must be addressed here. If a storage device is able to be sized for power and energy independently of one another, then the unit power and energy costs are given as separate components from which the total cost must be obtained by summing over power and energy requirements. However, if the storage cell has a fixed power/energy ratio, then the costs are given as a complete system cost and either the power or the energy component must be used to find the total capital cost (whichever is higher). For example, if a 1 kW / 1 kWh battery cell cost \$100 and the power and energy components cannot be sized independently, then the unit capital cost of this device would be either \$100/kW or \$100/kWh, and even if the storage requirement were only 1 kW / 0.5 kWh, the battery would still cost \$100. The former system architecture will be referred to as a “flexible” system, and the latter as a “fixed” system for convenience. For flexible systems, the capital cost may be calculated as:

$$Capital = (BOSp + Cp) * P + (BOSe + Ce) * E \tag{9}$$

(BOS) encompasses costs of all components of a system other than the device itself. In this expression,(BOSp) is the balance of system cost per unit power (\$/kW),(BOSe) is the balance of system cost per unit energy (\$/kWh),(Cp) is the storage cost per unit power (\$/kW),(Ce) is the storage cost per unit energy(\$/kWh), P is the power rating of the storage device (kW), and E is the energy capacity of the storage device (kWh). For the fixed systems, the capital cost must be calculated as:

$$Capital = Max[(Cp * P), (Ce * E)] + BOSp * P + BOSe * E \tag{10}$$

In our study all used storage’s are considered as a fixed system architecture and the BOS is assumed to be included in the storage unit initial investment price. The below schedule shows that Super capacitors, putting in mind the very low energy density issue they have and flywheels have an overall better NPV than battery storage units.

7.2 Cost per inertia capacity unit

As mentioned earlier in equation (6), a certain amount of power can be linked to the moment of inertia, calculating at the maximum ROCOF limit of 2 Hz/S, a $1MW$ of power will be linked to an approximate of 250 $Kg.m^2$.
Based on:

$$Cost_J = Cost_{1MWunit}/J_{1MWunit} \tag{11}$$

And under the condition of being able to provide energy for 5 seconds, the inertia capacity value $\$/Kg.m^2$ for the Flywheel will be 1200 and for the Li-ION batteries 800, based on this numbers an acceptable financial compensation can be agreed on, an investor should also consider the storage unit lifetime and O&M cost for an accurate financial comparison. The data used for the economic evaluation are from (table 1), noticing that all numbers are indications and may vary significantly among different products and installations. What is used in the comparisons is the short-term PCS (0 to 30 seconds) due to the parameters and use of synthetic inertia, one of the main differences between long and short term PCS operation is the need for thermal control in the case of long term operation which increases the cost. The focus will be on Power Quality Energy Storage Systems financial properties as it differs from the Bulk Energy Storage Systems[14][12][15][16] .

7.3 Seatwirl financial study

To be able to tackle the Seatwirl financial study, Seatwirl will be considered as a normal operation power production unit in the first part and the gaining from not having to acquire a supporting wind farm storage unit in the second part. The results from both parts will be analyzed to get an indicator of the financial performance for Seatwirl.

parameters/Technology	Lead Acid(Valve regulated)	LI-ION	Sodium Sulphur	Super Capacitor	FlyWheel (High Speed 150kw/15min)
Life time (Years)	5	10	15	20	20
Life time (Cycles)	2000	4000	3000	25000	25000
Power related cost ($/kw)	250	200	350	300	300
Energy related cost ($/kwh)	300	500	350	10000-30000	1000
Fixed O&M cost ($/kw-year)	10	10	20	5	5
Variable O&M cost($/kwh)	0.01	0.7	0.7	/	/
Replacement cost($/kwh)	200	500	230	0	0
Round-Trip efficiency(%)	75-80	83-86	75-80	90-94	80-95
Deployment time	3-5ms	3-5ms	3-5ms	<10ms	<10ms
Power conversion system ($/kw)	350	350	350	270	350
NPV($)	1265491,634	1304573,464	1114355,748	1458885,597	1378885,597

Table 1: Energy storage parameters comparison table

7.3.1 Seatwirl as normal operation power production unit

Based on public information published by Seatwirl [17], the cost for a SeaTwirl turbine (once commercially available) could be lower than for a conventional horizontal axis turbine for offshore use. For conservatism the same cost is however assumed for the two kinds of wind turbines. With regards to [18], the cost is assumed to be 2000 $ per kW. The variable O&M will be set at 0.02 $ per kWh [19] [18]. the income was estimated based on the Nordpool day ahead market data from year 2002 till year 2016 and due to the lifetime set as 30 years and lack of data before 2002, older years was estimated based on average day ahead data. Electricity certificates will be considered for the first 15 years of operation based on the average of the daily closing prices of spot price contracts at the three largest brokers in the electricity certificate market in 2015. It is assumed that the offshore wind turbine will typically generate about 41% of the theoretical maximum output [20]

Production unit	Lifetime (Years)	Cost ($/kW Power)	Variable O&M ($/kWh)	NPV
1 MW Seatwirl	30	2000	0,02	-748288,3764

Table 2: 1MW Seatwirl NPV

Offshore wind power is receiving subsidies from the electricity certificate system but the cost is too high to compete with other renewable energy sources and because of that it will play an insignificant role in the Swedish energy system during the 2020's, a negative NPV was expected for current market prices[21].

7.3.2 Seatwirl reducing the need for storage units

Recent plans to install a $2MW$ battery at the $90MW$ Burbo Bank offshore wind farm [22] highlights the possibilities contained in inventions such as Seatwirl, although technical and financial information of the installation discussed are not fully available yet, a short analysis based on table [1] Lead acid and LI-ION batteries technical/financial information shows a possibility of a near half million dollars in savings for a period of 5 to 10 years with a $2MW$ battery, considering Seatwirl lifetime of 30 years, savings in the range of 1,5 to 3 millions dollars is expected in case of an offshore Seatwirl wind farm. Another way to look at it is similar to what is discussed in 7.2 "Cost per inertia capacity unit", a 1 MW Seatwirl unit with a $Padd$ limits of 0.1 can save in cost per inertia capacity unit what is estimated to be approximately 80,000$ over the lifespan of the turbine takeing into consideration the variable O&M.

7.4 Storage units environmental overview

7.4.1 Batteries

Lead Acid: Contains lead and sulfuric acid which may lead to a lead pollution.
LI-ION: Contains toxic and flammable materials.
Sodium Sulphur: High operation temperature (300 Celsius) pose high danger to the surrounding environment and contains corrosive materials [14].

7.4.2 Flywheel

Very low environmental effect, high speed rotations of the rotor may pose a safety hazard in case of a malfunction[14].

7.4.3 Super capacitor

Very low environmental effect, surrounding magnetic fields can pose a health hazard[14].

7.5 Storage units utilization time

It is very important for the storage unit acting as synthetic inertia to have high speed and ramp rate.

7.5.1 Batteries

LI-ION: In a range of milliseconds start up time/response time with unlimited ramp time [23] [24].

7.5.2 Flywheel

Response time to full power$<$10ms with a 6-15 min Duration at rated power based on the design and flywheel inertia to size of generator and converter ratio[25] [24] .

7.5.3 Super capacitor

In a range of milliseconds start up time/response time with Up to 100 % of power capacity per second ramp time[23] [24].

In conclusion li-ion batteries, super capacitors and flywheels are a very promising technologies in case decided to be used for synthetic inertia applications

8 Turbine modeling

Before getting into turbine modeling, the method of instantaneously having an added active power injection from wind turbines (Inertia emulation) will be discussed, this method will be implemented in our horizontal and vertical turbine models.

8.1 Inertia emulation

Starting to act once a frequency deviation exceeds a certain limit set by the controller and differs based on the country grid regulation. The inertial power control input to the grid is set to be proportional with the grid frequency and ROCOF:

$$P_{in} = -2 * H_{wt} * f * \frac{df}{dt} \tag{12}$$

When the frequency decrease occurs, P_{in} starts to increase due to negative ROCOF, the increasing continues till the frequency deviation becomes zero. A higher ordered power from the inverter will lead to reducing the rotor speed and releasing the stored inertial energy from the wind turbine generator. The added electrical power will be injected from the wind turbine simultaneously with any load increase/loss of generation. Due to the temporary increasing in electrical power the difference between the mechanical and electrical power becomes negative as shown in equation[13], so the rotor speed starts to decrease leading to the release of mechanical power and the decrease in tip speed ratio (λ) and power coefficient (Cp) .

$$W_{wt} * \frac{dW_{wt}}{dt} * 2H_{wt} = P_{mt} - (P_{e0} + \Delta P_e) \tag{13}$$

Where ΔP_e is the injected electrical power into the grid and P_{mt} is the captured mechanical power. If the rotor speed decrease below a threshold of approximately 0.7 pu, the rotor speed and the mechanical power can‘t get back to their initial values[26] [27]. Commercial examples of synthetic inertia generation for wind turbine generators are: General Electric WindINERTIA™, ENERCON Inertia Emulation.

All power electronics included in the wind turbine must be designed to handle such a instantaneous increase in active power. Speed controllers will detect rotor speed reduction and decrease torque demand which will counteract the additional synthetic inertia injected from the turbine, this can be solved by delaying the speed controller response or having a dummy rotation speed input that cancels out the reduction in speed caused by the additional torque, in this thesis simulated models speed controllers response will be proportionally delayed to get the most of the injected inertia. In order to limit injected inertia to a realistic portion and to protect and keep power electronics financially feasible, a maximum power limiter can be used. It is worth mentioning that a direct pitch angle regulation varying the pitch angle will change the mechanical power due to the rotor speed and power coefficient change leading to a change in the grid frequency, but this can’t be used in our model due to Seatwirl being a VAWT with no pitch control.

8.2 FPCVWT

As the model shown below, the full power converter vertical wind turbine (FPCVWT) is a type of vertical wind turbine generators which operates at variable rotation speed to maximize the output power efficiency.

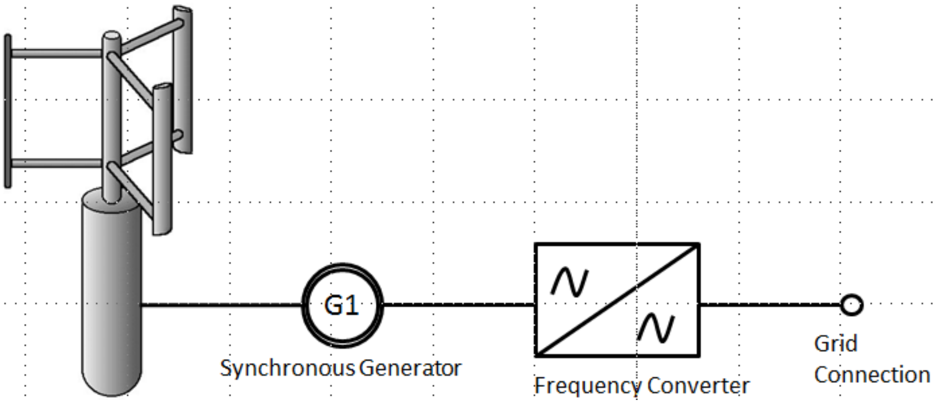

Figure 9: Full power converter vertical wind turbine model

The frequency converter consists of a machine-side PWM modulation rectifier, an intermediate dc system and a grid-side PWM modulation inverter. The main advantageous of this type of wind turbine generator is less mechanical strengths on the mechanical drive and higher efficiency in the variable speed. The main task of the frequency converter is to control the active rotor power in such a way that the rotation speed of the generator is following the wind speed in the most effective way. Additional control is the ac voltage control of each converter. The model of the frequency converter is represented as voltage source converters (PWM modulation converters) including intermediate dc voltage system. The FPCVWT model will be designed based on the below block diagram.

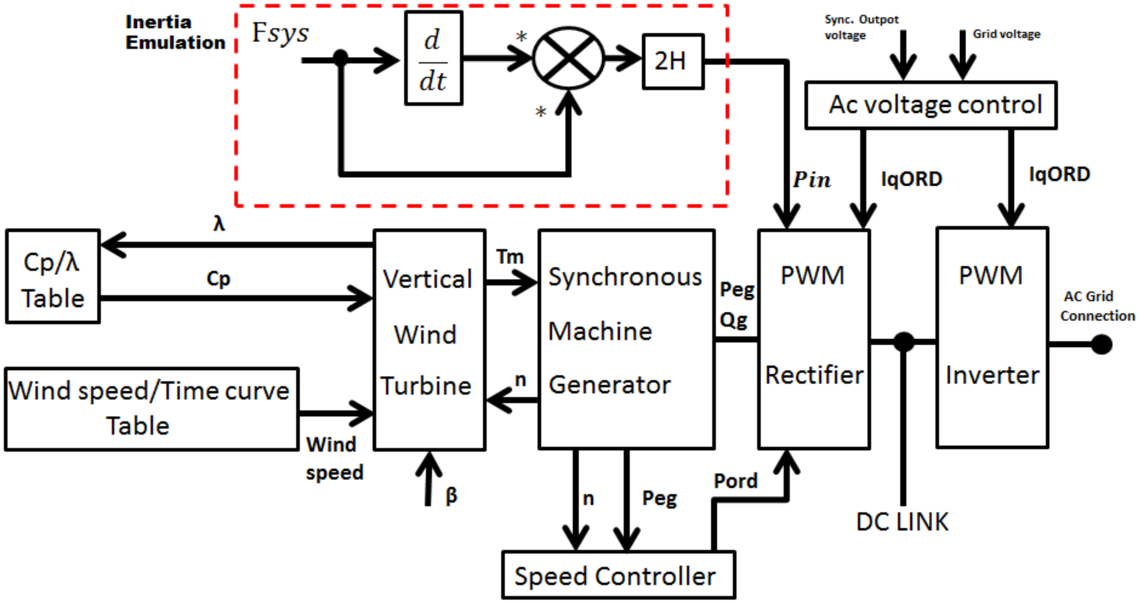

Figure 10: FPCVWT model block diagram

Where: β is the blade pitch angle in degrees, λ is the tip speed ratio, C_p is the efficiency of the wind turbine. F_{sys} is the system frequency, n is the rotation speed of the wind turbine in rpm, T_m is the mechanical torque, P_{eg} is the actual real power production, Q_g is the reactive power production, P_{in} added synthetic inertia, P_{ord} is the power order and Iq_{ord} the imaginary current order which controls the reactive power production/consumption of the PWM modulation converter of the FPCVWT. The added synthetic inertia P_{in} is added directly into the the converter in order to change P_{ord} limiting time delay to that of the converter only as inertial response time should take place before primary reserves is activated.

8.2.1 Vertical turbine

As the vertical turbine model is not available in SIMPOW, it has to be made based on the below equations using plain text than inserted as a customized library to the simulation program. Mechanical powerP_m is equal to the Power Coefficient C_p multiplied by the wind power.

$$P_m = C_p * P_w \tag{14}$$

Ideally C_p will equal $\frac{16}{27}$ or what called the Betz limits. The final mechanical powerP_m equation will be expressed as a function of air densityρ, rotor radius R, blade length h, wind speed V_0 and Power Coefficient C_p [28].

$$P_m = \frac{1}{2} * \rho * V_0^3 * R * h * 2 * C_p \tag{15}$$

The rotor mechanical torqueT_m can be calculated by

$$T_m = \frac{P_m}{w} \tag{16}$$

where w is the rotational speed in radians per second and it can be calculated by

$$w = \frac{\lambda * V_0}{R} \tag{17}$$

8.2.2 Speed control

The relation between power and wind speed can be shown in figure[10] where it contains an ideal wind turbine power curve, this relation determines how the control strategy will work and how much power can be extracted from certain wind.

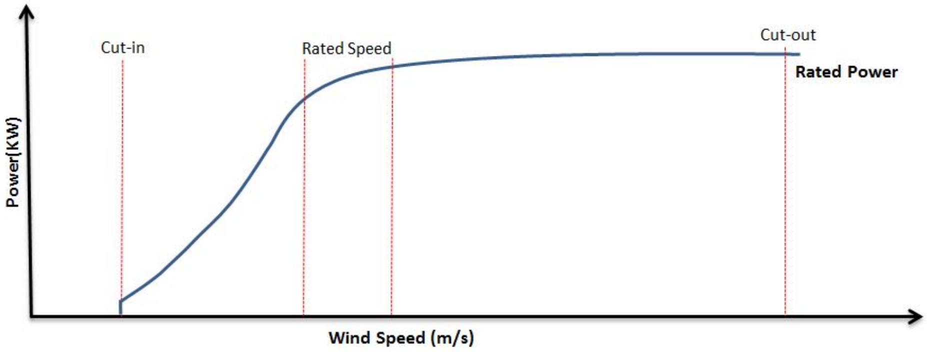

Figure 11: Ideal wind turbine power curve

The rotor speed is controlled to a fixed low speed rotation value at low winds and a maximum Cp, at rated speed power is controlled to its maximum at a maximum Cp or controlled to another point at the Cp/λ curve if needed, at high wind speeds blade angle will be controlled to keep a constant maximum power generated while Cp is decreased due to power transfer limitations in generator and converter. The way speed controller controls rotational speed and the generated real power of the full power converter wind turbine is by the output power order Pord as it can be seen in figure[9] and figure[11],is obtained from the speed control, which controls the rotation speed and generated real power of the FPCVWT, Figure 12. The input to the regulator is the actual real power generation and the speed. A speed reference is calculated from the actual real power generation. At low wind speeds and low active power generation, the speed reference is kept at the minimum speed reference value. The difference between the speed and the speed reference is derived and goes into the regulator of PI-type, the output is multiplied with the speed and the output is the power order to the machine model. The power order response is filtered and is limited both in magnitude and in its derivatives.

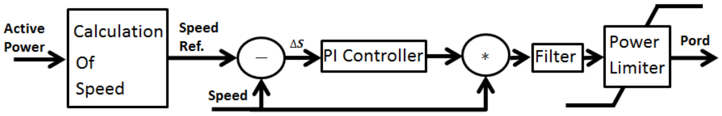

Figure 12: Speed Control Model block diagram

8.2.3 PWM modulation converters

By combining a pulse width modulation (PWM) rectifier and a (PWM) modulation inverter to a dc-link an ac/ac converter can be made with a sinusoidal input currents and bidirectional power flow.

8.2.4 Pitch control

Not existing in our vertical model.

8.2.5 Synchronous machine

Standard synchronous machine model is used for the FPCVWT generator with one field winding, one damper winding in d-axis and one damper winding in q-axis.

8.2.6 ac Voltage Control

The imaginary current order, Iqord, is obtained from the ac voltage control system, which controls the reactive power production/consumption of the PWM modulation converter of the FPCVWT, The input is the ac bus voltage and the ac voltage reference, parameters and the integration limits are user-defined data.

8.2.7 Inertia constant

The inertia constant used for the generator in this model is calculated based on Seatwirl experiment trial data and after weighting adjustments due to the information not been public yet by Seatwirl that J=5390695.8 $kg.m^2$ for a 1 MW unit with an average rad/s of 2.11 used for a wind velocity of 13.2km/h, from equation (5)

$$0.5 * J_{seatwirl} * W_{seatwirl}^2 = 0.5 * J_0 * W_0^2 \tag{18}$$

We get:

$$\frac{J_0}{J_{seatwirl}} = \frac{W_{seatwirl}^2}{W_0^2} \tag{19}$$

The reason for using the square can be understood by looking at the Revision of Mechanics Basics [29], assuming a flywheel is rotating at a speed ω1 and we want to find its equivalent inertia at the network frequency level, it will have a conversion ratio between the rotating subjects then the kinetic energy should be the same whether it is fitted on the network or Seatwirl side. Substituting in (8) $J_{sys-seatwirl} = \frac{5390695.8*2.11^2}{(100*\Pi)^2} = 243.17\ kg.m^2$, where $J_{sys-seatwirl}$ is the Seatwirl inertia converted to the system side. From $H_{seatwirl} = \frac{E_{kin}}{S_B} = \frac{J\omega^2}{2S_B}$ we find that $H_{seatwirl}$ is calculated to be: $H_{seatwirl} = 0.5 * \frac{5390695.8*2.11^2}{1MW} = 12sec$.

8.3 FPCHWT

The FPCHWT model will be designed based on the below block diagram, for this wind turbine, an existing SIMPOW turbine model will be used.

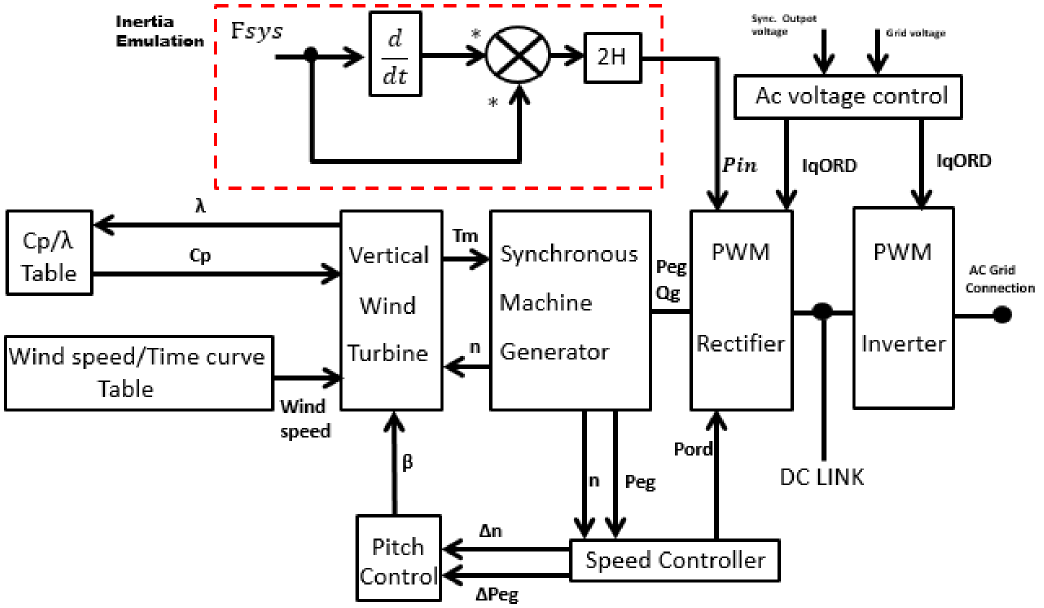

Figure 13: Horizontal model block diagram

8.3.1 Horizontal turbine

Based on the SIMPOW Horizontal turbine model. The rotor mechanical torqueT_m can be calculated by

$$T_m = \frac{P_m}{w} \tag{20}$$

Where P_m is calculated by

$$P_m = 0.5 * \rho * V_0^3 * R^2 * \pi * C_p \tag{21}$$

and the rotation speed of the wind turbine in p.u w is calculated by

$$w = \frac{2 * \pi * n}{60} \tag{22}$$

The tip speed ratio is given by the equation

$$\lambda = \frac{v_t}{v_0} \tag{23}$$

Where $v_t$is the tip speed of the blades in m/s.

8.3.2 Pitch control

Pitch control output is the the blade pitch angle in degrees β, which controls wind power capturing or the wind turbine mechanical torque. The input of the pitch control is the needed power and the speed deviation from the speed controller.

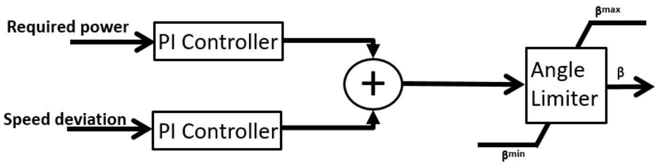

Figure 14: Pitch control model diagram

8.3.3 Inertia constant

The inertia constant for the generator used in this model is 5.5 seconds based on the SIMPOW model and an approximation based on other references [30].

9 Simulations results

The power system where the comparison will take place between a full power converter HAWT and a Seatwirl is a two-area system from Prabha Kundur's book [31]with slight changes such as changing one of the steam generators into a wind turbine and some transmission lines lengths changes. The used steam turbines are with one field winding, one damper winding in d-axis and two damper windings in q-axis with saturation. 2-winding transformers are modelled as ideal transformers where the first winding is connected to the first node, the second winding to the second node. Load connected to Bus7 is absorbing 200 MW in active power and 80 MVAR in reactive power. Load connected to Bus9 is absorbing 500 MW in active power and 80 MVAR in reactive power. Transmission lines will have 0.0001 resistance per length unit, 0.001 Reactance per length unit and 0.00175 total susceptance per length unit.

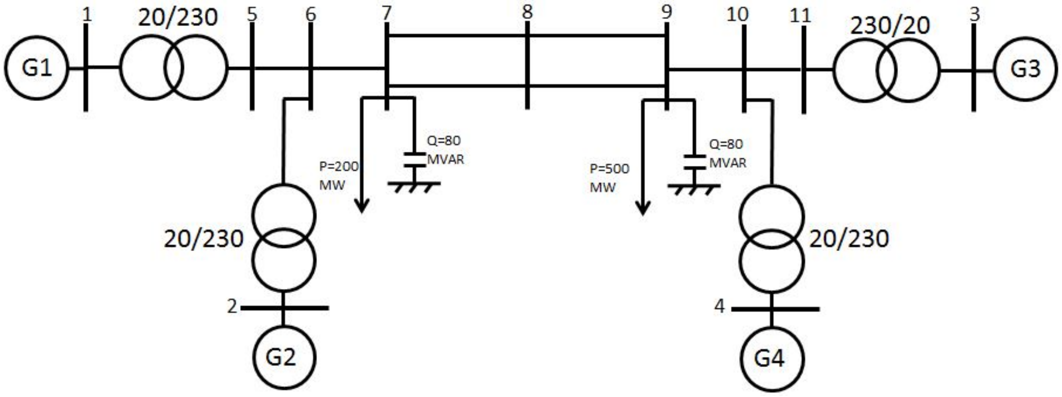

Figure 15: The basic two-area system used for the simulations

System frequency is 50 HZ, system rated power is 320 MW. G1 is the wind turbine with a rated power of 320 MW, G2, G3 and G4 are a typical steam turbines rated 200 MW,250 MW and 255 MW in the same order. Inertia response comparison between horizontal and vertical turbines will be mainly compared with rated speed wind. A delay will be presented in the speed controller and the converters are over diminsioned for the reasons described in chapter 9. A fault that leads to the disconnection of G2 is presented at second 150 where the wind turbine inertia response is observed, other faults on line(7,8) and on G4 will be implemented in sub section 10 and 11. One thing that was highly observable during the thesis simulations and can easily be overlooked by mistake is the fact that while synthetic inertia covers the power gap for a very short time between supply and demand, it can be observed as a spike in power due to the high power input in a very short time, meaning that it should be taken into consideration that during this time enough capacity in the power grid, relays tuning and adequate capacity for the power electronics should be considered.

9.1 Simulated wind turbines results verification

The used horizontal turbine model is based on the SIMPOW horizontal turbine model with various changes on the converters to be able to implement synthetic inertia. The vertical wind turbine model is based on the Seatwirl weighted data such as the λ/CP table, inertia constant, torque vs wind speed curve, power vs wind speed curve and various mechanical/physical data. The comparison below is between the simulated vertical model curves done in this thesis and a representation of the Seatwirl curves after weighting adjustment and modification so the real accurate Seatwirl data and some dynamic aspects wont be visible.

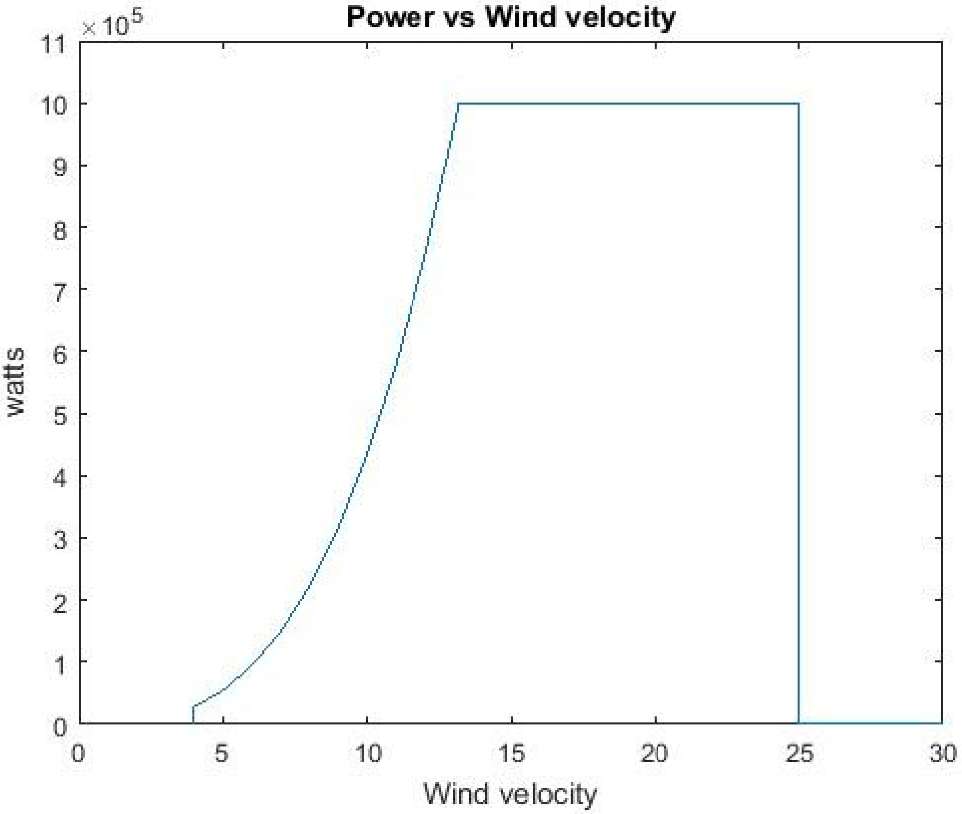

Figure 16: Seatwirl Power vs Wind velocity

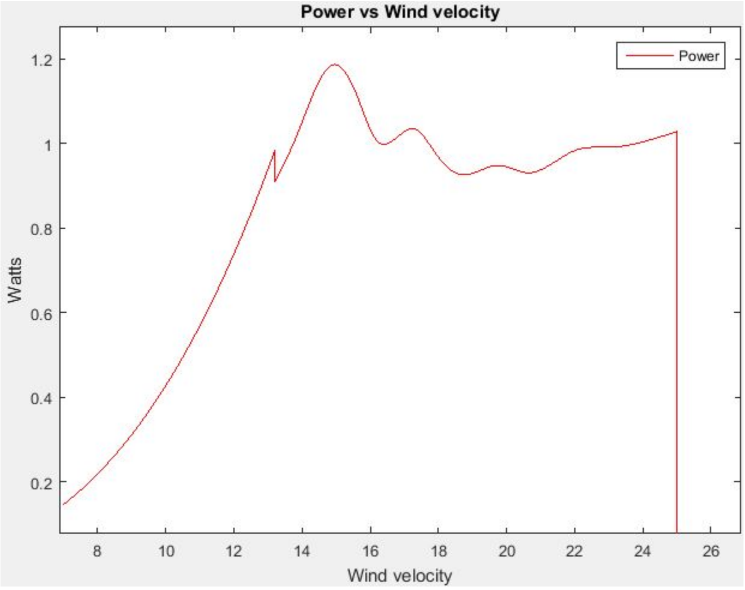

Figure 17: Vertical turbine simulation Power vs Wind velocity

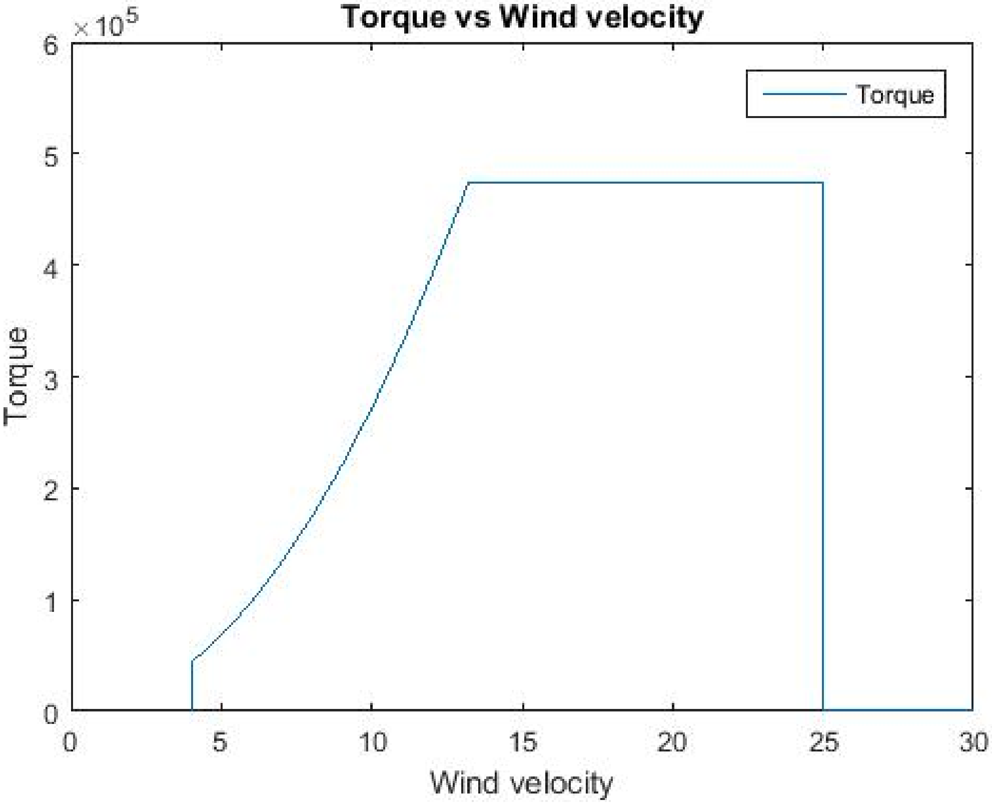

Figure 18: Seatwirl torque vs Wind velocity

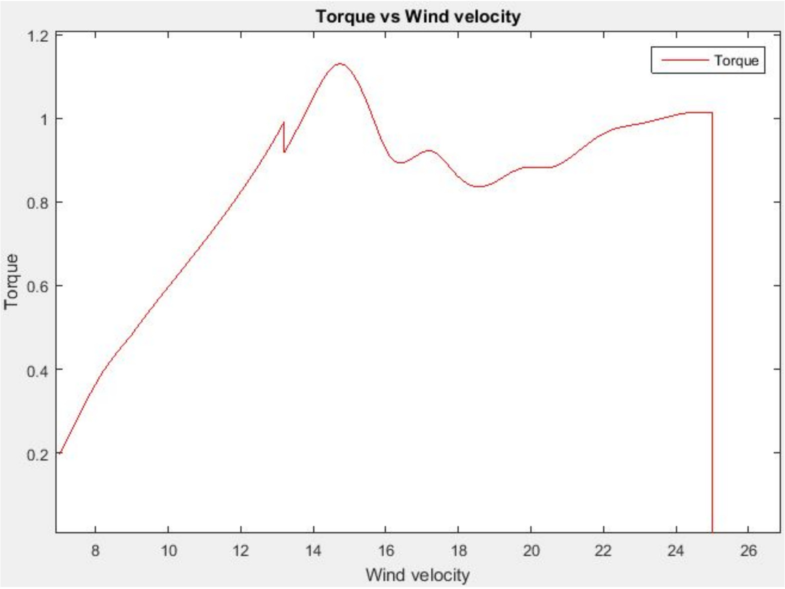

Figure 19: Vertical turbine simulation torque vs Wind velocity

9.2 System synchronous generator G2 during fault

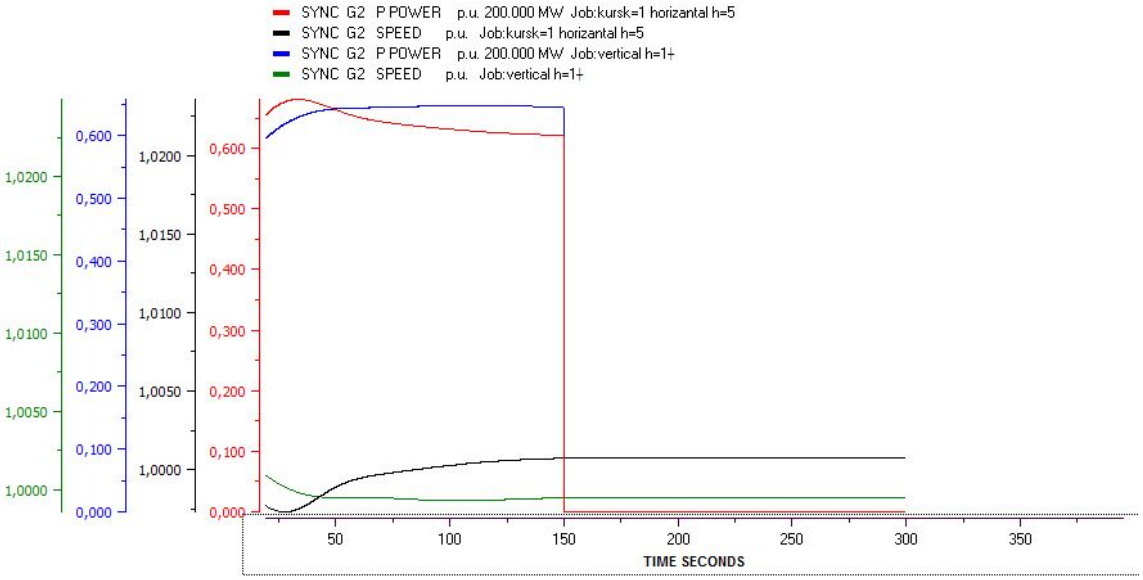

Figure 20: Synchronous generator G2 during fault

Where the fault of disconnecting G2 is at 150 second to allow studying the inertial reaction of other synchronous generators in the system and the synthetic inertial response of the wind turbines, figure[20] compares the speed and power reaction of G2 in two systems, one with horizontal turbines and the other with the vertical wind turbines. It is noticed that the speed after the fault is remaining constant while it should be increasing in real situation, this is related to SIMPOW simulation reaction in the case of a generator disconnection.

9.3 System synchronous generators inertial response during fault

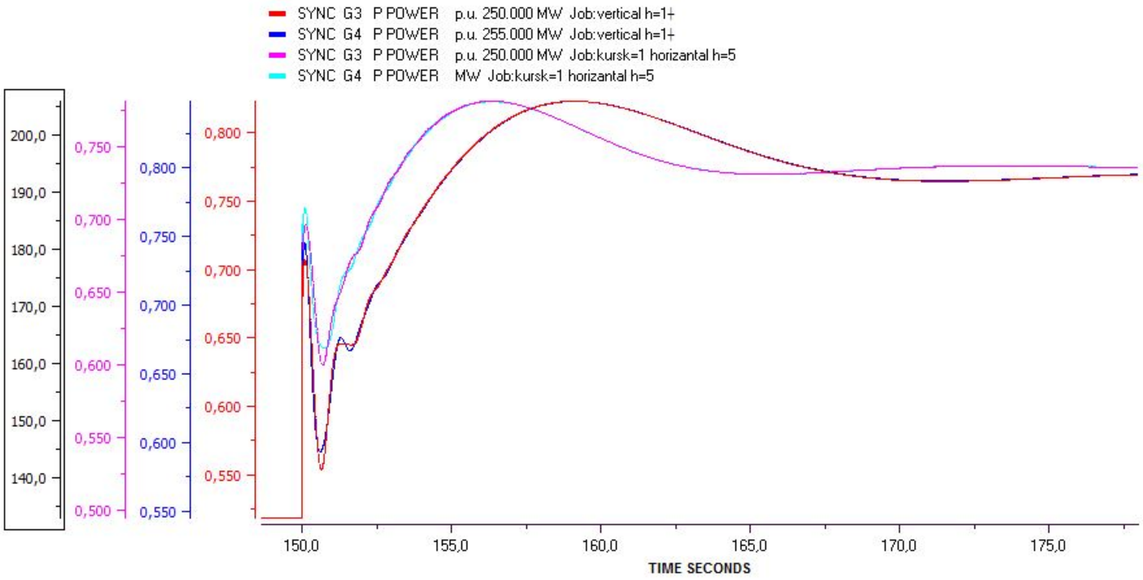

Figure 21: Synchronous generators G3 and G4 inertial response during fault

The figure compares the inertial response of G3 and G4 synchronous generators in two systems, one with horizontal turbines and the other with vertical wind turbines, it is noticed that the synchronous inertia reaction in both systems is approximately the same.

9.4 Horizontal and vertical turbine frequency drop during fault with no synthetic inertia control implemented

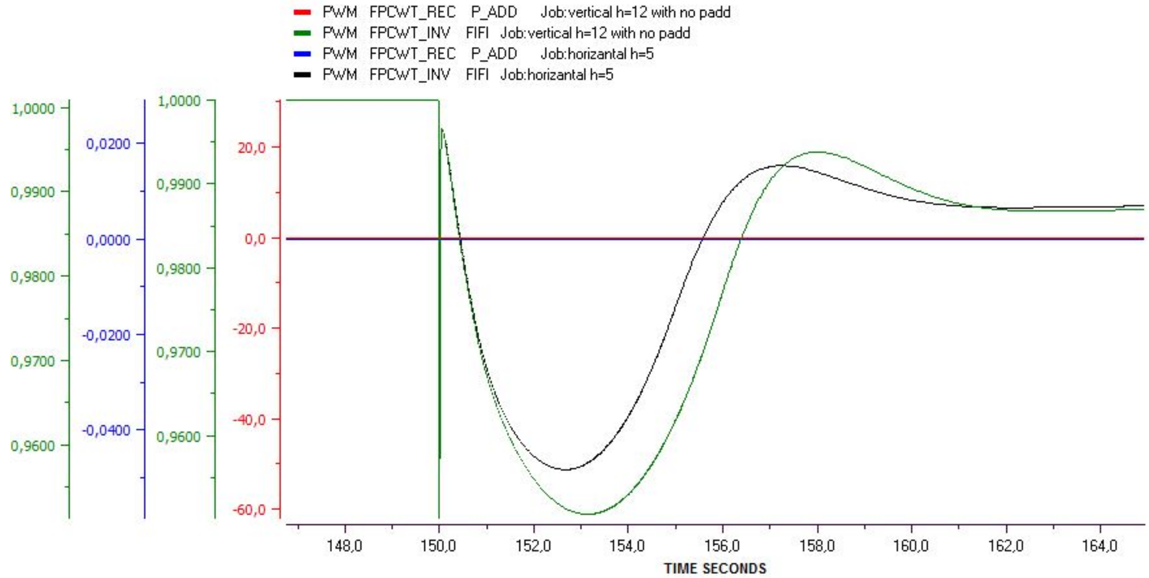

Figure 22: Horizontal and vertical turbine frequency drop during fault with no synthetic inertia control implemented

In figure [22] where P-ADD represents the injected kinetic energy and FIFI represent the system frequency, it is shown that no inertial response exists, this is due to the power electronics that works as a buffer between the network frequency and the turbine, different characteristics and the existence of pitch control in the horizontal wind turbine results in differences between the two turbines curves.

9.5 Horizontal and vertical turbine frequency drop during fault while synthetic inertia control is implemented

Due to the loss of 200MW generation based on the pre-described fault, a frequency drop is expected.

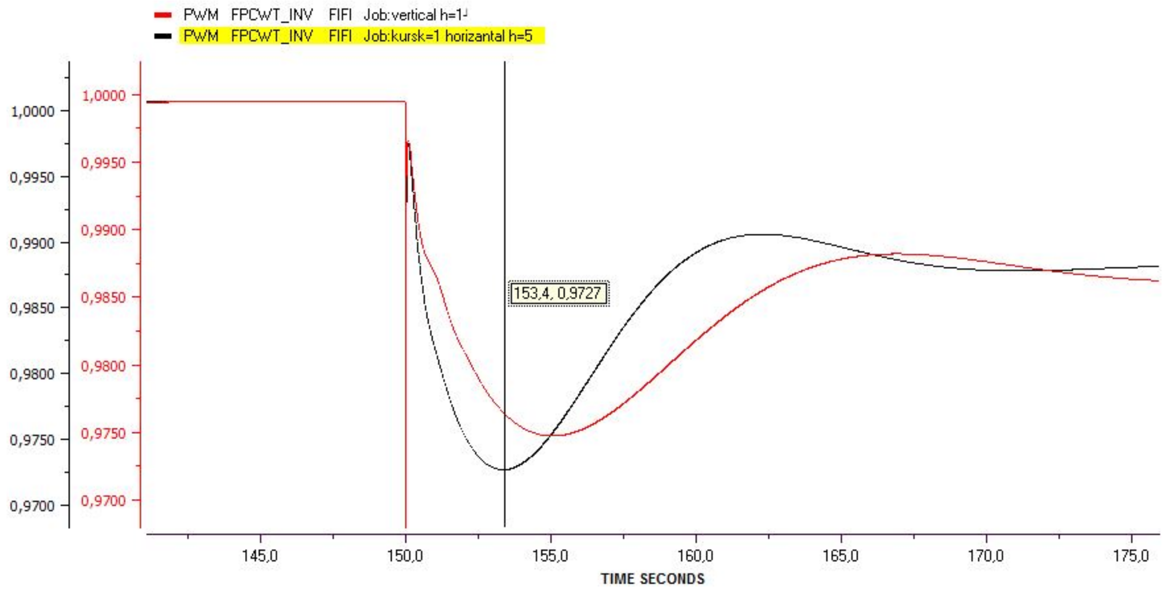

Figure 23: Horizontal and vertical turbine frequency during fault while synthetic inertia control is implemented

The ROCOF for horizontal turbine is steeper than that of the vertical due to the inertia difference between the two turbines, it can also be noticed that a bigger drop in frequency magnitude occurs(48.63 HZ) in case of the horizontal turbine, while vertical frequency drop stood at (48.735HZ). Comparing with the figure showing the frequency drop without the synthetic inertia control implemented a better nadir and ROCOF can be noticed.

9.6 Horizontal and vertical turbine synthetic inertial response

When a fault occurs at the power grid, the inertia control scheme discussed earlier implemented in the turbine will reduce rotor speed momentarily proportional to the ROCOF, releasing the stored kinetic energy in the generator.

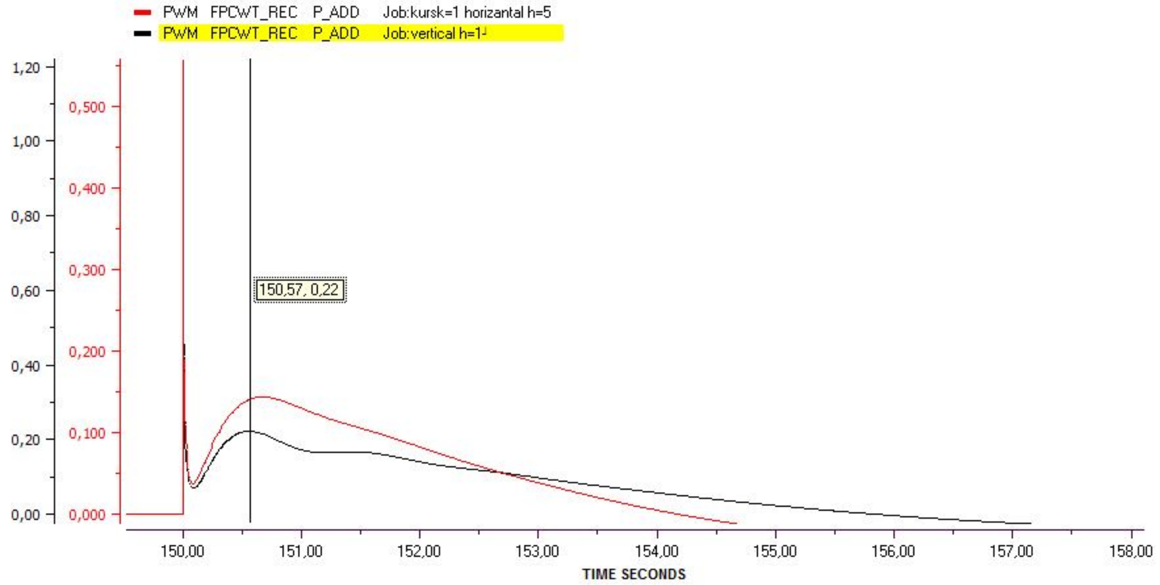

Figure 24: Horizontal and vertical turbine inertial response

A bigger P_{add} can be noticed in the vertical turbine case due to higher inertia constant, this leads to less ROCOF as shown in the previous frequency drop subsection. In case a P_{add} limit of 0.1 pu was set for power electronics economical and safety related issues, we will notice a longer P_{add} Peak time of 0.1 pu for the vertical turbine compared to the horizontal turbine as shown in the figure below, this difference is entirely dependent on the inertia constant value we assign in the inertia emulation, we could get the opposite result by increasing this factor for the HAWT and decreasing it for the VAWT.

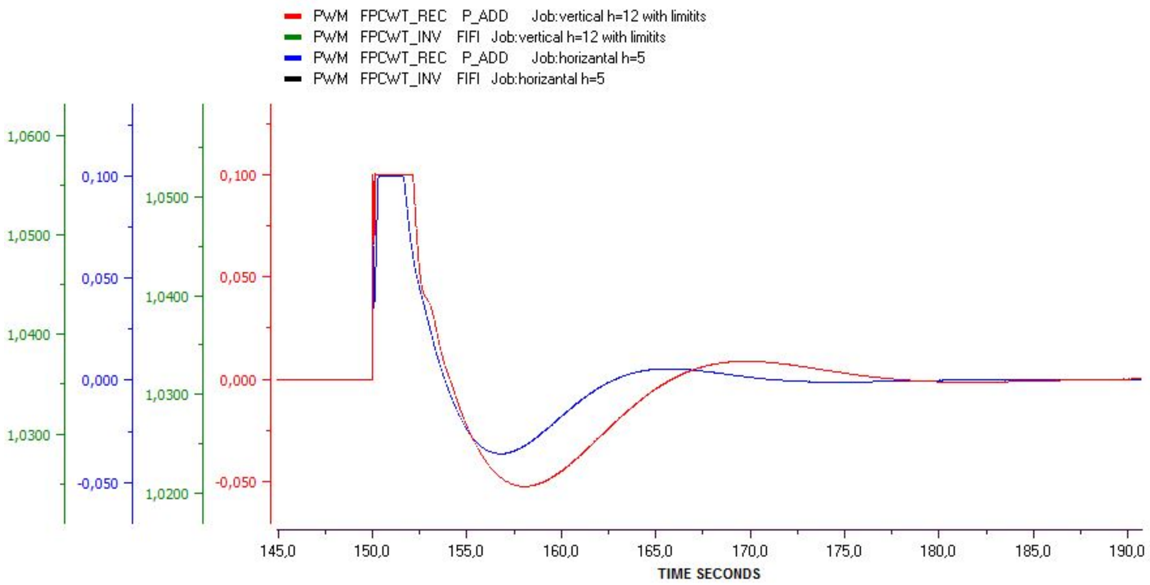

Figure 25: P_{add} time comparison between vertical and horizontal

It can be noticed that the time difference is not proportional with the inertia constant difference, due to that the control scheme will be still operational and P_{add} will still be affected by ROCOF changes which will start to flat out before the limited vertical turbine P_{add} peak time of 0.1pu ends.

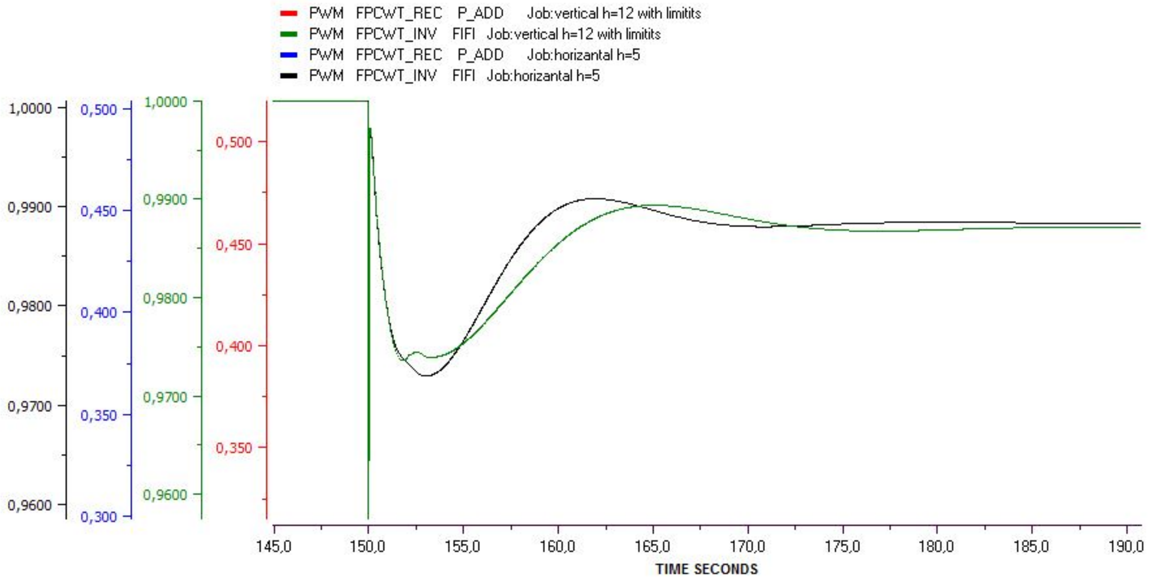

Figure 26: Limited P_{add} effect on grid frequency

9.7 Horizontal and vertical turbine generator speed response while synthetic inertia control is implemented

We notice a reduction in turbine speed during the fault, which is expected according to the synthetic inertia control scheme implemented in order to release the kinetic energy. A slightly higher speed variation is noticed in the horizontal turbine than the vertical turbine.

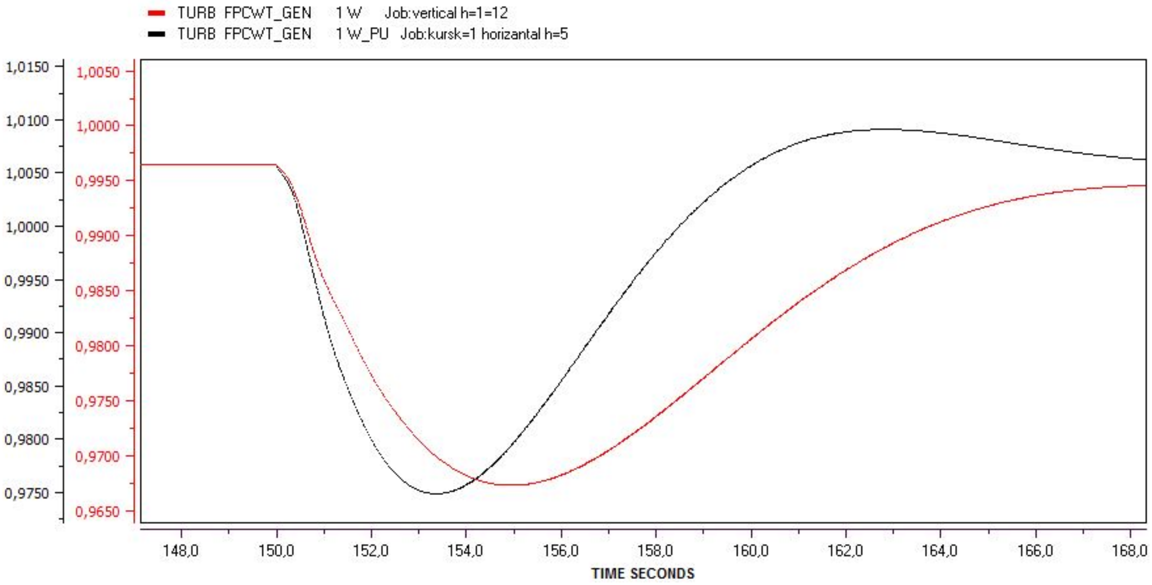

Figure 27: Horizontal and vertical turbine speed response during fault

9.8 Horizontal and vertical turbine generator mechanical torque response while synthetic inertia control is implemented

It is noticed that torque starts to increase in accordance with supplying the extra power out of the different turbines, longer torque increment time depends on the volume of extra power provided.

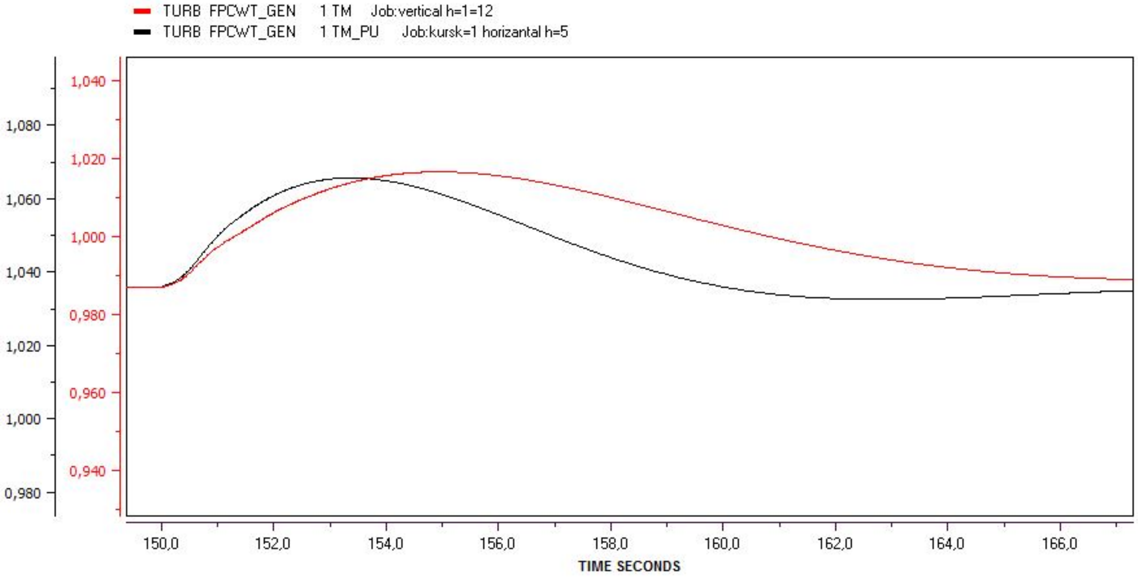

Figure 28: Horizontal and vertical turbine torque response during fault

9.9 Synthetic inertia during line 7,8 fault

At 150 seconds one of the lines between bus 7 and bus 8 will be permanently cut off, the second line power capacity will be able to handle the diverted load. However, a transient can be observed where synthetic inertia acts to dampen the oscillation's. A sudden increase in frequency for short period occurs at 150 seconds is counteracted with a power reduction from the turbine side.

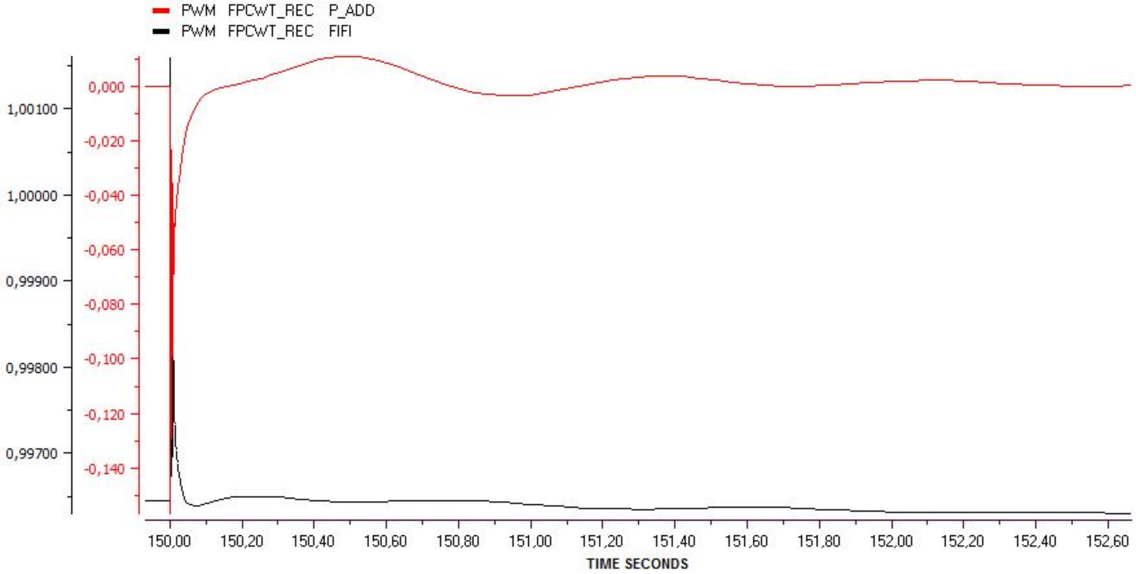

Figure 29: Vertical turbine synthetic inertia during line 7,8 fault

9.10 Synthetic inertia during G4 disconnection

A disconnection on G4 should be of a great impact on the system due to the near approximate to the biggest load in the system on bus 9, the system was able to withstand such fault with both horizontal with synthetic inertia control and vertical with synthetic inertia control turbines, ROCOF and nadir differences between both cases can be clearly noticed.

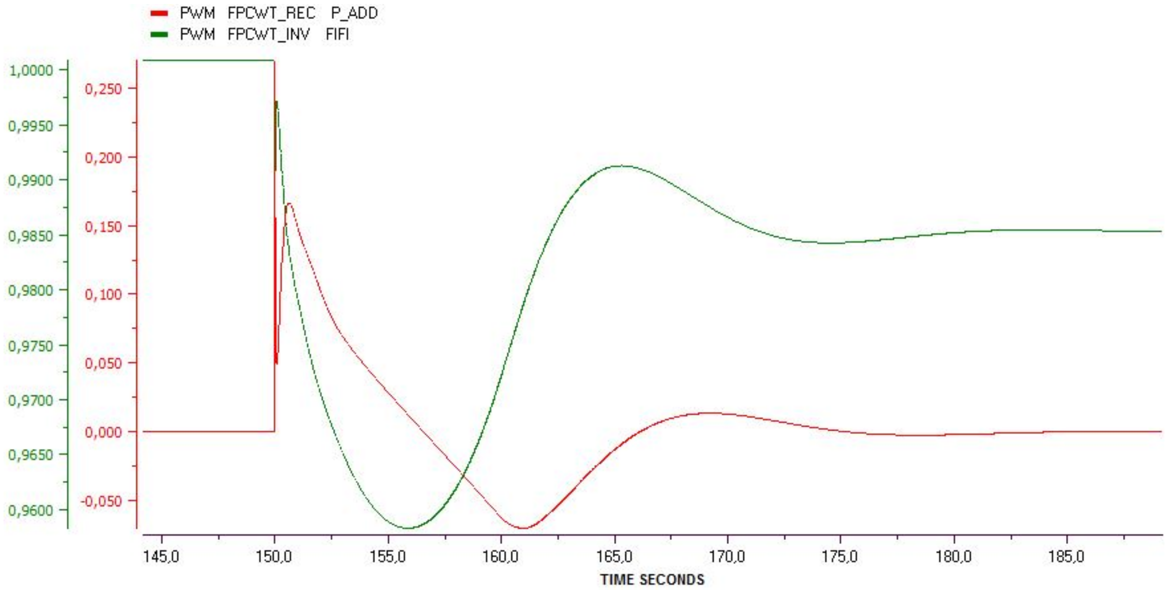

Figure 30: Horizontal turbine synthetic inertia during G4 disconnection

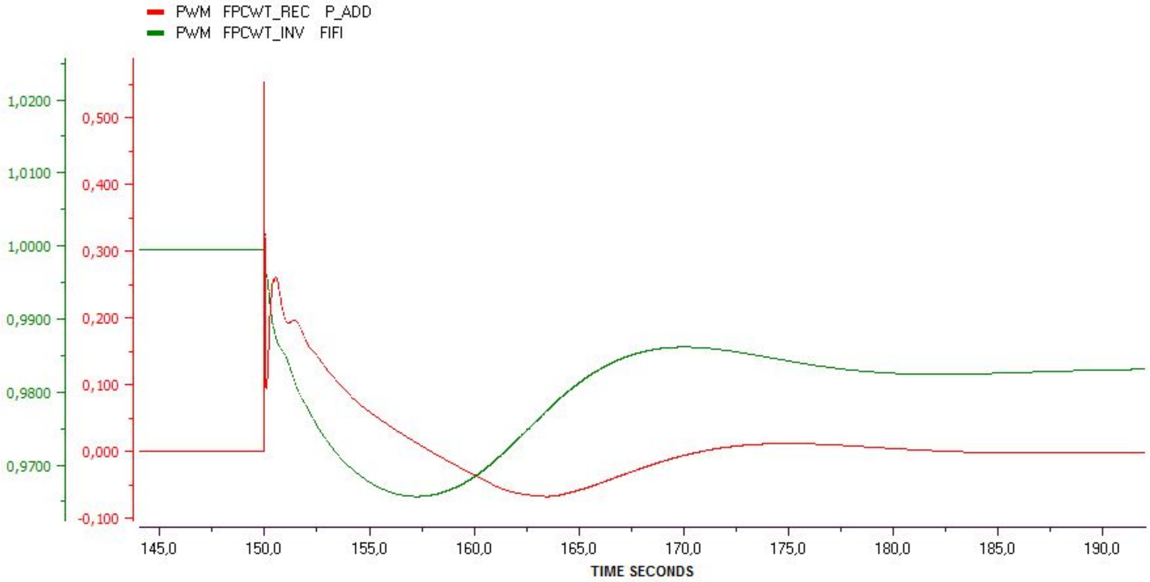

Figure 31: Vertical turbine synthetic inertia during G4 disconnection

9.11 Synthetic inertia during modified G4 disconnection

An increase in G4 power from 255 MW to 299 MW will be implemented while a decrease of the same value will be subjected on G3. In the first case where a horizontal turbine is used a lost of synchronize can be noticed after approximately a 25 seconds from the fault occurrence.

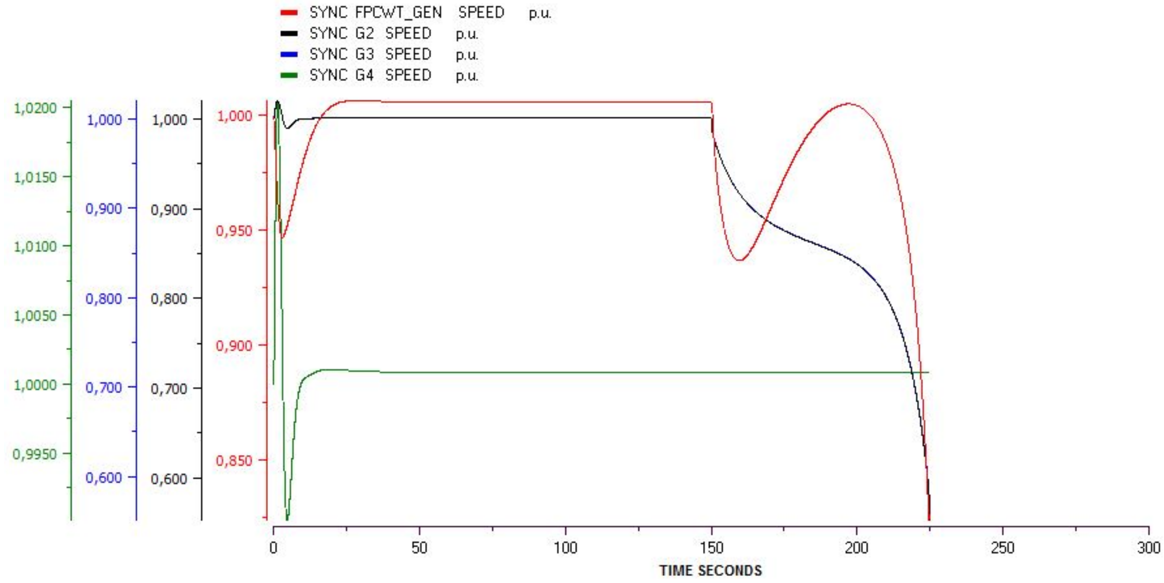

Figure 32: Horizontal turbine synthetic inertia during modified G4 disconnection

In the second case the vertical turbine will be used for the same fault, the system survives the fault effects and all generators are still in synchronize due to the extra kinetic energy injected in the case of the vertical turbine, G4 remains its speed after the fault in SIMPOW simulation but have no effect on the system after its disconnection.

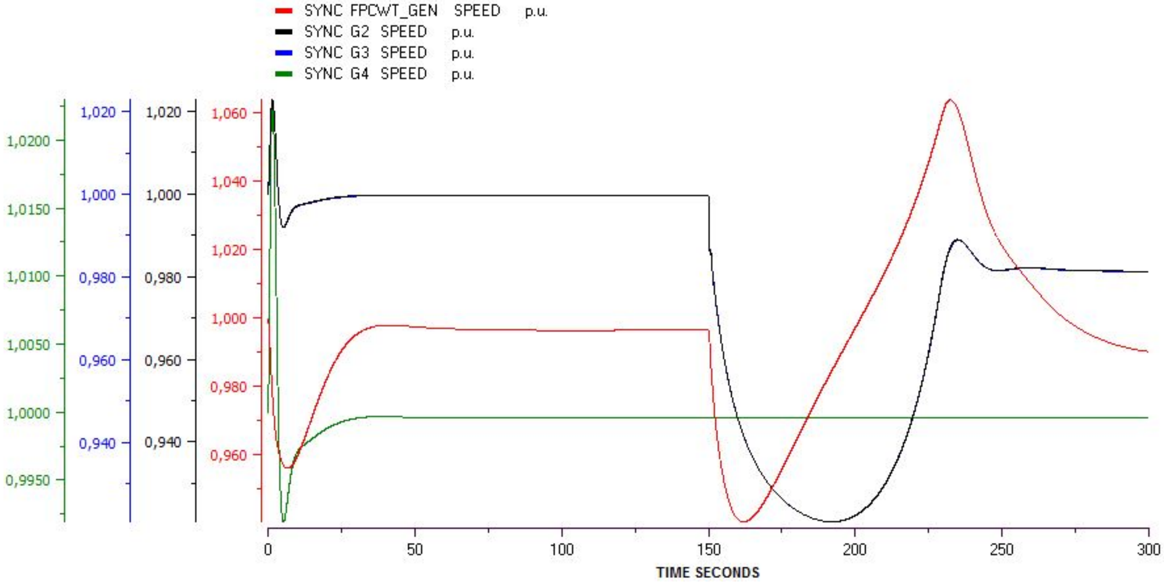

Figure 33: Vertical turbine synthetic inertia during modified G4 disconnection

10 Discussion and analyses

Analyzing the results in the previous chapter it can be noticed that:

- Stored kinetic energy can be utilized momentarily to improve the frequency quality and limit the ROCOF, a positive effect can also be noticed on the frequency variation magnitude (transient frequency nadir).
- Restoring utilized turbine kinetic energy from the network occurs directly after the injection end, this may effect the network stability, figure below highlights power contribution and recovery stages.

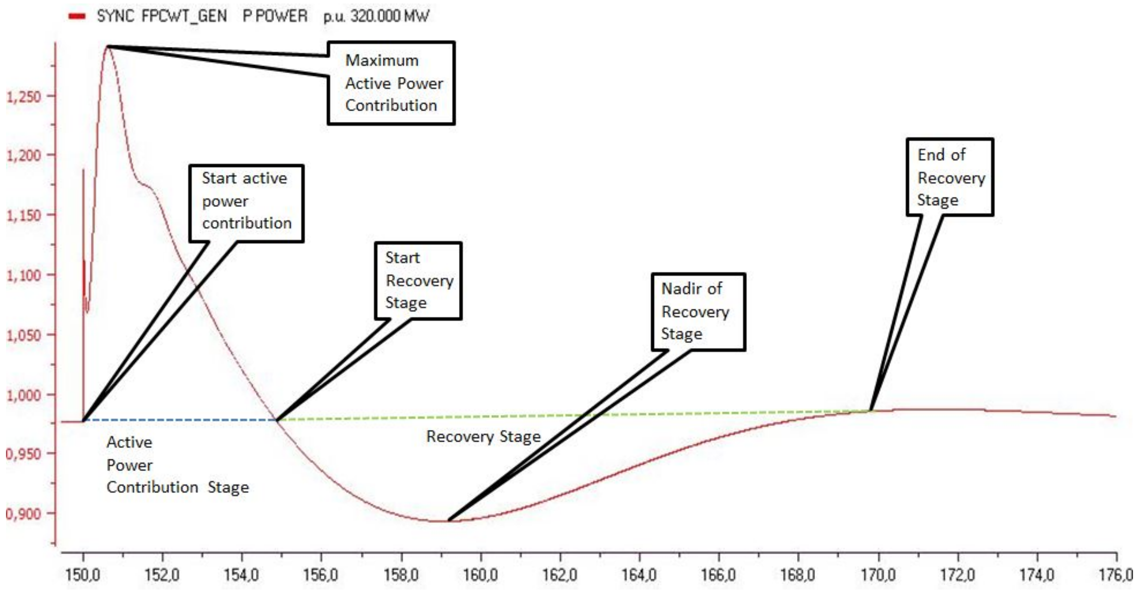

Figure 34: Power contribution and recovery stages

- Restoring utilized turbine kinetic energy from the network negative effect on stability can be mitigated by delaying the restoring time and dividing the windfarm turbines restoring time over different time slots, this will reduce the windfarm power output as it is operating at lower speeds but will have less effect on the network stability.
- The utilized kinetic energy during fault has a lot of similarities with the synchronous inertia response but it is not the same[32], the figure below shows a comparison between G3 synchronous inherent inertia and the synthetic inertia of the vertical wind turbine limited to 0.1pu for one second after the fault, for a longer comparison 9.3 and 9.6 are relevant. The reason why this difference occurs is possibly due to the synthetic inertia control scheme linking the injected kinetic energy with the system frequency deviations and the power electronics delays.

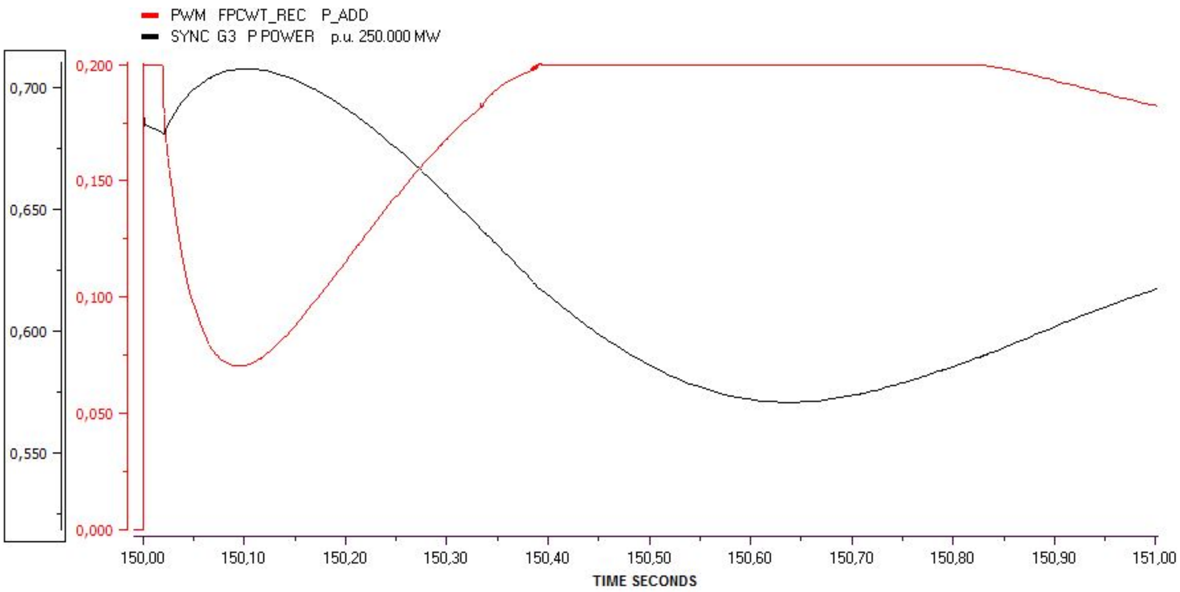

Figure 35: Comparison between synthetic and synchronous inertia

- With higher inertia constant an improved ROCOF, reduced frequency deviation magnitude (transient frequency nadir) and a faster to normal frequency recovery can be noticed.
- A filter was applied in the synthetic inertia scheme to avoid acting on very small system frequency variations and noise, acting on that level will effect he simulation stability and won‘t be applicable in actual usage due to excessive mechanical effect on the turbine.
- Limitations on the injected kinetic energy may be necessary to protect the power electronics and prevent the turbine from stalling, limits can be changed based on the network needs, power electronics ratings and turbine capabilities.
- Limitations on the injected kinetic energy will reduce the effect on the ROCOF, frequency deviation magnitude(transient frequency nadir)and frequency recovery time.
- Even with limitations, higher inertia leads to higher kinetic energy contribution due to longer peak energy injection time.
- Longer peak energy injection time is also decided by grid frequency deviation as the synthetic inertia equation is related with the grid frequency ROCOF.
- Each network will have different duration where frequency is effected purely by inertial response depending on other grid power generation types and governor settings, in another words different primary response times.
- Some very short duration stability issues (single milliseconds) can be noticed at the beginning of the frequency wave forms when the fault begins due to simulation issues.
- Loads are modeled as constant power loads.
- When no synthetic inertia control scheme was implemented, the horizontal turbine frequency nadir and ROCOF where better than the vertical turbine probably due to different characteristics and the existence of pitch control in the horizontal wind turbine.
- After synthetic inertia control scheme was implemented, the vertical turbine frequency nadir and ROCOF where better than the horizontal turbine due to better inertia coefficient.

11 Ethical and sustainable development aspects

The main purposes of this thesis is to study the possibility of using different storage unit as a synthetic inertia source, observing the effect of the synthetic inertia on the frequency and considering Seatwirl as a possible solution for a better frequency stability in the future, as to the knowledge of the thesis writer no publications was done regarding simulating synthetic inertia in vertical wind turbines using Simpow or any similar program. Developing the synthetic inertia capabilities for wind farms is a response for the future power grid needs and challenges, this developed capabilities has an ethical background helping in developing it in the way it is nowadays and some environmental effects. Also it was studied in our thesis an offshore wind turbine invention called Seatwirl, we will review the ethical and sustainable development aspects of such invention.

11.1 Ethical aspects

11.1.1 Over synthetic inertia

- Through out the thesis it was mentioned how traditional synchronous generators produce inertia needed for frequency stability in fault cases while RES don't generate any type of inertia as power converters decouples it from the network while they still both receive the same market price, this is giving the wind farms power producers an advantage over traditional power producers which means that equal opportunities rules are not valid anymore, by implementing grid codes that enforce frequency stability tasks over wind farms power producers a more fair competing can exist between different power producers.

- Giving the means for wind farms power producers to use their turbines kinetic energy as synthetic inertia depending on various control methods keeps them in the competition considering the new grid codes, especially that they are no longer in need to combine traditional generating methods running all the time with the wind farm to satisfy the new grid codes.

- Some synthetic inertia methods can be utilized on older wind turbines that was not manufactured to have synthetic inertia [33], this will reduce the cost on old wind farms power producers to update their wind farm to the new gird codes an unlikely to cast them of competing with other producers.

11.1.2 Over Seatwirl

- By using offshore wind farms, the competing over synthetic inertia reserves won't be limited to available land where already established traditional power generators have an advantage over relatively new renewable generation, land adequacy in some islands is more important issue than other bigger countries and land limitation can be a disadvantage for newly RES producers.

11.2 Sustainable aspects

11.2.1 Over synthetic inertia

- It can limit the need of using other storage units as a synthetic inertia source, resulting in reducing chemicals and materials usage for the production of these storage units and the electrical connections systems needed to connect the storage units to the existing electrical grid.

- facilitate the transfer to RES from the traditional power sources eliminating the synchronous inertia advantage and making this transfer more technically and financially visible as wind power producers have no longer to add traditional sources of generation to meet with the grid standards.

- Based on the previous point, a reduction of gas emissions is an anticipated result from a lower share of traditional fossil power in the total grid generated power.
- Improving frequency stability will reduce the possibilities of major faults in the system and blackouts, which means less possibility of the network need to "Black start" which is usually done by traditional fossil generators and less possibility that large facilities need to re-boot and loose materials and extra power.

11.2.2 Over Seatwirl

- Wind turbines is a sustainable way to generate power, which basically Seatwirl is a wind turbine product. Adding to that the improved and new features Seatwirl have will make it easier to do the change to wind energy away from the traditional fossil fuel energy.

12 Future work

The thesis tried to cover the synthetic inertia technology aspects of Seatwirl by showing and implementing the control scheme used, simulating synthetic inertia response and the effects on the network frequency, comparing by simulation the differences of synthetic inertia generated between HAWT and Seatwirl, a financial comparison between Seatwirl synthetic inertia and various storage units. However, there is a plenty of future work that can be done to improve and deepen the understanding of the thesis topic such as:

- As mentioned in chapter[9], instead of slowing down the speed controller response, an improved control scheme can be achieved by having a dummy rotation speed input that cancels out the reduction in speed caused by the additional torque. .
- Using a more realistic larger system with bigger variety of faults and events can improve the turbine synthetic inertia response understanding.
- This thesis is based on weighted theoretical data of the 1MW Seatwirl that does not exist yet, having a more accurate date and a control scheme from Seatwirl after the prototype is functional can highly improve the outcome and bring additional challenges to tackle.
- The recovery stage after the synthetic inertia contribution can poses a threat to a network with high wind energy penetration, developing various control schemes to divide and delay the recovery stage over different time slots may prove to be very beneficial.
- A lot of assumption have been made studying the financial aspects of Seatwirl, a more detailed and accurate information would be beneficial for further more accurate estimations.
- There were various stability issues in the turbine models specially during rapid speed changes, more optimized controllers constants and methods would generate a more stable model.

13 Conclusions

This thesis discussed ROCOF variations due to the RES increased penetration in the power system and how synthetic inertia can help to reduce the negative effect of such development. Inertia constant variation and how it effects the network stability was discussed through serious of HAWTS and VAWTS simulations where longer Inertia constant has shown increased positive effect on the frequency quality. Different applications for providing synthetic inertia were discussed and financially compared, Seatwirl is an invention that can provide certain amount of power in addition to synthetic inertia in case needed by the network was technically and financially discussed where it showed a possible opportunity for added system stability and cost savings compared with traditional horizontal turbines as a standalone or were traditional horizontal turbines are combined with storage units.

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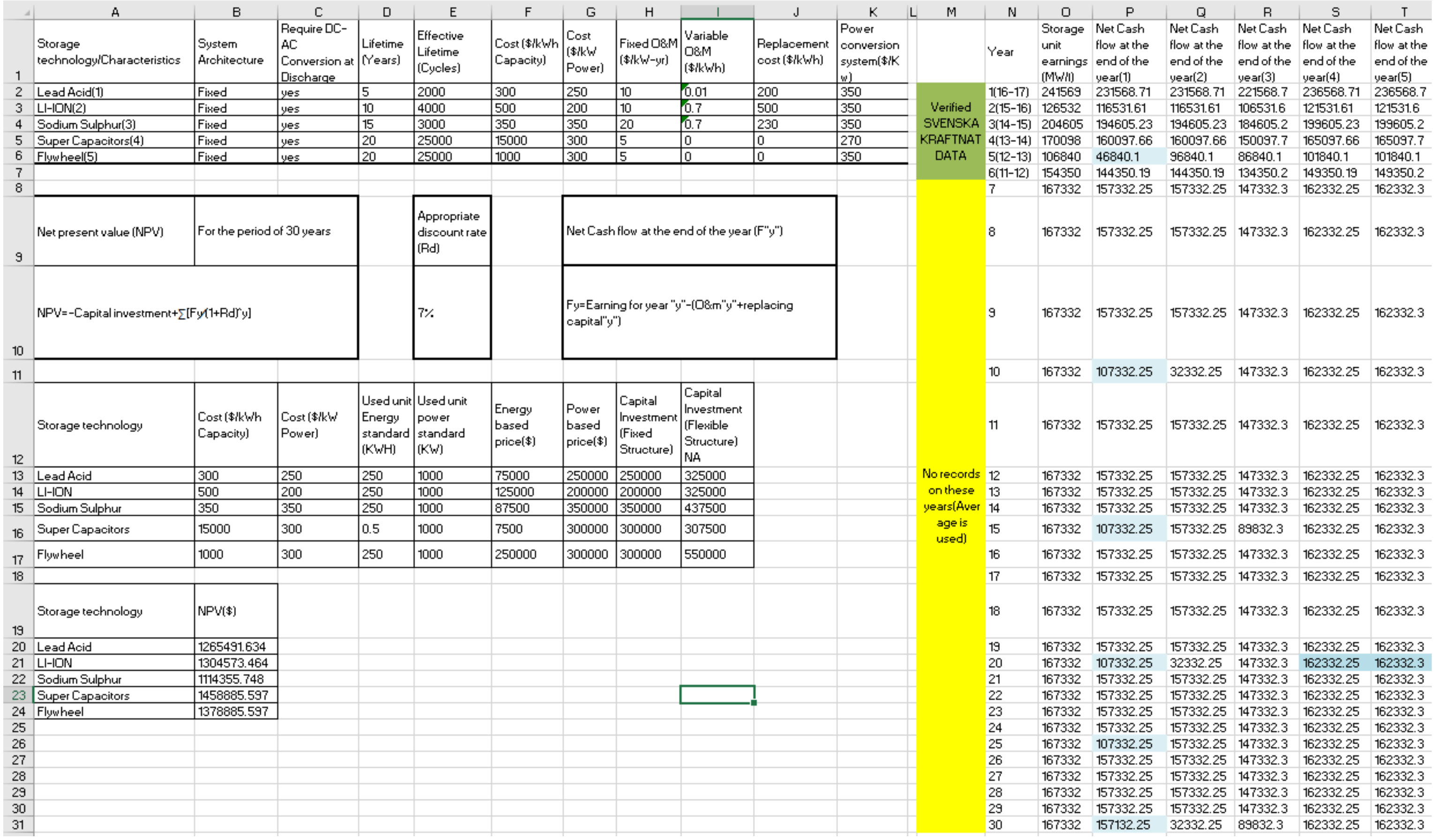
14 Appendix1



Storage technology/Characteristics	System Architecture	Require DC-AC Conversion at Discharge	Lifetime (Years)	Effective Lifetime (Cycles)	Cost ($/kWh Capacity)	Cost ($/kW Power)	Fixed O&M ($/kW-yr)	Variable O&M ($/kWh)	Replacement cost ($/kWh)	Power conversion system($/Kw)
Lead Acid(1)	Fixed	yes	5	2000	300	250	10	0.01	200	350
LI-ION(2)	Fixed	yes	10	4000	500	200	10	0.7	500	350
Sodium Sulphur(3)	Fixed	yes	15	3000	350	350	20	0.7	230	350
Super Capacitors(4)	Fixed	yes	20	25000	15000	300	5	0	0	270
Flywheel(5)	Fixed	yes	20	25000	1000	300	5	0	0	350

Net present value (NPV)	For the period of 30 years
NPV=-Capital investment+∑[Fy/(1+Rd)^y]	

Appropriate discount rate (Rd)
7%

Net Cash flow at the end of the year (F"y")
Fy=Earning for year "y"-(O&m"y"+replacing capital"y")

Storage technology	Cost ($/kWh Capacity)	Cost ($/kW Power)	Used unit Energy standard (KWH)	Used unit power standard (KW)	Energy based price($)	Power based price($)	Capital Investment (Fixed Structure)	Capital Investment (Flexible Structure) NA
Lead Acid	300	250	250	1000	75000	250000	250000	325000
LI-ION	500	200	250	1000	125000	200000	200000	325000
Sodium Sulphur	350	350	250	1000	87500	350000	350000	437500
Super Capacitors	15000	300	0.5	1000	7500	300000	300000	307500
Flywheel	1000	300	250	1000	250000	300000	300000	550000

Storage technology	NPV($)
Lead Acid	1265491.634
LI-ION	1304573.464
Sodium Sulphur	1114355.748
Super Capacitors	1458885.597
Flywheel	1378885.597

	Year	Storage unit earnings (MW/l)	Net Cash flow at the end of the year(1)	Net Cash flow at the end of the year(2)	Net Cash flow at the end of the year(3)	Net Cash flow at the end of the year(4)	Net Cash flow at the end of the year(5)
Verified SVENSKA KRAFTNAT DATA	1(16-17)	241569	231568.71	231568.71	221568.7	236568.71	236568.7
	2(15-16)	126532	116531.61	116531.61	106531.6	121531.61	121531.6
	3(14-15)	204605	194605.23	194605.23	184605.2	199605.23	199605.2
	4(13-14)	170098	160097.66	160097.66	150097.7	165097.66	165097.7
	5(12-13)	106840	46840.1	96840.1	86840.1	101840.1	101840.1
	6(11-12)	154350	144350.19	144350.19	134350.2	149350.19	149350.2
No records on these years(Average is used)	7	167332	157332.25	157332.25	147332.3	162332.25	162332.3
	8	167332	157332.25	157332.25	147332.3	162332.25	162332.3
	9	167332	157332.25	157332.25	147332.3	162332.25	162332.3
	10	167332	107332.25	32332.25	147332.3	162332.25	162332.3
	11	167332	157332.25	157332.25	147332.3	162332.25	162332.3
	12	167332	157332.25	157332.25	147332.3	162332.25	162332.3
	13	167332	157332.25	157332.25	147332.3	162332.25	162332.3
	14	167332	157332.25	157332.25	147332.3	162332.25	162332.3
	15	167332	107332.25	157332.25	89832.3	162332.25	162332.3
	16	167332	157332.25	157332.25	147332.3	162332.25	162332.3
	17	167332	157332.25	157332.25	147332.3	162332.25	162332.3
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	28	167332	157332.25	157332.25	147332.3	162332.25	162332.3
	29	167332	157332.25	157332.25	147332.3	162332.25	162332.3
	30	167332	157132.25	32332.25	89832.3	162332.25	162332.3

Figure 36: Storage units NPV