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Modelling of Synthetic Inertia In Simpow

Master of Science Thesis

Anusha Barman

Division of Electric Power Engineering
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Department of Energy and Environment
Division of Electric Power Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Chalmers University of Technology

Abstract

The Transmission System Operators (TSOs) are now imposing strict technical requirements on the wind turbines, due to the high penetration of wind energy in the power system. One requirement being that the wind farms provide frequency control in the event of mismatch between the load and power generation for the reliable and secure operation of the power system.
This thesis focuses on implementing, testing and analysing control techniques, for both Doubly Fed Induction Generator (DFIG) and Full Power Converter (FPC) wind turbines, which can extract the kinetic energy available from the rotating parts of the wind turbine and utilise it to improve the inertial response of the system and consequently the frequency stability of the power system.
The technique of adding an additional power control loop in the wind turbine model is first implemented on a small one-bus power system having only one synchronous machine and later on a rough model of the Nordic Power system. Significant improvements in frequency response are noticed in both cases along with limitations involved with the two wind turbine models. In case of DFIG wind turbine, certain abnormal responses are observed and highlighted. Additionally, possible reasons and ways of mitigating these in the Simpow model has been discussed.

Keywords: Wind turbines, DFIG , FPC, Frequency Response, Synthetic Inertia, Nordic Grid.

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Anusha Barman

Contents

Chapter 1

Introduction

In recent times, the penetration of wind energy into the power system has risen significantly and is expected to rise in the future[8]. On one hand, it is safe, clean and abundant but on the other hand, it has significant impact on the power system in terms of frequency stability. Frequency control is important for a secure and stable power system[8].

In the conventional power stations, synchronous machines are used in which the stator is directly connected to the grid. Due to this coupled nature of the grid and the synchronous machines, both the rotational frequency of the machines and the frequency of the grid must change in tandem [15]. The deceleration of the synchronous machines leads to the release of a certain amount of kinetic energy to the grid in the form of electrical energy in a very short duration of time.

However, in Variable Speed Wind Turbines the presence of power electronic converter cause a decoupling between the machine and the grid [4] which in turn implies that there is no natural feedback between the grid frequency and rotational frequency of the machine. This implies that a change in grid frequency will not have an impact on the machine and therefore, the kinetic energy stored in the wind turbines will not contribute to the inertia of the grid.

By devising proper control techniques, the kinetic energy available from the rotational parts, such as the blades, gearbox of the wind turbine can be made available to improve the inertial response of the system and consequently the frequency stability of the power system [2], [13] and [21].

1.1 Aim

The aim of this thesis is to develop a dynamic model of Doubly-Fed Induction Generator Wind Turbines (DFIG WT) and Full Power Converter Wind Turbines (FPC WT) incorporating synthetic inertia and to study its effect on the frequency stability of a power system. The two wind turbine models will separately be implemented on a Nordic network to analyse its performance on a more realistic power system depending on the location of the fault in the network. The models will be implemented in the simulation software Simpow.

1.2 Task

The main tasks of this thesis include:

1. Literature review
   - Synthetic inertia and its effect on frequency stability of a Power System
   - The available wind turbine models
   - The control strategies
   - Grid codes and its requirements from different countries
2. System Modelling
   - Doubly-Fed Induction Generator Wind Turbine
     (a) Wind turbine
     (b) Controllers
   - Full Power Converter Wind Turbine
     (a) Wind turbine
     (b) Controllers
   - Modelling the one-bus system
3. Test the models on the one-bus system
4. Modelling of the Nordic network
5. Implementation of the Model on the Nordic Network

The first task involves gathering relevant data that have been published on the topic of synthetic inertia to get a good understanding of the concept which will aid in building and implementing the model. This will include studying the effect of synthetic inertia to the change of system frequency, the parts of the system which can provide the synthetic inertia and the time duration for which the support is provided. In addition, information regarding the grid codes of various countries and their requirement from wind farms towards frequency stability will be collected and used when designing the model. This will be followed by the study of the already existing control techniques and their implementation.

In the second task, modelling of the system will be carried out. This task involves several smaller sub-tasks. There are four main blocks in the wind turbine which need to be modelled. The aerodynamic block which will aid to simulate the conversion of the wind energy to rotational energy, followed by the turbine block which represents all the mechanical dynamics of the machine, pitch and speed control block and the generator block based on the one-mass model in dq co-ordinate system. Next, the frequency dependant load will be modelled and finally, the control techniques incorporating synthetic inertia will be modeled and implemented into the system.

In the third task, one-bus power system with one synchronous generator and the load will be modelled. The wind turbine obtained in the previous task will be tested on these power system. Simulation on the entire system will be carried out and results obtained will be evaluated and necessary changes will be made to improve the performance of the system.

And finally, once the models have been tested on the one-bus system, A simplified Nordic grid network will be designed in Simpow and the two models will be implemented on this system and their performance will be analysed.

1.3 Method

To get a good understanding of the concept of synthetic inertia relevant data from journals and technical papers which have been published on the topic will be collected. Information regarding the grid codes in different countries will be collected from the documentation published by the TSOs (Transmission System Operators) in these countries.

Next, modelling of the system will be carried out. The DFIG WT and FPC WT models will separately be designed in DSL (Dynamic Simulation Language). Data from manufacturers datasheet will be used for designing the various components of the wind turbines; wind profile, rotor dimensions and ratings will be used to model the wind turbine model. The controllers will be incorporated in the DSL code by setting values for the different time and proportional and integral constants. The frequency dependant load will be modelled using relevant mathematical equations.

Following this, a one-bus power system will be modelled by providing the parameters of the machine, governor type and inertia of the system and the models will be tested on this system. Once the model has been tested on the one-bus system, the Nordic network will be implemented based on the information available about the generators and loads in the Nordic Network. Simplifications in the network will be done wherever necessary. The two wind turbine models will be implemented and tested on this network.

1.4 Significance

With the recent fuel crisis and the need to curb climate change, the focus of policy makers has now shifted to generating electricity through renewable sources, mainly solar and wind. This shift in focus has resulted in an increase in the number of wind installations around the world and is expected to grow in the future [10]. Europe witnessed a 10.5% increase in wind energy capacity per year from 2013 and by the end of 2014, 10.2% of EU's electricity consumption was covered by grid-connected wind power [10].

But with an increase in the penetration of wind turbines in the power system, the wind turbines will have a bigger effect on the behaviour of the power system and may even begin to cause grid stability problems since they do not take part in voltage and frequency control in case of a power imbalance [14].

This thesis presents the modelling of two different wind turbines namely Doubly Fed Induction Generator and Full Power Converter Wind turbine which help in understanding its working and its behavior in an electric power system. With high level of wind penetration in the power system, the problem of blackout during large disturbances arises. This thesis work focuses on modelling and implementing suitable control strategies for the wind turbines to reduce the risk of blackout during large disturbances and hence improving the stability and reliability of the system. In this thesis work, one particular method of improving the stability of the power system is implemented which provides the foundation of investigating other possible ways of improving the stability of the system and also studying its effectiveness in large power systems with high level of wind penetration.

Chapter 2

Technical background

Wind turbine can broadly be classified into two groups- fixed speed wind turbines and variable speed wind turbines. In fixed speed wind turbines, the stator is directly connected to the grid and as the name suggests, the rotor rotates almost at a fixed speed based on the grid frequency. In the event of a wind fluctuation, the electrical output power of the wind turbine fluctuates which in turn adversely affects the stability and quality of the grid.

On the other hand, in variable speed wind turbines (VSWT) the rotational speed of the turbine rotor is allowed to vary in accordance to the variation in wind speed. Variable speed wind turbines can further be classified into *(a) VSWT with variable rotor resistance (b) VSWT with Doubly Fed Induction Generator (c) VSWT with Full Power Converter.*

2.1 Frequency Control

In the case of an imbalance between the generation and the demand, the system frequency changes at a rate determined by the total system inertia. If a change in system frequency causes a change in the rotational speed of a generator and thereby its kinetic energy, then such a generator is considered to contribute to the system inertia [16]. This power associated with this change in kinetic energy is either fed to the power system or taken from it and known as inertial response. In conventional synchronous generators, inertial response is naturally observed. However, in the case of variable speed wind turbine, the presence of power electronic converters between the machine terminals and the grid, the wind turbines do not contribute to the inertial response [11]. With a higher degree of wind penetration into the power system, the lower the system inertia and therefore larger changes in frequency during disturbances. This has led to the transmission system operators to specify several technical requirements on the wind turbines.

2.2 Grid Code Requirements

The transmission system operators (TSOs) have the important task of maintaining the reliability and stability of the power system through proper power dispatch.

With the number of wind turbines used in the power system increasing throughout the world, the TSOs need to revise the grid codes in order to incorporate these wind turbines without compromising on the stability of the system and also impose certain technical requirements on the wind turbines.

Denmark, Germany Spain and UK [8] are some of the countries which have high level of wind penetration in the power system. It is in these countries where the grid codes pertaining to wind turbines have evolved drastically over the last few years. However, in UK and Ireland the requirements from wind turbines for frequency control are stricter than in continental Europe since UK and Ireland do not have access to the power reserves in the interconnected network of continental Europe [6]. But this trend is expected to be observed in continental Europe with more and more wind turbines being added in the power system.

The requirements for frequency operation differs from every country and a summary of this can be found in table 2.1 It specifies the frequency range within

Table 2.1: Operating frequency limits by codes of different countries

Country	Continuous Operating Frequency limit(Hz)
Denmark	49.5-50.5
Germany	49-51.5
UK	47.5-52
Spain	48-51.5

which the wind turbines are required to operate without changing their active power output.

Out of the several grid codes which discuss about wind penetration in the grid approximately only half of the grid codes specify requirements related to primary frequency response control [5] but no detailed requirements are specified about inertia in these grids. Further information on the requirement from wind turbine for inertia can be found in [3] which tries to give an overview of various grid codes on this aspect of wind turbines as per the year 2011.

Chapter 3

Modelling Of The Wind Turbines

This chapter explains the various parts of the wind turbine models and how they are modelled.

3.1 Doubly Fed Induction Generator Wind Turbine

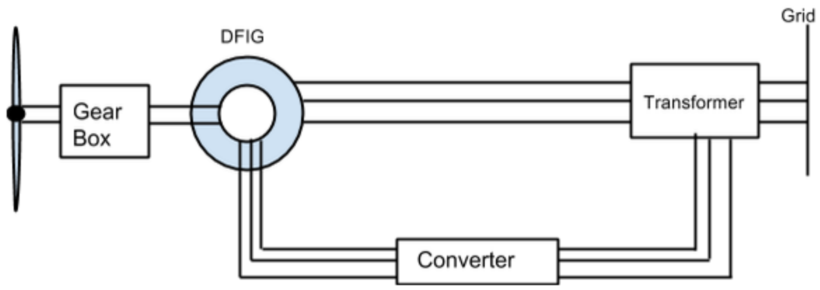

Figure 3.1: Doubly-fed Induction Generator Wind Turbine

The characteristic feature which sets apart the doubly fed induction generator (DFIG) form the squirrel cage generator is that the rotor is connected to a three phase voltage source converter through slip rings. The presence of the converter allows the frequency to be maintained at a constant value irrespective of the wind speed by controlling the rotor and grid currents.

Figure 3.1 represents the Doubly-fed induction generator wind turbine. As it can be seen, the stator is directly connected to the grid and the rotor is connected to power electronic converter through slip rings. The power electronic converter needs to handle only a part of the total power (approximately 20-30%).

Less mechanical stress on the drive-train and low cost of the frequency converter are some of the advantages of the DFIG wind turbines [18].

3.1.1 Modelling of DFIG

The DFIG model used in Simpow for this thesis has a fairly detailed generator model while the frequency converter is modelled as a voltage source converter. It also includes a blade pitch control system which turns the blade at high wind speed conditions in order to capture less wind by the turbine and thus maintain the power production within allowable range. Speed control systems are also included in the modelling and a crow bar control system is added for protection purpose.

The doubly fed induction machine designed in Simpow has the following main sections also known as modules in Simpow:

1. Asynchronous Machine (wound rotor induction generator)
2. Wind Turbine Model
3. Speed Control Model
4. Pitch Control Model
5. AC voltage Control System
6. Crow-bar Control System Model

Figure 3.2 shows the block diagram of the DFIG model [19].

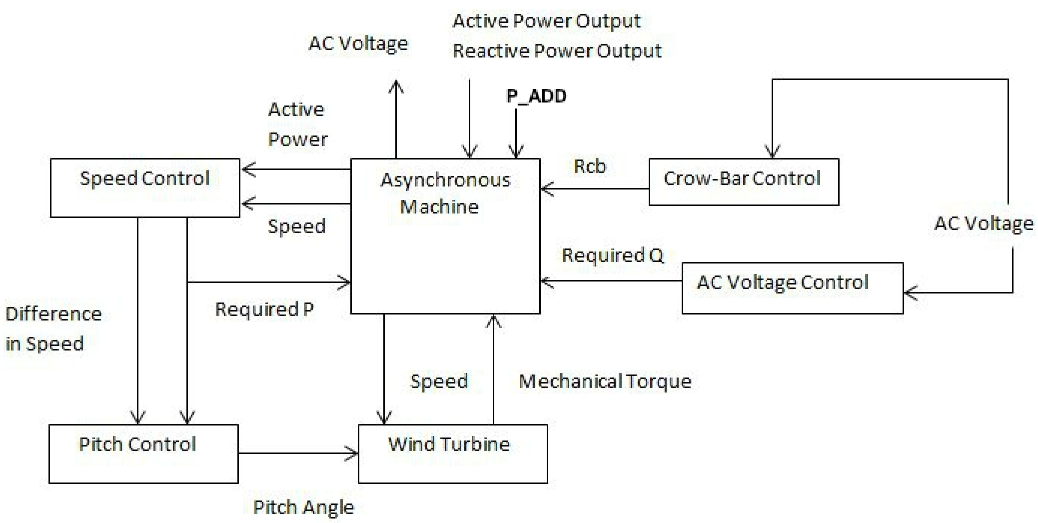

Figure 3.2: Block Diagram for Doubly Fed Induction Generator model

3.1.1.1 Wind Turbine Model

The mechanical power obtained from the captured wind can be expressed as a function of air density, area of the blades, speed of the wind and a term C_p known as the Coefficient of power which is measurement of how efficiently the turbine converts the wind energy into electrical output.

$$P_m = \frac{0.5 \times C_p \times \rho \times \pi \times R^2 \times v_w^3}{S_n} \tag{3.1}$$

Further, C_p can be expressed as a function of tip speed ratio and the blade pitch angle, i.e $C_p = f(\lambda, \beta)$ based on a number of curves at different blade angles

β. The tip speed ratio is defined as the ratio between the speed of the tip of the blade and the actual velocity of the wind given by the equation

$$\lambda = \frac{v_t}{v_w} \tag{3.2}$$

and $v_t = \omega_t \times R = \frac{2\times\pi\times n\ R}{60}$.

Consequently, the mechanical torque produced from the wind can be expressed as

$$T_m = \frac{P_m}{\omega} = \frac{0.5 \times C_p \times \rho \times \pi \times R^2 \times v_w^3}{\omega \times S_n} \tag{3.3}$$

where
ρ is the air density in kg/m^3
R is the length of the blades in m
S_n is the rated power of the DFIG in MVA
v_t is the tip speed of the blades in m/s
v_w is the wind speed in m/s
n is the rotation speed of the wind turbine in rpm
ω is the rotation speed of the wind turbine in p.u
T_m is hte mechanical torque in p.u
P_m is the mechanical power in p.u
β is the blade pitch angle in degrees

For the implementation, the value of C_p as a function of tip speed ratio and blade angle must be known. This is included in the model in the form of tables. To start the simulation, the tables used are the default tables that are available in Simpow. For future projects, these tables will be loaded from an external text file which will help in making this model more generic and compatible with different kinds of wind turbines and wind tables. The output of this module is the mechanical torque available from the turbine in per unit which acts as one of the inputs to the asynchronous machine.

3.1.1.2 Speed Control Model

In order to obtain maximum energy from the wind, the speed of the rotor should vary in accordance with the speed of the wind. The speed control model is basically a PI controller whose input is the actual power generation and the speed. The output of the model is the required power which controls the rotating speed by manipulating the generated real power of the DFIG. The speed reference is calculated using actual real power production. The block diagram of the speed controller can be found below

3.1.1.3 Pitch Control

The block diagram of the pitch controller is shown below. The output of this model is the blade pitch angle β , which controls the captured wind power, while the required power and the speed deviation from the speed control block act as input. Similar to the speed control model, the pitch control model block consists of PI controller. The blade angle response is filtered and is limited both in magnitude and in its derivatives.

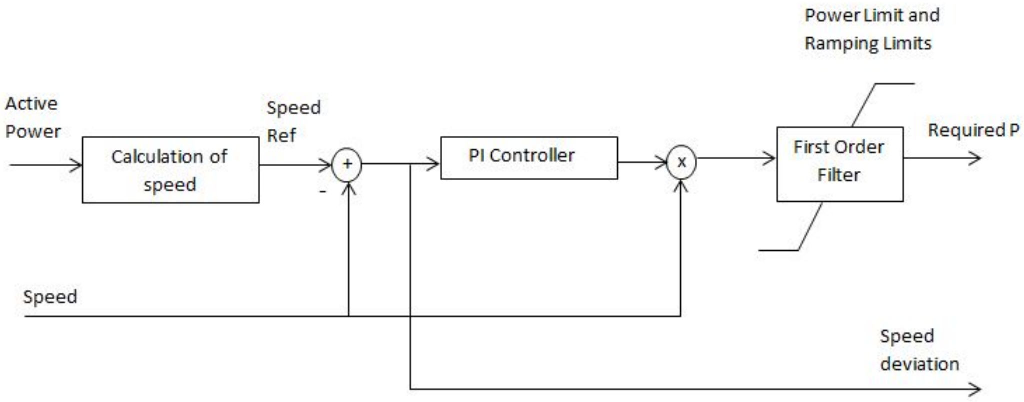

Figure 3.3: Block Diagram of Speed Control Model

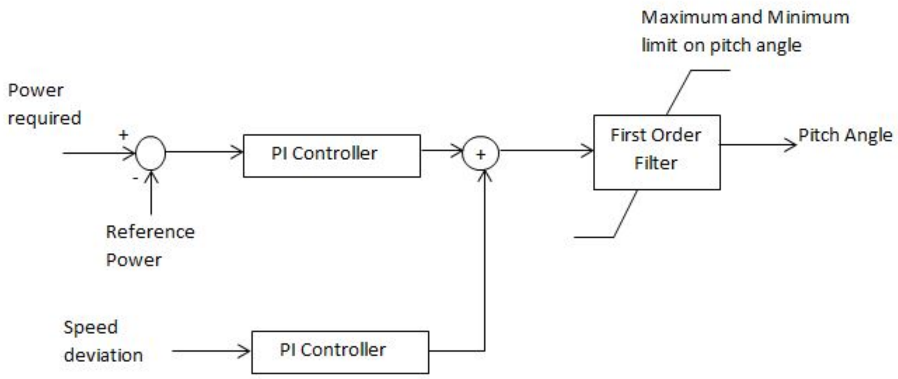

Figure 3.4: Block Diagram of Pitch Control Model

3.1.1.4 Asynchronous machine

The asynchronous machine is based on one-mass model using the mechanical inertia of both the wind turbine and the rotor of the generator. The model also includes the power electronic converter which handles the rotor current. The machine is modelled based on the equations defined by the Fransesco Sullah method [20]. The equations for stator and rotor side voltage and currents are defined in dq- coordinate systems. In addition, the torque equation is also defined in this section. The model is available in Simpow and is used for the wind turbine modelling. Developing a new model for the asynchronous machine is beyond the scope of this thesis.

3.1.1.5 Crow-Bar Control

In this block, the state of the crow-bar resistance is obtained, i.e whether the resistance is connected or disconnected in the machine model. The ac bus voltage with upper and lower limits acts as the input to this block.

3.1.1.6 AC Voltage Control

This block is used to maintain the reactive power output of the DFIG. The ac voltage acts as the input to the block and the PI regulator with upper and lower limits is included to maintain the reactive power production/consumption.

3.2 Full Power Converter Wind Turbine

Doubly fed induction generators and Full Power converter wind turbines are both based on variable speed generators but the difference between them is the presence of a synchronous machine in the full power converter wind turbine in comparison to the asynchronous machine in the doubly fed induction generator wind turbine. Also, in DFIG, only the rotor side is connected to a converter, which handles only 20-30% of the total power, and the stator is directly connected to the the grid [18]. However in the FPC wind turbine the frequency converter consists of a grid side inverter, a machine-side rectifier and an intermediate dc system and transfer the entire real power from the generator to the grid which in turn helps the generator output to adapt to the desired system frequency. The frequency converter controls the active power in a way that the speed of the generator follows the wind speed in the most efficient way [19]. This section illustrates the different modules of the FPC wind turbine.

3.2.1 Modelling of FPC

The FPCWT model used in Simpow is designed in such a way that the PWM Converters can produce or consume reactive power to maintain unity power factor at the generator terminals and also control the grid side voltage. The model is valid for wind speeds upto 25 m/s. Switching patterns for the power electronics converters is beyond the scope of the thesis and hence not considered while modelling the converters. It also includes a blade pitch control system which turns the blade at high wind speed conditions in order to capture less wind by the turbine and thus maintain the power production within allowable range. Speed control systems are also included in the modelling. The block diagram is as shown in figure 3.5

The FPCWT designed in Simpow has the following main sections also known as modules in Simpow:

1. Synchronous Generator model
2. Wind Turbine Model
3. Speed Control Model
4. Pitch Control Model
5. AC voltage Control System
6. PWM Converter model
7. Shunt Capacitor

The wind turbine model, speed control, pitch control and AC voltage control modules are modelled in a similar way as discussed in the previous section of Doubly fed Induction generator wind turbines. The modules which are unique only

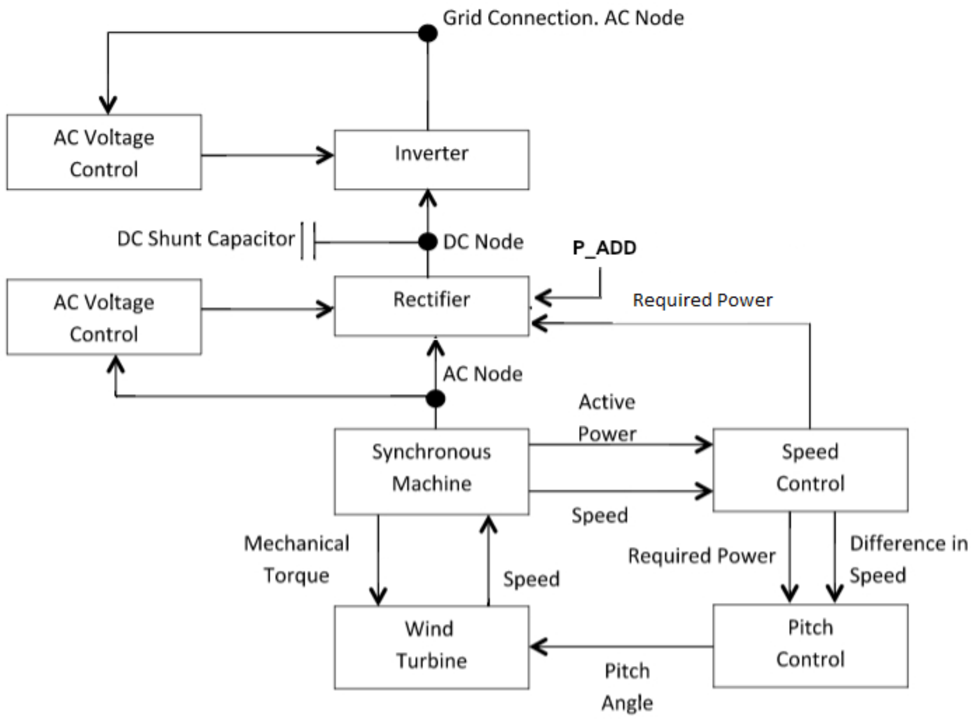

Figure 3.5: Block Diagram for Full Power Converter Wind Turbine Model

to the FPC wind turbines are the PWM converter modules along with the shunt capacitance and the Synchronous machine.

3.2.1.1 PWM Converter

The PWM converter consists of a grid side inverter which maintains the DC node voltage by controlling the level of current and a machine side rectifier in a manner to make sure that the power output from the the speed controller module equals the power order required from the speed controller.

The PWM converter has an internal PI regulator to control the current and power independently and a simplified model of the converter is as shown in figure 3.6. P_L corresponds to the no-load losses. The real and imaginary parts of the current passing through the reactance are in accordance to the orders from the controllers.

3.2.1.2 Shunt Capacitor

The capacitor is designed as a standard capacitor whose size is dependant on the chosen time constant of 10-20 ms and is calculated using the equation

$$T = \frac{0.5 \times C \times U_{DC,N}^2}{P_{DC,N}} \tag{3.4}$$

where C is the DC capacitance in μF, $U_{DC,N}$ is the nominal DC voltage in kV and $P_{DC,N}$ is the nominal DC power in MW.

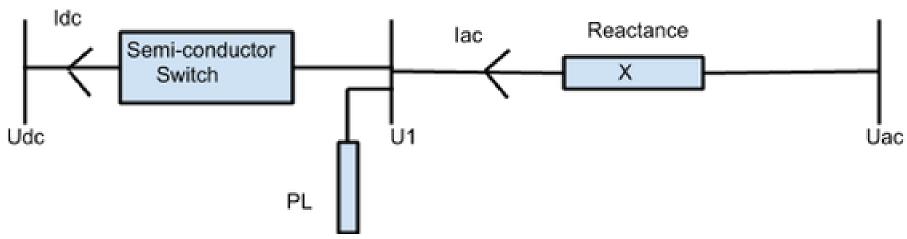

Figure 3.6: PWM converter model

3.2.1.3 Synchronous Machine

A standard model of the synchronous machine with constant field voltage available in Simpow is used for this. The rating of the synchronous machine is higher than the power rating of the converter.

Chapter 4

Simulation of DFIG Wind Turbine

This chapter describes the steps incorporated to design a simple power system and then incorporating the synthetic inertia into the system for improved frequency response.

4.1 Implemeting a simple power system

Once the complete model of DFIG wind turbine is available for implementation, it needs to be tested on a power system. In Simpow, in order to run a dynamic simulation on a power system, three different kind of files are required. An OPTPOW file which provides the power flows and initial conditions for the analysis of the dynamic models. A DYNPOW file where the dynamic models of the system are defined. And finally, a DSL file where the user defined models are initiated and implemented.

Giving relevant information in the three different files, the one line diagram as shown in figure 4.1 is implemented. The details of the different wind turbine parameters are shown in table 4.1

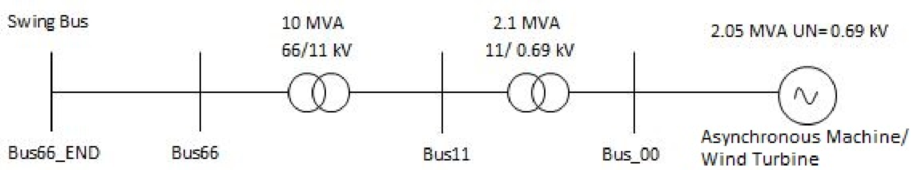

Figure 4.1: Single line diagram for the wind turbine

The wind profile used for the system is as shown in figure 4.2. As it can be seen, there are three distinct wind speed regions; Wind speed of 12 m/s in the duration 0-130 seconds, wind speed of 9 m/s in the duration 140-250 seconds and the wind speed of 6 m/s from 270-350 seconds. The machine takes a some initial time of 10 seconds to settle down to its steady state. The same wind profile will be used for the FPC model described in chapter 5. Figure 4.3 shows the corresponding rotor speed W_PU and output power PG_PU of the DFIG for the wind profile used.

Table 4.1: Wind turbine data used for the simulation

Parameters	Value
S: Rated Power in MVA	2.05
H: Interia constant	5.5
Rotor Reactance in per unit	0.07
Stator Reactance in per unit	0.18
Minimum Speed in per unit	0.7
Maximum Speed in per unit	1.5

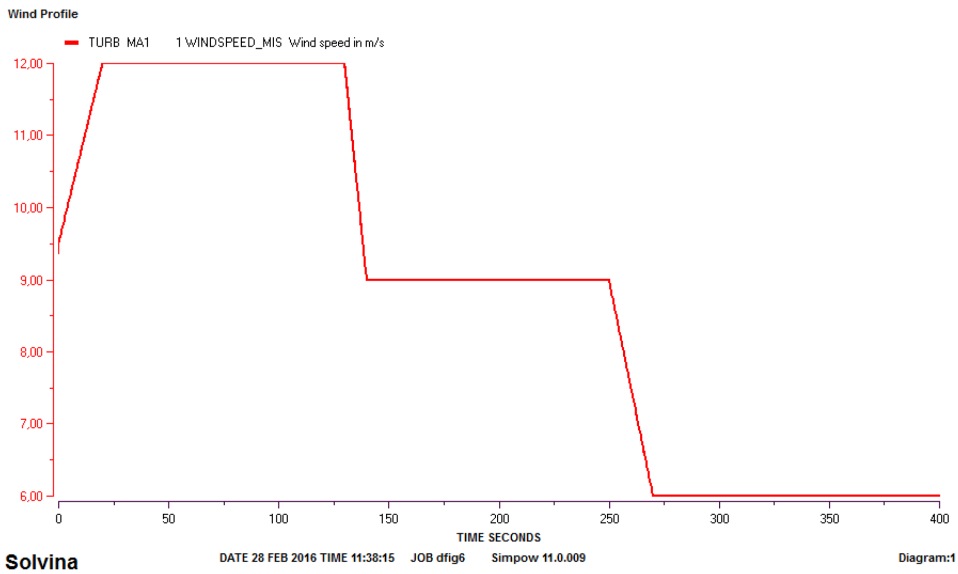

Figure 4.2: Wind Profile Used for Simulations

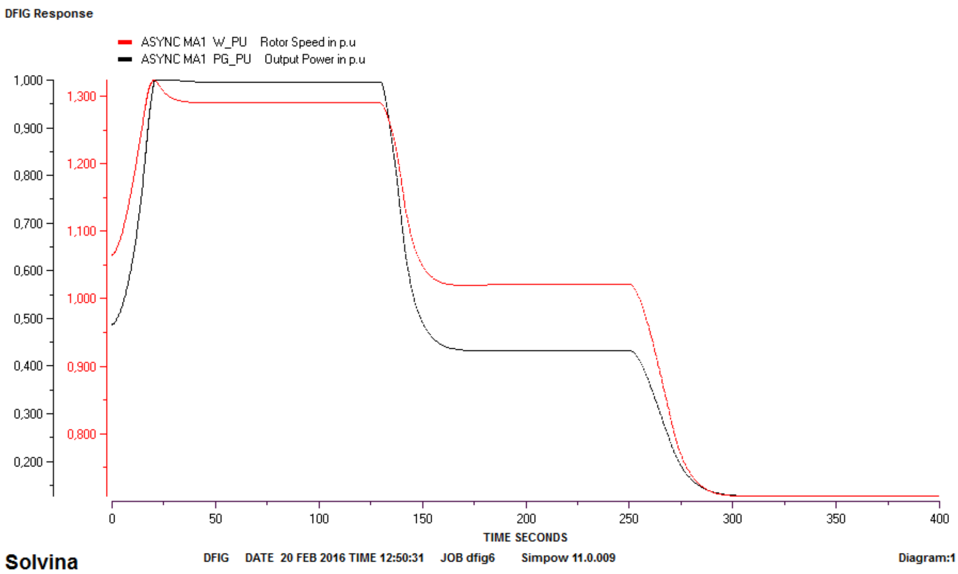

Figure 4.3: Rotor speed and output power of the wind turbine for the given wind profile

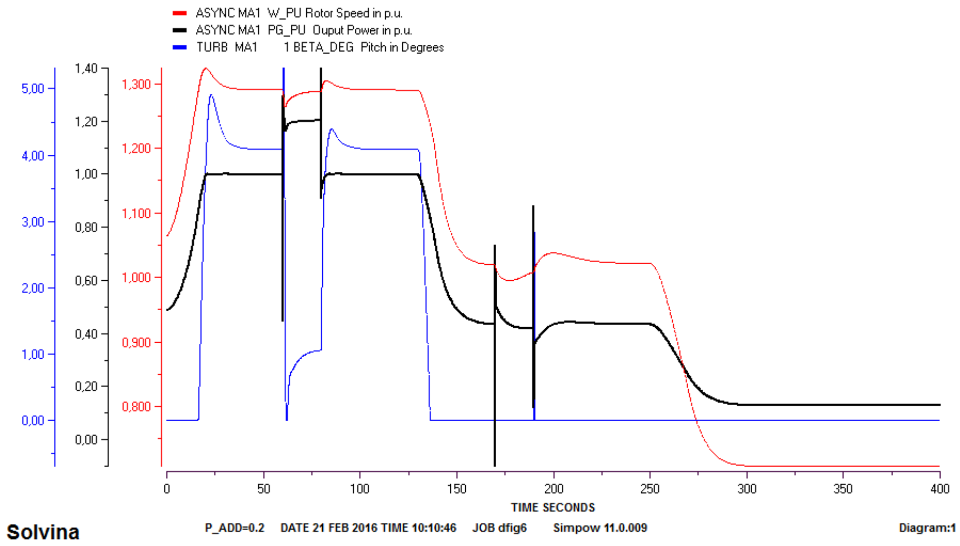

Figure 4.4: Output of asynchronous machine with P_ADD =0.2 p.u applied in high and medium wind region

In the block diagram of the two wind turbine models described in chapter 3, an additional power term P_ADD is given as input to the wind turbine model. Initially, to test if the model is working as desired this P_ADD term will be given as small input steps of ±0.2, ±0.3 and ±0.4 p.u for a duration of 20 seconds each, at different wind conditions. In later sections this will be replaced by the actual synthetic inertia term added into the system. The calculation of the synthetic inertia can be found in section 4.2 .

One such example is shown in figure 4.4. Here a P_ADD step of 0.2 p.u is applied in the high wind region and the medium wind region, each for a duration of 20 seconds and the maximum allowable power rating is restricted to be 1.3 p.u. In the high wind speed region at instant 60 seconds, an additional power step P_ADD = 0.2 p.u is added. Correspondingly a small reduction in speed W_PU is observed and also pitching of the wind turbine which is represented by the blue curve BETA_DEG. It is because of the pitching of the blades which makes it possible to get the increase in power output PG_PU. On the other hand, in the medium wind region at instant 170 second when P_ADD of 0.2 p.u is applied, there is a reduction in the rotor speed W_PU and the rotor speed controller takes over setting the output back to the point that can be sustained at the present wind speed. In the medium wind speed region, the speed controller is designed in way that it responds faster than the pitch controller and it is because of this that a faster reduction in the power output PG_PU is observed. Certain spikes can be observed at the instants when P_ADD is introduced into the system at high wind and medium wind speeds. Since the the models are based on the rms-modelling using vectors (dq-coordinates), the vectors take sometime to recognize that there has been some change or a disturbance in the system. This is could be one of the reason for the spikes observed in the plots. Moreover, since these last only for a couple of milliseconds, they will be neglected from this point.

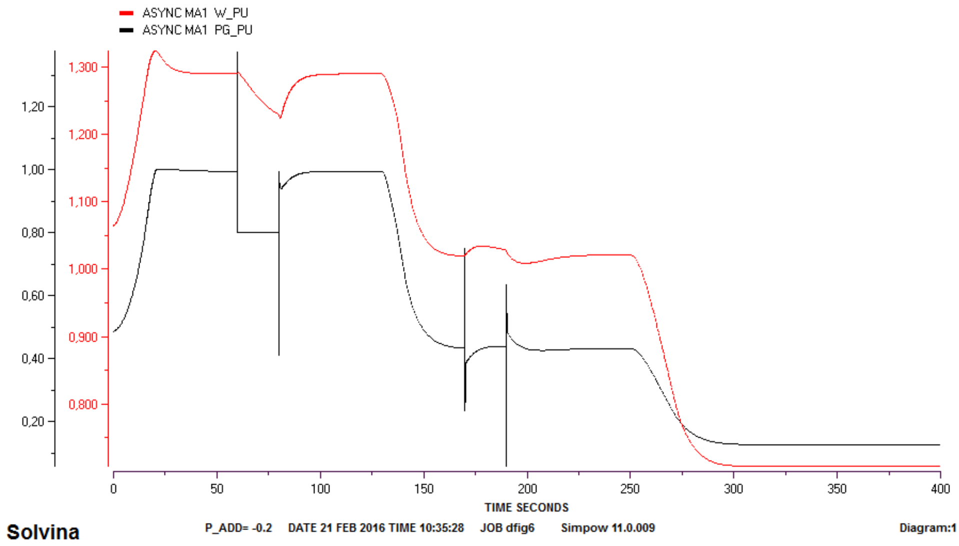

Figure 4.5: Output of the asynchronous machine at *P_ADD*= - 0.2 p.u

To check whether the wind turbine would support the scenario of over frequency due to loss of a load, a negative value of P_ADD was applied to the model at high wind and medium wind speed conditions. This can be seen in figure 4.5

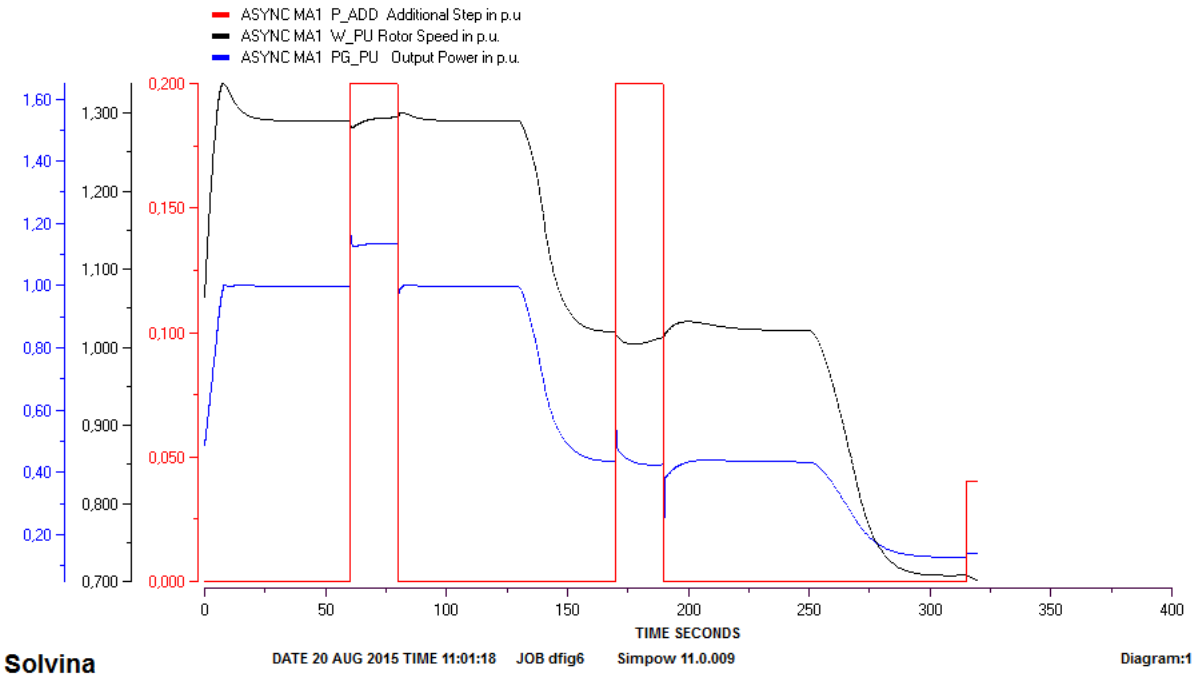

Figure 4.6: Stalling of simulation for the DFIG wind turbine at low wind speed with *P_ADD*=0.04 p.u.

It is also observed, that at low wind conditions, the maximum value of P_ADD that the model could handle is 0.03 p.u. Any value higher that this would cause the rotor speed to fall below the minimum set rotor speed of 0.7 p.u and thereby causing the simulation of the wind turbine to stall as seen in figure 4.6. Since it is a negligible value, it was concluded that synthetic inertia cases in the following sections, will be tested only in medium and high wind conditions.

Once the model is tested for an external P_ADD term, a power system with a synchronous machine and a load is designed. Necessary changes are made in the Simpow files to obtain this. This was to test the wind turbine model on a low scale but more realistic power system. The synchronous machine used in this case is rated at 100 MVA and the governors are designed in a way so as to get a realistic and acceptable response from the synchronous machine. The one line diagram can be seen in figure 4.7.

4.2 Synthetic Inertia

In conventional power system comprising of synchronous machines, kinetic energy is released from the rotating mass whenever there is a drop in grid frequency. The kinetic energy released aids in reducing the change in frequency drop. But in variable speed wind turbines, this does not happen automatically due to the presence of the power electronics converters which decouples the wind turbine from the grid. With more and more wind turbines being operated in the present power system, and in several cases replacing the conventional synchronous machines, the total inertia of the system is getting reduced and this can result in a rapid drop in the frequency in case of a big disturbance [7]. In order to have a stable and reliable power system it becomes highly necessary to restore this system inertia in the variable wind turbines.

Wind turbines have a considerable amount of kinetic energy stored in them during operation. This energy can be used to provide the frequency support to the grid. This can be achieved by adding an additional loop in the control system block of the speed and pitch control of the wind turbine [4].

This control loop senses any change in frequency and in accordance to that introduces a term which is equal to

$$P\_ADD = -2 \times H \times w \times \frac{dw}{dt} \tag{4.1}$$

which moves the set-point of the power output desired from the wind turbine. In the above equation, H is the moment of inertia of the rotating mass and ω is the rotor speed. For simulation in Simpow, this term was added in the dsl-code of the asynchronous machine model as an extra input.

4.3 Case Setup

In order to test the synthetic inertia in a power system, an additional synchronous machine and a load were added to the Bus 66, as seen in figure 4.7. Two different test scenarios were set up and the corresponding results were obtained; the first case has a large synchronous machine, rated at 100 MVA in comparison to the wind turbine rated at 2.05 MVA while the second case involves a synchronous machine

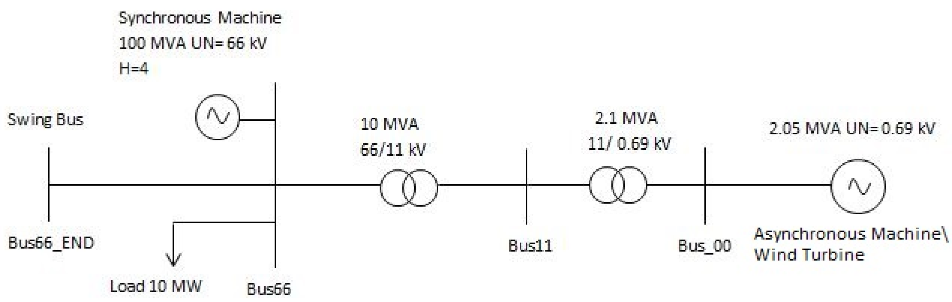

Figure 4.7: Single line diagram with the synchronous machine and load included

whose rating is comparable to the rating of the wind turbine, i.e 10 MVA. The base value is selected as 2.05 MVA for all the cases. Once the system is setup the disturbances were introduced beginning with the line disconnection between Bus66 and Bus66END at time instant of 75 seconds creating an electric island. This was followed by the load connection of 1 MW at 200 second and finally a load disconnection of 1 MW at 350 seconds. Since the main focus of this thesis work was to study the response of the wind turbine in an electric islanding condition, the event corresponding the the line disconnection at time instant of 75 seconds is not given high importance and hence not shown in the following plots.

4.3.1 Case 1: Large Synchronous Machine

In this case, the synchronous machine added to the system is rated at 100 MVA in comparison to the wind turbine which is rated at only 2.05 MVA. The equation for synthetic inertia is

$$P\_ADD = -2 \times k \times H \times w \times \frac{dw}{dt} \tag{4.2}$$

where k is a constant and is used to vary the level of synthetic inertia introduced into the system. The values of k considered in this case are k=0, 1 and 4. These vales are tested for three wind conditions: High wind (12 m/s), medium wind(9 m/s) and low wind (6 m/s). The value of P_ADD was limited to ± 0.2 per unit to make sure that the addition of the additional power term does not cause any damage to the wind turbine and to protect the wind turbine from stalling.

In the following figures, W_PU corresponds to rotor speed in p.u, PG_PU is the output power in p.u, P_ADD is the synthetic inertia added in p.u and FY is an output variable available in Simpow which is equal to the system frequency. For simulation purpose, couple of first order filters were included in the Simpow files to help improve the quality of signal FY.

Figure 4.8 shows the response of the system with no synthetic inertia, i.e $k = 0$. At time instant 200 seconds, when a disturbance occurs due to the addition of an external load, there is a significant increase in the rotor speed W_PU and power output PG_PU which is not normal since this is the case with no synthetic inertia added into the system.Similar observations is made when another disturbance is introduced into the system at 400 seconds, which causes the rotor speed, W_PU to reduce. A possible reason for this could be that the integrators which build up the

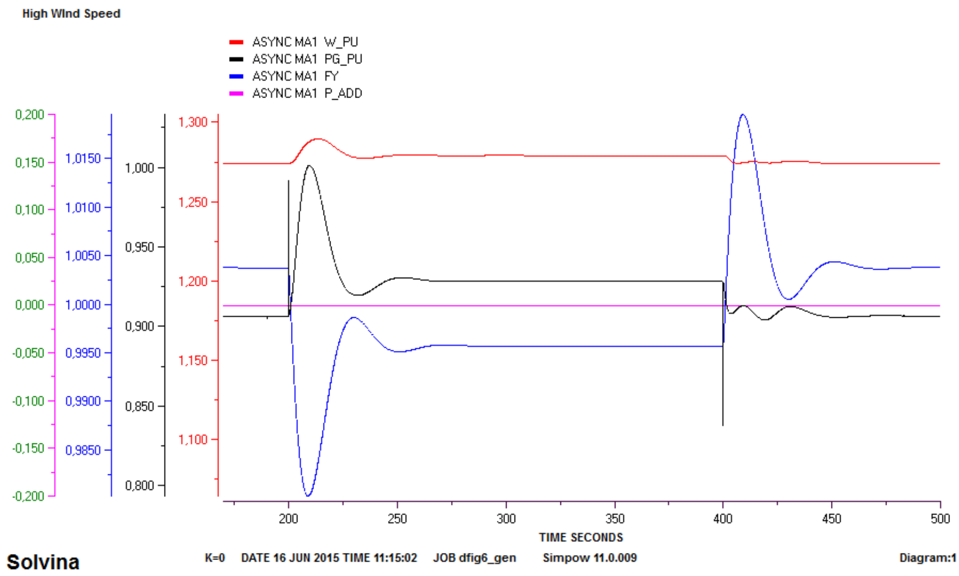

Figure 4.8: Output of the wind turbine with k=0

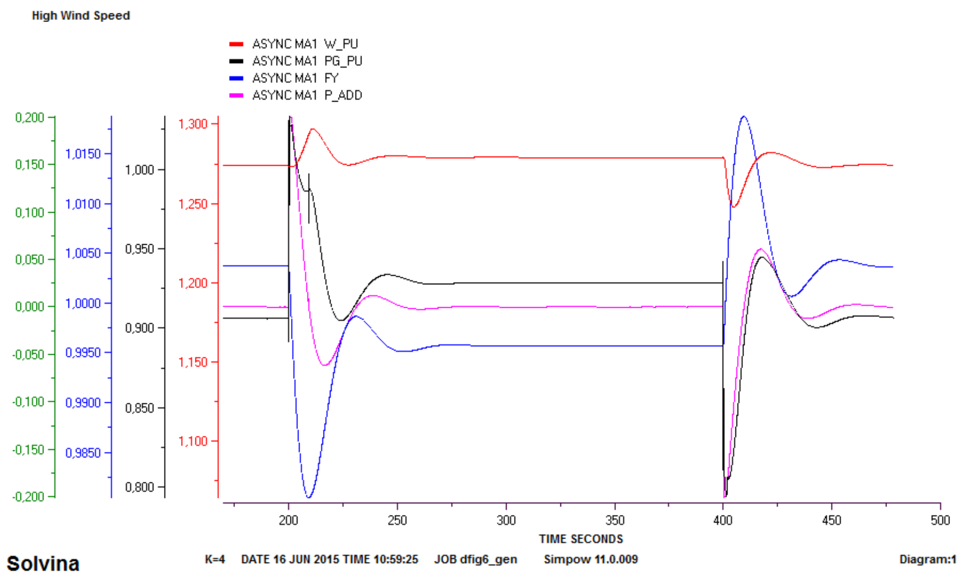

Figure 4.9: Output of the wind turbine with k=4

different controllers of the DFIG model and designed for this system are not well suited for frequency deviations. To find the exact controller and the parameter which needs further tuning, a more thorough investigation needs to be done. This can be done by changing one controller parameter at a time and running the simulations and the process repeated for every controller until the desired response from the system is obtained. Since this investigation is beyond the scope of this thesis, it has been prescribed as a future work for the improvement of the models in Simpow.

From figure 4.9 with $k = 4$ it can be seen that when there is a drop in frequency FY due to the addition of an external load at 200 seconds, the power from the wind turbine PG_PU increases due to the synthetic inertia added. Similarly, an increase in P_ADD is also observed. However, since the synchronous machine is several times larger than the wind turbine, the system frequency is dominated by the large synchronous machine and the effect of the synthetic inertia is negligible, i.e it does not aid the frequency response of the system significantly and this can be seen by comparing the system frequency FY from the figures 4.8 and 4.9. An unexpected observation can be made from the plot which clearly indicates that the controller in the DFIG model needs further studying and consequently more tuning to suit frequency deviations; the rotor speed increases instead of decreasing when there is an increase in the load step at 200 seconds and similarly there is a decrease in rotor speed when there should be an increase in the rotor speed at 400 seconds. Another probable solution to rectify this problem could be to study the various the inputs and how they are fed to the controllers to be able to handle the changes in the system frequency.

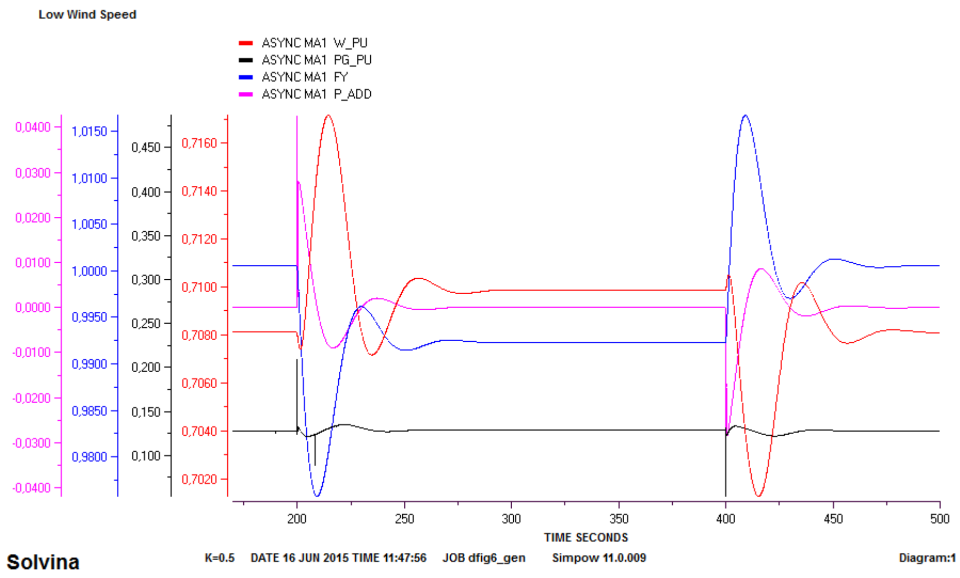

Figure 4.10: Wind turbine Output at low wind speed condition with k=0.5

At low wind speed, the maximum value of k the wind turbine can sustain is 0.5 as seen in figure 4.10. Any value higher than this causes the wind turbine model to become highly unstable. This can be seen from figure 4.11

4.3.2 Case 2: Small Synchronous machine

In this case, a synchronous machine rated at 10 MVA was connected at Bus66 in place of the synchronous machine rated at 100 MVA and the same wind turbine rated at 2.05 MVA is used. Like in the previous case, the value of synthetic inertia is tested for different value of k and at high and medium wind speed condition, i.e 12 and 9 m/s respectively. Equation 4.1 denotes the synthetic inertia added into the system. To make sure that the addition of P_ADD term does not cause any damage to the wind turbine, its value was limited to ± 0.2 p.u.

Figure 4.12 and 4.13 show the response of the the system for synthetic inertia value $k = 3$ and $k = 0$ respectively. From figure 4.12 with $k = 3$ it can be seen that when there is a drop in frequency FY due to the addition of an external load

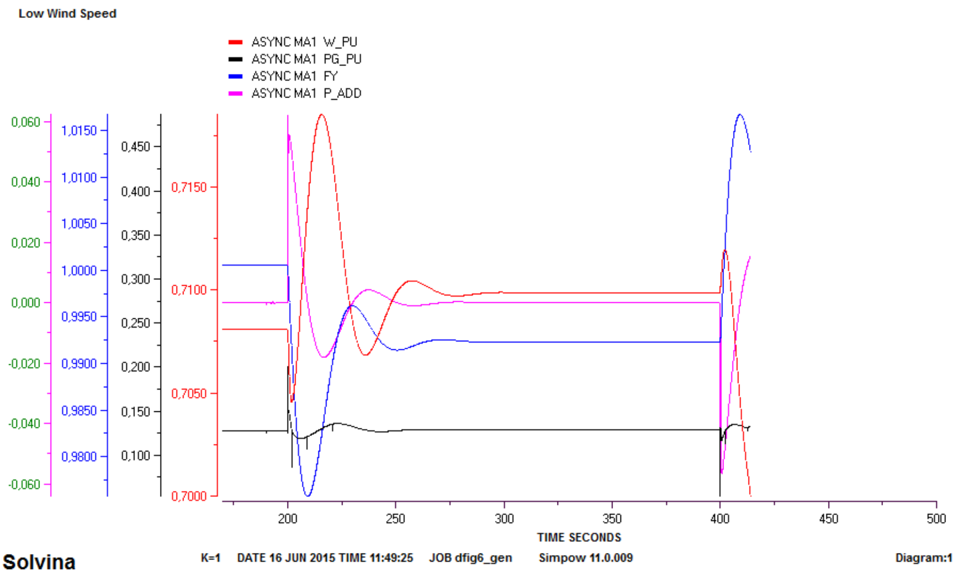

Figure 4.11: Wind turbine output at low wind speed condition with k=1 which causes the system to become unstable.

at 200 seconds, there is a reduction in rotor speed W_PU and consequently the power output from the wind turbine PG_PU increases by approximately 0.2 p.u for a duration of 1.2 seconds thus helping the frequency response of the system. This can be justified by comparing the drop in system frequency FY for the two cases: with $k = 0$ the lowest value is 0.9800 p.u and with $k = 3$ the lowest value is 0.9825 p.u from figure 4.12 and 4.13 respectively. Another observation that can be made is that the rate of change of frequency is slower in the case of $k = 3$ than in the case with $k = 0$.The reason why a more significant improvement in frequency response is observed in this case when compared to the previous case is that the rating of the two machines is now quite comparable to each other and both machine contribute equally to maintain the system frequency.

Similar improvement in frequency response can be observed in the case of over-frequency, i.e when the total generation is greater that total load from figure 4.14 and 4.15 by reducing the power output of the wind turbine PG_PU.

From figure 4.16 and 4.17, it can be seen that the addition of synthetic inertia does not improve the frequency response significantly in the medium wind speed region, i.e 9 m/s. Here again, an abnormal response is observed in the rotor speed W_PU.

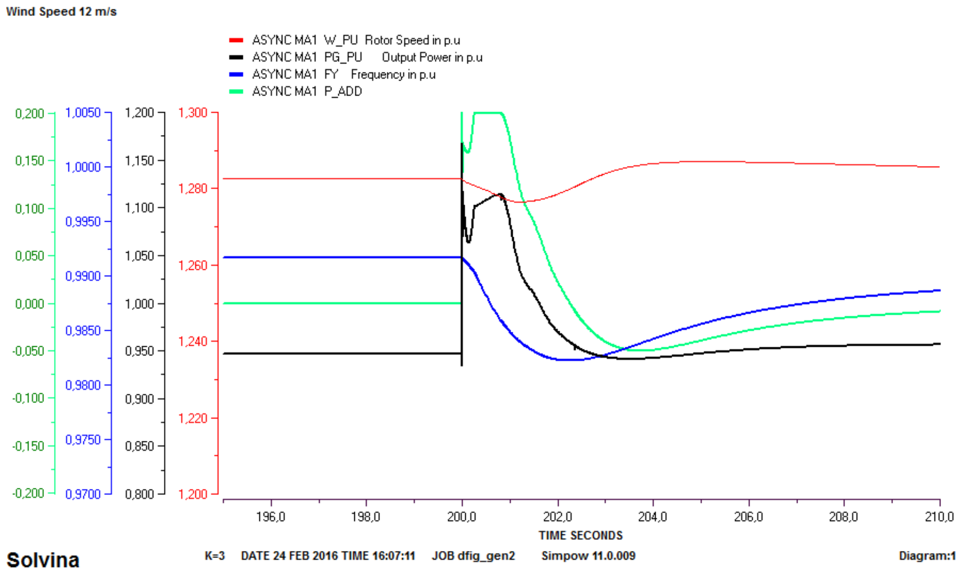

Figure 4.12: Output of wind turbine at high wind speed with k=3

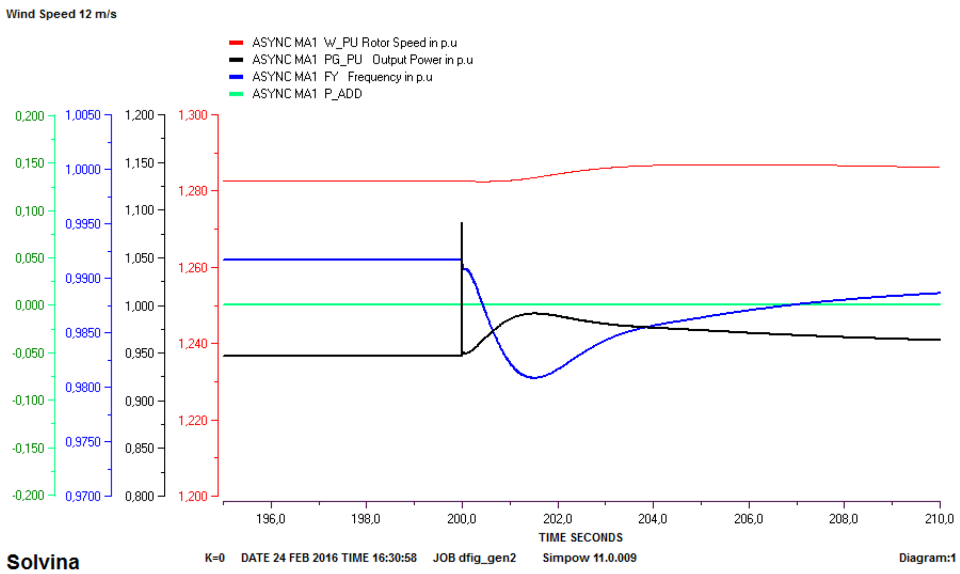

Figure 4.13: Output of the wind turbine at high wind speed with k=0

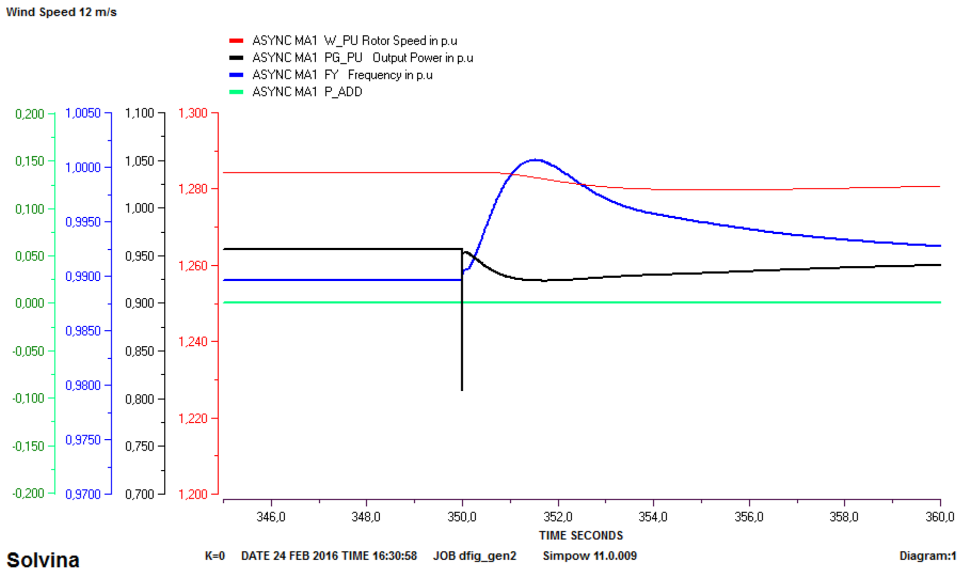

Figure 4.14: Output of the wind turbine in high wind speed in case of over-frequency with k=0

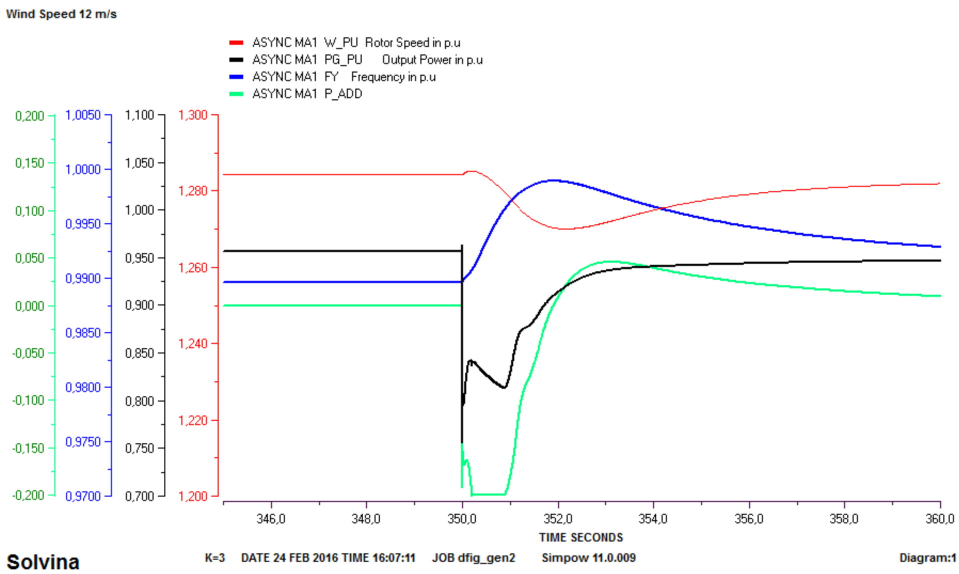

Figure 4.15: Output of the wind turbine in high wind speed in case of over-frequency with k=3

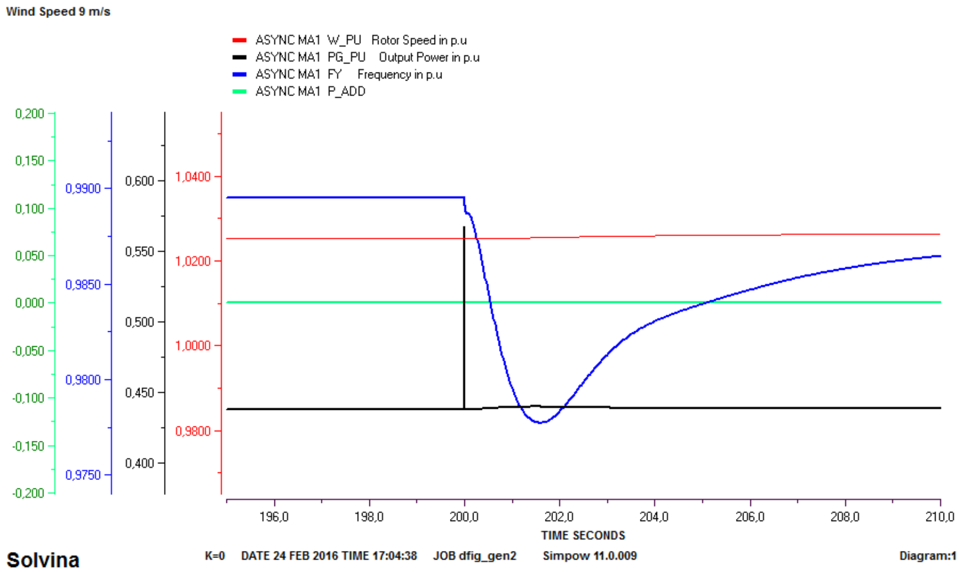

Figure 4.16: Output of the wind turbine in medium wind speed region with k=0

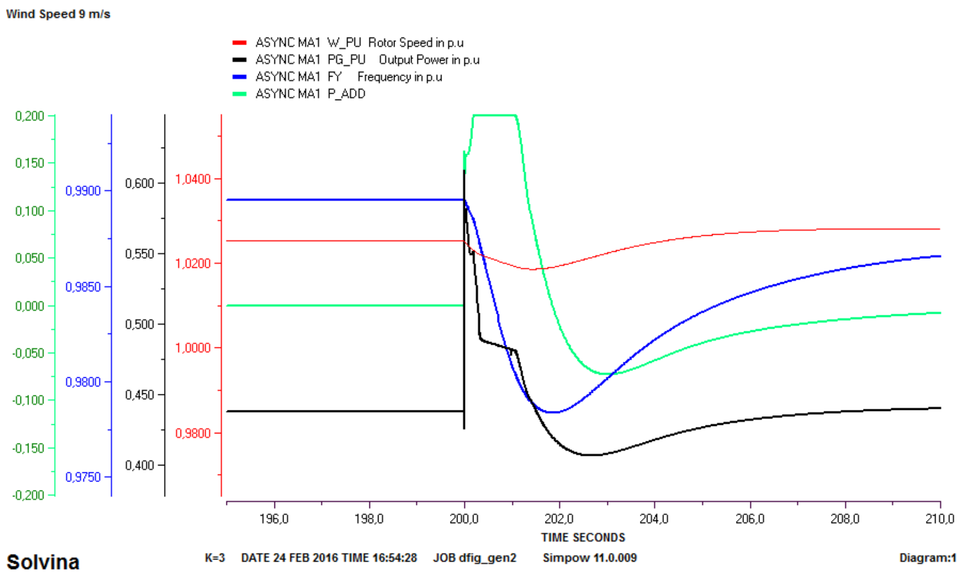

Figure 4.17: Output of the wind turbine in medium wind speed with k=3

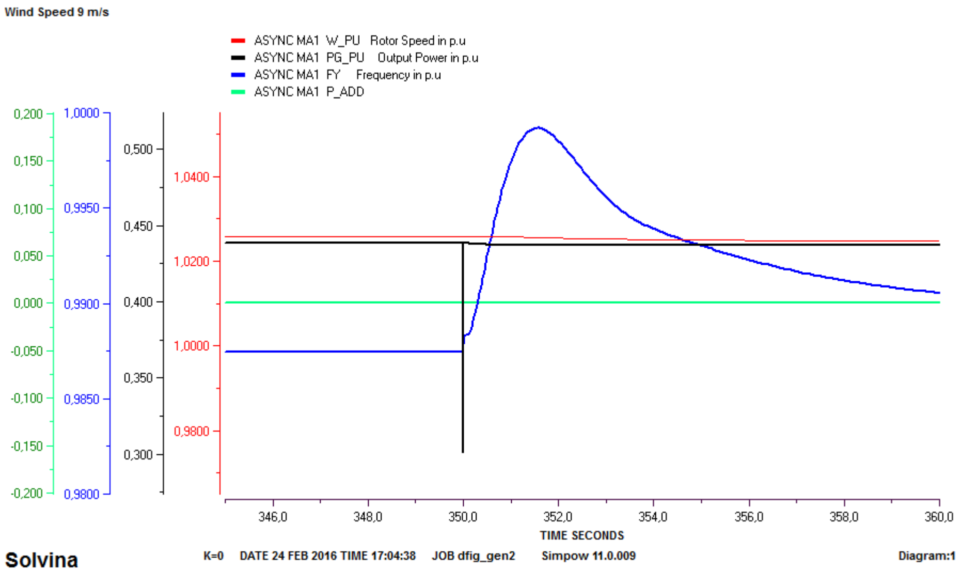

Figure 4.18: Output of the wind turbine in medium wind speed in case of over-frequency with k=0

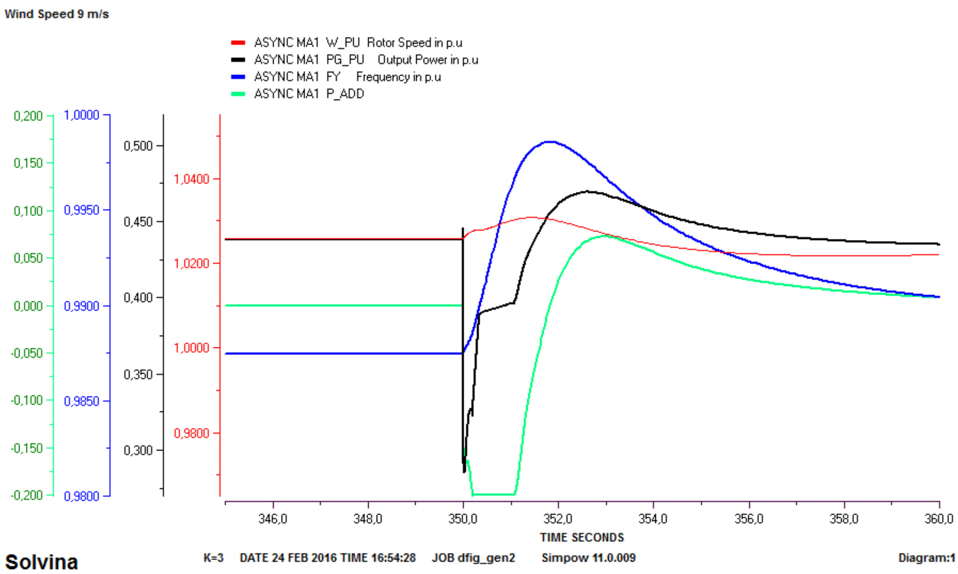

Figure 4.19: Output of the wind turbine in medium wind speed in case of over-frequency with k=3

Chapter 5

Simulation of FPC wind turbine

This chapter describes the simulation results of a full power converter on a small power system and the effect of adding synthetic inertia in the model.

5.1 Implementation on a small power system

Once the complete model of FPC wind turbine is available for implementation, it needs to be tested on a power system. By giving the relevant information to the various Simpow files, the one line diagram built for the small power system is shown below. A standard transformer is included to step up the voltage and a capacitor is connected to BUS_DC.

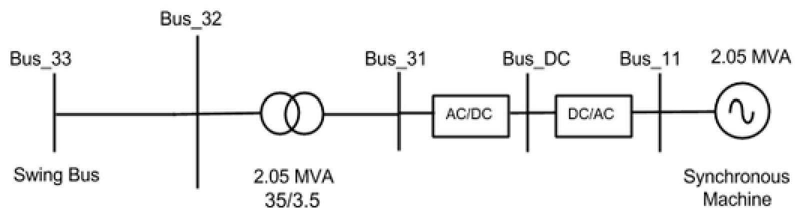

Figure 5.1: Single line diagram for FPC wind turbine

Table 5.1: Wind turbine data used for the simulation

Parameters	Value
S: Rated Power in MVA	2.05
H: Interia constant	5.5
No-load losses in PWM Converter in per unit	0.02
Series Reactance of PWM converter in per unit	0.3
Minimum Speed in per unit	0.4
Maximum Speed in per unit	1.0902

To test the response of the FPC wind turbine, small steps of external additional power T_ADD, are given to the system at two different wind conditions; 12 m/s and 9 m/s for a duration of 20 seconds and the corresponding output from the wind turbine is observed. The wind profile used is similar to the one used for DFIG wind turbine and shown in figure 4.2. The T_ADD term is incorporated in the model by modifying the dsl-code of the model. T_ADD is the same thing as P_ADD and it is given to the system as shown in figure 3.5. In all the following plots, PAC_PU is the output power from the wind turbine, T_ADD is the synthetic inertia included in per unit and FIFI is the variable available in Simpow which is equal to the system frequency.

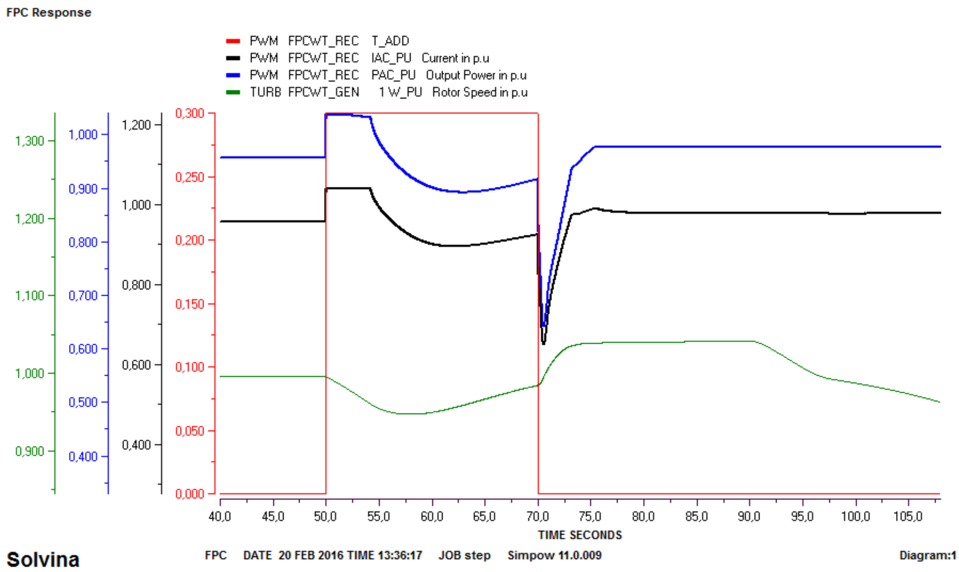

Figure 5.2: Step response for FPC during high wind speed with additional step of 0.2 p.u.

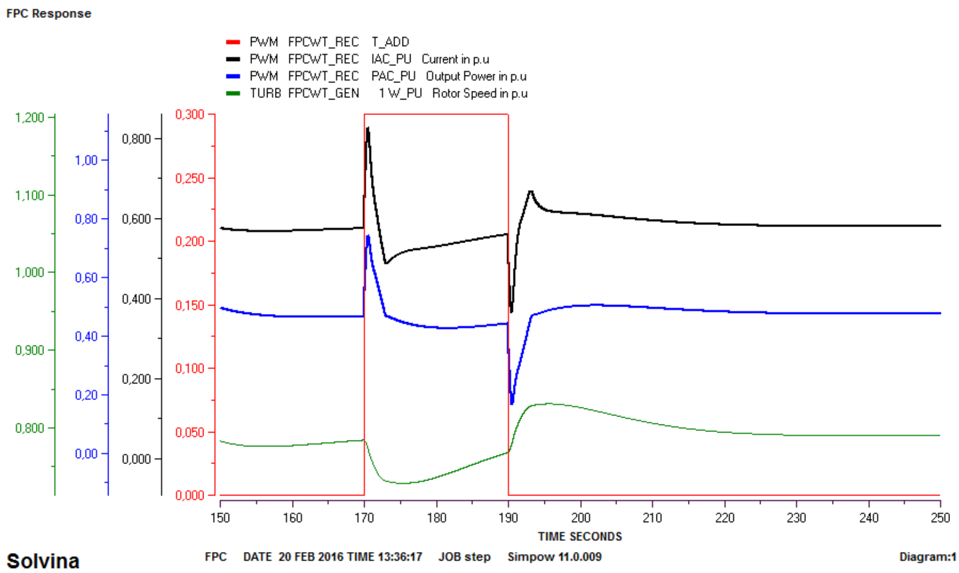

Figure 5.3: Step response for the FPC during medium wind speed with additional step of 0.2 p.u.

Figure 5.2 and 5.3 show the response of the FPC wind turbine with an additional step of 0.2 p.u during high wind speed and medium wind speed respectively. As it can be observed, during high wind speed condition the addition of T_ADD causes the speed of the wind turbine W_PU to reduce and consequently causes an increase of the output power PAC_PU of the wind turbine for a duration of 2.5 seconds. Since pitch control comes into action during high wind speed condition, it is possible to get the extra boost in the power output for a sustained period of time. Another observation that can be made is that eventhough $T\_ADD = 0.2$ p.u is added, the output power PAC_PU does not increase to 1.2 p.u. This is because the maximum current allowable is set to 1.04 p.u and this level s reached at 52 seconds and this is represented by the black curve IAC_PU. On the other hand, in the case of the medium wind speed, the addition of T_ADD cause the output power to increase for a much smaller period of time which is 1 seconds in this case.

Similar tests were done for T_ADD values of 0.1, 0.3 and 0.4 p.u. To check whether the wind turbine would support the scenario of over frequency due to the loss of a load, a negative value of T_ADD was also applied to the model at high wind and medium wind speed conditions independently.

Once the model was tested for an external T_ADD term, the power system was modified to include an additional synchronous generator rated at 10 MVA and an additional load at BUS_32. The corresponding single line diagram is as shown in figure 5.4.

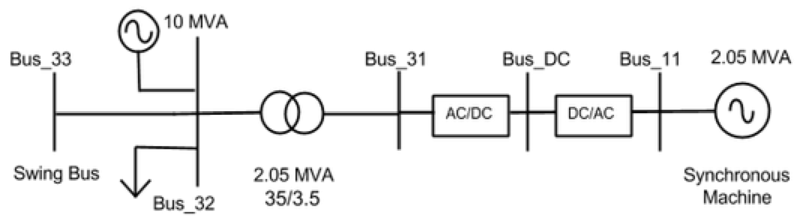

Figure 5.4: Modified single line diagram

5.2 Case Setup

To incorporate the synthetic inertia in the wind turbine model, the dsl-code was modified by introducing an additional power term

$$P\_ADD = -2 \times k \times H \times w \times \frac{dw}{dt} \tag{5.1}$$

which shifts the set point if the input power order to the wind turbine. As in the case of DFIG wind turbine, limits are set on the maximum value of T_ADD to ±0.2 p.u. Disturbances were then introduced to the system starting with the disconnection of the line between BUS_32 and BUS_33 at 75 seconds, followed by the connection of an small load at 150 seconds at BUS_32 which cause the frequency of system to drop and finally disconnecting this load from the bus at 350 seconds. The value of k in the above equation was changed to vary the degree of the synthetic inertia added into the system whenever there is a change in system frequency. The entire procedure was carried out for two different wind speeds; 12 m/s and 9 m/s.

Figure 5.5 show the response of the wind turbine for k=0, which corresponds to a case when no synthetic inertia is included in the system, and and figure 5.6 shows the response with k=3.

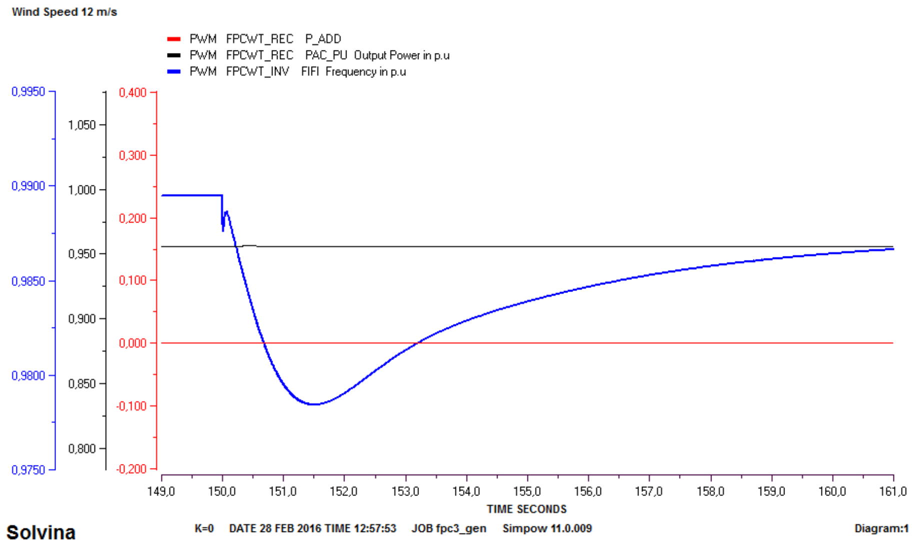

Figure 5.5: FPC output with no synthetic inertia included, i.e k=0

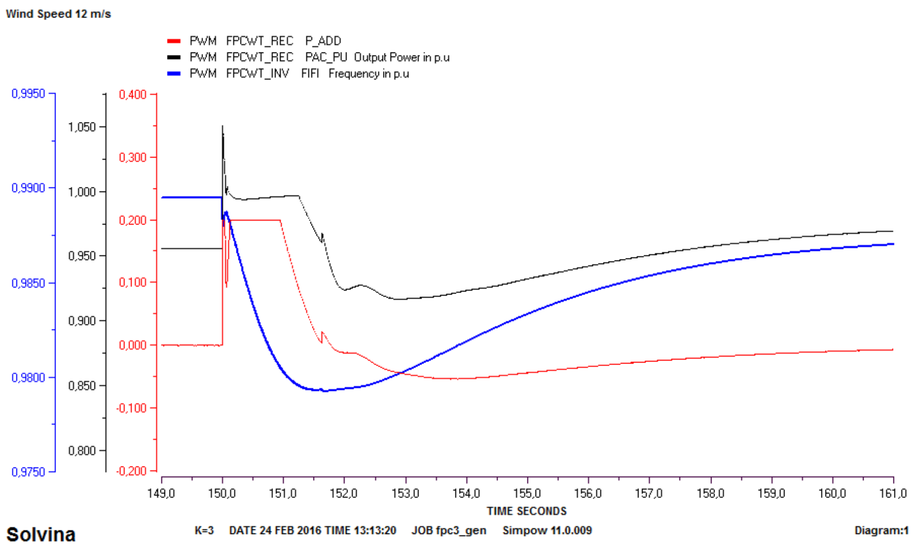

Figure 5.6: FPC output with k=3

As it can be observed, with $k = 3$ when there is a drop in system frequency at 150 seconds, the power from the wind turbine P_AC increases from 0.95 p.u to 1.02 p.u for a duration of 1.7 seconds thus helping the frequency response of the system. This can also be justified by observing the drop in system frequency FIFI in the two cases; in the case of $k = 0$ the system frequency drops to a lower value when compared to the case of $k = 3$. Also the rate of change of frequency with k=3 is slightly slower than in the case with k=0.

Similar frequency response can be observed in the case when the generation is greater than the load demand, i.e when the system frequency increases. Figure 5.7 and 5.8 correspond to these cases. In the case when $k = 3$, the P_AC reduces to reduce the increase in system frequency and thus improving the frequency response of the system.

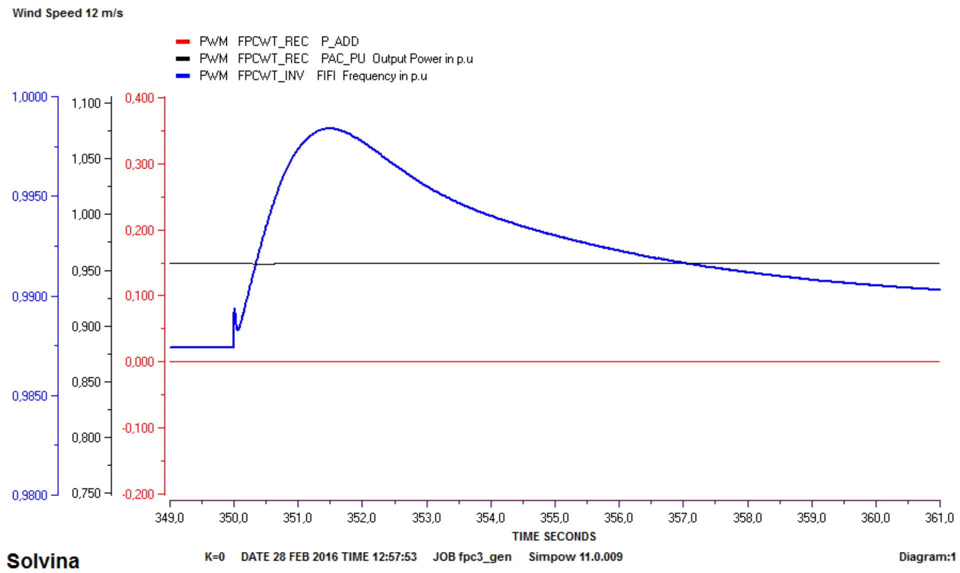

Figure 5.7: FPC output in case of over-frequency with k=0

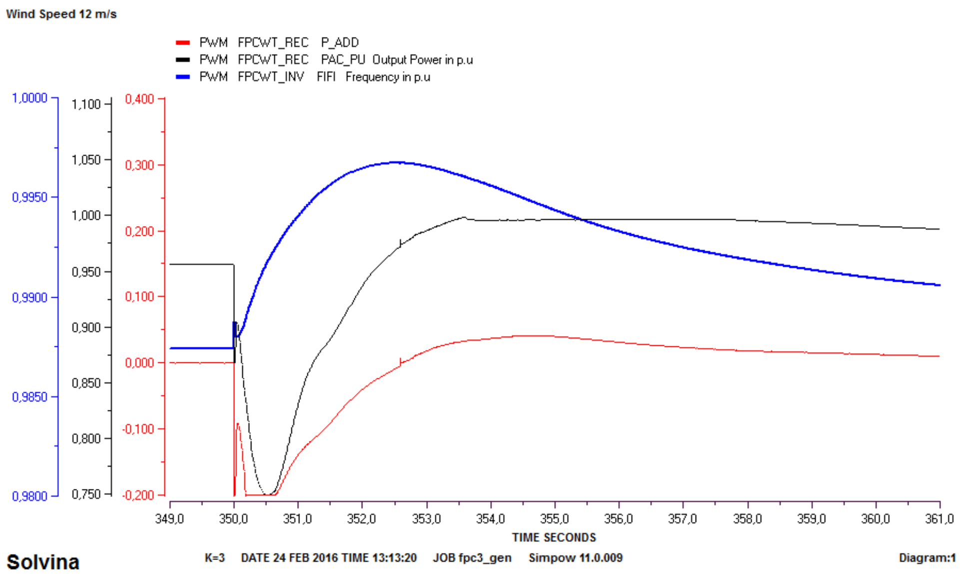

Figure 5.8: FPC output incase of over-frequency with k=3

In the case of medium wind region with calculated synthetic inertia, the simulation was highly unstable and simulation times lasted for as long as 30 minutes. Therefore, only one case with $k = 1$ was simulated and compared with the case with no synthetic inertia added as in figure 5.9. The results with $k = 1$ are as shown in figure 5.10. In this case too, when there is a drop in frequency at 150 seconds, the power output from the wind turbine PAC_PU is increased by 0.11 p.u and remains high while the frequency is dropping and starts to decrease when P_ADD does consequently improving frequency response of the system.

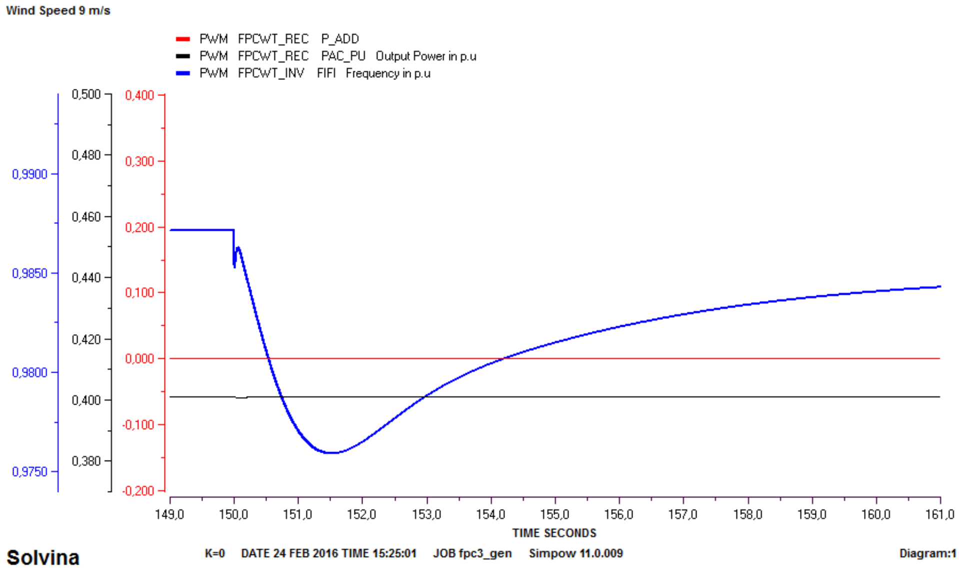

Figure 5.9: FPC output with k=0 in medium wind speed region

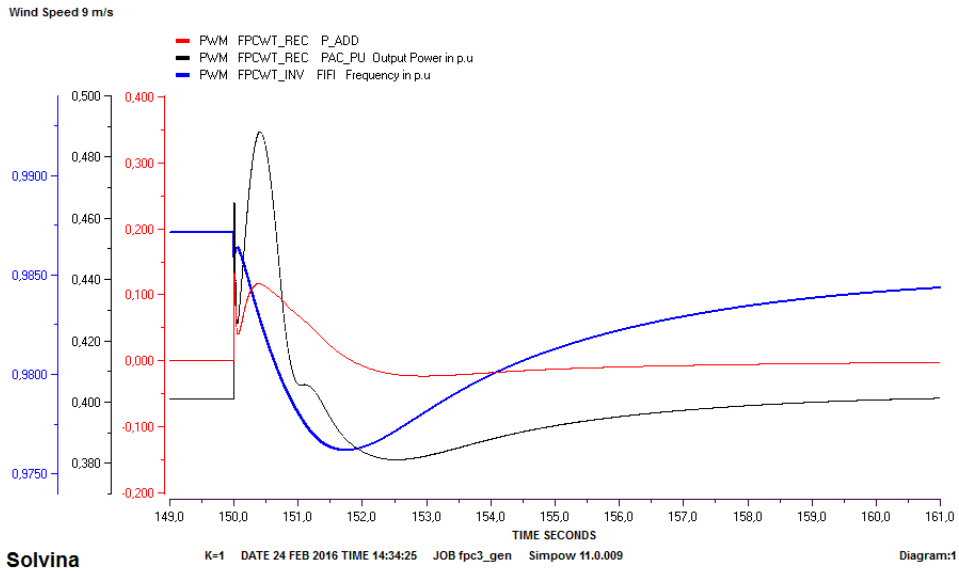

Figure 5.10: FPC output with k=1 in medium wind speed region

Figure 5.11 and 5.12 show the response of the FPC in case of over-frequency with $k = 0$ and $k = 1$ respectively.

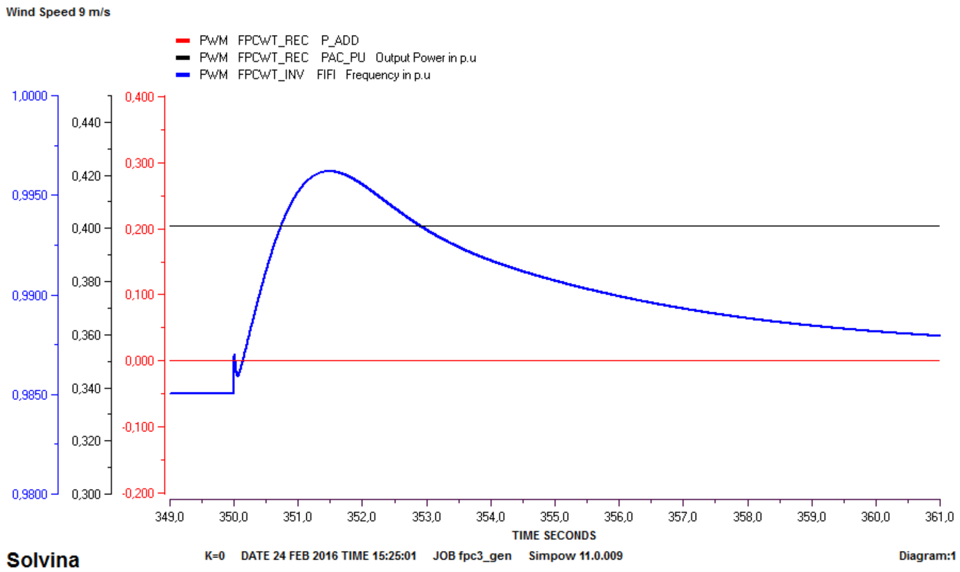

Figure 5.11: FPC output during over-frequency condition with k=0 in medium wind speed condition

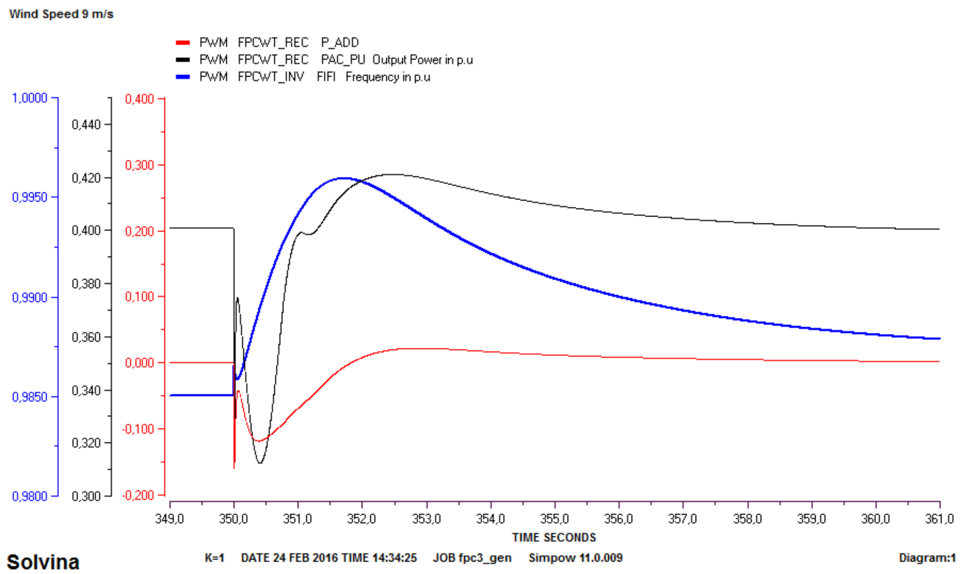

Figure 5.12: FPC output during over-frequency condition with k=1 in medium wind speed contion

Chapter 6

Implementation on a larger network

In a power system, any mismatch between the production and consumption of electricity causes an imbalance in the system and leads to a deviation in system frequency [15] and if this deviation exceeds a predefined range of frequency then it can adversely affect the stability of the power system.

With the rapid growth in the wind energy and its contribution towards the total energy production in the Nordic region, it has urged the TSO to revise the grid codes in accordance with the high level of wind penetration in the system to provide a reliable power system operation [1]. More strict demands are being imposed on the wind turbine to provide support to the system in case of disturbances. The grid codes specify the frequency range within which the generators need to operate and the duration of operation.

Frequency controlled reserves are used to compensate the deviation between the generation and consumption of electricity and are classified into two types: Frequency controlled normal operation reserve and Frequency controlled disturbance reserve. According to Nordic System operation agreement [9], *the frequency controlled reserve for normal operation shall totally amount to 600 MW* for a frequency range of 49.9 and 50 Hz. And for frequency deviation between 49.5 and 49.9 Hz the frequency controlled disturbance reserves 1200 MW.

To test the two wind turbine models on a larger power network, a rough equivalent model of the Nordic Power system is implemented by collecting information regarding average energy consumption and total installed capacity of hydropower and windpower of each country in the Nordic region. The summary of this can be found in table 6.1 and table 6.2 [17] [12].

Table 6.1: Estimated production of energy in the Nordic Region every year

Estimated total production TWh/year	Hydro	Thermal	Wind	Total
Finland	15	50	1	66
Norway	130	0	2	140
Sweden	65	65	11	150
East Denmark	0	8	2	10
Total	210	123	16	365

Table 6.2: Installed Capacity in the Nordic countries

Installed Capacity 1000 MW	Hydro Power	Wind Power
Finland	3	1
Norway	29	1
Sweden	16	5
East Denmark	0	1

Table 6.3 summarizes the rough average power production in the different countries [17]. The details from this table is then used to implement the Nordic grid and consequently the single diagram for the network is obtained.

Table 6.3: Rough Average Production per year

Rough Average Production 1000 MW	Hydro	Thermal	Wind	Total
Finland	1.7	5.7	0.1	7.4
Norway	14.8	0.0	0.2	16.0
Sweden	7.4	7.4	1.3	17.1
East Denmark	0.0	0.9	0.2	1.1
Total	24	14	2	42

6.1 Response with DFIG wind turbines

Figure 6.1 shows the single line diagram of the power system with the DFIG wind turbine.

Hydro1 represents hydro-power generation which helps in frequency control, Hydro 2 represents hydro-power generation which does not aid in frequency control, Thermal represents thermal power generation. Table 6.4 summarises the production from each kind and consequently the total generation. It is assumed that 5000 MW of power is produced by the wind turbine at full wind speed condition. To balance the generation, a load of 45000 MW is connected to Bus_Nordic.

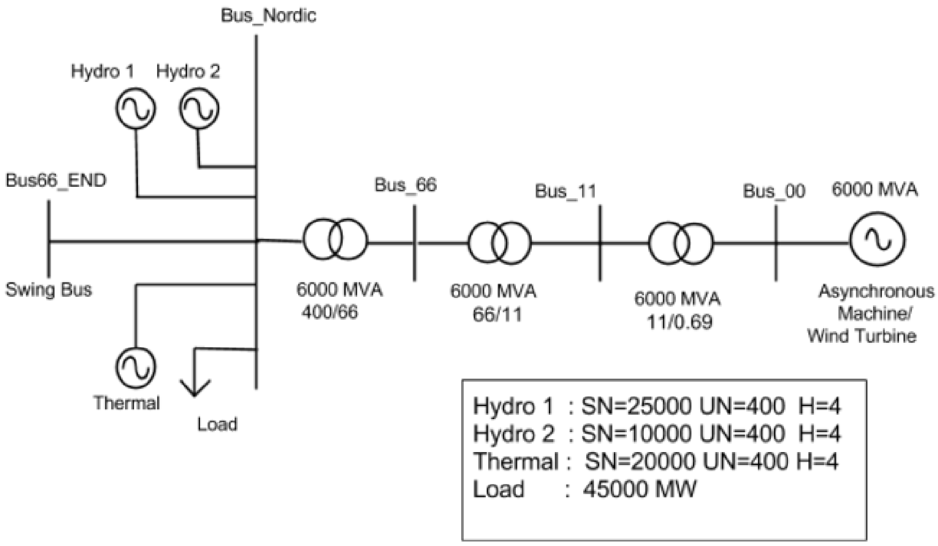

Figure 6.1: Single Line Diagram of the Nordic network with DFIG wind turbine

Table 6.4: Power Production from different sources

Type of Power Production	Power Generated in MW
Hydro1	5000
Hydro2	20000
Thermal	15000
Wind	5000
Total	45000

The regulators of the synchronous machines are tuned in such a way that a loss of 1000 MW causes a frequency drop of 0.5 Hz transiently and 0.15 Hz stationary.

Figure 6.2 and 6.3 shows the response of the system with and without the use of synthetic inertia in the model respectively during wind speed of 12 m/s. To create disturbances in the system, the line between Bus_Nordic and Bus66_END was disconnected at 75 seconds, followed by connecting an additional load at the Bus_Nordic at 200 seconds and finally this additional load was disconnected from the bus at 400 seconds. W_PU represents rotor speed in per unit, PG_PU is the power production in per unit, FIFI is the variable available in Simpow which is equal to the system frequency, P_ADD is the synthetic inertia added in per unit and TR2 BUS_11 BUS_00 is the power production on the low voltage side of transformer in MW.

In figure 6.2, it is observed that there is decrease in the rotor speed W_PU and a consequent increase in the output power PG_PU when there is a drop in frequency at 200 seconds. This is an unexpected response since the synthetic inertia is set to zero. With synthetic inertia set to zero, the system should have continued operating at the same power output power PG_PU and same rotor speed W_PU. A situation similar to the one mentioned in section 4.3. But in that case, the rotor speed had increased when there was a drop in frequency. Both these unexpected result indicate that the controllers in the DFIG model need further tuning to be able

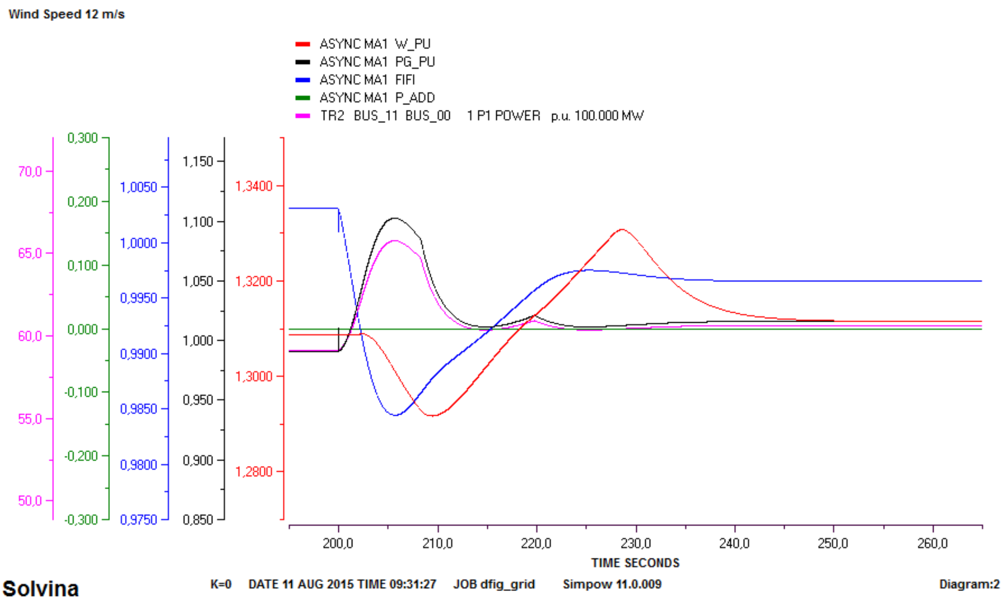

Figure 6.2: Frequency response of the network with no synthetic inertia

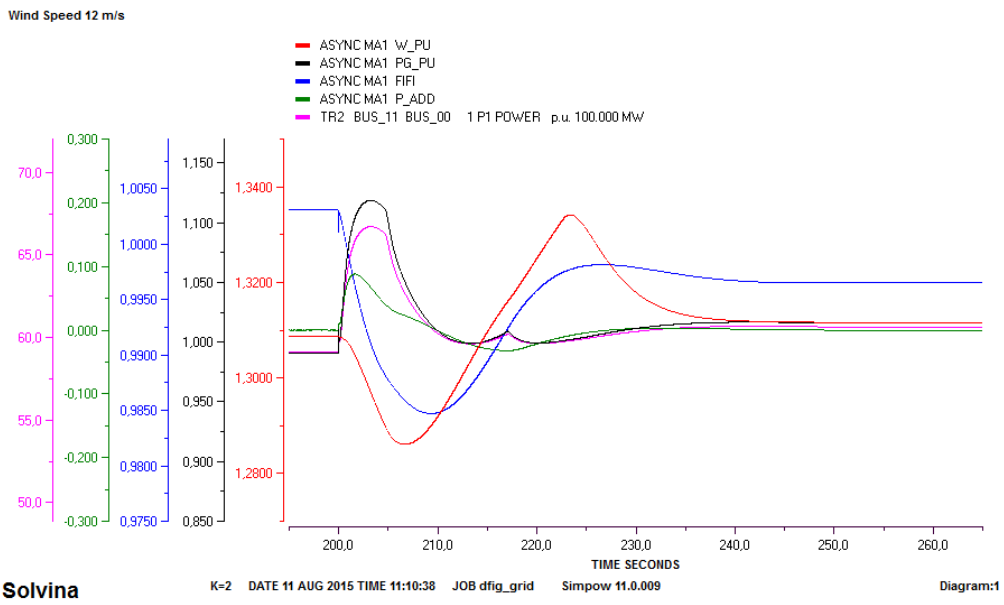

Figure 6.3: Frequency response of the network with synthetic inertia. K=2

to support the simulation condition when no synthetic inertia support is provided by the turbines. Also, it can be observed from figure 6.2 that the rotor speed W_PU continues to vary at a fast rate inspite of the frequency steadily becoming constant. This further strengthens the need of modifying the controller and its inputs and tuning it to obtain acceptable response and is suggested as a future work on this thesis.

Figure 6.3 shows the response with synthetic inertia $k = 2$. Since all the generating units are closely connected and connected to the same grid, with wind power generation forming only a small percent of the entire grid no significant change in system frequency is expected.However, a slight change in frequency FIFI is noticeable by comparing figure 6.2 and 6.3 . Similarly, a slight increase in the power output of the wind turbine PG_PU can be noticed at time instant 200 s in the case with synthetic inertia included. The frequency response becomes worse with the addition of the synthetic inertia however, the rate of change of frequency is much slower in the case with synthetic inertia.

Similar observations can be made in the case of over frequency, i.e when the generation level exceeds the level of load connected to the system from figure 6.4 and 6.5. In this case too, the rotor speed W_PU and output power PG_PU act in a unexpected manner when there is a disturbance in the system at 400 seconds in the case when the synthetic inertia is set to zero.

The maximum frequency in case with synthetic inertia is 1.015 per unit whereas in the case with no synthetic inertia, the maximum frequency is 1.020 per unit.

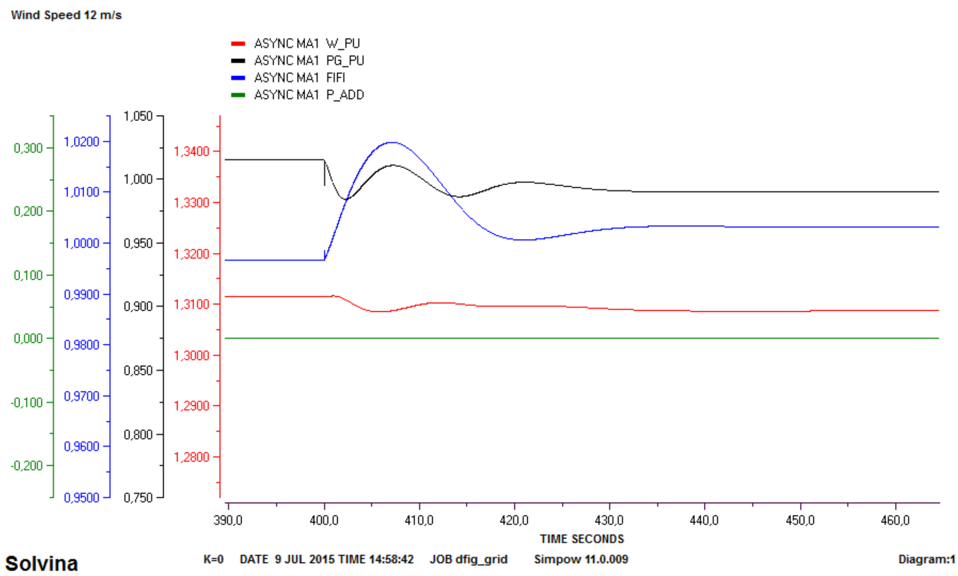

Figure 6.4: Frequency response of the network with no synthetic inertia

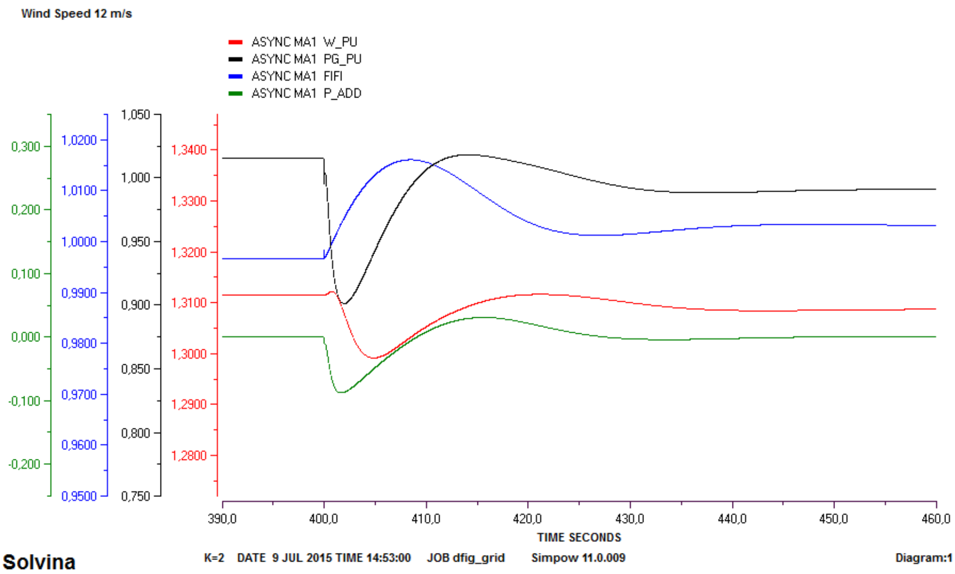

Figure 6.5: Frequency response of the network with synthetic inertia

6.2 Response with FPC wind turbines

The single line diagram for the system with FPC wind turbines is as shown in figure 6.6.

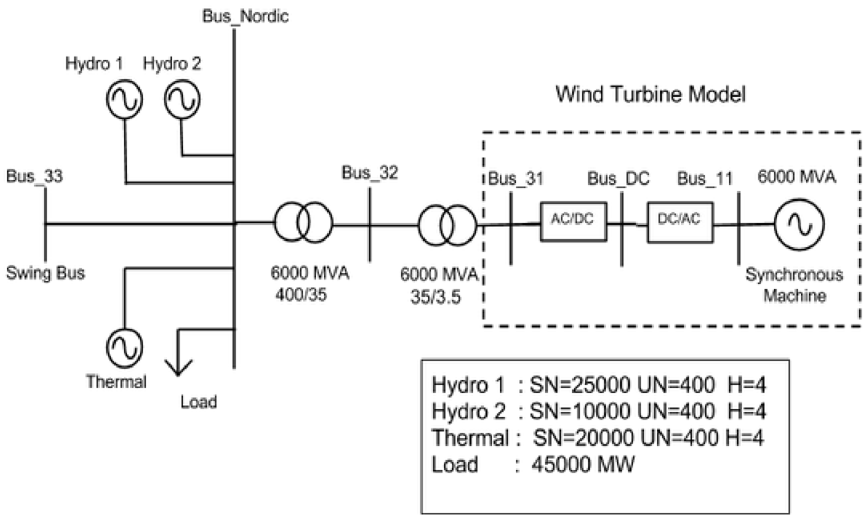

Figure 6.6: Single line diagram of the Nordic network with FPC wind turbines

In the case with FPC wind turbines in the power system, two scenarios were tested. In the first scenario, the current rating of the power converter IMAX was maintained at 1.04 p.u and the response from this is plotted in figure 6.7 and 6.8

As can be seen from the figures, there was no significant increase in the power output when frequency drops inspite of the synthetic inertia being included. Next, the current rating was increased to 1.1 p.u and in the case a more significant increase in the power output, and correspondingly a change in frequency was observed for the

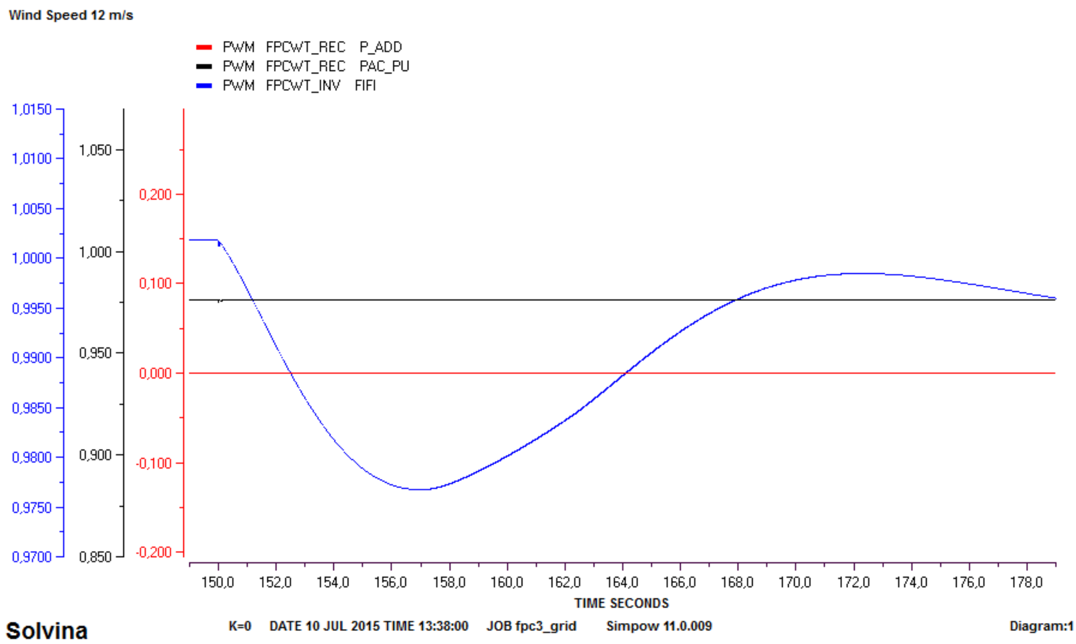

Figure 6.7: Frequency response with current rating 1.04 p.u and k=0

case with and without the synthetic inertia. Also, the rate of change of frequency is much slower in the case with synthetic inertia. Figure 6.9 and 6.10 represent these.

With no synthetic inertia included, the system frequency drops by 2.5% when the line between Bus_Nordic and Bus_33 is disconnected at 150 seconds. But with the the synthetic inertia included, the frequency drops by only 2%. In the plots, P_ADD is the synthetic inertia added in per unit, PAC_PU is the output power in per unit and FIFI is the variable equal to the system frequency.

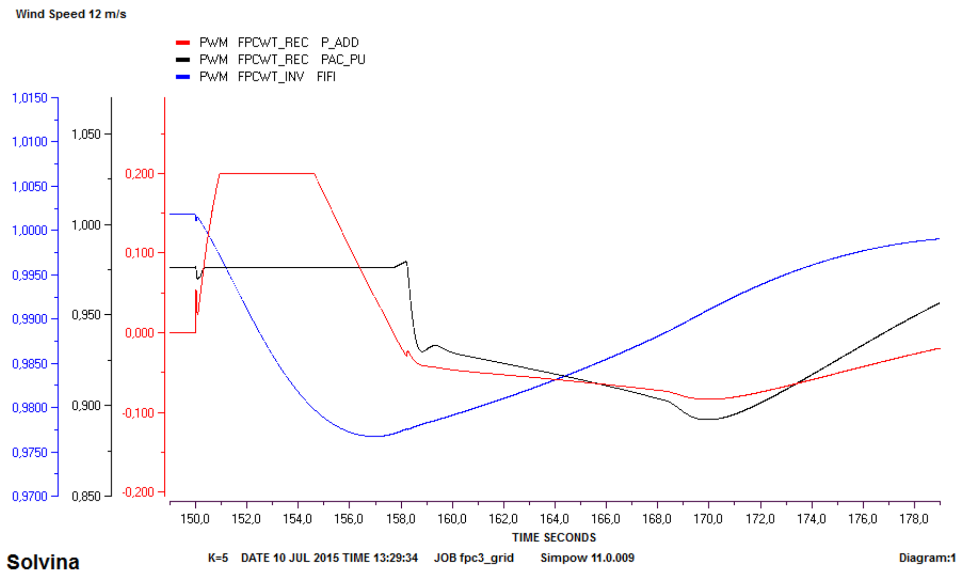

Figure 6.8: Frequency response with current rating 1.04 p.u and k=5

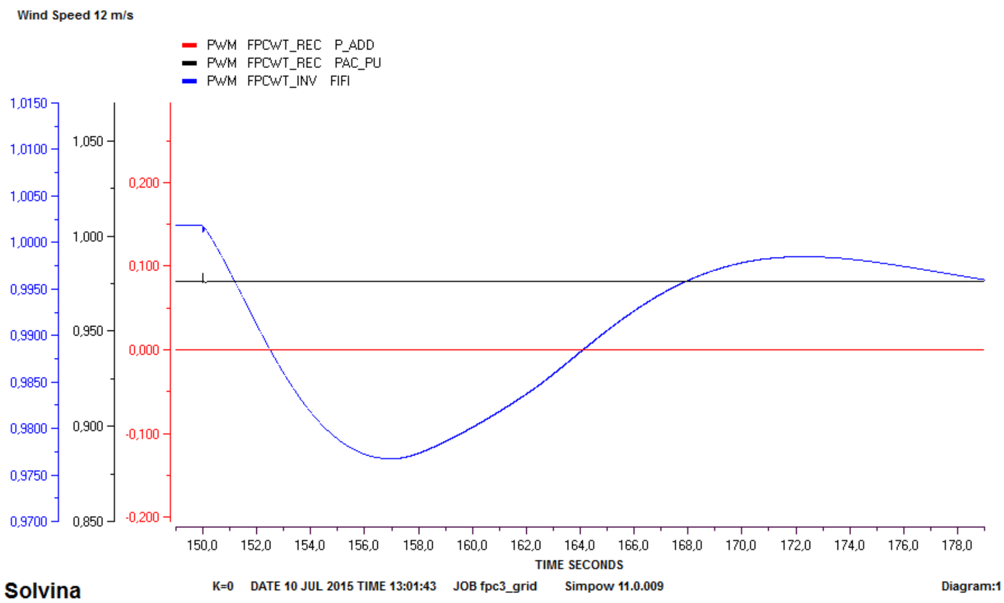

Figure 6.9: Frequency response with current rating 1.1 p.u and no synthetic inertia

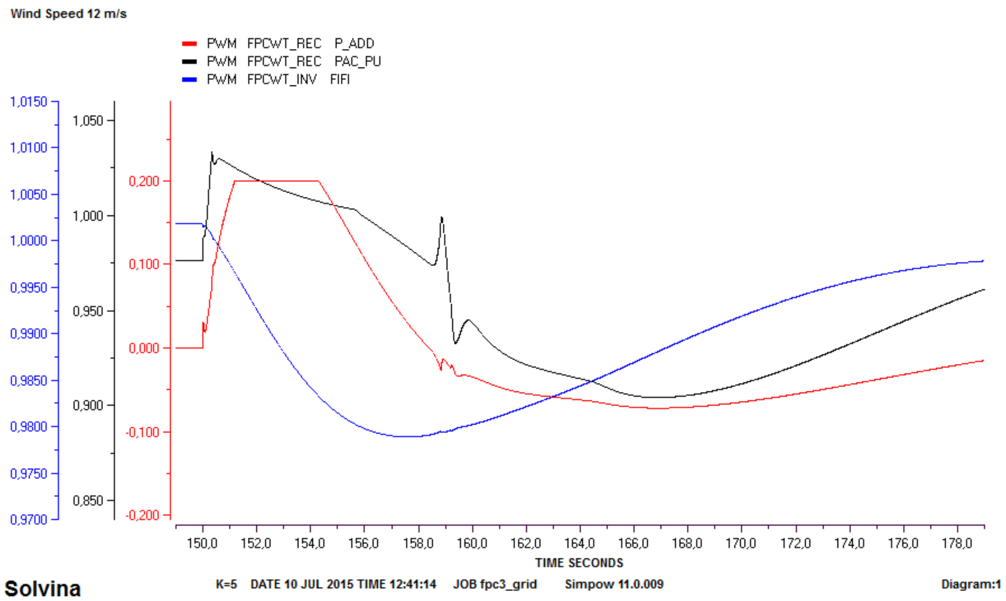

Figure 6.10: Frequency response with current rating 1.1 p.u and k=5

Since the power converters in the power system can be slightly bigger in order to accommodate the reactive control, the case with power rating of 1.1 p.u is acceptable. Also, as long as the semi-conductor switches are not heated up beyond their thermal limit, the current through them can exceed slightly beyond their rating for a short duration of time; In this case it is 8 seconds. The control circuit must be able to reduce the excessive current before the switches are overheated.

Chapter 7

Conclusions and Further Work

In this thesis, the dynamic models of the DFIG wind turbines and FPC wind turbines were implemented and their performance analysed with the addition of synthetic inertia in the controller. By making a few changes in the dsl-code of the wind turbine models, it was possible to get a certain level of inertial response from the wind turbines. It was observed that during the high wind speed it was possible to get a much higher level of inertial response from the wind turbines due to pitching of the blades but this was not the case in the low wind region as it caused stalling of the simulation. There is no significant difference between the response from the DFIG wind turbine and FPC ind turbine, as both the models respond in the same manner when synthetic inertia is added in the form of small steps and in the form of calculated value which depends on the rate of change of frequency.

A rough model of the Nordic network was designed and implemented and the two wind turbine models were independently tested on this network for their inertial response. Information regarding the total generation and type of power generation, i.e thermal, hydro and wind power , in the Nordic countries is collected and then used to implement the model of the network. Since this Nordic network was a rough representation of the actual Nordic network, with all the generators tightly connected to one common base and the wind production being only a small percentage of the total generation it was natural to get a very small improvement in the inertial response. This was observed in both the wind turbines. One certain point that could be clearly observed in the case of the FPC wind turbine was that by slightly increasing the size of the rating of the power converter, it was possible to get a significant improvement in the inertial response from the turbine.

The controller of the FPC wind turbine used in Simpow is quite unstable for the medium and low wind speed which causes the run time of the simulation to run for several minutes. This can be improved by designing the entire controller from scratch and then tuning it as per the requirement. The controllers of the DFIG are not very well suited for the frequency deviation and this could be overcome by designing a new controller which can adapt better to frequency changes. Also, in this thesis a rough model of the entire Nordic network is implemented. To get a more realistic results from the wind turbine a more detailed model of the Nordic network needs to be implemented in Simpow. The dsl-code developed in this thesis could also be tested for different networks having different percentage of wind turbines connected in the network.

Bibliography

[1] I.D Margaris A. Basit A.D Hansen and J.C Hansen. "A Review of Grid Requirements for Wind Farm in Denmark and China". In: ().

[2] Rogério G. de Almeida and J. A. Peças Lopes. "Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation". In: *IEEE Transactions on Power Systems* 22.3 (Aug. 2007).

[3] Peter Wibaek Christensen and German Claudio Tarnowski. "Inertia for Wind Power Plants- State of the art review- year 2011". In: *Presented at the 10th International Workshop on Large-Scale of Wind Power, Aarhus, Denmark* (Oct. 2011).

[4] Janaka Ekanayake and Nick Jenkins. "Comparison of the Response of Doubly Fed and Fixed-Speed Induction Generator Wind Turbines to Changes in Network Frequency". In: *IEEE Transactions on Energy Conversions* 19.4 (Dec. 2004).

[5] *EWEA Generic Grid Code Format for Wind Power Plants*. URL: `http://www.ewea.org/`.

[6] Andreas Sumper Francisco Díaz-González Melanie Hau and Oriol Gomis-Bellmunt. "Participation of wind power plants in system frequency control: Review of grid code requirements and control methods". In: *Elsevier* (2014).

[7] J.B Ekanayake G. Ramtharan and N.Jenkins. "Frequency support from doubly fed indcution generator wind turbines". In: *The Institute of Engineering and Technology. Power Generation* 1.1 (Mar. 2007).

[8] Müfit Altın. Ömer Göksu and Remus Teodorescu. "Overview of Recent Grid Codes for Wind Power Integration". In: *IEEE Transactions on Sustainable Energy* 4.4 (Oct. 2013).

[9] Nordel Market Development Group. *Description of Balance Regulation in the Nordic Countries*. Tech. rep. Nordel, 2008.

[10] Global Wind Energy Council (GWEC). *Global Wind Report. Annual Market Update 2014*. Tech. rep. Global Wind Energy Council(GWEC), 2014.

[11] A. El Zawawi I.A Gowaid and M.El Gammal. "Improved Inertia and Frequency Support from Grid-Connected DFIG Wind Turbines". In: *IEEE* (2011).

[12] *International Energy Statistics*. URL: `https://www.eia.gov/`.

[13] Mats Wang-Hansen. Robert Josefsson and Haris Mehmedovic. "Frequency Controlling Wind Power Modeling of Control Strategies". In: *IEEE Transactions on Sustainable Energy* 4.4 (Oct. 2013).

[14] J.G Slootweg H.Polinder W.L Kling. “Dynamic Modelling of a Wind Turbine with Doubly Fed Induction Generator”. In: *IEEE* (2001).

[15] Prabha Kundur. *Power System Stability and Control.* McGraw-Hill INC, 1994.

[16] Alan Mullane and Mark O’Malley. “The Inertial Response of Induction-Machine-Based Wind Turbines”. In: *IEEE Transactions on Power Systems* (2005).

[17] Nordic Energy Regulators NordREG. *Nordic Market Report 2014*. Tech. rep. NordREG, Nordic Energy Regulators, 2014.

[18] Andreas Petersson. “Analysis, Modelling and Control of Doubly-Fed Induction Genertors for Wind Turbines”. MA thesis. Chalmers University of Technology, Sweden, 2005.

[19] *Simpow, Power System simulation software Manual.* Solvina. 2015.

[20] Francesco Sulla. “Modeling of Asynchronous Machines in Simpow”. MA thesis. Royal Institute of Technology (KTH), Stockholm, Sweden., 2003.

[21] Nayeem Rahmat Ullah and Torbjorn Thiringer. “Primary Frequency Control Support from Variable Speed Wind Turbines”. In: *IEEE Transactions on Energy Conversions* (2004).