Frequency Reserves in Future Power Systems

Aleksander Adam Morelowski

Energy Technology, EPSH4-1036, 2022 November

Master's Project

STUDENT REPORT

AALBORG UNIVERSITY

Copyright © Aalborg University 2020

The following programs have been used throughout the report: MATLAB®, DIgSILENT PowerFactory.

AALBORG UNIVERSITET
STUDENTERRAPPORT

Second year of Msc study at the Technical Science Faculty
Energy Technology
Pontoppidanstræde 111
9220 Aalborg Ø
http://www.tnb.aau.dk

Title

Frequency Reserves
in Future Power Systems

Theme

Advanced Project in Electrical Power Systems and High Voltage Systems

Project Period:

01/06/2022 - 07/11/2022

Project Group:

EPSH4-1036

Participants:

Aleksander Adam Morelowski

Supervisors:

Jayakrishnan Radhakrishna Pillai
Sanjay Chaudhary

Pages: 51
Appendix: -
Electronic Files: 10.5GB
Submission date: 07-11-2022

Abstract:

Future power systems are incorporating more and more sources utilising renewable energy, *e.g.* solar and wind energy. The goal of incorporating as much of this energy, and replacement of old conventional generators, comes with a cost that frequency stability of these systems can be compromised. Some of crucial properties of systems, like in this case system's inertia, are worsen. Utilising DigSilent PowerFactory, a simple two area grid is modelled, as well as dynamic response of elements like synchronous generators, wind turbine, solar power plant and battery energy storage. Controls of these assets are studied and implemented for cordinaed actions of primary and secondary frequency control. Grid is challenged with different cases and primary and secondary reserves are operated to keep the grid stable. The increase in renewable energy penetration worsens the conditions for the frequency excursions. As an aid for this tendency the battery energy storage system is introduced as quickly reacting reserve.

Nomenclature List

Special Symbols and Denotations

Symbol	Description	Derived unit	Unit
C	Capacitance	Farad	F
f	Frequency	Hertz	Hz
I	Current	Ampere	A
t J	Inertia	Kilogram meter squared	$kg \cdot m^2$
K	Gain value	-	-
k_{Pf}	Active power frequency sensitivity	-	-
k_{Qf}	Reactive power frequency sensitivity	-	-
L	Inductance	Henry	H
n	Rotation speed	Rounds per minute	-
P	Active power	Watt	W
p	Number of poles	-	-
Q	Reactive power	Volt-ampere-reactive	VAr
R	Resistance	Ohm	Ω
S	Apparent power	Volt-ampere	VA
t	Time	Seconds	s
T	Torque	Newton meter	$N \cdot m$
U	Voltage	Volts	V
X	Reactance	Ohm	Ω
δ	Voltage angle	Degrees	$^\circ$
θ	Phase angle	Degrees	$^\circ$
ρ	Power factor	-	-
ϕ	Phase difference	Degrees	$^\circ$
ω	Mechanical velocity	radians per seconds	rad/s

Acronyms

Acronym	Abbreviation of:
DSO	Distribution System Operator
OHL	Overhead Lines
PMSG	Permanent Magnet Synchronous Generator
PV	Photovoltaic
PWM	Pulse Width Modulation
R	Residential Load
RE	Renewable Energy
REG	Renewable Energy Generation
RES	Renewable Energy Source
RoCoF	Rate of Change of Frequency
RPC	Reactive Cower Control
SG	Synchronous Generator
SO	System Operator
TSO	Transmission System Operator
WPP	Wind Power Plants
WTG	Wind Turbine Generator
BESS	Battery Energy storage system

Contents

Introduction 1

The time of fossil fuels is about to run out, the benefits and progress humanity achieved with their help can no longer be sustained. Renewable energy sources are under constant research and development to find a sustainable source of energy, capable of replacing fossil fuels. Nowadays, the focus is on implementing solar and wind generated energy. Since the installed power of these two particular resources has already increased to a significant level, new challenges are upon electrical system operator around the World. The eco-friendly factor of solar and wind energy is widely appreciated but the challenge comes from the fact how they generate the energy and should not be underestimated. System operator are obliged to guarantee access to electric energy, which is a challenge on it's own, not to mention doing that with large amount of uncontrollable generation in a system. Sun irradiation and wind are intermittent sources, meaning that wind speed and insolation are factors that cannot be controlled. The conventional generation is almost fully controllable and rely only on the stock of fuel *e.g.* oil or gas. On top of that, the old conventional plants are being decommissioned and closed, reducing the amount of generation with desirable characteristics. System operators to fulfil their duty need to assure system's stability, with above mentioned trends it is becoming more and more challenging. When it comes to stability, it can be simplified as system's generation matching the demand at all time. That is reflects in frequency being stable, meaning the speed of rotating masses remains uninterrupted. Maintaining the frequency as close to the nominal target is one of the critical properties that allow for stable operation [1].

Neither operators can fully predict a potential shift in demand, nor can they aid every possible system malfunction. In theory, any mismatch in the equilibrium of generation and load will result in frequency excursion. To cover as much of unpredictable situations as possible power reserves are predicted and deployed when necessary. One of modern examples of the renewable power disturbing the frequency stability is from January 2004 in Denmark. Powerful wind over vast area resulted in wind turbines reaching the cut off speed and a mismatch of 1,700 MW in power [2]. When it comes to solar generation the German power system had to revise the protection protocols when installed solar power became significant in 2005/06. Large amount of solar panels in low voltage level could be disconnected at once as an effect of frequency reaching 50,2 Hz and compromise system's stability [3][4].

Well established methods of determining the necessary reserves to assure system's stability need to be revised, due to the amount of renewable energy generation (REG) present in modern power systems. The power reserves referred to as frequency reserves, are deployed on regular basis as well as during an emergency (contingency reserves). Typically these reserves are allocated as remaining power in conventional generating units or in units that are capable of adjusting their output within the given time window. Most known example of such a reserve unit is a pump-hydro storage, that supply additional power when necessary, and consume power to regain that capability. With the advancement of lithium-ion batteries, and increased need for fast ramping reserves, they are now mainly considered for such a role not only locally but on a large scale too. A prominent example would be the investment in south Australia the "Hornsdale Power reserve" (HPR). A battery energy storage system implemented in that region successfully improved stability in the region and proved to be economically reliable investment. According to one year operation studies of the HPR the services provided by the batteries pose opportunities for grid stability and allow for increased penetration of REG. Consequently, allowing for lower lower energy prices [5].

1.1 Problem Statement

Renewable energy generation is often a distributed generation (DG) and highly intermittent source of energy in a modern power system. Potential under- or over-generation due to their nature can advert the system's frequency stability. In modern power systems the share of conventional generation is constantly decreasing at a cost of the intermittent REG share's growth. When increasing the REG penetration level system's stability cannot be compromised. Speed and scale of power changes and thus frequency excursions are directly correlated to the system's properties like inertia and power reserves. The frequency reserves need to be able to counteract any frequency excursions independently of their nature. Within the increase of REG in a given system the need for frequency support increases as well.

Implementation of energy storage (ES) can be considered as an alternative to conventional reserves and can allow for higher REG penetration level. Ongoing research and development of battery technology positively impacts the costs of potential battery energy storage system (BESS). Battery's characteristics like fast reaction time, ability to store energy for extend periods of time as well as scalability makes them a desirable solution for ES. Another advantage of implementation of BESS is the possibility of placing the BESS in the grid's location facing stability issues. Problems with DG are very often local due to large amount of generation located in suitable spots that present high potential for solar or wind energy.

This work will concentrate on the system's frequency stability and estimation of reserves capable of providing inertial, primary and secondary response required for system with high penetration of REG. A battery energy storage will be modelled and it will be assessed whether BESS is a suitable source of frequency reserves in a gird with high penetration of REG.

1.2 Objectives and Success Criteria

The main objective of this work is to assess the effect of high penetration of REG on the frequency stability of exemplary two-area grid. The inertial response of the system as well as primary and secondary response will be investigated. An implementation of battery energy storage as a viable solution for strengthening the grid frequency stability will be analyzed.

In order to answer the main objective of this work a sub goals are defined along with success criteria.

1. Implementation of primary and secondary control in an exemplary, 2-area benchmark grid.
2. Modelling and implementation of various levels of renewable generation as solar and wind generation, to the benchmark grid. Modelling of these resources will be simplistic with preservation of rates of change widely used in engineering practise.
3. To model and implement a battery energy storage system to the grid. With appropriate response time and real life response characteristics.

Success criteria

The frequency reserves are assessed in terms of inertial response and both primary and secondary response. When fulfilling the requirements the reserves are named sufficient. The inertial response of the grid is assumed to be sufficient when the change to ROCOF, after integration of REG, is less than 0,25 Hz/s. The primary frequency response is capable of arresting the frequency within matter of secondary from any given reference contingency. The secondary frequency response is assessed as sufficient if the frequency is stabilized within acceptable range of ±20 mH from the nominal frequency and within 15 minutes from being deployed.

The BESS performance is assessed on behalf of frequency nadir that is reached during the reference contingency events.

1.3 Methodology

In this chapter the ways of conduct regarding certain actions are listed and explained. The subject is intended to be analised in a simulation tool DigSilent PowerFactory. In order to simulate the dynamic behaviour of grid's elements like synchronous generators and system's frequency, dynamic models that are part of inbuilt library and other available applications are used, and modified. In that way the primary and secondary control are implemented. In order to simulate the renewable energy sources, significant simplifications are made and the mentioned resources are modelled as static generators. In order to take into account the significant phenomenons of volatility of these power sources the ramping behaviour is studied and applied through a simple model. A beforehand developed excel spreadsheet is dictating the output of solar farm or a farm of wind turbines. Simulations of critical increase of load, meaning a drop of load grater than this and possible to simulate with the given simulation tool renders the benchamerk point unstable. Case of drop of load and cases including volatility of REG. First, when a critical increase happens at the bottom of ramp that reduces the power output of REGs to further worsen the conditions for existing reserves. Second, when the REG is first reduced to zero to require the control to increase the output power, that REG regains with adequate ramp their power and is allowed to continue to provide power to the grid and when reaching the peak a large portion of load is switched off. In this case a severe over generation can be produced challenging system's stability. Simulations are conducted with increasing number of resources providing power to the grid; Starting with only conventional generation, later introducing wind farm and solar farms and lastly adding a large scale battery energy storage system. Above mentioned cases are simulated through different setup of the same benchmark grid of Kundur two area grid, and compared frequency stability wise.

1.4 Limitations

Complexity level can be drawn very high, in order to achieve the results some aspects important to grid's stability are omitted. For example no voltage stability is considered during simulations in order to keep the difficulty of studied task manageable. Utilised grid is not a prefect fit for dynamic simulations regarding frequency stability. In the original form system in fully loaded, in order to free some of the reserves in the system, loads are reduced by 100 MW and 200 MW. Simplistic approach is also applied when it comes to stability studies, a widely known N-1 simulation case is not applied since the system could not handle a disconnection of one of the 4 generators. Model of load , in reality is both frequency and voltage dependent, in this work the model is asked to remain stable in certain boundaries of voltage and independently of frequency. Loading of the elements is ignored, therefore important aspect of possible contingencies is omitted and system is deemed to be able to handle some cases when it could be a challenge for the given connection to transfer the available power. BESS model is applied by a rule of thumb, and no optimization of it's ratings is conducted in order to yield the best possible results. The modern REG have some capacity to participate in frequency regulation, however in this work these are full omitted.

2 State of The Art

To alleviate the frequency excursions mechanisms of inertial response (IR) and reserves allocated for frequency stability are utilized.

During the initial period of frequency deviation the IR of synchronous machines helps to slow down the change in frequency. It relays on the kinetic energy that is located in the rotating mass of big conventional generation (CG) units. When frequency *e.g.* drops, this kinetic energy is sucked out buy the system and the rotating speed of the generator drops. The amount of inertia in the system is directly correlated to the speed of change in frequency during a contingency. The exemplary response can be seen in Figure 2.1.

Primary frequency regulation (PFR) that helps to stabilize the frequency within seconds from the event can be provided by units that are capable to full fill such a requirement. The window of operation is up to 30 s after the event. The moment frequency excursion is stopped system is in a new steady state. Current frequency will deviate from the nominal target of 50 Hz. As seen in Figure 2.1 the frequency is arrested but is below the nominal frequency. Typically, the generators that supply this service are already operating but are not at their output limits.

Subsequently, the secondary frequency response (SFR) restores the frequency to the nominal target and frees the primary units. The target of these reserves is to restore the systems frequency within 15 minutes. The process of deployment is visible in Figure 2.1 when the frequency starts to approach the nominal value and the share in power generation of primary reserves decreases.

The last service that is deployed are the tertiary reserves that support and relive secondary reserves in the process of frequency restoration.

Sizing, of the power reserves is done according to quite a freq criteria and is a trade-off between systems security and costs of saving generation exclusively for unlikely event. If the frequency deviation is too big to be recovered by the actions explained above, typically a mechanism of load shedding is deployed. By this action the resulting configuration of the system can be stabilized and an attempt of reconnecting the load can be made.

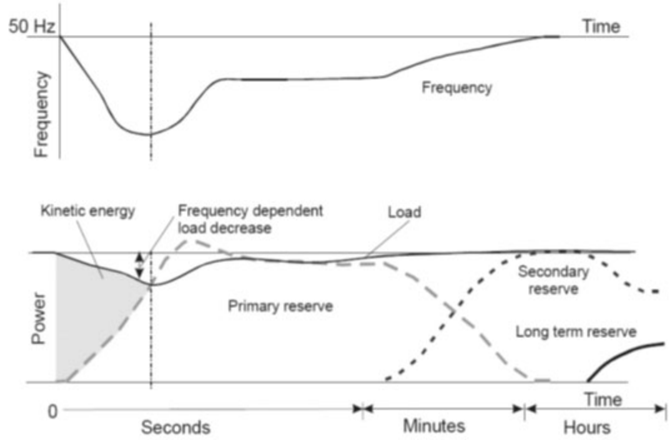

Figure 2.1: Exemplary utilization of frequency reserves during frequency excursion [6]

2.1 Inertial system response

Inertia of an object is its' property to resist the change, for power system change in energy of rotating masses of synchronous generators. When there is a disturbance in the system, the energy stored in the rotating mass is released. The swing equation 2.1 shows the relationship between systems inertia, the rate of change of frequency (ROCOF) that are equal to mismatch between generation and demand in a system [6].

$$\frac{2H}{f_0}\frac{df}{dt} = \frac{P_g - P_l}{S_{sys}} \tag{2.1}$$

Where, H is the inertia constant, δ is the angular position of rotor with respect to synchronously rotating reference, P is power of mechanical input and electrical output, and t is time.

The inertia constant states how long it takes to bring the machine from synchronous speed to a standstill, if rated power is extracted from it while no mechanical power is fed into it. The swing equation ties together the rate of change of frequency (ROCOF) and the inertia constant. When solving for the ROCOF it can be seen that it is inversely proportional to the systems inertia. Meaning that the lower the system inertia the faster the change in frequency. With increased penetration of converter based RG the amount of rotating mass and consequently systems inertia is decreasing. Meaning the changes in frequency are faster, greater and can lead to system instability[7].

Since the amount of inertia determines the ROCOF the increased penetration of renewable generation have negative impact on this parameter. In 2019 in Texas, ERCOT conducted studies of "critical inertia" that allows for Load response to arrest the frequency before the under-frequency load shedding is deployed. The determined "critical inertia" was approx. $90\,\mathrm{GW}\cdot\mathrm{s}$ and although the ERCOT has high penetration level of REG especially wind, the monitored inertia levels did not reach this value yet. Developed protocols together with online monitoring of inertia allow for acquiring additional inertia reserves when the inertia drops below $105\,\mathrm{GW}\cdot\mathrm{s}$ [8].

Large scale PVPP are allowed to provide frequency response in Europe, with use of frequency sensitive mode. One of the methods is to implement the PVPP with a frequency-watt function. According to J. Neely *at.al.* implementation of this function allows to lower the frequency nadir after an event of *e.g* line fault [9].

One o f the measures to counteract the constantly decreasing system inertia is implementation of virtual inertia. The principle of virtual inertia is to make the converter act as a synchronous generator from the grid point of view. This is done by appropriate control technique when the frequency excursion is detected. As being said the goal is to emulate the SG behaviour but there are several approaches when doing that. The control technique can be based on SG model, or rely on the swing equation, it can be a frequency-power response based or Droop-based. Each of these methods have some strong points and drawbacks, which can be seen in the Table 2.1. For more in-depth information on each of mentioned techniques to model the virtual inertia please see [10].

Table 2.1: Summary of virtual inertia control topologies

Control technique	Features	Drawbacks
SG model	Accurate replication of SG dynamics Frequency derivative not required Phase locked loop (PLL) used only for synchronization	Numerical instability concerns Typically voltage-source implementation; no over-current protection
Swing equation	Simpler model compared to SG based model Frequency derivative not required PLL used only for synchronization	Power and frequency oscillations Typically voltage-source implementation; no over-current protection
Frequency-power response	Straightforward implementation Typically currentsource implementation; inherent over-current protection	Instability due to PLL, particularly in weak grids Frequency derivative required, system susceptible to noise
Droop-based	Communication-less Concepts similar to traditional droop control in SGs	Slow transient response Improper transient active power sharing

2.2 Primary frequency reserves

Actions of primary reserves lead to arresting the frequency and the response of units that provide this service needs to be within seconds, therefore the primary frequency control (PFC) is fully automatic control.

Typically the primary generating units are governed by droop control that regulates the output of a generator. The speed governor senses the change in speed of the rotor and the mechanical output of the turbine is adjusted to compensate for the change. Process of regulation is done according to the droop characteristics that defines the change in power depending on the sensed change in frequency [1]. An exemplary droop is shown in Figure 2.2, the regulation is linear with insensitivity rage that is introduced to avoid unnecessary actions for frequency deviations up to ±10 mHz [11].

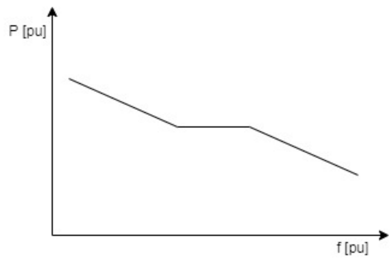

Figure 2.2: Simplistic example of droop applied control with a deadband included

The lower the sensed frequency the larger the power output of the generator. The droop is calculated as shown in Equation 2.2 [1]

$$R_{\%} = \frac{Percent\, speed\, or\, Frequency\, change}{Percent\, power\, output\, change} \cdot 100\% \qquad (2.2)$$

When it comes to estimation of necessary reserves that allow for actions defined in introduction of chapter 2, a world wide approach is according to a N-1 criterion. In that case the primary reserves need to cover a loss of the biggest generation unit. Some regions over the world utilise a N-2 criterion or 1% of maximum estimated hourly load for the given day[7].

In region of Europe the European Network of Transmission System Operators for Electricity (ENTSO-E) joins their action to create a stable European grid. The biggest credible contingency according to [12] is the reference case of loss of 3000 MW of generation. The capacity of primary reserves that all the countries need to have is defined according to Equations 2.3-2.4

$$C_i = \frac{E_i}{E_u} \qquad (2.3)$$

$$P_{pu} = C_i \cdot P_{pi} \qquad (2.4)$$

Where C_i is a contribution coefficient, E_i is the electricity generated in the control area and E_u is the sum of electricity production in all control areas of the synchronous area. The P_{pu} is the total primary control reserve for the entire synchronous area. The P_pi of the control area is the share of the reserve for the synchronous area[11][12].

ENTSO-E defines regions as continental Europe, Nordic region, UK region, Ireland region and Baltic region. A control area is allowed to increase its primary control reserve by 30% up to 90 MW by offering to cover part of the obligations of other control areas. For events that result in frequency excursion grater than ±200 mHz entire capcity of primary reserves in all countries needs to be deployed. The reserves need to be deployed within 15s for contingencies below 1500 MW. For greater contingencies(up to the 3000 MW) the deployment should happen according to linear relation-ship between 15-30s.

The impact for solar generation is considered to be corresponding to the impact the wind generation has on reserves. In multiple studies in the US and over the World the impact of wind generation on PFR (or alternative services) is considered negligible since, the sizing criterion is typically a loss of the biggest generation unit [13].

The methods of sizing of these reserves inclines that implementation of REG should not impact the sizing of these reserves. However, in majority of studies the analyse grid had a maximum penetration of wind up to 25%.

2.3 Secondary frequency reserves

Secondary control is a local control for all the control areas. The task of this control is to restore the system frequency to the nominal value while allow primary reserves to restore their capacity in case of another event.

When the primary reserves are deployed the state of tie-line flows might differ from the scheduled. By the actions of secondary reserve also the tie-line power flow is supposed to be returned to scheduled values [12].

In ENTSO-E the sizing of this reserve requires that about two thirds of the reserve has to be within the particular regulating area[12][14]. The capacity is according to the empirical formula Equation 2.5 of minimum requirement for "noise signals".

$$R = \sqrt{a \cdot L_{max} + b^2} - b \tag{2.5}$$

Where "a" is a constant 10 MW as "b" is equal to 150 MW and The L_{max} is the hourly maximum load of the day [11].

This menthod is a guidance by ENTSO-E and often local TSOs implement their own sizing of this type of reserves. Next it is checked if acquired limits are within the range of recommended values from ENTSO-E. As en example in [15] it is stated the Spanish system operator (REE) determines the amount of secondary reserves for transition and non-transition hours, according to equations 2.6 and 2.7 consequently.

$$R_{SEC} = 6 \cdot \sqrt{P_{SYS}} \tag{2.6}$$

$$R_{SEC} = 6 \cdot \sqrt{P_{SYS}} \tag{2.7}$$

Where P_{SYS} is hourly power system load. In REE the secdonary reserves is a split between upwards and downwards service by factor K. On top of these regulations REE established a minimum value of these reserves that sum up to a total minimum threshold of 900 MW for secondary. reserves. So

The other sizing approach is based on keeping Area Control Error (ACE) equal to zero with use of equations 2.8-2.9.

$$ACE = P_{calc} - P_{sched} + K \cdot (F_a - F_s) \tag{2.8}$$

$$P_{control} = -\beta \cdot ACE - \frac{1}{T_n} \int ACE \cdot dt \tag{2.9}$$

Where P is active power of units calculated and scheduled, F is frequency actual and scheduled. β is proportional factor of the secondary controller in the control area. T is representing time, and ACE is the area control error [11].

When the secondary reserves are deployed, the frequency must be brought to the nominal frequency (within the dead band) within 900 seconds. Since as mentioned in 1 the rate of change of frequency maters as well, the change of power output is supposed to be regulated. Some typical values are given in [11] for oil- or gas generators, nuclear power plants etc. The rates of change are of single percentages of maximum power output within a minute.

Impact of renewable generation is most prominently visible in regulating reserves. In Europe secondary reserves full fill the role of both contingency and regulating reserves. Studies analyze the net load of wind with the net load alone variations over a period of time, end evaluate the impact of wind generation on that parameter. Than the standard deviation between these two is determined and applied to calculate reserve covering a range *e.g.* 99.7% of potential deviations.

2.4 Contingency Reserves

Newer approach to the short term reserves is as implemented in Nordic synchronous area, a part of ENTSO-E, a service called frequency containment reserves (FCR) [16]. The time frame of these reserves is seconds from the event to 30 s, and up to 15 minutes after which they are fully replaced by frequency recover reserves (FRR). So earlier identified primary reserves can be part of this reserve. In the Nordic area the FCR is combinined of two products for normal operation and for disturbance (FCR-N and FCR-D)[17]. The deplyment thresholds for these two products are simmilar to ealier mentioned PFR. The FCR-N need to be fully operating for deviations reaching 49,9 Hz and 50,1 Hz. Within this range the output has to change proportionally. And similarly to the the previous product the FCR-D is deployed in ranges of 49,9 Hz up to 49,5 Hz for upwards regulation, and 50,1 Hz to 50,5 Hz for downwards regulation [16][17].

2.5 Battery Energy Storage

Constantly decreasing prices of lithium-ion (li-ion) batteries, as an economic incentive, are increasing the potential of BES. However, a large scale applications are still a financial challenge.

Some of the main advantages of BESS are: high efficiency, long cycle life, low maintenance requirements, high energy density and flexibility regarding the placement of the storage [18][19].

BESS are improving the grid parameters, from stabilizing the frequency oscillations, participating in frequency regulation to improving the overall frequency performance [20][21].

To improve the inertial response the BESs can be utilised to emulate the inertia [22]. Coordinated constant droop control and coordinated adaptive droop control strategies allow BES to implement system with virtual inertia improving the response during a frequency contingency. The use of BESS allows progress in replacement of the CG. Saving the energy from RG in low demand hours can be transferred into peak demand hours.

The BESS is controled at the inverter, the abc-dq frame is used, to control active and reactive power with appropriate current.The output power is controlled in inverse proportion to the derivative of the grid frequency[22].

BESS operational algorithm is typically droop based. Through the scope of frequency appropriate actions are allocated. For the dead-band region of the characteristic, the BESS is not required to participate in frequency regulation and usually is allowed for actions to re-establish the state of charge (SOC).

During these action it is not allowed to impact the system frequency so the charging power is limited to couple percentages of the BESS nominal power output. These actions are supposed to maintain the BESS SOC in established boundaries that will allow for sufficient action in case of significant frequency excursion. In [23] the dead-band is ± 30 mHz and it is the steady state operation. In this frequency range the SOC is managed between 0.5-0.8pu, the BESS charges and discharges with maximum of $\pm 5\%$ of rated power output. For SOC between 0.63-0.67 no action is recommended. If the SOC is outside of these operational boundaries the charge and discharge rates are scaled to $\pm 10\%$ of the rated power output. When it comes to operation outside this range a necessary response is calculated and the choice is made between the nominal power and the necessary response power. All of these restrictions and guidelines are to reassure the appropriate frequency response and to increase the cycling life of BESS.

Authors in [19]introduce the Danish and German primary frequency response and a service called enchanted frequency response (EFR) that was developed in the UK. The basics of PRF are as explained in 2.2 and according to ENTSO-E standards when it comes to full deployment after contingency resulting in frequency excursion grater than 200 mHz. However, there is a difference of BESS control in the dead-band and the dead band ranges also vary. In Germany the dead-band is only ± 10 mHz while in Denmark it is the well known± 20 mHz. the entities ins Germany can charge or discharge the BESS with rate of

±5% of the rated power output while in Denmark no actions are assigned for the dead-band range. The EFR allows requires a response within specified ranges within short amount of time (1 s). Specific percentage of output limits are deffined for when the frequency goes outside the dead-band of ±50 mHz to ±250 mHz. If the deviation in frequency is greater than 0,5 Hz full rated power output is required[19].

2.6 Summary

The impact renewable energy has on the grid's frequency reserves is unclear. Sizing of primary frequency reserves is widely dependent on the size of the largest, online generation unit in the grid.

Secondary reserves when sized

REG can or is obliged (depending on the location and TSO) to provide frequency regulation services. However, if no incentive is provided these services result in decrease of potential revenue of REG source. This is due to the fact that the asset proving such ancillary services need to keep a headroom for their power output or need to reduce it, effectively reducing their billable hours.

Sizing of the reserves is done either statistically or dynamically. When the first approach is utilised the reserves are fixed for the entire time interval*e.g.* a single day. This may lead to large overestimation of required reserves during the day, since the critical period is the afternoon peak that has to be covered. The dynamic approach adjusts the reserves accordingly to a given time interval *e.g.* each hour of single day. consequently leading to reserves kept at appropriate, different level for each hour. Both of these approaches are affected by the input data such as weather forecast. The accuracy of forecast according to [13] are largely dependant on the forecast horizon and are a manner of separate study. In short, the smaller the forecast horizon the smaller the forecast error and consequently smaller reserves are required. However, sudden gusts of wind or clouds covering large areas of PV plants are mostly random event and cannot be predicted too accurately. Thus the literature suggest adjusting the reserves by a factor of renewable energy integrated.

Grid scale BESS with multiple techniques to emulate the behaviour of synchronous machine are more and more often considered for improving system stability. The scalablity, price reduction, long term storage properties as well as very fast response time make BESS a suitable candidate for grid frequency support services. Therefore, in this work the frequency reserves will be allocated mainly in implemented BESS that will supply the already existing reserves from the conventional generation. Since the methodology of REG replacing the CG directly affects the power reserves, the study will attempt to identify possible level of REG when

Ultimately the sizing of all the reserves is a compromise. To be able to cover every possible contingency for certain the amount of reserves necessary would yield huge costs. Therefore, a trade-off between an acceptable risk and cost of the reserves is made.

Modelling of AGC 3

3.1 Control of the Power Generation

For the project the approach for control of generation units, SG specifically, is intended to be modeled as the well-established primary and secondary control of active power generation. The replacement of deployed reserves after the initial frequency response, by tertiary reserves, is not modeled or analysed. As explained in chapter 2, the primary frequency response is required to stop the deviation of frequency from the nominal value and establish the new stable point. Consequently, deployed secondary frequency reserves bring the system's frequency to the nominal conditions, meaning being in acceptable boundaries from the nominal value of 50 Hz, in case of this project. In the Figure 3.1 en exemplary response to an frequency excursion is shown and mapped according to the above mentioned.

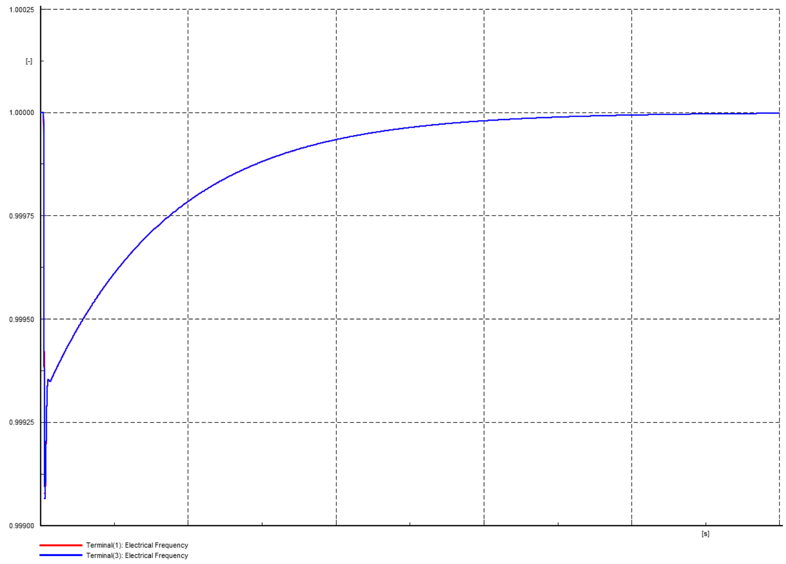

Figure 3.1: Exemplary frequency response

The action of automatic generation control (AGC) has 4 distinct steps: the inertial response, primary response, secondary and tertiary. The action of tertiary power reserves is not a part of this work and thus is ignored further on. The system's behavior during the initial period after the frequency excursion depends on the amount of inertia and defines the rate of change of frequency (ROCOF) and how low the frequency will drop (frequency Nadir), at the same time the primary reserves are deployed and intend to arrest the frequency. After the stable point is achieved the secondary response intends to bring the frequency to the nominal values. To have a clear picture of each mentioned action the initial period of Figure 3.1 is shown in Figure 3.2. The initial drop and ROCOF are the results of existing inertia, the f_{Nadir} is reached and the reaction of primary reserves start to boost the frequency.

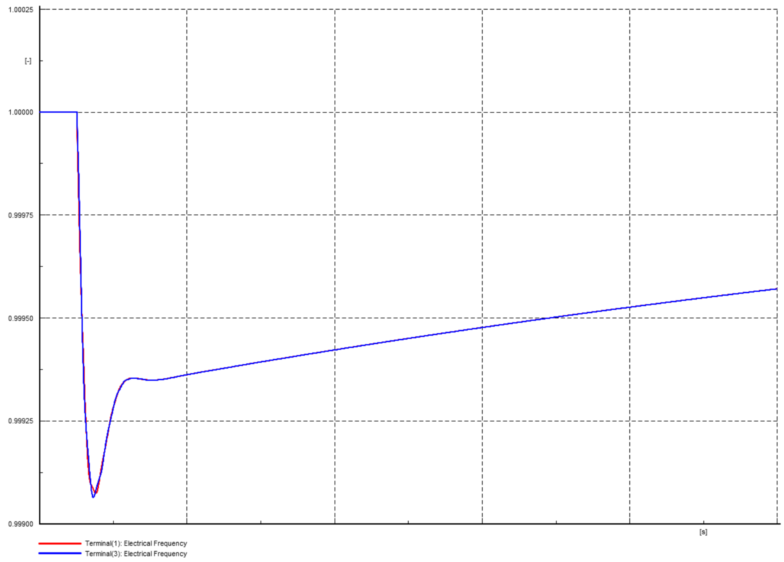

Figure 3.2: Initial period of exemplary frequency response

Implementation of control is done using a dynamic simulation language (DSL) in the DigSILENT PowerFactory. The approach how the modelling of dynamic behaviours is done can be seen in [24] in the chapters 29 and 30. The DSL modelling approach requires very specific operations to be done in order to represent a dynamic behaviour of some object. As mentioned in [24], the modelling requires creation and definition of (in a descending order, from the most to least global):

1. Simulation frame,
2. Common model,
3. Block definition,

so they all account for the composite model of *e.g.* a generator. The implemented control structure is based on the one presented but authors in [25]. Simplified structure, to draft all the necessary principles, is shown in Figure 3.3.

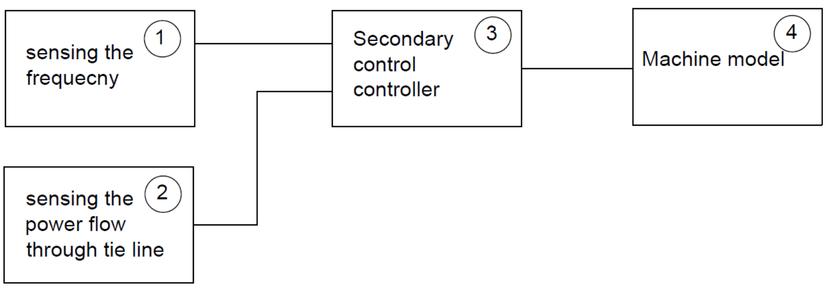

Figure 3.3: Simplified structured of implemented control

The initial step is focused on sensing the frequency and power imbalance in a tie line, these tanks are performed in blocks of equivalent type to number 1 and 2. The information acquired allows for calculating the necessary correction in power generation that is done in the third block. Lastly, the correction is passed, ultimately, to the appropriate governor of each modeled machine to impact the output power. Majority of calculation and impact is done in block number 3. When the information of the sensed frequency and power change is passed to the block number 3 both the frequency and power are compared to set references. After the change in frequency is calculated it is multiplied by a parameter of area bias in $\frac{MW}{Hz}$. The difference in power flow at the reference point *e.g.* a tile line nod in a given area, is now added to the calculated power change necessary due to frequency excursion and passed to a proportional-integral (PI) controller. The rate of change of the controller's output is limited with the use of a ramp block, in order to take into account complex dynamics involved in the change of generators output *e.g.* time constant of steam turbine or boilers. Finally, power change is shared between generators in the control area according to developed factors. Simplified manner of signal flow is seen in Figure 3.4 for a single generator participating in the power regulation. The entire control is implemented using per unit values of relevant data.

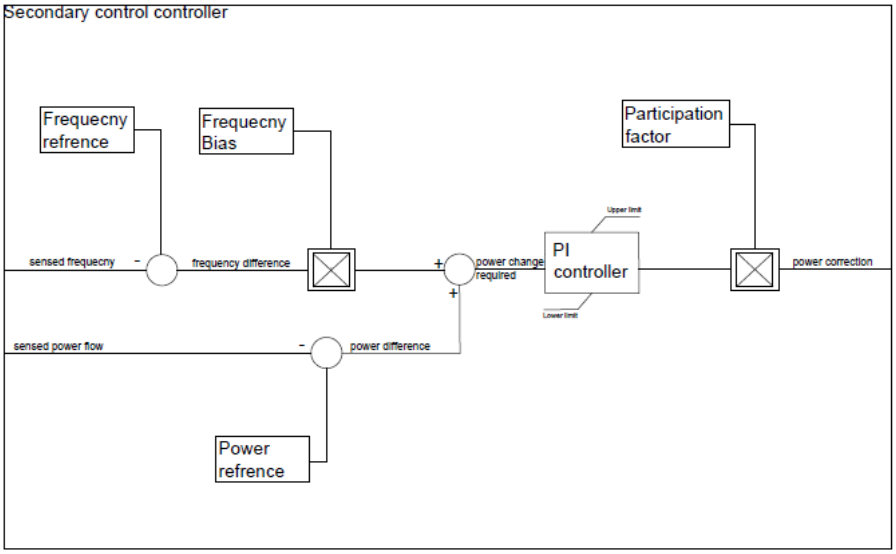

Figure 3.4: Simplified structured of implemented PI controller

Actions of the above mentioned control are passed to the only block that can physically impact the output of the generator to the generator's governor.

3.2 Primary control

All of the control refers to the SG model and its power output. The frame fitted with all the sensing information as well as dynamic models can be seen in Figure 3.5. The most important parameters are the sensed frequency and information about the power output.

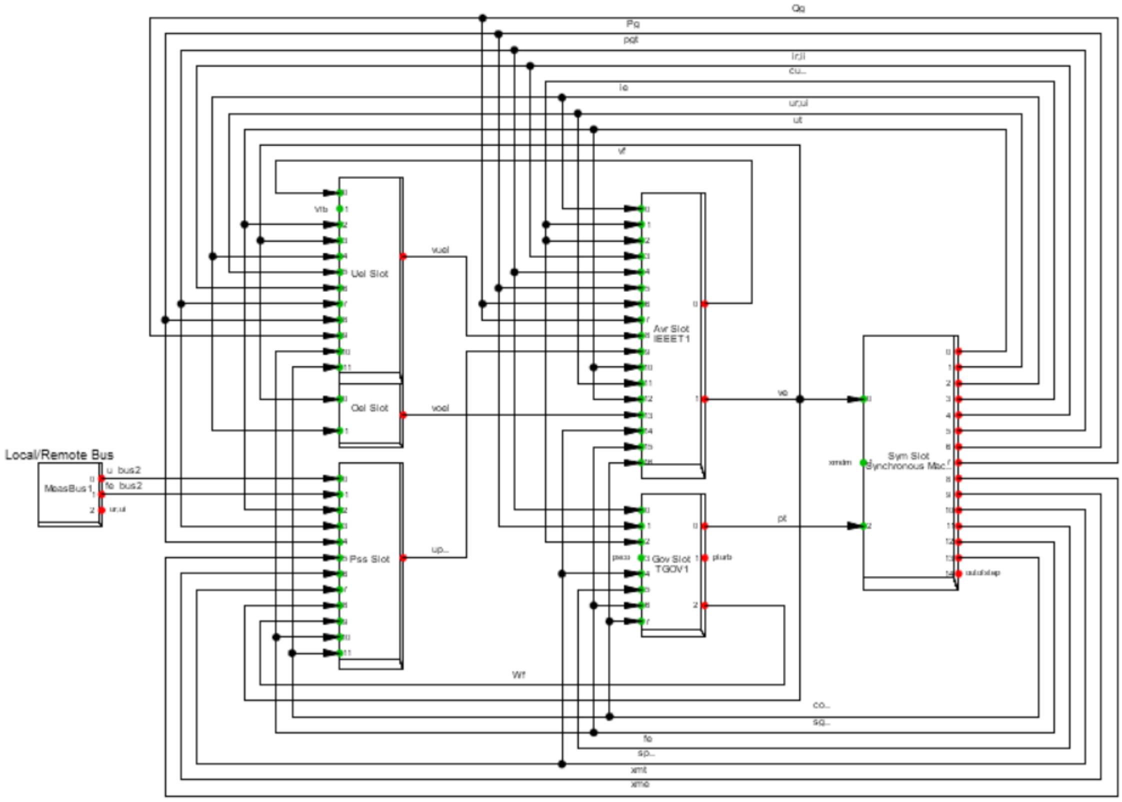

Figure 3.5: Structure of Control of synchronous generator in simulation tool DigSilent PowerFactory

The governor when fed with information on power output and frequency determines the required power correction and passes forward the desired output value.

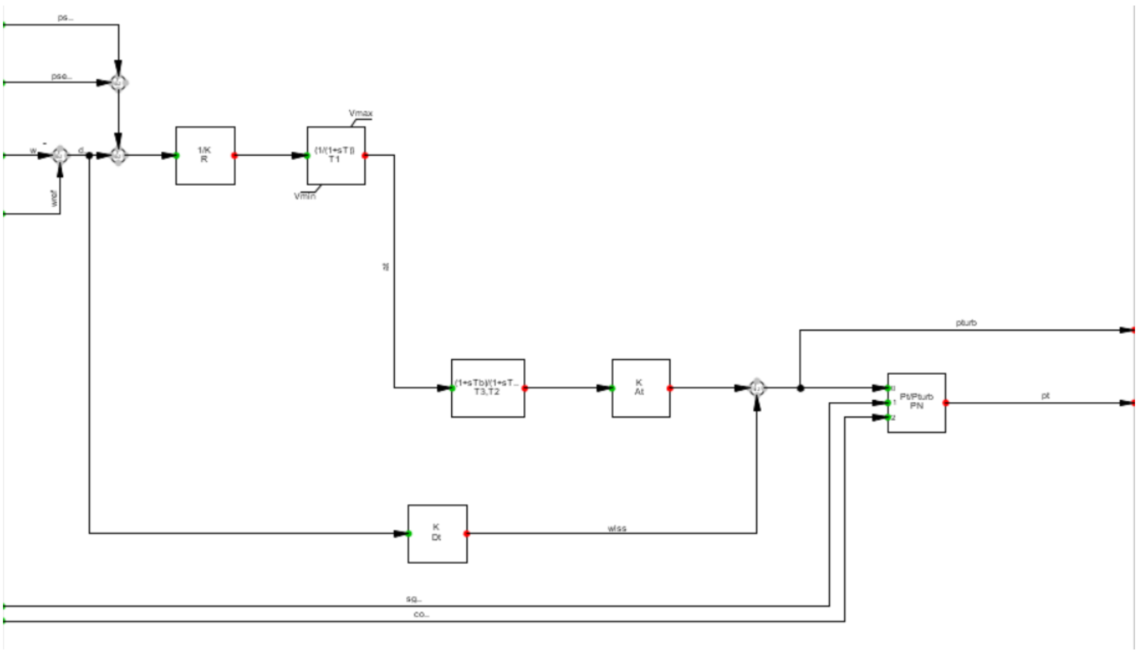

Figure 3.6: Structure of turbine governor in simulation tool DigSilent PowerFactory

The AVI control ensures voltage stability, and is not further inspected or modified during this project, yet is implemented as a crucial art of working model of synchronous generator.

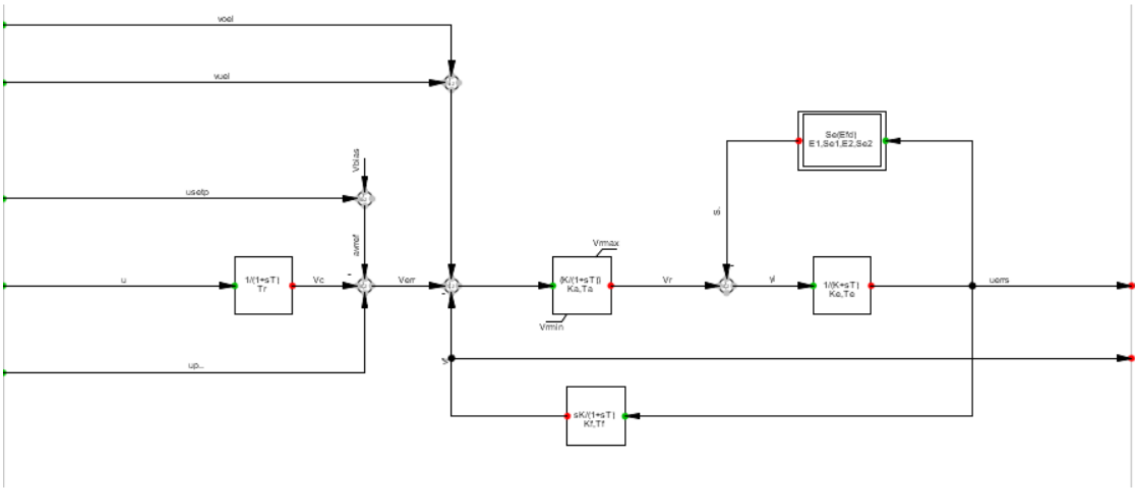

Figure 3.7: Structure of Control of voltage regulation by SG in simulation tool DigSilent PowerFactory

3.3 secondary control

Secondary control utilises all the elements used for primary control and an additional PI controller with a feedback loop of power of the generator, to further impact the output power.

The simple structure can be seen in Figure 3.4. That allows for recovery of frequency to the nominal value, to be able to impact the tie line power flow, additional sensing of part in that tie line is necessary. The sensed power is compared by the bottom branch of the controller, and the additional power from the supplying area has to be drawn.

All of that happens until the desired frequency is achieved and desired power flow in the tie line is present as well. The required powers are being split between the generators in the given area with set up participation factors.

3.4 Summary

Automatic generation control is capable of monitoring crucial parameters and response in real time to the sensed disturbances. In order to do that appropriately the elements impacting the frequency need to be modeled with as great precision as possible, otherwise the outcome of control can be uncertain. In PowerFactory, in order to model the controls of generators with dedicated DSL a composite frame and common models need to be created and assigned. The composite frame is responsible for gathering the elements that need to be coordinated and to create the connection path between them. The common models are graphic representations of complex dynamic equations that model the behaviour of the given element and put out the results of the given inputs. That is why it is crucial to ensure appropriate assignment of the models and correct interconnections. It will allow for implementation of control for the grid's elements in further work in this project.

Validation of AGC 4

In this chapter the principles of control strategies as well as methods of implementations are validated with use of simplified systems. Each step of AGC implementation is explained and shown with attention to crucial principles for each control level. The first part outlines the basics of system's inertial response. Second section indicates the principles of primary control and the join action. Third section elaborates on the deployment of units participating in secondary response. At the and all the main points are again summarized and lay fundamentals for next chapters, and what can be expected from main system.

It is intended to validate the created control in a simple system before implementing it in the target grid. In this part, the amount of reserves is not significant as long as they are able to provide necessary services. In order to achieve the goals mentioned above a simple system consisting of a single synchronous machine is utilised to validate primary and secondary control. The system is visible in Figure 4.1.

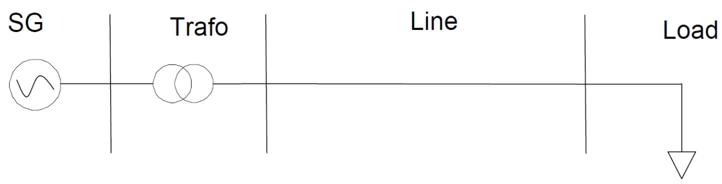

Figure 4.1: Single machine system for primary control validation

When it comes to tie line control, a simple two area system is implemented where all the developed control is applied and tested, see section 4.3.

To eliminate additional phenomenons that might impact the system's stability and control behaviour,*e.g.* voltage instability, parameters like line length etc. are implemented to have small to no impact for this series of simulations.

4.1 Inertial response

An inherit property of system is how it deals with sudden disruptions of frequency, that behaviour rely on the system's inertia. The amount of existing inertia decides how fast the frequency changes in case of an event. Crucial parameter when it comes to that is the rate of change of frequency (ROCOF) and should be kept in reasonable boundaries, otherwise, when breached could mean system cannot recover from an event of certain severity and further measures need to be taken.

When simulating a frequency excursion due to load increase or generation loss, at reasonable level of 5-10%, in the system in Figure 4.1 it can be seen that the ROCOF is approx. 0,999 Hz/s and system responds correctly to the event. However, if the same simulation is repeated with exaggerated load increase of 50%, the ROCOF increases dramatically to 999 Hz/s and system is not capable of stabilizing in time.

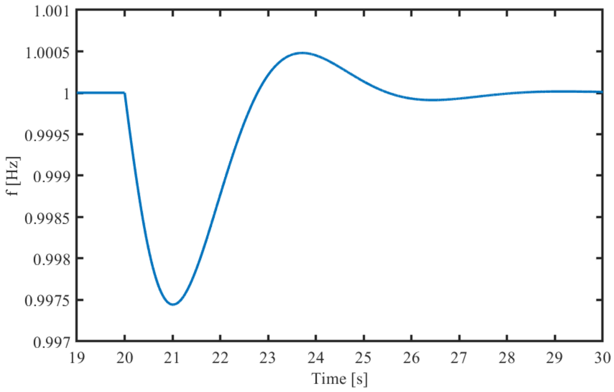

Figure 4.2: ROCOF in 1 machine system

As one of today's goals is to move away from fossil fuels and integrate more green energy, a respective result is reduction of conventional generation. Consequently, the amount of mechanical energy (rotating masses) that is present int the system is getting lower and lower. Thus, the system's inertia is lower and that also affects the speed with which the frequency can change, as seen in Figure 4.3.

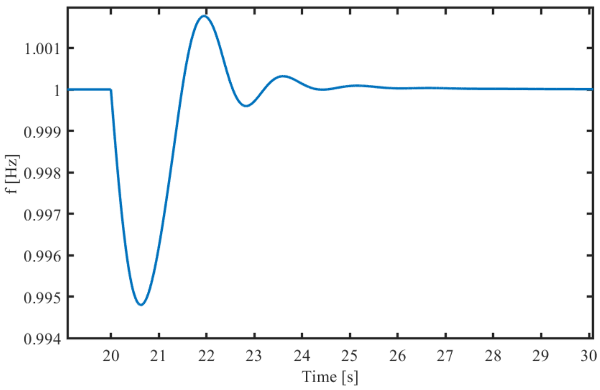

Figure 4.3: ROCOF in 1 machine system with lower inertia

From Figure 4.3 it is visible that the less inertia there is in the system the greater the ROCOF during an event, and the system is more likely to lose stability.

4.2 Primary response

When modelling the primary control in Digsilent PowerFactory it is necessary to use DSL and create the simulation frame. In case of primary control when implementing the generic model of SG the composit frame "$SYMframe2nodroop$"is picked from standard library frames. Due to specifics of the project the only blocks in the composite frame that are utilised for primary control are the SM's governor and automatic voltage regulation (AVR) blocks. For the governor a standard steam turbine governor "$govTGOV1$" is implemented form existing library. *This is a simple model representing governor action and the re-heater time constant effect for a steam turbine. The ratio, T2/T3, equals the fraction of turbine power that is developed by the high-pressure turbine.* The implemented automatic voltage regulator is "$avrIEEET1$". *This model is widely used to represent systems with shunt dc exciters as well as systems with alternator exciters and uncontrolled shaft-mounted rectifier bridges.*

Actions of these units, as intended in a stage of primary control, aim to put to a hold to any detected frequency excursion within 30s. Validation of implemented models is done with generic cases of step increase as well as step decrease of load that result in frequency disturbances. Load is modelled with use of library dynamic models ("$LOD1$") and set up to be constant by adjusting parameters according to [24].

As mentioned above, the cases of 5% step load changes are implemented to validate the implemented dynamic models of primary control. As seen in Figure 4.4 the loading is increased resulting in a frequency dip. The frequency reaches the "f_{NADIR}" at 49,5 Hz and recovers to a new steady state at 49,8 Hz. The governor actions start just after the power imbalance is detected, approx. at 6 s the increase of generator output power is commencing. It can be seen that the time of all actions is approx. 26 s, being within the 30 s window expected for a properly working primary control. Furthermore, it can be seen that the frequency is stabilised successfully.

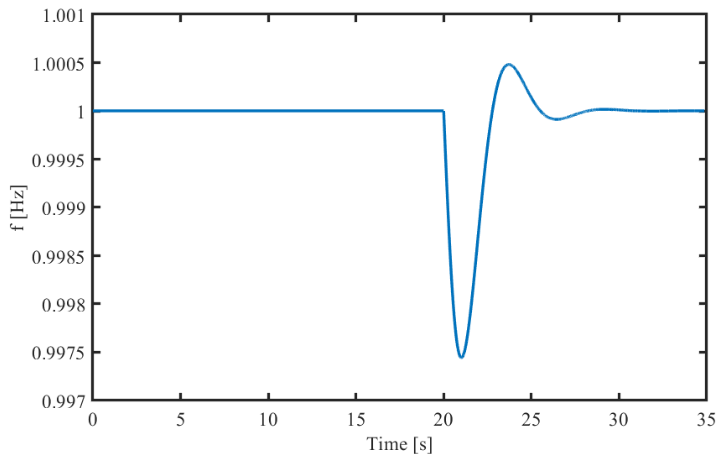

Figure 4.4: load inc validation

Consequently, the control is tested for over frequency coming form a drop of 5% of load. The clear over frequency conditions are seen in Figure 4.5 as well as the correct response from controls. The output power is reduced at time 6 s and new steady state frequency of 50,5 Hz is reached at 26 s.

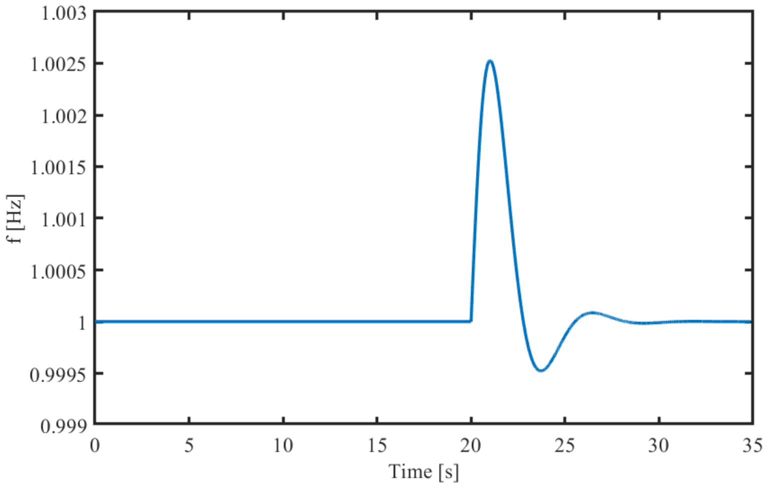

Figure 4.5: load down validation

Results validate the implemented control at the level of primary control.

4.3 Secondary response and tie line control

When modelling the secondary control for this project the approach is to build on the already implemented primary control. The existing library simulation frame is adjusted for the purpose of secondary , see Figure 3.3. Interconnecting developed frame of SG into new frame representing AGC for the entire designated area. Frequency is sensed at the busbar nr. 3 and this information is passed from block 1 to the PI controller where the correction of power is calculated (block 3).

The Information of sensed power and frequency is passed over and corrections are applied in the PI controller. Once the difference from nominal frequency is established an area REGULATION BIAS is applied, resulting in necessary power generation adjustment to counter the frequency excursion. Simultaneously, the tile-line power exchange is monitored and compared to a target value. The determined power difference in tie-line is added to the already calculated power correction due to frequency deviation. In the next step, the proportional-integral controller scales the response signal that is passed through and divided according to participation factors of machines in the given control area.

The tie line control is applied only in area that contributes to the flow of power to the other area *e.g* area A to area B.

For purpose of testing a simple two area system is created. Areas A and B are interconnected synchronously by a tie line that export active power of 100 MW from area A to the area B at all times. System has in each area single synchronous generator, single step-up transformer, single transmission line, and a single load. The system's overview can be seen in Figure 4.6

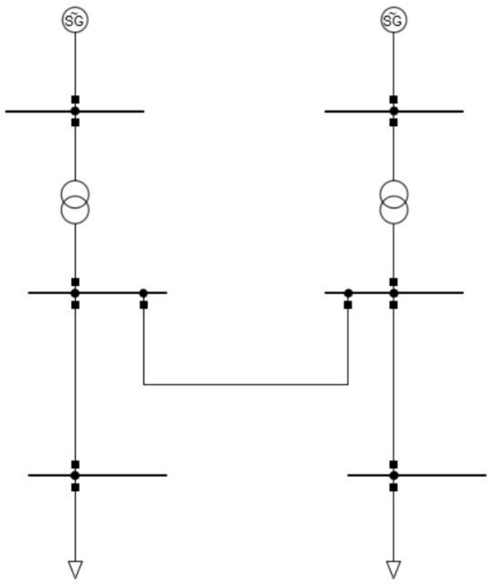

Figure 4.6: Overview of simple two area test system

Simulations where a load is varied and the results are posted below. It is explained and outlined the action of control and how it affects the generators and tie line and what does that mean for the system's stability.

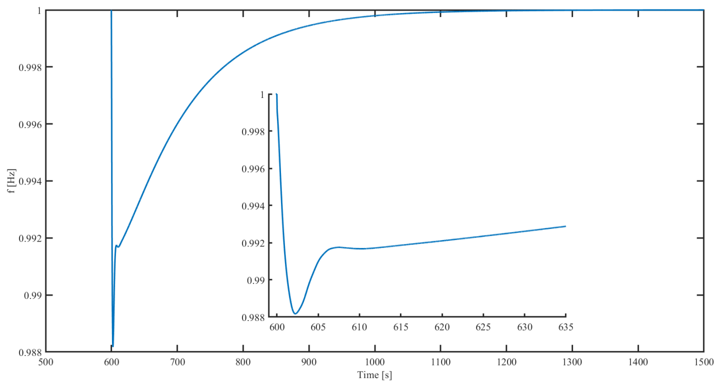

Figure 4.7: Simple 2 area system's frequency during increase of load with a zoom in perspective of the initial frequency drop and recovery

It can be seen that the frequency sinks due to step load increase at 600 second. The parameters of that event are "f_{NADIR}" is equal to 0.9882 that equates to 49,41 Hz. The frequency hits it's lowest value within abound 2 seconds form the event, meaning the registered ROCOF can be estimated at around 0,2565 Hz/s. The primary response manages to kick in on time to stop the frequency drop and to counter act it and stabilise it. It can be see that from around 610 second mark the secondary control kicks in and recovers the frequency to 50 Hz within 15 minutes (900 seconds) from the event as seen in Figure 4.7 in the zoomed out portion of the graph.

4.4 Summary

Modeled controls monitor and impact the frequency as intended. Primary control, is able to stop the frequency excursion and stabilise it. Secondary control impacts the frequency over longer period of time. It helps to reestablish the frequency at nominal value with satisfactory precision, that is greater than 1% in case of the simple system, and over expected period of time. Also the branch of secondary control responsible for tile line power flow, is able to fulfill the expected duty. The power in the tile line is brought to the scheduled value with satisfactory precision. Developed control is later modified and extended to the benchmark grid, but all the findings, principles and correlations hold true.

Modelling of Battery Energy Storage 5

In this chapter model of battery energy storage system (BESS) as well as controls of it are validated, analyzed and explained. Basic testing and validation of the model is done in a simple custom grid, that can be seen in Figure 5.1. The grid consists of single generator, step up transformer, cable connection and a single load. The battery energy storage, represented by a voltage source, is connected to the system at the load bus by a PWM converter and another step-up transformer.

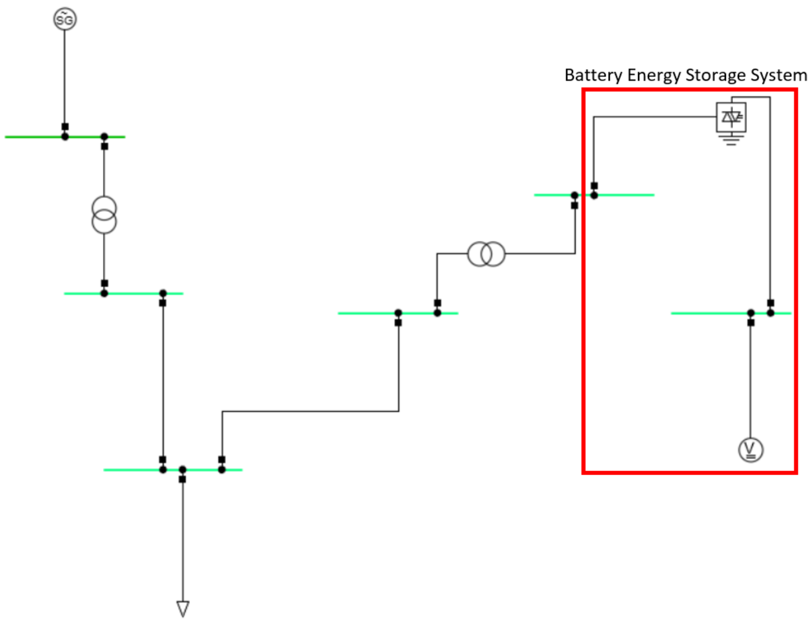

Figure 5.1: Simple system utilised for BESS model validation

Testing consist of simple load manipulation, ensuing frequency imbalance is supposed to be covered exclusively by the BESS. In an instance of 5 s the load is increased by 5%, the applied change is a step change that is an alternative to loss of some generation or rapid increase in load. The response of BESS is discussed and judged on the given settings and output like *e.g.* droop or output power. BESS action is obliged to cover the necessary power imbalance for period of the simulation. The real life necessity of maintaining power output for a given time is not considered at this stage.

Model of Battery energy storage system (BESS) utilised in this thesis is adjusted and implemented with use of [26]. On the most outer layer the BESS is represented by two elements, a battery which represents storage capabilities, and by a converter, typically a

VSC with PWM capabilities. The converter is also a real part and it's mode of operation reflects how the battery control system is established as well as the impact on the grid in given circumstances.

Battery system composite model consists of common models of battery, battery cell with it's characteristics and measurement of the output current necessary for SOC estimation. The batteries frame is shown in Figure 5.2 and Figure 5.3.

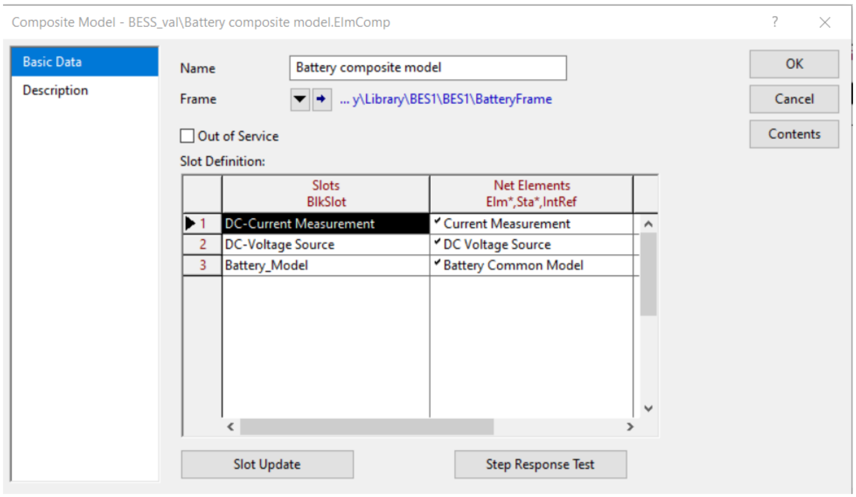

Figure 5.2: Frame construction of the battery system in Powerfactory [26]

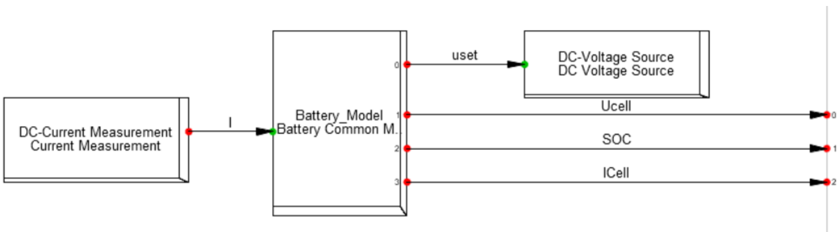

Figure 5.3: Graphic representation of battery system's frame construction in Powerfactory [26]

Crucial parameters when it comes to the battery model are initial SOC, nominal cell voltage as well as instantaneous voltage. The Discharge characteristic ($U_{(SOC}$) depends on the chosen battery chemistry and is one of the inherit properties modelled in the battery cell model. Multiple battery chemistries were utilized for energy storage's so far, nowadays, the focus is on the lithium chemistries, thus a lithium-ion chemistry is selected in the model.

The frame of BESS control is shown in Figure 5.4 and Figure 5.5. It represents the connections between measuring devices and the converter, as well as control logic over charge/discharge of the battery. The Battery composite frame is nested in the BESS frame.

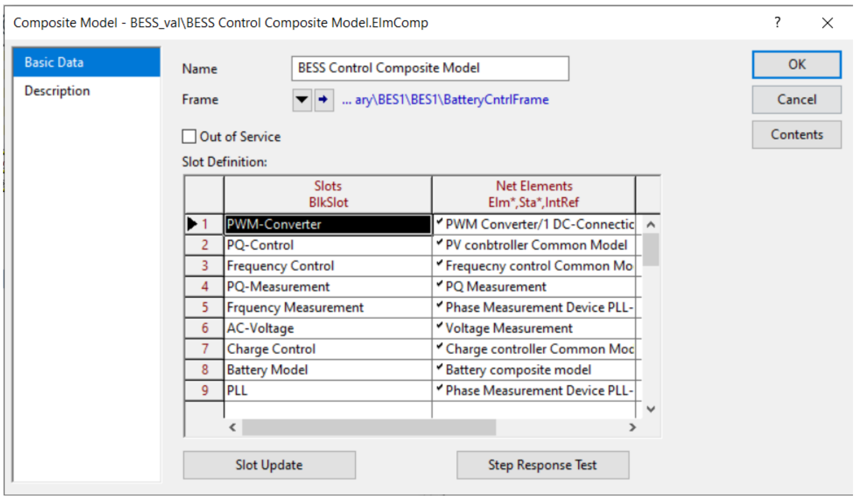

Figure 5.4: Frame construction for the Battery energy storage system in Powerfactory [26]

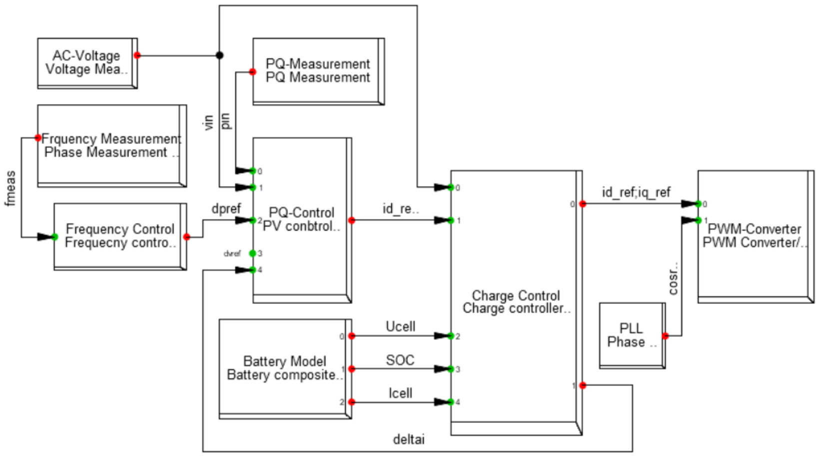

Figure 5.5: Graphic representation of battery energy storage's frame construction in Powerfactory [26]

The response of BESS is depended on the occurring conditions as well as the set up droop and deadband. The deadband is set to 0,02 HZ to avoid unnecessary deployment of BES during insignificant frequency fluctuations. When adjusting the droop parameter the frequency deviation that equates to output of BESS full power is identified. To show the BESS's behaviour simple simulation of 5% load increase is performed with different droop settings, see in figures 5.6 5.7.

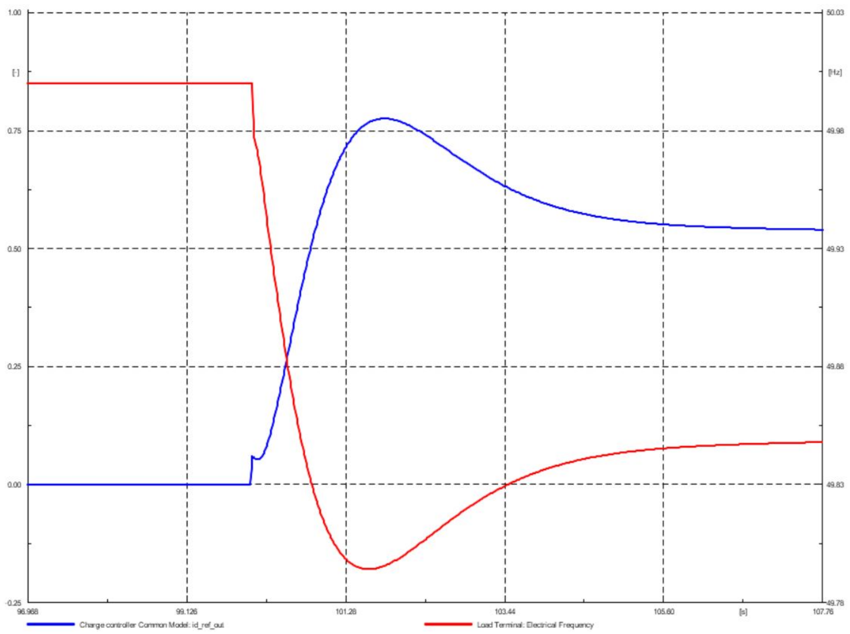

Figure 5.6: Output of BESS with droop settings R equal to 0.0005 for a given frequency event

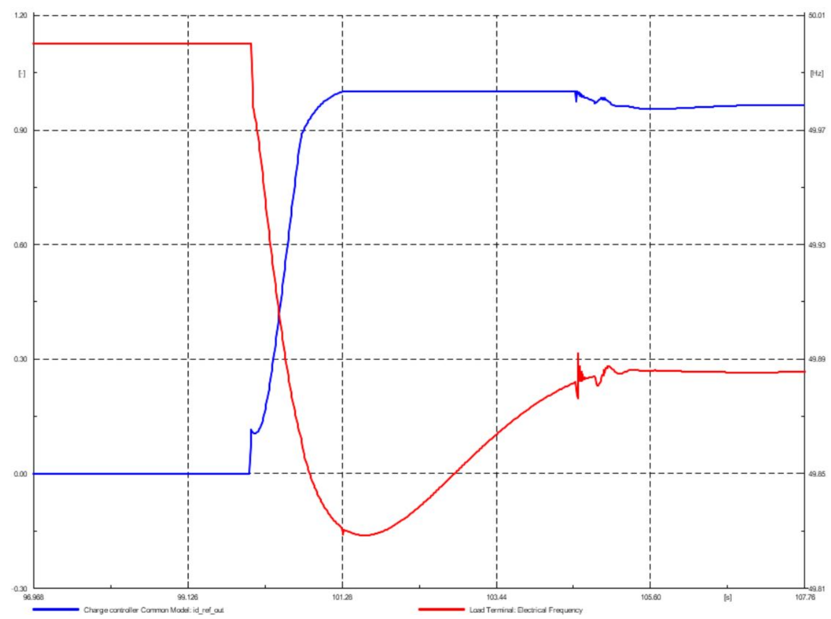

Figure 5.7: Output of BESS with droop settings R equal to 0.0002 for a given frequency event

It can be noted that at the moment of load increase, 20 s into the simulation, the systems frequency drops as of imbalance of aprox. 15 MW. The modelled BESS is included and the system's frequency behaviour is as follows. Within the set deadband the BESS detects the frequency deviation and starts its operation. In the first case the droop parameter is set to 0.005 which equals the full BESS power being activated for a frequency deviation of at least 0,25 Hz. The steady state frequency in this case is established at 49,865 Hz for the simulation meaning a deviation of 0,135 Hz from the nominal value. In the second simulation the droop is set to value of 0.002 and is activating full BESS power for a 0,1 Hz excursion. The steady state frequency in this case is established at 49,85 Hz according to the simulation software,while calculated value is es 49,87 Hz meaning a difference of 0,02 Hz.

There is a slight deviation between simulation results and the theoretical results. The deviations from time simulation can be seen above while the theoretical deviations are calculated in equations 5.1-5.2.

$$\Delta f_{ss} = \frac{15\,\mathrm{MW}}{\frac{1}{0.005}} = 0{,}075\,\mathrm{Hz} \tag{5.1}$$

$$\Delta f_{ss} = \frac{15\,\mathrm{MW}}{\frac{1}{0.002}} = 0{,}03\,\mathrm{Hz} \tag{5.2}$$

The difference in results comes from the droop parameter and applied dead-band. The dead-band is applied as a deviation from nominal frequency in direction of the excursion of the applied value, in this case 20 mHz. Results are droop dependent the smaller the droop the smaller the difference between the calculated steady state frequency and the simulation results. What is more the difference is constant for the applied droop.

The droop parameter allows for faster response of the full BESS power resulting in a steady state frequency closer to the nominal value. The matter of setting the droop parameter is limited by the speed equipment can react with and other external factors like costs.

In following chapters the showcased models are utilised to counter the issues connected with renewable generations. The fast reaction time is crucial advantage of the battery technology in order to prevent critical frequency excursions and can minimise the costs of reestablishing nominal frequency.

Simple study case is conducted. The system in Figure 5.1 i subject to a large change in load, an increase in load's active power consumed. The system's generator has implemented both primary and secondary controls, while BESS has 0,5 p u SOC a set deadband of 20 mHz and droop parameter - R as 0,002 p u . The simulation covers the incident, systems reaction, including the aid the BESS brings, and behaviour of BESS and how that behaves and does it impact the frequency stability. Frequency excursion reaches it's lowest point of 49,83 Hz at 101.7 seconds as visible in Figure 5.9. BESS begins to output power immediately after the frequency breaches the set deadband and can bee seen in upper plot in Figure 5.8, the controls simultaneously start increasing the generators output power that can be see in the same figure, in plot below.

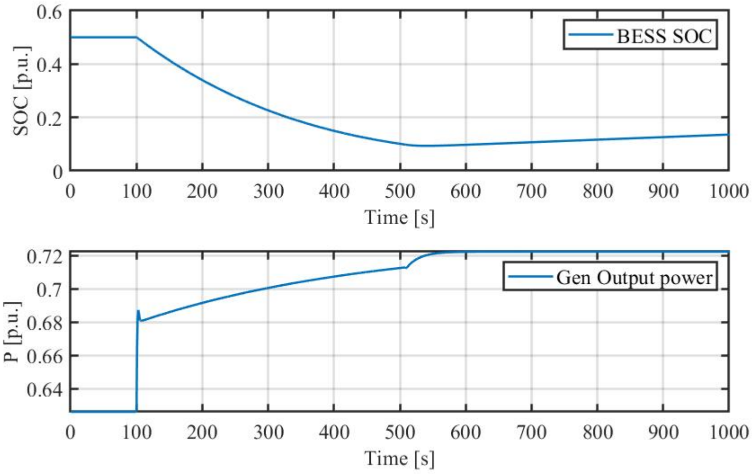

Figure 5.8: State of SOC of BESS and generator's output for a given frequency event

It can be noticed that when the BESS reaches the SOC that's being set as a limit, in this case 0,1 p u , the battery stops outputting power and intends to charge. Therefore, the visible notch in generator's power output that covers a power that is necessary for reestablishing frequency as well as to charge the BESS. As a result frequency experiences another small dip see Figure 5.9 that is depending on the set up minimum charging current, but the charging of BESS is set up so that the experienced frequency reduction cannot impact the system's frequency stability.

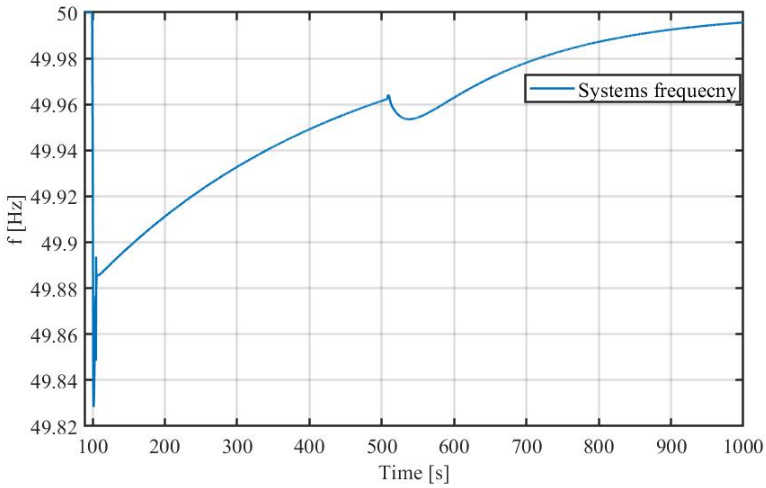

Figure 5.9: Resulting frequency of the system for a given frequency event

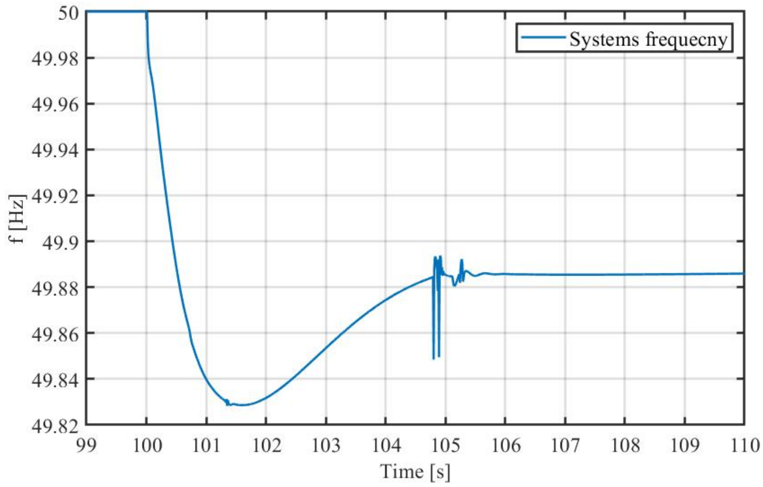

Figure 5.10: Zoom in of the resulting frequency of the system for a given frequency event

5.1 Summary

The BESS model to be implemented requires modeling of two parts, the management system and battery itself. It was found that the actions of BESS allow for less severe frequency excursions in case of exactly the same disturbance. What is also significant is the speed the BESS can and is allowed to react with. The faster the injection of power the better the result in frequency namely frequency nadir. This is a crucial property why BESS is chosen as a medium to increase the reserves and help aid the issues of REG.

System simulations 6

In this chapter all the relevant simulations regarding systems frequency stability are conducted. An outline of what kind of simulations are taken into account is drawn in the beginning, as well as simulations themselves are systematized. No power limits were considered for the system's transfer lines as a limiting factor. System faces numerous challenges some of which are load variations, hardships regrading generation schedule and it's capacity and these days a large about of uncontrolled power being supplied to the grid at the lowest level and in large quantities. In Figure 6.1 the Kundur's system utilised for simulation is shown, as well as typed of simulations are identified in the figure with separate numbers at location of event or REG or BESS placement.

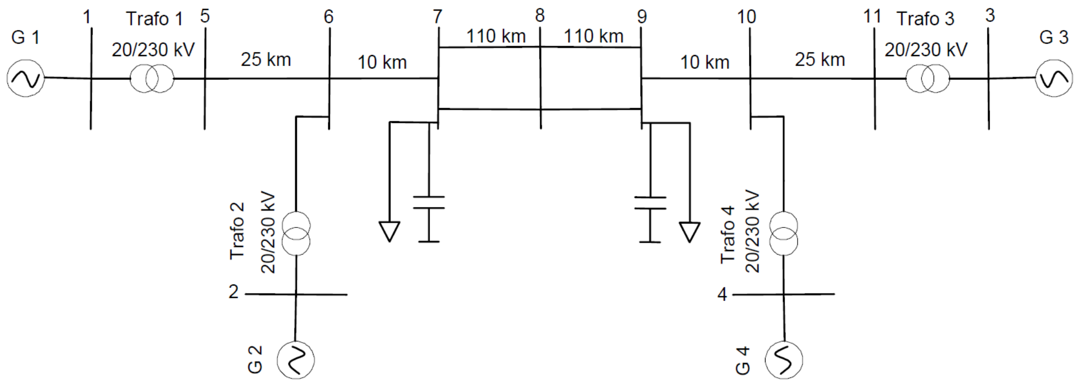

Figure 6.1: Caption

6.1 Types of simulations

In this section different cases of system's contingencies are listed and elaborated. Each mentioned contingency is systematized, simulated and analyzed for the utilised system and conditions. The methodology and approach behind each simulation and the assumptions for each particular event are explained. All of the simulations are conducted for increasingly larger percentage of REG penetration.

6.1.1 Loading increase

Step change in load is applied, it is worth notice that it might be a certain exaggeration and an instant connection of such large loads to the grid are rare and are done in a more elaborate way. However it is considered a worst case scenario, compared to daily peaks that are expected and ramp up over time, thus is still considered. System itself can withstand a symmetrical load increase of 6% of both loads, thus cases of 2% and 5% are simulated.

6.1.2 Drop of load

This section intends to analyze how system handles drop of large loads that might occur in critical situations. In order to do that aggregated loads at both areas of the system will be reduced by the same proportion of their initial value. The project intends to simulate a failure of the largest loads that might be connected to a grid not only a midday/night troughs that are both expected and gradual events. In this case the limiting factor for frequency stability is the speed units reduce their power with, it is intended to reflect as realistic speed of change in output power of generators as sufficient for the studies to be relevant.

6.1.3 Impact of REG volatility

In this section the impact of REG output instabilities is examined and simulated. The effects of the REG being scattered over a system are not analysed and the modelled REGs are aggregated. REGs are connected to the system at the same busbars the conventional generation is, see Figure 6.2. Renewables replace with theirs output power the power that would be supplied by the synchronous generators.

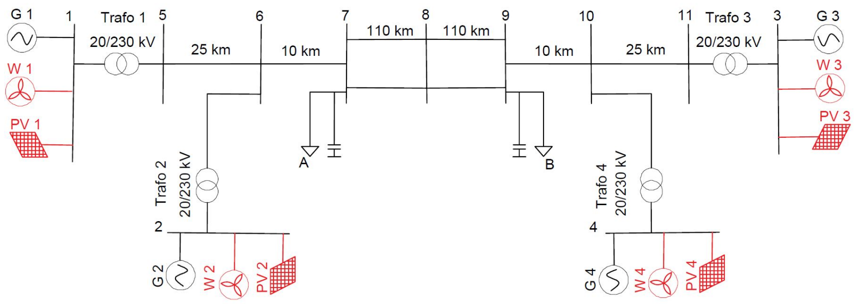

Figure 6.2: Integration of REG into the Kundur's 2 area grid

Assumptions as *e.g* conditions for wind and solar are assumed equal over the entire system, are made to further simplify the analysis. REG can participate in various ways in frequency regulation *e.g* output curtailment. However, since it is an objective to maximise the use of green energy the REG outputs maximum possible power at any given time. Main focus for conducted studies is the effect of ramping behaviour of the REGs for system's stability and consequently impact on necessary frequency reserve.

Wind power is modelled as a static generator at the point of connection of conventional generators. The output power is dependent on an excel file that models the behaviour of wind farm output. Since the actual ramp events of wind generation are dependent on multiple criteria *e.g.* placement of the wind farm, number and type of wind turbines, etc. a simplistic approach is implemented for this project. A general wind ramp of 10 %/min is assumed and utilised for ramping events in both directions.

In PowerFactory solar arrays are implemented in the point of connection of conventional generators as static generators. The output is simulated using an excel file that dictates the output power at specific time. For the purposes of this project the behaviour of the resource is of only importance thus specific nuances of solar power are not discussed. Most significant behaviour is how fast the output power changes for solar farms. It is well known that the output changes with solar irradiates and is very dynamic thought out the day but a simplistic approach is applied. This fact is demented on a number of conditions but for the purposes of this project it is assumed that in general the changes to the output power do not exceed 10 %/min [27]. Over course of the simulations solar power changes with the mentioned rates in both directions during ramping events. To have the entire solar generation in a given system, vary with the above mentioned speed, is extremely unlikely and this speed is used to pose a significant challenge for the system's controls and conventional generation.

6.1.4 BESS implementation

Battery energy storage system is implemented into the Kundur's 2 area network similarly to how it is done in chapter 5. The same model but scaled in terms of power and capacity is applied as a grid scale application connected to busbar nr. 9 in area B, since the power rating of loab in area B is far greater, so the most common issues will be most affecting in area B.The purpose of BESS is to inject large amount of power as quickly as feasible in order to reduce the severity of occurring contingency and allow for deployment of slower acting reserves. Placing of BESS in the utilised benchmark grid is shown in Figure 6.3.

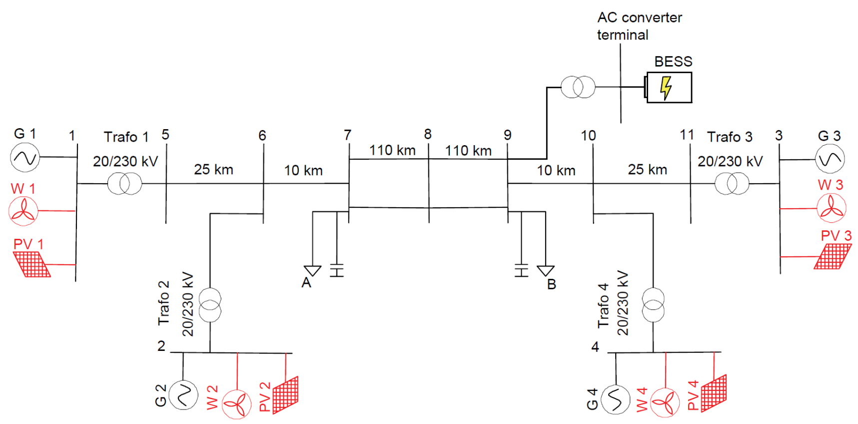

Figure 6.3: Integration of BESS into the Kundur's 2 area grid

The sole problem of placing the BESS in the given grid has to be carefully studied.

Large storage deploys with adequate linear rate of $R = 0.0004$, to act quickly utilising battery technology capabilities yet to have enough charge for large load and generation miss matches and not impact battery's lifetime without necessity.

6.1.5 Simulation order

The simulations are applied with increasing level of complexity due to layering of effects from increasing levels of REG and BESS. All levels of control introduced and explained in chapter 4 and chapter 5 are active during the presented simulations when being a part of the simulation. Firstly, simulation without any REG are executed where the benchmark is set. Subsequently, the simulation with introduced REGs is conduced and lastly simulation that includes both REG and BESS. All the yielded results are compared on a graph for the given case and discussed.

6.2 Conventional generation

In this section the conventional generation is subjected to number of cases which are explained in section 6.1. Both primary and secondary control are utilised for simulations to establish benchmark for the grid when REG and BESS are introduced. To systematize the simulation results the frequency is monitored through out the entire contingency as well as active and mechanic power of all the generation machines. Voltage is another parameter that reduces the level of REG integration, but since it is not the main goal of this project it is only monitored and mentioned in critical cases. The initial conditions are set according to inertias and establish the starting power of each generator as in Table 6.1

Table 6.1: generators starting point

Gen		Gen1	Gen3	Gen3	Gen4
P	[MW]	625	625	624	624

An event of load increase is introduced, the effect on system can be observed on it's elements and the reaction of control. The increase of load happens instantaneously at 200 s mark by a 7% of active power consumed by both aggregated loads in area A and area B. The frequency plot in seen in Figure 6.4, where frequency dips to lowest point of frequency Nadri being 49,733 97 Hz wchich can be read of the zoomed in portion of the graph. The rate of change of frequency is read of the slope the frequency declines with over the entire period of the frequency declince. Meaning a difference of 0,0184 Hz over a course of initial200 ms equating to ROCOF being 0,0018 $\frac{\text{Hz}}{\text{s}}$

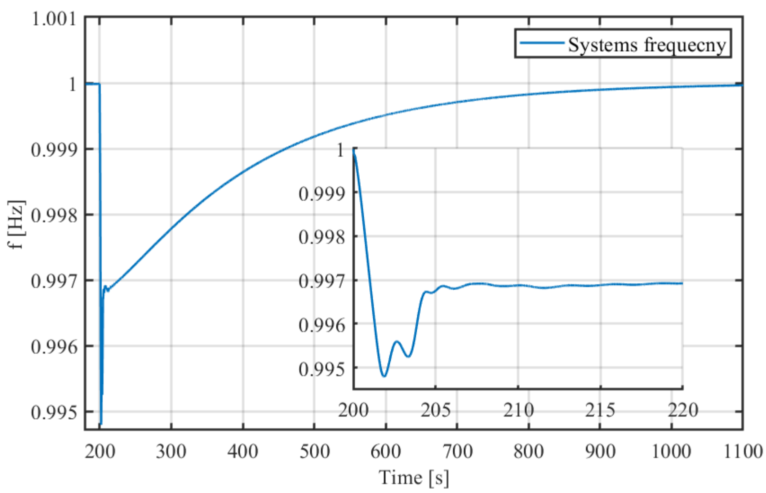

Figure 6.4: Systems frequency with exclusively conventional generation during simulation of instantaneous total active load increase by 7%

The controls of conventional generation act as a reaction of frequency extending over a permissible range and counteract it. In Figure 6.5 the increase of generation is shown, by all 4 generators. Due to similarity between machines 1 and 2 and machines 3 and 4 in the figure their power processes are on top of each other. It can be noticed that controls as a quick response generate and overshoot to be able to stabilise the frequency over short period of time. The powers of pairs of machines rise to 0,949 p u for area A and 0,961 p u vales with small differences of less than 0,001 p u . Continuing the process of frequency stabilisation the controls reduce outputs of the generators, however once the frequency is under full control end during the process of recovering the additional requirements, in this case of powers in the tile line between the areas, also need to be met. Thus, the final powers are settled at 0,9128 p u for area A and 0,9493 p u for the area B. In is necessary to remember that even though the area A is exporting power to area B, the demand for power in the area B is significantly larger therefor the noticeable difference in power generation between the areas.

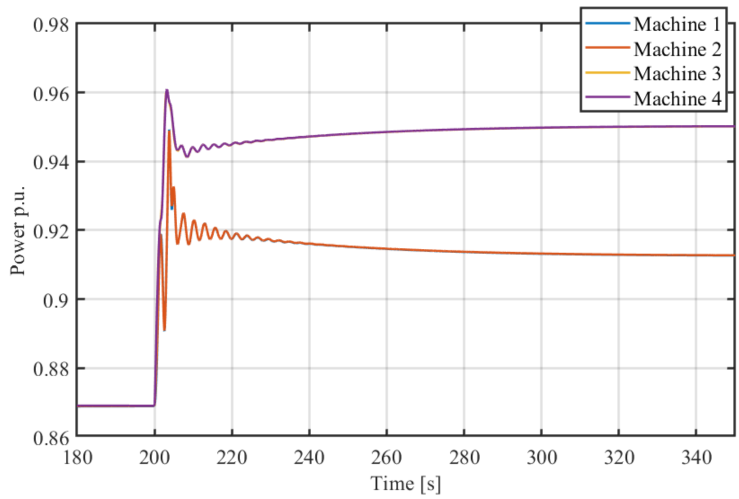

Figure 6.5: State of power production of each machine is the system during the frequency excursion in event of instantaneous total active load increase by 7%

The consequence of power imbalance and power regulation is a disturbed power flow in the tie line. For a period of about 100 s the power flow from area A to area B is different from the scheduled value. In Figure 6.6 it can be seen that the power flow goes through a disturbance at the mark of load increase on 200th second and process of recovery and regulation until it settles at almost exact value from before the event.

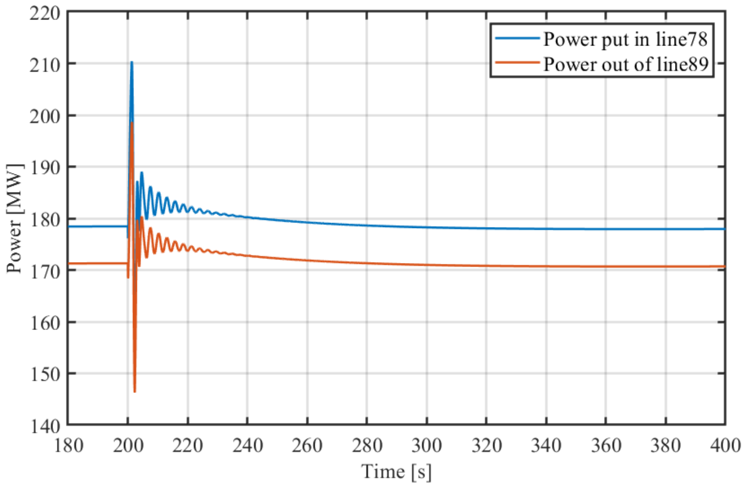

Figure 6.6: State of power being send between the area A and area B through tie line for the instantaneous total active load increase by 7%

The input of the tie line - marked with color blue in Figure 6.6 shows how much power is drawn from the area A and the orange plot shows how much power is delivered to area B after all the losses along. The final powers are 177,9 MW and 170,7 MW which are larger by approx. 0,5 MW from the starting values. Large disturbances of power can be noticed in the first few iterations of the control, they appear due to large gain of PI control introduced in chapter 4, by reduction of the gain the intensity of the changes can be smoothed.

Alternative simulation is conducted for a instantaneous drop load resulting in large amount of active power load being taken from the systems. At the 200th second mark 10% of active load is droped resulting in over generation and thus frequency excursion, expecting to put the system in over-frequency state. The top frequency value of 50,3252 Hz is reached at approximately 202,6 s. The ROCOF is 0,0033 $\frac{\text{Hz}}{\text{s}}$ and is deemed to be stable. As seen in the zoom in portion of the graph in Figure 6.7is reached within approx. 10 s from the event and frequency recovers to initial value over the course of 900 seconds.

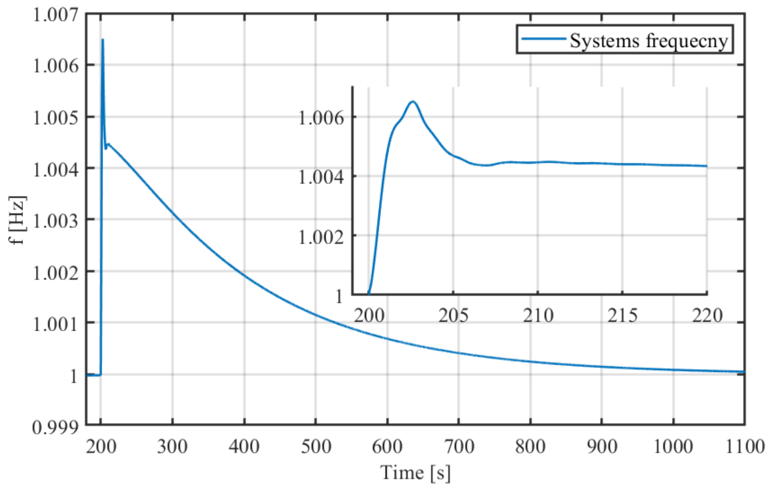

Figure 6.7: Systems frequency with exclusively conventional generation during simulation of instantaneous total active load decrease by 10%

Since the system is in a state of over generation the controls notified but sensors of over-frequency adjust the set points of generators to reduce the output and aid the situation. All generators reduce their outputs from initial value at 0,896 p u to 0,806 p u in case of area A and to 7544 p u for the area B. The smallest values of the generators output can be seen to be lower, see Figure 6.8 than the final set point due to the controls being under dumped in order to achieve a satisfactory response time. It is worth noticing that the power set points settle relatively fast within 100 s from the event. The plots of machines 1 and 3 are overlapped with plots of machines 2 and 4 consecutively, and any value differences can be considered irrelevant.

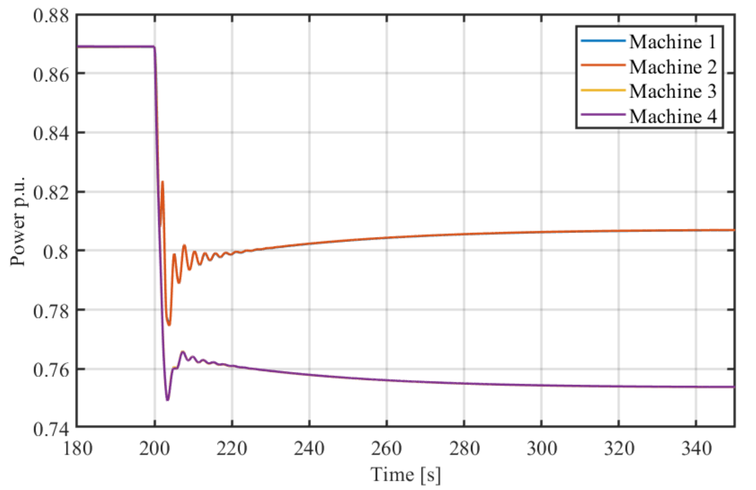

Figure 6.8: State of power production of each machine is the system during the frequency excursion in event of instantaneous total active load decrease by 10%

The power flow in the tie line is also disturbed and goes from 178,4 MW to 179,3 MW for the power that Area A introduces, and from 171,3 MW to 172,3 MW which is the power that area B is able to utilise. Which are differentiate from the initial values by less than

1%.

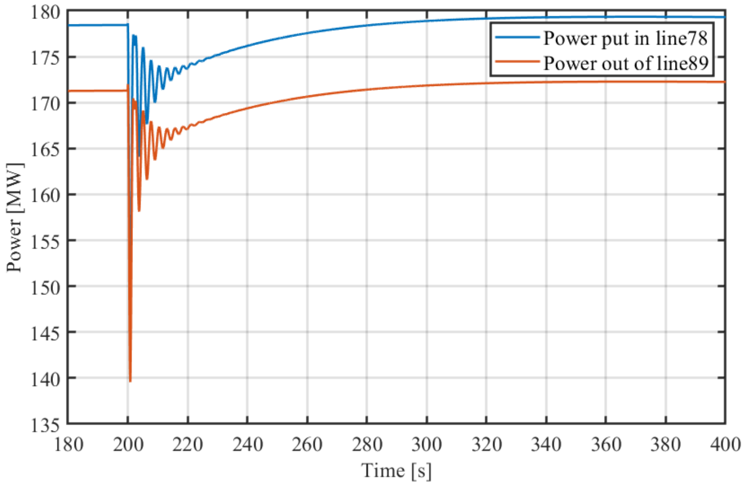

Figure 6.9: State of power being send between the area A and area B through tie line for the instantaneous total active load decrease by 10%

6.3 REG integration

Increasing level of penetration of green energy sources means that at the given time instance certain % of load is supplied with the REG.

$$REG_{Penetration\%} = \frac{P_{REG}}{P_{Load}} \cdot 100\% \tag{6.1}$$

The resources of REG like solar and wind are subject to constant change and fluctuation, so is the output power of the plants utilising them. The ramps utilised for this work are explained in section 6.1 under subsection 6.1.3 and are set as in Equation 6.2.

$$SOLAR/WIND_{Ramp} = \frac{\Delta P}{\Delta t} \cdot \frac{10}{60} = 10\,\frac{\%}{\min} \tag{6.2}$$

The impact of REG sources comes from appearance and lack of power in the system due to their volatility, however that brings appropriate actions of existing control into consideration. Reduction in solar or wind power cause deployment of reserves and there is a possibility of reappearance of power from REG back in the system, thus a potential over generation scenario. During this volatile period a load event is also possible to happen, for this work it is assumed to appear in least favourable circumstances, *e.g.* drop of load after initial reduction in REG power -> deployment of reserves-> REG powers are reconstituted -> deployed reserves plus extra power from REGs plus a drop of load in the system at frequency in high point, or a load increase at the lowest point of REG power output decline.

What is distinctively visible in figures 6.10 - 6.12 is that the increasing amount of REG results in more and more severe conditions when it comes to *e.g.* frequency nadir or top frequency after an event. For REG penetration level of 10% the $f_{Nadir} = 49.6898$ when a load is increased at 540 s mark is larger by approx. 70 mHz compared to REG being at

20%. At the higher REG level system experiences lowest frequency at $f_{Nadir} = 49.6195$ for the same event. The time frames over which the lowest frequency is achieved is also suggesting a more challenging conditions for increased penetration of REG. Time stamps of the lowest experienced frequency are $t = 541.861$ and $t = 541.831$, consequently for REG level of 10% and 20%. The difference of 30 ms is noted and can be an issue when it comes to Rocof protection setting. Furthere more the very parameter of rocof is worse the larger the penetration of REG, for the 10% it is at $ROCOF_{10\%} = 0{,}1689\,\frac{\mathrm{Hz}}{\mathrm{s}}$ while for the 20% case it is $ROCOF_{20\%} = 0{,}1692\,\frac{\mathrm{Hz}}{\mathrm{s}}$. The difference being small and inconclusive when it comes to how severe the impact is, since the amount of inertia in system is the same for both cases. For the simulation where the drop of load happens simultaneously to the downwards ramping of REG sources, at the 60 s mark, the noted rocof is at $ROCOF_{10\%} = 0{,}1104\,\frac{\mathrm{Hz}}{\mathrm{s}}$ and $ROCOF_{20\%} = 0{,}1168\,\frac{\mathrm{Hz}}{\mathrm{s}}$ for both cases. This indicates the increasing challenge of the increased speed with which frequency changes under conditions where the power without inertia is withdrawn from the system. The frequency plots from which the above mentioned frequency parameters are derived can be seen in Figure 6.11. The frequency after initial boost remains dropping tendency until 550 s due to constant reduction of power generated by REG sources

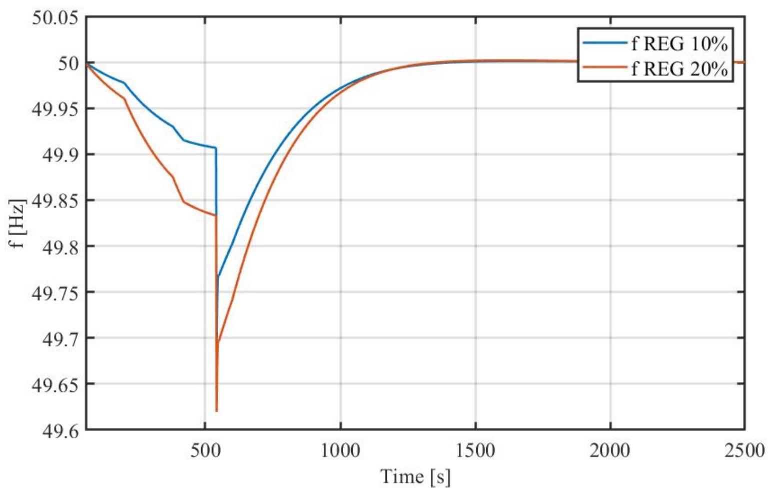

Figure 6.10: increase of load for lowest frequency point due to REG volatility

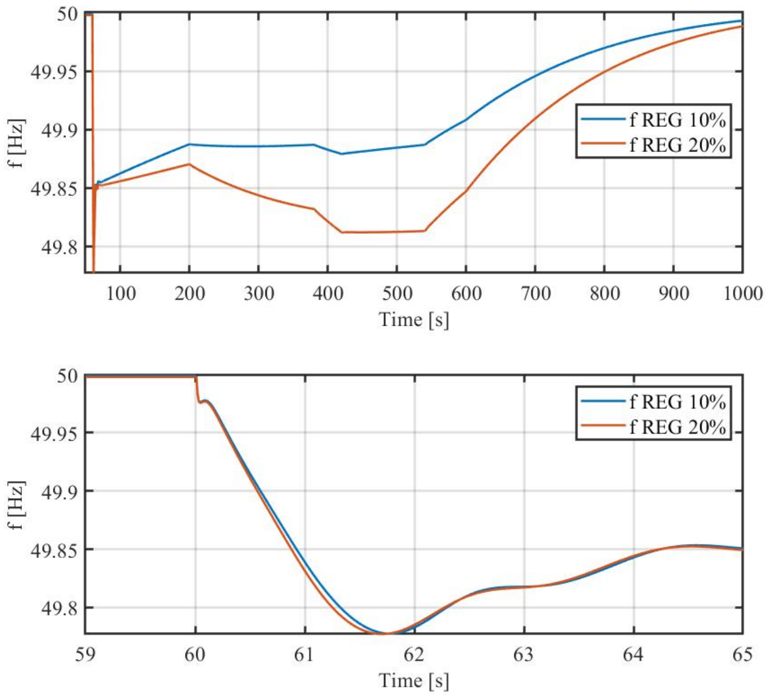

Figure 6.11: Increase of load at the 60 second mark along reduction of REG power, for different penetrations of REG sources

Similar conclusions can be drawn from case when the least optimal scenario for drop of load happens, as in Figure 6.12. The top frequencies the system experienced are f_{max1}=50.3703Hz for 10 of REG and f_{max1}=50.4421Hz for 20% of REG. Time instances for these peaks in frequency are 1352,29 s and 1352,05 s consecutively. While the rocof in these cases is found to be approx. $ROCOF_{10\%}$=0,1825 $\frac{\mathrm{Hz}}{\mathrm{s}}$ and $ROCOF_{10\%}$=0,1887 $\frac{\mathrm{Hz}}{\mathrm{s}}$ where the faster rate of change is detected for the larger penetration of REG.

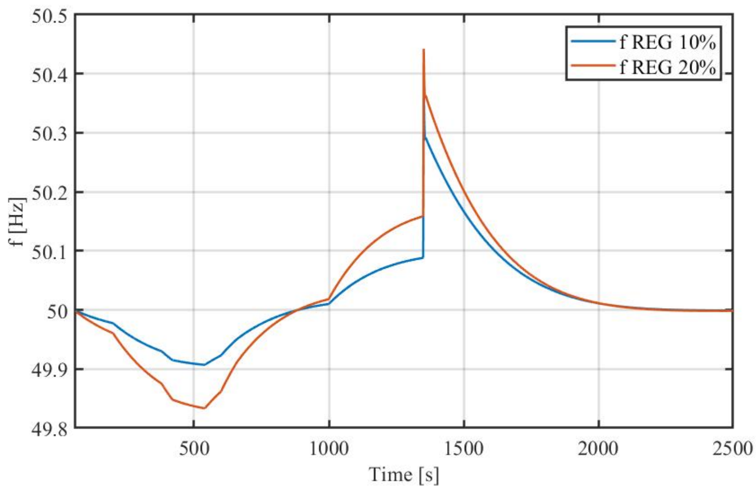

Figure 6.12: Drop of load when reserves are fully deployed

The frequency is a result of balance between the power produced and consumed at the given point in time. During the conducted simulations the impact of generators is visible along the changes in frequency, thus the highest and the lowest generation set points are at the lowest and the highest point of frequency. Since the case of increasing load by 7% is a border simulation, the generators outputs are already close to maximum values, as seen in figures 6.13 - 6.14 The powers at the peak of frequency after an event, along with the time instance, and steady state value can be seen in Table 6.2. It can be seen that with the increase of REG the time over which the powers at the peak of frequency are achieved is visible shorter. The powers of SG1 and SG2 at these instances are larger for lower REG level due to SG1 and SG2 covering for the lack of generation and increase of load in area B through the tie line, thus the intuitive behaviour of these two units.

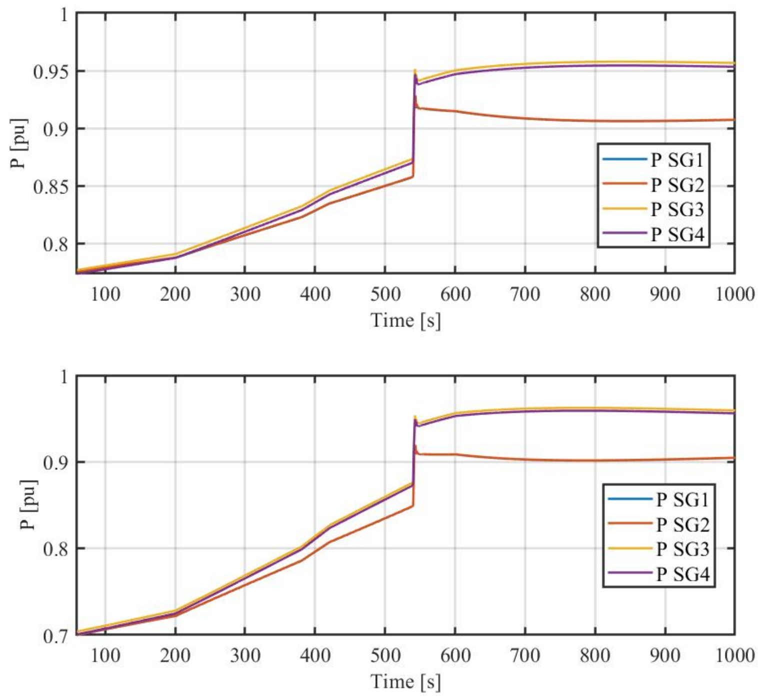

Figure 6.13: Powers of SGs during increase of load and reduction of REG power output different REG levels

Table 6.2: Output of generators for increase of load at the most challenging point

Generator	REG 10%			REG 20%		
	Power at peak [p.u]	Time of P at peak [s]	Steaty state power [p.u.]	Power at peak [p.u]	Time of P at peak [s]	Steaty state power [p.u.]
SG1	0.9284	543.5317	0.9134	0.9192	543.4817	0.9134
SG2	0.9285	543.4817	0.9136	0.9194	543.4817	0.9136
SG3	0.9516	542.8317	0.9510	0.9537	542.8117	0.9511
SG4	0.9472	542.9117	0.9477	0.9493	542.1017	0.9477

When it comes to the severe cases of load drop it is important to notice, the very important factor in the systems reaction is from the controls of generators. The simulation as mentioned above constitutes of reduction of REG sources output from full to zero and than increase back to full power. At the last step of power increase the 10% of total load is drooped creating a scenario for possible severe over generation. As visible in Figure 6.14, along the reduction of solar and wind energy, the controls of generators aim to keep frequency in desired range. At the instance of drop of load a large spike in frequency, see Figure 6.12, is present. The magnitude of this above mentioned spike is enhanced by created over generation due to SGs controls. The larger the share of REG in power supply, that had to be replaced before the event, the larger that peak. It is seen in the pots of generators outputs that a rapid drop had to be mad to aid the excursion. Since, the conventional generation is also inert in its nature that extends the period over which too much power is present in the grid. The controls take a good estimates what is the required to achieve the balance and keep the frequency at the target value. This can be seen in small differences between the initial outputs after the event and the steady state, see Table 6.3. The time over which the reduction in power is made is dependent on the accuracy of control and the inertial properties of machines, thus no visible time differences there. Machines in area B (3 and 4) with larger inertial constants take 0,7 s to 0,8 s longer compared to machines from area A (1 and 2). After the necessary correction to keep the system stable the machines adjust their outputs to also keep the tie line power flow as scheduled.

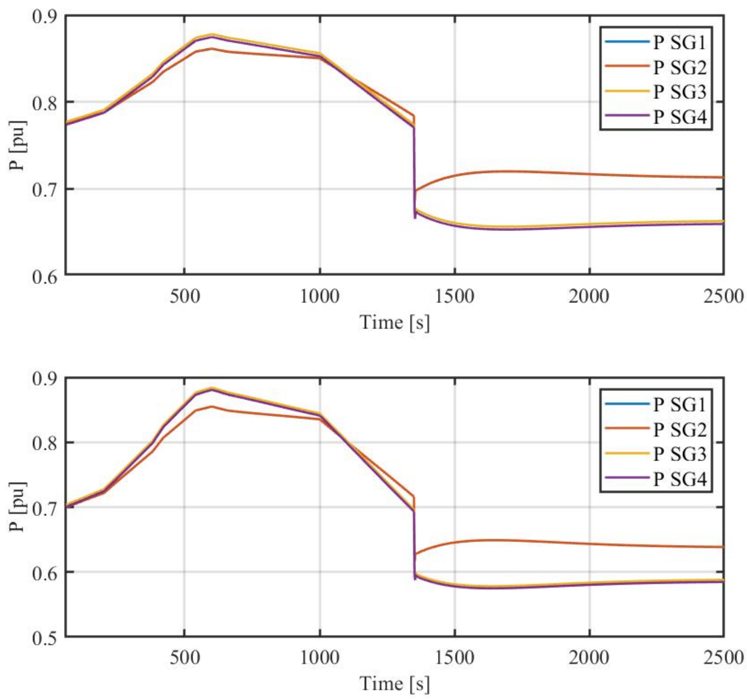

Figure 6.14: Output of generators for drop of load at the most challenging point

Table 6.3: Output of generators for drop of load at the most challenging point

	REG 10%			REG 20%		
Generator	Power at peak [p.u]	Time of P at peak [s]	Steaty state power [p.u.]	Power at peak [p.u]	Time of P at peak [s]	Steaty state power [p.u.]
SG1	0.6857	1353.1	0.7131	0.6171	1353.1	0.6385
SG2	0.6859	1353.1	0.7133	0.6174	1353.1	0.6387
SG3	0.6687	1353.8	0.6629	0.5909	1353.8	0.5881
SG4	0.6654	1353.9	0.6595	0.5876	1353.9	0.5848

What can be clearly visible from figures 6.15 and 6.16 is that due to ramping power of REG the tie line experiences fluctuations of power. These fluctuations are larger, the larger the total amount of REG power. However, in the instance of either an increase or drop of load the variation is sharp and can have large, short, swings of power. The peaks seem to be more dependent on the reaction of control itself than the amount of installed REG.

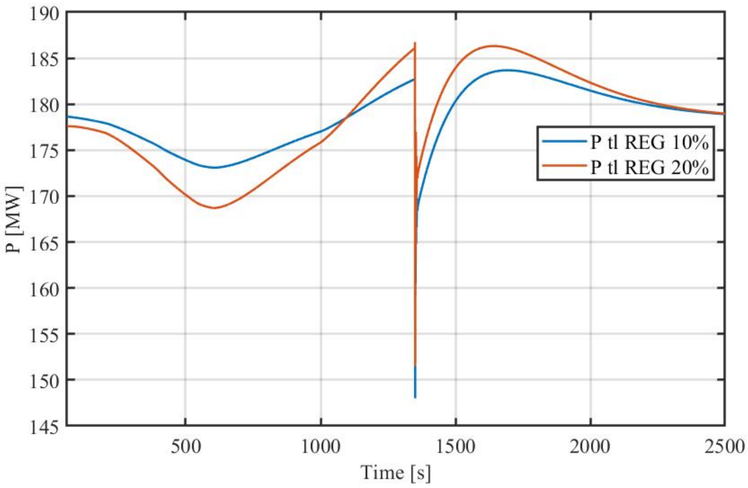

Figure 6.15: state of tie line power transfer for drop of load at the most challenging point

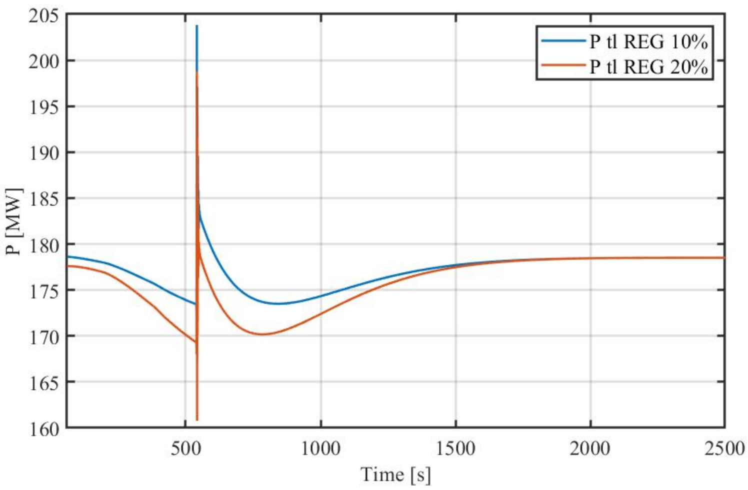

Figure 6.16: state of tie line power transfer for increase of load at the most challenging point

6.4 BESS introduction

The BESS is integrated into the utilised two area system according to subsection 6.1.4, and the way it is connected can be seen in Figure 6.3.

The same set of cases is simulated on now the system that is fitted with 4 SG, 4 PV power plants, 4 WTG plants, and a single grid scale BESS.

To take advantage of BESS as a quickly acting reserve the droop parameter is set to $R = 0.0004$ what equates to full power output for a change in frequency of 200 mHz. And as a quickly reacting asset, the dead band is coordinated with the typical dead band for the SG of 20 mHz, when no action is taken by BESS. The investigated case of BESS has a power of 30 MW, and a capacity of 120MWh.

During a showcase simulation where the only reason for frequency excursion is REG volatility, the BESS helped the system but the current coordination between it and control did not allow for full frequency recovery for either case of REG. Simulation was also incomplete for REG level of 20%, due to instability. This can be seen in Figure 6.17.

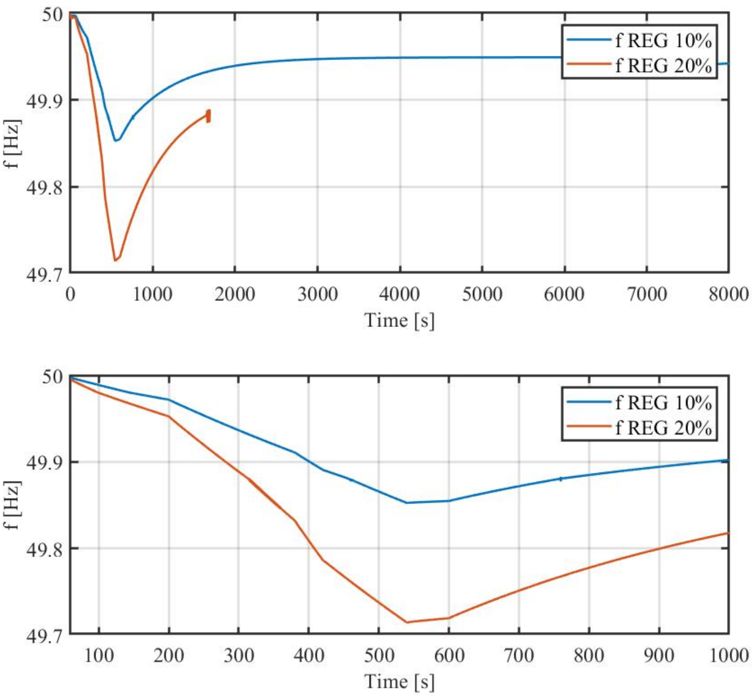

Figure 6.17: System's frequency after integration of BESS into the Kundur's 2 area grid

The initial drop is being covered by both conventional generation and energy storage, this can be verified on next Figure 6.18 and Figure 6.19, where it is visible that the powers of both assets rise when the generation from wind and solar is reduced. The simulation encounters instability for case when REG penetration level is equal to 20%. The frequency parameters are summarised, in Table 6.4, where it can be seen that the higher the penetration of REG the lower was the frequency nadir. Moreover, the time over which the lowest frequency point is achieved is shorter by 0,02 s for case with higher REG, for the conduced simulation.

Table 6.4: Frequency parameters of system including the BESS for decline and rise of REG output power

REG 10%			REG 20%		
f_{Nadir}	t_{fNADIR}	f_{ss}	f_{Nadir}	t_{fNADIR}	f_{ss}
49.8524	540.7917	49.9420	49.7142	540.7717	-

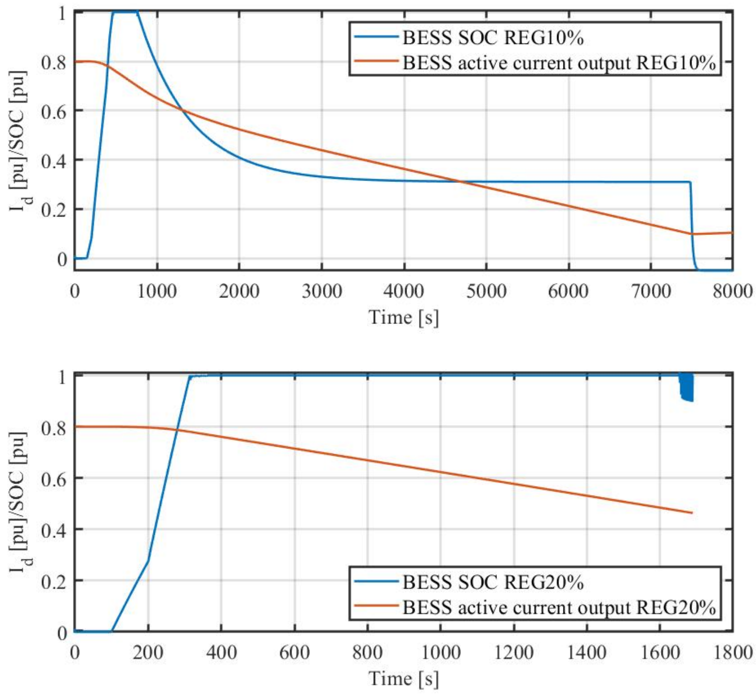

Figure 6.18: BESS state of charge with graph of output current a measure of active power output along the frequency plot of the system.

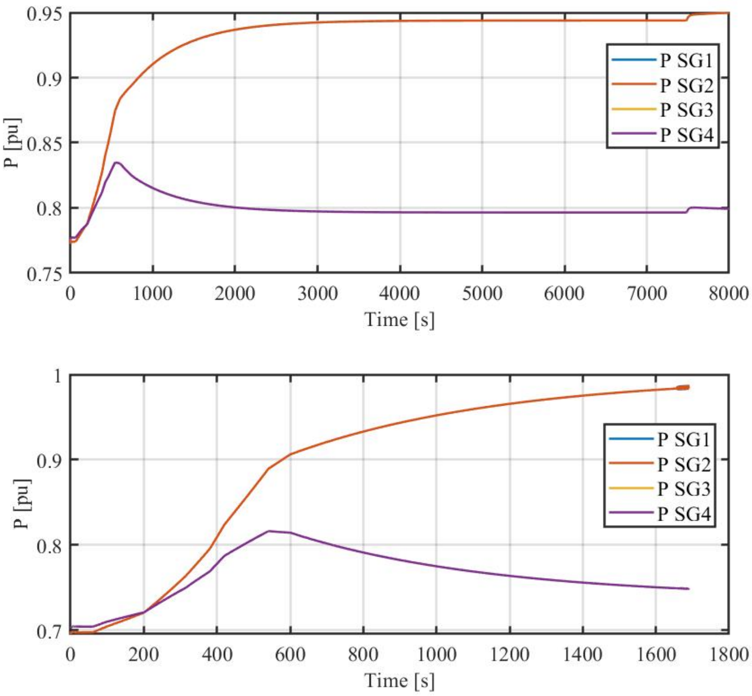

Figure 6.19: Powers of system generators during fall and rise of REG, after integration of BESS into the grid

The BESS's current linearly rises to maximum value and sustains for the necessary time while compensating for the lack of active power, see Figure 6.18. During that time the SOC is being reduced, while the calculated percentage output is sustained. Once either the frequency is back in acceptable range or the SOC is at the limit, the power output stops. Coordinated actions of BESS and control keep the frequency within a stable range, however the secondary control does not achieve it's goals. It has failed to bringing the frequency to target value of 50 HZ and to be able to send through the tile line the scheduled power. This is possibly connected tot he fact the BESS restrains the power send through the tie line and does not allow for ramp up of SG from area A. As a result final goals cannot be fulfilled.

When conducting simulations with increase or drop of load simulation tool DigSilentPowerFactory experienced instabilities during certain points of simulation, and lost credibility for the results and results themselves after a short period of time. The events themselves did not destabilise the model, but the number of interaction and perhaps the way the model is set up did not allow the solving engine to come up with results. The intended results would be an initial aid of frequency, with f_{Nadir} being closer to the nominal fequency compared to the cases when no quickly reacting resource was present in the grid. The impact the BESS should have is both magnitude wise and time wise, consequently increasing the stability and allow for further integration of REG or decommission of certain amount of capacity of conventional power plants.

Conclusion 7

Over the course of this project an understanding and knowledge regarding system inertial response, primary control, secondary control, issues with renewable energy sources and basics of battery energy storage implementations, were exercised and applied. Basics of direct programming in dynamic simulation language (DSL) in simulation tool DigSilent PowerFactory were understood and exercised. Dynamic generic models of the synchronous generators, loads and battery energy storage were studied, and applied according to this thesis purposes. Meaning simplifications to recieve the feedback from models only in the realm of frequency, to ensure understandable studies over frequency phenomenons that are induced.

The initial, crucial period of frequency excursion is highly dependent on the amount of system's inertia. This parameter is directly correlated to the amount of mass that is spinning, that is connected to the given grid. The tendency of replacement of conventional generation with REG reduces the energy that is accumulated in these masses and thus lowers the system's inertia, resulting in less stiff gird. In this work the REG is modelled as static generator and remains very stable unless specified differently, that can create a false sense of security.

Each and every event challenging the equilibrium between the generation and consumption of power has far more dire consequences. The sole role of the primary response, and reserves allocated for this purpose, is to stabilise the grid. In this work, the parameters for existing synchronous generators are defined by the grid and the grid's author. They are adjusted and developed for the purpose of simulations and directly determine the further behavior of the grid during frequency events. To create some amount of power in reserve the loads are adjusted in this thesis.

In the first few seconds, the frequency excursions need to be stopped, to be able to do that the reaction time of both sensing/control and the power source needs to be quick enough. The primary reserves once deployed are not withdrawn too quickly, so the frequency rebound will most commonly happen. Since the deployed power is not matching exactly the consumption the new steady frequency is achieved. This is a window during which most critical improvements can happen if strengthening these reserves. During the critical period when primary reserves attempt to save the system, the order of how much power in which part of the system is made, changes. Secondary control slowly reestablishes that order with some new values so that there is no mismatch. During that process, the power transfers, which may be crucial for other areas or grids, are also being taken into consideration and perhaps reestablished to the scheduled values. A large time scale (15min) allows for careful injection of additional power to both keep the balance and save money.

Typically after deployment of these two reserves the last reserve, the tertiary replaces the reserves deployed, over the course of hours to ensure system's flexibility to sustain another event. In this work, the tertiary reserve is not considered and the simulations are kept on a shorter time window and no replacement of the deployed reserves is simulated. When the renewable energy is being introduced into the grid, it is a goal to consume as much of it as possible. It is visible during the simulations that the more REG is present in the system the more impact it has on its stability. Since the REG is distributed over the grid, the conditions for them are different over the distance. However, in this work a simplification and thus a more challenging approach is taken, where all the REG is impacted the same in the entire system. The frequencies hit during severe drops of frequency are being hit faster and lower. That is the result of a necessary time delay for controls of existing reserves to satisfy the need for power balance. The BESS implementation in the industry is on both fronts, as a local support for the REG and as a grid scale asset to aid the stability. In this work only a narrow approach is analysed, where in a large system the frequency is supposed to be supported only at one point. A rule of thumb was utilised when deciding the BESS energy rating, however with utilisation of different battery technologies and creating BESS an asset strictly fitting the primary reserves could prove better results in terms of frequency stability. Conducted simulations are worst-case events and it can be argued that perhaps a step down in these is appropriate to financially reduce the challenge and yet still provide support in most cases.

An important aspect that can also be a limiting factor for the REG penetration level is voltage support, so studies combing both of these issues can yield more realistic results.

8 Future Work

Aspects that can be considered to progress the work from this thesis:

- Implementation of a more complex model of renewable resources. This would allow for more degree of freedom. It can be expected that the additional capabilities of REG would allow the grid to withstand greater power-load imbalances. The WTG could also be used to provide some minimal amount of inertia, it can be expected to result in reduced RoCof as well as yield better results for frequency excursions.
- Compilation of REG models with strategies utilised in the industry to ensure stability *e.g.* wind and solar day a head forecast or hourly predictions or a case where a BESS local to the REG source is implemented to ensure hourly output. That practise is expected to greatly reduce the risks connected with how volatile the REG is, and allow for more power to be supplied by it. Having a more predictable source of power could allow for better planning of the power share for the given time.
- Identification of how much more REG can be fitted to the given grid, with assumed and fulfilled stability conditions. It is suspected that the increase of power that can be quickly injected into the system can result in potential increase of REG penetration. The amount of power provided by a BESS would need to be able to in time arrest the frequency. It is expected there is a limit on how much BESS can be an asset that allows for more REGs due to the rapid changes in frequency that may become a limiting factor of the stability.
- identification of how much the reserves need to change when BESS is implemented. It is expected that the BESS allows for a reduction in *e.g.* primary reserves coming from synchronous generators. Subsequently, the secondary reserves need to be either increased or kept the same so ensure the frequency could be reestablished at the nominal value. It is expected that the tertiary reserves would need to increase in their total power, the trade of in this case being potential costs benefits in reduction of primary frequency reserves.

This work studies how battery energy storage system can be utilised as a quick-acting reserve and how it can improve conditions during frequency events. It is crucial to keep in mind that the application has to fit the actual grid, and this work is more of a proof of concept that an exemplary application. And by no means this work is able to fully cover the broad topic that is just ahead of future power systems.

Bibliography

[1] P. Kundur. *Power System Stability and Control*. McGraw-Hill, 1994.

[2] P. B. Eriksen, A. G. Orths, and V. Akhmatov. Integrating dispersed generation into the danish power system - present situation and future prospects. In *2006 IEEE Power Engineering Society General Meeting*, pages 7 pp.–, 2006.

[3] Michael Döring. Dealing with the 50.2 hz problem. `https://www.modernpowersystems.com/features/featuredealing-with-the-50.2-hz-problem/a`, January 2013.

[4] R. Brundlinger, T. Strasser, G. Lauss, A. Hoke, S. Chakraborty, G. Martin, B. Kroposki, J. Johnson, and E. de Jong. Lab tests: Verifying that smart grid power converters are truly smart. *IEEE Power and Energy Magazine*, 13(2):30–42, March 2015.

[5] Paul Gleeson, Aurecon. Hornsdale power reserve year 1 technical and market impact case study. `https://www.aurecongroup.com/markets/energy/hornsdale-power-reserve-impact-study`, 2018.

[6] V. Knap, S. K. Chaudhary, D. Stroe, M. Swierczynski, B. Craciun, and R. Teodorescu. Sizing of an energy storage system for grid inertial response and primary frequency reserve. *IEEE Transactions on Power Systems*, 31(5):3447–3456, Sep. 2016.

[7] Noel Cunniffe (EirGrid) Sheila Nolan (EirGrid) Hannele Holtinnen Caroline Bono Ye Wang Marie-Ann Evans Endika Urresti Padrón Wojciech Jaworski Przemyslaw Kacprzak Bernardo Silva Anastasios Oulis Rousis, Goran Strbac. D2.1 state of art literature review of system scarcities at high levels of renewable generation v1. Technical report, Program -H2020 COMPETITIVE LOW CARBON ENERGY 2017-2-SMART-GRIDS, 04 2018.

[8] Inertia: Basic concepts and impacts on the ercot grid. Technical report, ERCOT, 04 2018.

[9] J. Neely, J. Johnson, J. Delhotal, S. Gonzalez, and M. Lave. Evaluation of pv frequency-watt function for fast frequency reserves. In *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pages 1926–1933, March 2016.

[10] M.anisha Maharjan B.P. Bhattarai T.M. Hansen U. Tamrakar, D.ipesh Shrestha and R. Tonkoski. Virtual inertia: Current trends and future directions. *MDPI Applied Science*, 7(654), 2017.

[11] UCTE OH. Appendix1 - load-frequency control and performance. Technical report, National Renewable Energy Laboratory, 06 2004.

[12] UCTE OH. P1 – policy 1: Load-frequency control and performance [c]. Technical report, National Renewable Energy Laboratory, 03 2009.

[13] H. Holttinen, M. Milligan, E. Ela, N. Menemenlis, J. Dobschinski, B. Rawn, R. J. Bessa, D. Flynn, E. Gomez Lazaro, and N. Detlefsen. Methodologies to determine operating reserves due to increased wind power. In *2013 IEEE Power Energy Society General Meeting*, pages 1–10, July 2013.

[14] Erik Ela, Michael Milligan, and Brendan Kirby. Operating reserves and variable generation. Technical report, National Renewable Energy Laboratory, 09 2011.

[15] F. Fernández-Bernal, I. Egido, and E. Lobato. Secondary reserve limitation to wind power penetration in the spanish power system. In *2014 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, pages 147–152, 2014.

[16] ENTO-E. Technical requirements for frequency containment reserve provision in the nordic synchronous area - draft 2017. Technical report, ENTO-E, 06 2017.

[17] E. Agneholm, S. Meybodi, M. Kuivaniemi, P. Ruokolainen, J. Ødegård, N. Modig, and R. Eriksson. Fcr-d design of requirements – phase 2. Technical report, ENTO-E, 01 2019.

[18] T. Feehally, A. J. Forsyth, R. Todd, M. P. Foster, D. Gladwin, D. A Stone, and D. Strickland. Battery energy storage systems for the electricity grid: Uk research facilities. In *8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016)*, pages 1–6, 2016.

[19] Y. Hu, X. Cao, N. Schofield, and N. Zhao. Evaluation of bess management strategies for grid primary and enhanced frequency response. In *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, pages 2530–2537, 2019.

[20] I. Serban and C. Marinescu. Control strategy of three-phase battery energy storage systems for frequency support in microgrids and with uninterrupted supply of local loads. *IEEE Transactions on Power Electronics*, 29(9):5010–5020, 2014.

[21] S. Zhang, Y. Mishra, and G. Ledwich. Battery energy storage systems to improve power system frequency response. In *2014 Australasian Universities Power Engineering Conference (AUPEC)*, pages 1–5, 2014.

[22] S. M. Alhejaj and F. M. Gonzalez-Longatt. Impact of inertia emulation control of grid-scale bess on power system frequency response. In *2016 International Conference for Students on Applied Engineering (ICSAE)*, pages 254–258, 2016.

[23] H. Jo, J. Choi, K. A. Agyeman, and S. Han. Development of frequency control performance evaluation criteria of bess for ancillary service: A case study of frequency regulation by kepco. In *2017 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, pages 1–5, 2017.

[24] DIgSILENT GmbH. Digsilent powerfactory version 2019 user manual. `https://www.digsilent.de/`, 2018.

[25] José Luis Rueda Francisco M. Gonzalez-Longatt. *PowerFactory Applications for Power System Analysis*. Springer, Loughborough UK, 2014.

[26] DIgSILENT GmbH. Digsilent powerfactory application example battery energy sotring ssytem bess. `https://www.digsilent.de/en/faq-reader-powerfactory/do-you-have-an-application-example-for-a-battery-energy-storage-system-bess.html`, 2020.

[27] Somboon Nuchprayoon. Ramping behavior analysis of ground mounted solar pv generation in mae hong son, thailand. In *2018 5th International Conference on Electric Power and Energy Conversion Systems (EPECS)*, pages 1–5, 2018.