Master Thesis

GRID FREQUENCY STABILITY STUDY

Prepared at: Summer Semester 2014
Submitted by: Mohd Firdaus bin Mohd Ab Halim
Student ID: 803966

SUPERVISOR 1: PROFESSOR MIKE ZEHNER
SUPERVISOR 2: PROFESSOR DR. ING MARTIN NEUMAIER
AUTHOR DECLARATION

I hereby declare that the project entitled "GRID FREQUENCY STABILITY STUDY" submitted to the University of Applied Science Rosenheim is a record of an original work done by me under the guidance of Prof. Mike Zehner and Prof. Martin Neumaeir. This project is submitted in the partial fulfillment of the requirement for the award of the degree of Master Electrical/Electronic and Information Technology. The result embodied in this thesis has not been submitted to any other Institution for the award of any degree.

Mohd Firdaus bin Mohd Ab Halim
ID: 803966

Place and Date
Abstract

This thesis is focus on the behavior of the electrical grid frequency in European country. There are many researches’ conducted dedicated into maintaining the electricity supply versus the demand through penetration of more renewable energy, but this thesis will be looking into how does the grid frequency behaves in day to day and what causes it to fluctuates or is there any kind of signal pattern that can be analyzed and perhaps use it to provide more information towards the grid stability control. This research reviews the strategy of managing the electrical grid stability adopted the European Energy authority and other method employed by other modern country, for example the United States or The United Kingdom. A frequency measurement device is designed in our own facility to gather as much data as time permit because there is no raw grid frequency data published openly by any researcher thus far. The studies also covers factor contributes to the grid instability, future electricity model, various frequency control techniques and case study, from the journal and conference paper. Towards the end of the study, multiple frequency plot will be presented and discussed so that it can provide valuable the authorize institution, to maintain network grid stability.
ACKNOWLEDGEMENT

I have taken enormous efforts in this thesis. However, it would be difficult without the kind support and help of many individuals and organizations. I would like to extend my sincere thanks to all of them.

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Very special thanks to Prof. Dr.-Ing. Simon Schramm, whom had shared his frequency data for the purpose of reference data for our measurement validation.

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# Table of Content

## Abbreviation and acronyms

vii

## List Of Tables And Figures

ix

*Figures* ix

*Table* xi

## Chapter 1 Introduction

1

## Chapter 2 Thesis Planning

4

2.1 Gantt Chart 4

2.2 Explanation 4

## Chapter 3 Grid Frequency Regulation

5

3.1 Overview of European Transmission System 5

3.2 North America (Texas) Grid Frequency Regulation 5

3.3 Grid Frequency Regulation Issues 6

3.4 Renewable Energy Scenario in Germany 8

3.5 Effect of Wind Turbine and Solar Power Towards Grid Stability 9

3.6 ENERGY Trading 12

## Chapter 4 Dynamic Demand

14

4.1 World Electricity Demand Pattern 14

4.2 Frequency Adaptive Power Energy Reschedules (FAPER) 14

4.3 Dynamic Demand Technology in UK 15

4.4 Dynamic Demand Home Appliance as Frequency Regulation 16

## Chapter 5 Alternatives Method in Stabilizing Power Grid

18

5.1 Smart Metering 18

5.2 Rolling Blackout or Load Shedding 18

5.3 Energy Storage as Frequency Regulation 19

## Chapter 6 Development of the Grid Frequency Measurement Device

22

6.1 Literature about Grid Frequency Measurement 22
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Work done</td>
<td>69</td>
</tr>
<tr>
<td>8.2 Analysis outcome</td>
<td>70</td>
</tr>
<tr>
<td>Chapter 9 REFERENCE</td>
<td>74</td>
</tr>
<tr>
<td>Chapter 10 Appendices</td>
<td>77</td>
</tr>
<tr>
<td>A. Sketches to perform Analog Read on Arduino pin 0</td>
<td>77</td>
</tr>
<tr>
<td>B. Matlab program code to generate the sampling voltage graph</td>
<td>78</td>
</tr>
<tr>
<td>C. Sketches to Perform Frequency Measurement with Improved Accuracy Method</td>
<td>78</td>
</tr>
<tr>
<td>D Frequency Distribution Tables for Figure 7-11</td>
<td>80</td>
</tr>
<tr>
<td>E Frequency Distribution Tables for Figure 7-15</td>
<td>81</td>
</tr>
<tr>
<td>F Frequency Plot from 28 July to 9 August</td>
<td>82</td>
</tr>
<tr>
<td>F1 MINIMUM Hourly Frequency</td>
<td>82</td>
</tr>
<tr>
<td>F2 maximum Hourly Frequency</td>
<td>82</td>
</tr>
<tr>
<td>G Gnu Plot Code for carpet plot</td>
<td>83</td>
</tr>
</tbody>
</table>
## Abbreviation and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog Digital Converter</td>
</tr>
<tr>
<td>AUFLS</td>
<td>Automatic Under-Frequency Load Shedding</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
</tr>
<tr>
<td>DDC</td>
<td>Dynamic Demand Control</td>
</tr>
<tr>
<td>DEC</td>
<td>Decimal</td>
</tr>
<tr>
<td>DG</td>
<td>Distribution Generation</td>
</tr>
<tr>
<td>EEPROM</td>
<td>Electrically Erasable Programmable Read-Only Memory</td>
</tr>
<tr>
<td>EEX</td>
<td>European Energy Exchange</td>
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<tr>
<td>EMS</td>
<td>Energy Management System</td>
</tr>
<tr>
<td>ENTSO-E</td>
<td>European Network Transmission System Operator For Electricity</td>
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<tr>
<td>EPEX</td>
<td>European Power Exchange</td>
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<tr>
<td>ERCOT</td>
<td>Electric Reliability Council Of Texas</td>
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<tr>
<td>ESB</td>
<td>Electricity Supply Board</td>
</tr>
<tr>
<td>FAPER</td>
<td>Frequency Adaptive Power Energy Reschedules</td>
</tr>
<tr>
<td>FCDM</td>
<td>Frequency Response By Demand Management</td>
</tr>
<tr>
<td>FDRS</td>
<td>Frequency Disturbance Recorders</td>
</tr>
<tr>
<td>FNN</td>
<td>Forum Network Technology / Network Operation</td>
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<tr>
<td>FTP</td>
<td>File Transfer Protocol</td>
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<tr>
<td>GW</td>
<td>Giga Watt</td>
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<tr>
<td>IDE</td>
<td>Integrated Development Environment</td>
</tr>
<tr>
<td>KV</td>
<td>Kilo Volt</td>
</tr>
<tr>
<td>mHz</td>
<td>mili Hertz</td>
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<tr>
<td>MVA</td>
<td>Mega Volt Ampere</td>
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<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<tr>
<td>REG</td>
<td>Regulation Reserve</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control And Data Acquisition</td>
</tr>
<tr>
<td>SGM</td>
<td>Simplified Grid Model</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
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<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>ee) TSO</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>ff) UCTE</td>
<td>Union For The Co-Ordination Of Transmission Of Electricity</td>
</tr>
<tr>
<td>gg) VAC</td>
<td>Voltage Alternating Current</td>
</tr>
<tr>
<td>hh) VDE</td>
<td>Association for Electrical, Electronic &amp; Information Technologies</td>
</tr>
<tr>
<td>ii) WTG</td>
<td>Wind Turbine Generator</td>
</tr>
</tbody>
</table>
LIST OF TABLES AND FIGURE

FIGURES
Figure 1-1 Map of European System Operator by Group .................................................. 1
Figure 1-2 EU27 Electricity production distributed by source ........................................... 2
Figure 1-3 Number of incident where the frequency if beyond the normal operation 49.9Hz to 50.1Hz. Source: Statnett ................................................................. 3
Figure 2-1 Subject code 9591 Master Thesis Schedule ..................................................... 4
Figure 3-1 Regulating Reserve Classification versus response time ..................................... 5
Figure 3-2 SCADA/EMS System Block Diagram ............................................................. 6
Figure 3-3 Grid Tie-Inverter Block Diagram ....................................................................... 7
Figure 3-4 Solar PV growth in Germany by year ................................................................... 8
Figure 3-5 Frequency deviation in the evening from 2002-2008 ........................................ 9
Figure 3-6 typical power output distribution of wind mill driven at optimum location (blue) and standard location source [10] (red) .................................................. 10
Figure 3-7 System frequency dynamics when WTGs participate in system frequency regulation function source [10] ........................................................................................................... 10
Figure 3-8 Frequency Data of 15% PV penetration at two SGM1 (slow) and SGM2 (fast) source [12] ......................................................................................................................... 10
Figure 3-9 Frequency Data of 30% PV penetration at two SGM1 (slow) and SGM2 (fast source [12] ......................................................................................................................... 10
Figure 3-10 Generation unit behavior in the schedule time frame source Transelectrica ......... 13
Figure 3-11 Power system market flows of operation source University of Stuttgart ........... 13
Figure 4-1 FAPER System Overview .................................................................................. 15
Figure 4-2 Operation Strategy of Dynamically Controlled Refrigerator Source [18] ............ 16
Figure 4-3 Comparison simulated system frequency regulates by dynamic demand versus spinning reserve Source [18] .......................................................................................... 16
Figure 5-1 Frequency Deviation without Energy Storage Source [21] ................................. 20
Figure 5-2 Figure Frequency Deviation with Energy Storage Source [21] ........................... 20
Figure 5-3 Typical Flywheel main component ..................................................................... 21
Figure 6-1 FDR System Block Diagram Source [23] ............................................................ 23
Figure 6-2 FDR Equipment ............................................................................................... 23
Figure 6-3 Schematic diagram to produce desired output voltage ....................................... 25
Figure 6-4 Voltage signal of desired output voltage .......................................................... 25
Figure 6-5 Setup for trial measurement ................................................................................ 26
Figure 6-6 Voltage versus n th number of sample .............................................................. 27
Figure 6-7 Analog input versus n th number of sample ...................................................... 27
Figure 6-8 Two signal with same sample size with different points of reading start ............ 29
Figure 6-9 Signal with larger sample size ............................................................................ 29
Figure 6-10 Flow chart of frequency measurement technique for Arduino board ................ 30
Figure 6-11 Zero-crossing method slow sampling rate ...................................................... 31
Figure 6-12 Zero-crossing method slow sampling rate ...................................................... 32
Figure 6-13 GoBetwin0 Window Interface ........................................................................ 34
Figure 6-14 Data files format in CSV file .......................................................................... 35
Figure 6-15 Data files format in text file ........................................................................... 35
List of Tables and Figures

Figure 6-16 Hardware Setup for Frequency Measurement.......................................................... 36
Figure 6-17 Excel graph with data from Arduino versus Screenshot graph from Netfrequenz.info website.......................................................................................................................... 36
Figure 6-18 Excel graph with data from Arduino 1HOUR versus Screenshot graph from Netfrequenz.info website.................................................................................................................. 37
Figure 6-19 Scatter Plot Comparison Arduino data(blue) and Reference data (red) 26 July 2014 .............................................................................................................................................. 38
Figure 6-20 Scatter Plot Comparison Arduino data(blue) and Reference data (red) 27 July 2014 .............................................................................................................................................. 38
Figure 6-21 Frequency at 16/6/2014 2:36PM   Figure 6-22 Frequency at 16/6/2014 4:58PM. ................................................................................................................................. 39
Figure 6-23 Screenshot of Processing program to Log data to file................................................. 40
Figure 6-24 Screenshot data captured from processing................................................................. 41
Figure 6-25 Frequency data 27/6/2014 3:27PM   Figure 6-26 Frequency data 27/6/2014 6:24PM.................................................................................................................................................. 41
Figure 6-27 Frequency data at 27/6/2014 9:22PM ...................................................................... 42
Figure 6-28 Frequency data at 30/6/2014 11:37AM .................................................................. 42
Figure 7-1 Frequency Graph during Earth Hour day and a week before...................................... 46
Figure 7-2 Carpet Plot of frequency deviation from nominal values in July 2011 to Jan 2012 posted 10.2.2012........................................................................................................................... 47
Figure 7-3 Carpet Plot of Frequency deviation from nominal values in the morning Figure 7-4 Carpet Plot of Frequency deviation from nominal values in the late evening.............................................. 48
Figure 7-5 Quality of Grid Frequency by Swissgrid ..................................................................... 49
Figure 7-6 Frequency versus time from 2003 to 2010- Swissgrid................................................ 50
Figure 7-7 Frequency variation versus time from 2003 to 2010- Swissgrid................................. 51
Figure 7-8 Simulated Frequency Deviation for Different Amount Of Secondary Reserve Source Red Eléctrica de España (REE)......................................................................................... 52
Figure 7-9 Simulated Frequency Deviation for Different Time Constant Source Red Eléctrica de España (REE).................................................................................................................. 53
Figure 7-10 Simulated Frequency Deviation for Different Max Gradient Source Red Eléctrica de España (REE).................................................................................................................. 54
Figure 7-11 One Minute Graph 12:53PM to 12:54PM................................................................. 54
Figure 7-12 One Minute Graph 12:54PM to 12:55PM................................................................. 54
Figure 7-13 One Minute Graph 12:55PM to 12:56PM................................................................. 55
Figure 7-14 Frequency Distribution of all three data groups......................................................... 55
Figure 7-15 15Minutes Graph 12:52PM to 1:12PM................................................................. 56
Figure 7-16 15 Minutes Graph 1:12PM to 1:31PM................................................................. 56
Figure 7-17 15 Minutes Graph 1:32PM to 1:46PM................................................................. 57
Figure 7-18 Frequency Distribution Combination of all three data group.................................... 57
Figure 7-19 Line plot of grid frequency at 15:30PM to 16:30PM................................................. 58
Figure 7-20 Average, Max and Min of Frequency Data versus Time (decimal)......................... 59
Figure 7-21 Average, Max and Min of Frequency Data versus Time (decimal)......................... 59
Figure 7-22 Average, Max and Min of Frequency Data versus Time (decimal)......................... 60
Figure 7-23 Frequency Distributions an Hour Average Combination of all three data groups... 60
Figure 7-24 Frequency Hourly Average 28 Jun to 9Jul............................................................. 61
Figure 7-25 Frequency 3D Hourly Average 5 July to 9 July ......................................................... 62
Figure 7-26 Frequency Hourly Deviation (50Hz -Average Hz) 28 July to 9 August............... 62

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List of Tables and Figures

Figure 7-27 Phelix volume traded and Frequency Deviation versus time at 10 July 2014 .......... 63
Figure 7-28 Phelix volume traded and frequency deviation versus time at 11 July 2014 .......... 64
Figure 7-29 Frequency 6 Minute Average July to 9 August 06:00AM to 12:00PM ..................... 64
Figure 7-30 Frequency 6 Minute Average 28 July to 9 August 20:00PM to 24:00PM ............. 65
Figure 7-31 Box Plot of 6 minutes data at early morning ......................................................... 66
Figure 7-32 Box Plot of 6 minutes data at late evening ............................................................... 66
Figure 7-33 Frequency Distribution Early Morning ................................................................. 67
Figure 7-35 Frequency Distribution Early Morning ................................................................... 67
Figure 7-34 Frequency Distribution Late Evening ................................................................. 68
Figure 7-36 Frequency Distribution Late Evening ................................................................... 68
Figure 8-1 Frequency Deviation Carpet Plot for 32 days ................................................................. 72
Figure 8-2 Carpet Plot Frequency Deviation from year 2011 to year 2014 .............................. 73

TABLE
Table 3-1 Frequency Statistic for Case 1 Source [12] ................................................................. 12
Table 3-2 Frequency Statistic for Case 2 Source [12] ................................................................. 12
Table 6-1 Arduino clock rate and the number of sample to reach 50Hz .................................... 28
Table 6-2 Possible result using 116 microseconds Clock Rate ................................................... 30
Table 6-3 Analog data of 116 sampling rate .............................................................................. 33
Table 6-4 Expected Result from Improved Accuracy ............................................................... 33
Table 6-5 Error between Arduino Data versus reference data ............................................... 39
Table 7-1 Rate of frequency prediction success in percentage Source [27] ............................... 45
Table 7-2 Summary of Statistical Data of 1 Minute ................................................................. 55
Table 7-3 Summary of Statistical Data for 15Minutes plot ..................................................... 57
Table 7-4 Sample of average, maximum, minimum and time ................................................. 59
Table 7-5 Statistical Data of Distribution Fit ........................................................................... 67
Chapter 1 INTRODUCTION

There are multiple power plants connected to the network grid in general to meet the consumer demand. In Europe, some countries are sharing the same grid as it is economical and practically could increase grid stability by having alternatives energy source if unexpected event occurs. The European Network of Transmission System Operator for Electricity (ENTSO-E) was formed in 2008 to minister the network grid operation and development plan for EU country. ENTSO-E is divided into regional groups, and each member is responsible to monitor and manage the supply and demand of their respective area. Refer to Figure 1-1 to see the region group distribution across Europe continent.

![Map of European System Operator by Group](http://epp.eurostat.ec.europa.eu/)

**Figure 1-1 Map of European System Operator by Group**

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Electricity generation around the world still largely rely on fossil fuel (natural gas, coal) as the energy source because it is the cheapest way to produce electricity. According to European Commission Eurostat up to November 2012, the electricity production distributed by source, 52% of the electricity comes from conventional thermal, 27%, 12%, 6% and 3% respectively comes from nuclear, hydro, wind and other sources [1]. The electricity transmission through the grid therefore largely influenced by the power generated through thermal energy. This thermal energy heats the water in a structured piped around the boiler to create high pressure steam. The steam then drives the turbine blades which connected to the turbine generator which converts mechanical energy to an AC electrical energy. A transformer is used to convert this generated electricity to a higher voltage AC and connected to the grid. The inertia of a turbine generator on the other hand refers to the turbine generators external force to change its speed of rotation. To change the speed of the turbine generator, the plant operator should either add more energy (increase the speed) or remove the energy (decrease the speed) of the turbine. Synchronous generator used in power plant means the generator is locked into synchronization with the grid frequency its’ connected [2].

Electricity produced at the power plant is step up to a high voltage (120 KV or higher) to minimize the loss of energy especially at a long distance transmission. The energy available on the grid must closely match the load or demand. More power on the grid would result in loss of effort because energy on transmission line cannot be stored while insufficient power would result in power failure on state or even national level if it is not being managed properly. Power plant is geographically distributed in distribution system and the operation of

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2 http://epp.eurostat.ec.europa.eu/
Powering up or shutting down due to any reason has to be carefully studied to ensure the grid stability. There are two types of power regulation, voltage-based regulation and frequency-based regulation. In mesh networks, voltage-based regulation is not suitable due to the complexity of parameters reconfiguration each time a new plant is introduced. Therefore, frequency-based regulation is used in all power plants to control the generation amount to match the demand. The drop in frequency at the grid indicates that the demand is higher than the supply, hence signaling the plant operator to speed up the generator. Hopefully, the study that we journeyed could help to give beneficial information to the power company and grid operator to create a better strategy to control the grid frequency. Figure 1-3 provides us with a very good indicator that how the frequency deviation increases its trend between year 1995 to year 2010 and how important this research is to the community as a whole.

Figure 1-3 Number of incidents where the frequency is beyond the normal operation 49.9Hz to 50.1Hz.
Source: Statnett³

³ http://www.statnett.no/en/
Chapter 2 THESIS PLANNING

2.1 GANTT CHART

Figure 2-1 Subject Code 9591 Master Thesis Schedule

<table>
<thead>
<tr>
<th>TASK NAME</th>
<th>MONTHS</th>
<th>DURATION IN WEEKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. LITERATURE REVIEW ON GRID FREQUENCY CONTROL</td>
<td>Mar</td>
<td>17</td>
</tr>
<tr>
<td>2. LITERATURE REVIEW ON FACTORS CONTRIBUTING TO GRID FREQUENCY FLUCTUATION</td>
<td>April</td>
<td>24</td>
</tr>
<tr>
<td>3. MEASUREMENT SYSTEM DESIGN AND TROUBLESHOOTING/DEBUGGING</td>
<td>April</td>
<td>7</td>
</tr>
<tr>
<td>4. MEASUREMENT SYSTEM IMPLEMENTATION</td>
<td>May</td>
<td>21</td>
</tr>
<tr>
<td>5. DATA GATHERING</td>
<td>June</td>
<td>28</td>
</tr>
<tr>
<td>6. LITERATURE REVIEW ON PAST ISSUES AND ANALYSIS METHOD</td>
<td>Jul</td>
<td>18</td>
</tr>
<tr>
<td>7. ANALYZING GRID FREQUENCY DATA</td>
<td>July</td>
<td>11</td>
</tr>
<tr>
<td>8. REPORT &amp; PRESENTATION</td>
<td>August</td>
<td>12</td>
</tr>
</tbody>
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2.2 EXPLANATION

The thesis planning is divided into eight major steps. As the reader can see in Figure 2-1 Master Thesis Schedule, some of the tasks are overlapping each other for us to be as efficient as possible. Some minor steps were not included inside the chart such as discussion with the supervisor, equipment sourcing, purchasing process and literature on other topics related to grid frequency analysis.

The whole project duration is 21 weeks or 5 months. The maximum period for this subject is 6 months but we managed to pull it a month earlier. It does not mean that the project is less quality; instead it is far more scientific than what we have planned before. Most of the working hours went to measurement device construction and data analysis. At least 4 hours a day spent on the laboratory and another 2 hours from home. The subject itself weight 27 credit points which is equivalent to 27 hours in a week.
Chapter 3 GRID FREQUENCY REGULATION

3.1 OVERVIEW OF EUROPEAN TRANSMISSION SYSTEM

The "Union for the Co-ordination of Transmission of Electricity" (UCTE) for continental Europe had come out with continental Europe Operational Handbook on frequency control and regulating reserve. The Operational Handbook can be obtained online from the UCTE main website and the sole purpose is to keep balance between demand and supply of the electricity. It comprises of guideline to the Transmission System Operator (TSO), electricity generation companies and relevant stakeholder. UCTE grid is the largest synchronous electric grid in the world with 50 Hz mains frequency [3]. Three stages of frequency control are defined in Policy P1 of the operational handbook. Each has its own scope of operation such as response time, frequency deviation limit and megawatt amount [4].

![Graph 3-1: Regulating Reserve Classification versus response time](image)

*Figure 3-1 Regulating Reserve Classification versus response time.*

3.2 NORTH AMERICA (TEXAS) GRID FREQUENCY REGULATION

In Texas United State, The Federal Energy Regulatory Commission was given the authority to ensure that the bulk power system is operated under mandatory reliability standard and

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*Asko Vuorinen, "Planning of Optimal Power System" Finland 2007*
cyber security protection for the bulk power system [6]. It employs similar frequency control
guideline as published in Operational Handbook by UCTE. The deviation of the frequency at
the initial stage is managed by the Primary Frequency Response governed by Turbine
Governor, generally delivered completely within 12 seconds to 14 seconds. Secondary
Frequency Response handled by Electric Reliability Council of Texas (ERCOT) which is a
single balancing authority. The control is done through Automatic Generation Control (AGC)
which is part of SCADA/EMS (Supervisory control and data acquisition/Energy Management
System/Generation Management System). Regulation Reserve (REG) operates in two ways.
REG UP Reserve increases the generation by controllable load reduction while REG DOWN
Reserve decreases the generation by controllable increase load.

![Figure 3-2 SCADA/EMS System Block Diagram](image)

3.3 GRID FREQUENCY REGULATION ISSUES

Most of the electrical powers supplied to the grid are generated by synchronous generators;
hence controlling the power supply using frequency regulation is the ideal way to go. As of
today, we are aware that the trend of producing electricity is greater towards an alternative
and clean energy which could trigger some concern towards the current frequency regulation
method of controlling the balance of the grid. Alternatives sources such as wind generator
and photovoltaic are connected to the grid via grid-tie inverter. The grid-tie inverter controls
the frequency, phase angle and voltage value of the alternative source so that it matches the

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5Arthur Gardiner, “Frequency Control” 27th ERCOT Region Operations Training Seminar, Texas Reliability
Entity, May 2011
main grid parameters. This problem may not be occurring at any time soon, but as more grid-tie inverter source increases, the stability of the grid frequency may be affected one day.

There have been many researches about the effect of grid-tie inverter on the grid stability. One of the notable researches is using Matlab/Simulink to simulate the condition of the grid as more and more source coming from the grid-tie inverter. The simulation of the distributed generation was done through a simple single phase surrogate model. The relationship between grid phase and the corresponding change in the inverter voltage were determined through multiple derivation and calculated assumption. The results from the simulations are obtained over a full exploration of parameter space via simplified models. The study conclude that the grid-tie inverter does not affect the frequency of the grid, however it only applicable if the system allows an acceptable steady state solution Nevertheless, as the inverter continues to supplies a larger percentage of the load, the power factor of the distribution system as seen by the grid will decrease as long as there is a reactive component on the load that is not steady state. Typically any power factor above 0.9 from the grid-ties inverter is acceptable to a utility, although this varies based on local regulations. In cases such as this, power factor restrictions might define the practical limits of inverter penetration [6]. It is hope that more research will be done in this field not only to understand the effect of the grid tie inverter, but also to extend the use of the technology as frequency regulation.

![Grid Tie-Inverter Block Diagram](image)

*Figure 3-3 Grid Tie-Inverter Block Diagram*®

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Grid Frequency Regulation

3.4 RENEWABLE ENERGY SCENARIO IN GERMANY

In the year 2000 to 2005, photovoltaic (PV) power plant operated in a small number. The requirement during that particular period for a low voltage generation plant connected to the network grid, it must switch off immediately if the system frequency increased to 50.2 Hz. After several years of economic booming in Germany, more PV plant were installed and connected to the network grid reaching more than 14 GW in 2010. Figure 3-4 shows the growth of solar PV energy in Germany. Since the old requirement could potentially lead to disconnecting large capacity of power when the grid frequency reaches 50.2 Hz, VDE/FNN transitional agreement was introduced in 2010 [8]. Based on the requirement in general, the existing plant and new plant had to retrofit according to the recommended setting of VDE/FNN (Association for Electrical Electronic & Information Technologies)/Forum network technology / network operation). A reconnection of the PV power plant after disconnection procedure is defined in the application guide Option 1 and 2, and it can be implemented via inverter’s firmware update or changing Electrically Erasable Programmable Read-Only Memory EEPROM. Option 3, in the other hand can be implemented through parameter change, which requires the change of software parameter; in which the distribution generation (DG) has to be disconnected from the network in order to implement Option 3.

![Increase of solar PV in Germany](image)

*Figure 3-4 Solar PV growth in Germany by year*

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7Jens. C. Boemer et all, “Overview of German Grid Issues and Retrofit of Photovoltaic Power Plants in Germany for the Prevention of Frequency Stability Problems in Abnormal System Conditions of the
An emergency discussion was taken place in August 2008 by UCTE ad-hoc group due to rising concern on the grid frequency variation increases in the evening when no more PV energy is being harness. Figure 3-5 shows the rising trend of frequency variation by comparing different years, represented by colors. The normal operation of the UCTE grid is between 49.95 Hz to 50.05 Hz. The figure below shows that the grid frequency operates within the normal boundary most of the times during evening until 2004. In 2005 onwards, it the frequency variation goes beyond the normal boundary down to 49.93 Hz during evening. The development of the electricity markets in the European countries in combination with the continuous increase in market participant and its activities has its consequences. The grid was experiencing more and more frequency deviation and at higher peak swings around the change of the full hours, specifically at times when tariffs and schedules are being changed.

![Figure 3-5 Frequency deviation in the evening from 2002-2008](image)

### 3.5 Effect of Wind Turbine and Solar Power Towards Grid Stability

Unlike conventional power plant, wind turbine and solar photovoltaic produce variable output. During windy day and sunny day both power plant respectively will have higher output peak. The power output is sometimes predictable and sometimes way off than what is expected based on the change of the weather. The variability output impact the reliability of the power supplied to the grid. Even known to have a reliability issue, more wind turbine is installed across the world due to its environmental friendly features. This situation also impacts the conventional power plant, where it has to ramp up or ramp down its generation whenever the supply from wind and solar power plant is not meeting the expected output.


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The worst case scenario would be when the wind or solar power plant reaches peak for a small period of time the conventional power plant has to reduce its generation reaches a point where it has to be shutdown or lost its productivity. The scenario would be very uneconomical for the conventional power plant as the fuel will cost more during start up, not to mention the lost made from not selling the electricity. Figure 3-6 shows the differences in power output produce by wind turbine generator (WTG) at optimum location and standard location. It shows how big is the effect of the location of installation of the wind turbine on its output.

Figure 3-6 typical power output distribution of wind mill driven at optimum location (blue) and standard location source [10] (red).

Figure 3-7 System frequency dynamics when WTGs participate in system frequency regulation function source [10].

Figure 3-7 shows the simulation of the effect of wind turbine generator towards the grid frequency as the WTG’s sources increase in the network grid [10]. The simulation uses a test system of 100 MVA turbo generators as a based power system and a wind farm model of 67 MVA Double Feed Induction Generator where the data was taken from [11].

Figure 3-8 Frequency Data of 15% PV penetration at two SGM1 (slow) and SGM2 (fast) source [12]

Figure 3-9 Frequency Data of 30% PV penetration at two SGM1 (slow) and SGM2 (fast source [12]

As we can see at 40% load supplied by the WTG, the grid frequency dropped almost 0.4 Hz
at 50% from 67 MVA\(^9\). The frequency dropped below than 49.5 Hz at 0% or when no power produced from the WTG. Even though frequency regulation takes only 15 second to compensate the supply lost, it will be devastated to even think what happen to the whole system when the wind energy peaks and dip every now and then. The author concludes that it is not technically sound to even consider wind turbine to replace the conventional thermal generator for grid frequency regulation.

Another study in the United States was also conducted regarding the impact of renewable energy, specifically on the increased of PV penetration on the 60 Hz grid frequency. The author used two Simplified Grid Model (SGM) slow response generator (in Western North America) and fast response generator (such as in Hawaii), to resemble the actual grid at distribution level, without spinning reserve. The reason was to really evaluate the impact of the PV on the grid frequency in the order of seconds. Two concentrated PV penetration values were studied, Case 1-15% and Case 2-30%. The result of 9000 second of simulation with a variable solar insolation is shown in Figure 3-8 and Figure 3-9. Table 3-1 and 3-2 shows the statistic of the grid frequency data [12]. The study also touched on other related issues on the PV, but we will only focus on the frequency variation from the two level of PV penetration.

It appears that the minimum frequency has dropped to another 0.43 Hz while maximum frequency increased 6.67 Hz from Case 1 to Case 2 on SGM1. Even thought better statistic simulated for SGM2, it still shows that when PV penetration increases, the grid frequency will fluctuates higher.

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\(^9\)With no wind share, the increased load at 5s resulted in a fall in frequency from 50 to 49.48 Hz whereas with 50% wind presence, the frequency falls to 49.24 Hz. Likewise, during the load change at 15s, the frequency rises to 50.11 Hz without wind support and to 50.18 Hz with wind support [12].
### Grid Frequency Regulation

#### Table 3-1 Frequency Statistic for Case 1 Source [12]

<table>
<thead>
<tr>
<th>Minimum Frequency (Hz)</th>
<th>Maximum Frequency (Hz)</th>
<th>Average Frequency (Hz)</th>
<th>Standard Deviation (Hz)</th>
<th>RMSE (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGM1</td>
<td>59.57</td>
<td>60.67</td>
<td>60.03</td>
<td>0.128</td>
</tr>
<tr>
<td>SGM2</td>
<td>59.97</td>
<td>60.33</td>
<td>60.09</td>
<td>0.084</td>
</tr>
</tbody>
</table>

#### Table 3-2 Frequency Statistic for Case 2 Source [12]

<table>
<thead>
<tr>
<th>Minimum Frequency (Hz)</th>
<th>Maximum Frequency (Hz)</th>
<th>Average Frequency (Hz)</th>
<th>Standard Deviation (Hz)</th>
<th>RMSE (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGM1</td>
<td>59.14</td>
<td>67.32</td>
<td>60.32</td>
<td>0.636</td>
</tr>
<tr>
<td>SGM2</td>
<td>60.06</td>
<td>60.79</td>
<td>60.32</td>
<td>0.167</td>
</tr>
</tbody>
</table>

### 3.6 ENERGY TRADING

Electrical energy trading in European country is managed by European Energy Exchange that operates in Leipzig, Germany\(^\text{10}\). The trading activity has a significant impact towards the network grid stability and is an important part of the demand balancing system\(^\text{11}\). An imbalance demand and generation can occur in a short period of time during settlement of the trading. Figure 3-10 shows the small mismatch between demand and generation due to dynamic behavior of the generation. An illustration of how the power system market operates is shown in block diagram, Figure 3-11. A case study further discuss about the issues related to the frequency deviation and energy trading is discussed in Chapter 7.5

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\(^{10}\) http://en.wikipedia.org/wiki/European_Energy_Exchange

\(^{11}\) Looking at the morning hours of the day, the demand side shows a forecasted increasing behaviour of the load. Due to the market rules, the demand side needs to order 1-h block based products to cover this load. The generator side generates the ordered amount of energy following the 1-h-schedules as tight as possible to reduce imbalance energy costs. Between the continuously increasing load and the stepwise increasing generation a power imbalance occurs. After the change of the hour, there is a large power surplus turning into a power deficit as the load increases continuously [31]