SRI LANKAN POWER SYSTEM FREQUENCY STABILITY WITH FAST GROWING RENEWABLE POWER ADDITION

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Department of Electrical Engineering

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Abstract

World is moving forward to a renewable energy base era while retiring conventional thermal energy generation. With this world trend in renewable energy, Sri Lankan power sector has also planned to integrate more renewable energy into the Sri Lankan power system within recent years.

This research analyzes the effect of renewable energy integration in small island mode power systems like Sri Lanka with actual measured data. Impact of the intermittent nature of the renewable power and the replacement of conventional power plants with non-inertia supportive renewable plants are mainly focused in this research work.

This research demonstrates renewable power variations in Sri Lanka and subsequent power system stability with these variations. Simulation results indicate that power system is not stable with high share of renewable power integration. Combined operation of selected conventional power plants and renewable power plants has been proposed to stabilize the power system. Technological improvements of the renewable plants to mitigate adverse effects were also addressed during simulations.

Keywords: Renewable energy sources, Wind power, Solar power, Power system stability, Frequency control, Intermittency, PSS/E simulation

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Y.M.T.A. Sandamal

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List of Abbreviations

Abbreviation	Description
LTGEP	Long Term Generation Expansion Plan
CEB	Ceylon Electricity Board
PSS/E	Power System Simulation for Engineers
LNG	Liquefied Natural Gas
HVDC	High Voltage Direct Current
HMOP	Hydro Maximum Off Peak
WSMDP	Wind and Solar Maximum Day Peak
VSC	Voltage Source Converter
LCC	Line Commutated Converter
ORE	Other Renewable Energy
ST	Steam Turbine
GT	Gas Turbine
PS	Pump Storage
AI	Artificial Intelligent
DFIG	Doubly Fed Induction Generator
SCADA	Supervisory Control And Data Acquisition
GSS	Grid Sub Station
LVPS	Lak Vijaya Power Station
UFLS	Under Frequency Load Shedding

CHAPTER 1

1. INTRODUCTION

Sri Lanka is an equator-close country with a high potential of renewable energy resources. Among the major renewable resources, comparatively large hydroelectric power has exploited almost its highest possible economic potential. Secondly, as indigenous resources, Other Renewable Energy (ORE) potentials have become an alternative source of energy for the future due to the low impact on environment compared to other fossil fuel-based sources of energy. Sri Lanka has a history of enabling the development of distributed renewable energy resources in the electricity sector, and the renewable energy contribution continues to increase as the demand for electricity increases.

1.1 Background

1.1.1 Renewable power development in Sri Lanka

Recent ten years data shows that power system is operated by maintaining renewable power share around 30% to 60% from the total generation [1]. Government and policy makers' expectation is maintaining this high renewable energy share in the future power system as well. Total Sri Lankan renewable energy share of past ten years is shown in figure 1.1.

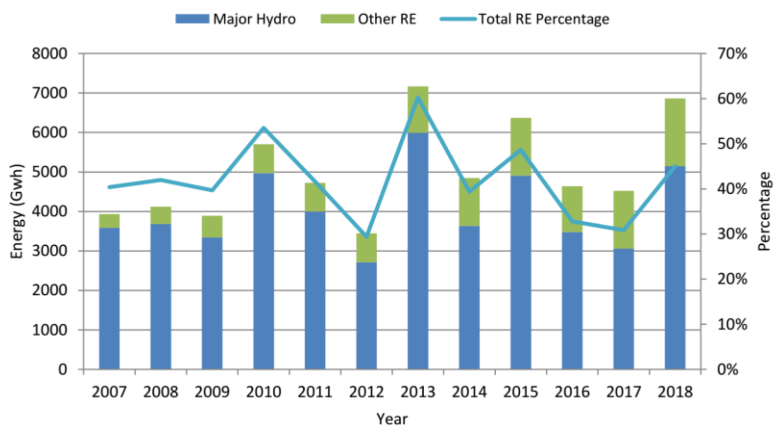


Figure 1.1: Past 10 years renewable energy share

1.1.2 **Renewable power development in World**

Renewable energy has been identified worldwide as a major source of electricity generation for several years. The estimated share of renewables in global power production was over 26 percent by the end of 2018.

Solar and wind power are increasing in terms of installed capacity, and combined installed capacity exceeded 489 and 564 GW in 2018, respectively, at global level. For a fourth consecutive year, net capacity additions for renewable energy are higher than for fossil fuels and combined nuclear power, and renewables now account for more than one-third of the global installed capacity.

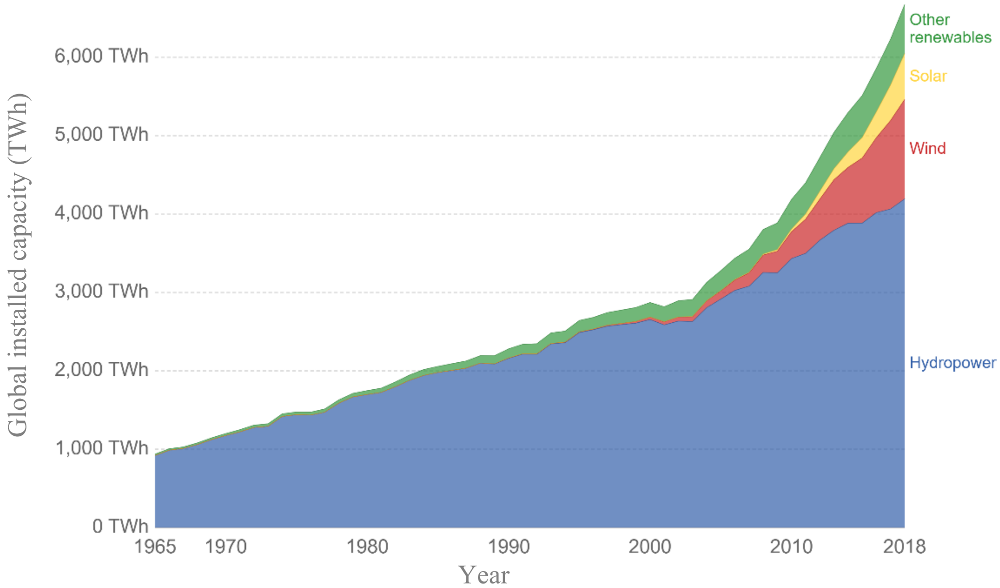


Figure 1.2: Renewable power development in World

These sources also play an important role in some countries at the individual country level. Denmark is leading, as in previous years, with 69% of the power coming from renewables. The share of renewables of energy in Germany and the UK is 32 percent of the broader EU economies.

The rapid increase in renewable energy generation continued in 2018, with a 14% rise. In terms of volume, the largest increase in China accounted for almost 50 percent of global growth.

1.1.3 **Major hydro power development**

At the present year, Sri Lankan major hydro potentials have been harnessed to its' maximum economical level. CEB owned, system connected seventeen major hydropower plants produce 1398.95 MW power output. 35MW Broadlands hydropower, 122MW Uma Oya multipurpose hydro power and 30.2 MW Moragolla Hydro Power projects are committed plant in recent future. Under the Moragahakanda Irrigation Project, Moragahakanda hydropower is in operation producing 25 MW to national grid. Seethawaka and Thalpitigala are other candidate hydro power projects that have to be developed in future. Total expected major hydro power generation with committed and candidate plants is 1,625.05 MW [1].

1.1.4 **Solar power development**

During the literature review, it is found that Sri Lanka is having strong solar irradiance due to a country which closes to equator. Solar energy resource map of Sri Lanka indicate that Sri Lankan annual average global horizontal irradiation varies from 4.5 to 6 kWh/m^2/day [2]. With this high irradiance levels and initiatives given by the Sri Lankan government, large scale solar power projects were being rapidly increasing in Sri Lanka. As a result of that, 51.36 MW capacity eight number of solar power plants were connected to system at the start of year 2019 [1].

1.1.5 **Wind power development**

The analysis of wind energy resources carried out as an account of the research funded by a U.S. government agency shows the potential of onshore wind energy in Sri Lanka. Further it has identified several wind regimes in the country as 'Central Hill', 'West Coast & Islands' and 'Southeast Coast'. Sri Lankan wind resource has identified seasonal variations especially in central Hills. Figure 1.3 shows the Sri Lankan onshore wind speed variation over separate wind regimes [3].

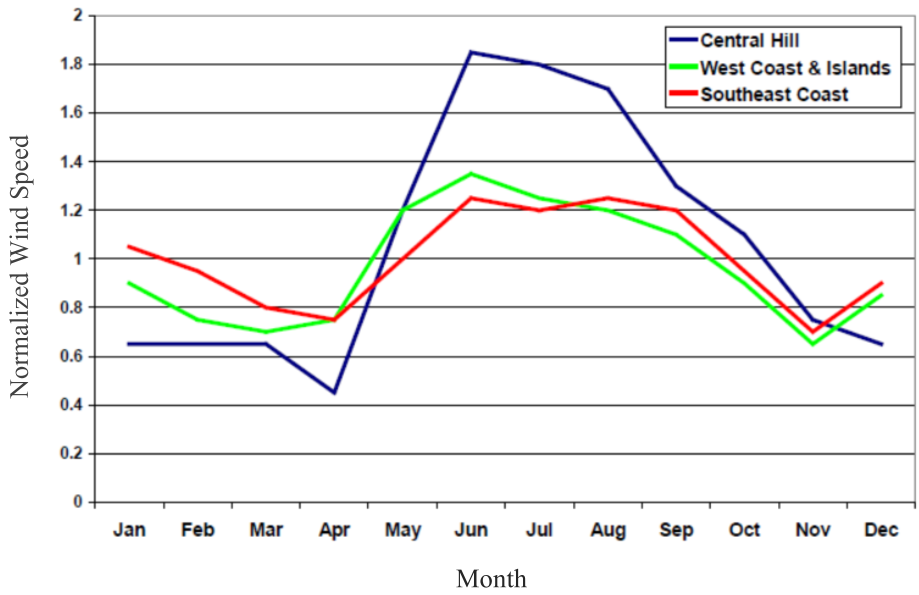


Figure 1.3: Sri Lanka – Monthly Normalized Wind Speed by Month

At the end of year 2018, 128.45 MW capacity, 15 numbers of wind power projects were connected to the national grid [1].

1.1.6 Biomass and Mini hydro power development

Biomass and mini hydro have added in capacity wise 37.09 MW and 368.53 MW generations respectively at the end of year 2018. Speciality of hydro power and biomass power generation are not intermittent in performance. This short time constant power availability is positively impact to the short-term power system stability. Further biomass capacity in scheduled year 2035 plan is 124 MW and mini hydro capacity is 619 MW [1].

1.1.7 Intermittency nature of Wind and Solar Power

Wind and solar photovoltaic sources are highly intermittent and seasonal in nature. Intermittent renewables are challenging because they interfere with the conventional methods of planning the electrical system's daily operation. Their power varies across multiple time horizons, forcing the system operator to adjust their day-to-day, hour-to-day and real-time operating procedures.

While contemplating solar energy, it is generally only available during daylight hours, so the system operator must change the day-to-day schedule to include generators that can easily adjust their power output rapidly to counterbalance the fluctuation in solar generation. Besides the daily fluctuations caused by sunrise and sunset, the output of solar panels can also suddenly change due to clouds. The uncertainty caused by clouds will make it harder for the system operator to determine how much additional energy will be required during the next hour of the day, making it difficult to measure exactly what each generator's output should be.

Fast variances in wind and solar output not only disrupt the hourly charging phase of grid planning, but also the second-to-second balance between total electricity supply and demand. Because the extent of sudden power generation shortfalls or excesses is enhanced by wind and solar, the system operator needs more reserve power ready to respond at a notice to ensure that the grid remains balanced. It will be a major challenge for the coming years and decades to further reduce the costs associated with renewable variability.

1.2 Problem Statement

Large interconnected power systems, which are having high inertia and relatively large spinning reserve can tolerate the variations of wind and solar power effectively. Such power system can absorb large share of wind and solar power into that system.

Small islanded mode power systems like Sri Lanka cannot be considered as same as the global power system. According to the forecast data, maximum demand of Sri Lanka at year 2030 is around 4.7 GW. Renewable power integration plan of CEB proposed solar and wind total power generation as at year 2030 is more than 2 GW.

Preliminary study data shows that solar power and wind power both are having significant variation over small time scale in Sri Lanka. As the incorporation of solar and wind power increases, problems created by intermittent solar and wind power have become increasingly prominent. A clear understanding of intermittent solar and wind power will help to reduce it effectively.

1.3 Research goals and objective

The aim of this research is to analyze maximum absorption capacity of wind power and solar power giving due consideration towards the system stability of the power system within next ten years.

1.4 Research Methodology

1. Identify the wind and solar power behavior in Sri Lanka
   - Data collection from large scale solar and wind plants
   - Analyze collected data to interpret degree of variability and correlation among them
2. Select power model to analyze system behavior with wind and solar integration
3. Update, tune and validate the power system model
4. Model the solar and wind plants for stability analysis
5. Develop the power system model for year 2030
6. Simulation cases development by considering daily load curve patterns and maximum renewable power availability times of the day
7. Stability analysis (frequency, voltage, angular) of the system to check the integration limit of solar and wind power
   - Base case analysis
   - Wind and Solar with pump hydro plants
   - Wind and Solar with Thermal plants
   - Wind and Solar with HVDC interconnection
   - Ramp reduction with Energy storage systems

CHAPTER 2

2. LITERATURE REVIEW

2.1 Ramp rate calculation

The estimation of the ramp rate plays a very important role in this analysis. In this study, ramp rate defined as a generator or plant can increase (ramp up) or decrease (ramp down) generation speed. While evaluating the variance of solar and wind power, the ramp rate is calculated as the increase in solar or wind power output of a solar or wind power plant over two consecutive duration period Δt. During utility scale power output analyzing in this study, ramp rate was considered as the change in generated power from second to second, with MW/second as its unit.

Though there is no fixed calculation of the ramp event, a ramp event at time t can be considered if the magnitude of the increase or decrease in electricity generation at the same time Δt ahead of t is greater than a threshold σ, fixed by our choice. Let $P_S(t)$ be the power generated at time t. Then the case of the ramp will happen if the following formula is valid [4].

$$|P_S(t + \Delta t) - P_S(t)| > \sigma \qquad \text{------------------------} \ (1)$$

Here if the value of $P_S(t + \Delta t) - P_S(t)$ is positive, the event is ramp-up event or otherwise ramp-down event. Though the function $P_S(t)$ representing the power generated at time t is continuous in time, due to feasibility of data acquisition, $P_S(t)$ can be considered as discrete time-event using fixed time intervals. In this study, one second time interval was selected for that.

2.2 DFIG Wind Turbine Model

The WT3 PSS/E wind turbine stability model was used to simulate performance of a wind turbine employing a doubly fed induction generator (DFIG) with the active control by a power converter connected to the rotor terminals.

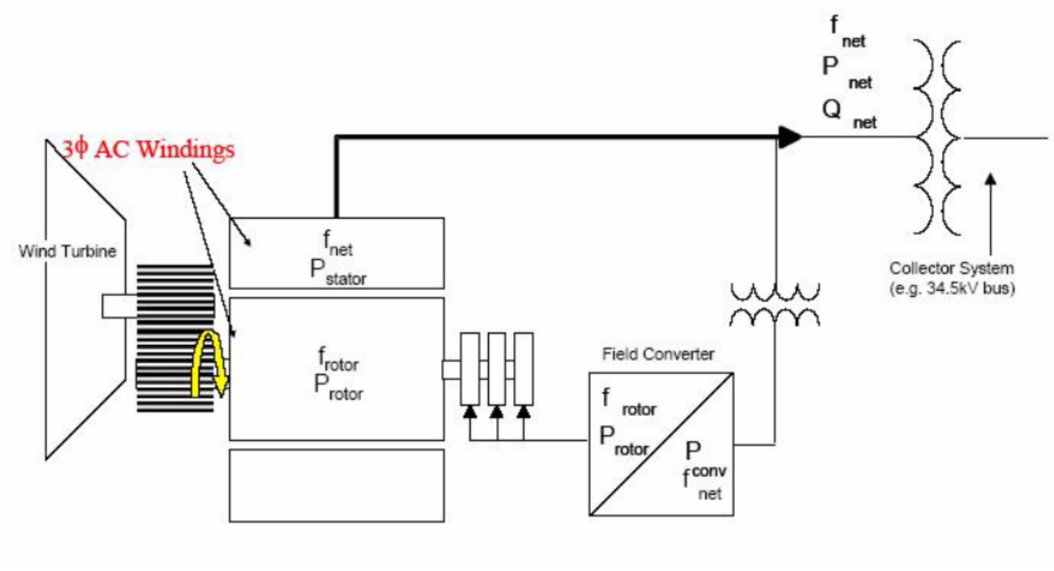


Figure 2.1: Doubly Fed Induction Generator with the Active Control by a Power Converter Connected to the Rotor Terminals

PSS/E WT3 Generic Wind Model comprises models as follows:

- WT3G: generator/converter model
- WT3E: electrical control model
- WT3T: mechanical control (wind turbine) model
- WT3P: pitch control model

There are two separate WT3G1 and WT3G2 generator / converter models available. The WT3G2 model recommended for new dynamic configurations, incorporates changes to the original WT3G1.

WT3G1 and the upgraded WT3G2 versions can be used with the electrical control system WT3E1. Figure 2.2 illustrates how these models interact.

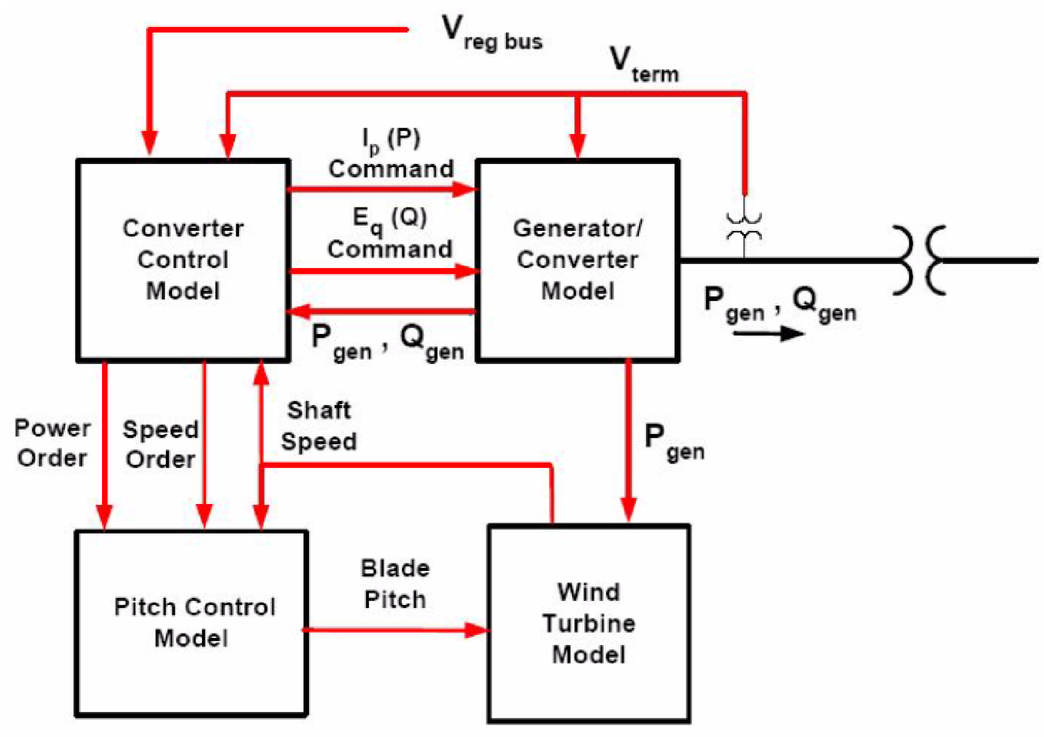


Figure 2.2: Interaction among Generic Wind Models

2.3 Photovoltaic (PV) System Model

The PSS/E Solar PV Unit dynamic stability model was used to simulate performance of a photovoltaic (PV) plant connected to the grid via a power converter. The PV Model comprises the following modules:

- PVGU: power converter/generator module
- PVEU: electrical control module
- PANEL: linearized model of a panel's output curve
- IRRAD: linearized solar irradiance profile

The modules are conventionally defined as wind modules with the generator/ converter module PVGU, the electrical control module PVEU, the mechanical module PANEL and the pitch module IRRAD. The power converter/ generator module measures the current injection into the grid based on filtered active and reactive power commands from the electrical control module. The control module for the converter contains responsive and active power controls. The reactive control calculates the reactive current command for the different control options, which could be any of the following:

- Remote bus voltage control
- Power factor control
- Reactive Power control

2.4 Voltage source converter based HVDC

VSC-based HVDC is an important technology suitable for strengthening weak systems of transmission and distribution. VSC HVDC power transmission uses IGBT-based voltage source converters with advanced control strategies. Not only does it achieve efficient power transmission, it also provides dynamic reactive power support for the connected AC systems. VSC HVDC technology is the cutting-edge application of electronic power and a crucial technology for smart grid systems.

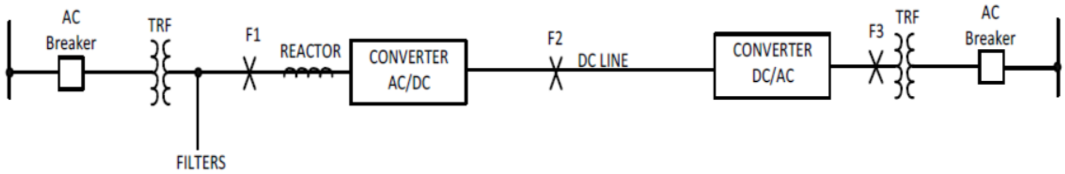


Figure 2.3: VSC HVDC transmission scheme

Figure 2.3 demonstrates a point-to-point VSC transmission scheme consisting of two VSCs interconnected on the DC side through a DC transmission line and connected on the AC side to two separate AC grids. On the AC side of the VSC, you can connect a passive or active AC network. If the VSC is connected on its AC side to a passive network, the power flow can only be on the AC side from the DC input side to the passive load. Nevertheless, if the AC side is connected to an active AC network, by regulating the VSC's AC voltage output, the power flow can be in both directions.

Since VSC HVDC uses modular IGBT technology, it has fast response times, good controllability, versatile operating modes, short circuit current of the network and passive grids. The VSC HVDC is also an efficient way to solve an isolated grid transmission of large-scale power outage and long-distance electricity. There are several options for the DC circuit and converter systems with VSC HVDC transmission.

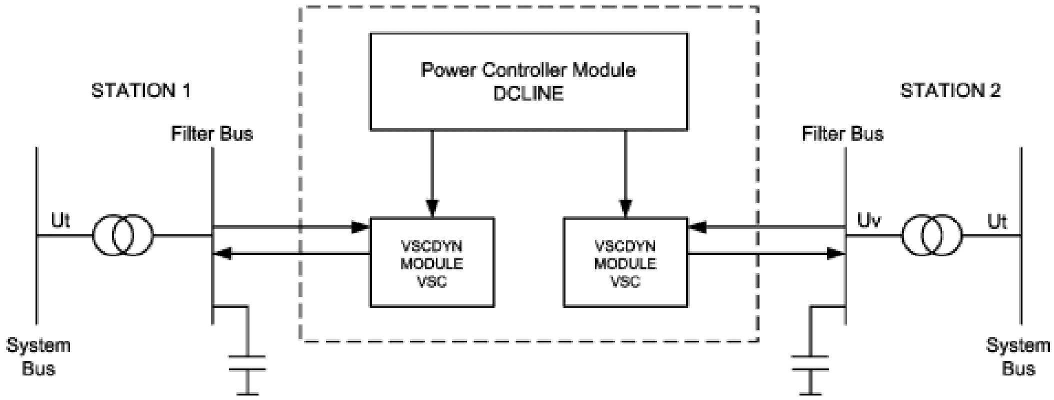


Figure 2.4: VSCDCT Model

The PSS/E DC transmission line dynamics model (VSCDCT) consists of three modules, two voltage source converter modules (VSCDYN) for the VSCs at each DC line terminal and one DC transmission line module (DCLINE) for the DC connection. VSCDCT is a current injection model. Figure 2.4 displays the modules for the dynamic model of the VSCDCT PSS/E.

2.4.1 **VSCDYN Module**

The VSCDYN module was used to represent a VSC converter's control functions. The VSCDYN module recognizes the following control actions:

- AC voltage control or reactive power control
- Active power control or DC voltage control
- Current output limitation
- Power ramping
- Converter blocking

CHAPTER 3

3. WIND & SOLAR DATA COLLECTION AND ANALYSIS

This chapter focused on data collecting from large scale wind & solar plants in Sri Lanka and analyzing collected data for detail study. Data was collected from the separate locations of the country to distinguish the behavior of each of them. Identification of exact behavior of these renewables would contribute to mitigate it effectively.

3.1 Wind Power

Sri Lankan wind resource map (Appendix C) indicates the potential of wind energy around the country [3]. To extract this identified energy, private investors are more interested to invest in wind power field with government's positive incentives. At the movement, there are several commissioned 10 MW plants in the system which are owned by private parties. Largest commissioned wind plant size in Sri Lankan power system is 10 MW. Apart from that fully CEB owned 103.5 MW Mannar wind park development has been started and expect to be commissioned at year 2020.

For this study, data was collected from three 10 MW wind plants in North-Weston province. Details of these 3 plants are shown in table 3.1.

Table 3.1: Data of the wind plants

Name of the plant	Pawan Danavi	Vidatamunai	Seguwantivu
Plant Capacity	10 MW	10 MW	10 MW
Turbine Type	850 kW (Gamesa G58-850)	800 kW (Gamesa AE-59)	800 kW (Gamesa AE-59)
Generator	Synchronous	Synchronous	Synchronous
Hub Height	65 m	60 m	60 m
Rotor Diameter	58 m	59 m	59 m
Power	100% variable	100% variable	100% variable

Regulations	speed	speed	speed
Number of Turbines	12 turbines	13 turbines	12 turbines

Wind speed and power were recorded in all three plants in per second resolution. Period of data recorded was 2018 February, 2018 May, 2019 March, 2019 May, 2019 June and 2019 July.

3.1.1 **Wind speed and power variation in a regular day**

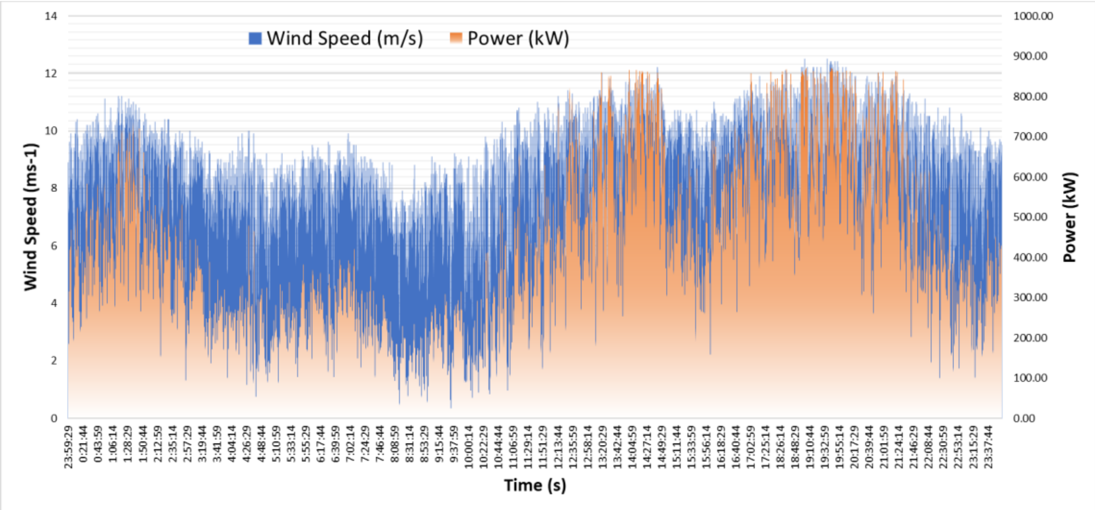


Figure 3.1: Wind speed (ms^{-1}) & Electrical power output (kW) variation of 24 hours

Relationship between wind speed and power of one wind tower (850 kW) in 10 MW wind plant is illustrated in figure 3.1. Recorded 24 hours, one second resolution data was used to draw above graph. This day was selected to properly illustrate wind power variation from its minimum level to rated power (0 kW to 850 kW) in a regular day. Wind speed also has changed from minimum level to 12 ms^{-1} in above selected day.

3.1.2 **Wind speed and power variation within four minutes**

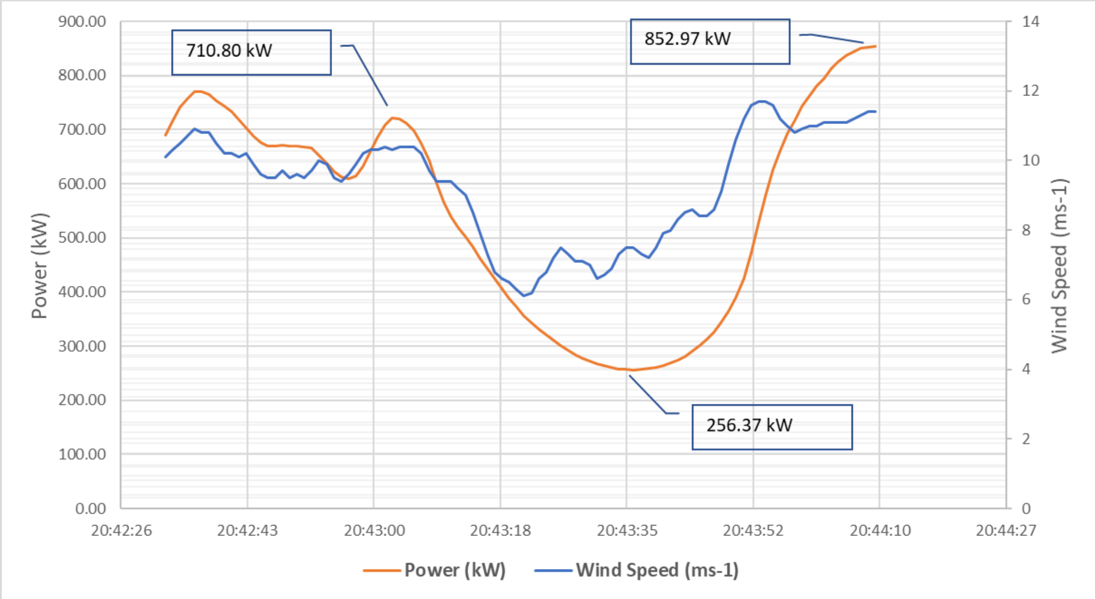
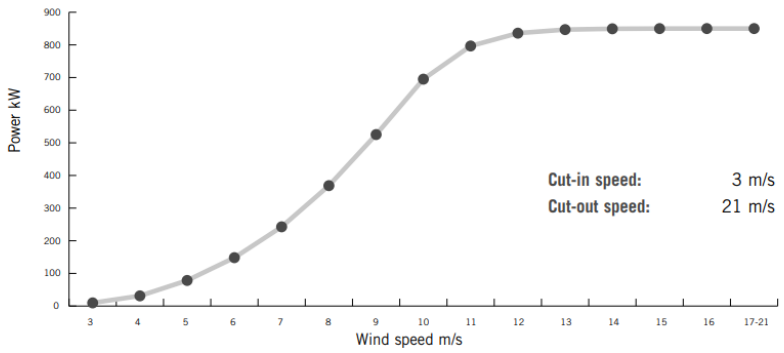


Figure 3.2: Wind speed & Electrical power output within four minutes

Observed major power variation of a single wind turbine in small resolution is shown in figure 3.2. Considering above four minutes' event, wind speed has changed from 10.4 ms^{-1} to 6.1 ms^{-1} within fifteen (15) seconds time. This speed change reflects 454.43 kW power change within 31 seconds time in wind generator. It is equal to 0.53 PU change within 31 seconds. In next time span, with the wind speed rising, wind power increased to its' rated power. Power change with 32 seconds time is 596.6 kW. This is equal to the 0.70 PU ramp up. Those observed outputs were compared with the respective wind turbine (Gamesa G58-850 kW) characteristics to ensure validity of recorded data.

3.1.3 **Wind turbine characteristics**



Speed (m/s)	Power (kW)
3	9.7
4	31.2
5	78.4
6	148.2
7	242.7
8	368.8
9	525.3
10	695.0
11	796.6
12	835.9
13	846.8
14	849.3
15	849.9
16	850.0
17-21	850.0

Figure 3.3: Power Curve of Gamesa G58-850 kW (air density: 1.225 kg/m^3)

3.1.4 **Wind speed and power variation among individual wind towers of a Wind plant**

Wind speed of individual wind turbines were recorded in 10 MW Wind plant. In this wind plant, all wind towers are connected to controlling center via fiber communication link. Individual anemometers have been installed in top of each wind tower to measure wind speed separately. As a result of that instantaneous power and wind speed of each wind tower can be monitor from the control center. Per second wind speed and power of twelve wind towers were recorded separately for the analysis. Cumulative wind speed variation over consecutive seven minutes is illustrated in figure 3.4 on same time frame.

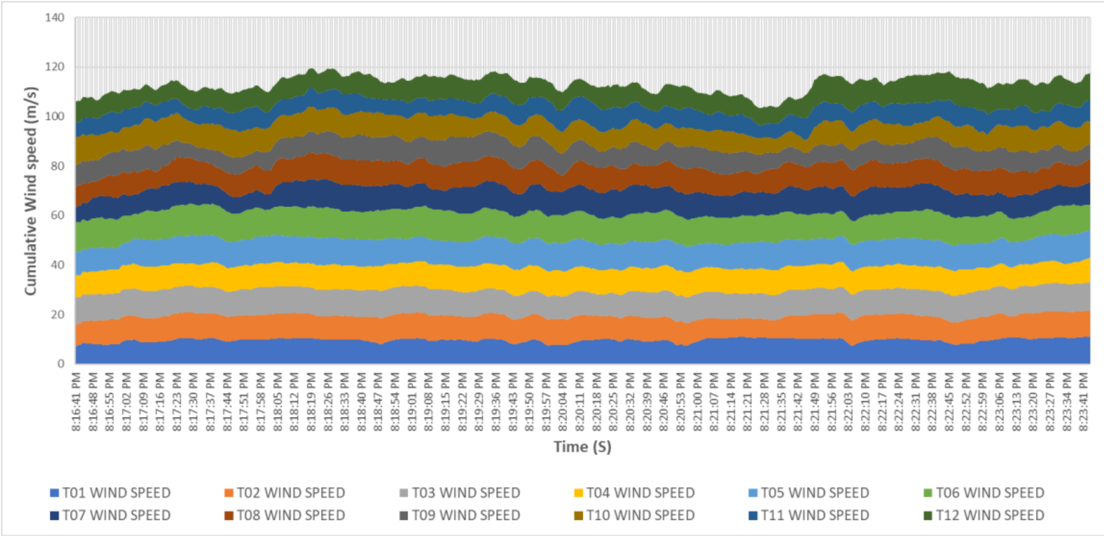


Figure 3.4: Wind speed of 12 wind towers

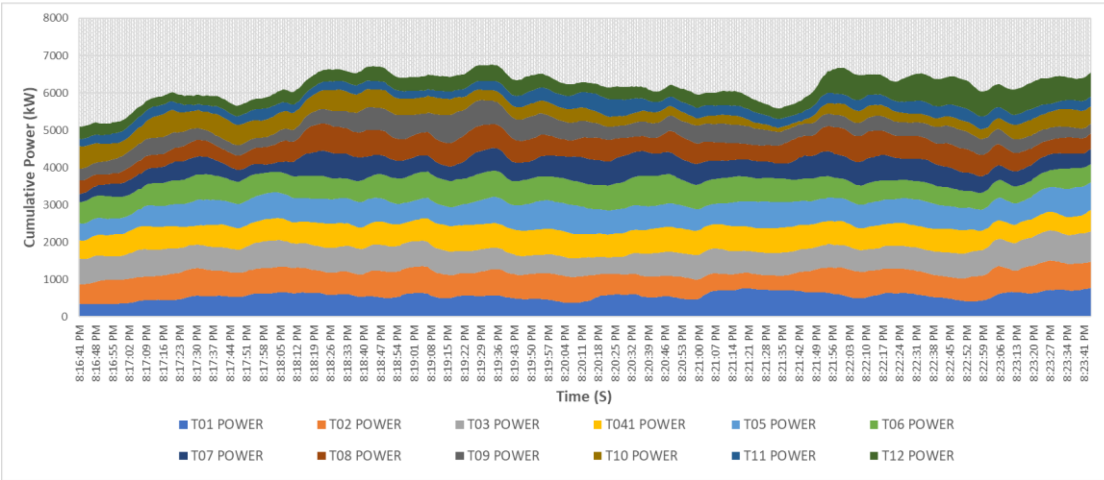


Figure 3.5: Wind power output of same 12 wind towers

Power generated over same seven minutes were recorded in each wind generator on per second scale. Cumulative wind power generation of twelve wind towers is illustrated in figure 3.5.

These two figures illustrate the relationship between wind speed and wind power of a large wind plants. Wind power output variation is comparatively lower than the wind speed variation due to the inertia of wind turbine. But there is a considerable variation in total wind power output of wind plant with the time, that has to be considered during planning studies.

By considering Sri Lanka's large wind power plants distribution, still larger plants are situated in North-Western coastal zone. The existing largest size of wind plant is 10 MW. Construction of 100 MW wind park in Mannar island has been started. For this study, wind power data was collected from 10 MW three wind plants in Puttalam and Kalpitiya areas.

Per second resolution data acquisition and recording for a longer period is a practically challenging task, because normally per second data is not normally recorded in SCADA system. Further recording and analysis of millions of data is a difficult task (consecutive one second resolution data recording in 12th day reaches one million data in the database; further MS Excel can only analyze 1,048,576 rows). But for the better accuracy, data was collected for several weeks.

Wind data was collected from HV side of the transformer and control center SCADA system. These two data collection points were selected to get proper idea of individual wind generator variation and variation as a whole wind plant. Further SCADA system outputs could be verified from power analyzer outputs.

And also power plants' tripping data were recorded during data collecting time. Those data should be filtered out before the analysis, to get actual ramping data for the study. Accuracy of the calculated largest ramping events were checked by graphical presentation in respective time frames.

To extract all the maximum ramp events, recorded millions of one second data of all plants were separately analyzed for 1, 3, 5, 10, 20, 30 and 60 seconds durations. Observed maximum power variations were tabulated in Table 3.2.

Table 3.2: Maximum power variations of wind plants

Observed Duration (S)	Ramp Up / (PU)			Ramp Down / (PU)		
	Data Set 1	Data Set 2	Data Set 3	Data Set 1	Data Set 2	Data Set 3
	Kalpitiya	Puttalam	Single Unit	Kalpitiya	Puttalam	Single Unit
1	0.08	0.05	0.27	-0.08	-0.09	-0.2
3	0.09	0.08	0.27	-0.09	-0.09	-0.23

5	0.1	0.1	0.37	-0.11	-0.1	-0.3
10	0.13	0.14	0.53	-0.12	-0.13	-0.4
20	0.17	0.18	0.63	-0.15	-0.18	-0.47
30	0.19	0.25	0.69	-0.17	-0.19	-0.54
60	0.2	0.28	0.7	-0.21	-0.24	-0.6

Data Set 1	Analyzed data from 10 MW Wind plant at Kalpitiya
Data Set 2	Analyzed data from 10 MW Wind plant at Puttalam
Data Set 3	Analyzed data from 850 kW single turbine in a 10 MW Wind plant

Wind power variability of selected three wind plants was carefully monitored. Observed maximum ramp down rate of individual wind turbine is comparatively high, compared with whole wind plant's ramp down rate.

3.1.5 **Wind ramp event occurrence probability**

Observed wind ramp up and down events were further analyzed to find out the ramp event occurrence probability. Figure 3.6 shows the drawn graph based on the calculated occurrence percentages.

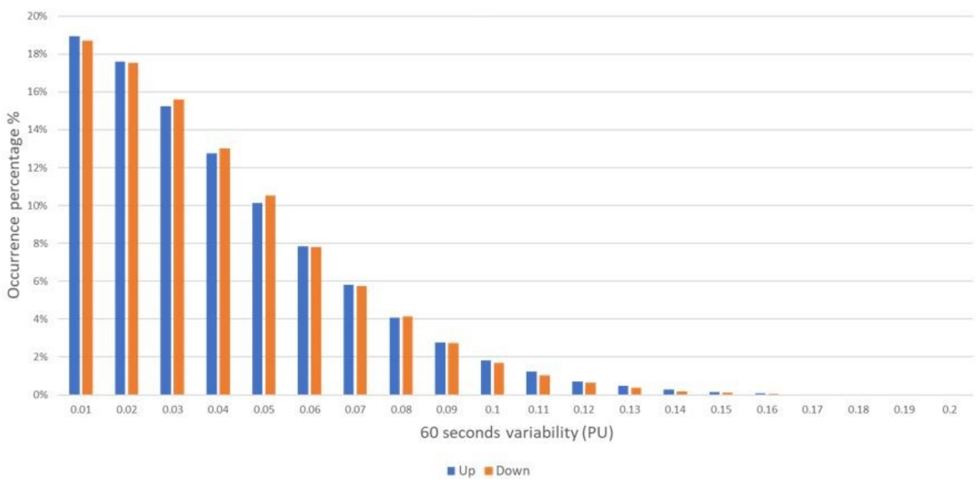


Figure 3.6: Occurrence probability of wind ramp events

3.2 Solar Power

The largest commissioned solar plant size in Sri Lankan power system is 10 MW. There are several 10 MW plants in the system which are owned by private parties. Further 100 MW scale major solar parks are proposed in LTGEP undergoing the preliminary study conducted in southern and northern part of the country. In this study data was collected from Hambantota and Vavunia solar plants. Historical data from November 2016 to December 2016 and recorded data in March 2019 and July 2019 were used for the analysis. Both irradiance (W/m^2) and electrical power output were recorded in one second resolution. Details of these 2 plants are shown in table 3.3.

Table 3.3: Data of the solar plants

Name of the plant	Sagasolar	Vydexa Lanka
Plant Capacity	10 MW	10 MW
Location	Hambantota	Vavunia
Units operational	48,000	35,721
Invertor type	Standard PV	Standard PV
PV Modules	Solon SE	JA Solar 350Wp
Annual net output	19 GWh	23GWh
Site area	45 acres	54 acres

3.2.1 Weather conditions impact on solar power

Fast moving cloud cover above solar plants result sudden fluctuations in the irradiance level. Irradiance variations reflect total power variations in the solar plants. Observations of the solar plants clearly indicate that weather conditions are severely impact on power output. Cloud cover impact observed in Hambantota Saga solar plant is illustrated in figure 3.7.

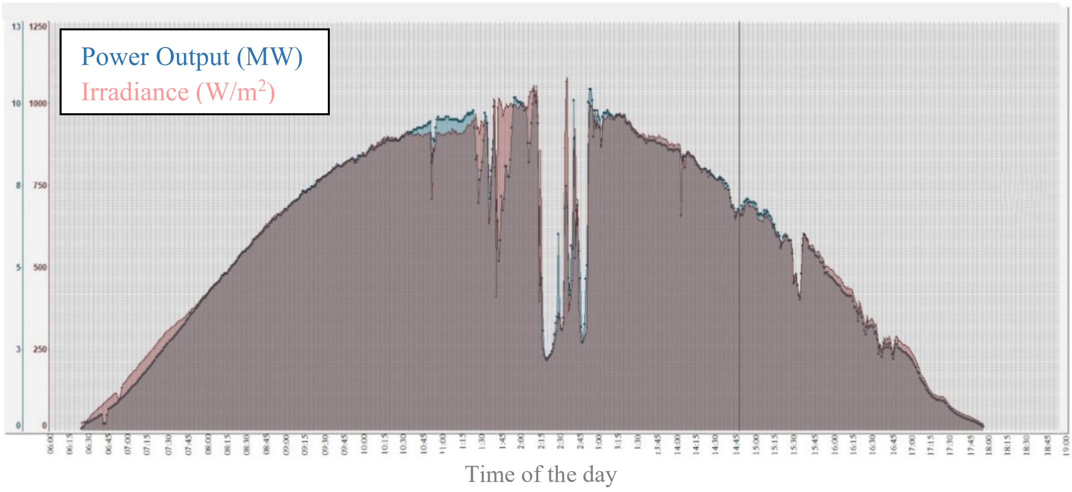


Figure 3.7: Impact of a cloudy condition on solar plant

System control center’s daily generation curves (Appendix E) shows that day peak of the daily generation curve reaches in between 11 AM and 1 PM. At the same duration solar power output also reach to its maximum level. Highest solar power variation also found in the same duration. With these observations, day peak with highest solar integration case is a compulsory case to analyze system’s worst impact.

Plant tripping data was observed during data recording and removed all those data by filtering out before the analysis. Accuracy of the calculated largest ramping events was checked by graphical presentation in respective time frames.

To extract all the highest ramping events, recorded millions of one second data was analyzed for 3, 5, 10, 20, 30, 40, 50 and 60 seconds durations. Among the observed two plants, highest ramp rate was observed from Hambantota plant. Those observed highest solar power variations were tabulated in Table 3.4.

Table 3.4: Maximum solar power variations

Observed Duration (S)	Ramp up (PU)	Ramp Down (PU)
3	0.10	-0.11
5	0.16	-0.15
10	0.24	-0.19
20	0.30	-0.24

30	0.37	-0.34
40	0.45	-0.44
50	0.53	-0.54
60	0.59	-0.60

Analyzed data shows that ramp down rate due to irradiance level drop is much closer to ramp up rate due to irradiance level increasing. But in small durations, ramp up rate is somewhat higher than ramp down rate.

These analyzed data outputs were used to model the solar plant's output variation in simulation studies.

3.2.2 Solar ramp events occurrence probability

Observed ramp up and ramp down events were further analyzed to find out the ramp events occurrence probability. The drawn graph based on the calculated occurrence percentage is shown in the figure 3.8.

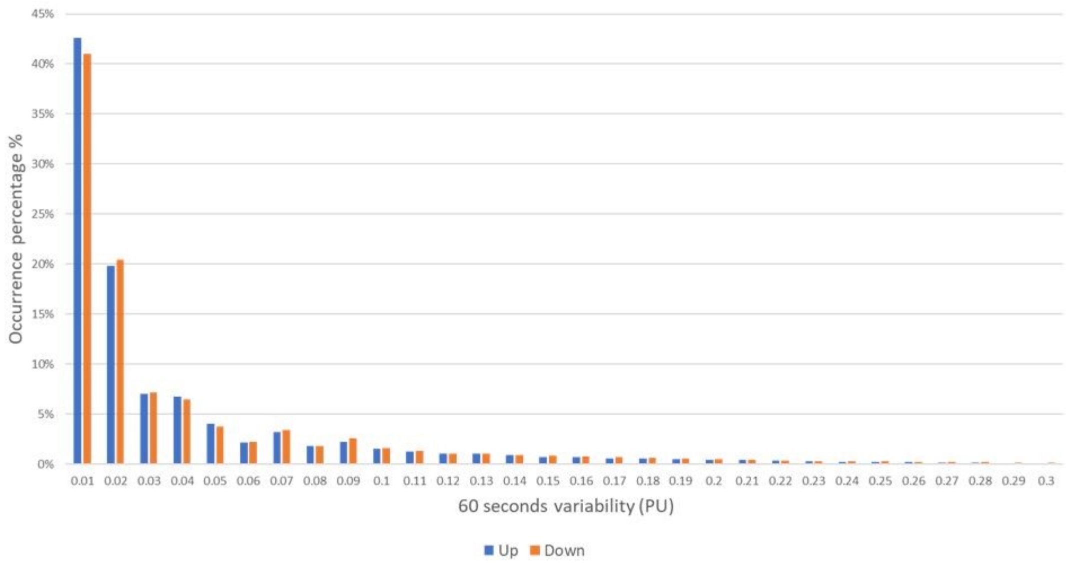


Figure 3.8: Occurrence probability of solar ramp events

CHAPTER 4

4. POWER SYSTEM MODELING

Present and future proposed power system had to be modeled using an appropriate software tool. Main objectives of the software tool were, power system modeling, conduct load flow analysis, conduct dynamic analysis and conduct contingency analysis using that software. Commercial software which is widely available for satisfy above mentioned requirements are PSS/E, PSLF, PSCAD, MATLAB, etc.… Among those, PSS/E software was selected for this study by considering great flexibility to use of advance features including above requirements.

Initial system modeling was conduct using the PSS/E software version 33. Conventional and renewable generators were modeled using the generic models in the PSS/E model library.

Virtual inertia integrated wind turbines are manufactured by the 'General Electric' who is a reputed manufacture in the wind turbine industry. They have developed PSS/E wind model which integrated virtual inertia function called 'WindINERTIA'to simulate wind virtual inertia feature. This developed model is included in PSS/E version 34.2, vendor specific model library. Therefore, PSS/E software version 34.2 was used for some selected cases analysis.

4.1 Transmission System model validation

Power system model has to be tested and validated before further analysis is being carried out. Data of four recent tripping events were collected and followed transmission system model validation procedure [5] to check the congruity of modeled system with actual system behavior. Actual variation snapshot data which was recorded in 'Ben Recorder' was used to compare the simulation results of PSS/E developed model. Four system disturbance events' data was taken from the System control center for the comparison. Those four events are:

- Partial system failure occurred from West Coast Plant tripped on 22nd July 2017 rejecting 270 MW due to failure in fuel line.
- LVPS Generator 03 tripped at 14:32 hrs on 10 February 2018 rejecting 268 MW from system & system recovered with operation of UFLS stage III.
- SUB E-Kolon 132kV cable tripped from Sub E end at 9:52 hrs on 16 September 2018 causing SUB E to be dead. At the same time LVPS unit 02 tripped rejecting 270 MW from the system. System recovered with the operation of UFLS stage III.
- A major system failure occurred at 08:14 hrs on 19 March 2019 with the tripping of Athu-Kolon both circuits due to operation of backup protection affecting 16 GSSs and Samanalawewa, ACE Embilipitiya, Laxapana Complex generation.

Generation dispatch, loads, shut device status and BEN recorder data of all above four events were collected for the validation. Then load flow and dynamic validation carried out using PSS/E software. Actual and simulated system frequency was compared in all four cases. In all cases simulated system frequency variation was almost well-matched with actual frequency variation. Figure 4.1 shows comparison of simulated and actual frequency variation of a system disturbance event.

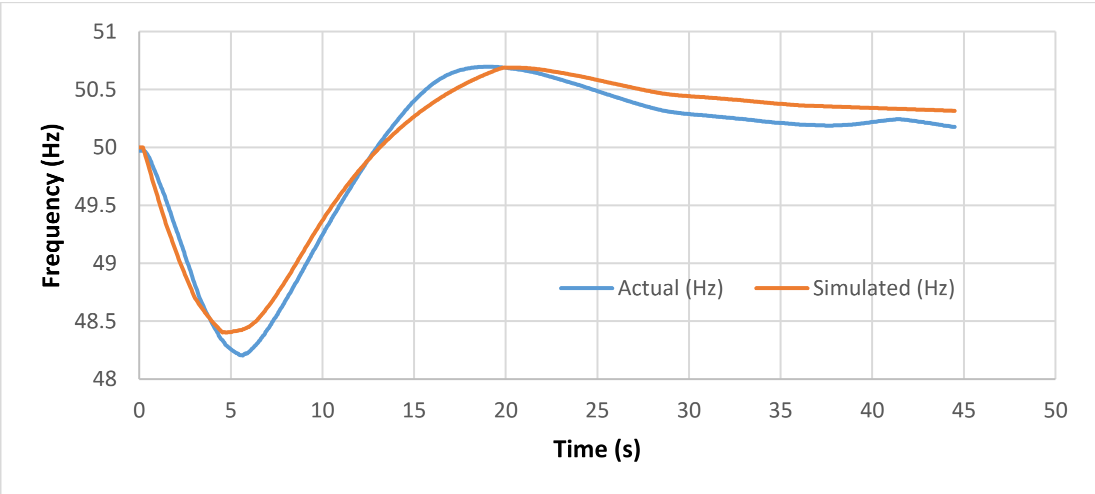


Figure 4.1: Comparison of simulated vs actual frequency variation

4.2 Sri Lankan power system at year 2030

Renewable power integration plan of Sri Lanka and long-term generation expansion plan of Sri Lanka were studied before selecting a year for the simulation. It was observed that several major power plants covering all main categories are planned to be installed within next ten years. Then the power system of Sri Lanka is getting more stable at the year 2030 by positively assuming all these major plants will be commissioned on time as per the LTGEP [1]. Those plants include,

- 2 x 300 MW New Supercritical Coal Power Plant
- 3 x 300 MW Natural Gas fired Combined Cycle Power Plant
- 3 x 35 MW Gas Turbine
- 320 MW Furnace Oil fired Power Plant
- 3 x 200 MW Pumped Storage Power Plant

When power system become more stable, it increases the flexibility of integration other renewable energy into system. Therefore, Sri Lankan power system at year 2030 was selected for the maximum renewable power integration analysis.

4.3 Power system stability analysis

System stability analysis was carried out such that maximize the capacity of solar power and wind power in Sri Lankan power system at year 2030. Main constraint of dynamic analysis was maintaining system frequency at 49.5 Hz to 50.5 Hz range.

4.3.1 Cases selection for simulation study

Generation dispatch schedule of the day is planned based on the availability of hydro, solar, wind, thermal and dendro resources. Hydro generation prominent and thermal generation prominent cases of day and night generation scenarios were analyzed to identify the worst response case under the renewable power intermittent nature. It shows that hydro governors are having slow response rate compared to the gas turbine governors. Therefore, power system is more stable with the gas turbine governors.

Considering wind and solar power contribution of the day and system generation variations, two main scenarios were selected for the dynamic study. These two cases cover the worst-case scenarios that can happen in the power system from wind and solar integration.

- Wind and Solar Maximum Day Peak (**WSMDP**) » Solar + Wind 100%
- Hydro Maximum Off Peak (**HMOP**) » Wind 100%

Load flow study, dynamic analyze and contingency analyze were carried out for all above cases.

4.3.2 Wind and Solar Maximum Day Peak (WSMDP)

During the day peak time with high irradiance level, solar power is getting maximized. Even though wind speed does not have such regular pattern, with the high wind speed, wind power also gives high power share during day peak time. Considering both resources, cumulative power contribution from both solar and wind is getting maximized during day peak time.

Further historical data records show that wind power contribution is maximize during the monsoon season. Considering all these incidences, wind and solar power maximized day peak scenario was developed to study the system behavior with these two resources.

Wind, solar, mini-hydro and dendro generation were considered as 100% during WSMDP simulation model development. Hydro generation was maximized by concerning the constraint of maintaining spinning reserve and frequency control. Rest of the load is matched with thermal generation.

4.3.3 Hydro Maximum Off Peak (HMOP)

Minimum generation of the day is occurred in between 01.30 AM to 3.30 AM. This period can be considered as night off peak in daily generation curve. Hydro maximum off peak case was developed to check the system stability during this off peak time, because hydro generators are having slow response rate.

Wind and hydro both resources are become maximize during the monsoon season. Therefore, wind and mini-hydro contribution was considered as 100% during this HMOP scenario. Major hydro and thermal plants having partial contribution by considering spinning reserve constraints and frequency control capabilities.

Some other restrictions have been implemented in the case of HMOP, which in year 2030 will become more practical. Under these restrictions, Sampoor coal one machine from each of the two plants was out of operation, one machine from Puttalam coal was out of service, and pump storage power plants were run in motor mode with a load of 187 MW.

4.3.4 **Generator dispatching sequence**

Generators were dispatched by considering available least cost generators in present system and proposed in LTGEP. At the choice of a generator to be dispatched, other capacities and limitations of existing power plants in the power system were also considered.

Power system was modeled by allocating Victoria bus as a swing bus. Therefore, all simulations were initiated by giving frequency control function to the Victoria governor. At the time of Victoria governor is not adequate to control the frequency in tolerable range, other supportive hydro governors were added to the system with frequency control feature. New Laxapana, Kothmale and Upper Kothmale hydro governors are the frequency control supportive hydro governors which used for above task.

When these conventional hydro governors were not adequate to regulate system frequency with wind and solar power fluctuations, below generators were dispatched to regulate system frequency.

- Pump storage power plants
- Gas turbine power plants
- HVDC interconnection

Solar and wind plant ramp rate reduction using battery storage system was also simulated to check the possibility of removing costly free governing machine from the system. Satisfactory system improvements were achieved under this technology with less governing generators and detailed findings are described in Chapter 5.

CHAPTER 5

5. FREQUENCY STABILITY ANALYSIS WITH WIND AND SOLAR POWER INTERGRATION

Power system stability with wind and solar power addition is discussed in this chapter. Power system frequency stability, voltage stability and angular stability were analyzed under all these cases. Wind power variations were simulated in HMOP scenario. Wind and solar power both added system variations were simulated in WSMDP scenario.

5.1 Wind ramp profile for simulation

Wind speed and power correlation among wind towers in a wind plant was evaluated during the study. Data shows that there is a high correlation of wind speed & power among individual wind turbines in a wind plant.

In the study, data was collected from three wind plants in North Western province. This data was collected during both the wind peak season and off peak season, as there is uncertainty that the largest ramp event would not occur in monitored period. While happening large ramp in major plant, other small wind plant may have some small ramping event. By considering all these situations, observed largest ramp in individual wind turbine were applied to the largest wind plant in the system. It was expected to cover most adverse wind variation that can happen in system from this ramp profile simulation.

In selected year 2030, Mannar 300 MW wind plant was the largest wind plant in the system. Therefore, Mannar wind plant was applied 0.0126 PU/s ramp down rate from 5^{th} second to 50^{th} second. Then waited for 5 second and applied 0.0162 PU/s ramp up rate until reaches rated power. Computed wind ramp profile is illustrated in figure 5.1.

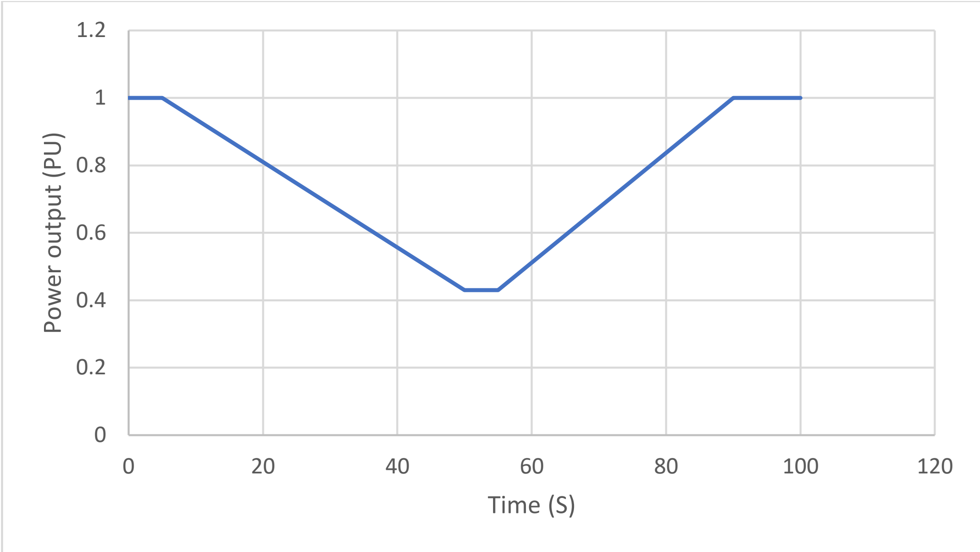


Figure 5.1: Wind ramp profile for largest wind plant

Base on the renewable integration study 2018, wind power projection at year 2030 is 967.8 MW. It consist with 244 MW from Puttalam, 300 MW from Mannar, 3.8 MW from Hill country, 390 MW from Northern and 30 MW from Eastern. Year 2030 power system was developed by allocating identified wind power developments in above locations.

The derived wind ramp profile was applied to the 300 MW Mannar wind park during the dynamic study. It subjected to deduct 170.1 MW wind generation from the system at the 50th second of dynamic simulation. This results in a proportional reduction of the cumulative wind generation to 797.7 MW.

5.2 Solar ramp profile for simulation

Detailed analyze of solar plant variation in two separate provinces shows that output power ramping events do not have any considerable relation, when plants are in separate locations. Largest solar ramping event was captured from the Hambantota solar power plant from both observed plants.

Main consideration of solar ramp profile development was simultaneous ramp event occurrence among major solar plants. But several studies [6] show that maximum solar ramping event occur in same instance at two separate solar plants is very rare incidence. Therefore, solar ramp profile was developed such that observed largest ramp event was applied to the largest solar plant in the system during simulation. In year 2030 system, largest solar plant is Pooneryn solar plant which is having 190 MW capacity. It was applied 0.011 PU/s ramp down rate from 5th second to 50th second. Then waited for 5 second at same generation and applied 0.014 PU/s ramp up rate until reach rated power during the simulation. Computed solar ramp profile is illustrated in figure 5.2.

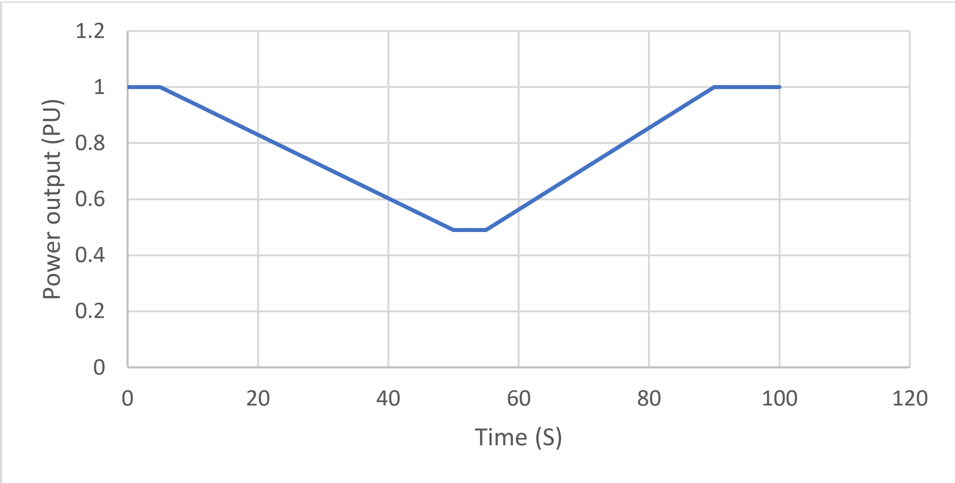


Figure 5.2: Solar ramp profile for largest solar plant

Base on the renewable integration study 2018, solar power projection at year 2030 is 1410 MW. From this total, it has planned 400 MW as roof top solar, 520 MW as grid connected solar from Southern region and 490 MW as grid connected solar from Northern region. Year 2030 power system was developed by allocating identified solar power developments in above locations.

In WSMDP case, rated power solar generation was considered apart from the roof-top solar. Because normally wind and solar both resources are maximized during monsoon season. Therefore, during monsoon season, whole country spread roof-top solar power generation was considered as 50% from its total. Finally for the WSMDP case, solar power generation was considered as 1210 MW.

By applying solar ramp profile to 190 MW Pooneryn solar park during dynamic analysis, Pooneryn solar generation is reduced up to 95.95 MW, resulting in total solar generation as 1115.95 MW at 50th second of dynamic simulation.

5.3 Maximum system impact from wind at night off peak

Night time prominent other renewable energy resource is wind from its nature. As discussed in chapter 4.4, wind power share is become maximize during night off peak time due to daily total generation is at its minimum level.

Dynamic simulations were conducted in HMOP scenario for monitor the system behavior with high wind situations. Outputs of the simulations conducted under HMOP case ware illustrated below.

HMOP all cases were simulated while wind ramp dynamic profile is running in 300 MW Mannar wind plant.

System frequency control function (swing bus) was activated in Victoria unit 01 machine. In this mode, system was stabled by starting stage 1 load shedding at 38th second with continuous wind power ramping down. But frequency varied in a large range. Therefore, further regulations were needed to be done by adding other governors. Observed system frequency response is shown in figure 5.3.

For required further regulation, free governor mode was activated in New Laxapana, Kothmale and Upper Kothmale hydro governors in addition to Victoria hydro governor. Observed system frequency response is shown in figure 5.4.

Then frequency was stabled in between 49.1 Hz to 50.4 Hz range. Further regulations were needed to maintain frequency in the acceptable range (1% toleration).

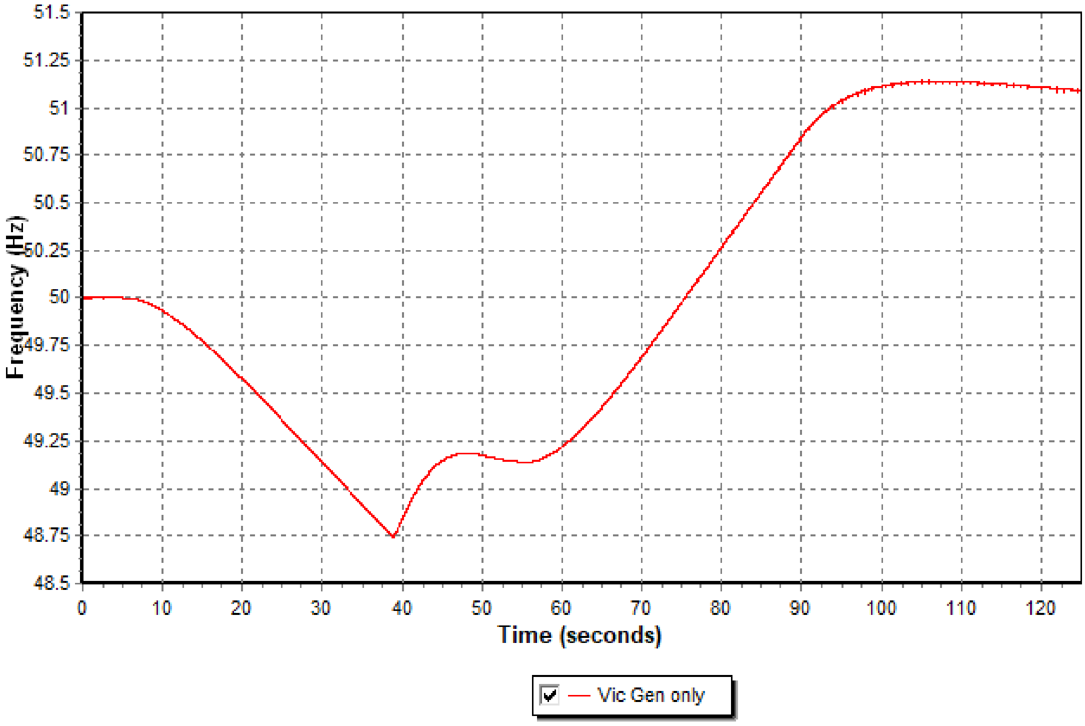


Figure 5.3: System frequency respose with Victoria unit 01 in free governor mode

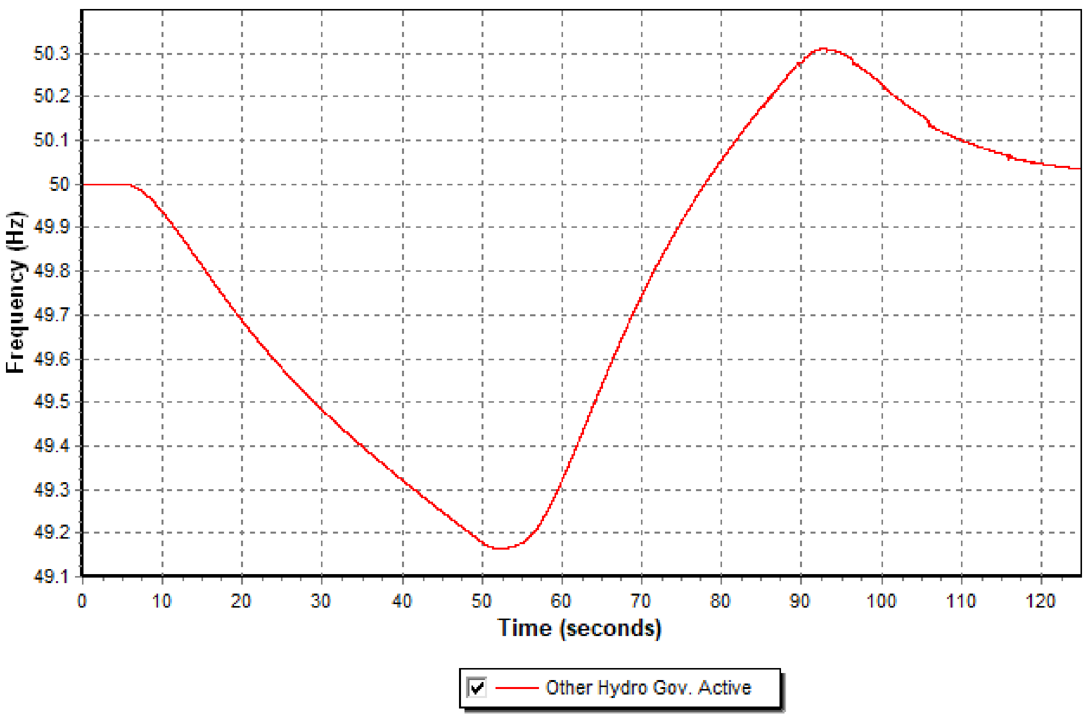


Figure 5.4: System frequency respose with Victoria & other hydro governors in free governor mode

5.3.1 Power curtailment of large wind plants

Largest wind plant of the LTGEP is Mannar 300 MW wind park. Power system was simulated by adjusting the amount of power generation from Mannar wind plant. Larger wind plants should be in dispatchable type to curtail the power generation during off peak times.

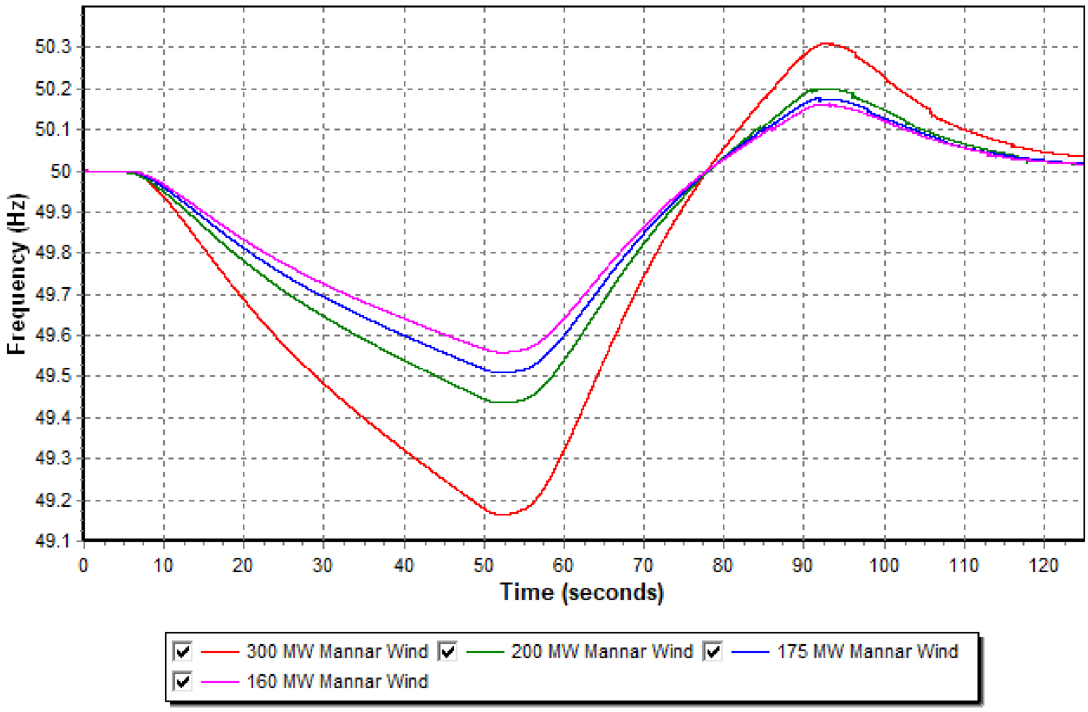


Figure 5.5: System frequency respose with hydro 'free governor' mode and wind power curtailment

Gradually reduce the power of the wind plant and simulate the power system while monitoring frequency variation of the system. When curtailing 125 MW power from the wind plant, frequency was stabled within ±1% range from its nominal.

5.3.2 System stability improvement with LNG plant

Previous simulations were proved that only hydro governors are not adequate to regulate the system frequency with the wind power variation. Proposed 300 MW LNG plants in LTGEP are consist with two 100 MW gas turbines and one 100 MW steam turbine. Gas turbines which are having fast response rate were shown significant stability improvement in power system. HMOP case with 'free governor' mode hydro and one LNG included simulation output is shown in figure 5.6.

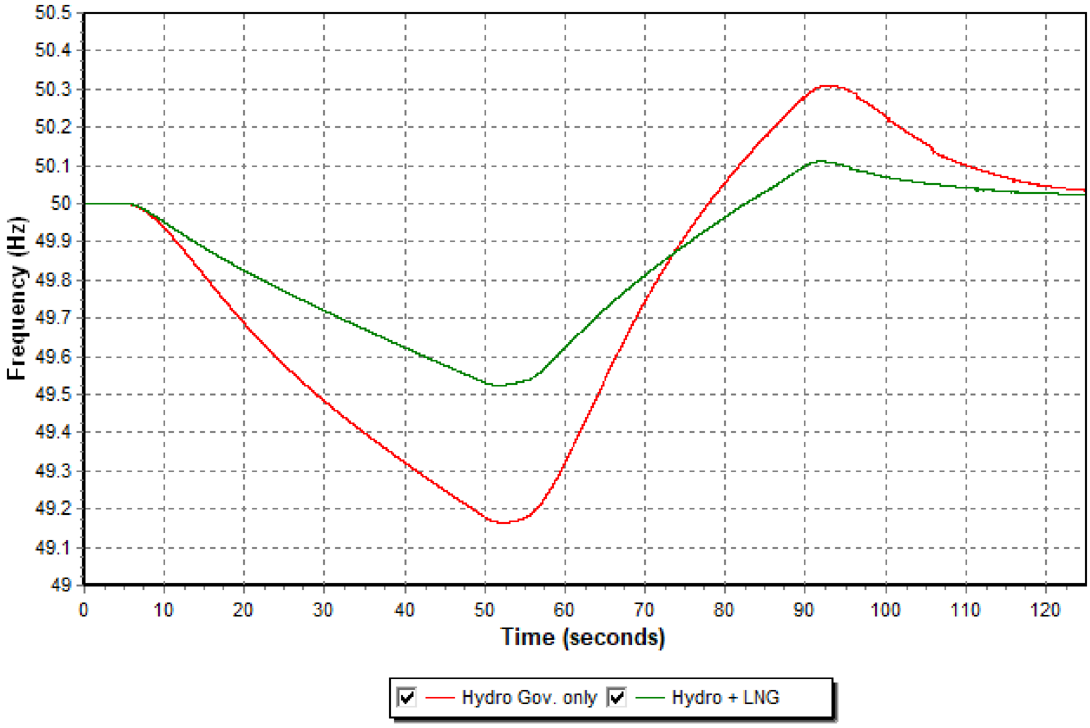


Figure 5.6: System frequency respose with hydro 'free governor' mode and LNG plant GT 'free governor' mode

System frequency was stabilized in the tolerable region by adding LNG plant with free governing mode.

Due to hydro with one LNG was an acceptable generation dispatch scenario to regulate system frequency, stability of the power system was evaluated by tripping largest generation unit in the system. Largest unit of the present and proposed system is LVPS 275 MW coal generator. Therefore, 275 MW LVPS Unit 01 generator tripping was given at 50th second, because system should be stable at its worst condition. Volatage & frequency respose corospond to this simulation is shown in figure 5.7.

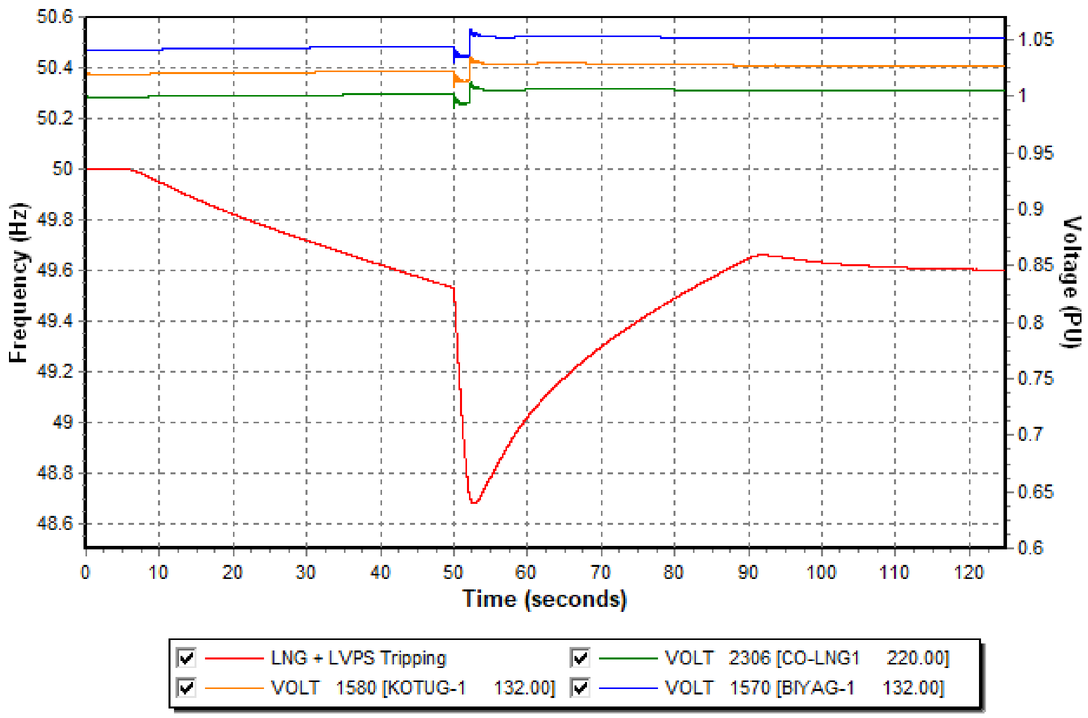


Figure 5.7: System volatage & frequency respose with Hydro Governors + LNG + 275 MW generation rejection

Even with the generator tripping, system was getting stabilized by initiating stage one load shedding. At this time period 'frequency', 'angular' and 'voltage' stability were monitored to confirm the parameters are well below the maximum limits.

5.3.3 System stability improvement with HVDC interconnection

Power system behavior of wind varying nature was simulated under this section while HVDC connection facilitates frequency regulation in the system. Simulation results shows that hydro with HVDC given superior frequency regulation compared with hydro only or hydro + LNG case. Frequency response of the system is shown in the figure 5.8.

Even LNG plants are not connected to the system, HVDC and hydro can operate the system smoothly in an integrated scenario of maximum wind power. contingency analysis also carried out for this case to verify system behavior during sudden disconnection of large machine from the system. LVPS 275 MW unit tripping was simulated for this objective. Its output is shown in figure 5.9.

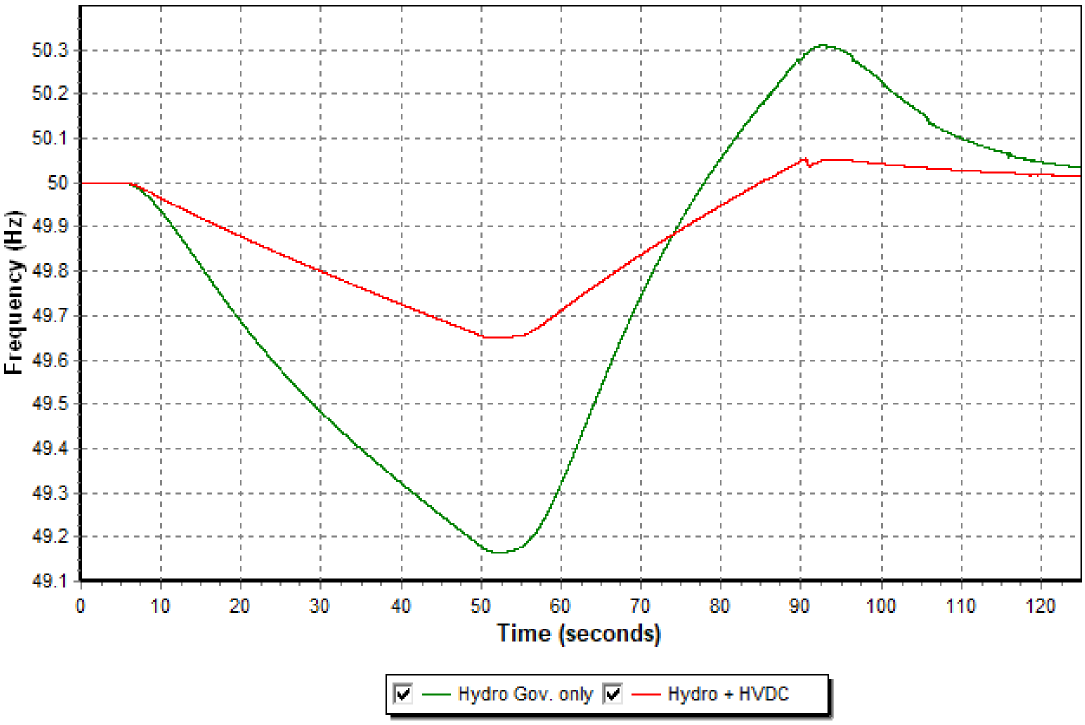


Figure 5.8: System frequency respose of hydro 'free governor' mode vs hydro 'free governor' mode + HVDC interconnection

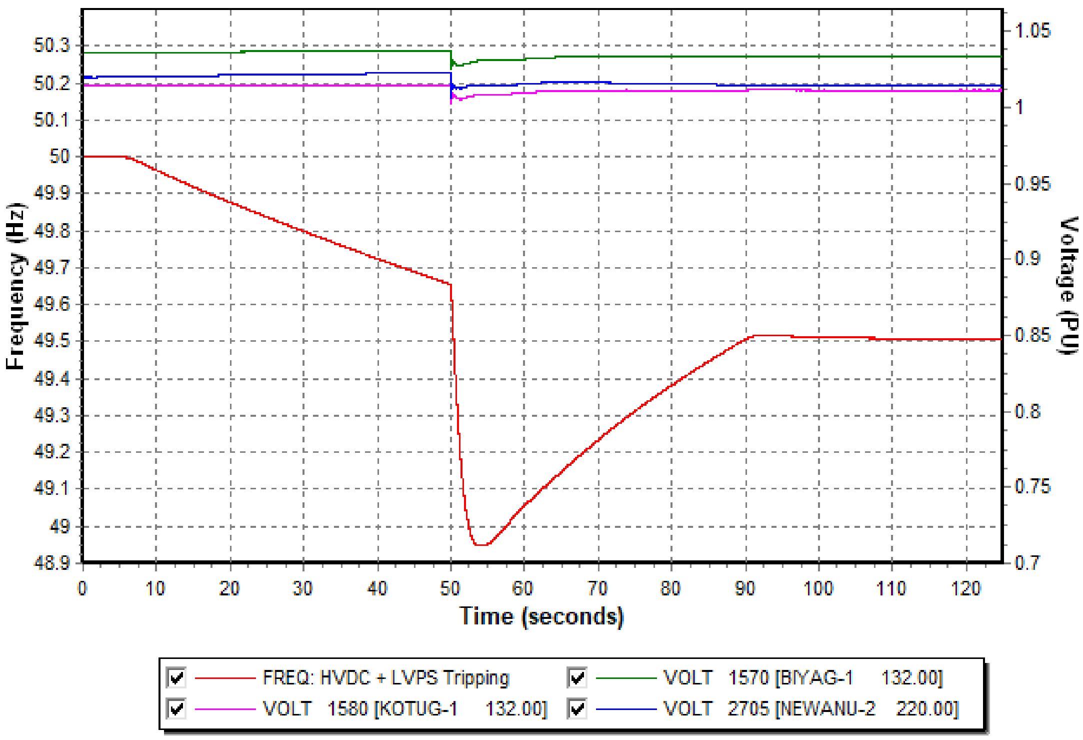


Figure 5.9: System volatage & frequency respose with Hydro Governors + HVDC + 275 MW generation rejection

5.3.4 Ramp rate control with Battery energy storage system

Wind power ramp rate was limited by connecting battery energy storage system to major wind plants. System improvement with introduced maximum ramp rate limit with battery energy storage system was evaluated in this simulation.

The goal of this total ramp rate limit is to reduce the operation of expensive thermal plants or other expensive rapid frequency control techniques.

By following this main objective, several ramp rates were simulated to identify the optimum ramp rate that can facilitate to operate only hydro governor to regulate system frequency.

0.4 PU/minute ramp rate was observed as maximum ramp rate limit that can allow for optimum operation. With this threshold, system can be operated within ±0.5 Hz frequency range with regulation of hydro governors. In year 2030 case, largest Mannar 300 MW wind plant was added this maximum limit and observed output is shown in figure 5.10.

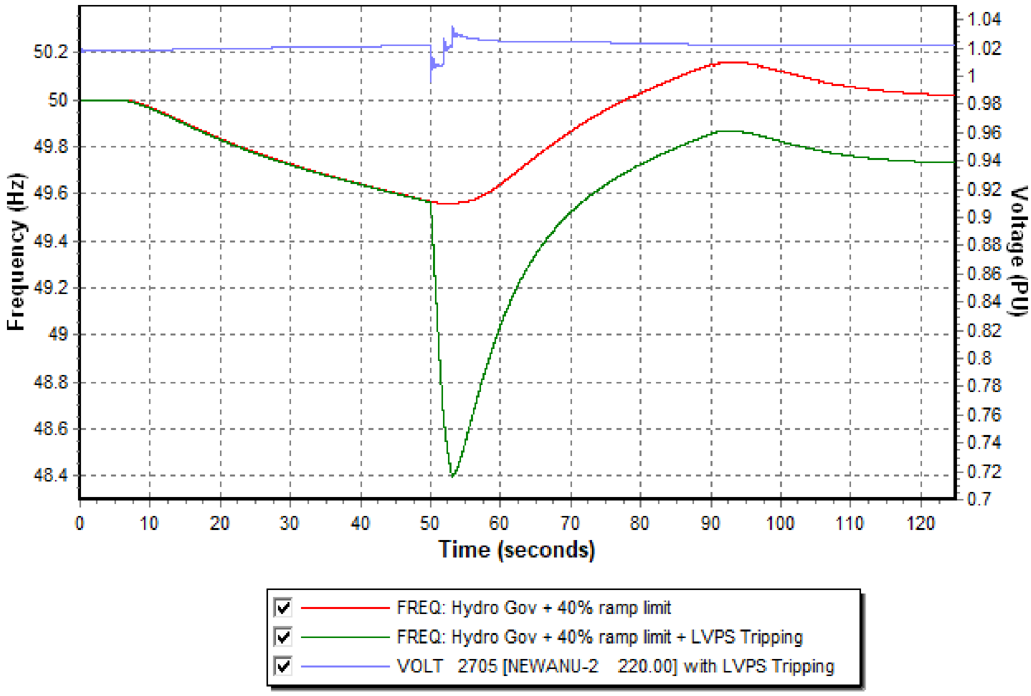


Figure 5.10: System volatage & frequency respose with maximum ramp rate limit & 275 MW generation rejection

But system stability is not strong as previous cases. During the contingency analysis, system was recovered by starting stage 2 load shedding at 52nd second.

All above HMOP case analysis were based on the maximum wind ramp applied to major wind plant in the system and considered all other wind plants' cumulative ramping rate as zero. But only for far extended worst case analysis, all other wind plants were given 0.1 PU/minute slow ramp while major plant was given high ramp. System stable cases under this scenario were illustrated in figure 5.11.

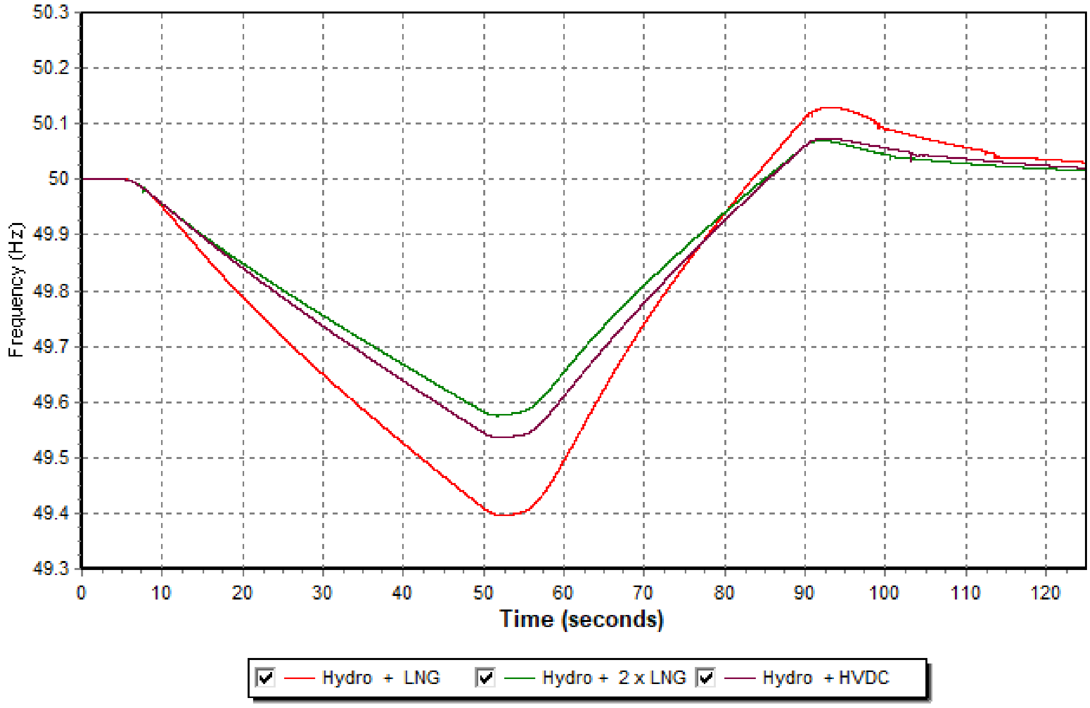


Figure 5.11: System frequency respose with further injected slow ramp to other wind plants

5.4 Maximum system impact from wind & solar at day peak

System stability impact from wind and solar both energy resources were evaluated under this section. As described in section 4.4.2, WSMDP network case was used to simulate the ramping event of both resources. Wind and solar ramp profiles discussed in section 5.1 & 5.2 were used with WSMDP case for ramping dynamic simulations.

Same generator dispatching sequence which followed by section 5.3 was used for this section simulation as well.

Initial simulations show that basic hydro machines' free governor control is not adequate to regulate the system frequency in both wind and solar varying nature. Figure 5.12 shows the system frequency output under the regulation of the hydro governor.

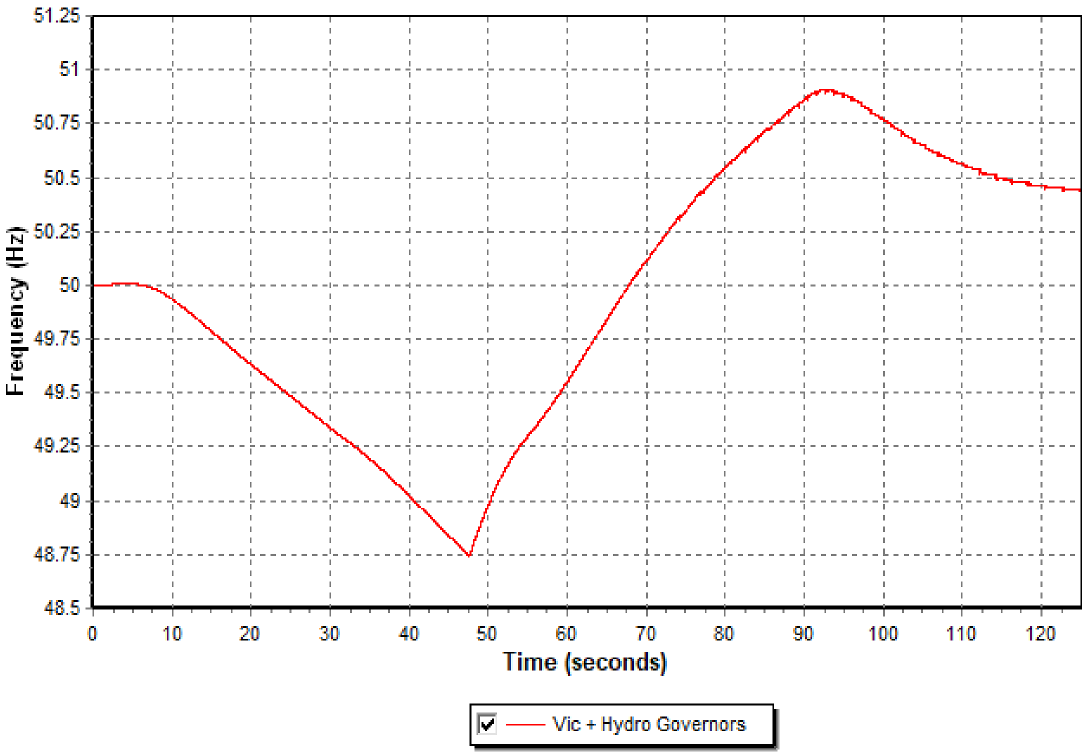


Figure 5.12: System frequency output with hydro governor control

System was getting stabled by initiating stage 1 load shedding at 47th second.

5.4.1 System stability improvement with PS + LNG or PS + HVDC interconnection

System stability improvements were evaluated with pump storage, LNG or HVDC interconnection due to hydro governors' support was not adequate.

In HMOP case, pump storage plant's governor support was not evaluated due to PS plants are in motor mode at off peak duration. But in WSMDP case, PS plant can be utilized for the frequency control. Therefore, that option also evaluated in this category.

All possible cost-effective scenarios were evaluated separately with these governor control options and outputs were illustrated in same graph for detail overview. Frequency outputs are shown in figure 5.13 with these three options.

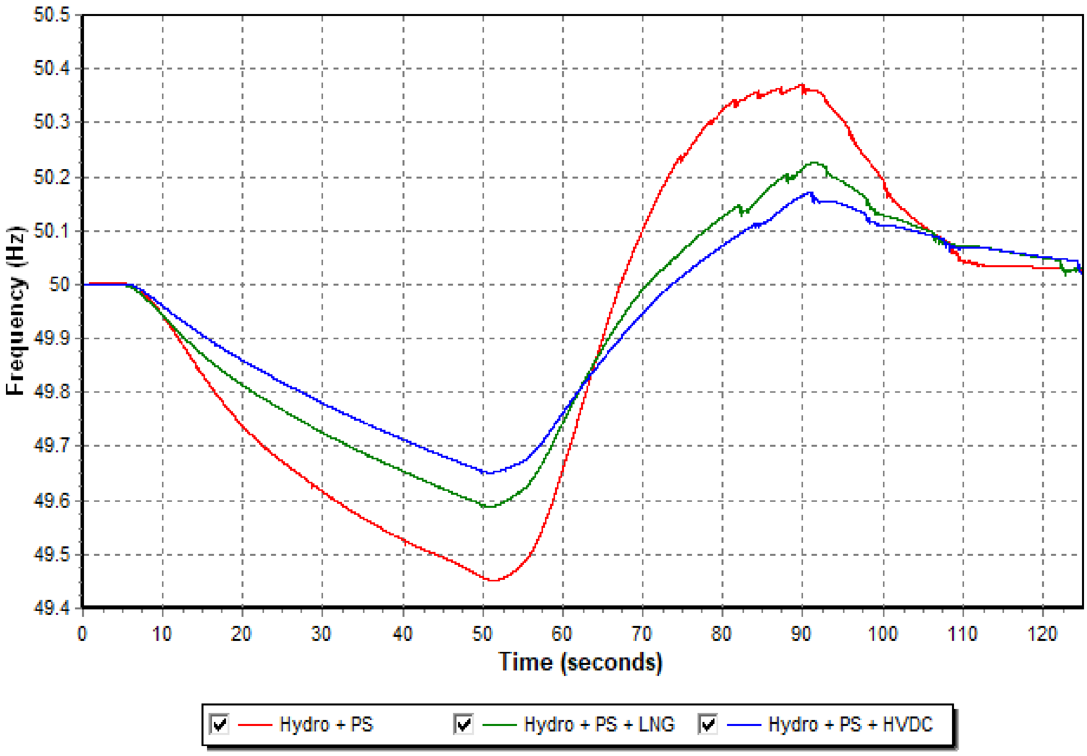


Figure 5.13: System frequency output with hydro governor + PS or LNG or HVDC

Outputs show that system is getting stable with pump storage plant addition. But maintain system frequency within ±0.5 Hz, more regulatory actions were required.

Any option of LNG or HVDC interconnection was sufficient to regulate remain part of the frequency as shown in figure 5.13. Contingency analysis is also carried out of these successful cases to monitor the behavior of system parameters.

5.4.2 System stability with HVDC interconnection

With observed better system performance of HVDC interconnection, HVDC interconnection and hydro behavior was also evaluated without PS or LNG plants. Result (figure 5.14) shows that system frequency goes below 49.5 Hz at the minimum point while wind and solar both resources are varying.

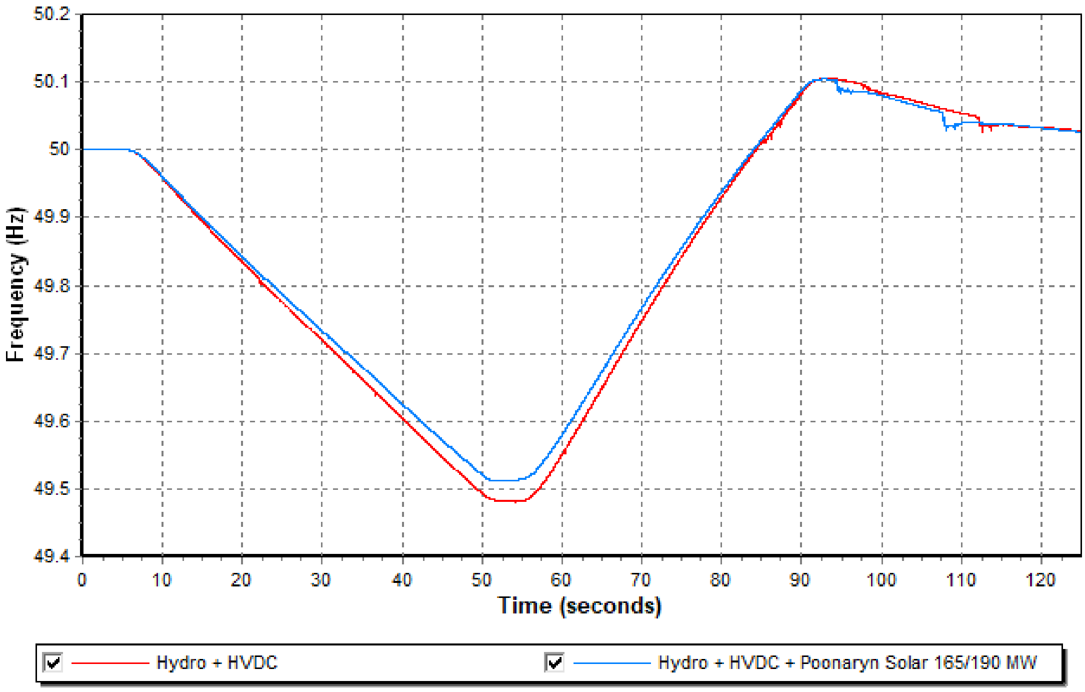


Figure 5.14: System frequency output with hydro governor and HVDC

Instead of introducing new machine to uplift the system frequency into tolerable range, solar power curtailing was tried in the largest solar plant. In this scenario, simulation was conduct by curtailing solar power from minimum level to optimum level. Acceptable frequency regulation was achieved by curtailing 25 MW from the Pooneryn solar plant.

Contingency analysis result shows that power system becomes much stronger when HVDC connection available. Under this scenario, power system is getting stable even without having any load shedding with 275 MW generator tripping. Figure 5.15 shows that frequency and voltage stability of the system during contingency.

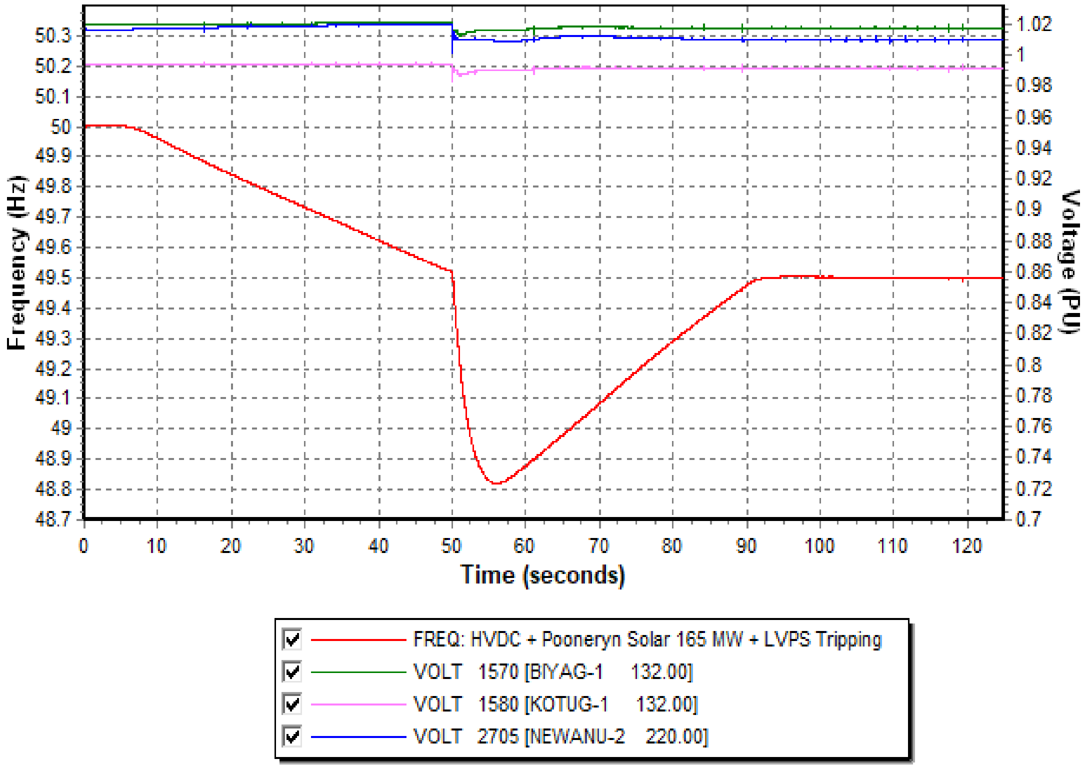


Figure 5.15: System volatage & frequency respose with Hydro Governors + HVDC + 275 MW generation rejection

5.4.3 System stability improvement with two LNG plants

When HVDC interconnection or pump storage plants are not available in the system, other possible combination is hydro and LNG plants. By concerning outputs of section 5.4.1, hydro and two LNG plants was dispatched to the system. Acceptable simulation output was received as shown in figure 5.16.

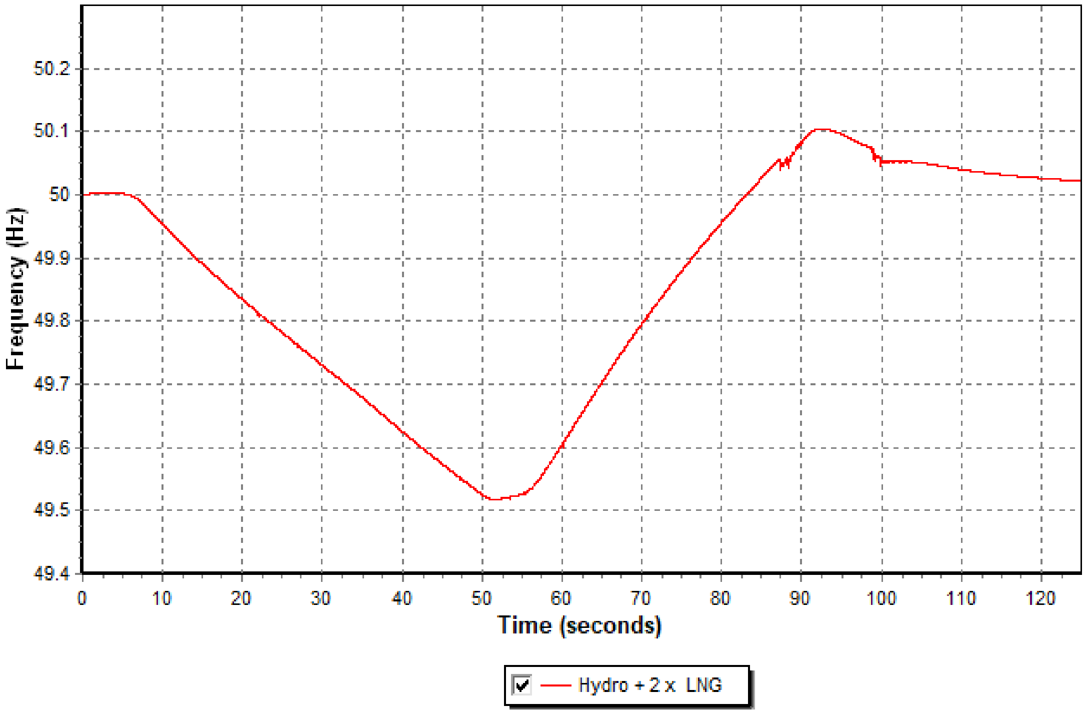


Figure 5.16: System frequency output with hydro governor and two LNG plants

Successful two LNG plants scenario was also evaluated for the contingency. Same as the HVDC interconnection, two LNG plants were also given better stability to the system. As figure 5.17 shown, with two LNG plants, system is getting stable without initiating load shedding.

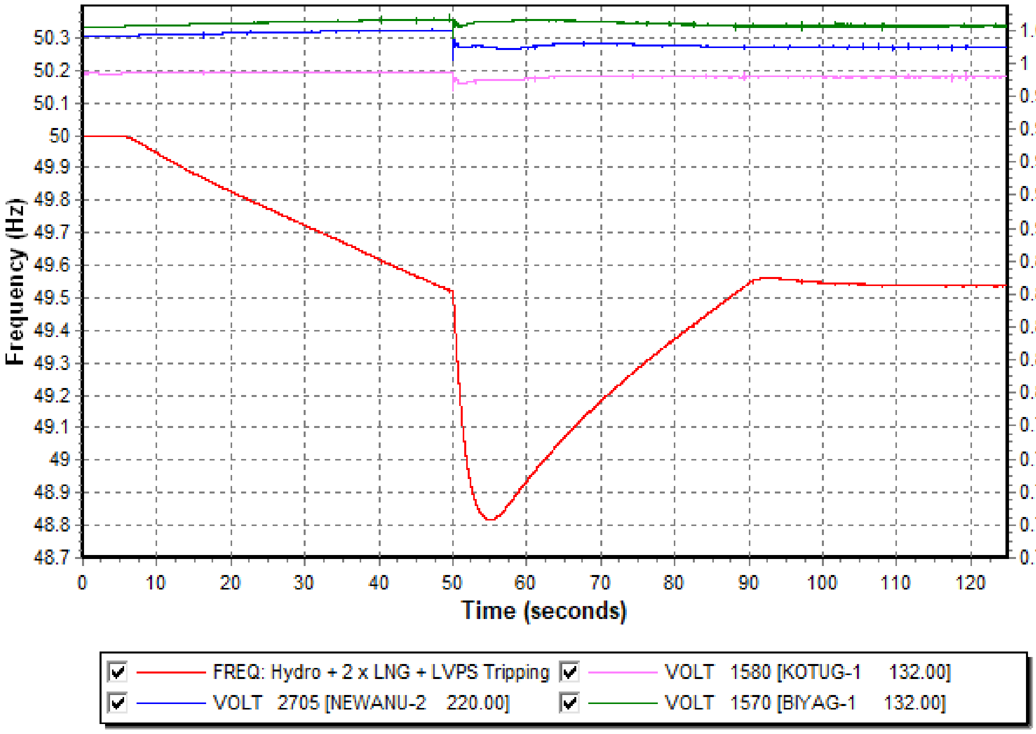


Figure 5.17: Frequency response with Hydro Governors + 2 x LNG + LVPS 275 MW unit tripping

5.4.4 Ramp rate control with Battery energy storage system

Solar and wind power ramp rate was limited by connecting battery energy storage system to major solar and wind plants. System improvement with introduced maximum ramp rate limit incorporate with battery energy storage was evaluated under this section.

Under previous night off peak scenario (HMOP), ramp rate was limited such that only hydro governors can regulate system frequency. But in the day peak, previous methodology is not practical. Because in the day peak generation, both solar & wind are in varying nature, system frequency cannot be regulated only with hydro governors.

Further implementing of ramp rate limit for the particular energy type should be unique. Implementing two ramp rate limits as day and night is also not an economical solution. Therefore, same ramp rate was used for the both cases.

Therefore previous 0.4 PU/minute ramp rate was used for both solar and wind power plants. In year 2030 WSMDP case, the largest Mannar 300 MW wind plant and 190 MW Pooneryn solar plant were operated under this maximum ramp limit.

Several evaluations were simulated to find out optimum dispatch machine type with introduced new ramp rate limit. Figure 5.18 shows simulation outputs which are plotted in same time frame.

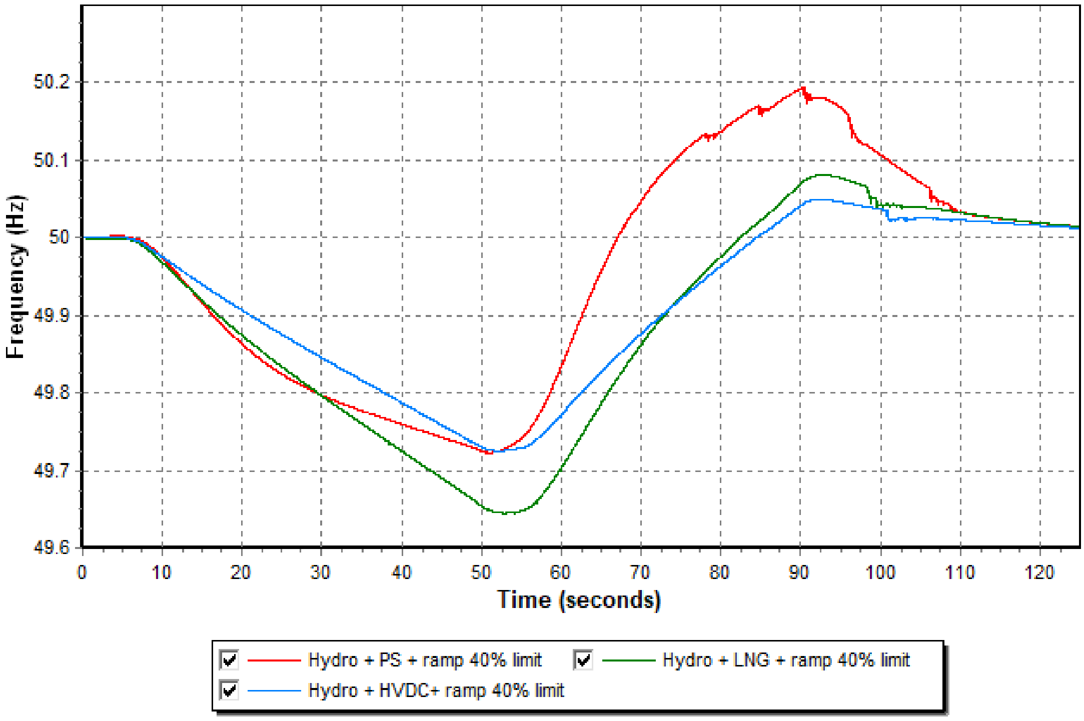


Figure 5.18: System frequency respose with maximum wind & solar ramp rate limit

Observed outputs in figure 5.18 was compared with outputs in section 5.4.1. It clearly shows that availability of the battery energy storage system can reduce the dispatching of costly generators.

CHAPTER 6

6. CONCLUSION AND RECOMRNDATIONS

6.1 Conclusion

Major trust areas of other renewable energy resources would be solar and wind for the immediate future. Therefore, solar and wind should be harnessed to the maximum potential giving due consideration towards the economic and technical viability of the power system.

Intermittency nature and non-inertia produced generating nature are the main drawbacks of these renewable energy resources.

Wind and solar power variations were closely monitored in per second scale for quantify the variation to planning studies. The data was recorded in several locations in Sri Lanka to validate the captured variations.

Observed data indicate that both solar and wind power plants have significant variations to be considered during planning of the power system. The simulation results illustrate that only least-cost hydro governors are not adequate to regulate system frequency when there is a high penetration of solar and wind power exist in power system.

Proposed LTGEP exhibits that renewable power share exceeds 23% from the total generation. At that point, two LNG plants or one LNG plant with HVDC interconnection is mandatory for the power system stability. Availability of the pump storage power plants in the system, can reduce dispatching of one LNG plant.

Seasonal variation and daily wind and solar power generation patterns indicate that renewable energy share in daily generation curve is only maximized for a few hours. Within this renewable share increased few hours, the maximum system impact can be expected. Therefore, the power system can be stabilized at the above-mentioned time period of the day by only curtailing wind or solar power.

Simulation of the battery storage system with wind and solar power plants reveals that the power system is reliable with less governor controlling units under renewable power varying nature. Optimum ramp rate limit was achieved through the introduction of a battery storage system to reduce the operation of costly governing units.

As a conclusion, renewable power share of the power system can be increased when fast frequency regulation supportive, conventional generators are available in the system. Otherwise, to improve the power system, battery storage system or HVDC interconnection should be implemented.

6.2 Recommendations

- Simulation outputs clearly show that dispatching of high costly generators was directly depend on the amount of wind and solar power availability and its' ramping rate. Looking at the nature of renewable energy, only a few hours per day maximize the wind and solar power generation. Further share of wind and solar power from the total generation is also maximized for a smaller period. Therefore, national dispatch planning center should have a proper idea about present and future renewable resources behavior. The development of a 'wind and solar forecasting system' would effectively achieve above objective. This system should comprise irradiance and wind speed data measuring centers in all feasible locations with online data transferring facility to renewable forecasting system.
- Implementing an Artificial Intelligent (AI) integrated dispatch planning software which incorporates with renewable energy forecasting system.
- Providing large wind and solar plant curtailment rights to system operator, undergoing dispatching instructions generated from dispatch planning software.
- Continuous upgrades of renewable energy integration studies. Because RE technology is continuously upgrading to address issues related to persistent technological barriers.

- Proper and timely implementing of major power plants. Because all planning and simulations were conduct based on the major power plants' implementing plan which is mentioned in LTGEP.

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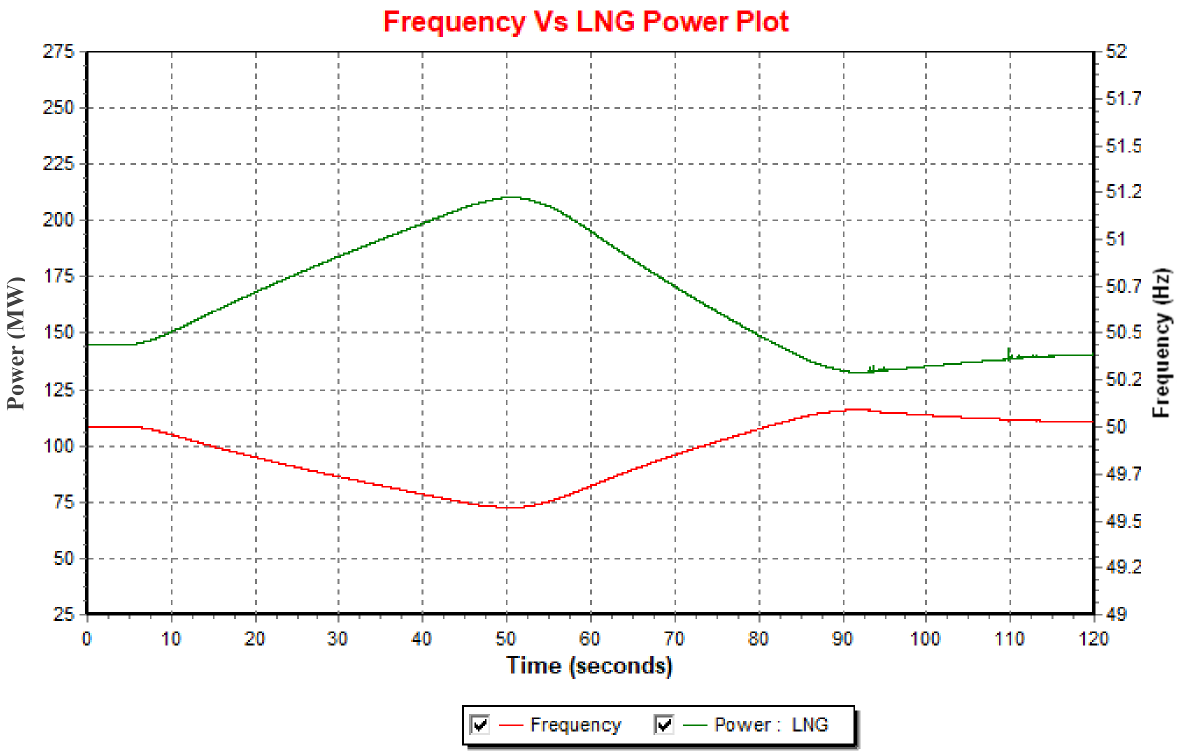
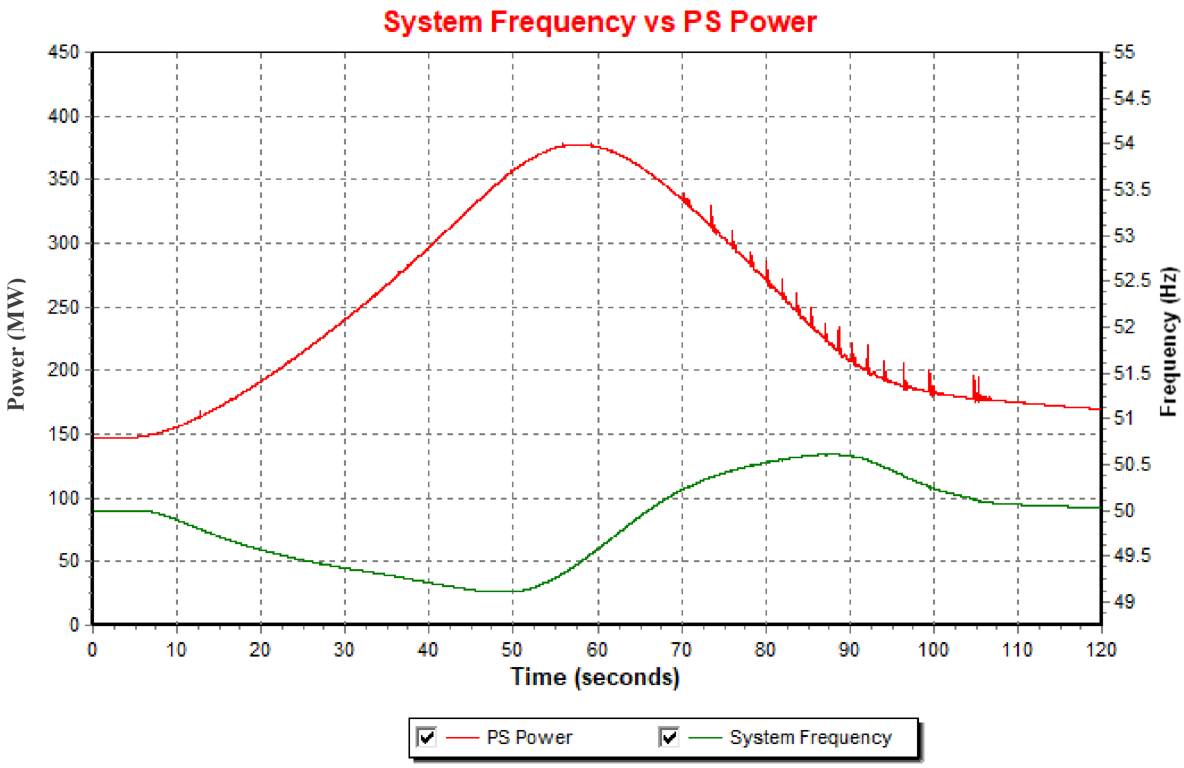
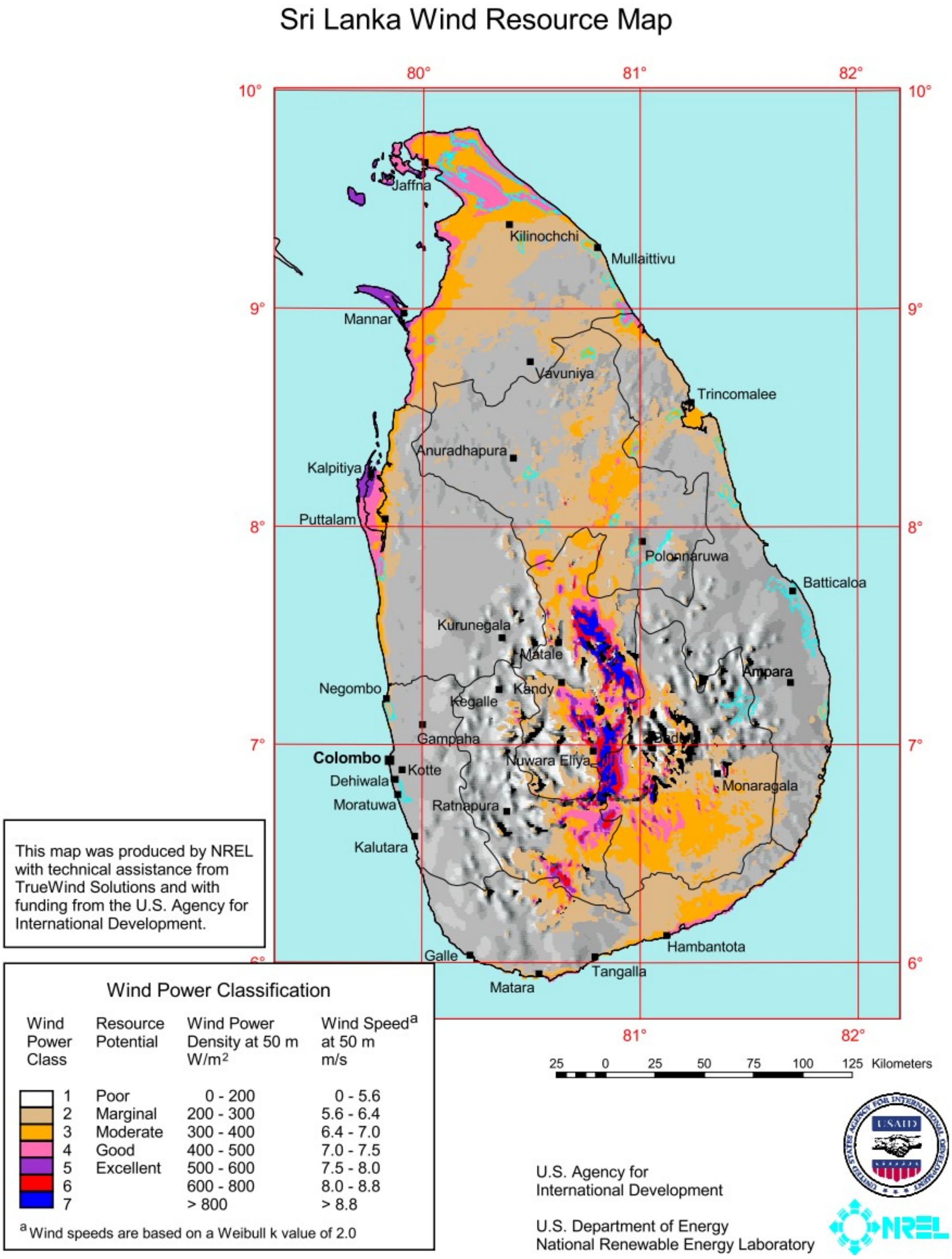
Appendix A: LNG Plant active power response with frequency variation



Appendix B: Pump Storage Plant active power response with frequency variation



Appendix C: Sri Lanka wind resource map



Appendix D: Wind turbine one second data

Time	Wind Speed (ms^{-1})	Power (kW)
20:42:32	10.1	688.88
20:42:33	10.3	717.19
20:42:34	10.5	741.09
20:42:35	10.7	756.47
20:42:36	10.9	769.38
20:42:37	10.8	770.67
20:42:38	10.8	764.49
20:42:39	10.5	752.59
20:42:40	10.2	743.68
20:42:41	10.2	732.79
20:42:42	10.1	718.60
20:42:43	10.2	703.18
20:42:44	9.9	687.87
20:42:45	9.6	676.08
20:42:46	9.5	669.47
20:42:47	9.5	670.19
20:42:48	9.7	670.80
20:42:49	9.5	669.68
20:42:50	9.6	668.79
20:42:51	9.5	667.67
20:42:52	9.7	665.48
20:42:53	10	653.48
20:42:54	9.9	637.48
20:42:55	9.5	622.50
20:42:56	9.4	612.08
20:42:57	9.6	609.67
20:42:58	9.9	614.59
20:42:59	10.2	632.67
20:43:00	10.3	658.69
20:43:01	10.3	686.90
20:43:02	10.4	707.49
20:43:03	10.3	720.68
20:43:04	10.4	719.28

Time	Wind Speed (ms^{-1})	Power (kW)
20:43:05	10.4	710.80
20:43:06	10.4	698.79
20:43:07	10.2	675.08
20:43:08	9.7	641.87
20:43:09	9.4	600.18
20:43:10	9.4	566.40
20:43:11	9.4	539.09
20:43:12	9.2	519.29
20:43:13	9	501.17
20:43:14	8.5	483.10
20:43:15	7.9	462.40
20:43:16	7.3	443.49
20:43:17	6.8	425.17
20:43:18	6.6	405.69
20:43:19	6.5	388.37
20:43:20	6.3	372.27
20:43:21	6.1	356.09
20:43:22	6.2	342.98
20:43:23	6.6	331.08
20:43:24	6.8	320.37
20:43:25	7.2	310.49
20:43:26	7.5	300.50
20:43:27	7.3	292.09
20:43:28	7.1	284.40
20:43:29	7.1	277.07
20:43:30	7	271.50
20:43:31	6.6	267.08
20:43:32	6.7	263.27
20:43:33	6.9	259.89
20:43:34	7.3	257.77
20:43:35	7.5	256.48
20:43:36	7.5	256.37
20:43:37	7.3	257.09

Time	Wind Speed (ms^{-1})	Power (kW)
20:43:38	7.2	258.49
20:43:39	7.5	260.79
20:43:40	7.9	263.59
20:43:41	8	268.37
20:43:42	8.3	274.19
20:43:43	8.5	280.98
20:43:44	8.6	290.29
20:43:45	8.4	300.50
20:43:46	8.4	312.00
20:43:47	8.6	325.69
20:43:48	9.1	344.38
20:43:49	9.9	364.47
20:43:50	10.6	389.08
20:43:51	11.2	425.49
20:43:52	11.6	472.28
20:43:53	11.7	526.47
20:43:54	11.7	579.37
20:43:55	11.6	625.77
20:43:56	11.2	661.67
20:43:57	11	693.58
20:43:58	10.8	716.37
20:43:59	10.9	742.67
20:44:00	11	761.18
20:44:01	11	779.58
20:44:02	11.1	794.28
20:44:03	11.1	811.57
20:44:04	11.1	826.19
20:44:05	11.1	836.58
20:44:06	11.2	844.48
20:44:07	11.3	849.88
20:44:08	11.4	852.97
20:44:09	11.4	853.90

Appendix E: Daily Generation curve