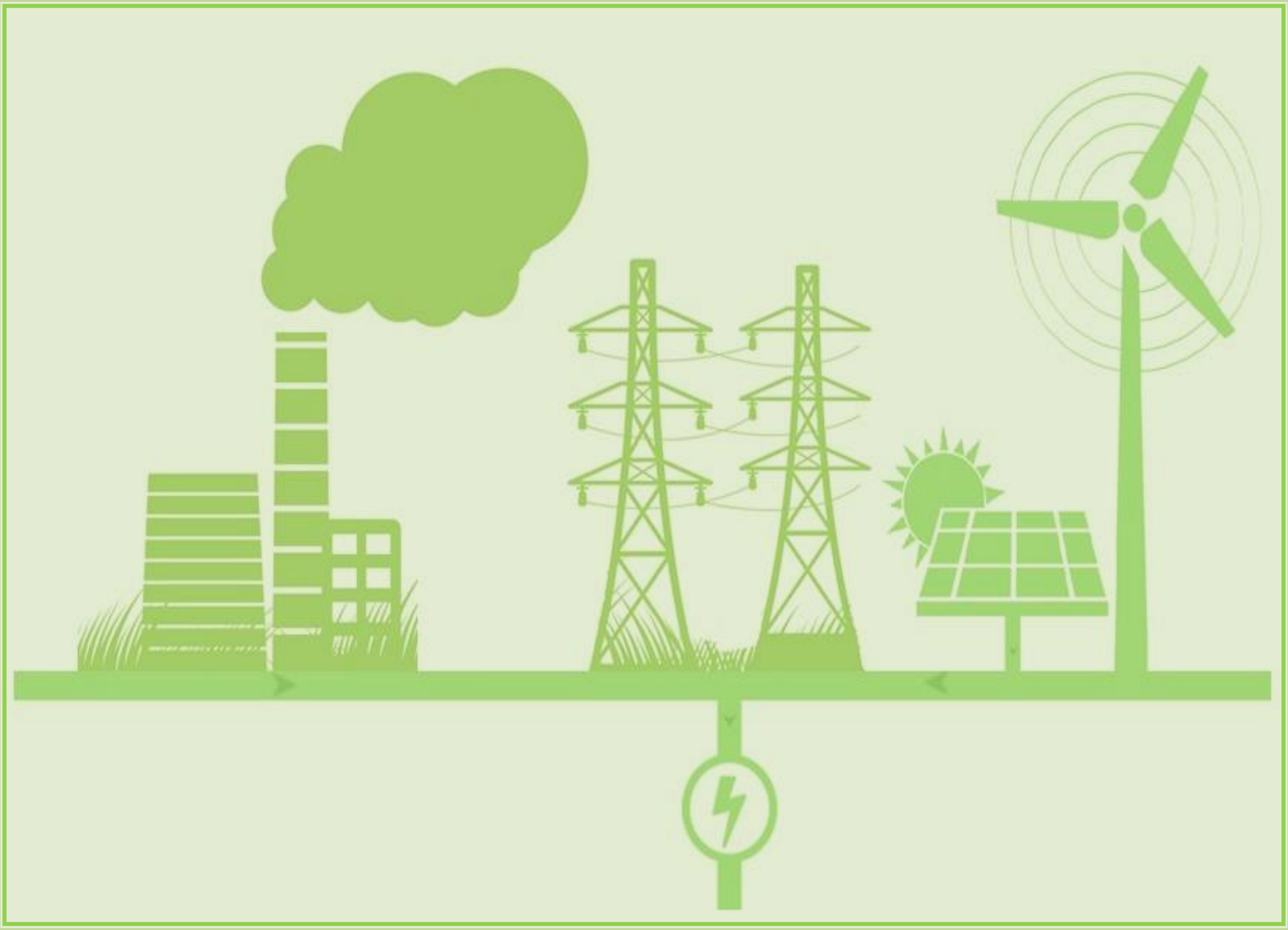
Renewable Energy Integration- Transmission an Enabler



A Report

Power Grid Corporation of India Limited

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Executive Summary

Presently total installed electricity generation capacity in India is about 305 GW (as on 31.07.16). Out of this about 14.5 % (44.23 GW) is through renewable generation (Wind (27 GW), Small Hydro (4305 MW), Solar (7805 MW) and balance biomass generation (4975 MW)).

Energy needs of the country is growing at a very fast pace to meet GDP growth rate. Present peak electricity demand of the country is about 160GW which is expected to grow to about 200 GW & 283 GW by the end of 2016-17 & 2021-22 respectively as envisaged in the 18th EPS report of CEA. However, above peak demand estimates are being reviewed by CEA which may be lower than above estimates as part of forthcoming 19th EPS. To meet growing demand and to reduce supply demand gap, there is a need of large capacity addition through conventional as well as from renewable energy sources. However, to achieve sustainable growth, energy security is of paramount importance.

Government of India is having an ambitious plan to achieve 1,00,000 MW Solar and 60,000 MW Wind generation in next five years. Solar capacity target of 1,00,000 MW by 2021-22 includes setting up of 34solar parks in various States, each with a capacity of at least 500MW (as ultra-mega solar power projects) thereby targeting around 20,000 MW solar capacity. These solar parks are envisaged by 2019. Balance Solar capacity comprises 40,000 MW Roof top Solar PV and 40,000 MW through distributed solar generation.

Wind and solar energy offer environmental benefits, low operating costs, and reduced dependence on imported fuel thus ensuring energy sustainability. However, wind and solar generation vary with wind speed, direction of wind and atmospheric temperature and solar insolation. This variability affects how power systems with high penetrations of renewable energy sources operate. Researchers across the globe are identifying these effects and finding solutions to address them to enable its grid integration. Apart from variability of RE resources other integration issues includes their integration cost, frequency response, system stability, system balancing etc.

In the same direction, an attempt is made to assess the balancing and stability issues with increased RE penetration in Indian context in this report. To analyse the above issues, two scenarios are considered for the timeframe of 2019. In one scenario 15% RE capacity penetration whereas in second scenario 30% RE capacity penetration is assumed for said timeframe.

Variability & Intermittency of Renewables: Power system from generation till consumption of power at load end has many variable parameters. On generation side renewable power generators (wind and solar generation) are considered to inherit most variability and intermittency. But, the demand side is also variable and changes every second. Power system operators cannot control the variation in demand but if we aggregate the variations in renewable generation over a large geographical area, we get lesser variation in generation pattern. An example of aggregation effect on wind and solar generation is shown below in Fig 1.

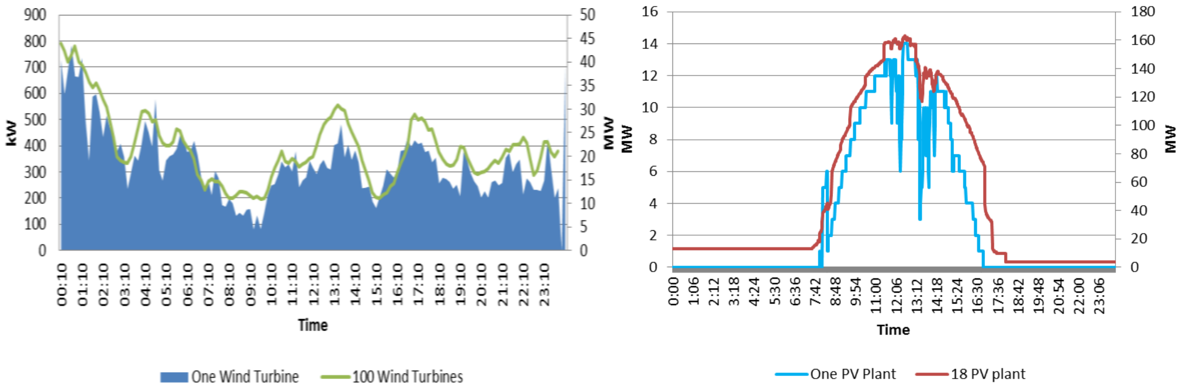


Fig. 1 Variation of Wind and Solar Power Output

Balancing Reserves: In order to meet the grid operating norms and maintain grid security, balancing reserves as well primary response is required from generation side. In lieu of this, CERC have issued many regulations and a roadmap to operationalize reserves into the grid from time to time.

According to CERC order "Roadmap to operationalize reserves in the country", a total of 12500 MW (4000 MW of Primary, 3600 MW of secondary and 4900 MW of Tertiary) of reserve is required to be maintained all the time.

Also, National Electricity Policy of 2005 mandates that a spinning reserve of at least 5% at national level should be created to ensure grid security, quality and reliability of power supply.

An exercise is done in this report to find the adequacy of balancing and ramping resources and was found that Indian grid can meet the balancing &ramping requirements in 15%scenario but not adequate in 30% RE penetration scenario for 2019-time frame. The summary of balancing reserve in both RE penetration scenario is as follows:

Table A: Balancing Reserve Requirement

RE Penetration Scenario	Balancing Reserve		Sufficient
	Required (in GW)	Available (in GW)	
15%	32	43	Yes
30%	48	43	No

In case of 30% scenario, the available reserve falls short of the requirement by about 5 GW. Hence, to meet the requirement in 30% scenario, there will be need of additional resources in the form of hydro or gas or any other resource which can provide flexibility of about 5 GW. This corresponds to additional installed capacity of 10 GW of either hydro (storage type) or gas [As a thumb rule, 50% of the capacity in summer is assumed to be available for balancing in hydro and gas]. In terms of supercritical plants, it corresponds to requirement of 25 GW of additional capacity. The additional requirement can be in the form of a combination of all these resources as well.

Further this balancing exercise has been carried out on all India aggregated level, if this is for specific states/regions, they may themselves fall short even in 15% scenario as in Tamil Nadu case presently due to which they have to resort to RE curtailment. Strong grid interconnections are essential to enlarge the balancing areas and to aggregate balancing resources as well.

Pumped hydro units are used to shift the load from peak hours to off-peak hours by consuming RE power during off-peak hours and delivering energy during peak hours. Reassessment studies carried out by CEA during 1978-87 identified 63 sites for pumped storage plants (PSP) with total installation of about 96,500 MW with individual capacities varying from 600 MW to 2800 MW. In India about 9 Pumped hydro storage units have been installed out of which only 4 (2450 MW) are operating in pumping mode. Rest units are in non-pumping mode due to various technical reasons. Details are given in following Table:

Table B: Pump Storage Plants in India

S. No.	Name of Project / States	Installed Capacity		Pumping mode operation	Reason for not working in pumping mode
		No. of units x MW	Total (MW)		
1.	Kadana St. I&II, Gujarat	2x60+2x60	240	**Not working**	Due to vibration problem
2.	Nagarjuna Sagar, Andhra Pradesh	7x100.80	705.6	**Not Working**	Tail pool Dam under construction
3.	Kadamparai, Tamil Nadu	4x100	400	Working	-
4.	Panchet Hill, DVC	1x40	40	**Not Working**	Tail pool Dam under construction
5.	Bhira, Maharashtra	1x150	150	**Not Working**	-
6.	Srisailam LBPH, Andhra Pradesh	6x150	900	Working	-
7.	Sardar Sarovar, Gujarat	6x200	1200	**Not Working**	Tail pool Dam under construction
8.	Purulia PSS, West Bangal	4x225	900	Working	-
9.	Ghatghar, Maharashtra	2x125	250	Working	-
		Total	**4785.6**		

Apart from above there are few other PSPs which are under construction/planning phase as given below:

Table C: PSP under construction/planned

S. No.	Name of the project/ State	Installed Capacity (MW)	Remarks
1.	Tehri St. – II, Uttarakhand	1000 MW (4x250 MW)	Under construction (Completion Expected by Sep 2019)
2.	Koyna Left Bank, Maharastra	80 MW (2x40 MW)	Under Construction
3.	Kundah, Tamilnadu	500 MW	DPR under preparation
4.	Malshej Ghat, Maharashtra	700 MW	DPR prepared by THDC. Implementation agreement to be signed.
5.	Humbarli, Maharashtra	400 MW	Under Survey & Investigation by THDC for preparation of DPR.
6.	Turga, West Bengal	1000 MW	Under Survey & Investigation by WAPCOS for preparation of DPR.
	Total	**3680 MW**	

As observed from above that PSPs being great balancing resource are not being used to their full potential due to technical and commercial reasons, there is a requirement for regulatory interventions/policy measures to encourage such projects. Efforts should also be made to expedite the commissioning of already under construction projects on time. In addition, there are many hydro plants which are feasible to be converted into pumped storage hydro plants. Feasibility should be evolved to encourage participation of such pumped storage plant for introducing more regulation into the grid with the increased renewable Penetration. Further, total envisaged PSP capacity 3680 MW need to be expedited for implementation particularly Tehri-II PSP which is in an advanced stage of construction.

Transient stability analysis and results:

One of the prime requirements for the operation of a power system is that the system needs to exhibit an ability to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. To assess the transient stability of a network, rotor angle stability and voltage stability are most relevant parameters.

In the present report, all India network is simulated in PSS/E to perform this study. Since India is emphasizing on large amount of renewable integration at utility scale progressively from present scenario, two scenarios of varying renewable capacity penetration (15% and 30%) in 2019-time frame are simulated to analyse its impact on stability of Indian grid. The Present Indian grid has nearly reached 15% renewable penetration. To reach 30% renewable penetration scenario, both unit de-commitment and lower conventional generation dispatch approach has been used. However, Rooftop and Distributed generation Solar expected to be interconnected at HV/LV network is not considered in these cases.

Study Assumptions: Based on the report on Partial Grid Disturbance in Western region grid on 12.03.14 (Mundra (4000 MW) generation tripping incident) and actual Restricted Governor Mode Operation (RGMO) response observed from major conventional generating stations in WR as well as operator feedback on governor response, governor action is considered only from reservoir type hydro generation (All India) as well as through thermal generators in southern region. However best and worst case are also considered where all governors are either active or inactive to see its impact on the grid while in different RE penetration scenarios. Wind and Solar generating units have been modelled using WECC recommended dynamic models.

To perform the transient stability study, various study scenarios have been simulated and effects of grid events in each region (NR, WR and SR) have been studied. The details of various scenarios studied are as follows:

Case-1.a (15%) & 2.a (30%): With governors in action & with reactive power support from solar inverters

Case-1.b (15%) & 2.b (30%): With governors in action & without reactive power support from solar inverters

Case-1.c (15%) & 2.c (30%): Without governor action & with reactive power support from solar inverters

Case-1.d (15%) & 2.d (30%): Without governor action & Without Reactive power support from solar inverters

In addition to these cases, a case of large RE generation complex tripping is carried out in all regions to study the impact of intermittency (sudden loss of huge generation capacity) of Renewable Generation.

Most of the existing as well as future potential of RE resources is in the northern, western and southern part of the country. Hence these three regions are considered to study transient stability. A large size renewable pocket is identified in three different regions and a three-phase fault was simulated (cleared after 100 ms followed with opening of line) in that pocket. Various parameters like frequency of the grid, conventional machine's rotor angle & power and voltages of buses located in three different regions and tie line flows between different regions are observed. Analysis of results included in the latter portion of the report.

The frequency response in case of all the studied scenarios for NR, WR and SR are shown below.

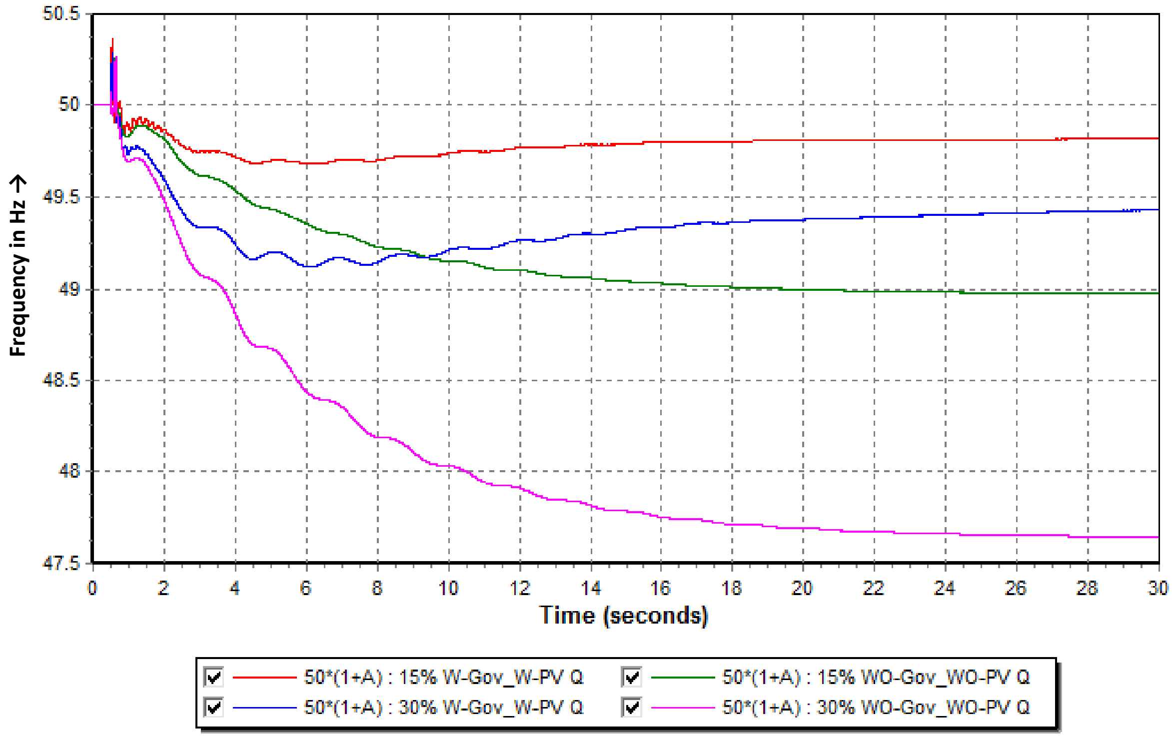


Fig. 2 Grid Frequency in Case of Bus Fault in NR

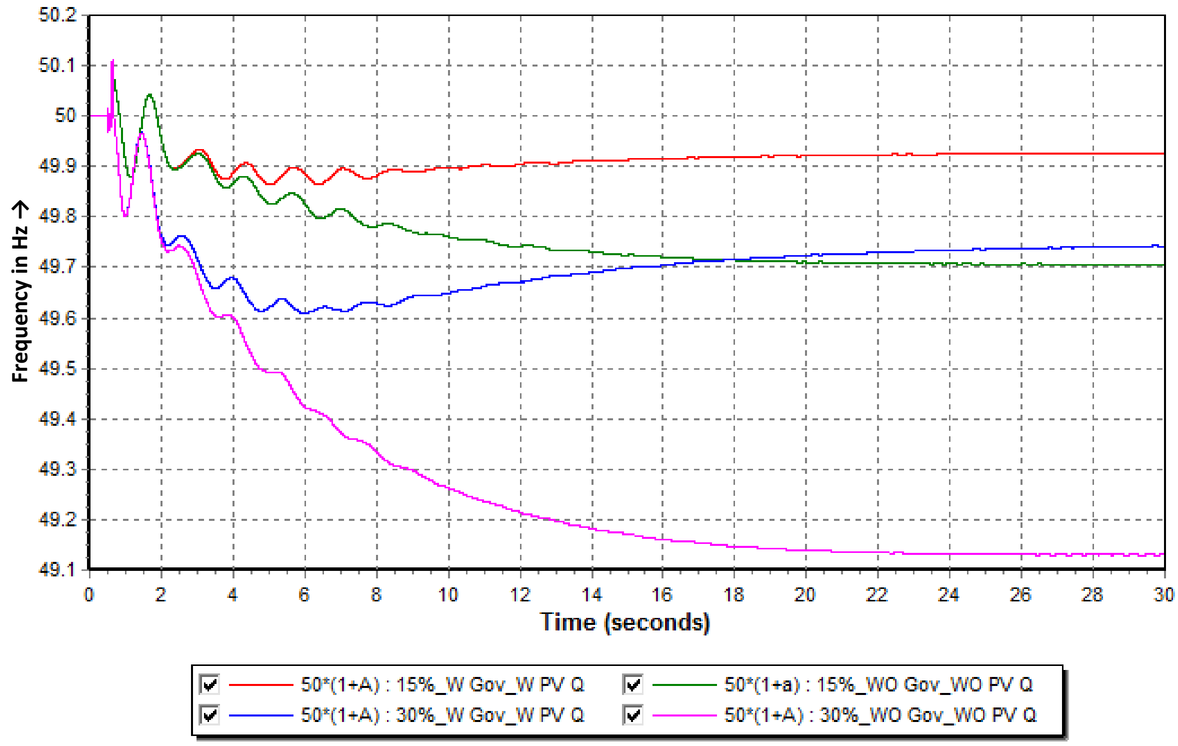


Fig. 3 Grid Frequency in Case of Bus Fault in WR

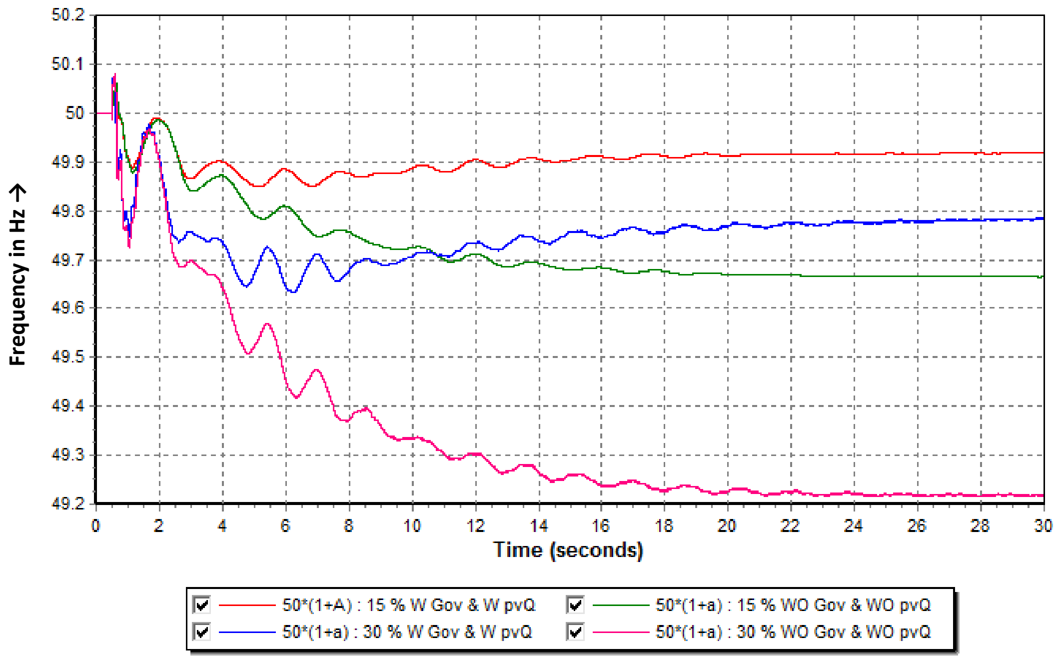


Fig. 4 Grid Frequency in Case of Bus Fault in SR

In all the above studied cases, it has been observed that power system is unable to restore frequency within IEGC grid frequency band of 49.9-50.05 Hz in post disturbance duration. Therefore, it is mandatory to enforce the governor operation of all available generating stations. Further support from secondary and tertiary reserves to restore the frequency within the band is required.

Apart from the regional case studies, few cases have been performed with the combination of enabled all India generator governor action, reactive power support from solar PV plants and LVRT compliance of Solar and Wind (only Type 3 and 4) plants.

With Limited governor action and with & without LVRT compliance:

As Low voltage ride through (LVRT) compliance is an important requirement from RE generators, a case has also been simulated to see the impact of LVRT compliance with limited governor response (majorly hydro). The plot of frequency variation with limited governors as well as LVRT compliance is as under:

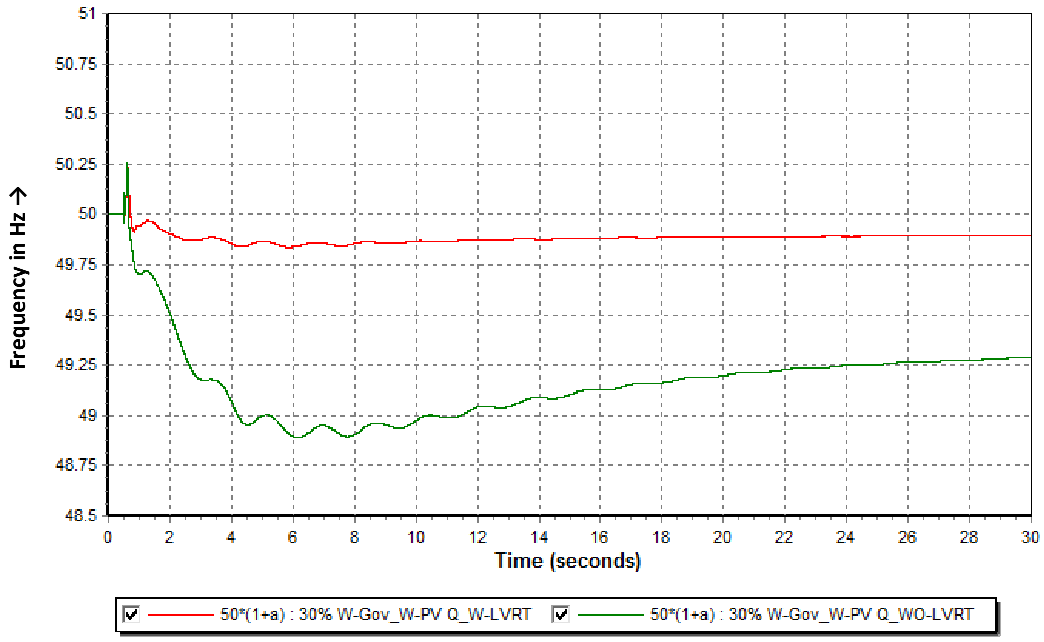


Fig. 5 Grid Frequency in Case of Bus Fault in NR

From above results it may be seen that LVRT compliance reduces the quantum of generation outage due to under frequency which in-turn helps the system in containing frequency drop during a major grid fault. In addition, if governor action of all thermal and hydro generators is considered, the steady state frequency will rise further in "49.9-50.05" Hz band.

Without LVRT compliance and with all India governor action:

In CERC order dated 13.10.2015 in matter of "Roadmap to operationalize Reserves in the country" governor action in the form of primary control for frequency containment drop or rise is mandated for all generating units as per IEGC provision. Further, secondary reserves through Automatic Generation control (AGC) need to be operationalized from 1st April, 2017. So, an additional case has been studied in which all the thermal generators have been considered with governor response. The plot of frequency variation in case of grid disturbance with governors enabled but without LVRT compliance is as under:

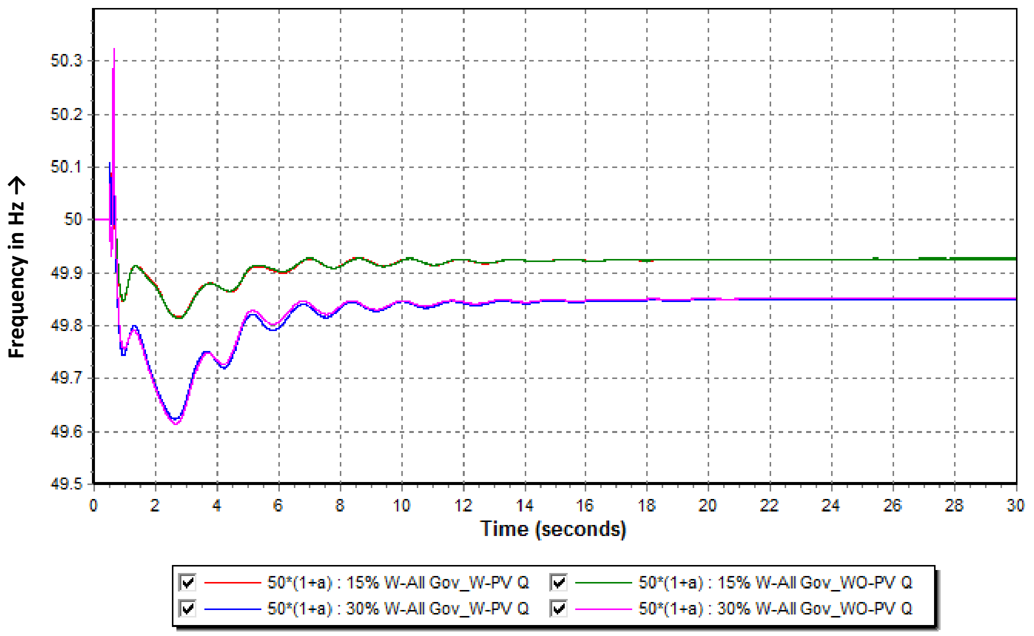


Fig. 6 Grid Frequency in Case of Bus Fault in NR

The above plot shows that the availability of governor response in thermal generators improves grid frequency response in case of severe faults and maintains frequency stability both in 15% as well as 30% RE capacity penetration case even without LVRT compliance. Also, as mentioned earlier in RE balancing that there is a shortfall in balancing reserve in case of 30% RE penetration scenario, which above graph also confirms.

Key Findings:

Through balancing resource as assessment exercise and transient stability analysis, key findings are as under:

1) **Variability and Intermittency**: Variability and Intermittency characteristics of RE can be subsided by dispersing RE generators on a wider geographical area i.e. aggregation.
2) **Reserve requirements by 2019**: 15% (74 GW) RE capacity penetration can be accommodated in grid by existing flexible generating sources in the grid (required: 32 GW, available: 43 GW) while for 30% (116 GW) RE capacity penetration, additional flexible reserves of about 5GW (required: 48 GW, available: 43 GW) is required. This corresponds to additional installed capacity of 10 GW of either hydro (storage type) or gas. In terms of supercritical plants, it corresponds to 25 GW of additional installed capacity. The additional requirement can be in the form of a combination of all these resources as well. Further scope for optimizing the existing hydro resources through regulatory initiatives at the intra state level also need to be recognized.
3) **Flexible generation:** Conventional generations are the major source of power system flexibility. Therefore, to operate grid under stable operating limits in high RE

penetration scenario, Governor Action and automatic voltage regulator (AVR) action of conventional machines are mandatory.

4) **LVRT compliance**: Due to large quantum of renewable generation at one site and absence of inherent inertial response, frequency response characteristics of the grid degrades and that is why requirement of spinning reserve in case of RE generation outage increases. To prevent this situation, Low Voltage Ride Through (LVRT) compliance of large scale RE generators are must.

5) **Outcome of Transient Stability results:** Angular stability is found not to be the limiting constraint for studied levels of RE penetration. From the results, it may be concluded that the overriding requirements for the grid security in case of large Scale RE penetration will be governor action, LVRT compliance and reactive support from grid scale PV power plants. Further, Inter-area oscillations present in some of the tie lines can be suppressed with the help of Power System Stabiliser (PSS) tuning.

Way Forward:

In order to facilitate implementation of higher penetration of RE and address above mentioned issues, it is proposed that following actions may be taken up.

- Provision of increased balancing reserves of about 5 GW by 2019 through various measures including regulatory initiatives at the intra state hydro level
- Enforcement of primary, secondary and tertiary reserves in line with CERC order "Roadmap to operationalize reserves in the country."
- Enforcement of governing action in all eligible generating plants.
- Technical Standards and protection requirement for renewables and Implementation
- Implementation for frequency response
- Need for LVRT regulation for large scale grid connected Solar Plants as well as HVRT requirement for wind & solar both.
- Implementation of Time of Day (ToD) tariff as a part of demand side management for all major categories of consumers.
- Demand Response (automatic/manual load control) as an additional measure to balance renewable generation
- Enforcement of power plant operation at technical minimum at 55% as mentioned in Central Electricity Regulatory Commission (Indian Electricity Grid Code) (Fourth Amendment) Regulations, 2015 with similar dispensation at the intra state level.
- Explore the possibility of further bringing down the technical minimum from 55% to 40% in case of some coal fired units for bringing about additional flexibility
- Policy & Regulation for development of transmission system for Single window clearance/ RE zones etc.
- Forecasting & Scheduling regulation at Inter and Intra-state level
- Regulation for Flexible Generation and Generation Reserves
- Research &Skill development in forecasting technologies

- Capacity Building of SLDC particularly in RE rich states.
- Introduction of PSS tuning in all eligible generating units.
- Deployment of Phasor Measurement Units in grid for better real time monitoring of power system health
- Establishment of new Pump storage plants identified by CEA as a balancing source and ensuring operation of existing PSPs in pumping mode.

Implementation for frequency response regulation: IEGC Regulations, 2010 mandates that "All thermal generating units of 200 MW and above and all hydro units of 10 MW and above, which are synchronized with the grid, irrespective of their ownership, shall have their governors in operation at all times…". Regulation also mandates that "All generating units shall normally have their automatic voltage regulators (AVRs) in operation."
The compliance to above regulations helps power system in maintaining grid stability in case of generation outages. However, past WR UMPP generation outage event has shown that majority of generators are non-complaint to these regulations which imposes a great challenge in case of high RE penetrated power system.
To address the grid stability issue due to lack of spinning reserve, CERC has issued an Order in the matter of "Roadmap to operationalize reserves in the country."

Ancillary Service regulation at inter and intra-state level: Ancillary Services need to be put in place as a complementary support services for reliable operation of the electricity grids. Ancillary Services provide a framework for operationalizing the spinning reserves and the modalities of scheduling, metering and settlement of the reserves. It would address congestion management issues and facilitate optimization at Regional & National Level and thereby facilitate integration of renewables too. Ancillary services are being implemented at the inter-state level and a similar framework needs to be implemented in the States also.
CERC "Ancillary Services Operations Regulations, 2015" in ISTS have been implemented on April, 2016.

Regulation for flexible generation and generation reserves: With increased level of RE penetration in grid, requirement of balancing reserve will increase. To meet balancing requirements CEA and CERC have issued many recommendations for conventional machines like minimum technical limits, governor action, ramp up/ramp down rate, etc. However, suitable commercial compensation mechanism has to be devised to promote such operation by conventional plants.

Skill development on RE/Demand forecasting and Capacity building: The personnel of SLDC/STU need to be trained on forecasting and scheduling of renewable generation sources.

Demand Response: Demand response can be used as an additional source of power system flexibility to compensate for the variability and uncertainty of RE generation. The gap between generation and demand can be reduced by careful planning on demand side. Contrary to load curve of developed nations developing nation has peak load in evening time. During peak load hours solar generation is not available and it reduces the effective utilisation of renewable energy sources. The Time of Day tariff mechanism can be very effective way to manage demand and shift evening peak to other than peak time when solar generation is at max. This requires time of day tariff implementation at all categories of consumer.

Also, with the help of smart meters with demand management system installed, variability and intermittency of renewable generation can be mitigated.

Electrical Energy Storage (EES) system: Electrical Energy storage system, due to its tremendous range of uses and configurations, may assist RE integration in many numbers of ways. These uses include, inter alia, matching generation to loads through time-shifting; balancing the grid through ancillary services, load-following, and load-levelling; managing uncertainty in RE generation through reserves; and smoothing output from individual RE plants.

The battery energy storage system (BESS) performs majorly two applications, energy application and power application. In energy application, BESS stores excess energy during off-peak hours and provide electrical energy during peak hours. In power applications, BESS is used to smoothen the renewable generation output and helps in maintaining the forecast vs. actual generation. The BESS is very fast acting system and can come online in matter of seconds.

Along with the above mentioned technical frameworks, required commercial frameworks/regulations like market design in case of high RE capacity generation in total power generation portfolio, incentivizing flexibility in conventional generation need to be addressed by MoP/CEA/CERC.

CHAPTER 1

INTRODUCTION

Chapter-1

Introduction

1.1 Background

To attain energy security and address environmental concerns, India is emphasizing on harnessing renewable energy resources. Presently installed generation capacity in the country is about 305 GW (Jul'16) which constitute capacity from conventional sources viz. coal (186.2 GW), Gas (24.5 GW), Nuclear (5.78 GW), and Large Hydro (42.85 GW). Balance 44.23 GW (14.5%) contribution is from renewable generation capacity which has 26.87 GW (62.7%) contribution from wind alone. Government of India is having ambitious plan to achieve 175 GW of renewable generation capacity by 2022 which include 100 GW from Solar, 60 GW from wind and balance from small hydro, Biomass etc.

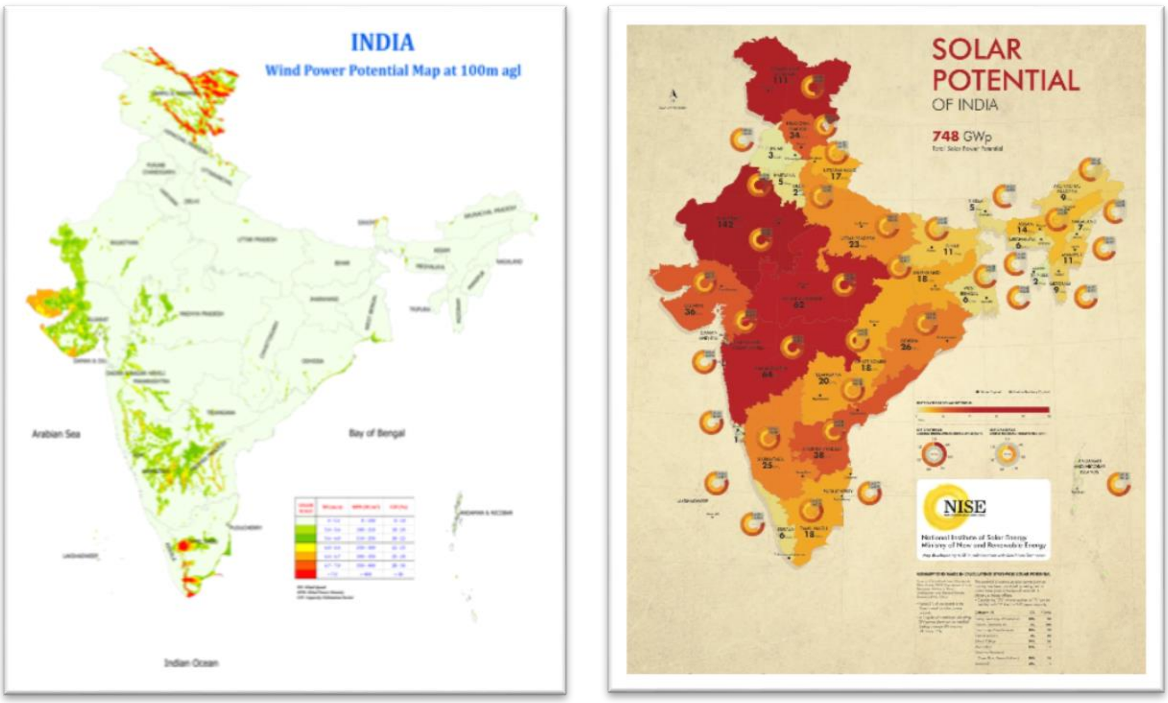


Figure 1 : Wind and Solar Potential in India (Source: MNRE)

In view of the greater RE penetration in future and its impact on grid due to its inherent characteristics of variability & intermittency characteristics, it is prudent to carry out balancing & Stability studies. In the present studies, Balancing study assesses adequacy & requirement of balancing & ramping generation reserves to mitigate volatility of RE through Net Load analysis. Stability studies are carried out to see impact of faults/intermittency with different order of capacity penetration (15% & 30%) on Frequency, Rotor Angle and Voltage Stability in the system.

1.2 Variability & Intermittency of Renewables

Wind and solar energy are considered as variable renewable generation resources because production varies based on the availability of natural resources i.e. wind and sun. However, they are not the only source of variation in a power system. The demand for electricity/load, also varies, and the power system was designed to handle that uncertainty. Short-term changes in load (over seconds or minutes) are generally small and caused by random events that changes demand in different directions. Over longer periods (several hours), changes in load tend to be more predictable. For example, there is a daily pattern of morning load pickup and afternoon load drop-off highly correlated with human behaviour. The key difference is that load variations are better understood/forecasted than wind and solar variations.

Some aspects of renewable energy variation are easily predicted. For example, the electricity production of an individual wind turbine is highly variable. But the aggregate variability of multiple turbines at a single site is significantly less. Further the aggregation of multiple wind generation sites over a large geographic area results in even lesser variability. Harnessing the "law of large numbers," variability smoothing over large areas, yields enhanced prediction. Variability also decreases as the timescale decreases. The variability of large-scale wind power over seconds or minutes is generally small. Over several hours, however, it can be large.

Figure 2 shows typical power generated by one and 100 wind turbines in a day at a location in Gujarat. It can be seen from the plot that 100 wind turbine power output is much smoother as compared to individual wind turbine.

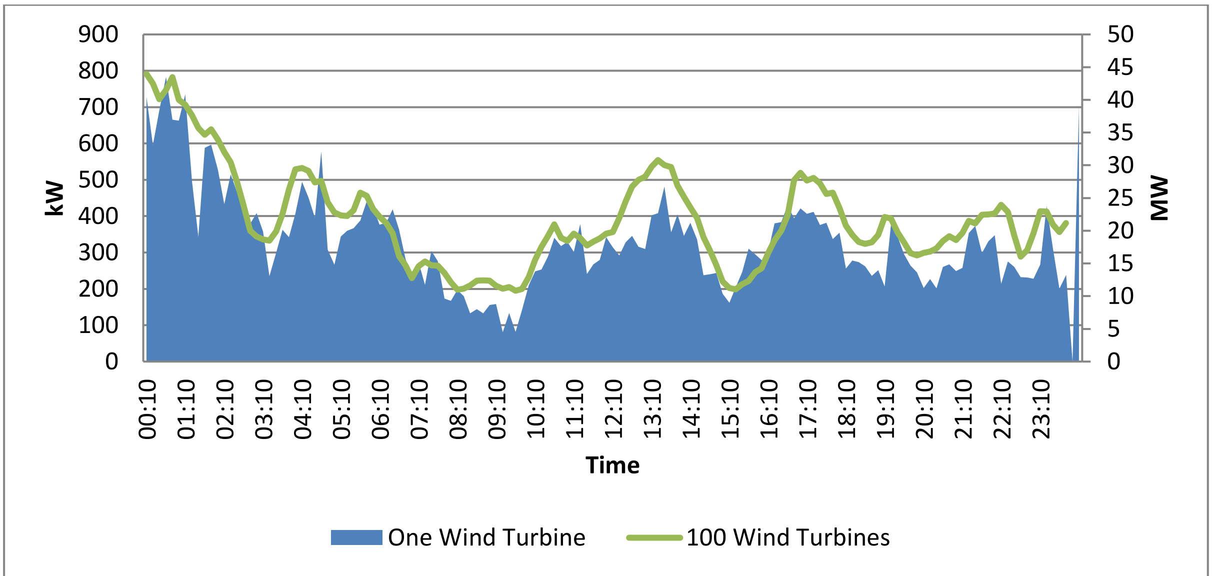


Figure 2: Wind Power Generation Profile of One and 100 Wind Turbines

Aggregation of Wind turbines/ Solar PV can be at plant level as well as at different plant locations. Power variability of wind plants dispersed at various geographic locations also reduces up to certain extent by aggregation of those plants over a time. *Figure 3* shows a wind power plant output of three different plants located in northern, western and southern part of India. *Figure 4* shows the aggregate output of all three plants which is much smoother than the individual wind power plant output.

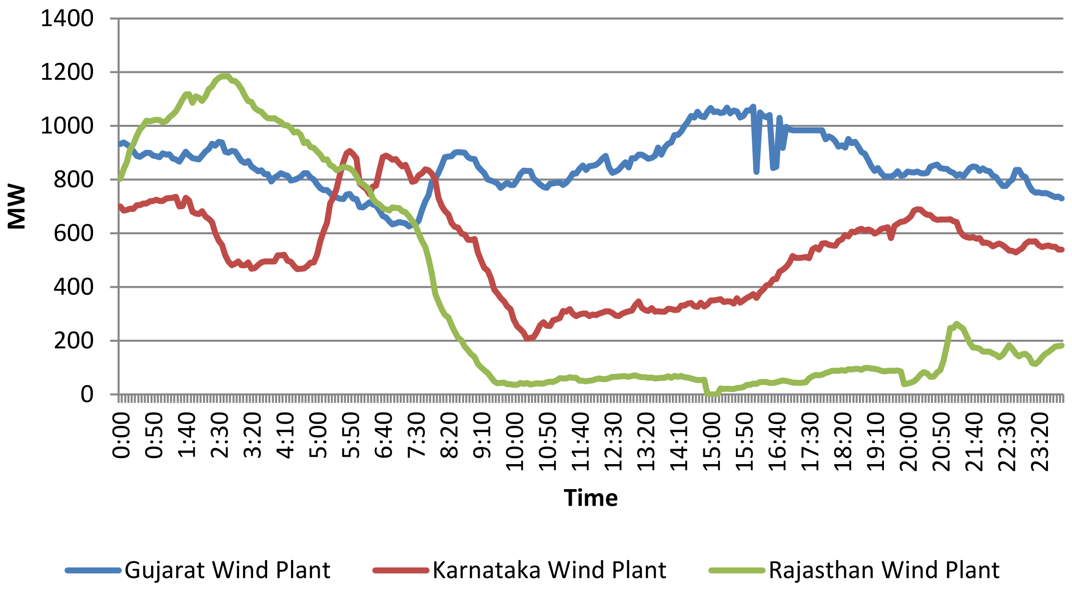


Figure 3: Typical Wind Power Plant Generation in Gujarat, Karnataka and Rajasthan

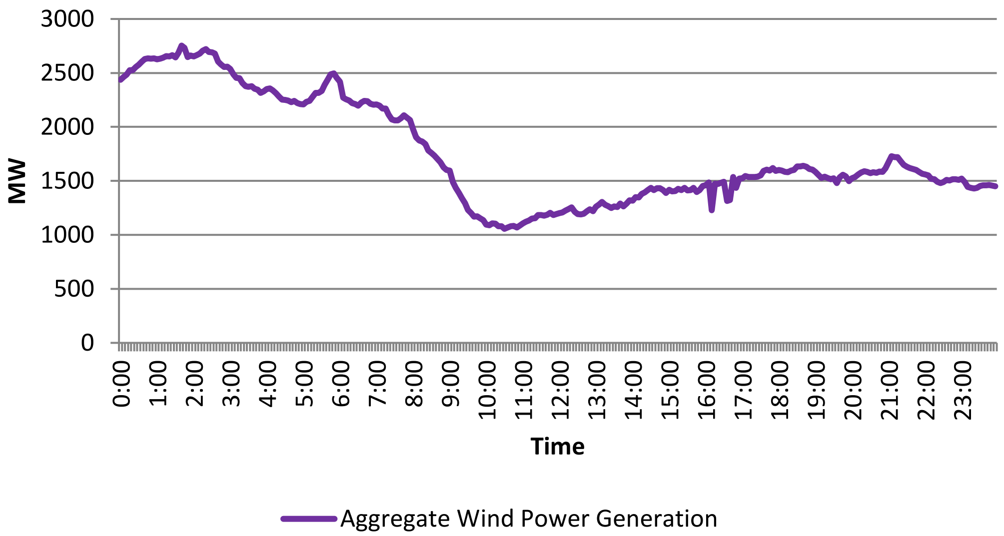


Figure 4: Aggregate Wind Power Generation of above Wind Power Plants

Solar PV plants also have characteristic of intermittency and variability. Variability is a measure of how the output from solar PV setup changes on a daily or longer period basis whereas intermittency is a measure of random changes (and disappearances) in PV output due to clouds. Some aspects of solar variability are predictable (for example, sunrise and sunset). Other aspects, such as intermittent cloud cover, are much less so. However, the same reduction in variability is observed for the aggregation of solar photovoltaic plants over a broad geographic area. *Figure 5* exhibits aggregation effect of one solar power plant and 18 solar PV Plant of a location in Gujarat.

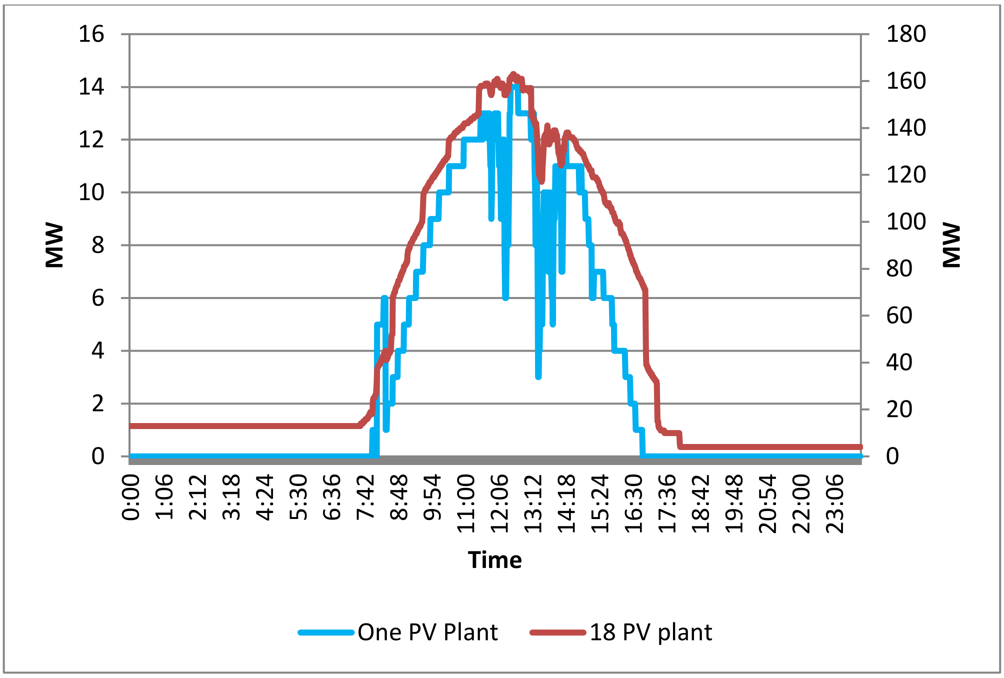
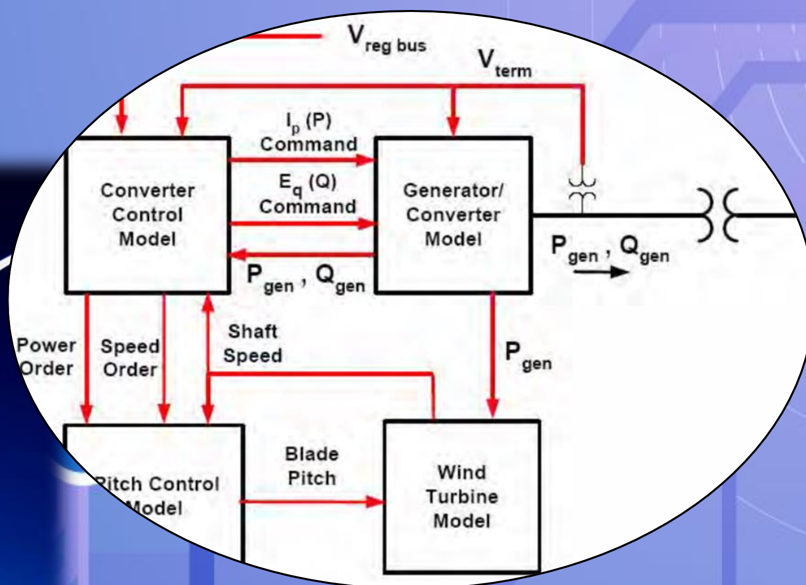


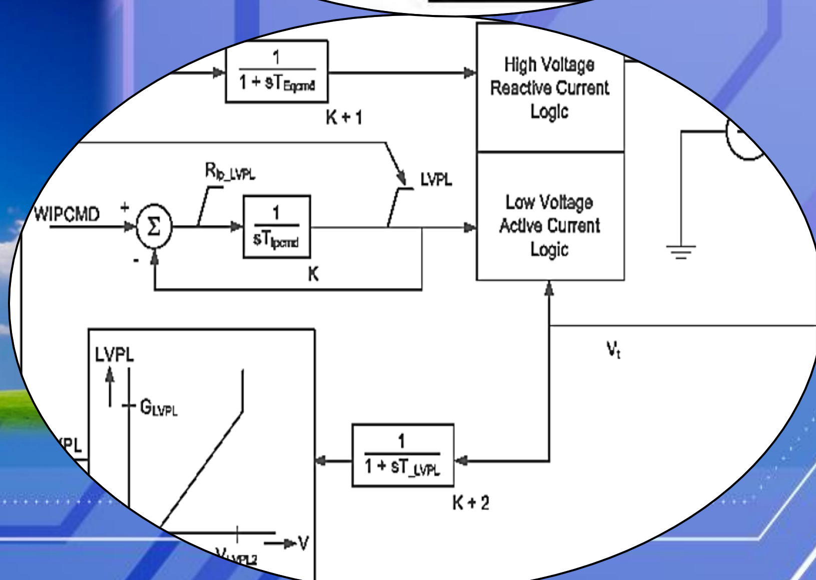
Figure 5: Aggregate Effect of Solar Power Plant Output of a location in Gujarat

All types of variability are being managed by the electric power system operator along with variable reserves/controls. With low penetrations of variable generation, the related impact and response are small because the wind and solar variability is much less than the load variability. At high penetrations, however, the renewable variability may be more challenging to respond to. In case of higher penetration of renewables, grid stability is also of major concern. Present study makes an attempt to analyse the impact on grid balancing and stability of varying RE with increased penetration level.

CHAPTER 2

RENEWABLE GENERATOR MODELING





Chapter-2

Renewable Generator Modelling

2.1 Wind Energy Turbines Models

In India, various types of wind turbine generator (WTG) are/being installed. As per WECC (Western Electricity Coordinating Council), WTGs are classified in following four types (*Figure 6*):

- Type 1 WTG – Fixed speed, Induction generator
- Type 2 WTG - Variable slip, Induction generator with variable rotor resistance
- Type 3 WTG - Variable speed, doubly fed asynchronous generators with rotor side converter
- Type 4 WTG – Variable speed generator with full converter interface.

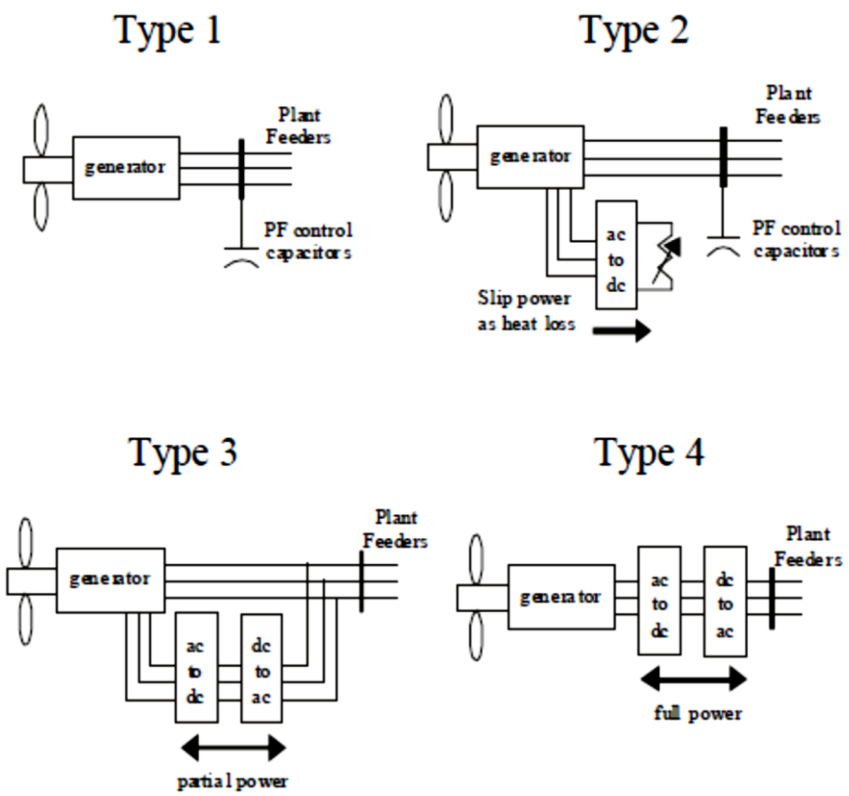


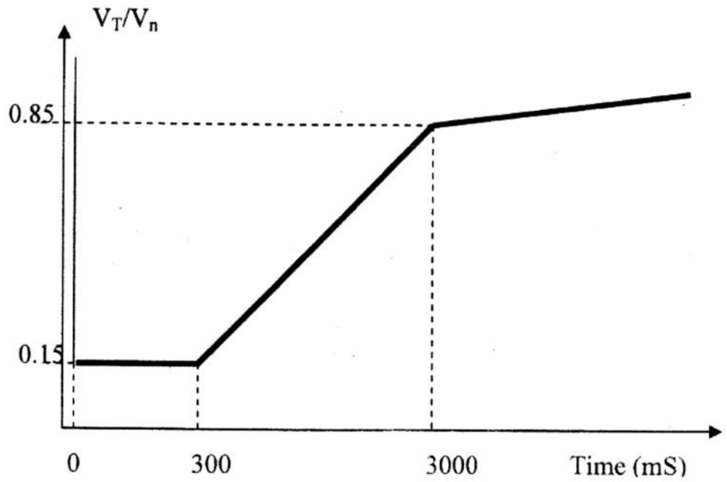
Figure 6: Wind Turbine Types

Out of these first three WTGs are Induction machines and forth type is a synchronous machine. Induction generators during their operation always absorb reactive power from the grid. They cannot supply reactive power to grid in any condition at their own. Synchronous machines have capability to supply reactive power to the grid as well as absorb reactive power from the grid during different operating conditions.

Due to such requirements, whenever a fault occurs near to a wind generation plant, voltages of surrounding buses drops including wind pooling station and electrical power supplied by generator also decreases instantaneously. But mechanical power input to the generator does not reduced instantaneously. Under this situation, the speed of generator can increase drastically. To avoid this, inbuilt protection system in generator disconnects it from the grid and wind turbine is stalled effecting supply to the grid.

Additionally, under such scenario, if a wind generation plant (Induction generator) keeps absorbing reactive power from the grid, then voltage at interconnection may drop further. Hence, to avoid such situation presently wind generation plants are disconnected from the grid instantaneously when the voltage at interconnection point falls below 0.85 pu (protection setting) as per the information received from wind IPPs. This issue is termed as Low Voltage Ride through compliance. This may become major issue, if such contingency arise near large capacity wind farm. In such situation, loosing of large capacity may impact reliability of power supply due to load generation mismatch, affect grid stability as well as financial burden on utility due to Deviation Settlement.

To keep stability of grid into mind various regulations have been notified by CEA. Technical Standard for Connectivity to Grid (Amendment) regulation 2013 has been published on 15 October 2013 in official Gazette. These regulations mandate wind generating station getting connected on or after completion of 6 months from date of publication of these regulations to comply with Fault ride through (FRT). In view of these regulations wind generating station connected at voltage level of 66 kV and above shall remain connected to grid when voltage at interconnection point on any phase or all phases dips up to level depicted by thick lines in following curve.



Where

V_T/V_n is the ratio of the actual voltage to the nominal system voltage at the interconnection point

Figure 7: Low Voltage Ride through (LVRT) Curve

Fault Ride Through (FRT) & Low Voltage Ride through (LVRT): The significant share of the wind power in the grid requires the wind generation remains in operation in the event of network disturbances like faults or sustained low voltage called as Fault ride through. The wind farms should also withstand with short term low voltages in the grid from the stability point of view is which is defined as low voltage ride through.

2.2 Solar PV Models

The solar PV plant model is largely based on the generic Type-4 wind model WT4. PV panels are decoupled from the grid by a power converter which is actually connected to the grid. PV plants are connected to the grid using the same technology used by Type-4 wind farm. From the point of DC link to grid connection, both PV and Type-4 wind technology use similar control and inverter technology to inject power to the grid.

2.3 Literature Survey

Most of the literature in this field focuses on identifying some of the problem associated with high PV penetration levels, but they are mainly focused on distribution systems. Very few studies are found in literature for high PV penetration level at utility scale. As the penetration of solar PV/Wind plant increases, its impact on the stability and operation of the grid needs to be well understood. Effects of tripping of a large PV plant are studied in and frequency response, output power from conventional unit and voltage response of buses are observed.

Similarly, a study has been carried out by National Renewable Energy Laboratory (NREL)to understand impacts of high RE penetration levels in North American Grid (Western wind and solar integration study phase III (WWSIS-III)), which carried out analysis on impact of two specific types of power system stability: frequency response and transient stability. The report concluded that it has not found any technical reasons to limit the increasing penetration of Renewable generation in the grid provided proper system planning and power system engineering practices has been followed.

High penetration level can significantly affect the steady state as well as transient stability of the system due to their distinct characteristic that differ from conventional generation resources. Considering above, the scope of the work is kept to identify the Impact of high PV/Wind penetration on the grid through analysing Frequency, voltage as well as rotor angle stability under various scenarios.

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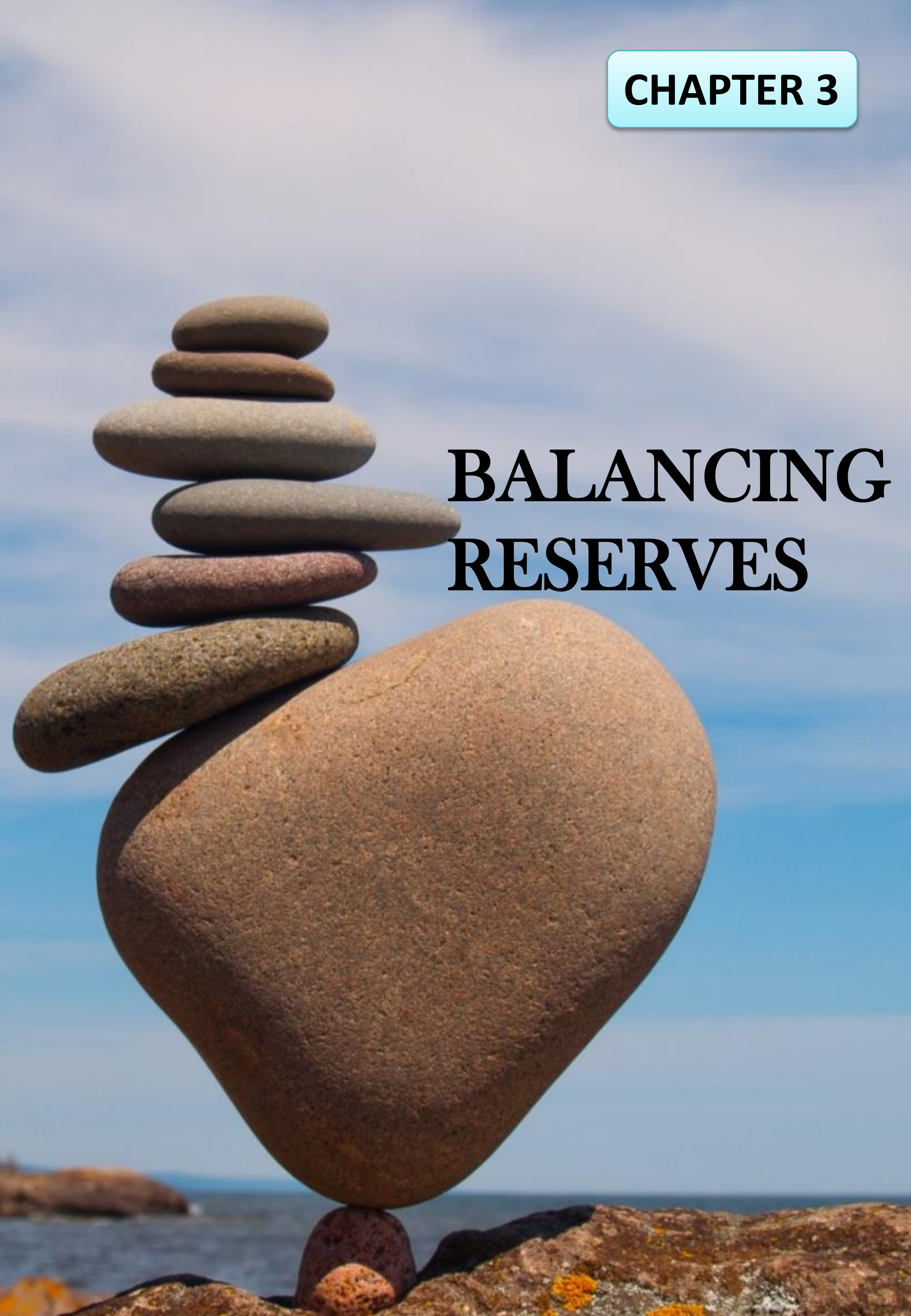
CHAPTER 3

BALANCING RESERVES



Chapter-3

Balancing Reserves

3.1 Balancing Requirements

In order to analyse increased need of system flexibility in terms of generation, load etc. on account of high renewable penetrations and its impact on power system, concept of “Net load” is derived and evaluated. This “Net-load” represents the demand that must be supplied by the conventional generation fleet if all of the renewable energy is to be utilized. The yellow area in the graph as under (*Figure 8*) represents demand, and shows the daily variability of demand on an hourly basis for a typical day. The green shows solar and wind energy, and the orange represent the demand-less-solar and wind energy that must be supplied by the remaining generators, assuming no curtailment of RES. The graph shows that the output level of the remaining generators must change more quickly and be turned to a lower level with penetration of solar and wind energy in the system. The figure also illustrates how wind generation can lead to steeper ramps, deeper turn downs and shorter peaks in system operations deliberated as under:

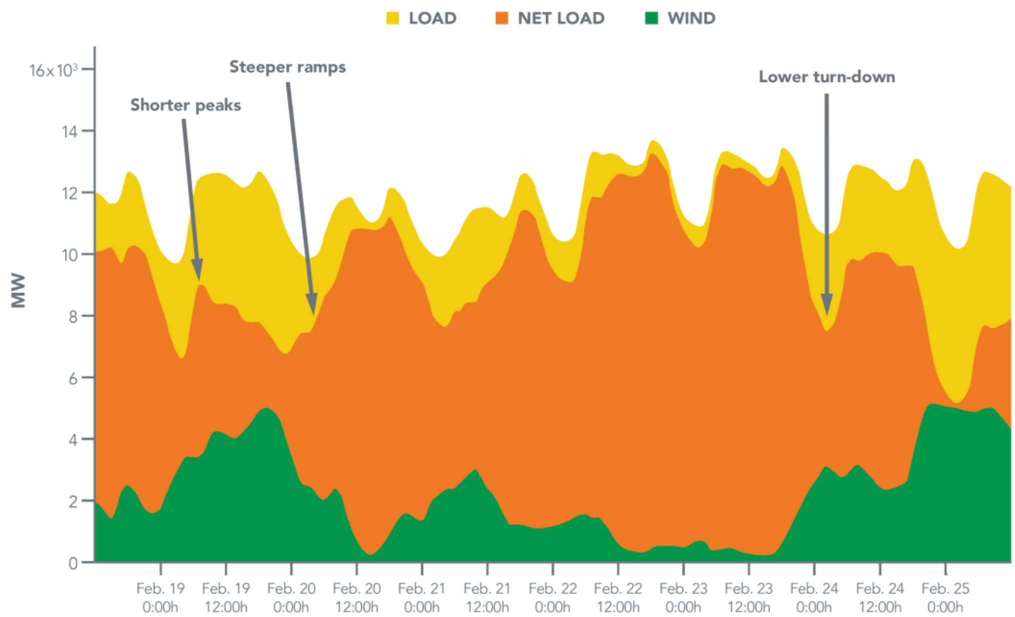


Figure 8: Typical Net load curve (Source-Flexibility in 21st century report)

Ramps – the rate of increase or decrease in dispatchable generation to follow changes in demand. Ramps can be steep if wind generation is decreasing at the same time that demand rises or vice-versa. In such situations, there may be a limit on dispatchable generator ramping rate that how much faster it can ramp down/up to accommodate rising/decreasing RE output feeding into the system.

Turn-downs - operation of dispatchable generators at low levels. High wind output during periods of low demand creates a need for generators that can turn down output to low levels of technical operation limits but remain available to rise again quickly.

Shorter peaks – Periods where generation is supplied at a higher level. Peaks are shorter in duration, resulting in fewer operating hours (low Plant Load Factor) for conventional plants, affecting cost recovery and long term security of supply.

In order to see balancing scenarios for different level of RE penetration (15% and 30%), balancing as well as net load curves are analysed as under for both scenarios for timeframe of 2019.

Also, balancing scenarios for Northern, Southern and Western region for 2019 timeframe for 15% & 30% scenario is shown in *Figure 11* to *Figure 16*. These plots are obtained by extrapolation of present day generations based on their present Installed Capacity (IC) and estimated IC by 2019.The regional scenarios are hypothetical where the complete regional demand is met by their own available resources. In western region, there will be need to shut down or reduce dispatch of some conventional plants to accommodate RE generations as must run. Other regions NR & SR can meet their estimated demand by 2019 by their envisaged resources. (Even though the current scenario is different where both NR & SR are importing power from WR & ER).

<u>All India Balancing Curve for 2019 (15 % RE Scenario):</u>

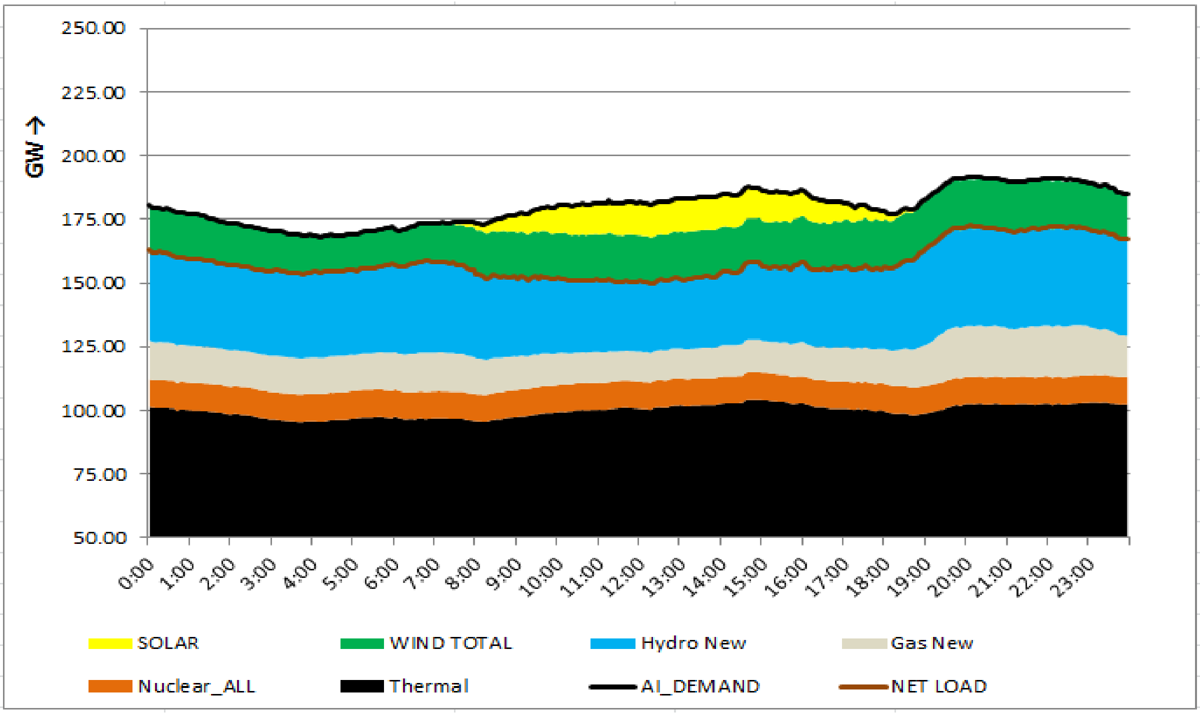


Figure 9: Typical Daily Load Generation Balancing Curve for 15% RE Penetration

All India Balancing Curve for 2019 (30% RE Scenario):

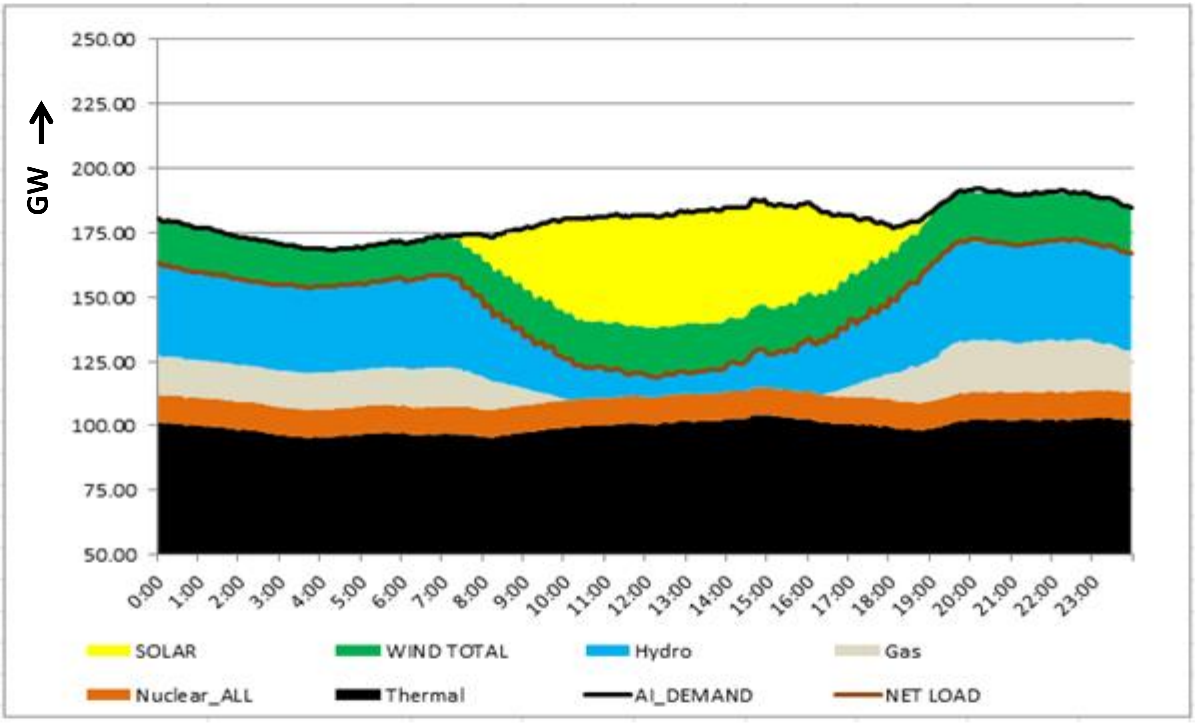


Figure 10: Typical Daily Load Generation Balancing Curve for 30% RE Penetration (Source-NLDC)

Southern Region Balancing Curve for 2019 (15% RE Scenario):

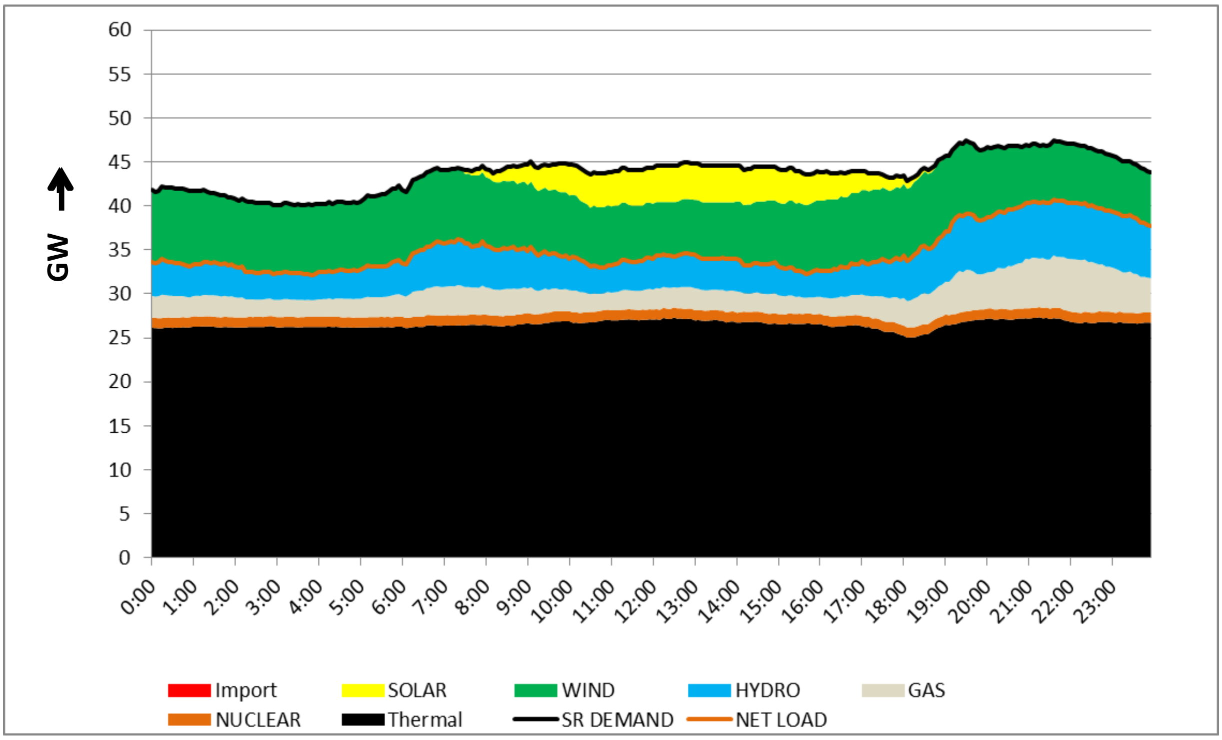


Figure 11 : Typical Daily Load Generation Balancing Curve for Southern Region 15%RE Penetration

Northern Region Balancing Curve for 2019 (15% RE Scenario):

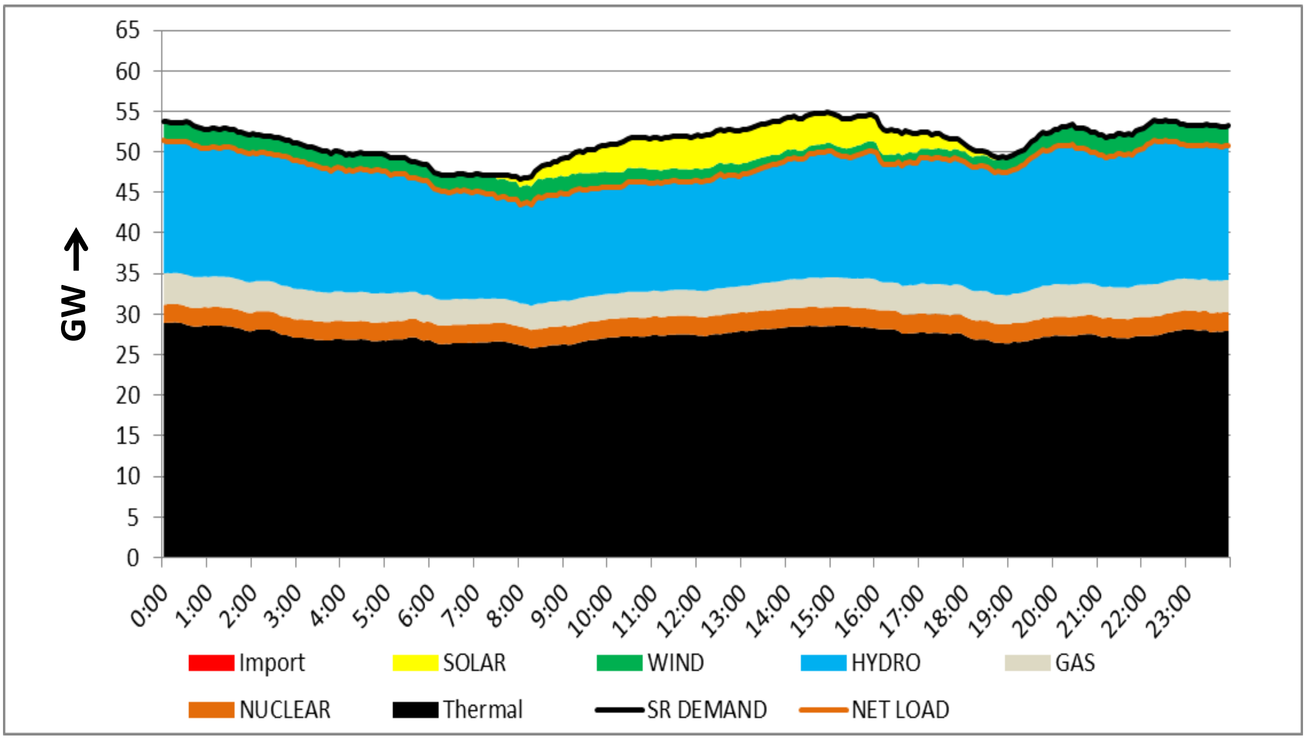


Figure 12: Typical Daily Load Generation Balancing Curve for Northern Region 15% RE Penetration

Western Region Balancing Curve for 2019 (15% RE Scenario):

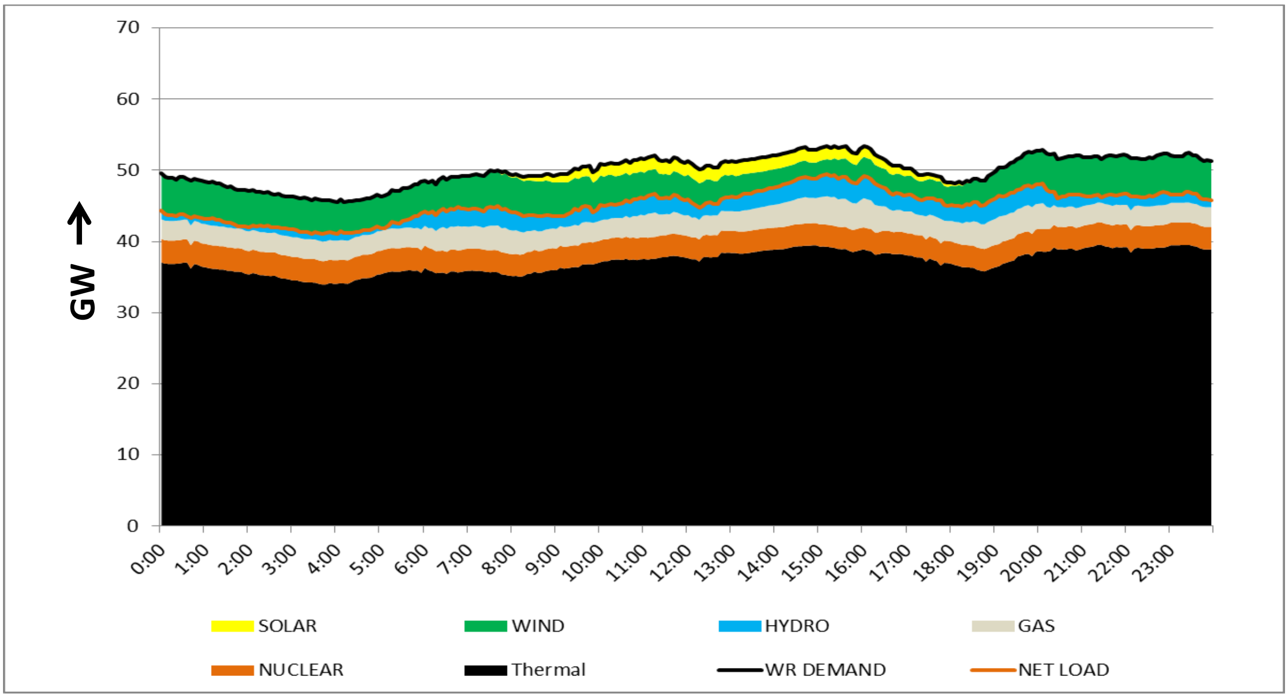


Figure 13: Typical Daily Load Generation Balancing Curve for Western Region 15%RE Penetration

Southern Region Balancing Curve for 2019 (30 % RE Scenario):

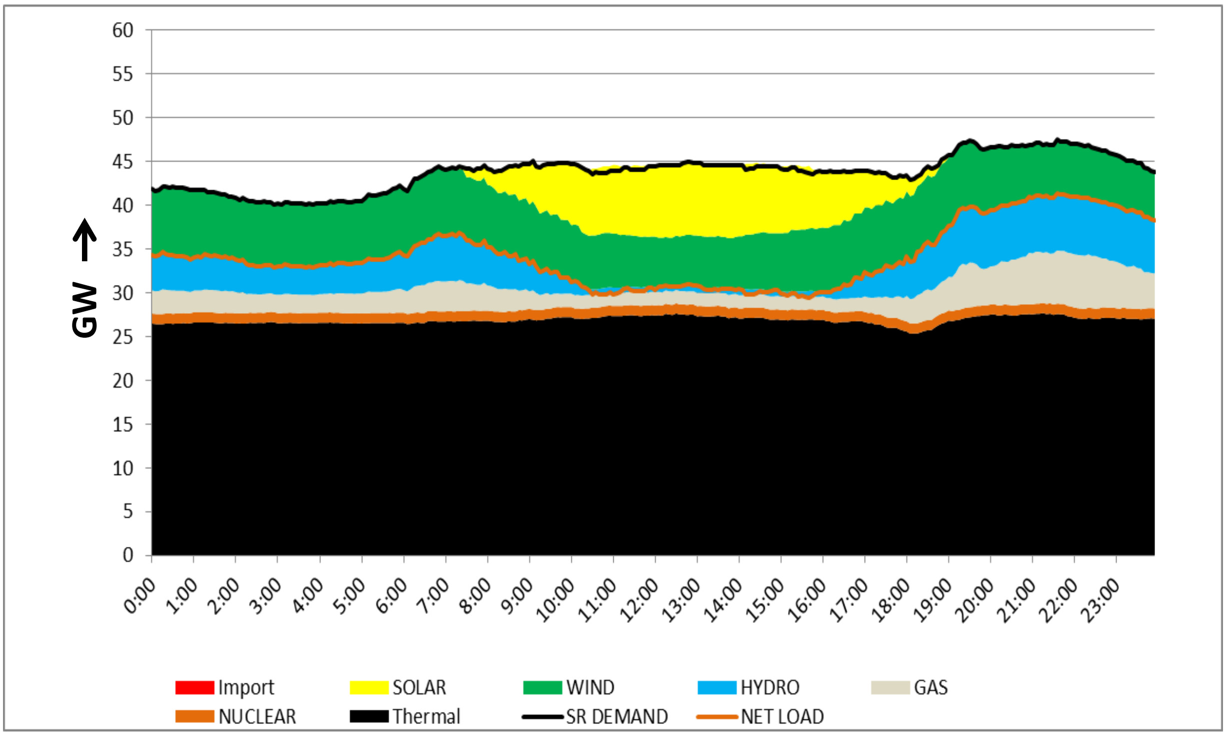


Figure 14 : Typical Daily Load Generation Balancing Curve for Southern Region 30%RE Penetration

Northern Region Balancing Curve for 2019 (30 % RE Scenario):

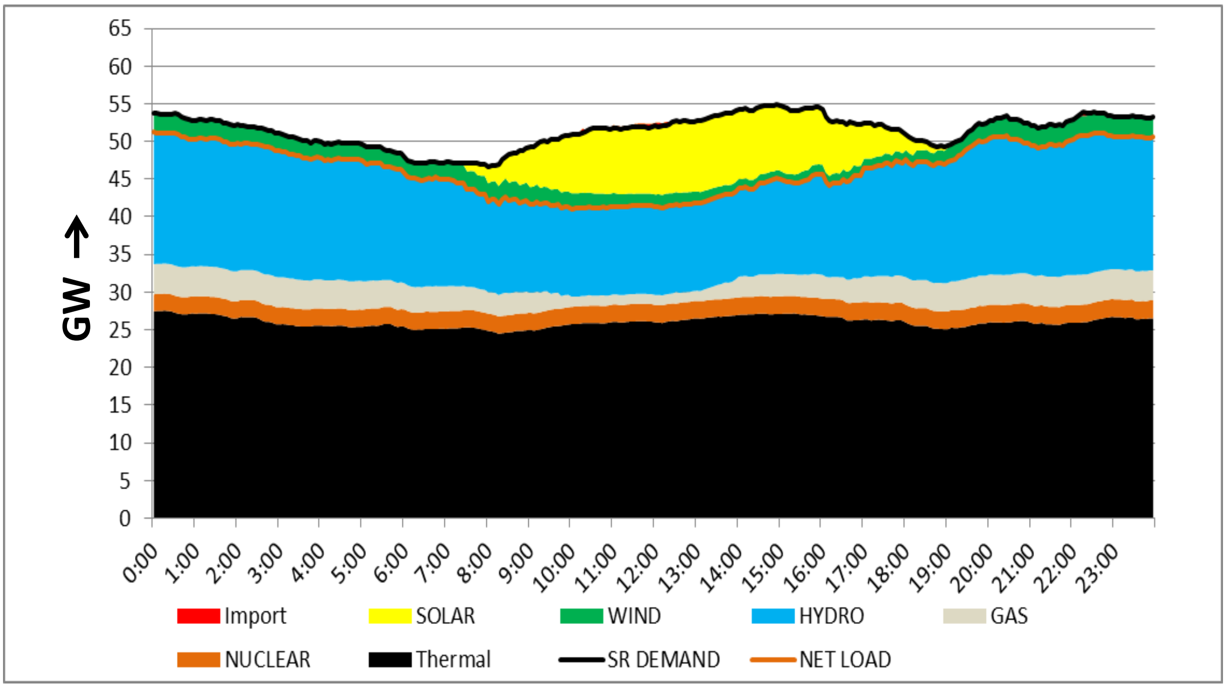


Figure 15: Typical Daily Load Generation Balancing Curve for Northern Region 30% RE Penetration

Western Region Balancing Curve for 2019 (30 % RE Scenario):

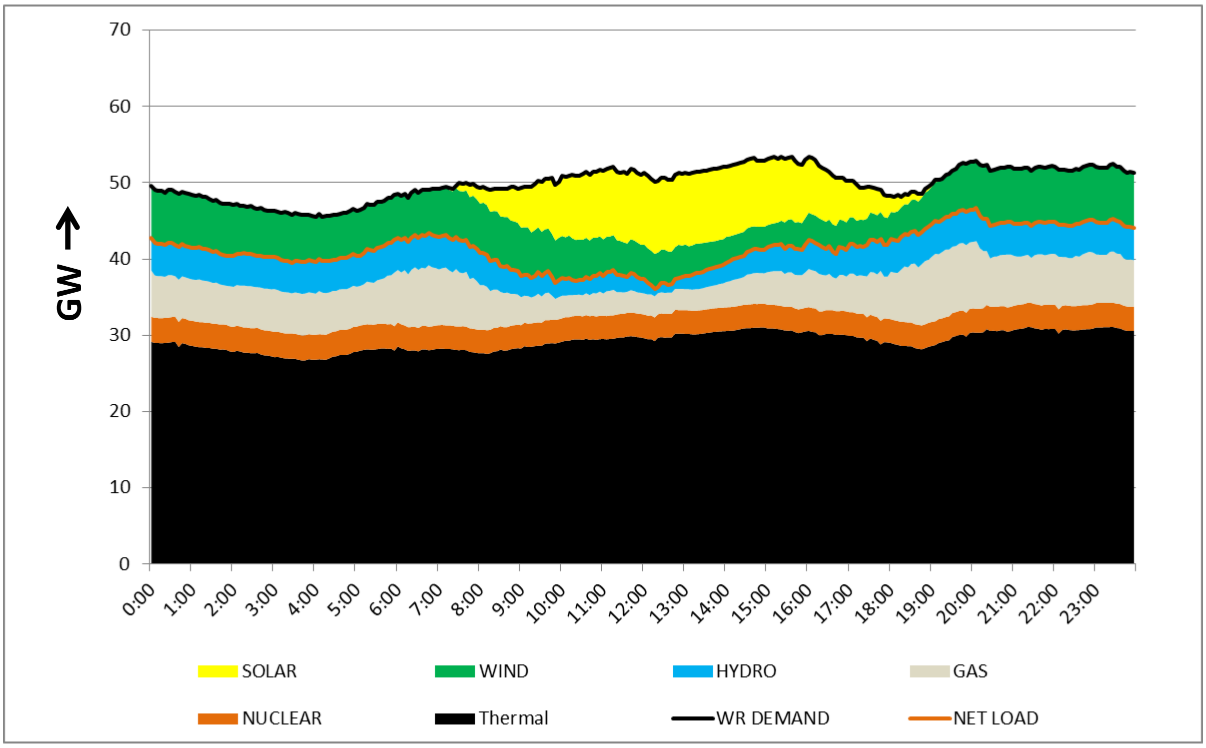


Figure 16: Typical Daily Load Generation Balancing Curve for Western Region 30%RE Penetration

Net Load= (Total Demand – Total RE Generation)

Net Load Plot for 2019 (15% RE Scenario):

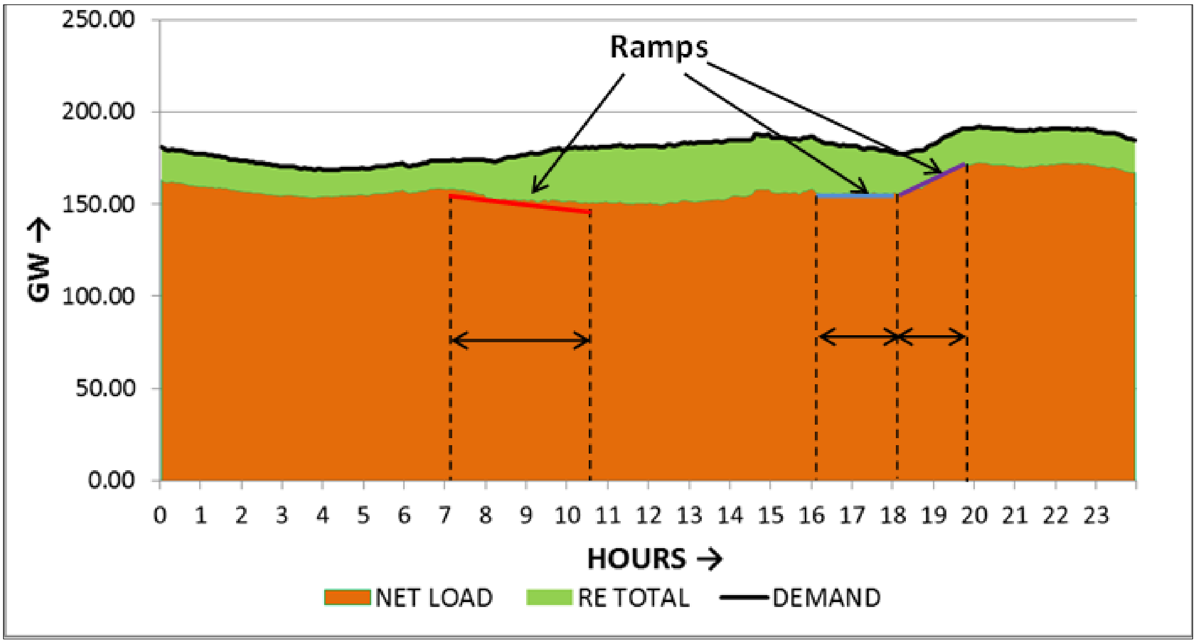


Figure 17: Net Load Plot (2019) for 15% RE Penetration

Net Load Plot for 2019 (30% RE Scenario):

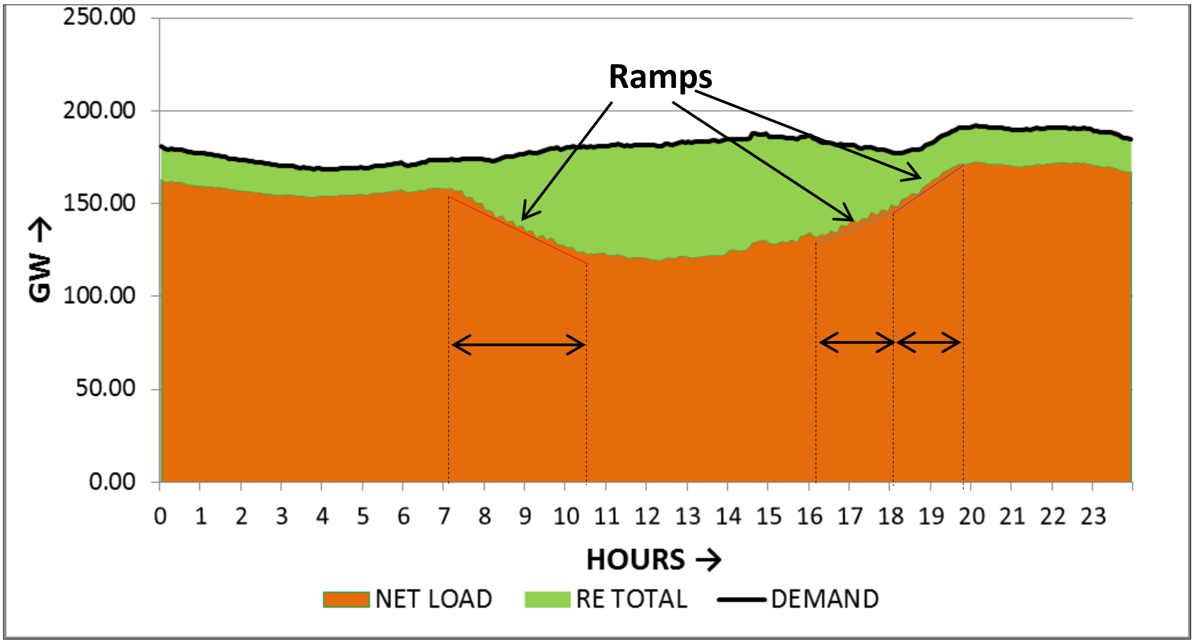


Figure 18: Net Load Plot (2019) for 30% RE Penetration

From the above plots, it is observed that ramp in Net load occurs due to rise in Demand during evening as well as rise/fall in RE Generation (mainly solar). It is also observed that the ramp in Net load generally occurs at three time durations (in a day) as give in Table 1 below

Table 1

Ramp Phase	Type	Time	Reason
Phase-I	Down	7-11 AM	Mainly due to rise in solar generation
Phase-II	Up	4-6 PM	Mainly due to fall in solar generation
Phase-III	Up	6-8 PM	Mainly due to rise in demand

During down ramp (of Net load) in the morning there will be a need to bring down the conventional generation through Balancing (Flexible) resources. Likewise, during up ramp there will be a need to raise conventional generation through balancing resources.

It was observed that ramp due to solar generation (both up and down ramp) is significantly higher in case of 30% as compared to 15% case. Total ramp required from 4-8 PM is higher in case of 30% scenario as compared to 15 % scenario. This also signifies the requirement of more balancing resources for higher RE penetration. Ramps for both scenarios are calculated from the plots and tabulated as below in Table 3.

As explained earlier in chapter 1, aggregated value of wind generation over all geographical locations provides a smooth curve. Same was observed in Balancing curves as well (Fig.10 &11). Solar generation is not available beyond 6 PM. Hence, the change in RE during 6-8 PM is negligible. So, the ramp rate due to rise in demand during evening time (6-8 PM) remains almost the same in both RE penetration scenarios. (A small difference of 25 MW/min in ramp rate is mainly due to a small contribution from solar plants (less than 10%) post 6PM due to delayed sunset in summer. Moreover, many solar plants are located in states of Gujarat & Rajasthan (Western Part of India) which further increases the solar generation beyond 6 PM). It can be seen that the Ramp up due to rise in demand (6-8pm) is more significant compared to other two ramps. In case of 30% RE Scenario, balancing ramp up generation requirement is almost 1.5 times higher than the requirement in case of 15% scenario. At present load ramping is met with available flexible resources. To meet ramps in 15% and 30% RE scenario, assessment of balancing resources is done in next section.

Table 2

Ramp	15% RE Scenario (MW/min)	30% RE scenario (MW/min)
Solar Morning Ramp(Down) 7-11 am	33	150
Solar Evening Ramp (Up)4-6 pm	17	125
Demand Evening Ramp(Up) 6-8 pm	250	275
Total Balancing Reserve Required during evening ramp (4-8pm)	32 GW in 4 hours	48 GW in 4 hours

3.2 Balancing & Ramping Resources

Balancing at a particular instant can be achieved by matching the total demand with the total generation. Since base load generation are constant throughout a day and renewable generations are intermittent and variable in nature, the balance load must be met through balancing resources.

Demand = Supply through Base Load + Renewable + Balancing Generation

Balancing Generation Required = Demand - Base Load – Renewable Generation

The estimated installed capacity during 2019 is given in the **Table 3** below.

Table 3

Scenario	Conventional					Renewable				All India Installed Capacity	All India Peak Demand
	Coal	Gas	Hydro	Nuclear	Total	Wind	Solar	Others	Total		
2019 (15%)	225	25	58.5	11.5	320	38	18	16	72	392	205
2019 (30%)	225	25	58.5	11.5	320	42	60	16	118	438	205

Generally, thermal and nuclear generations are considered as base load which remains almost flat throughout the day. Hydro (Storage) and Gas are the main generations used as balancing (Flexible) resources. Run of the river (RoR) plants are non-dispatchable and therefore are considered as must run plants. Typically, a supercritical unit can operate at the designed super-critical steam parameters between 80-100% of rated capacity. Thus, system can have about 20% variation in a flexible manner due to super critical technology.

For ramp up/ramp down rates, the Indian Electricity Grid Code (IEGC) clause 5.2 (i) states that *'The recommended rate for changing the governor setting, i.e. supplementary control for increasing or decreasing the output (generation level) for all generating units, irrespective of their type and size, would be one (1.0) per cent per minute or as per manufacturer's limits. However, if frequency falls below 49.7 Hz, all partly loaded generating units shall pick up additional load at faster rate, according to their capability'*.

A comparison of Ramp rates of different types of resources (base load as well as peaking & storage units) is tabulated in Table 4.

Table 4

Generation Technology	Min. Load (%)	Ramp Rate (%/min)
Coal	55-60	1-2
Supercritical Power plants	40	3
Nuclear	55-60	1-5
Gas Combustion Technology(Open Cycle)	50	22-25
Combined Cycle Gas Turbine	50	2.5-3
Hydro Storage	33	50
Battery Energy Storage	0	20

Source: Desert Power India-2050

From Table 2, it is found that the maximum ramp rate requirement is around 275 MW per minute in 30% RE Penetration scenario. Considering the envisaged installed capacity of conventional power plants by 2019 (From the Table 3) & ramp rates of different types of Generations(from Table 4), it can be concluded that we have adequate amount of ramping resources which can ramp up their generation within few minutes. For example, a hydro plant can ramp up their generation by 50% of their installed capacity in a minute. Supercritical plants can ramp up by 3% of their installed capacity every minute. Gas power plants can also contribute based on their type of operation (Open Cycle or Combined Cycle). Ramp rate is an instant value, hence the critical factor would be based on whether we have sufficient resources to provide continuous ramping for the required duration of peak load at the required ramp rate. Answer to this can be obtained by calculating the total Balancing Reserve.

In other words, from the Net Load plots in *Figure 17* and *Figure 18*, it can be observed that continuous ramping of generation is required from 4-8 PM to meet the demand. The total ramp up required to meet demand becomes the critical factor for RE Penetration. From Table 2it can be seen that, between 4-6 PM rise in net load is higher in 30% scenario compared to 15%. This is due to fall in solar generation. This increases the requirement of more flexible reserves. Hence by calculating the total Balancing reserve, whether the existing system can sustain high RE Penetration or not can be concluded.

Hydro Generation is an important resource for providing flexibility especially those with storage. The existing capacity of Hydro is around 42.8 GW out of which about 50% is Run of

River (RoR) and the remaining 50% is reservoir (storage) type. The generation from such resources vary over the year maximum being during the monsoon season from July to September. During this time, maximum generation is of the order of 30 GW whereas the minimum generation is around 15-20 GW. During lean generation time i.e. winters, maximum generation is in the range of 18-20 GW whereas the minimum generation is in the range of 4-8 GW. So, there is flexibility of around 10 GW round the year. This flexibility could be further increased with supporting regulatory measures (mainly at the intra state level where hydro tariffs are still single part and not linked to providing peaking support) to provide incentives for providing flexibility and higher peaking so that the installed capacity of 43 GW hydro can be more effectively utilized. This would be of great help in meeting the evening peak load when solar generation tapers off. Hydro generation pattern in year 2015-16 in this regard enclosed at *Figure 19*:

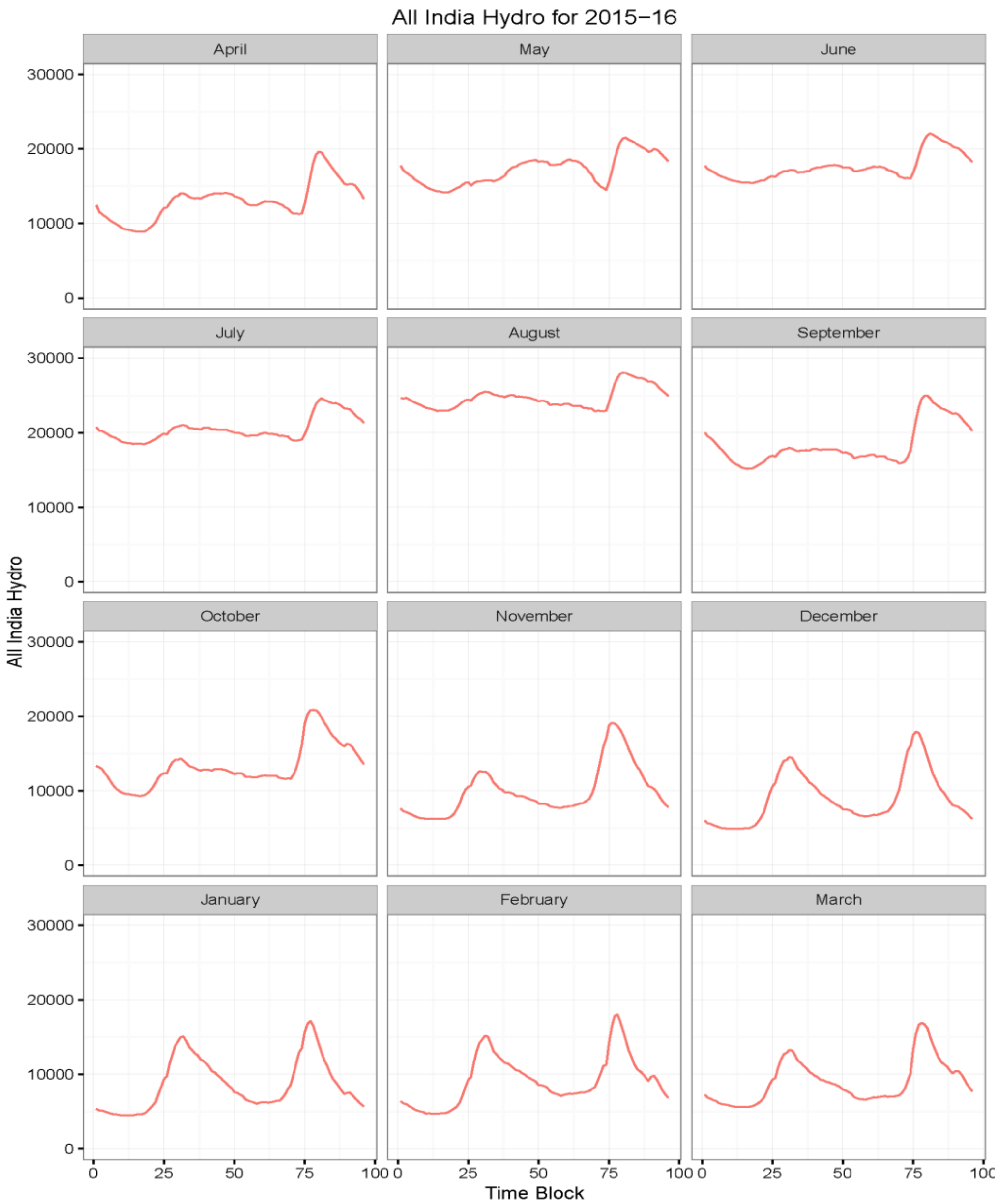


Figure 19: All India Hydro pattern [2015-16]

In2019 scenario, envisaged hydro capacity is 58.5 GW whereas supercritical thermal capacity shall be about 80 GW. Assuming50% of Hydro plants are of Storage types and PSP (as in current scenario), the expected storage capacity by 2019shall be around 29 GW. The existing installed capacity of gas is 25 GW and as per present trend it will remain the same in 2019 as well.

Considering above, total capacity available for Balancing in 2019 shall be 29GW (Hydro) +25GW (gas) +80 GW (Supercritical Thermal of 660 MW & above) = 134 GW. Based on present experience of grid operation, Sub critical units are not considered to be participating in balancing of load generation.

However, contribution of storage hydro in balancing also depends on seasonality in a particular region. However, as a thumb rule, around 50% of the capacity in summer is assumed to be available for balancing. Similarly, from the present scenario, gas power plants are operating at very low plant load factors (typically 15-20%) due to low availability of natural gas. Assuming sufficient availability of gas in future as a thumb rule, 50% of the capacity is assumed to be available for balancing.

Considering range of operation for hydro (storage) and gas as 50% and supercritical thermal as 20%, total generation available as balancing reserve is 50% of (29 +25) + 20% of 80= 27+16=43 GW

Table 5

Penetration Scenario	Balancing Reserve		Sufficient
	Required (in GW)	Available (in GW)	
15%	32	43	Yes
30%	48	43	No

From the above table, it is observed that with the given flexible resource composition (based on envisaged capacity addition programmes) through hydro (including PSP and reservoir type), gas and super critical thermal generation, it is likely to match the balancing &ramping requirements in 15%scenario but not adequate in 30% scenario.

In case of 30% scenario, the available reserve falls short of the requirement by about 5 GW. Hence, to meet the requirement in 30% scenario, there will be need of additional resources in the form of hydro or gas or any other resource which can provide flexibility of about 5 GW. As per the earlier thumb rule, 50% of the capacity in summer is assumed to be available for balancing in hydro and gas. This corresponds to additional installed capacity of 10 GW of either hydro or gas. In terms of supercritical plants, it corresponds to 25 GW of additional installed capacity. The additional requirement can be in the form of a combination of all these resources as well.

The above mentioned balancing exercise has been carried out on all India aggregated level, although, if the same balancing exercise is done at specific states/region level, available balancing reserve resources may fall short even in 15% case. For example, in present scenario, Tamil Nadu has to curtail RE due to non-availability of enough balancing reserve. Strong grid interconnections are essential to enlarge the balancing areas.

Demand response: Demand response can be used as an additional source of power system flexibility to compensate for the variability and uncertainty of RE generation. The gap between generation and demand can be reduced by careful planning of demand side. Contrary to load curve of developed nations developing nation has peak load in evening time. During peak load hours solar generation is not available and it reduces the effective utilisation of renewable energy sources. The Time of Day tariff mechanism can be very effective way to manage demand and shift evening peak to afternoon when solar generation is at max.

Demand response, supported by new smart grid, smart building and smart home technologies, is a promising source of power system flexibility in the future, but is still in its infancy. The rate at which it will mature and be widely applied depends heavily on an understanding of customer behaviour underlying the load demand, as well as on institutional and commercial innovations.

Electrical Energy Storage (EES) system: Energy storage, due to its tremendous range of uses and configurations, may assist RE integration in any number of ways. These uses include, inter alia, matching generation to loads through time-shifting; balancing the grid through ancillary services, load-following, and load-levelling; managing uncertainty in RE generation through reserves; and smoothing output from individual RE plants.

The battery energy storage system (BESS) performs majorly two applications, energy application and power application. In energy application, BESS stores excess energy during off-peak hours and provide electrical energy during peak hours. In power applications, BESS is used to smoothen the renewable generation output and helps in maintaining the forecast vs actual generation. The BESS is very fast acting system and can come online in matter of seconds.

Pumped hydro units are another method to shift the load from peak hours to off-peak hours by consuming RE power during off-peak hours and delivering energy during peak hours. Reassessment studies carried out by CEA during 1978-87 identified 63 sites for pumped storage plants (PSP) with total installation of about 96,500 MW with individual capacities varying from 600 MW to 2800 MW.

Out of total installed 9 Pumped hydro storage units only 4 are operating in pumping mode. Rest units are in non-pumping mode due to technical reasons. Details are given in following Table 6:

To meet RE balancing requirements, role of pump storage plants (PSPs) are also examined. In the CEA published report, "Large Scale Grid Integration of Renewable Energy Sources-Way Forward" on November 2013, list of installed/planned PSPs has been presented which are as follows.

At present, India has 9 major pump storage plants with total installed capacity of 4785.6 MW. Details are as below:

Table 6: Pump Storage Plants in India

S. No.	Name of Project / States	Installed Capacity		Pumping mode operation	Reason for not working in pumping mode
		No. of units x MW	Total (MW)		
1.	Kadana St. I&II, Gujarat	2x60+2x60	240	**Not working**	Due to vibration problem
2.	Nagarjuna Sagar, Andhra Pradesh	7x100.80	705.6	**Not Working**	Tail pool Dam under construction
3.	Kadamparai, Tamil Nadu	4x100	400	Working	-
4.	Panchet Hill, DVC	1x40	40	**Not Working**	Tail pool Dam under construction
5.	Bhira, Maharashtra	1x150	150	**Not Working**	-
6.	Srisailam LBPH, Andhra Pradesh	6x150	900	Working	-
7.	Sardar Sarovar, Gujarat	6x200	1200	**Not Working**	Tail pool Dam under construction
8.	Purulia PSS, West Bangal	4x225	900	Working	-
9.	Ghatghar, Maharashtra	2x125	250	Working	-
		Total	**4785.6**		

Out of above plants, Purulia and Ghatghar are pure pump storage (re-circulation type) plants and rest are Storage stations which functions throughout the year. These plants are operating in PSP mode just for few hours which is less than that contemplated in the project report due to the unavailability of surplus energy in the power system for more hours.

As mentioned in the Table 6, Nagarjunsagar, Panchet and Sardar Sarovar plants are not working in PSP due to tail race construction.

Apart from above there are few other PSPs which are under construction/planning phase as under:

Table 7: PSP under construction/planned

S. No.	Name of the project/ State	Installed Capacity (MW)	Remarks
1.	Tehri St. – II, Uttarakhand	1000 MW (4x250 MW)	Under construction (Completion Expected by Sep 2019)
2.	Koyna Left Bank, Maharastra	80 MW (2x40 MW)	Under Construction
3.	Kundah, Tamilnadu	500 MW	DPR under preparation
4.	Malshej Ghat, Maharashtra	700 MW	DPR prepared by THDC. Implementation agreement to be signed.
5.	Humbarli, Maharashtra	400 MW	Under Survey & Investigation by THDC for preparation of DPR.
6.	Turga, West Bengal	1000 MW	Under Survey & Investigation by WAPCOS for preparation of DPR.
	Total	**3680 MW**	

As observed from above that PSPs being great balancing resource are not being used to their full potential due to technical and commercial reasons, there is a requirement for regulatory interventions/policy measures are required to encourage such projects and efforts should be made to complete the commissioning of such projects on time. In addition, there are many hydro plants which are feasible to be converted into pumped storage hydro plants. Feasibility should be evolved to encourage participation of such pumped storage plan for introducing more regulation into the grid with the increased renewable Penetration.

3.3 Regulatory Requirement

As per CERC Order in the matter of Roadmap to operationalize reserves in the country dated 13.10.15, a committee under the chairmanship of Shri. A. S. Bakshi, Member CERC examined the technical and commercial issues in connection with spinning reserves and evolved regulatory interventions in this context. Committee also submitted its major findings in its final report to the CERC.

Committee emphasised that adequacy of supply and maintaining load-generation balance is one of the important element of ensuring grid reliability. Load variation, sudden disturbances in Power system or unplanned outage of generating units or transmission line can jeopardise Power system. Thus, to ensure 24x7 power supply, grid reliability and to facilitate large scale integration of RE sources, operators must have access to reserves at different locations to maintain load generation balance at all times.

National Electricity Policy of 2005 mandates that a spinning reserve of at least 5% at national level should be created to ensure grid security, quality and reliability of power supply. This amounts to almost 15 GW considering present all India installed capacity

(305 GW as on 31.07.16). However, capacity addition program is a continuous process to cater to the growing demand requirements. Hence the spinning reserve requirement shall also increase with increase in capacity addition.

Committee also emphasised that spinning reserves are required to be maintained of requisite quantum depending upon grid conditions. As per the recommendation, following types of reserves should be maintained which are classified based on timeline of initiation & functional need:

- Primary reserves of 4000 MW should be maintained on an All India basis considering 4000 MW generation outage (Single Largest generation Complex) as a credible contingency. The same should be provided by generating units in line with the IEGC provisions. Such reserves are realised through primary or automatic control of turbine speed governors:
    - All generators must operate with free governor mode (FGMO)
    - As per IEGC/CEA technical standards, in Thermal units all governors shall have a droop setting of between 3% and 6% whereas 0-10% in case of hydro units
- Each region should maintain secondary reserves corresponding to the largest unit size in the region
    - 1000 MW in Southern region; 800 MW in Western region; 800 MW in Northern region; 660 MW in Eastern region and 363MW in North-Eastern region (total approx. 3600 MW on an All India basis)

  Secondary control involves Automatic Generation Control (AGC) which delivers reserve power in order to bring back the frequency and area interchange to target values. This requires reliable telemetry and communication at units/LDCs. As per recommendation, AGC may be planned to be operationalized in the power system from 1.4.2017.

- Tertiary reserves should be maintained in a de-centralized fashion by each state control area for at least 50% of the largest generating unit available in the state control area.

  Tertiary control refers to manual change in dispatching and unit commitment to restore secondary control reserve.

  As per the analysis carried out to evolve tertiary reserve based on above approach, about 4900 MW capacity shall need to be maintained.

In view of the above, as per the recommendation grid should have at least following reserves (Table-8) by 2016.

Table 8

Reserve	Quantum (MW)	Duration
Primary Reserve	4000	2-5 sec
Secondary Reserve	3600	5 sec to few minutes
Tertiary Reserve	4900	Few min-hours
Total	**12,500**	

In addition, IEGC (4th amendment) dated 06.04.16 has ordered Technical Minimum Schedule for operation of Central Generating Stations and Inter-State Generating Stations. It stipulates:

- *The technical minimum for operation in respect of a unit or units of a Central Generating Station of inter-State Generating Station shall be 55% of Maximum Continuous Rating (MCR) loading or installed capacity of the unit of generating station*

Committee also recommended that "Ramp up" and "ramp down" rates are also important parameters for flexibility which would gradually be introduced through Regulations. Typical timeline for reserves is given in *Figure 20*.

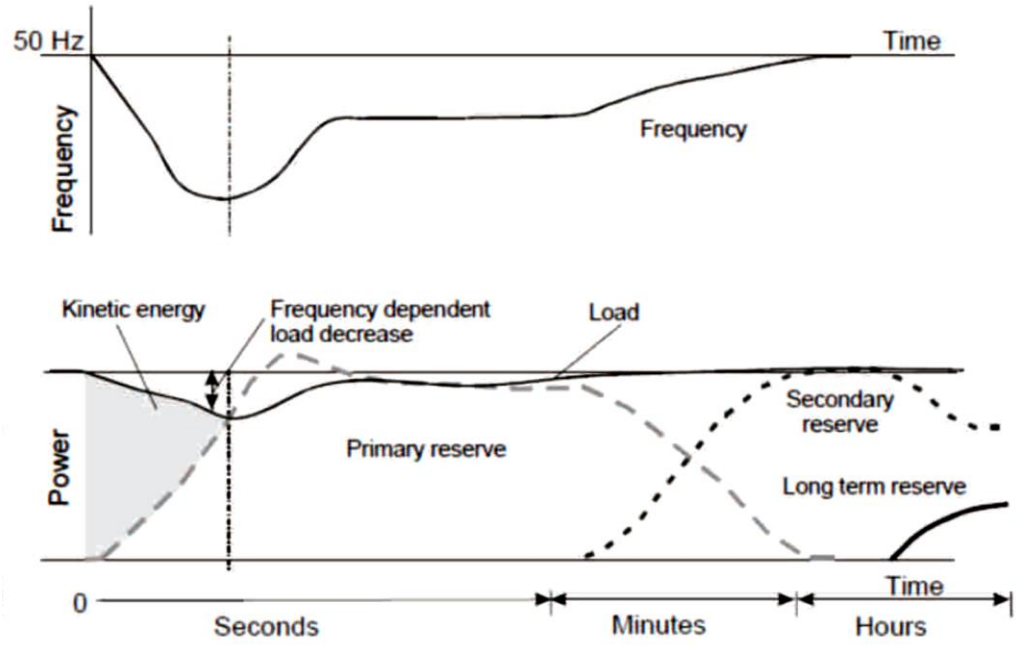
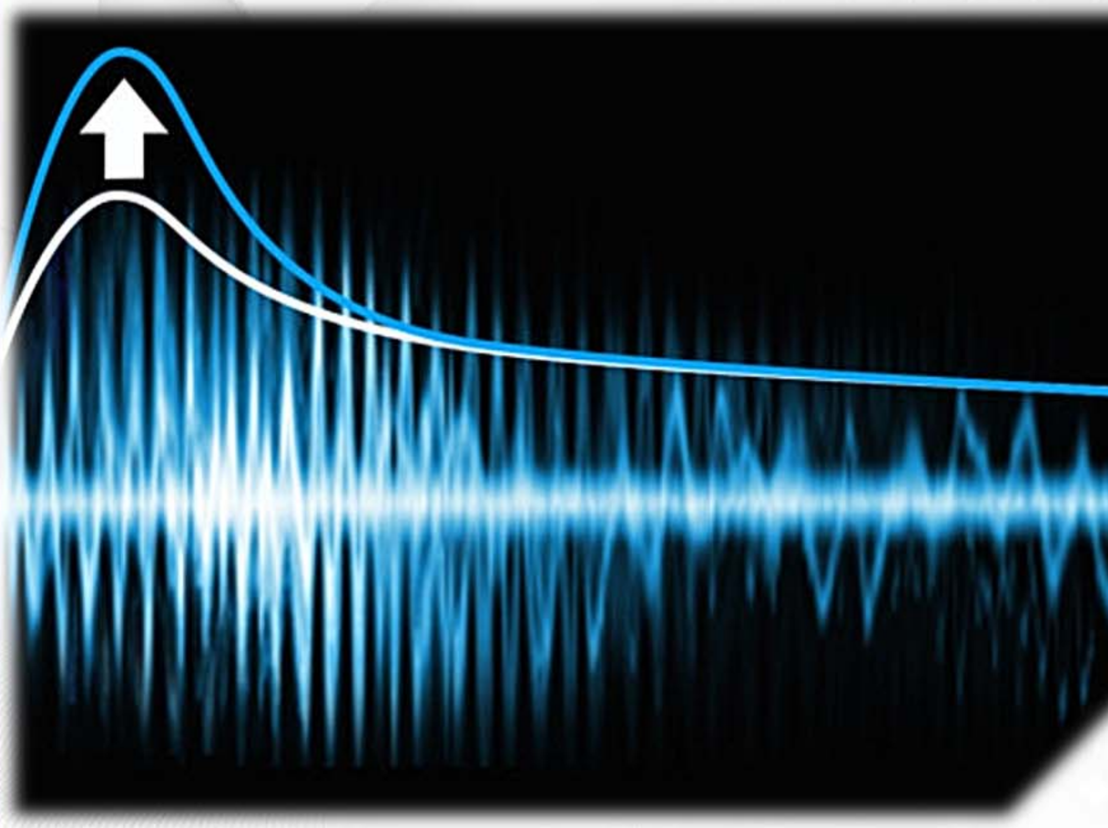


Figure 20: System Reserves

However primary/secondary/ tertiary reserves quantum will remain almost same until larger capacity generating units are added (as reserve requirement is based on largest capacity machine size in each control area) in capacity addition plan in each control area. Additional capacity required as per NEP (5%) can be kept from hydro, thermal or any other type of storage system.

CHAPTER 4

TRANSIENT STABILITY ANALYSIS



Chapter-4

Transient Stability Analysis

4.1Stability parameters

A fundamental requirement in the operation of a power system is that the system needs to exhibit an ability to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. The disturbance may be associated with an outage of a generator, transformer, line, loads, faults etc. Further load ability of lines and bus voltages are maintained within acceptable limits throughout the network despite changes in load or available transmission and generation resources.

To assess the transient stability of a network, rotor angle stability and voltage stability are most relevant parameters. In addition, studies address frequency stability aspects also.

(i) Rotor angle stability- As per classical stability theory, the generator will be stable for steady state rotor angles below 90° and unstable for above 90°. However, the rotor angles can swing into the unstable region during transient conditions and may be back in the stable-operating region. Power angle characteristic of a synchronous machine is represented in *Figure 21* as under

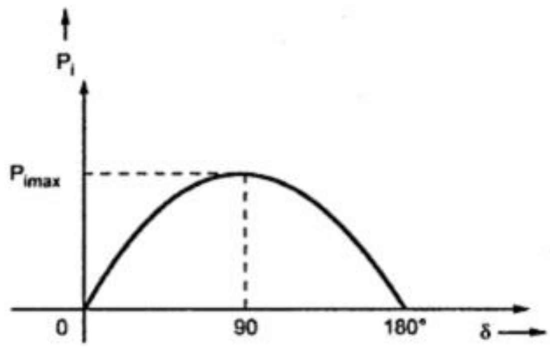


Figure 21: Power Output of Synchronous Generator

From the transient stability studies, the relative rotor angles are monitored. Depending on the rotor angle oscillation, the generators can be termed as stable, unstable or oscillatory. Typical rotor angle plots for the above three conditions are shown in *Figure 22*. If the rotor angle swings around 90° and decays very rapidly, then the generator is stable. If the rotor angle goes beyond 180° in the first cycle, then the generator is unstable. If the rotor angle continues to oscillate without damping, then the generator is oscillatory. The unstable and oscillatory cases are unacceptable.

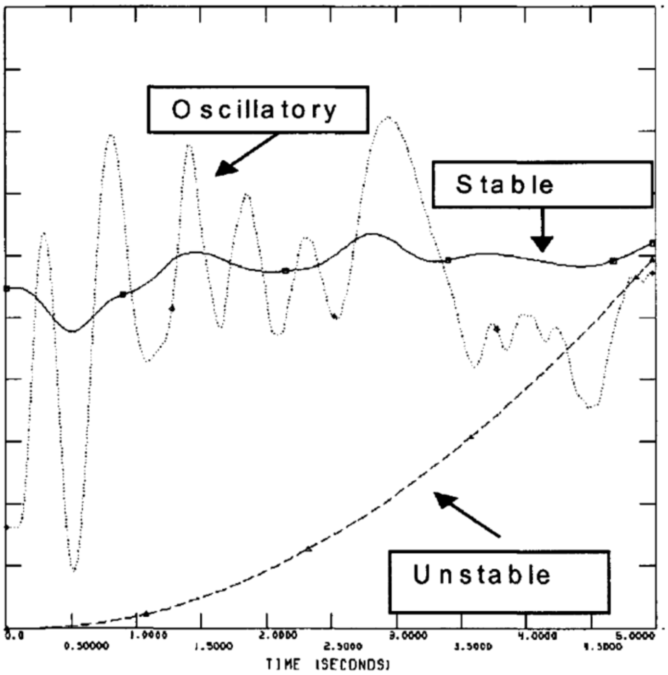


Figure 22: Machine rotor angle followed by grid disturbance

Voltage Stability- It is customary to monitor the bus voltages at critical locations during transient stability studies. During the fault, the bus voltage drops and upon fault clearing the voltage recovers. From the stability point of view, the voltage has to recover to the rated voltage immediately after fault clearing. Such a voltage condition is acceptable and is shown in *Figure 23*. If the voltage fails to recover and is oscillatory, then such a condition is marginal and is unacceptable. If the voltage falls below 60% of the rated voltage and fails to recover (voltage collapse), such a condition is unacceptable.

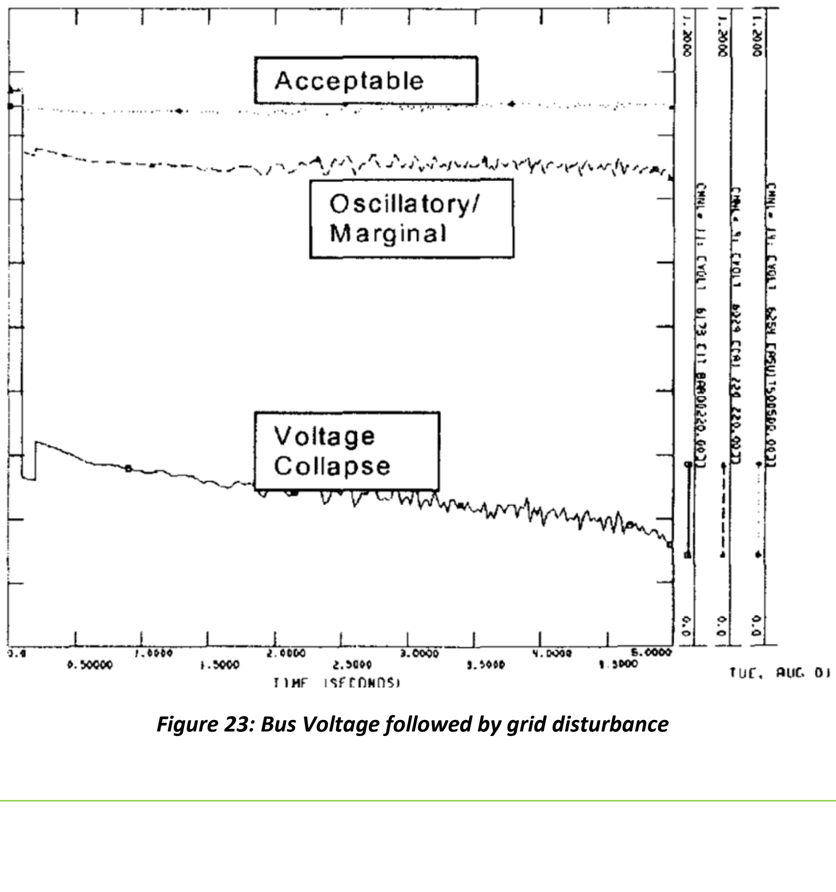


Figure 23: Bus Voltage followed by grid disturbance

Frequency Stability: The term 'frequency stability' refers to the ability of the power system to maintain steady acceptable frequency following a severe system disturbance resulting in a large generation-load imbalance. Technically, the frequency stability is a system-wide phenomenon which primarily depends on the overall system response to the event and the availability of substantial power reserves.

4.2 Methodology/Approach of Study

All India network is simulated in PSS/E to perform this study. Since India is emphasizing on large amount of renewable integration at utility scale progressively from present scenario, two scenarios of varying renewable penetration (15% and 30%) in 2019-time frame are simulated to analyse its impact on stability of Indian grid. The Present Indian grid has nearly reached 15% renewable penetration. To reach 30% renewable penetration scenario, both unit de-commitment and lower conventional generation dispatch approach has been used.

The conventional generator, HVDC lines, STATCOM, Wind and Solar Plants are modelled in PSS/E by their standard model available in PSS/E Library. Conventional generators models include generator, exciter and governor while wind and solar plants are modelled as per Western Electricity Coordinating Council (WECC) dynamic modelling guidelines.

To simulate LVRT non-availability, Under-voltage relay is installed in all Wind & Solar Plants with cut-off voltage at 0.85 pu. The plant will be tripped if the bus voltage goes below cut-off voltage(0.85pu) for a minimum duration of 50 ms.

India has renewable potential in northern, western and southern part of the country. To perform this study, a large size renewable pocket has been selected in three different regions and a three-phase fault was simulated (cleared after 100 ms followed with opening of line) in that pocket and stability response was analysed.

4.3 Study Assumptions

Based on the report on Partial Grid Disturbance in WR grid on 12.03.14 (Mundra (4000 MW) generation tripping incident) and actual RGMO response from major conventional generating stations in WR as well as operator feedback on governor response, governor action is considered only from reservoir type hydro generation (All India) as well as through thermal generators in southern region. The RGMO response from various generating units during this disturbance is given in Table7.

It is known that in Indian power sector, Power System Stabilisers (PSS) of conventional machines are not properly tuned to damp the power system oscillation. Therefore, the control action by PSS has not been considered in the simulation studies.

However best and worst cases are also considered where all governors are either active or inactive to see its impact on the grid while in different RE penetration scenarios.

Existing wind plants has been modelled as Type1 and Type-2WTG which does not have voltage control capabilities, whereas future wind plants have been modelled as Type-3 WTG which have generator terminal voltage control capabilities. Solar has been modelled as per standard WECC model available in PSSE. Typical Parameters for wind Turbine and solar plant models are given at Annexure -1.

Table 9 :RGMO Response of WR

Major generating Station in WR	Before the Event (MW)	After the Event (MW)	Generation Change (After the Event - Before the Event) (MW)
Korba	2266	2276	10
VSTPS	3637	3653	16
Sipat	2895	2893	-2
NSPCL	467	470	10
JPL Tamnar	942	953	10
LANCO Pathadi	276	276	0
SSP	755	761	5

LVRT capability in Solar PV Plants is not considered. It means that in case of low voltages at the point of interconnection, solar plants will be tripped. However it will take some time to trip the solar plant after sensing a low voltage at Point of Interconnection (POI). In that duration solar plants inverters can provide reactive power support to grid by converting available solar power in some study cases. Studies have been carried out by blocking reactive support as well as de-blocking this feature.

4.4 Study Scenario

In this study,as mentioned earlier a renewable capacitypenetration of 15% & 30% at all India level is considered to assess grid security and reliability. However, as the penetration calculation is done based on RE generation capacity normalised to total installed capacity, it may so happen that some of the states which are RE resource rich, there penetration may be higher than 15% level. This study is an effort to understand the challenges posed by the higher renewable penetration and take precautionary measures to handle such situations.

Solar maximized scenario in summer season is considered for the study.This is because the maximum solar generation is observed in summer. Solar maximized scenario occurs between 12-2PM. Hence from the present generation data, dispatch of Wind & Solar generators is taken as 40% & 80% respectively of their installed capacity. Further sub cases are formed based on governor response as well as solar inverter reactive support feature, detailed as under:

Case-1.a (15%)& 2.a (30%): With governors in action & with reactive power support from solar inverters

Case-1.b (15%) & 2.b (30%): With governors in action &without reactive power support from solar inverters

Case-1.c (15%) & 2.c (30%): Without governor action &with reactive power support from solar inverters

Case-1.d (15%) & 2.d (30%):Without governor action &without reactive power support from solar inverters

In addition to these cases, a case of large RE generation reduction/outage is carried out to study the impact of intermittency (sudden loss of huge generation capacity) of both wind and solar Generations.

4.5 Results and Discussion

Three RE rich pockets have been identified in three different regions viz. northern, western and southern to perform the study. Detailed stability studies with various conditions and analysis of such disturbances has been carried out as under:

4.5.1 Northern region

As Rajasthan has largest RE potential envisaged in entire NR, it has been considered as one of the study area. In the all India 15% & 30% RE capacity penetration scenario, RE generation in Rajasthan is considered as under:

Table 10

Rajasthan	Total Installed Capacity (GW)	RE Installed Capacity (GW)
15 % RE Penetration Case	25	13
30 % RE Penetration Case	35	23

To simulate disturbance, a three-phase fault is applied at 765kV Bikaner followed by clearing of fault after 100ms along with 765kV Bhadla (PG)-Bikaner line tripping. Bikaner bus is selected because of its proximity to Bhadla which is major connection point for solar generation in Rajasthan. As indicated earlier, RE generators are connected with under-voltage/over-voltage relay to also simulate outages during depressed grid voltage incidence (considering LVRT non-compliance).

Also, due to intermittent behaviour of solar PV plant, another disturbance with reduction of power generation from Bhadla SPV plant (about 600 MW in 15% RE penetration case and 800 MW in 30% RE penetration case) due to cloud coverage has been studied for all the study cases.

Further, to simulate variability behaviour of wind power generation, sudden reduction in wind generation of 1700 MW in case of 15% RE penetration scenario and 2500 MW in case of 30% RE penetration scenario have been studied.

Table 11 summarises the RE generation outage following bus fault clearing:

The RE generation outage mentioned above are in states of Rajasthan, Gujarat and MP. Also, from above, it can be observed that generation outage is less in the cases where reactive support from solar PV generators has been considered. In study case 2, about 10000 MW of RE generation is saved from outage with the help of reactive power support from solar inverters, which clearly shows the importance of LVRT and reactive power support from solar inverters.

Table 11

Generation Outage	Case 1.a	Case 1.b	Case 1.c	Case 1.d	Case 2.a	Case 2.b	Case 2.c	Case 2.d
Installed Capacity	7926	11057	7926	11057	9688	22007	9688	22007
Dispatch	6333	8680	6333	8680	7782	17440	7782	17440

For the sake of better presentation, plots of only extreme cases (case 1.a & 2.a and case 1.d & 2.d) have been shown.

A) <u>Frequency Stability</u>

<u>For bus fault:</u>

The frequency swings following 400kV grid fault are shown in *Figure 24*. From the figure, it can be observed that RE penetration level has significant impact on grid frequency. With increase in RE penetration, the severity of impact on system stability also increases as more generation gets tripped with nearby disturbances during low voltage period.

In case 1.a and 2.a (with governors & reactive support from PV during fault), frequency recovers to 49.8 Hz and 49.4 Hz respectively because of governor action of conventional and hydro generators. But, in cases 1.d and 2.d (without governor action & reactive support from PV during fault), frequency doesn't recover and settles at 49 Hz and 47.6 Hz. respectively due to non-availability of governor action which will violate the operating frequency band mentioned in Indian Electricity Grid Code (IEGC). At present frequency band stipulated by IEGC is 49.90 to 50.05 Hz.

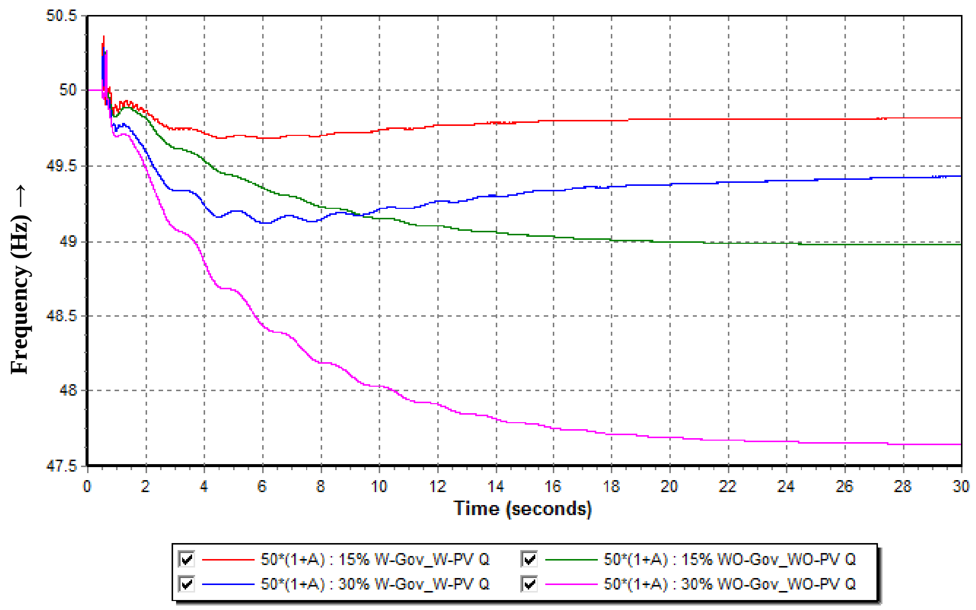


Figure 24: Grid Frequency

As the case 1.d matches more or less with present state of grid operations i.e. renewable penetration level as well as without governor response, from above results, power number is validated. As per the result, 1 Hz Frequency dip with 8680 MW generation outage, power number shall be 8680 MW/Hz which is just higher than current frequency response characteristics (FRC) of 8250 MW/Hz.[1]as expected. In study case 2, the power number degrades to 7266 MW/Hz.

Also, the comparison between above two levels of penetration shows drop of frequency nadir from 49.65 Hz to 49.15 Hz. This is due to reduced system inertia in higher renewable penetration scenario.

As shown in the graph at t = 0.6+secs., System frequency response just after fault is better in higher renewable penetration case. This is because of lower system load voltage depression, which is due to higher reactive power support from PV generation (bus voltage shown in *Figure 43*).

<u>Solar Intermittency Study:</u>

The system frequency behaviour shown in *Figure 25* is similar to the case mentioned above; although there is a difference in frequency response just after the fault. In case of bus fault case, frequency rises just after the fault because of system load voltage depression; but in this case frequency dips just after the solar generation outage which is due to the fact that system load voltage does not dip causing load greater than generation.

Also, *Figure 25* shows that for same level of generation outage, frequency nadir is lower in 30% renewable penetration scenario because of lower FRC. This confirms the findings of above bus fault case.

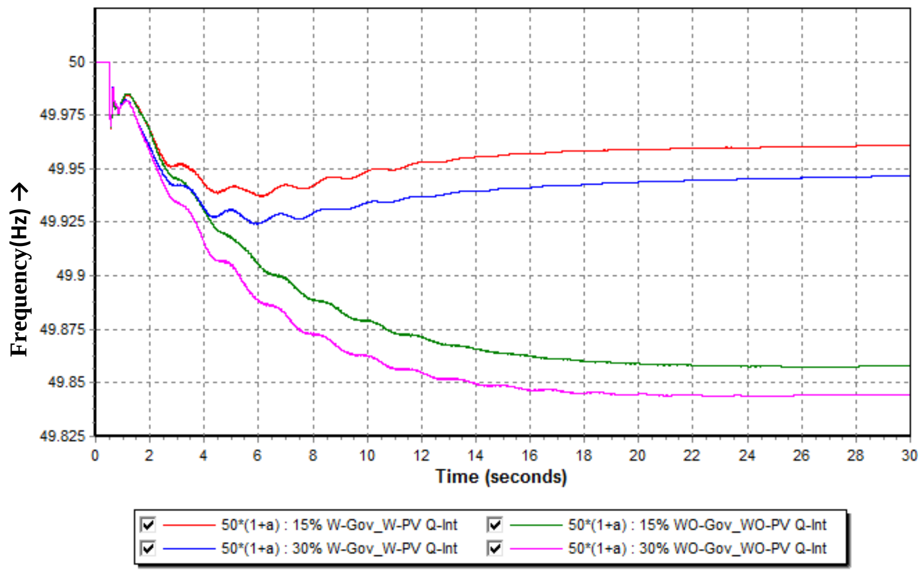


Figure 25: Grid Frequency

Wind Intermittency Study:

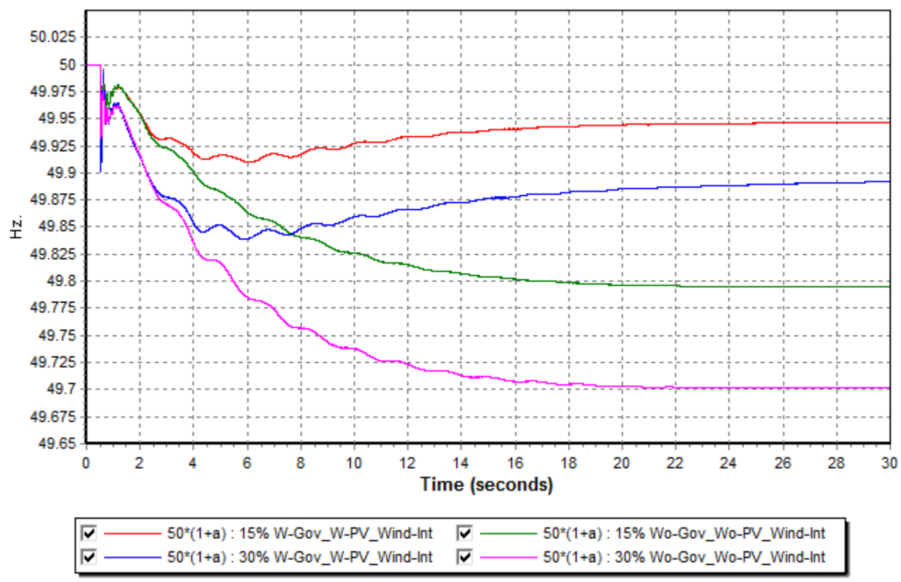


Figure 26: Grid Frequency

B) Rotor angle Stability

For Bus Fault:

From *Figure 27* to *Figure 28* it may be seen that angle and power from Giral Unit, a thermal generator in Rajasthan undergo oscillatory movement however stabilising after some time. The settling value of Power generated is not same as pre-fault condition because no steam turbine governor action is taken into account for Steam turbine machines in NR and WR. However, governor of steam turbine machines in SR are known to act; so, governors are enabled in SR machines.

Also, from the plot it can be observed that the oscillation frequency is between 0.5-1 Hz. This shows the presence of Inter-area oscillation in the system i.e. subgroups of generators swinging against each other.

The following plots of rotor angle and generated power from various conventional machines shows that there is very less impact of renewable penetration level in grid on operation of conventional machines, which indicates that rotor angle stability is not the governing factor to justify renewable penetration level in the grid.

However, careful observation of Figure 27 and *Figure 29* shows the increase in oscillation amplitude and settling time in case of higher renewable penetration.

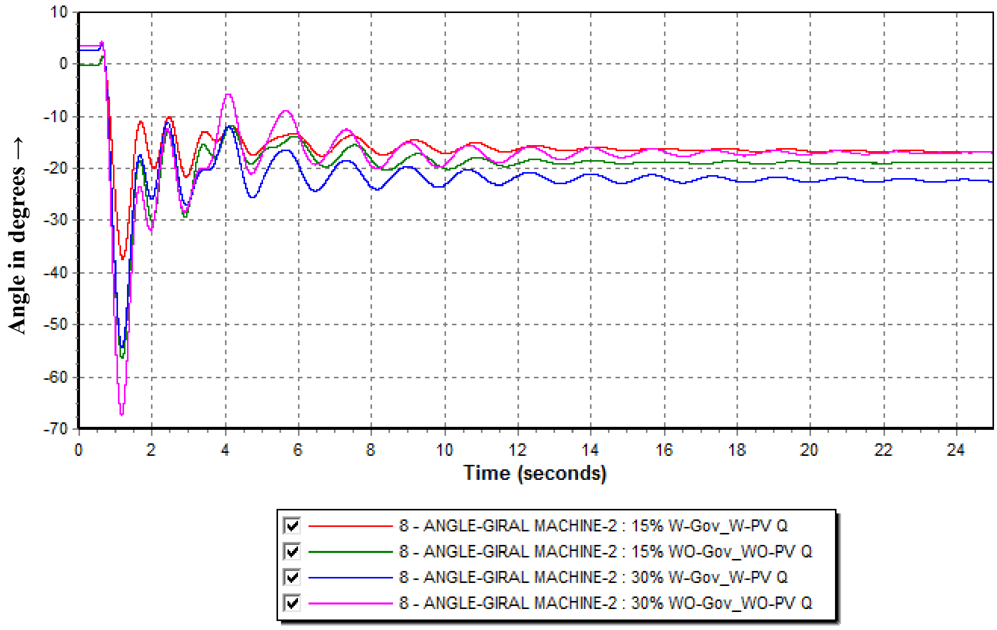


Figure 27: Rotor angle of machine 2 of Giral TPS (Northern region)

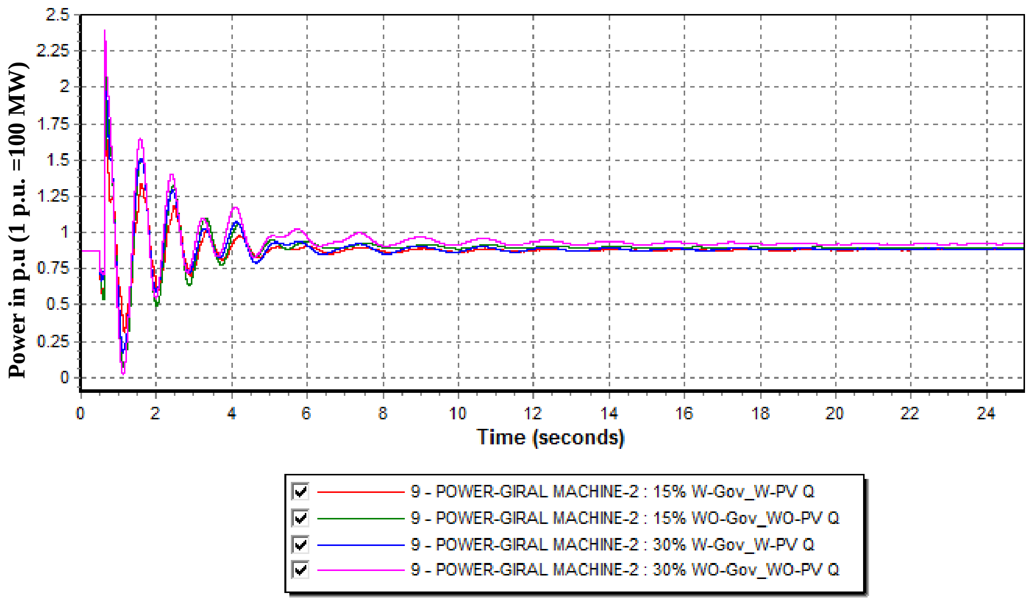


Figure 28: Generated Power of machine 2 (125MW) of Giral TPS (Northern region)

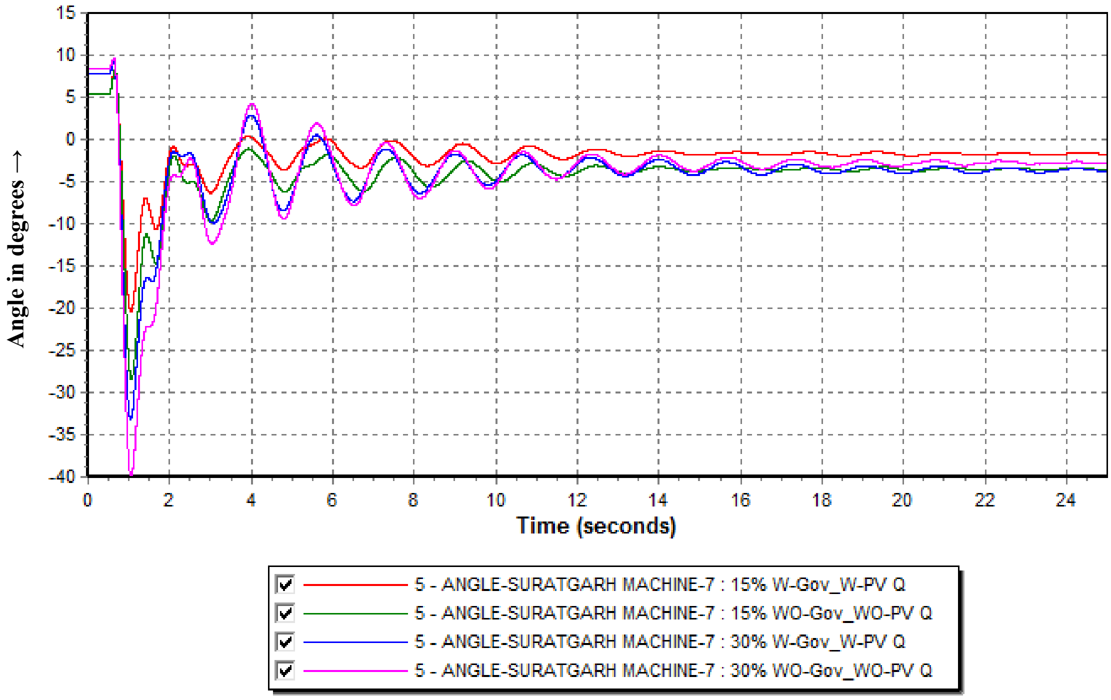


Figure 29: Rotor angle of machine 7 of Suratgarh TPS (Northern region)

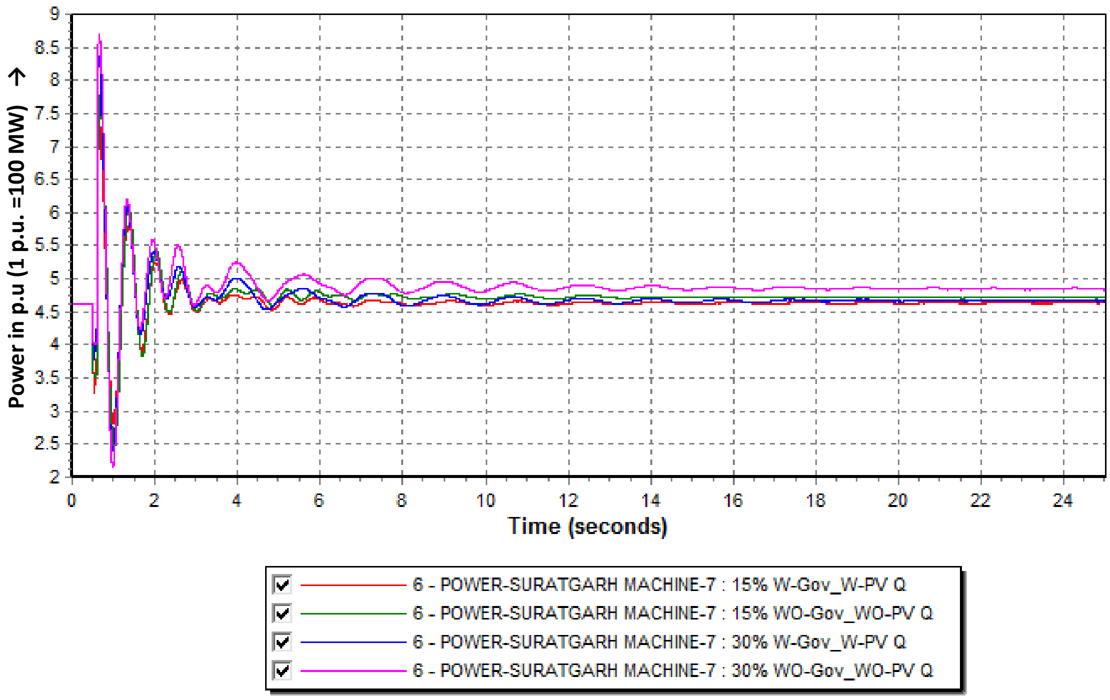


Figure 30: Generated Power of machine 7*(660MW)* of Suratgarh TPS (Northern region)

The power and angle plots of other regions (SR & WR) are as follows:

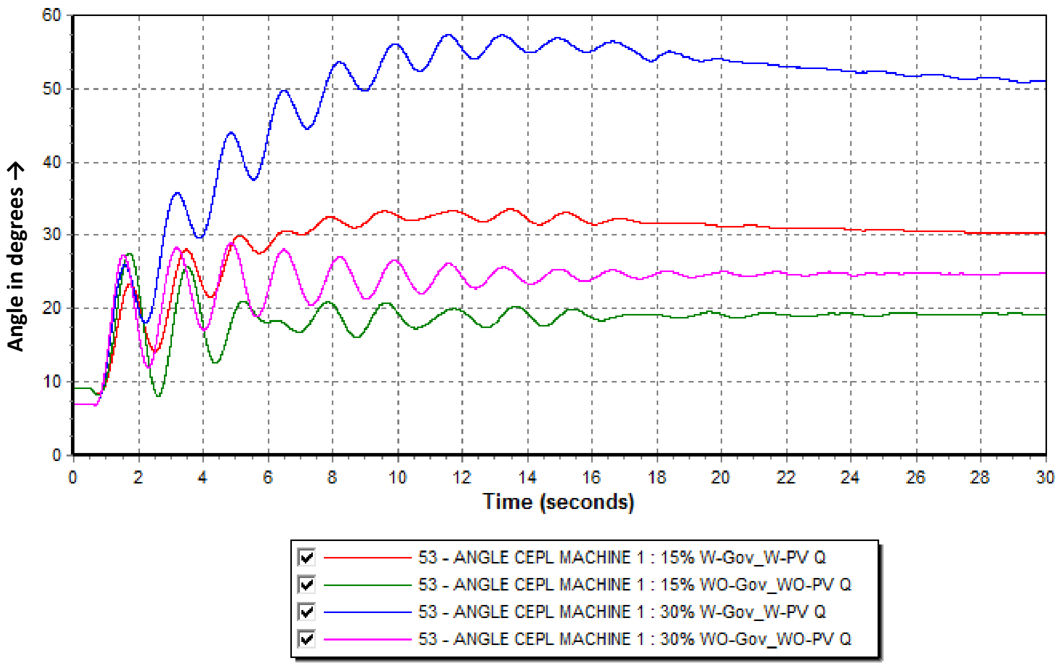


Figure 31: Rotor angle of machine 1 of CEPL UMPP(Southern region)

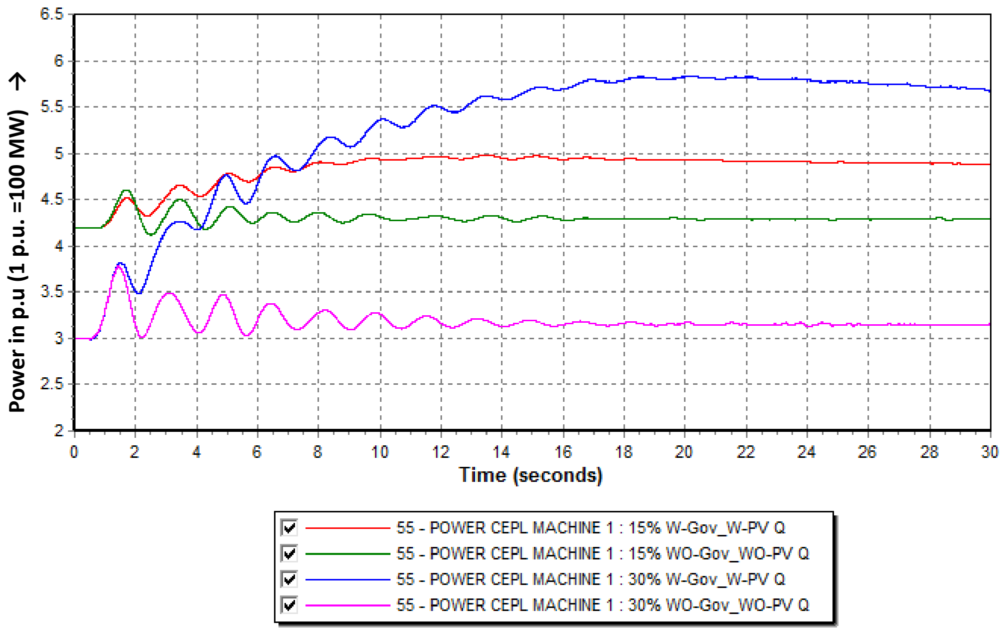


Figure 32: Generated Power of machine 1 (600MW) of CEPL UMPP (Southern region)

In *Figure 32*, the settling value of generated power is higher than pre-fault condition due to governor action.

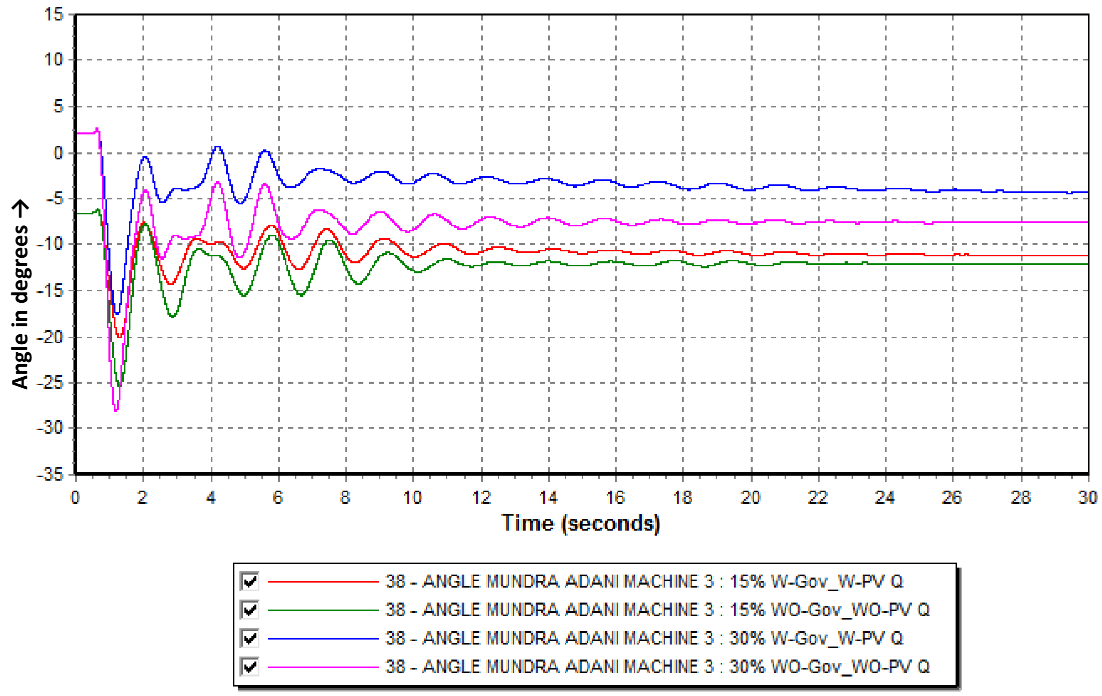


Figure 33: Rotor angle of machine 3 of Adani Mundra (Western region)

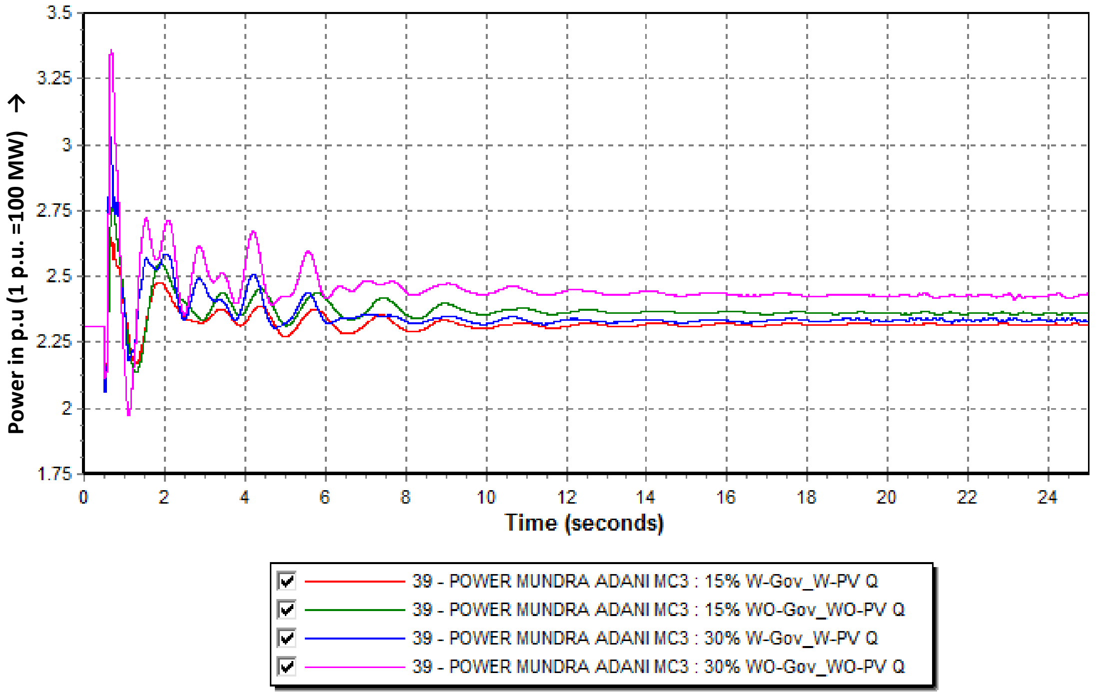


Figure 34: Generated Power of machine 3 (330MW) of Adani Mundra (Western region)

Solar Intermittency Study:

Figure 35 to *Figure 38* shows the rotor angle and generated power of nearby conventional machines to PV plant which has been considered for outage study. The following plots show no significant effect on conventional machine behaviour in this study case and shows stable operation following grid disturbance in the form of generation outage.

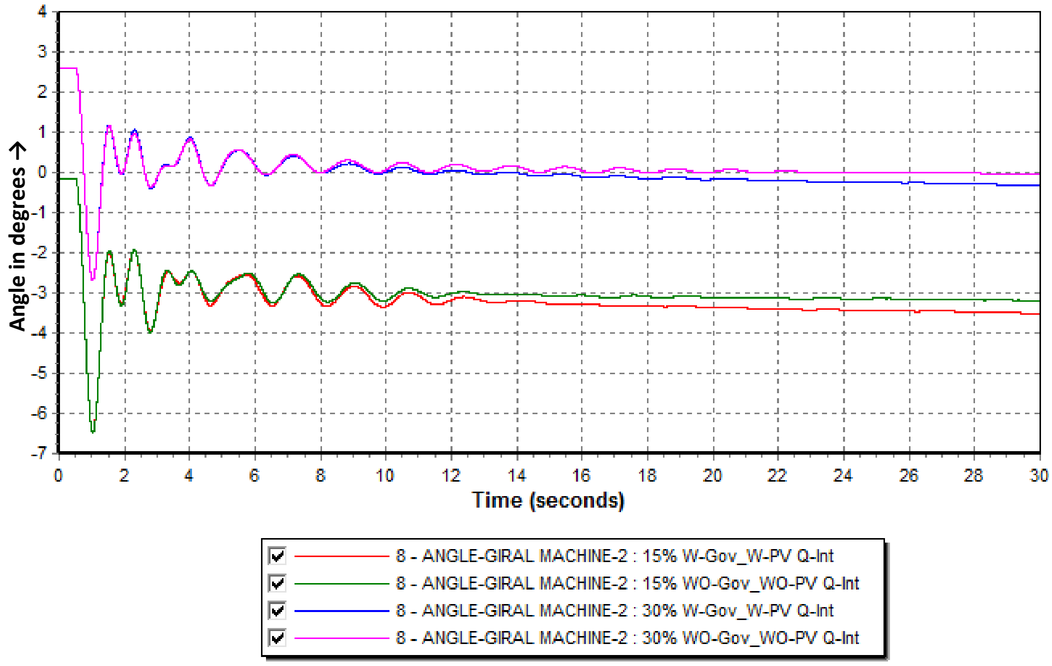


Figure 35: Rotor angle of machine 2 of Giral TPS (Northern region)

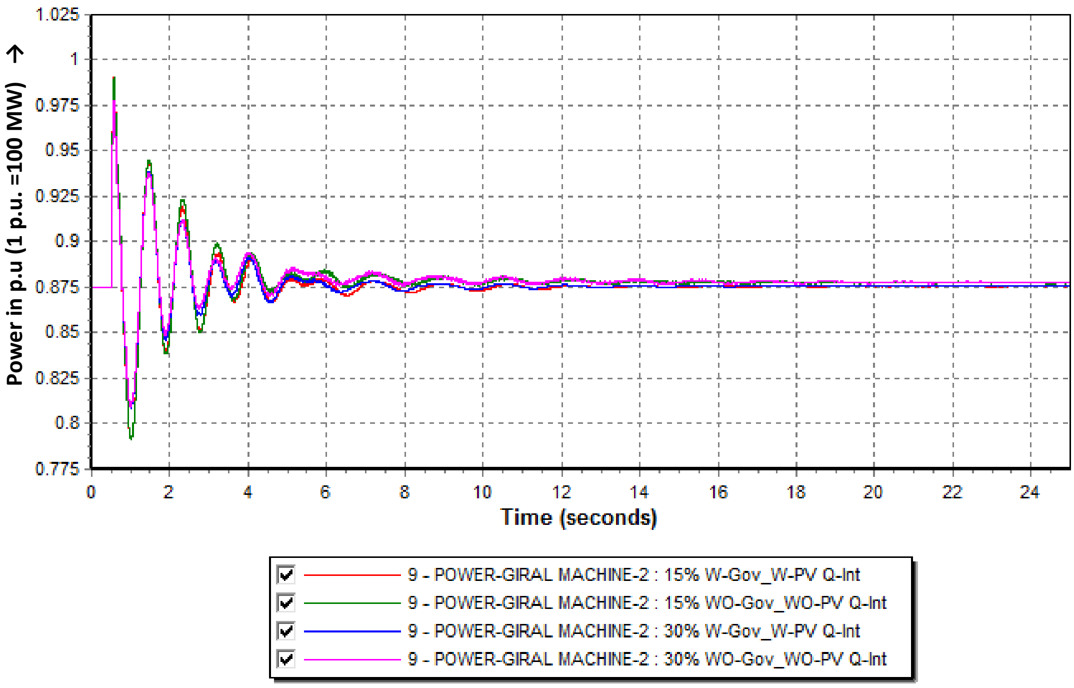


Figure 36: Generated power of machine 2 (125MW) of Giral TPS (Northern region)

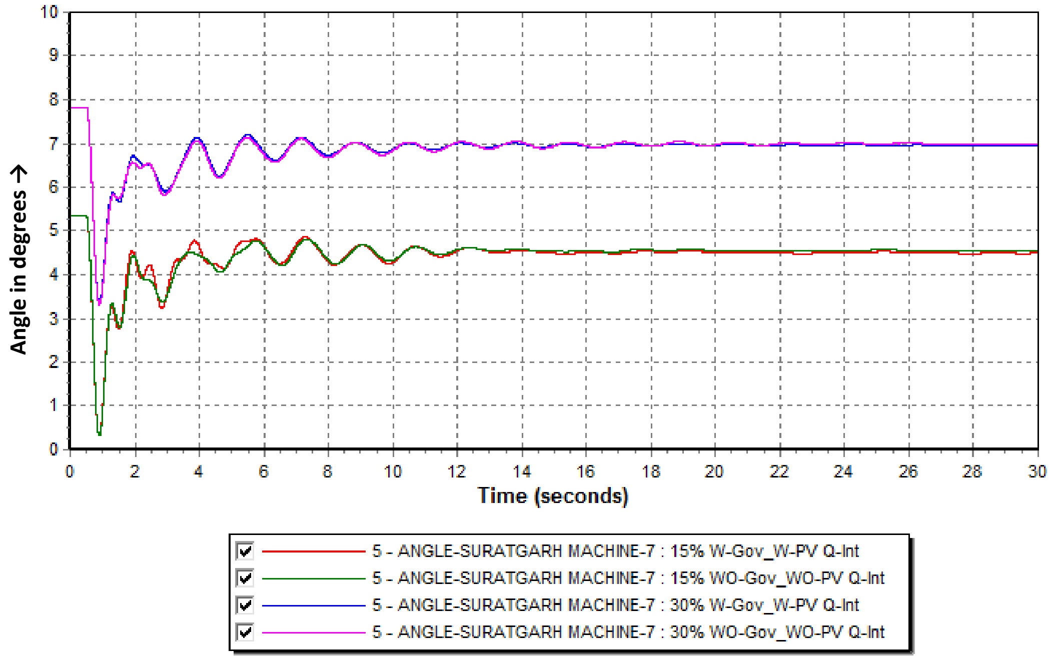


Figure 37: Rotor angle of machine 7 of Suratgarh TPS (Northern region)

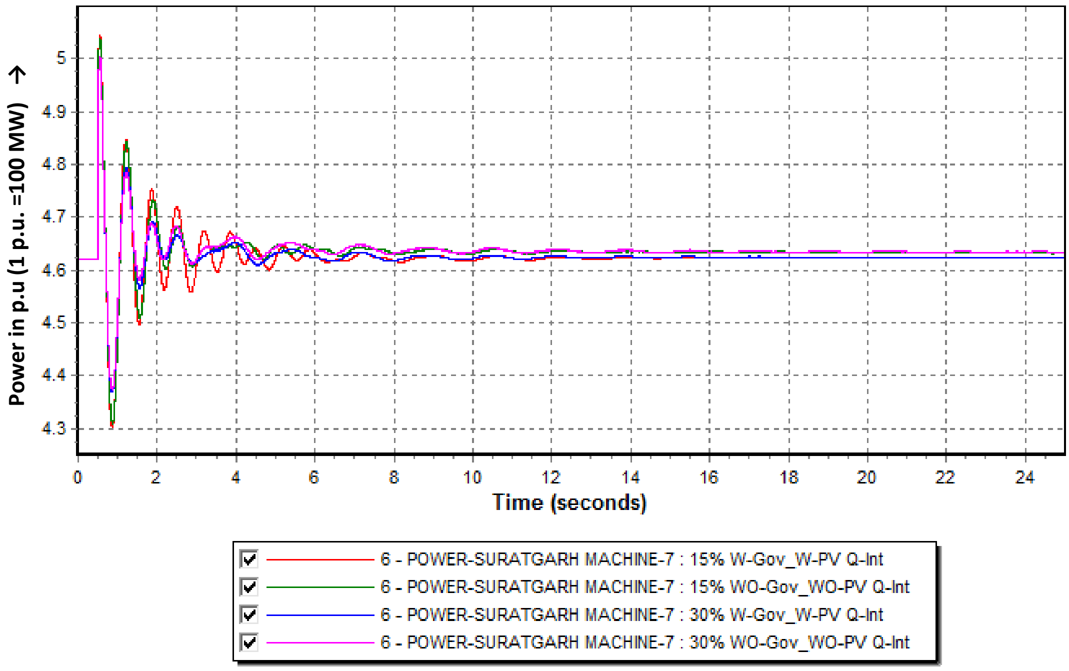


Figure 38: Generated power of machine 7 (660MW) of Suratgarh TPS (Northern region)

Wind Intermittency Study:

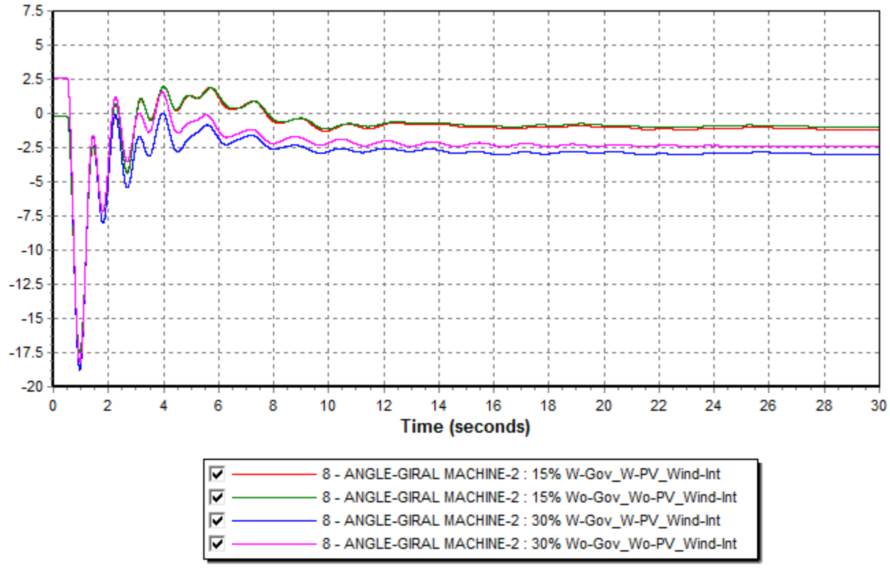


Figure 39: Rotor angle of machine 2 of Giral TPS (Northern region)

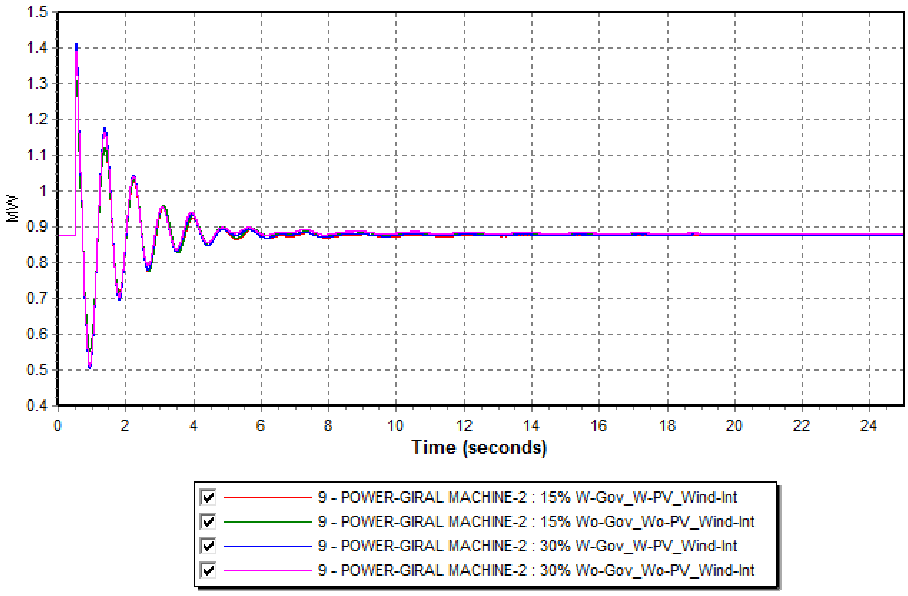


Figure 40: Generated power of machine 2 (125MW) of Giral TPS (Northern region)

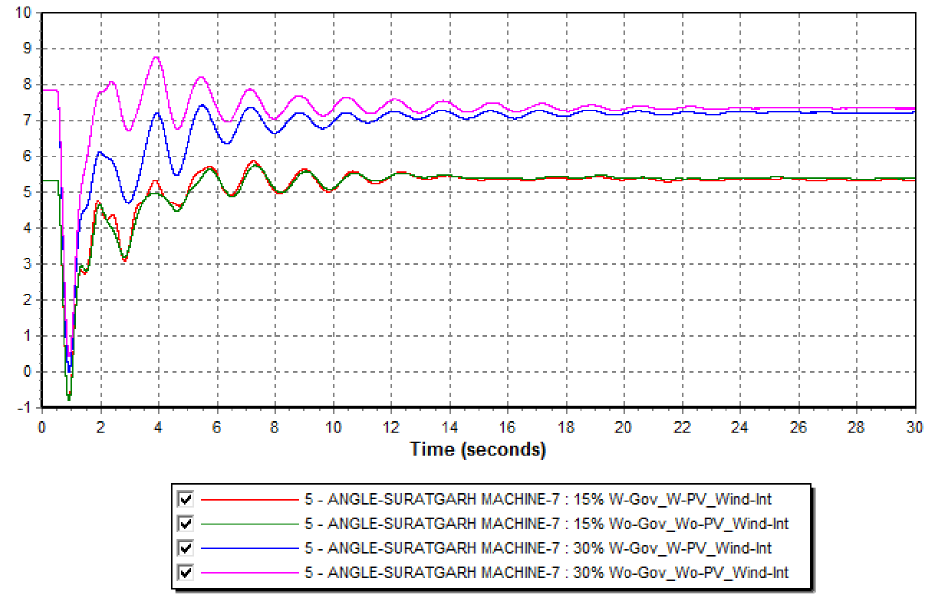


Figure 41: Rotor angle of machine 7 of Suratgarh TPS (Northern region)

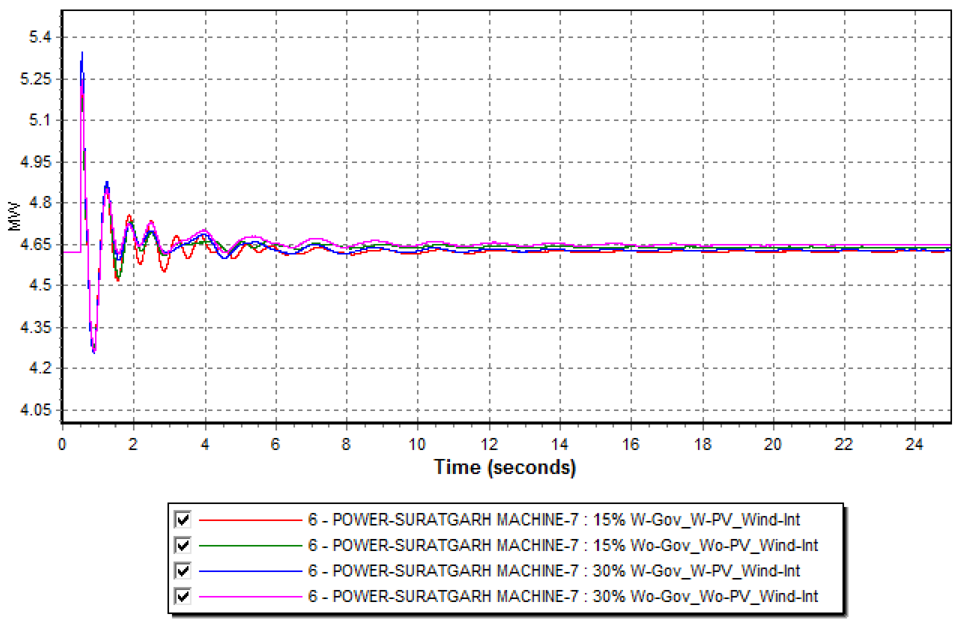


Figure 42: Generated power of machine 7 (660MW) of Suratgarh TPS (Northern region)

C) Voltage Stability

For Bus Fault:

Bus Voltage plots in *Figure 43* to *Figure 46* shows the recovery of system voltage following fault clearing. However, the post fault voltage overshoot is higher in case of higher RE penetration case. This is because of two reasons, one that a large amount of RE generation is under outage after fault clears which causes sudden under-loading of EHV transmission lines and secondly, huge amount of reactive power is supplied by solar PV inverters during fault.

The presence of reactive power support from PV plants helps to recover voltage during fault which protects under-voltage relay operation at remote buses. However, there is a drawback of this reactive support in the form of high voltage overshoot during post-fault condition; which if persisted can cause over-voltage relays to operate.

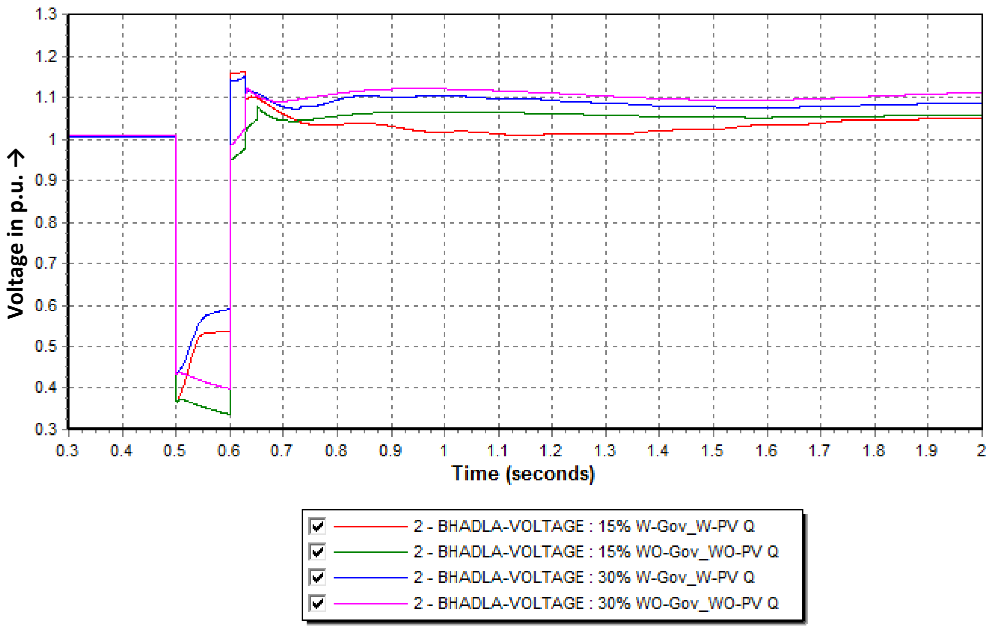


Figure 43: Bhadla 400kV Bus Voltage (Northern region)

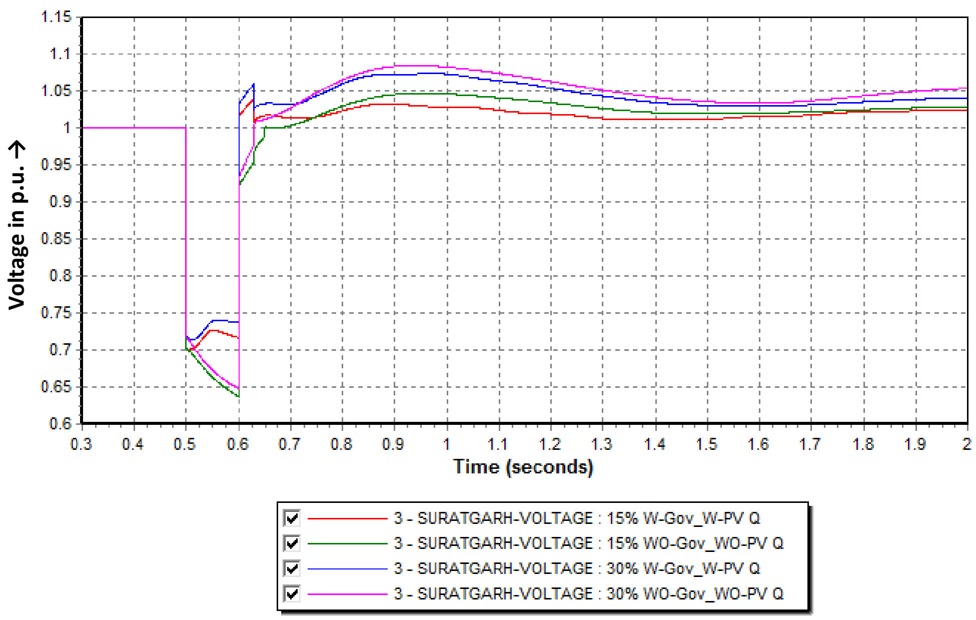


Figure 44: Suratgarh 400kV Bus Voltage (Northern region)

In figure 43 and 44, during t = 0.5 to t = 0.6 secs. bus voltage tends to recover in two cases which is due to reactive power delivered by solar PV inverters. Also, voltage recovery is better in higher renewable penetration level case.

The voltage plots of other regions (SR & WR) are as follows:

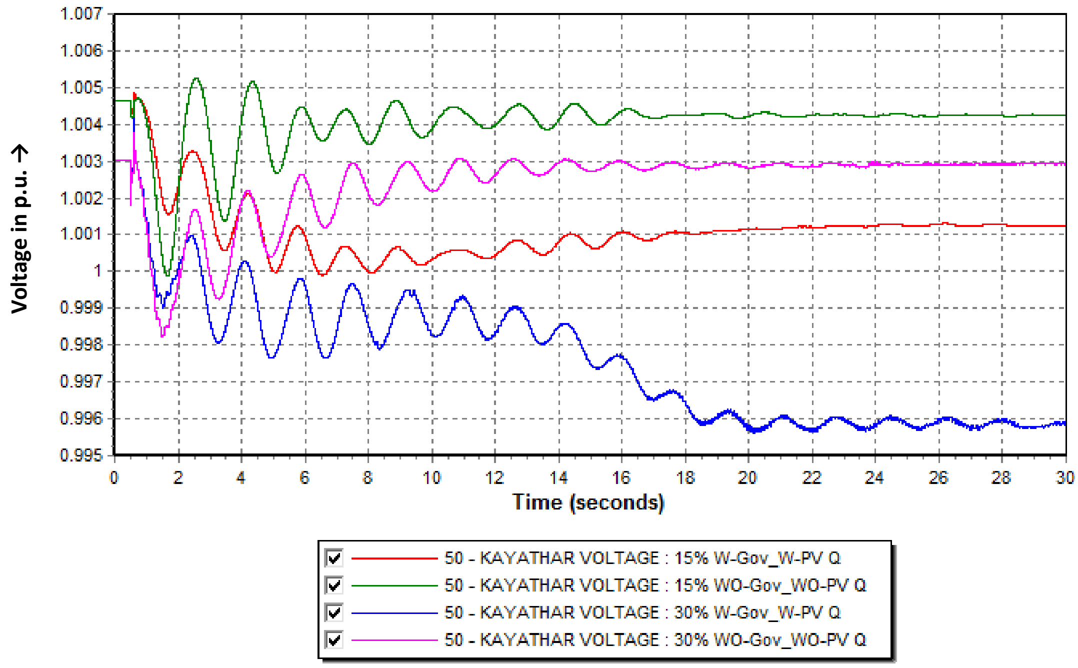


Figure 45: Kayathar 400kV Bus Voltage (Southern region)

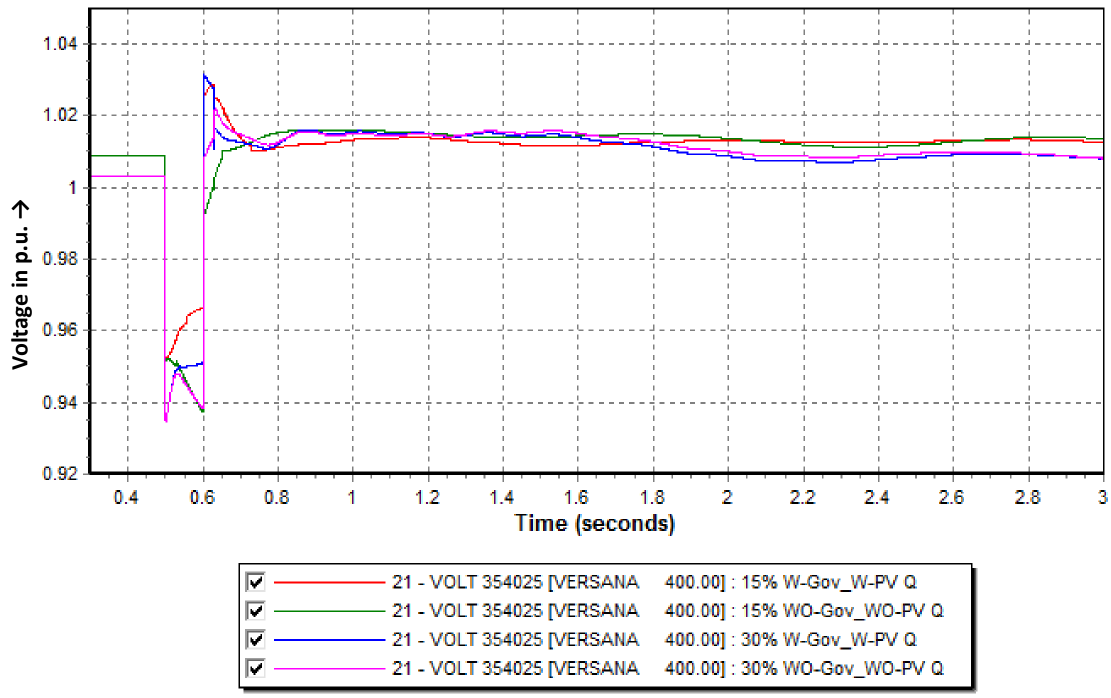


Figure 46: Varsana 400kV Bus Voltage (Western region)

Solar Intermittency Study:

In this case, the Bhadla bus voltage rises just after outage of generation. This is due to under-loading of connected EHV lines to Bhadla caused by generation outage.

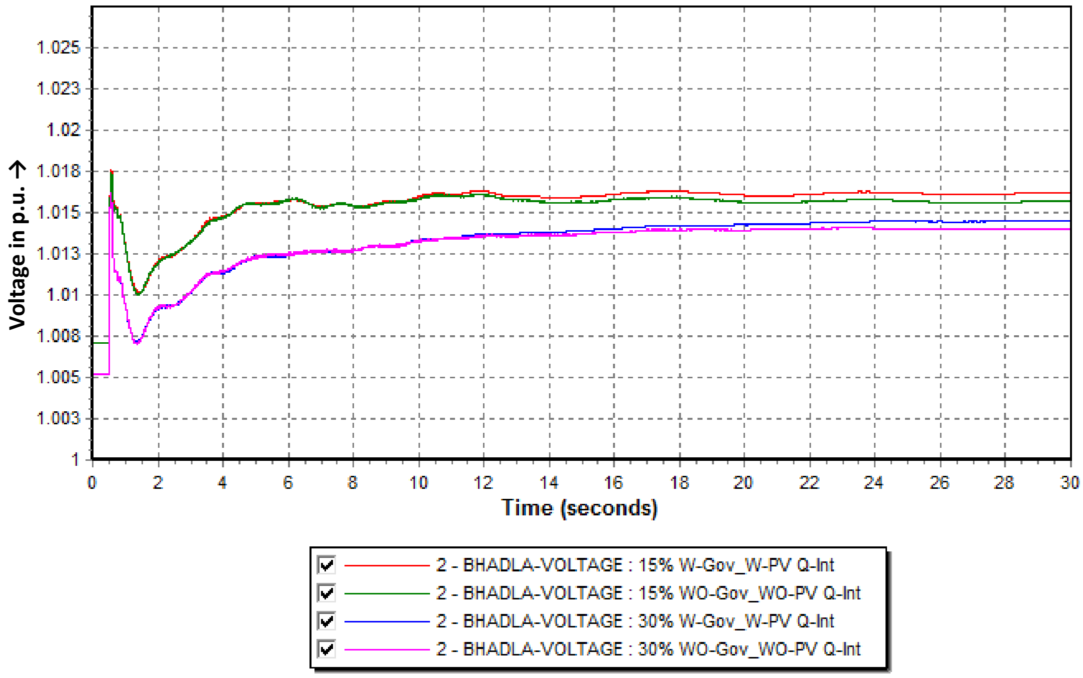


Figure 47: Bhadla 400 kV Bus Voltage (Northern region)

Wind Intermittency Study:

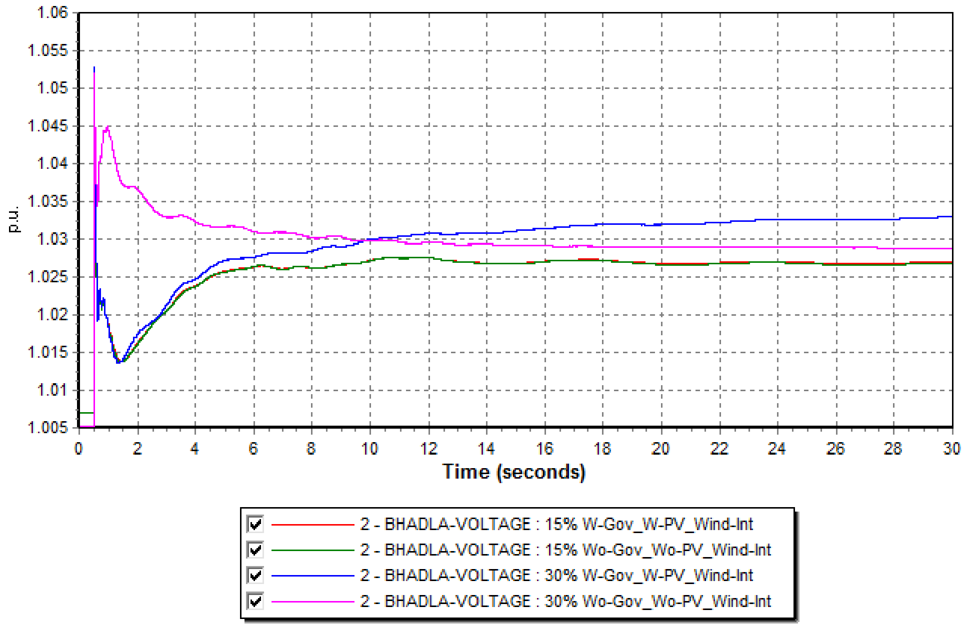


Figure 48: Bhadla 400 kV Bus Voltage (Northern region)

D) Inter State Tie-Line Power Flow:

For Bus Fault:

Power oscillations on some of the key inter-regional corridors (WR_NR, ER_NR, and SR_WR) are also observed during above indicated disturbance. It is observed that typically oscillation settles after few seconds even in worst cases of no governors and no reactive support from PV plants which shows grid stability; although, the oscillation amplitude and settling time is higher in 30% renewable penetration case. The oscillation frequency is about 0.5 Hz in all the cases.

Another observation from *Figure 49* to *Figure 52* is that in case of 30% renewable penetration the power oscillation is not completely damped and low frequency oscillations persist for more than 30 secs.

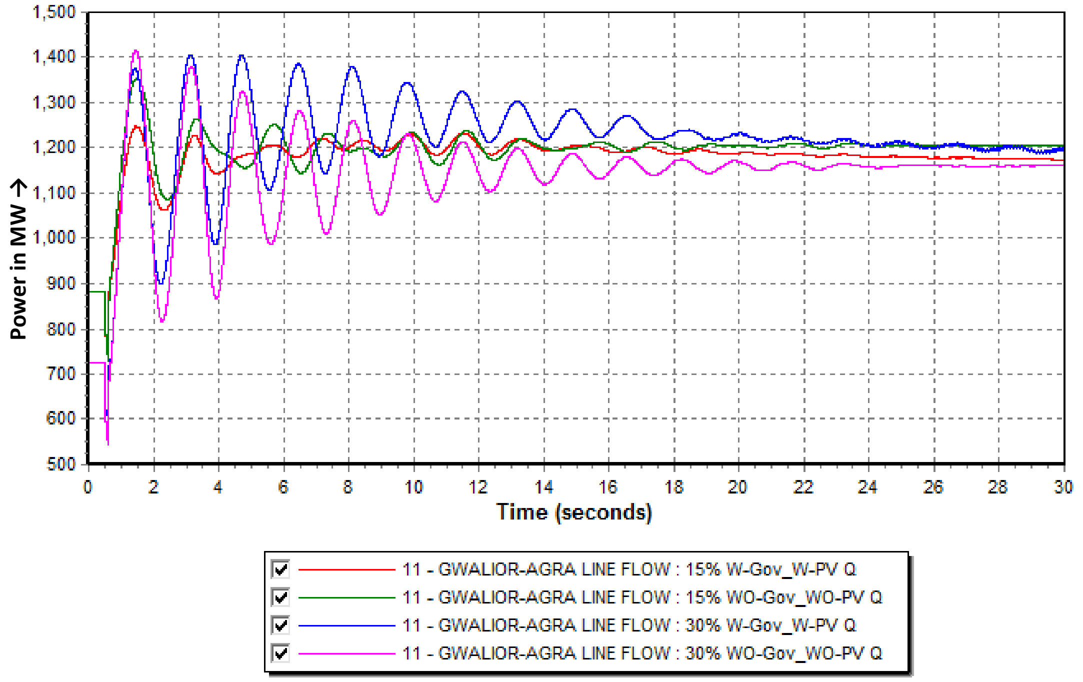


Figure 49: Gwalior-Agra 765kV Tie Line Power flow (WR-NR Link)

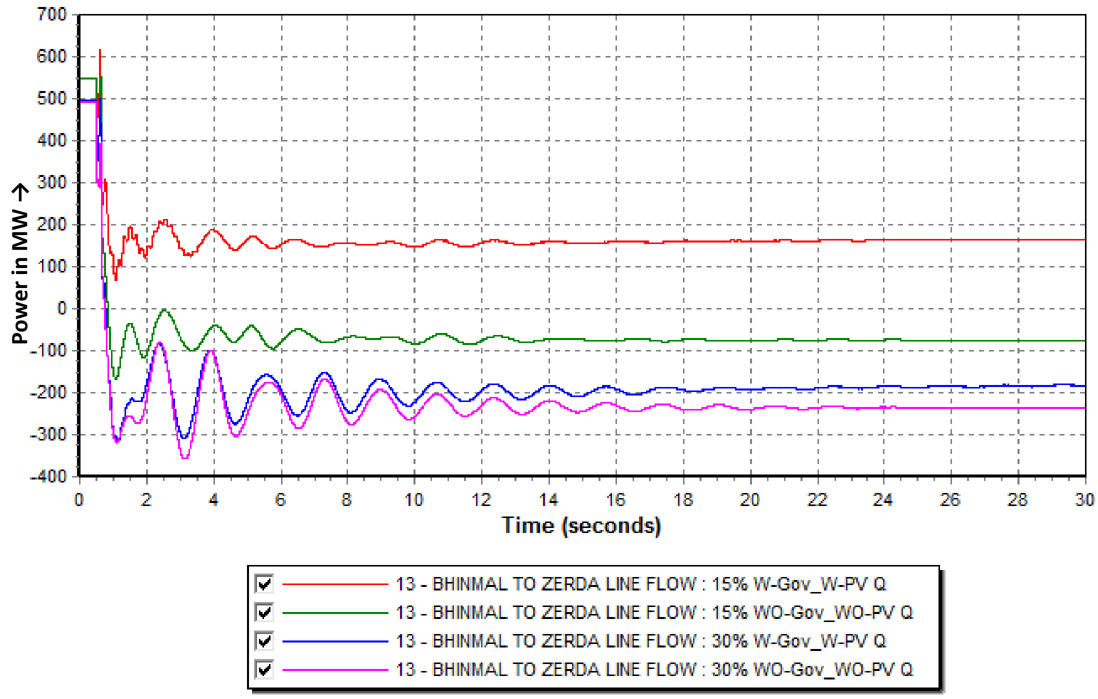


Figure 50: Zerda-Bhinmal 400kV Tie Line Power flow (WR-NR Link)

Figure 50 shows the power reversal in the tie line after fault. Before fault, power was flowing from NR to WR being Rajasthan surplus in RE power. After fault, majority of RE generation being LVRT non-compliant goes under outage and Rajasthan becomes power deficit. Thus, demand is met by import of power from other states.

The power flow in few other inter-regional tie lines are shown as under:

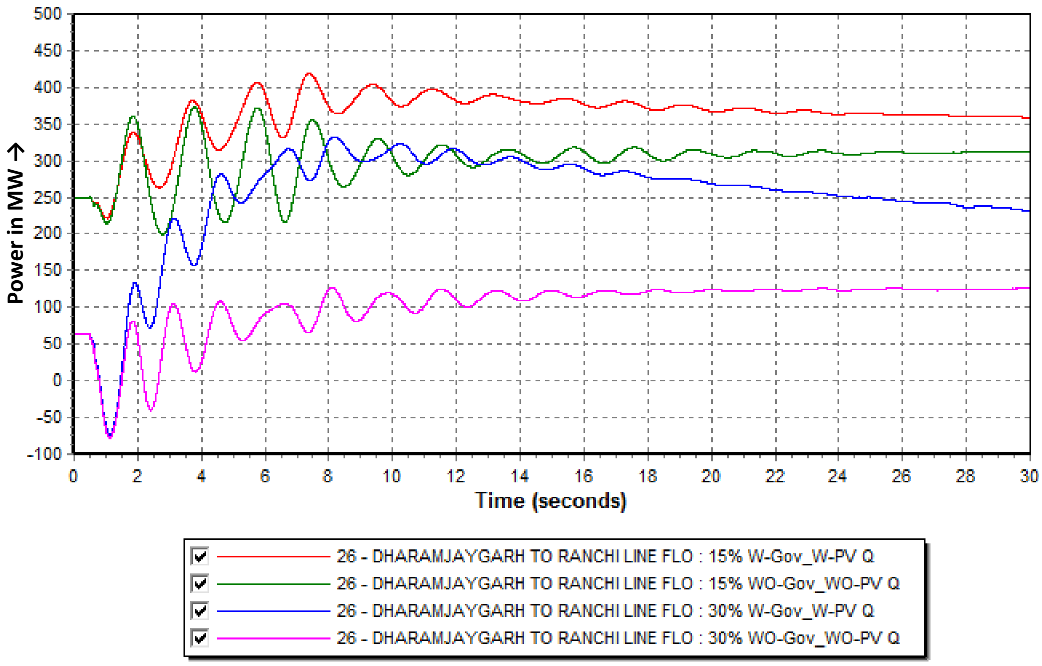


Figure 51: Dharamjaygarh-Ranchi 765kV Tie Line Power flow (ER-WR Link)

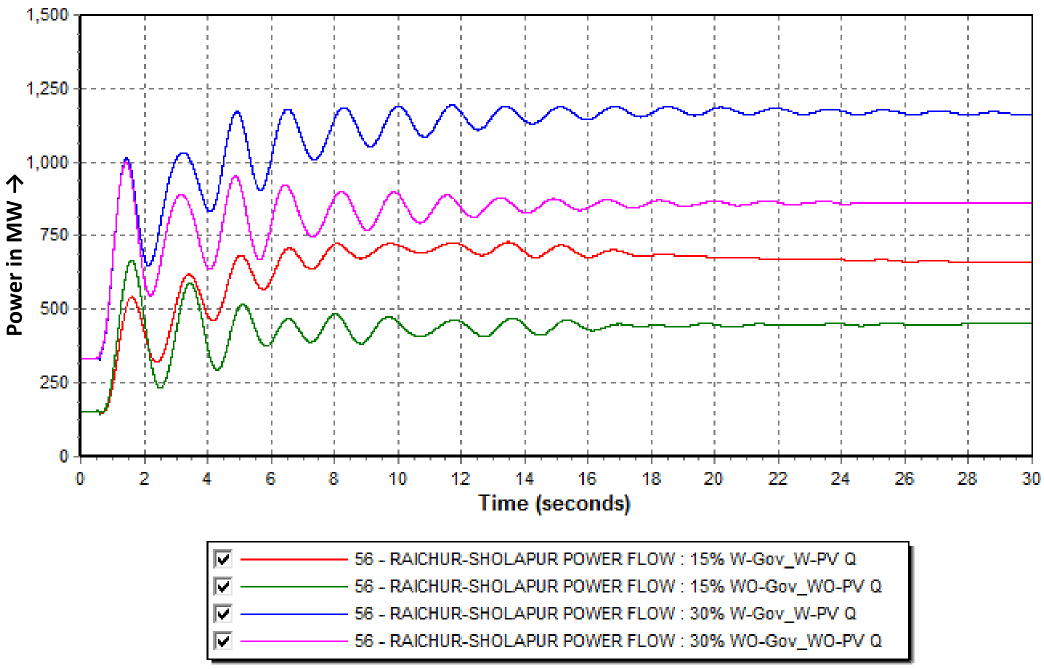


Figure 52: Raichur-Sholapur 400kV Tie Line Power flow (SR-WR Link)

Solar Intermittency Study:

For this case a damped oscillation in inter-area tie line power has been observed. As seen from the below plot the amplitude and duration of oscillation is very less compared to the case of bus fault. Also, the oscillations damp completely which is not the case with bus fault scenario.

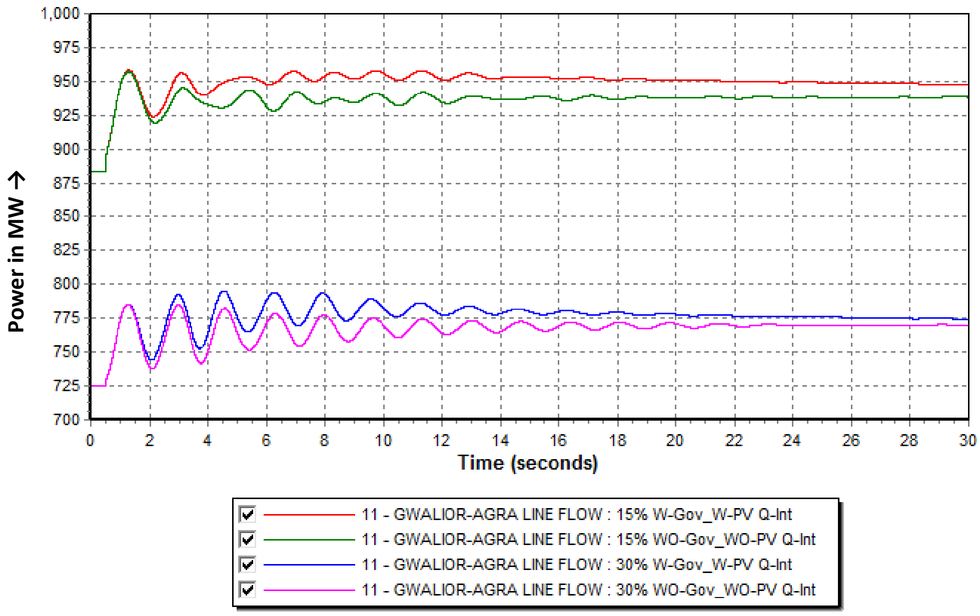


Figure 53: Gwalior-Agra 765 kV Tie Line Power flow (WR-NR Link)

Wind Intermittency Study:

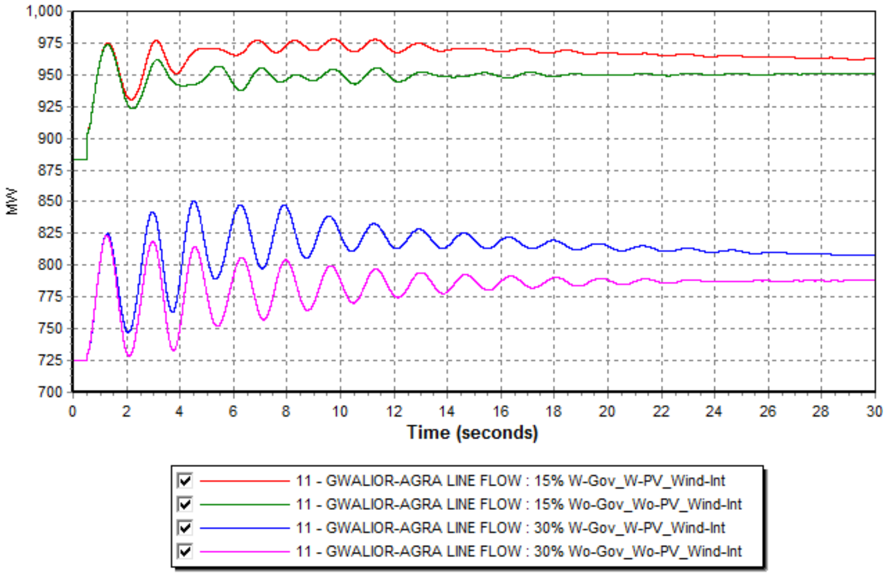


Figure 54: Gwalior-Agra 765 kV Tie Line Power flow (WR-NR Link)

4.5.2 Western Region

In Western region, Gujarat has exiting high RE potential; therefore, same is selected for study area under Western Region. In all India 15% & 30% RE Capacity penetration scenario, RE generation in Gujarat in 2019 time frame is considered as under:

Table 12

Gujarat	Total Installed Capacity(GW)	RE Installed Capacity (GW)
15 % RE Penetration Case	35	7
30 % RE Penetration Case	42	14

To simulate disturbance, a three-phase fault is applied at 400 kV Bhachau followed by clearing of fault after 100ms along with 400 kV Bhachau-CGPL line tripping. Bhachau bus is selected because of its proximity to Varsana which is a major connection point for Wind generation in Gujarat. As indicated earlier, RE generators are connected with under-voltage/over-voltage relay to also simulate outages during depressed grid voltage incidence (considering LVRT non-compliance).

Table-13 summarises the RE generation outage following fault clearing:

Table 13

Generation Outage	Case 1.a	Case 1.b	Case 1.c	Case 1.d	Case 2.a	Case 2.b	Case 2.c	Case 2.d
Installed Capacity	6151	6151	6151	6151	12889	13015	12889	13015
Dispatch	3098	3098	3098	3098	9476	9555	9476	9555

For the sake of better presentation, plots of only extreme cases (case 1.a & 2.a and case 1.d & 2.d) have been shown.

A) <u>Frequency Stability</u>

From *Figure 55* results similar to northern region case are observed for a disturbance in Gujarat which reveals that with the increase in penetration level, the drop in frequency also increases. In case 1.a and 2.a (with governor & PV reactive support), frequency recovers to 49.92&49.72 Hz respectively because of governor action. But in cases 1.d and 2.d (without governor & PV Reactive support) frequency doesn't recover and settles at 49.7 & 49.1 Hz respectively due to non-availability of governor action which will violate operating frequency band mentioned in IEGC.

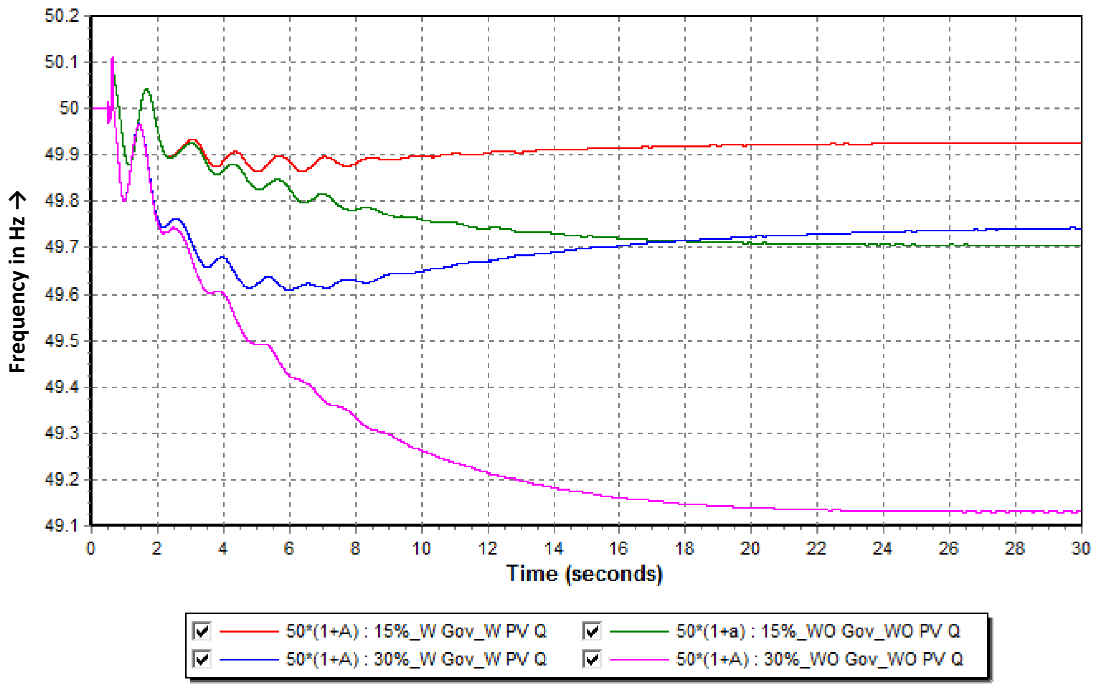


Figure 55: Grid Frequency

B) Rotor angle Stability

From *Figure 56* to *Figure 63* also it can be observed that angle and power from conventional generators go through an oscillatory motion and then settles after some time. The settling value of Power generated is same as pre-fault condition because no steam turbine governor action is taken into account. The oscillation frequency in the plots is in the range of 0.5-1 Hz in Mundra machine as shown in the *Figure 56*. This indicates presence of Inter area oscillation in the system.

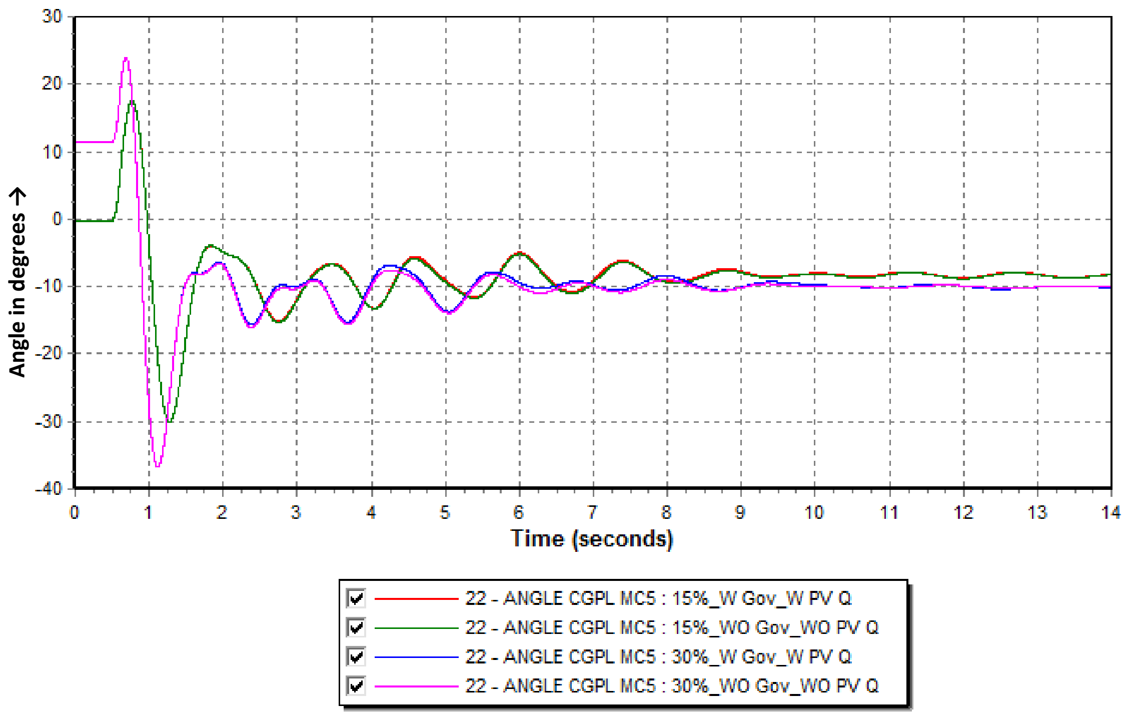


Figure 56: Rotor angle of machine 5 of Mundra(Western region)

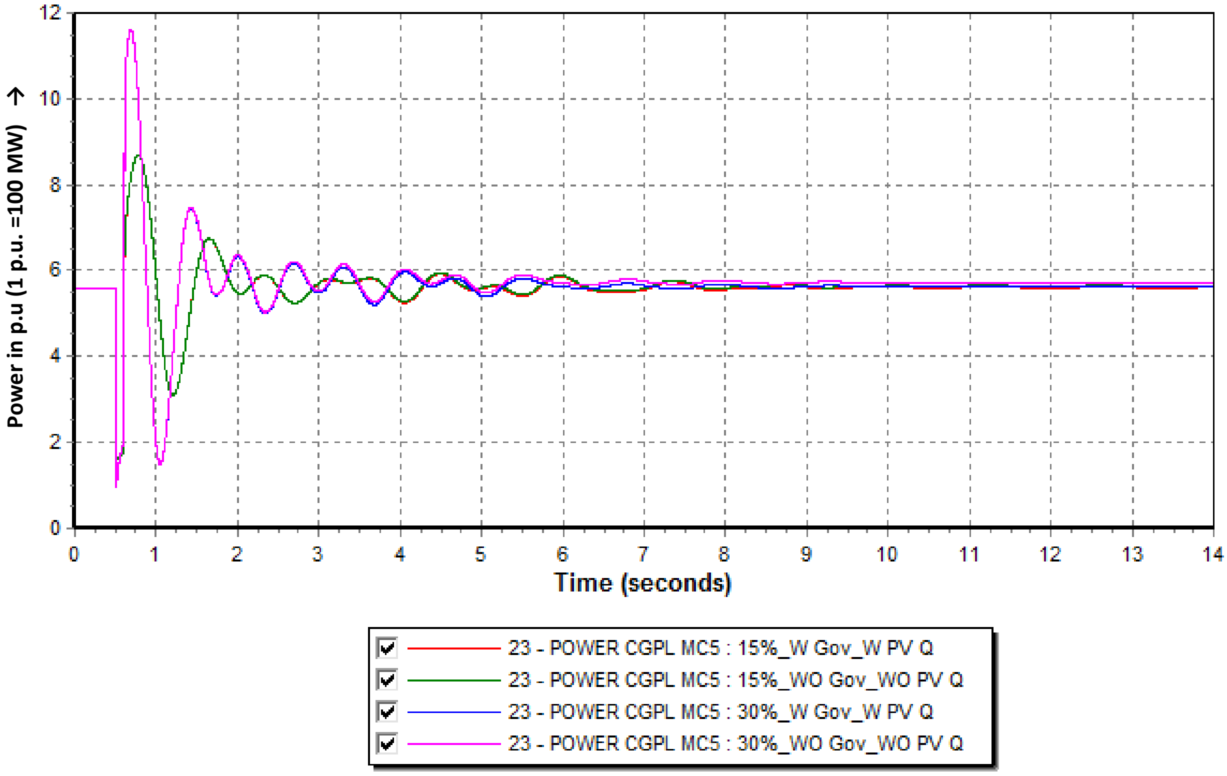


Figure 57: Generated Power of machine 5 of Mundra (Western region)

The oscillation frequency in the rotor angle is 0.75 Hz in EPGL plant machine as shown in the *Figure 58*.

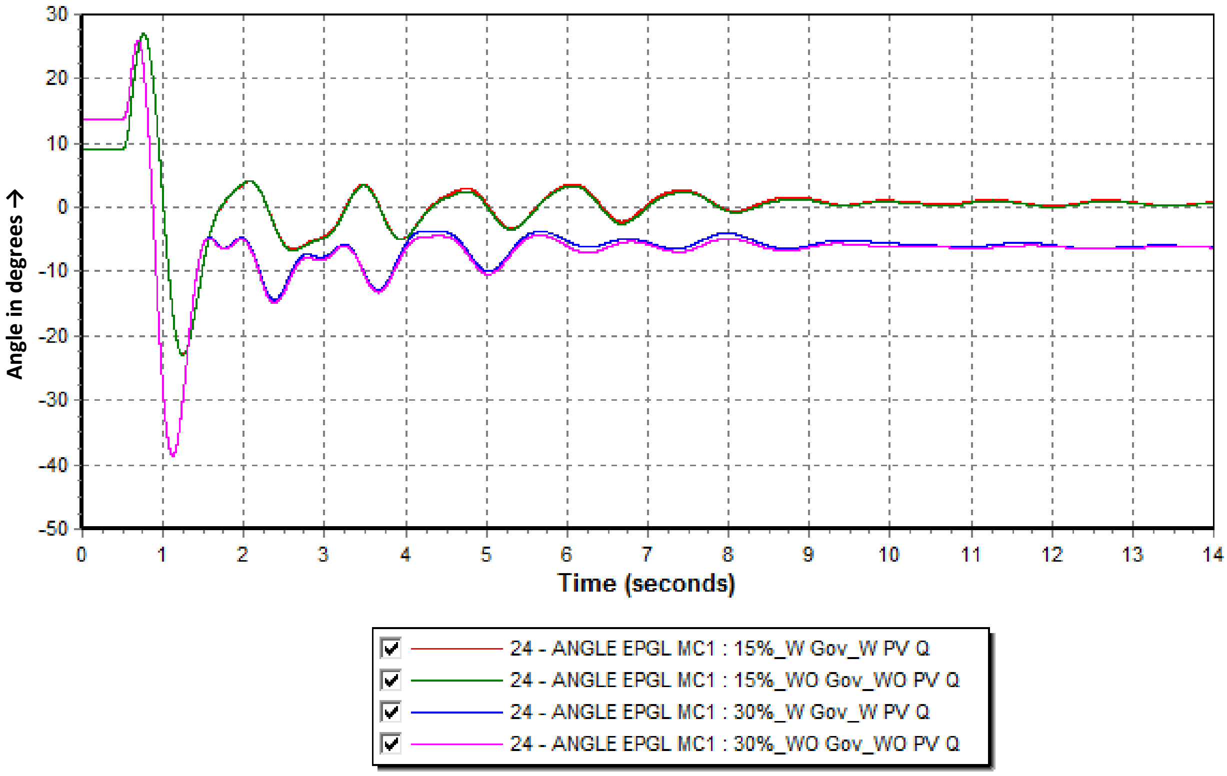


Figure 58: Rotor angle of machine 1 of EPGL TPS(Western region)

The oscillation frequency in the power of the EPGL plant machine is 1.5 Hz as shown in the *Figure 59*.

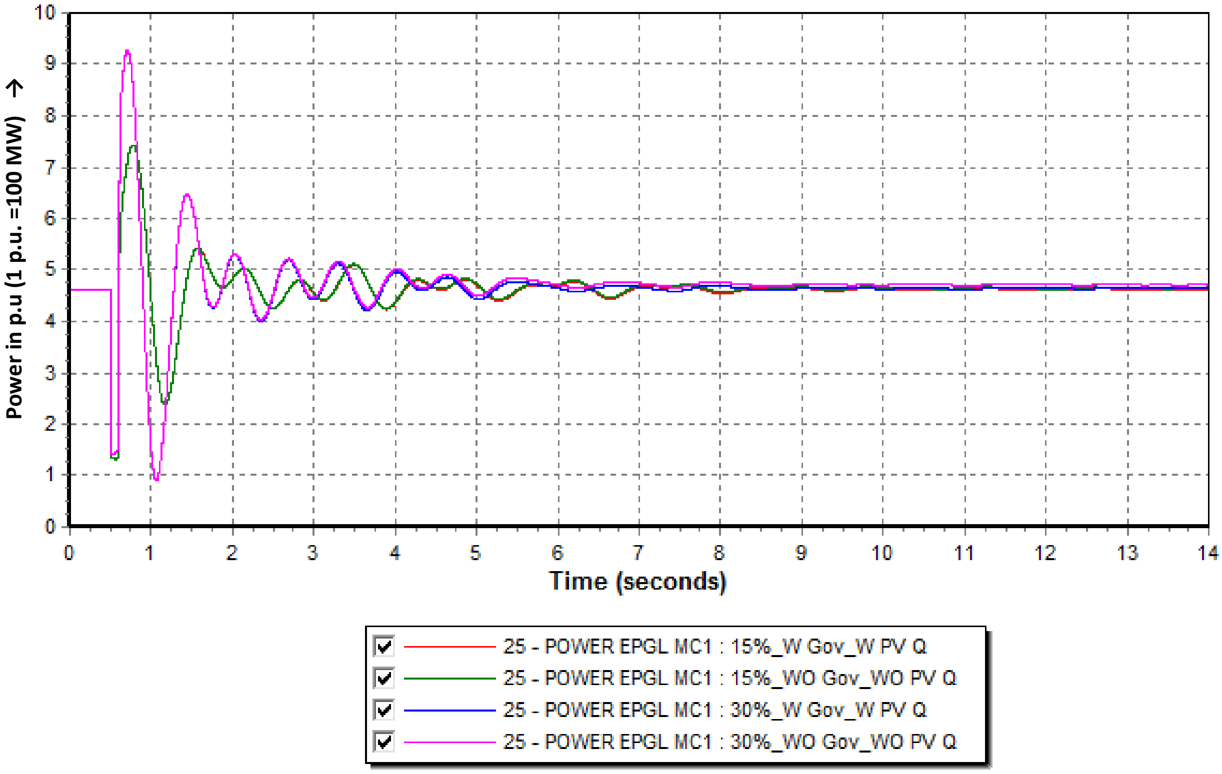


Figure 59: Generated Power of machine 1 of EPGL TPS (Western region)

The oscillation frequency of rotor angle of Neyveli machine is 0.6 Hz as shown in *Figure 60*.

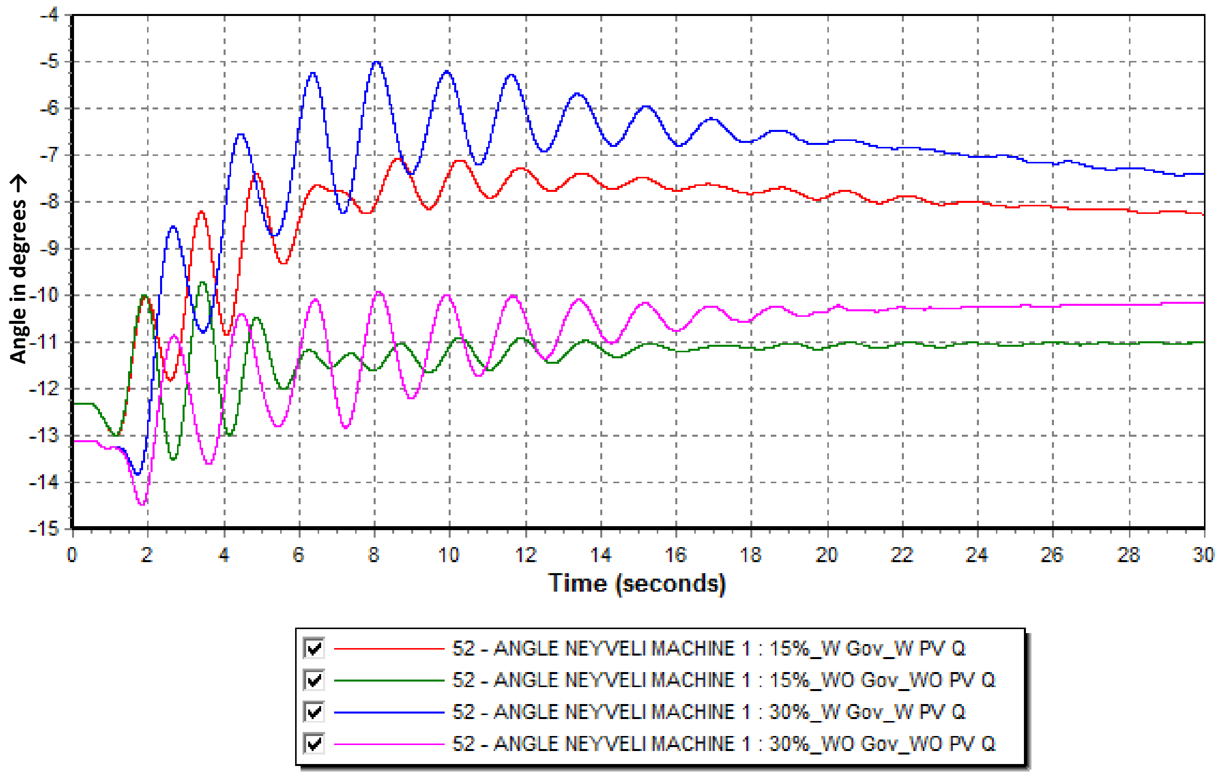


Figure 60: Rotor angle of machine 1 of Neyveli(Southern region)

The oscillation frequency of the power of Neyveli plant machine is 1.2 Hz as shown in *Figure 61*.

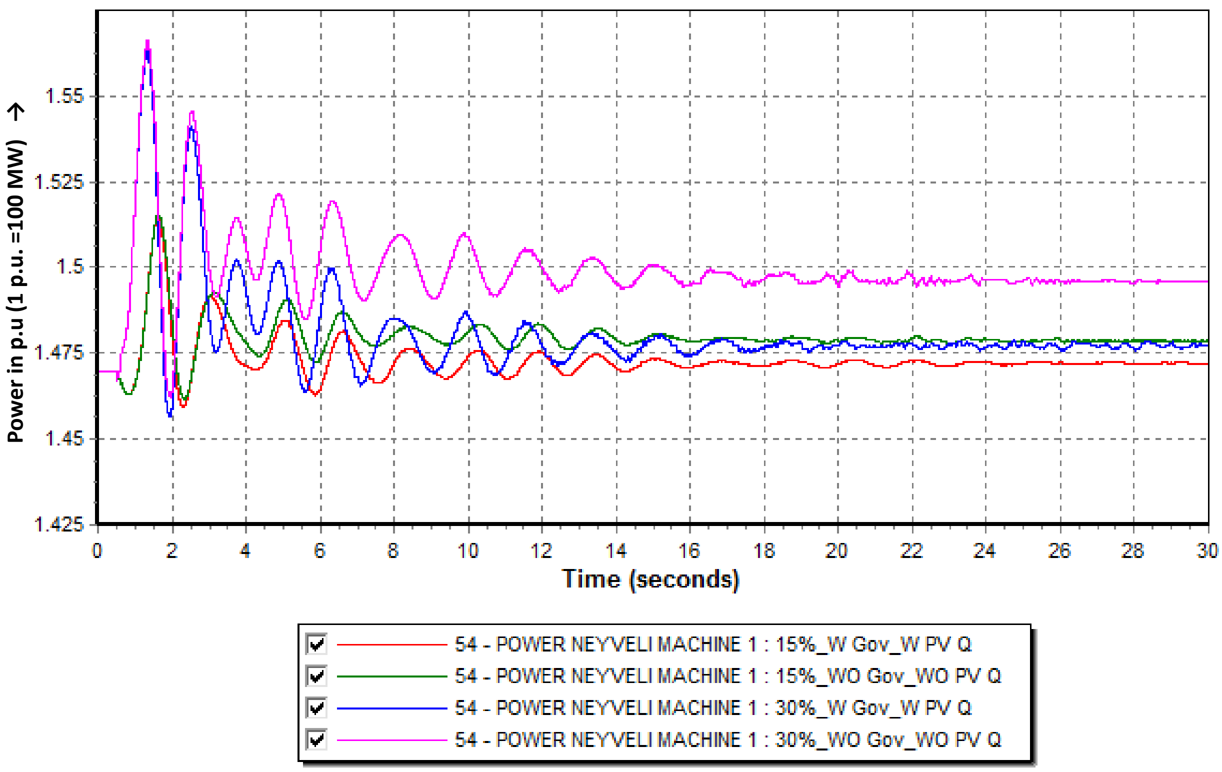


Figure 61: Generated Power of machine 1 of Neyveli(Southern region)

The oscillation frequency in rotor angle of Suratgarh machine is 0.75 Hz as shown in *Figure 62*.

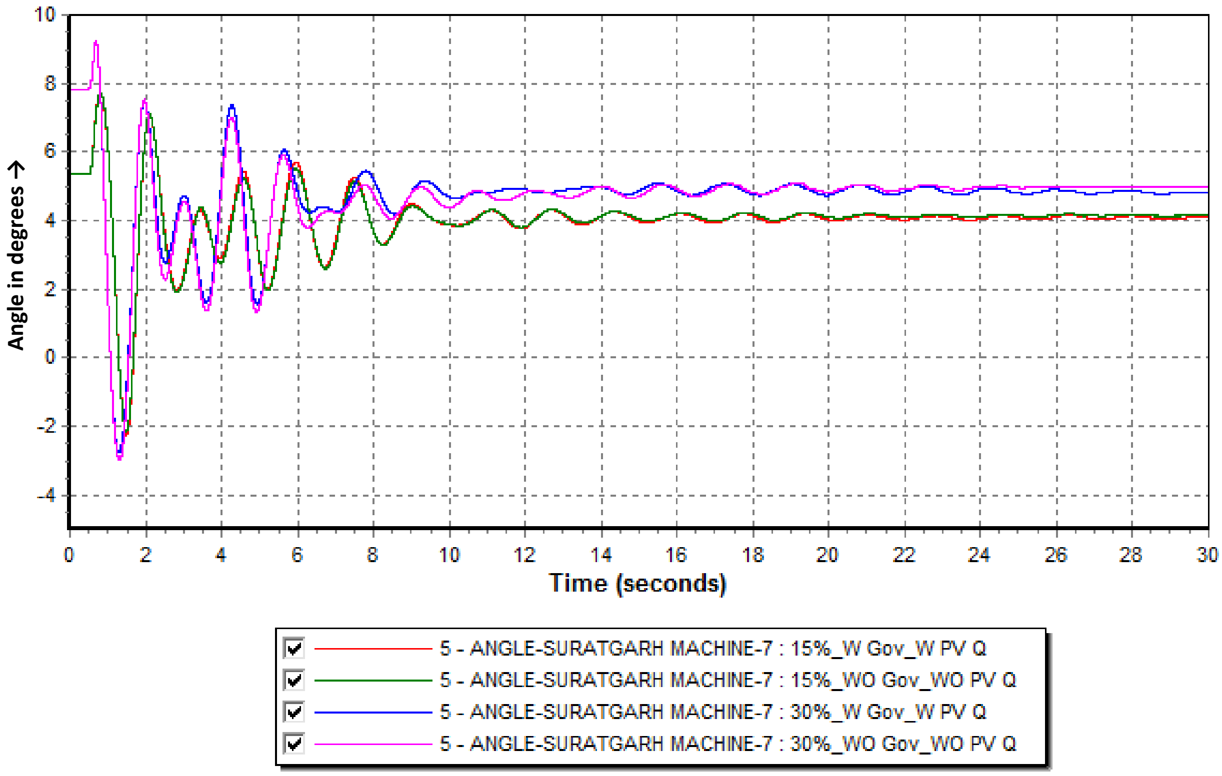


Figure 62: Rotor angle of machine 7 of Suratgarh TPS(Northern region)

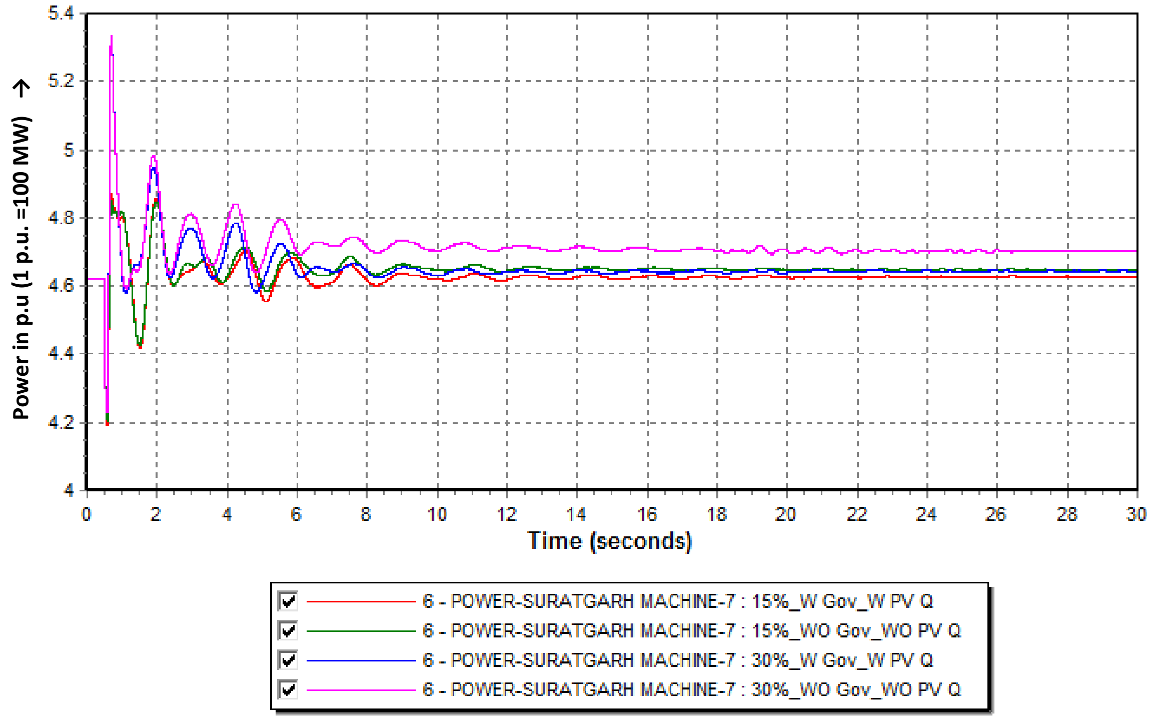


Figure 63: Generated Power of machine 7 of Suratgarh TPS (Northern region)

C) <u>Voltage Stability</u>

Bus Voltage plots in *Figure 64* to *Figure 67* shows that voltage recovers after fault is cleared. However, the post fault voltage overshoot is higher in case of higher penetration level case. This is because of two reasons, one that a large amount of RE generation is disconnected after fault clears which causes sudden under-loading of EHV transmission lines and secondly, huge amount of reactive power is supplied by solar PV generators during fault.

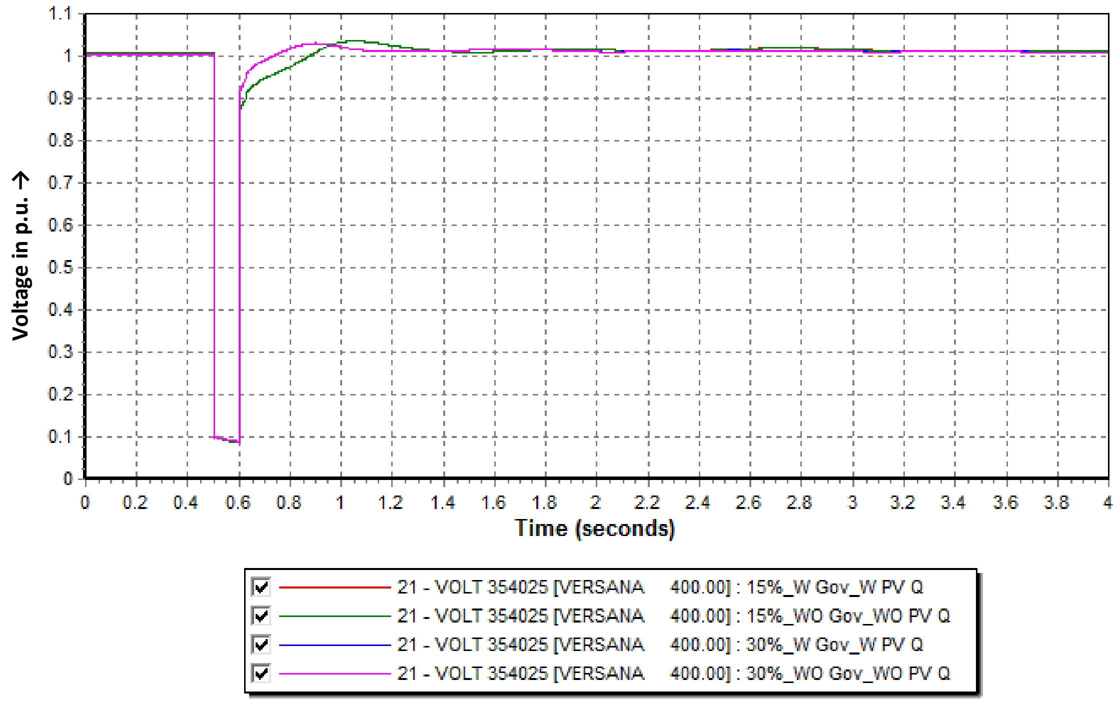


Figure 64: Varsana 400kV Bus Voltage (Western region)

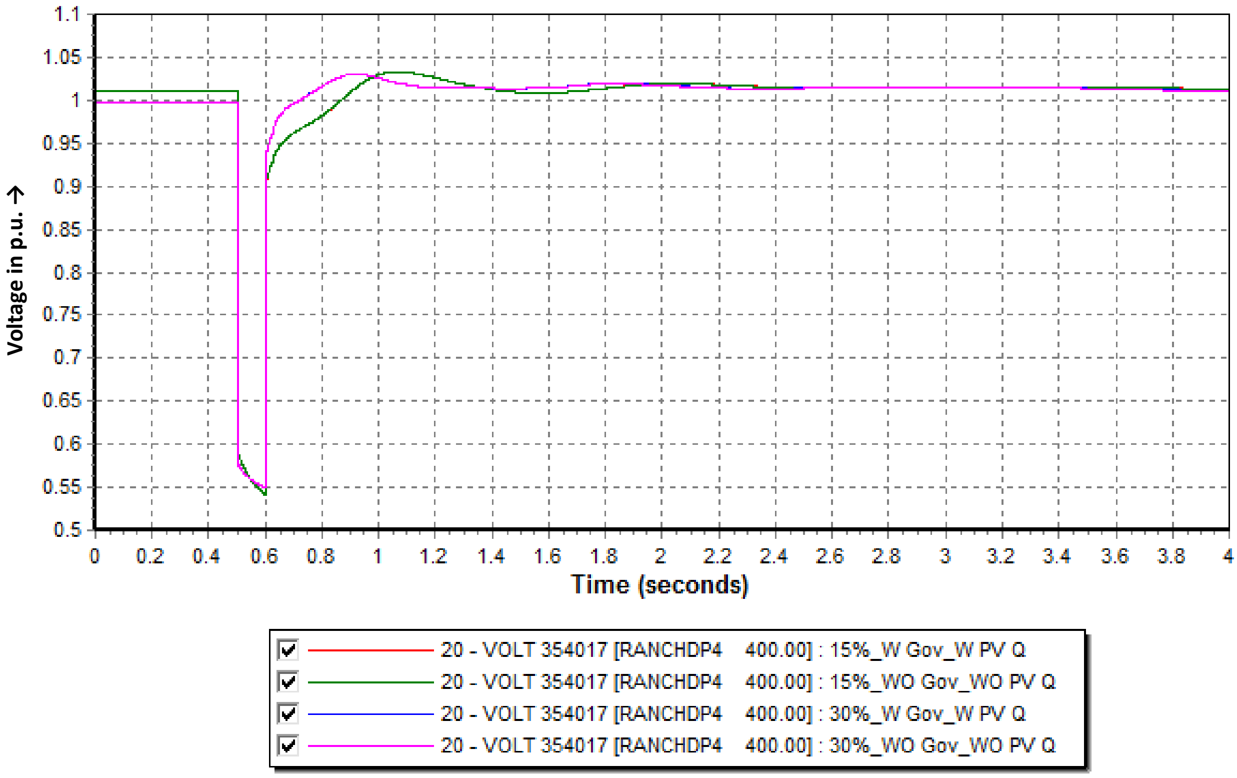


Figure 65: Ranchodpura 400kV Bus Voltage (Western region)

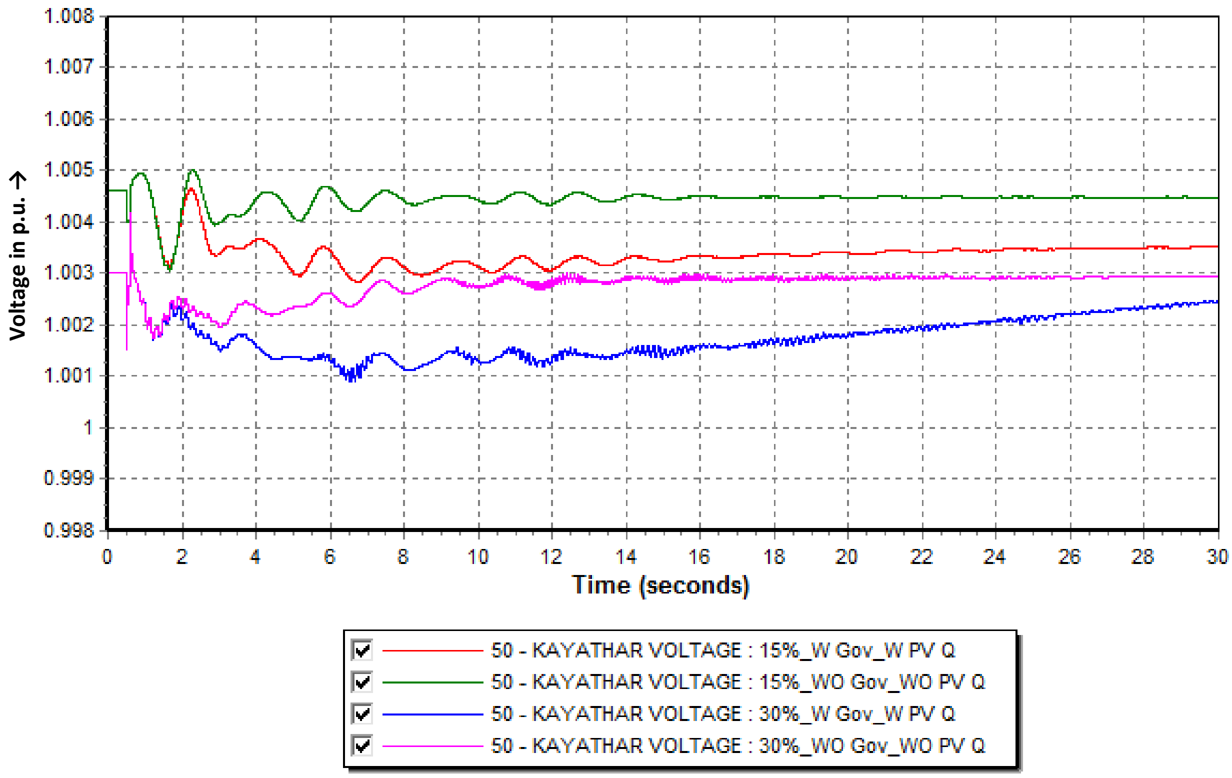


Figure 66: Kayathar 400kV Bus Voltage (Southern region)

Oscillations with frequency of 6 Hz are observed in the Bhadla bus voltage as shown in the *Figure 67*.

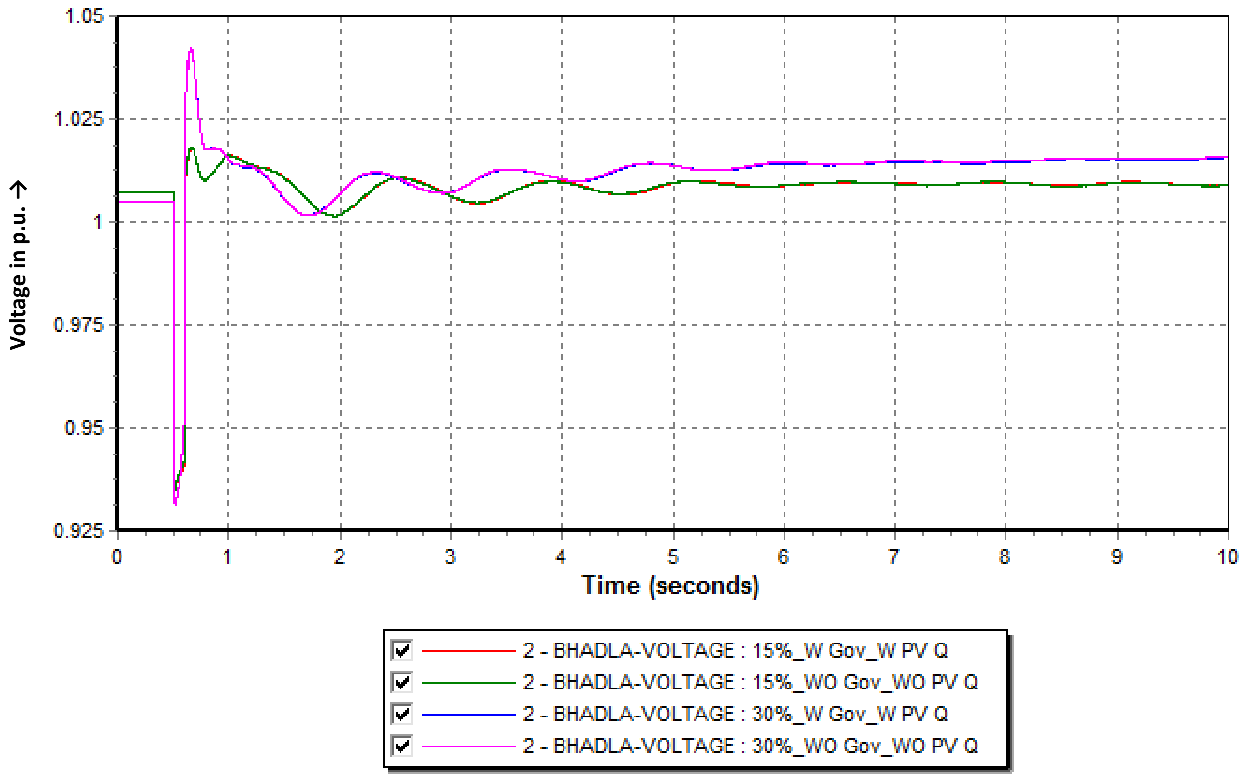


Figure 67: Bhadla 400kV Bus Voltage (Northern region)

D) <u>Inter State Tie-Line Power Flow:</u>

The oscillation frequency of power in the Agra- Gwalior tie line is 0.6 Hz as shown in the *Figure 68*.

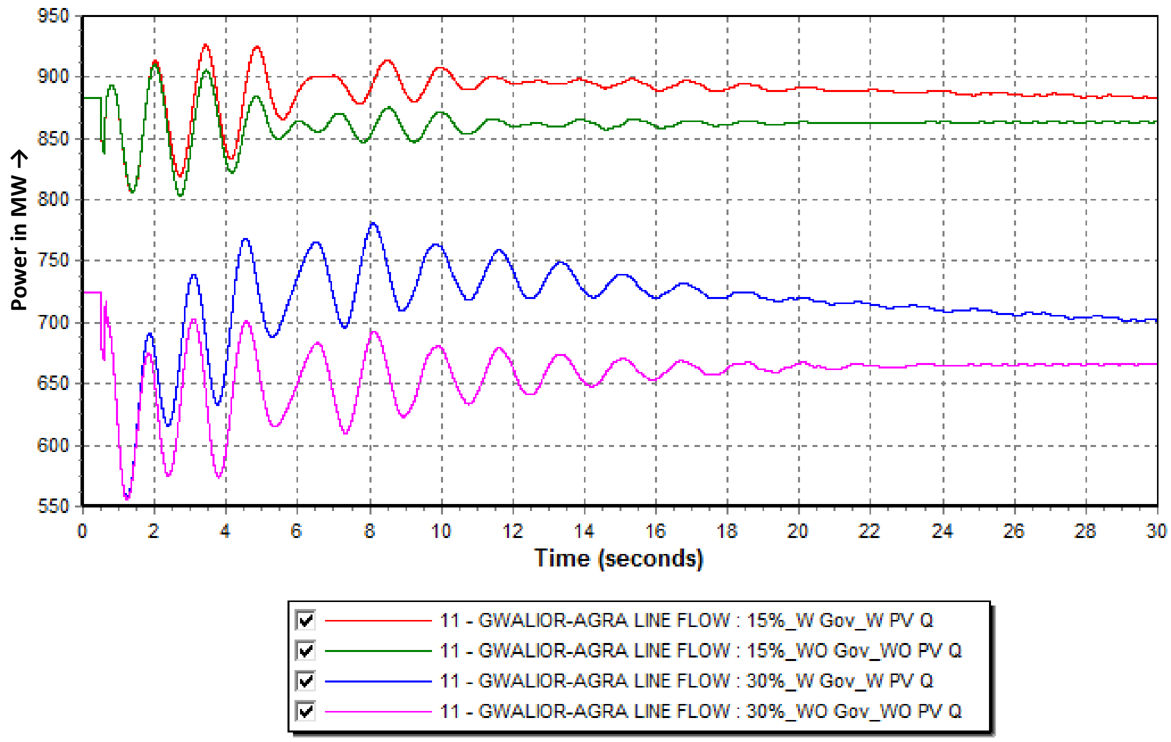


Figure 68: Gwalior-Agra 765kV Tie Line Power flow (WR-NR Link)

The oscillation frequency of power in the Dharamjaygarh- Ranchi tie line is 0.6 Hz as shown in the *Figure 69*.

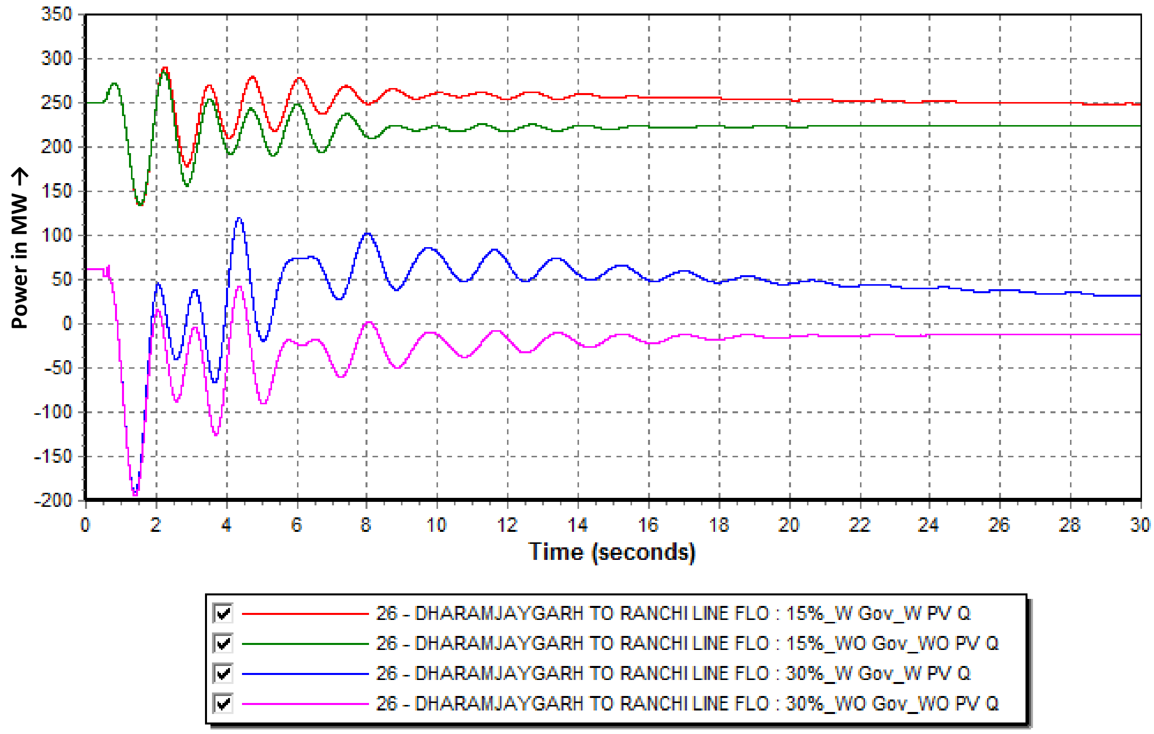


Figure 69: Dharamjaygarh-Ranchi 765kV Tie Line Power flow (ER-WR Link)

The oscillation frequency of power in the CGPL plant to Bachau line is 1.5 Hz as shown in the *Figure 70*.

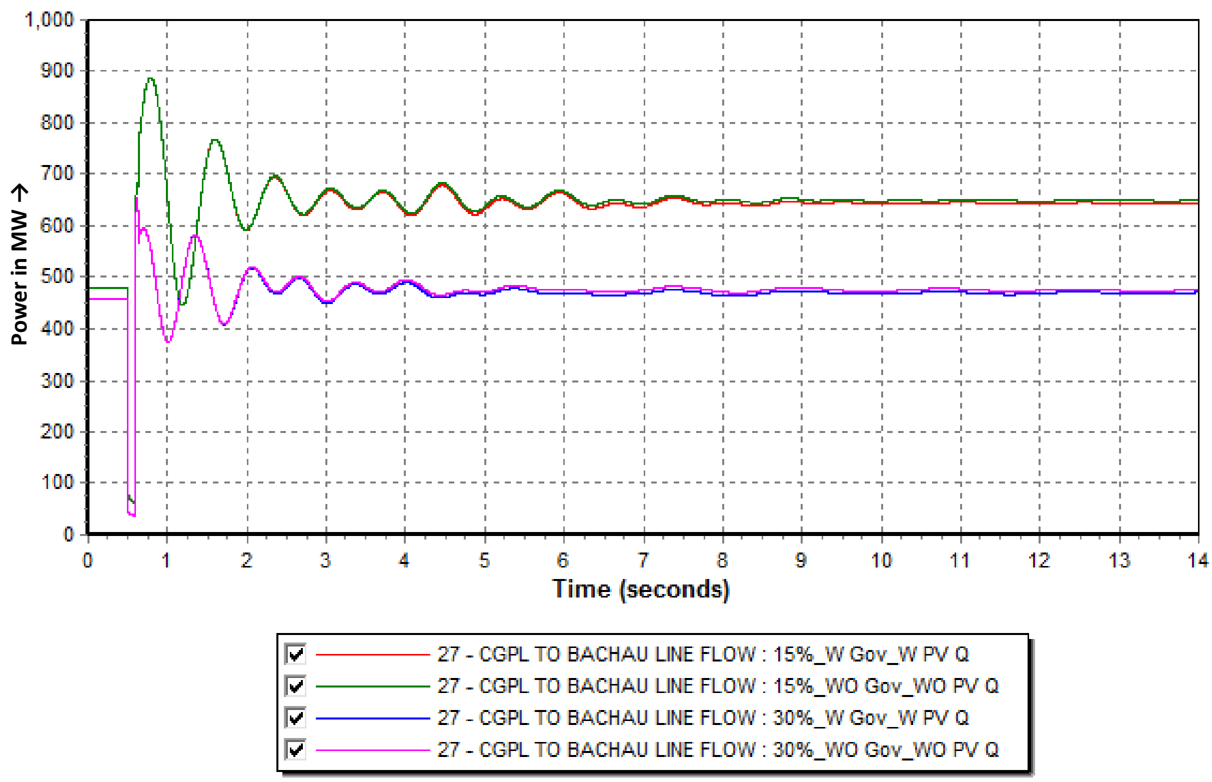


Figure 70: CGPL-Bhachau 400kV Line Power flow

The oscillation frequency of power in the Raichur-sholapur tie line is 0.6 Hz as shown in the *Figure 71*.

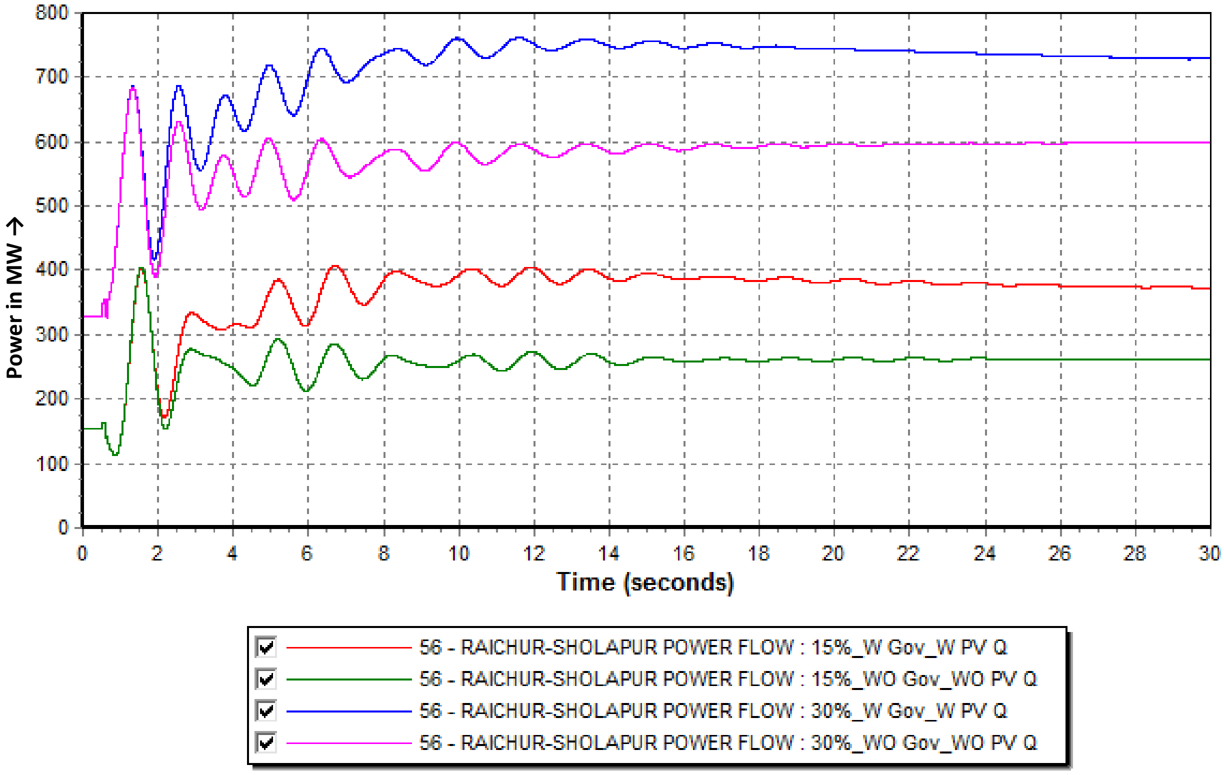


Figure 71: Raichur-Sholapur 400kV Tie Line Power flow (SR-WR line)

4.5.3 Southern Region

In Southern region, Tamil Nadu is the leading state in Installation of Wind generation. Presently, the installed capacity of Wind in South is about 11GW out of which 7.5 GW is installed in Tamil Nadu whereas Karnataka has around 3000 MW.

By the end of 2019, the installed capacity of Wind in Southern region is expected to reach 20 GW out of which Tamil Nadu will be having around 11 GW. Around 7 GW of Solar is also coming up as in solar parks in different states. As Tamil Nadu has higher RE generation as well as potential envisaged in SR, it has been considered as study area.

Karaikudi is the bus where the fault simulation is carried out to view the response of nearby conventional machines and outage of nearby wind and solar generations due to fault. The main reason for choosing Karaikudi is that it is a central location to nearby grid connected wind generators where maximum impact of generation loss on account of LVRT non-compliance can be seen (Due to the presence of wind pockets like Kayathar, Tirunelveli & Solar parks at Kamuthi & Tiruchuli).

The three-phase fault at 400 kV Karaikudi is cleared after 100ms followed by 400 kV Karaikudi-Kayathar line tripping. The Wind generators are connected with under-voltage relays.

Table 14

Tamil Nadu	Total Installed Capacity (GW)	RE Installed Capacity (GW)
15 % RE Penetration Case	40	11
30 % RE Penetration Case	47	18

Table-15 summarises the MW RE generation outage following fault clearing:

Table 15

Generation Outage	Case 1.a	Case 1.b	Case 1.c	Case 1.d	Case 2.a	Case 2.b	Case 2.c	Case 2.d
Installed Capacity	5553	5638	5553	5638	7844	8354	7844	8354
Dispatch	2749	2783	2749	2783	5823	6180	5823	6180

For the sake of better presentation, plots of only extreme cases (case 1.a & 2.a and case 1.d & 2.d) have been shown.

A) <u>Frequency Stability</u>

From *Figure 72* it can be observed that penetration level of RE has significant impact on grid frequency. With the increase of penetration level, the severity of impact on system stability also increases.

In case 1.a and 2.a (with governors & PV reactive support), frequency recovers to 49.95 Hz and 49.88Hz respectively because of governor action. But, in cases 1.d and 2.d (without governor & PV reactive support), frequency doesn't recover and settles at 49.8 Hz and 49.58 Hz. respectively due to non-availability of governor action which will violate operating frequency band mentioned in IEGC (49.9-50.05 Hz).

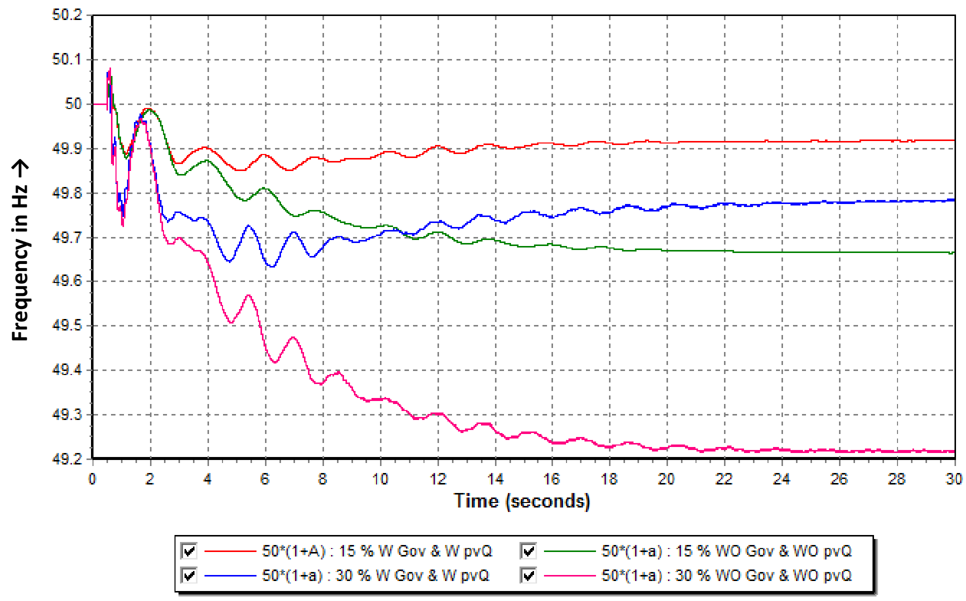


Figure 72:Grid Frequency

B) Rotor angle Stability

From *Figure 73* to *Figure 80*, it can be observed that angle and power from conventional generators go through an oscillatory motion and then settles after some time. The settling value of Power generated is slightly different from pre-fault condition due to steam turbine governor action. The oscillation frequency in the rotor angle is 0.5 Hz in Ramagundam TPS machine as shown in the *Figure 73*.

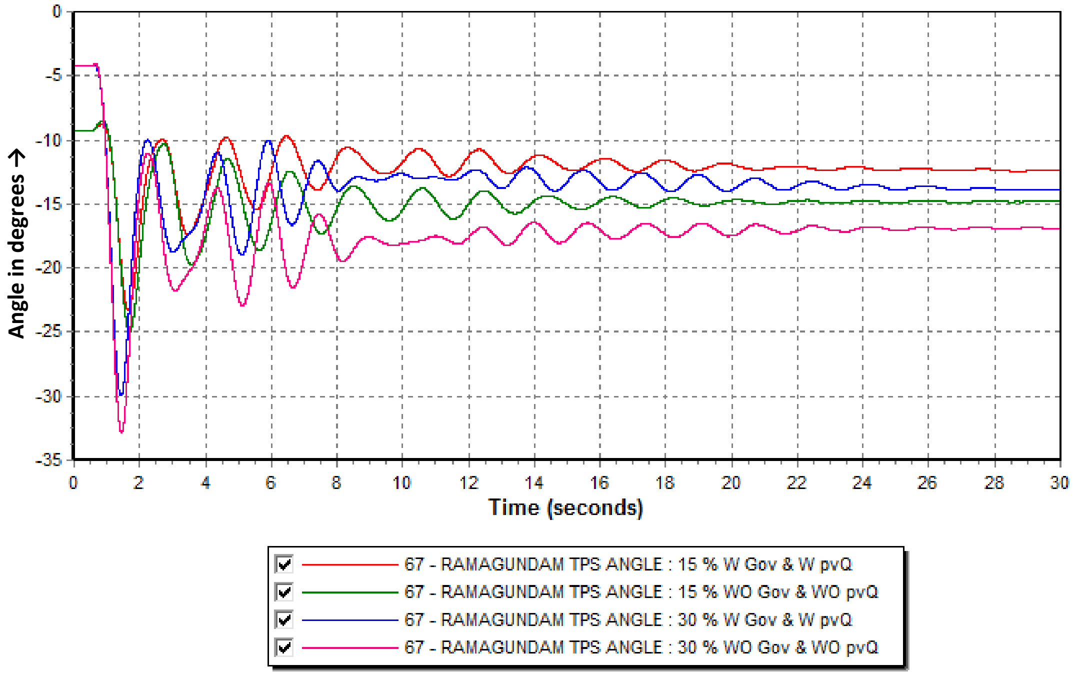


Figure 73: Rotor angle of machine 7 of Ramagundam(Southern region)

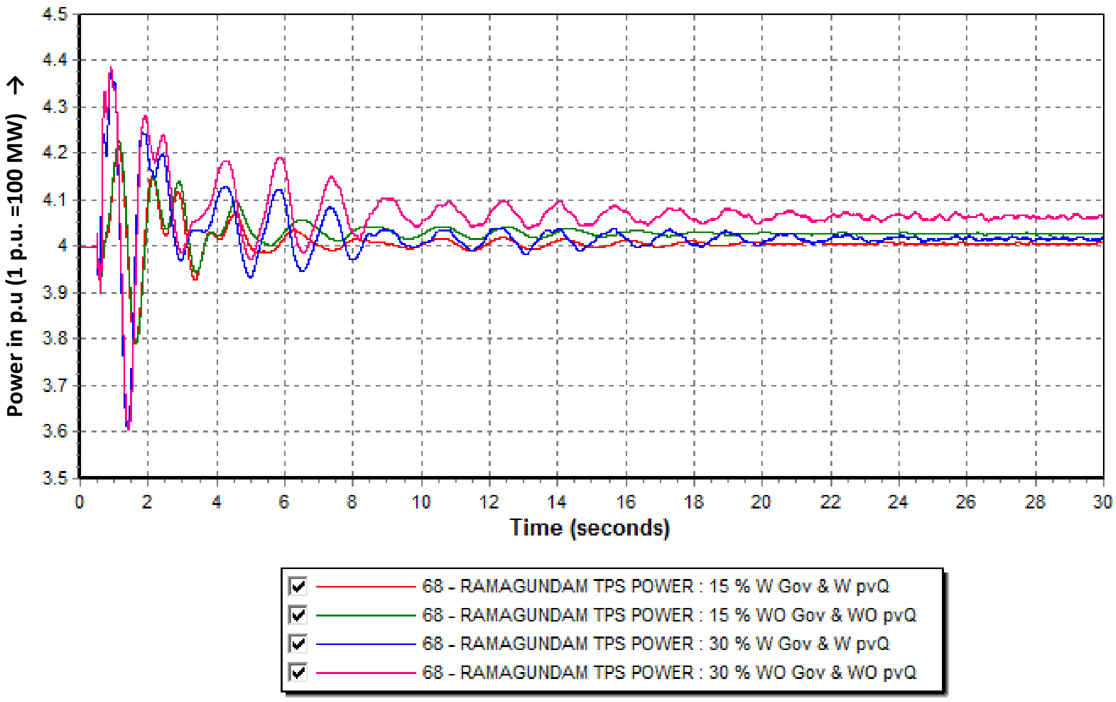


Figure 74: Generated Power of machine 7 of Ramagundam(Southern region)

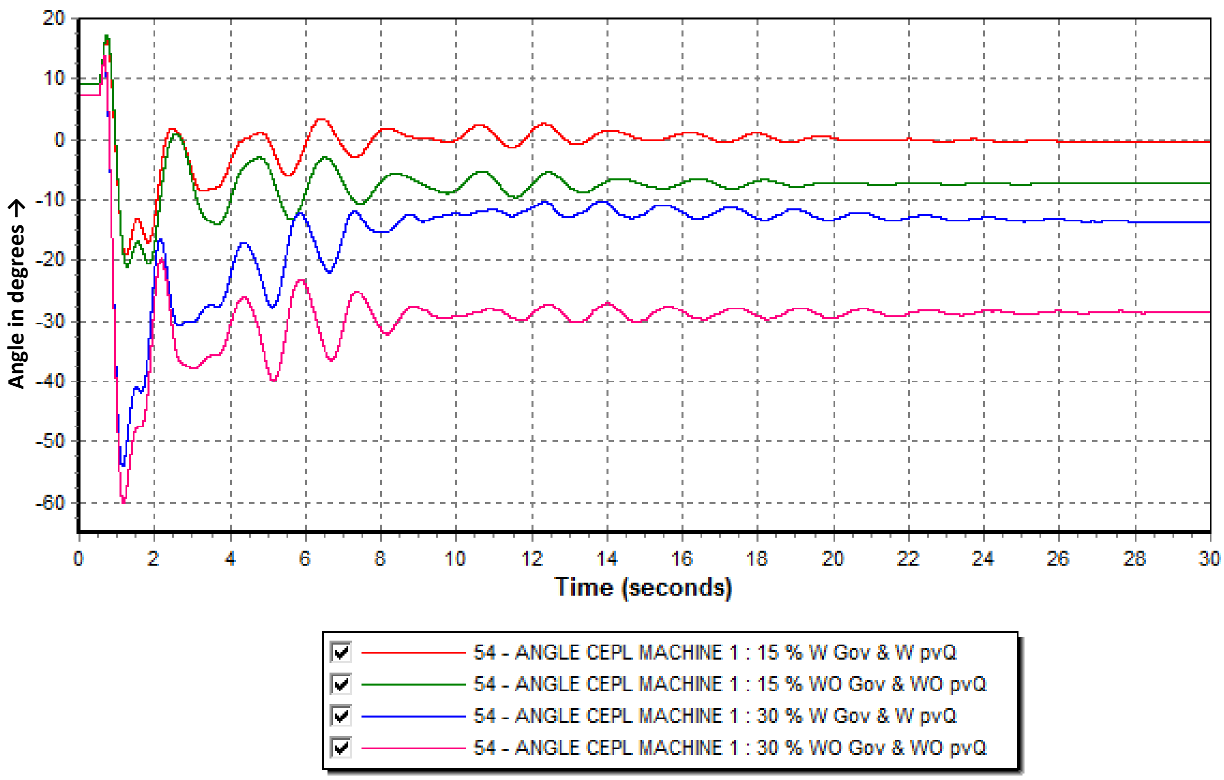


Figure 75: Rotor angle of machine 1 of CEPL TPS(Southern region)

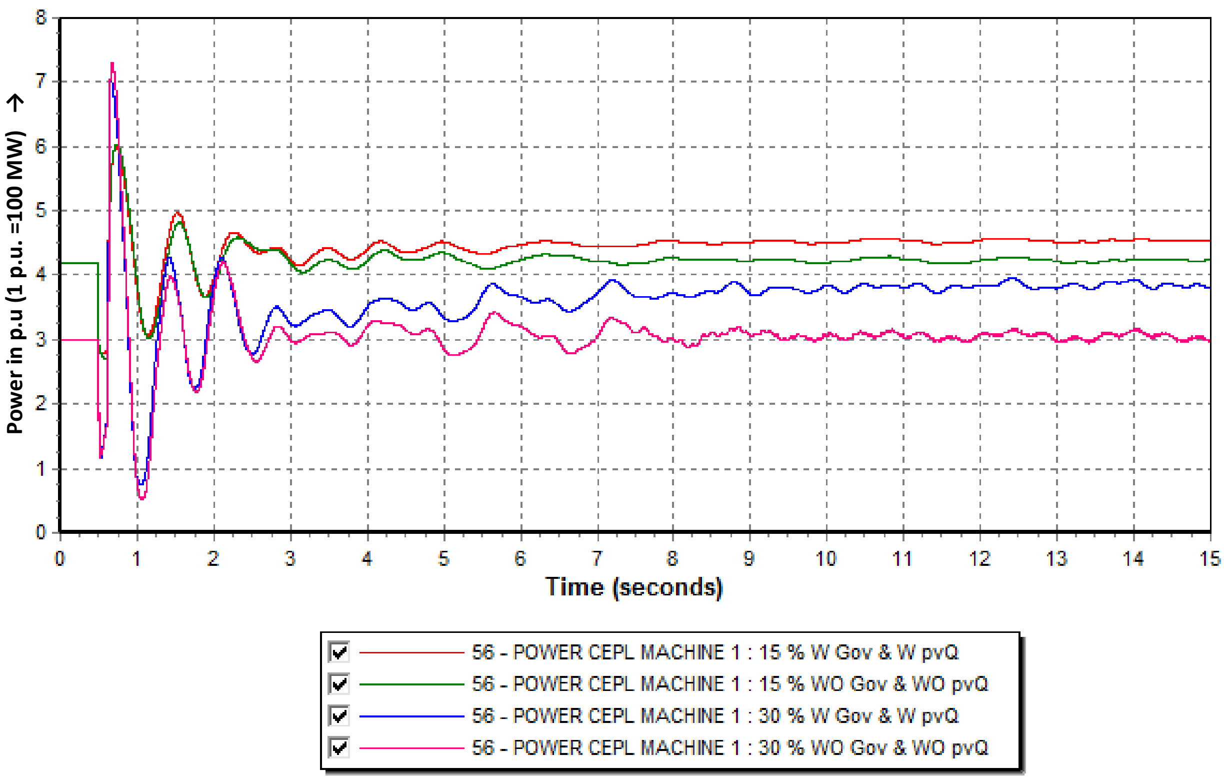


Figure 76: Generated Power of machine 1 of CEPL TPS(Southern region)

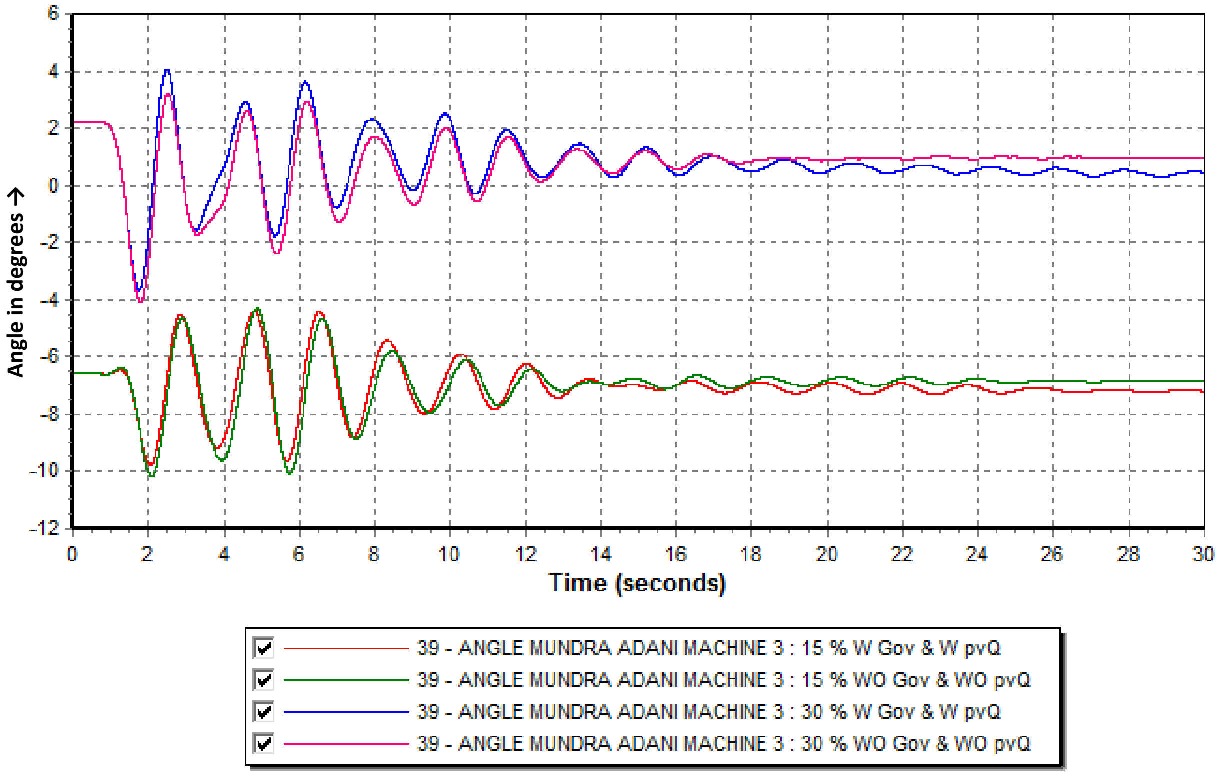


Figure 77: Rotor angle of machine 3 of Adani Mundra(Western region)

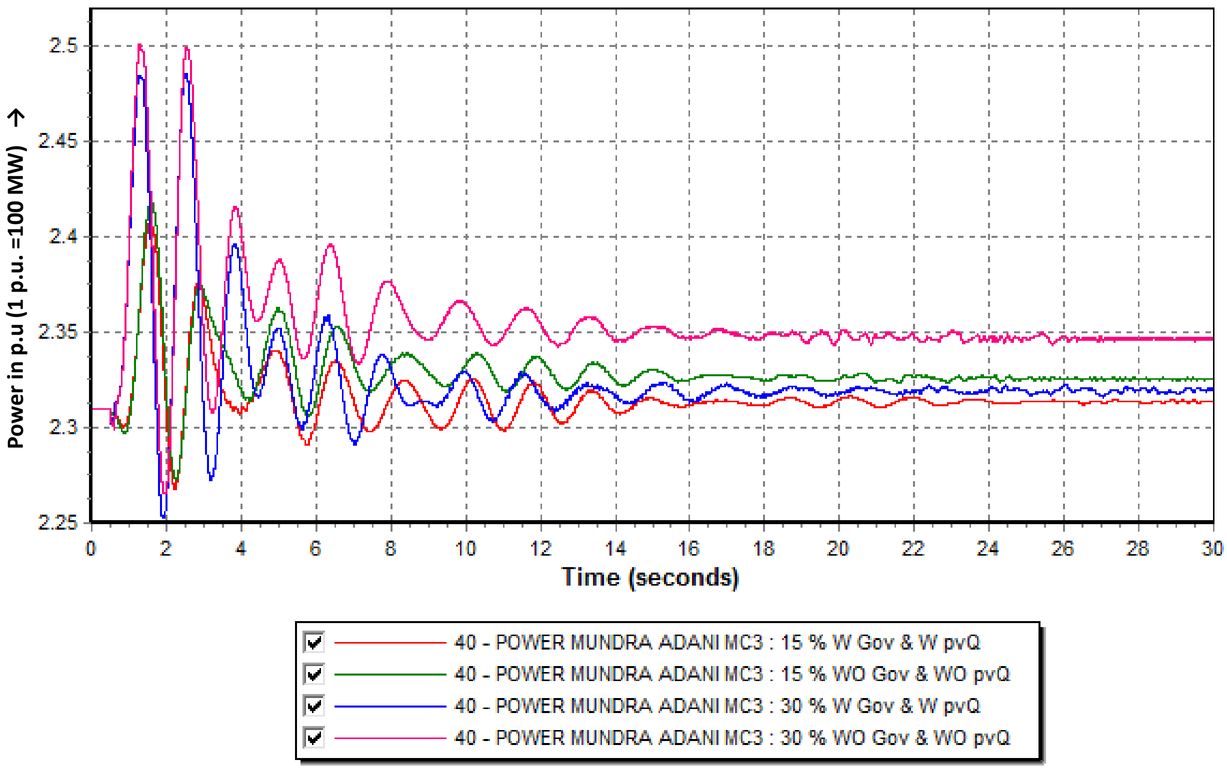


Figure 78: Generated Power of machine 3 of Adani Mundra (Western region)

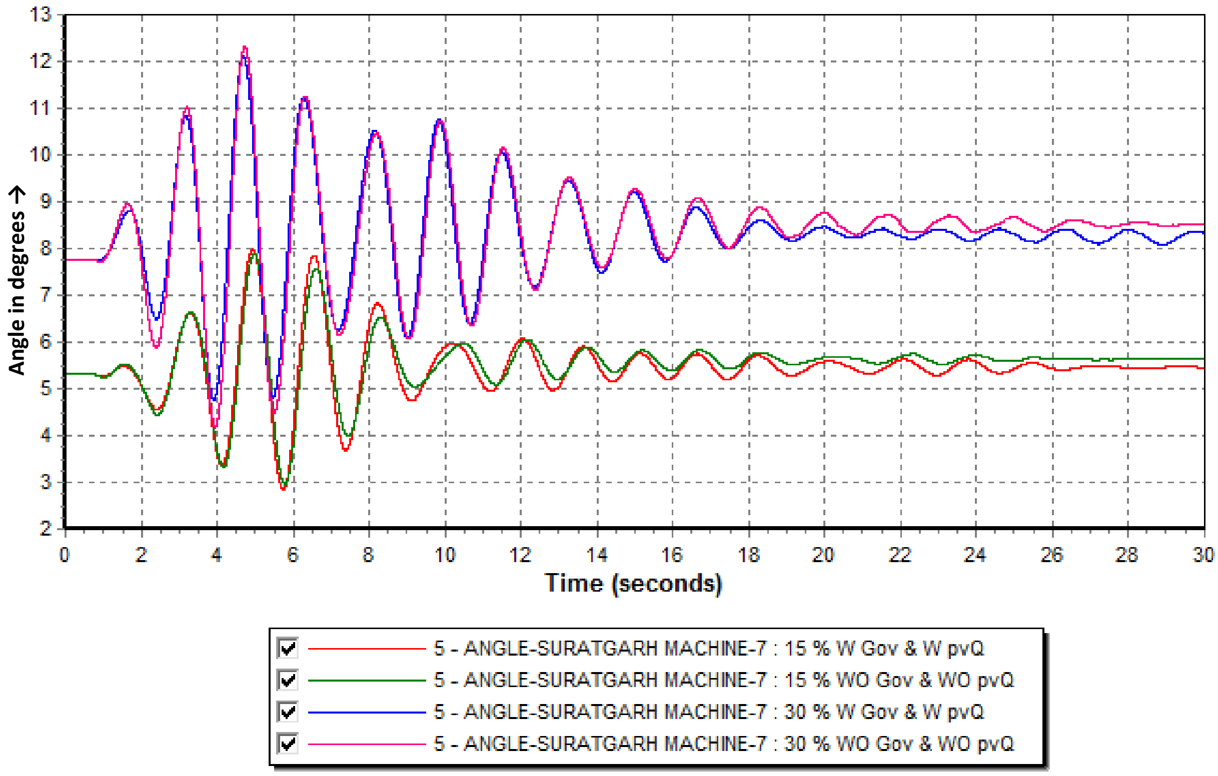


Figure 79: Rotor angle of machine 7 of Suratgarh TPS (Northern region)

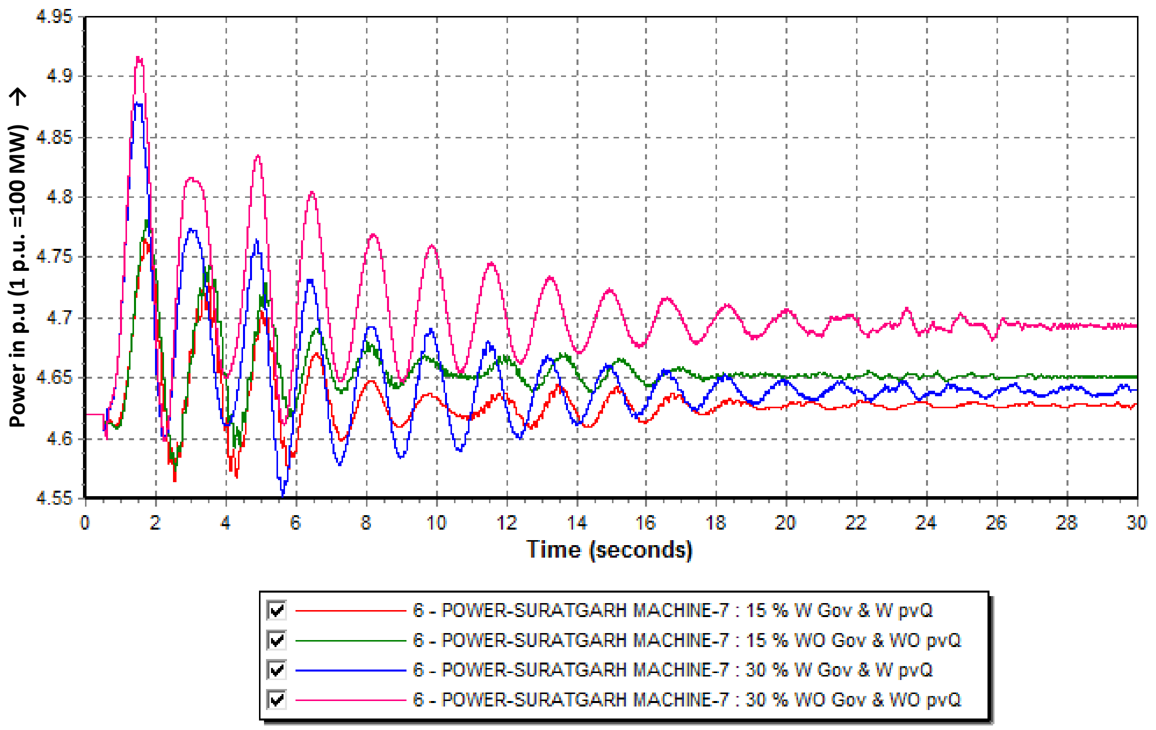


Figure 80: Generated Power of machine 7 of Suratgarh TPS (Northern region)

C) Voltage Stability

Bus Voltage plots in *Figure 81* to *Figure 84* shows that voltage recovers after fault is cleared. However, the post fault voltage overshoot is higher in case of higher penetration level case. This is because of two reasons, one that a large amount of RE generation is disconnected after fault clears which causes sudden under-loading of EHV transmission lines and secondly, huge amount of reactive power is supplied by solar PV generators during fault.

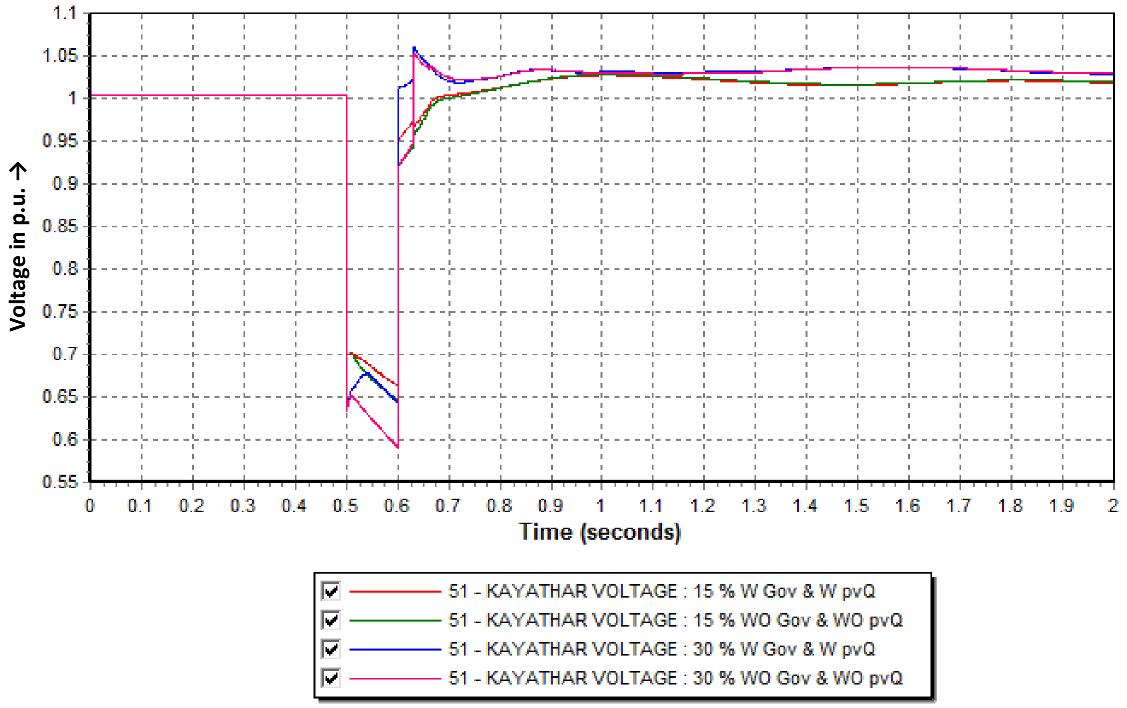


Figure 81: Kayathar 400kV Bus Voltage (Southern region)

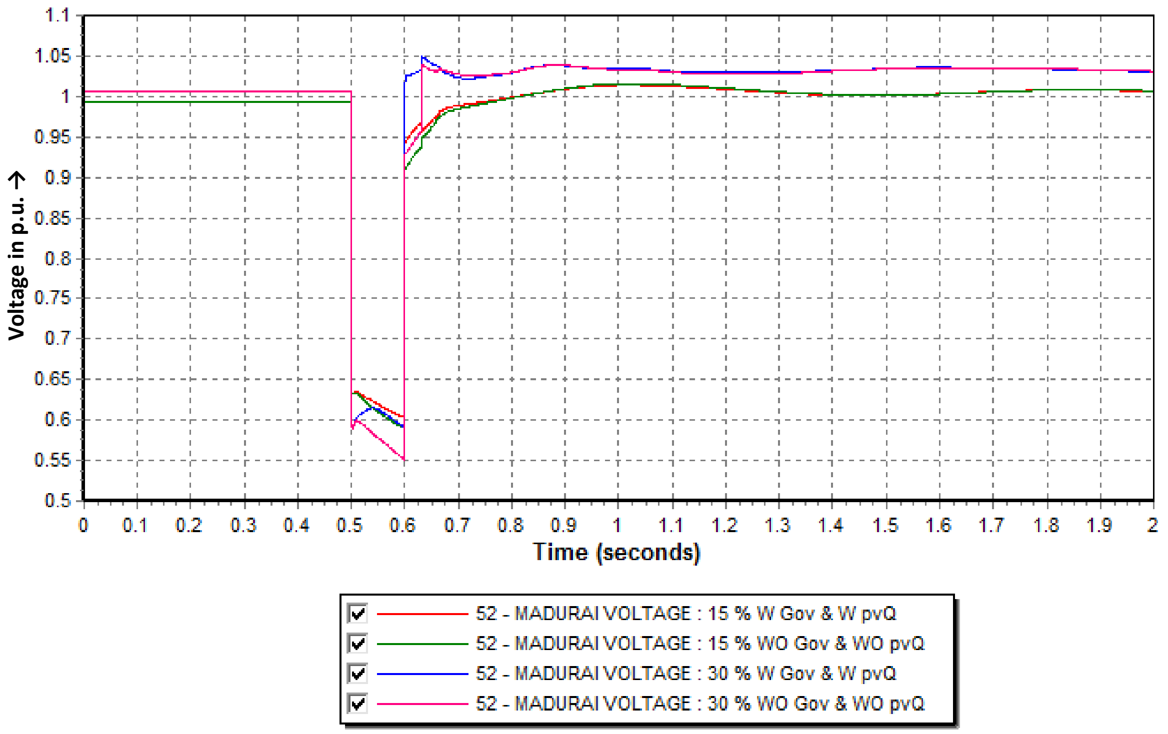


Figure 82: Madurai 400kV Bus Voltage (Southern region)

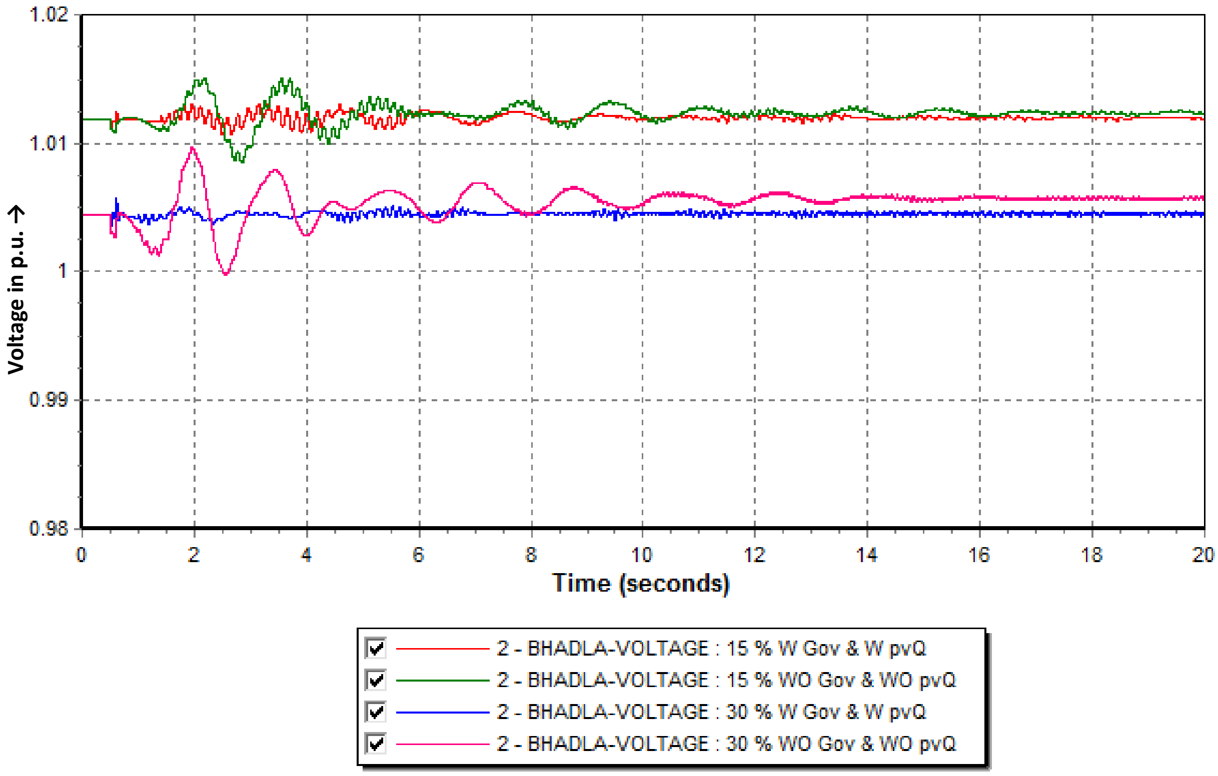


Figure 83: Bhadla 400kV Bus Voltage (Northern region)

Oscillations with frequency of 0.56 Hz are observed in the Bhadla bus voltage as shown in the *Figure 83*.

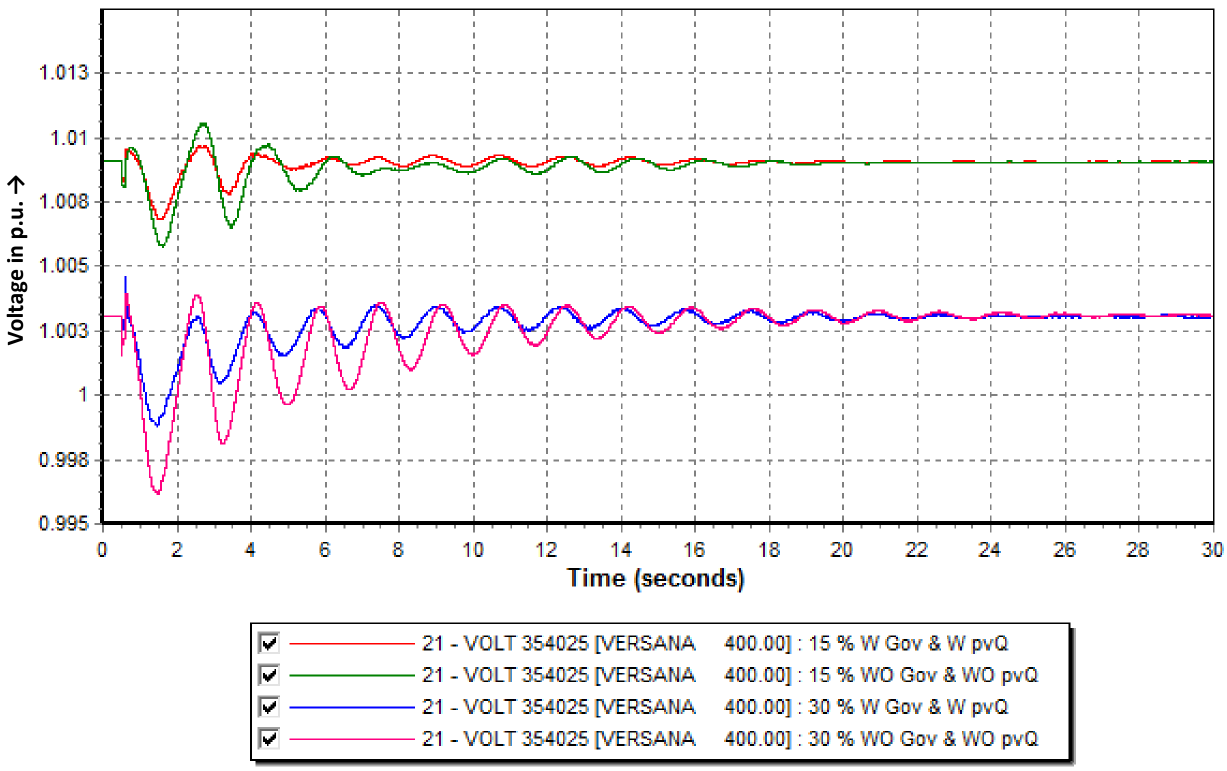


Figure 84: Varsana 400kV Bus Voltage (Western region)

D) Inter State Tie-Line Power Flow:

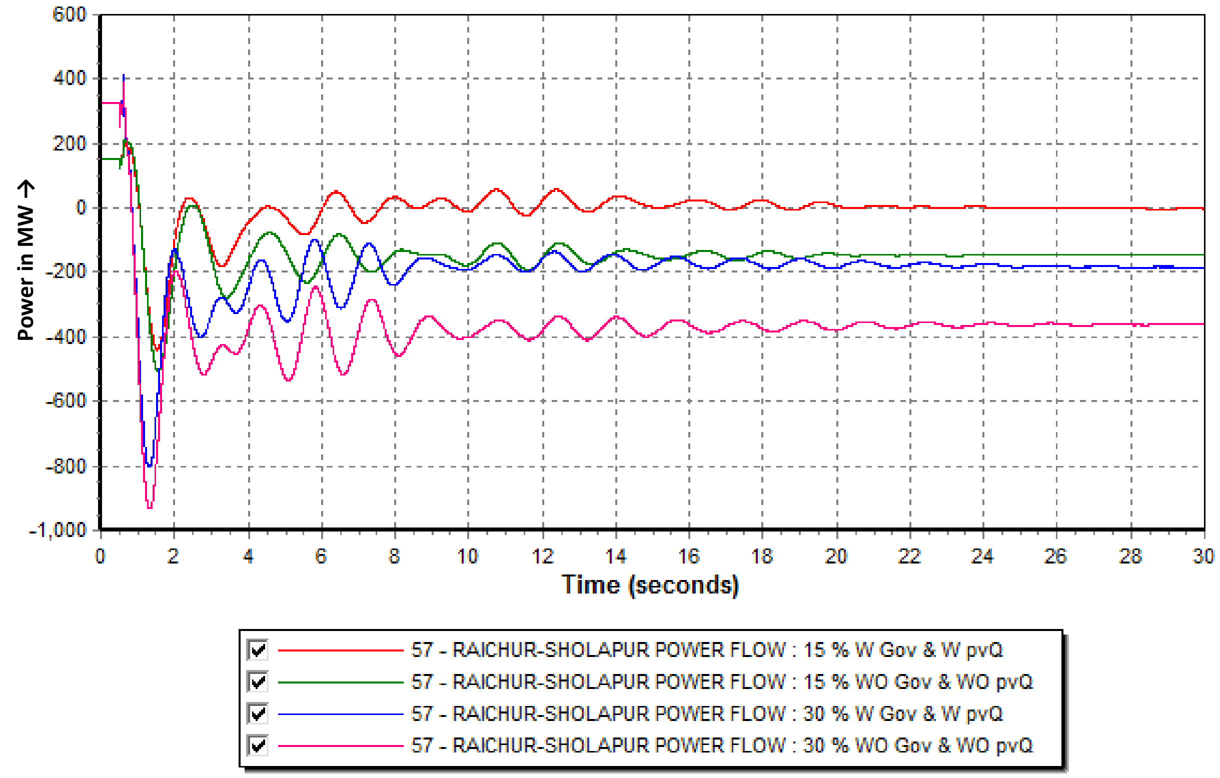


Figure 85: Raichur-Sholapur400kV Tie Line Power flow (SR-WR Link)

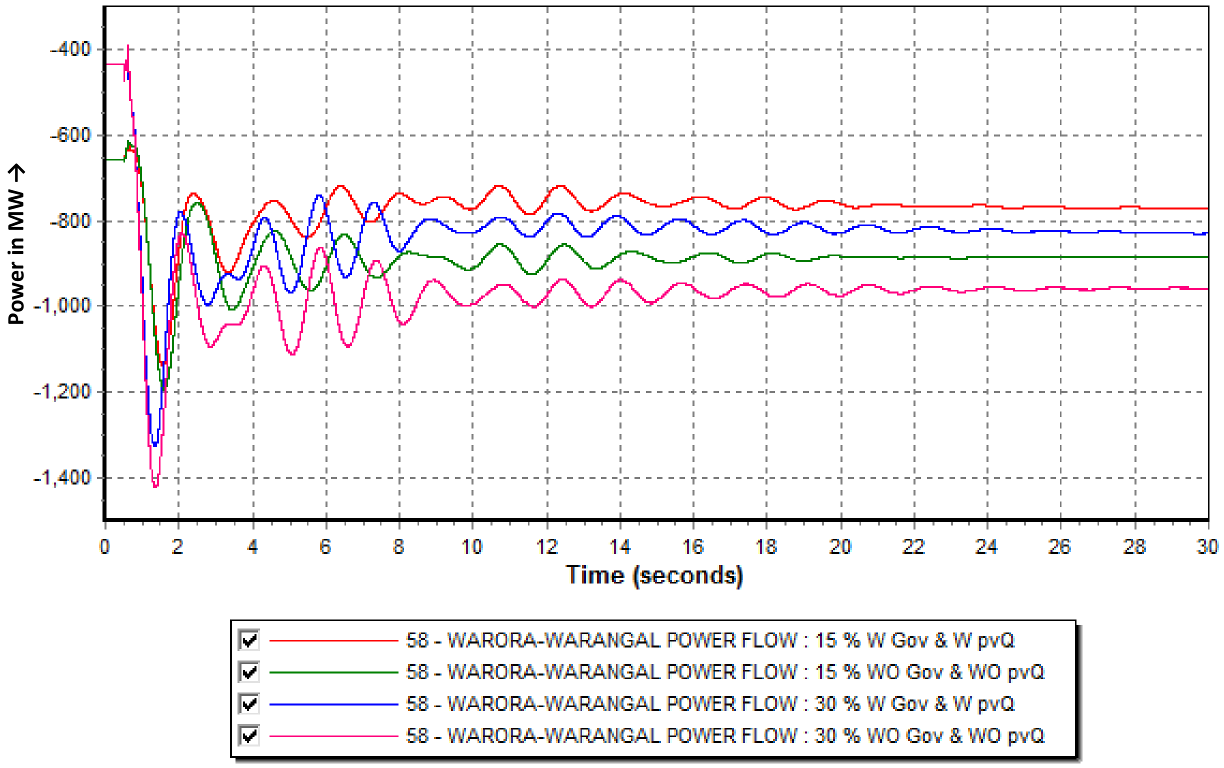


Figure 86: Warora-Warangal 400kV Tie Line Power flow (WR-SR Link)

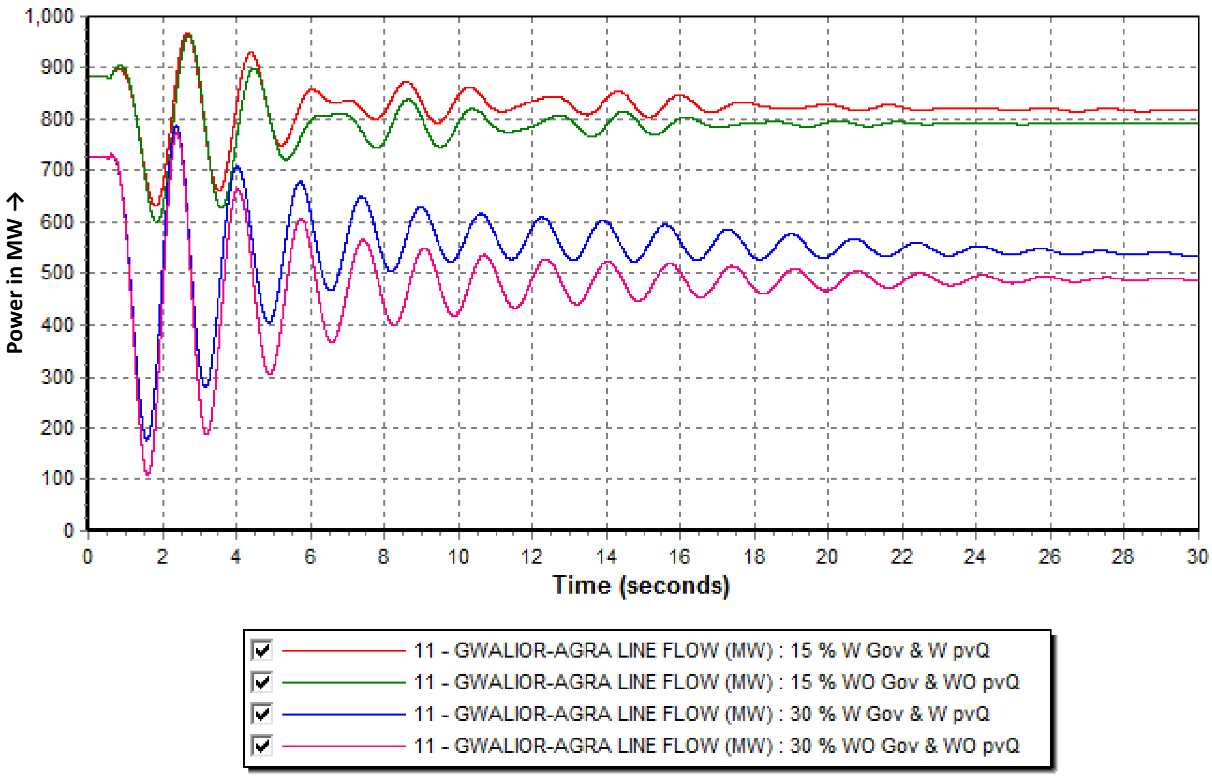


Figure 87: Agra-Gwalior765kV Tie Line Power flow (WR-NR Link)

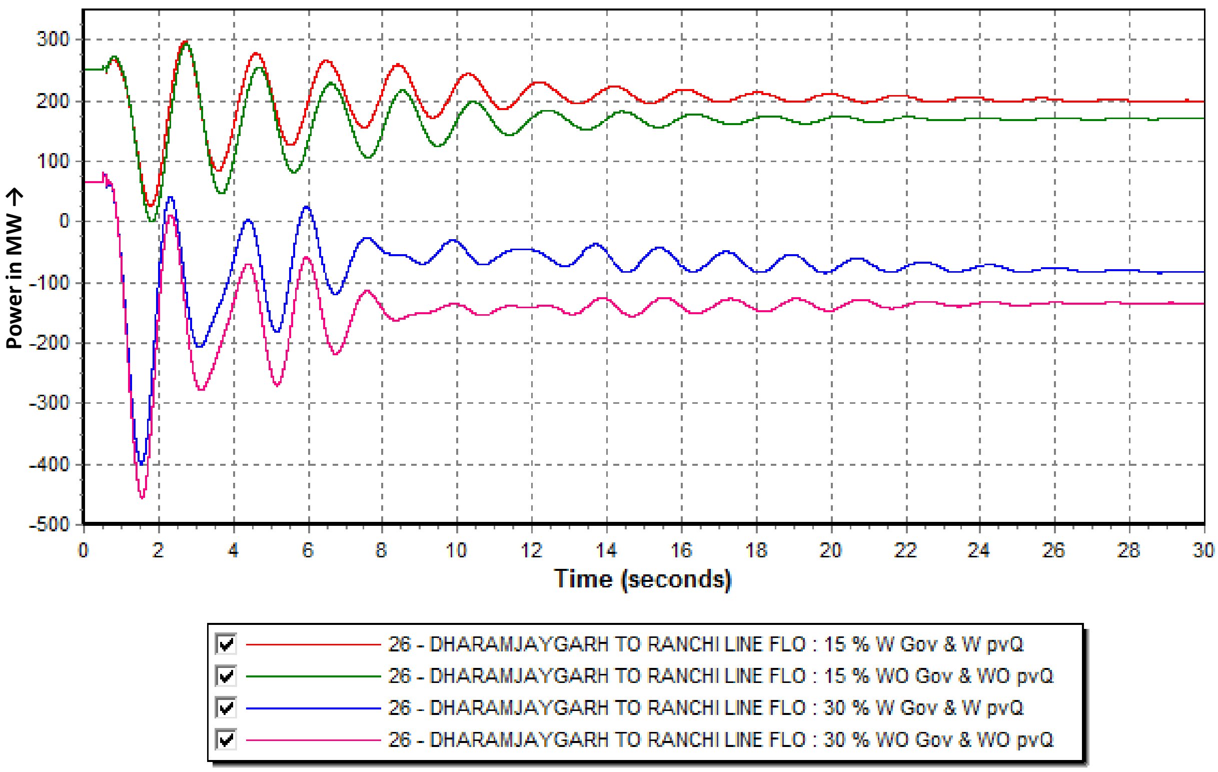


Figure 88: Dharamjaygarh-Ranchi765kV Tie Line Power flow (ER-WR Link)

Oscillations with frequency of 0.56 Hz are observed in the Raichur-Sholapur power flow as shown in the *Figure 85*.Same frequency oscillations are observed in other inter-regional lines as well.

E) Solar Intermittency Study

In addition to these cases, a case of solar generation outage is also studied to check the effect of intermittency of solar generation. In this case the largest renewable complex is disconnected from the grid and the effect of this on frequency, inter-regional power flow, governor action of nearby conventional machines etc. and other factors on the grid are observed. Practically this may happen when sudden cloud appears near the solar generation complex.

In this study, solar generation of Pavagada (2000 MW) & NP Kunta (1500MW) are disconnected from the grid instantaneously at t=0.5 sec. Due to the loss of generation of 3500 MW (dispatch at 80%: 2800 MW) there will be dip in system frequency as observed in *Figure 89*. Governor action in the conventional machines (*Figure 92*) and reactive support by nearby FACTS devices tries to bring up and stabilise the system frequency. Power oscillations are observed in inter-regional lines (*Figure 90* and *Figure 91*).

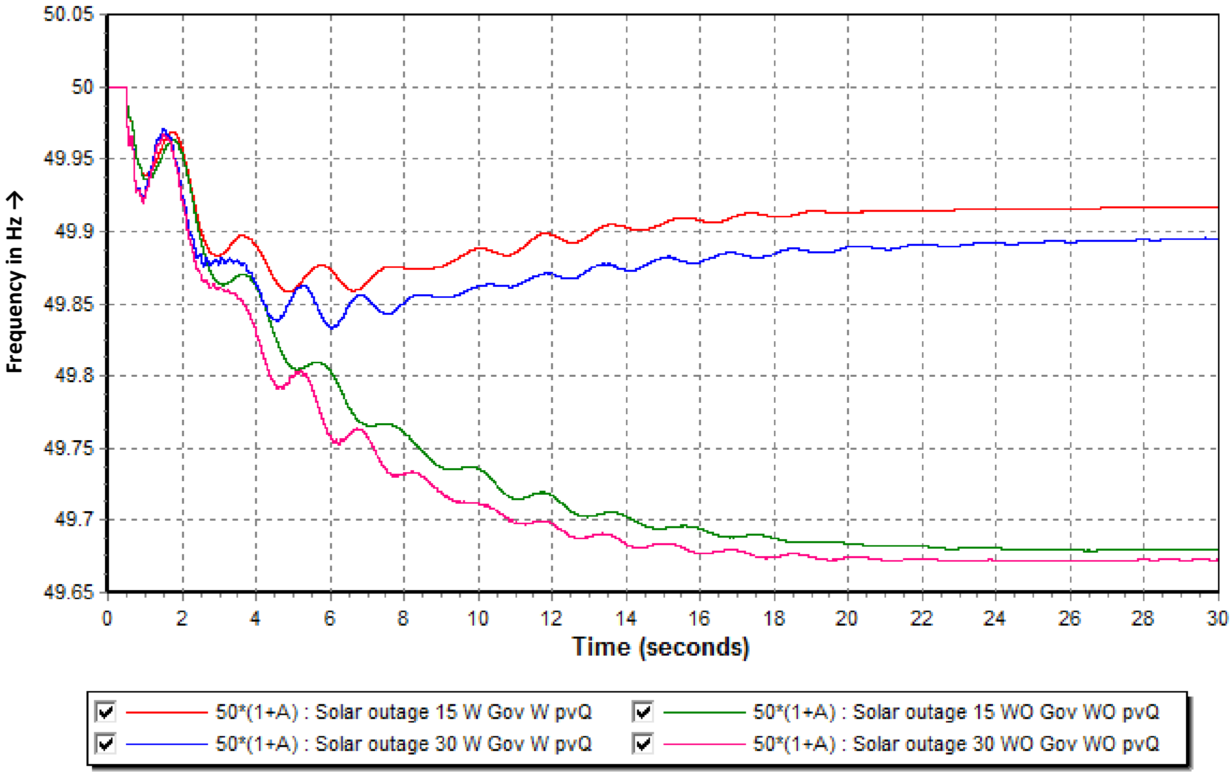


Figure 89: Grid Frequency

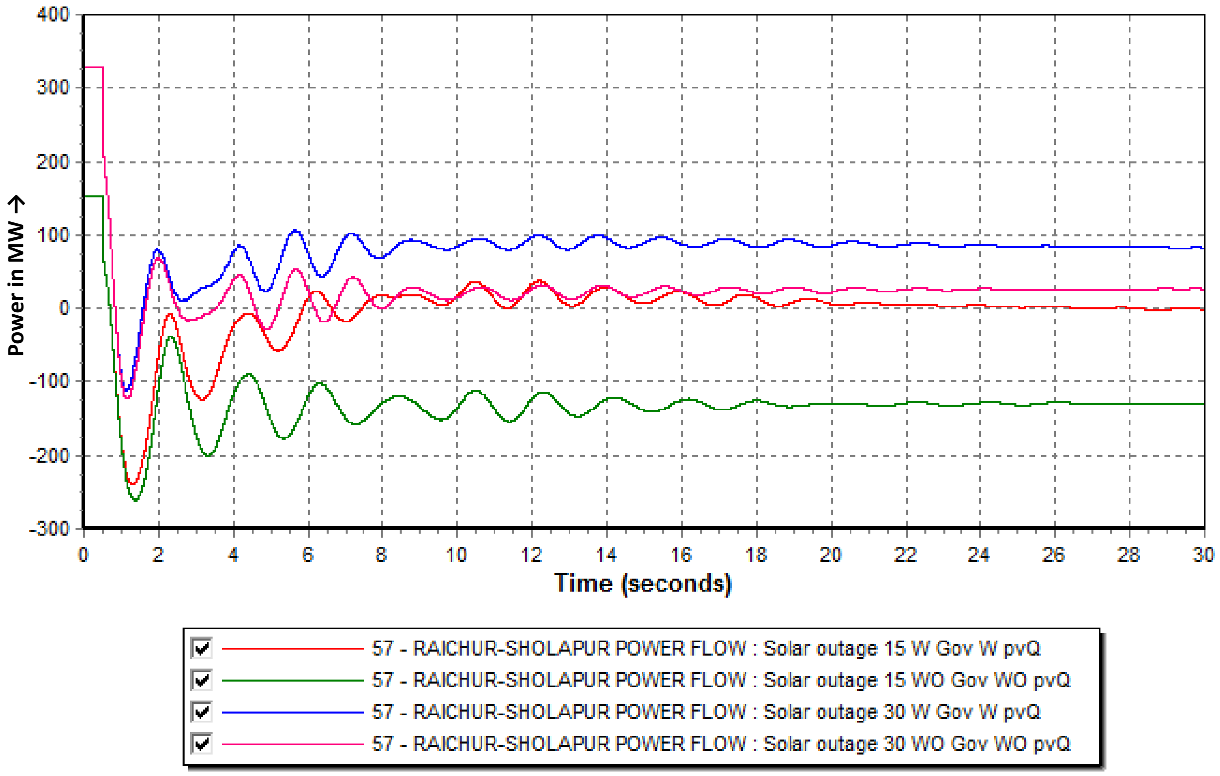


Figure 90: Raichur-Sholapur 400 kV Tie Line Power flow (SR-WR Link)

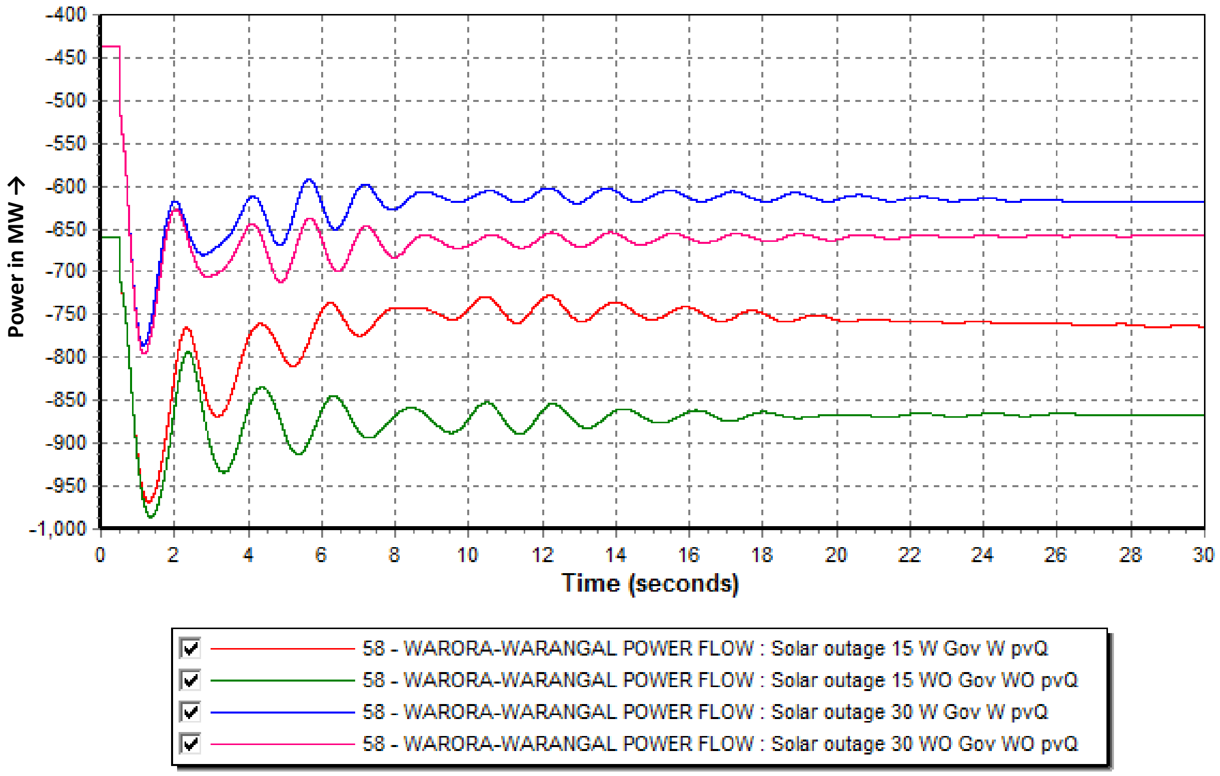


Figure 91: Warora-Warangal 400 kV Tie Line Power flow (WR-SR Link)

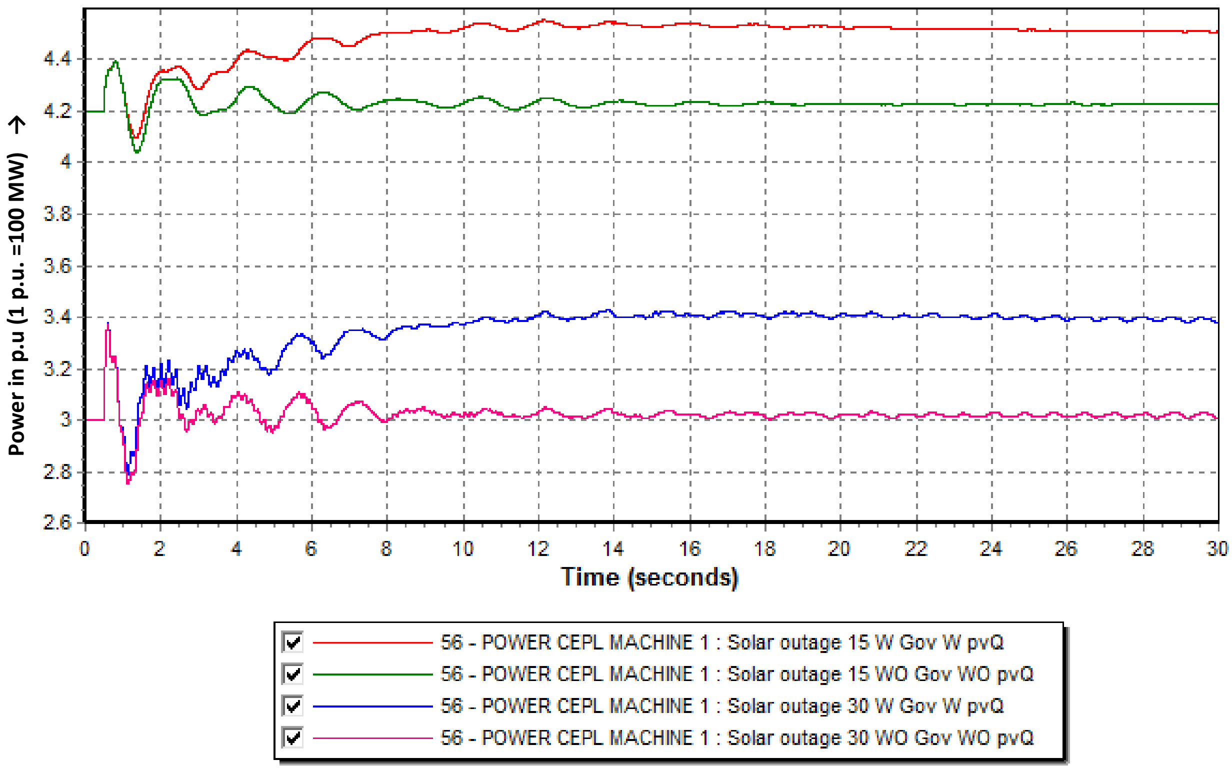


Figure 92: Generated Power of machine 1 of CEPL UMPP (Southern region)

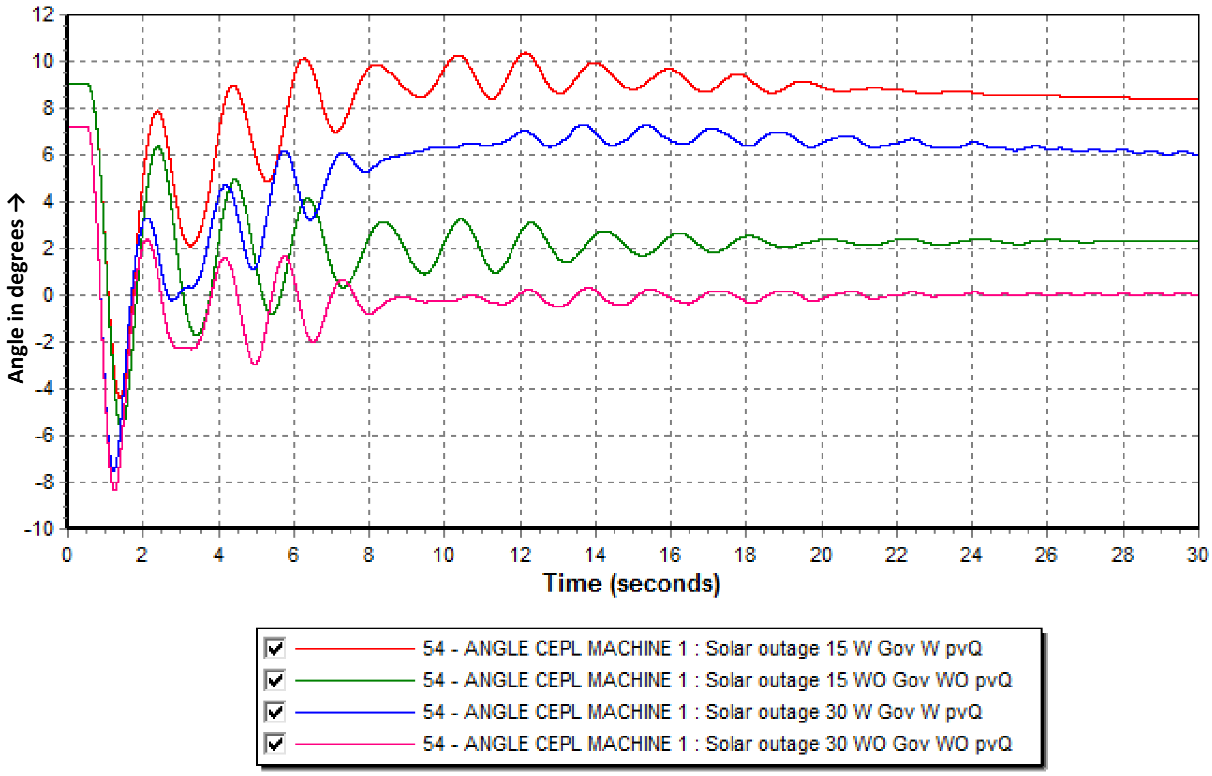


Figure 93: Angle of machine 1 of CEPL UMPP (Southern region)

F) Wind Intermittency Study

Similar to solar, a case of wind generation outage is also studied to check the effect of intermittency. In this case the largest wind complex is disconnected from the grid and the effect of this on frequency, inter-regional power flow, governor action of nearby conventional machines etc. and other factors on the grid are observed.

In this study, wind generations in Kayathar & Tirunelveli complex (Approx. 3500 MW of Installed Capacity) are disconnected from the grid instantaneously at t=0.5 sec. Due to the loss of generation, there will be dip in system frequency as observed in *Figure 94*. Governor action in the conventional machines (*Figure 98*) and reactive support by FACTS devices tries to bring up and stabilise the system frequency. Power oscillations are observed in inter-regional lines (*Figure 95* & *Figure 96*).

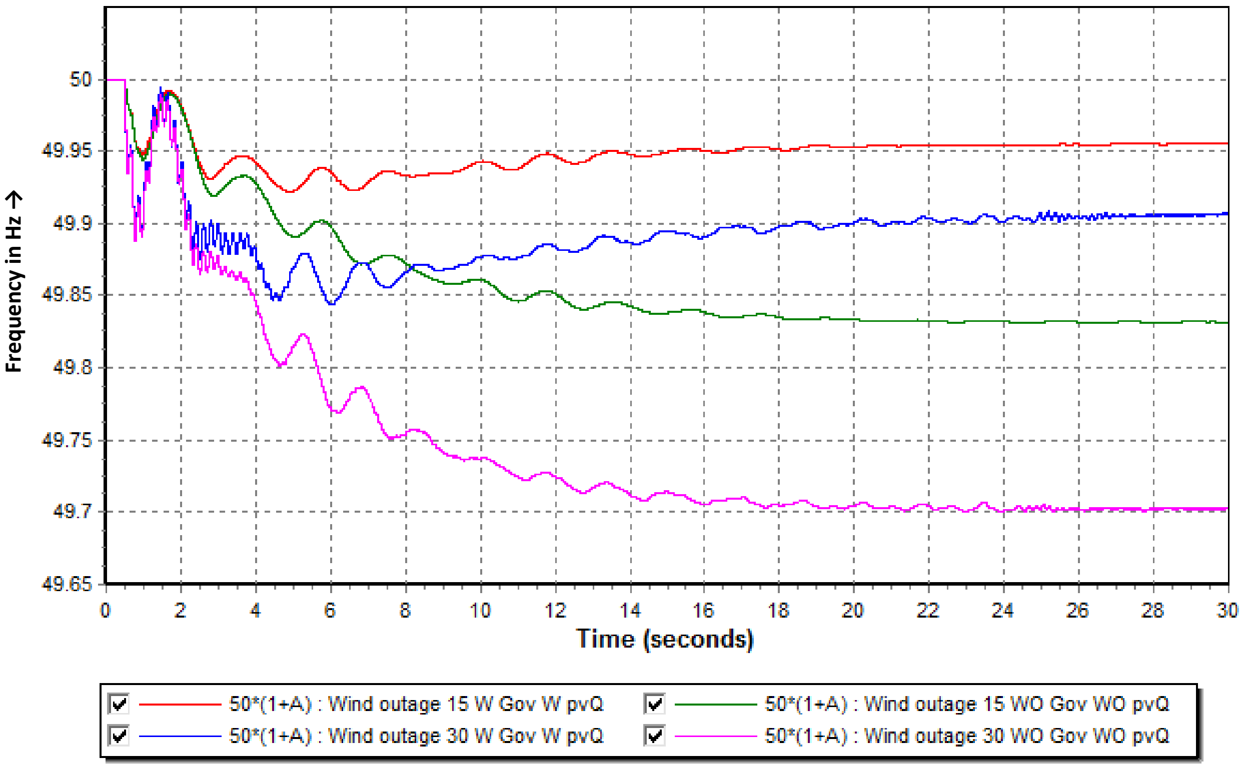


Figure 94: Grid Frequency

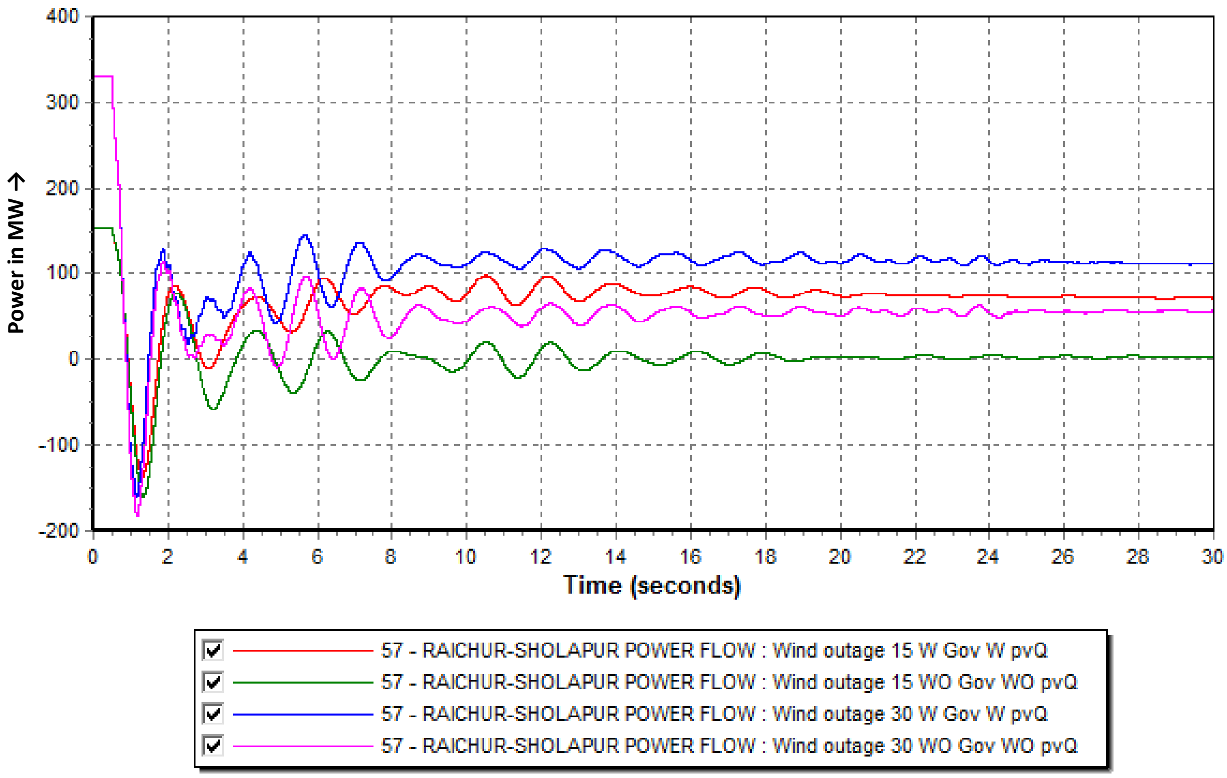


Figure 95: Raichur-Sholapur 400 kV Tie Line Power flow (SR-WR Link)

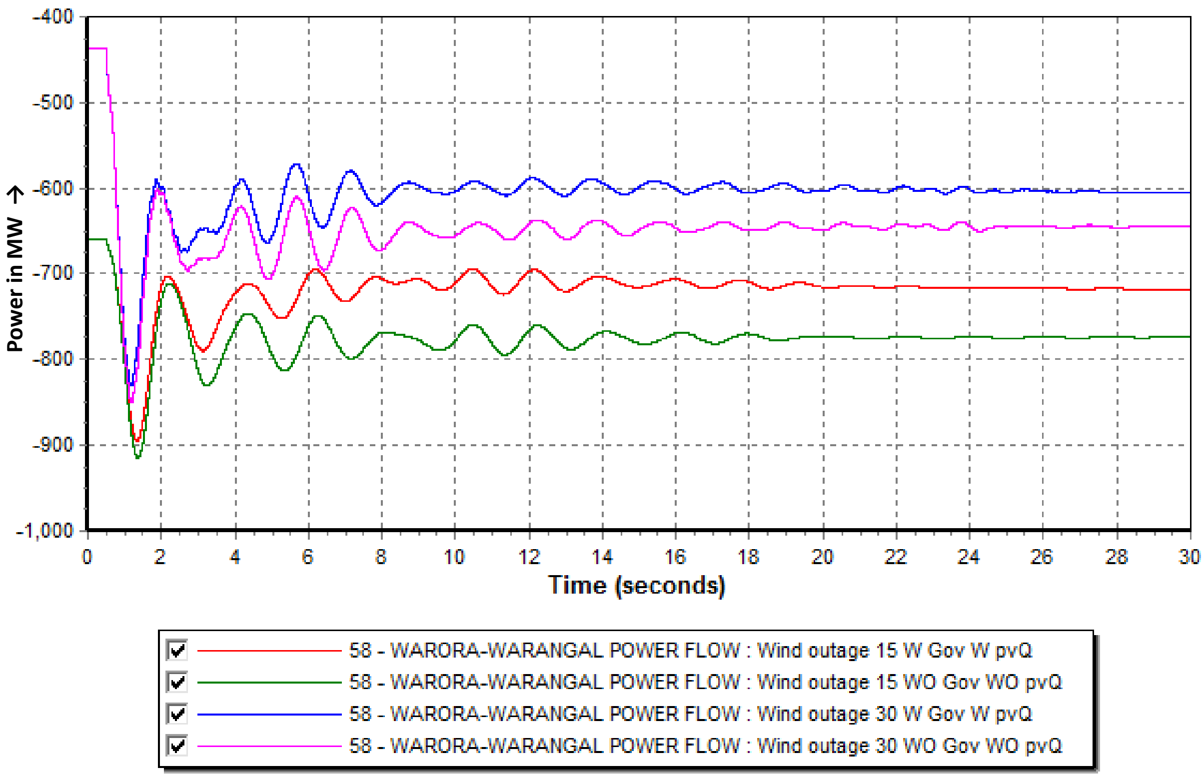


Figure 96 :Warora-Warangal 400 kV Tie Line Power flow (WR-SR Link)

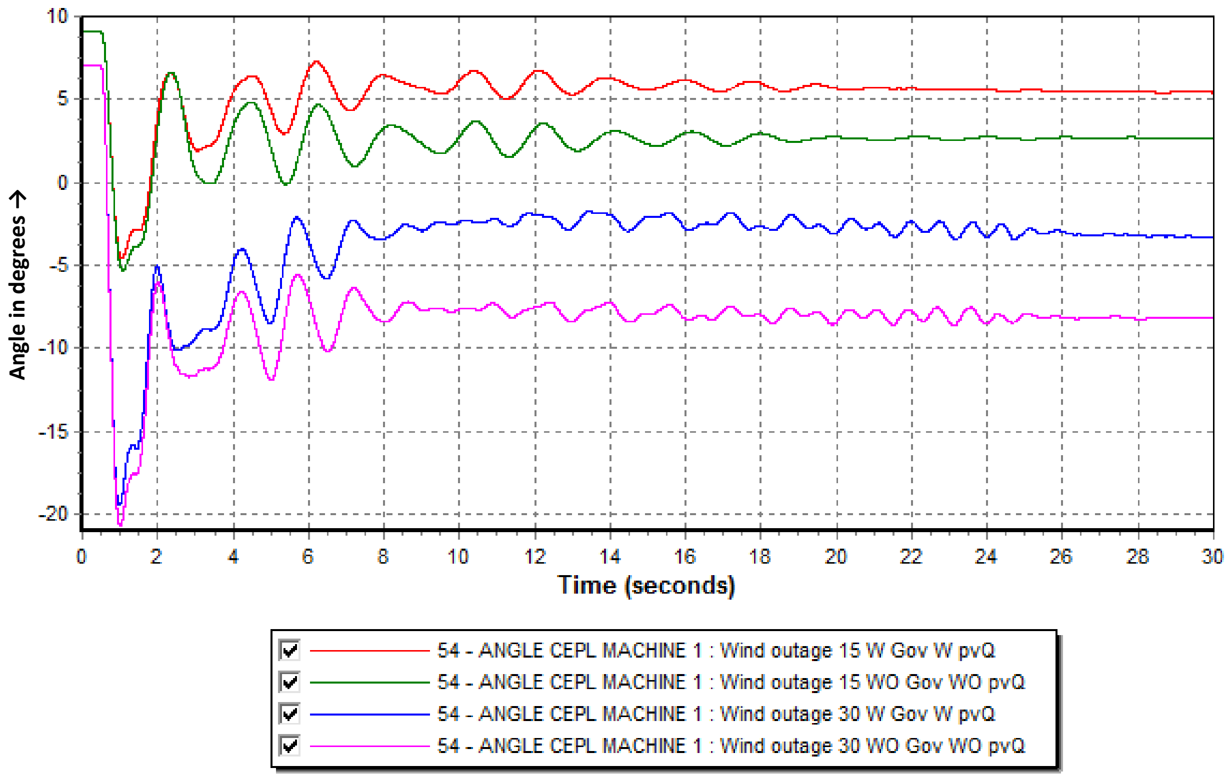


Figure 97: Angle of machine 1 of CEPL UMPP (Southern region)

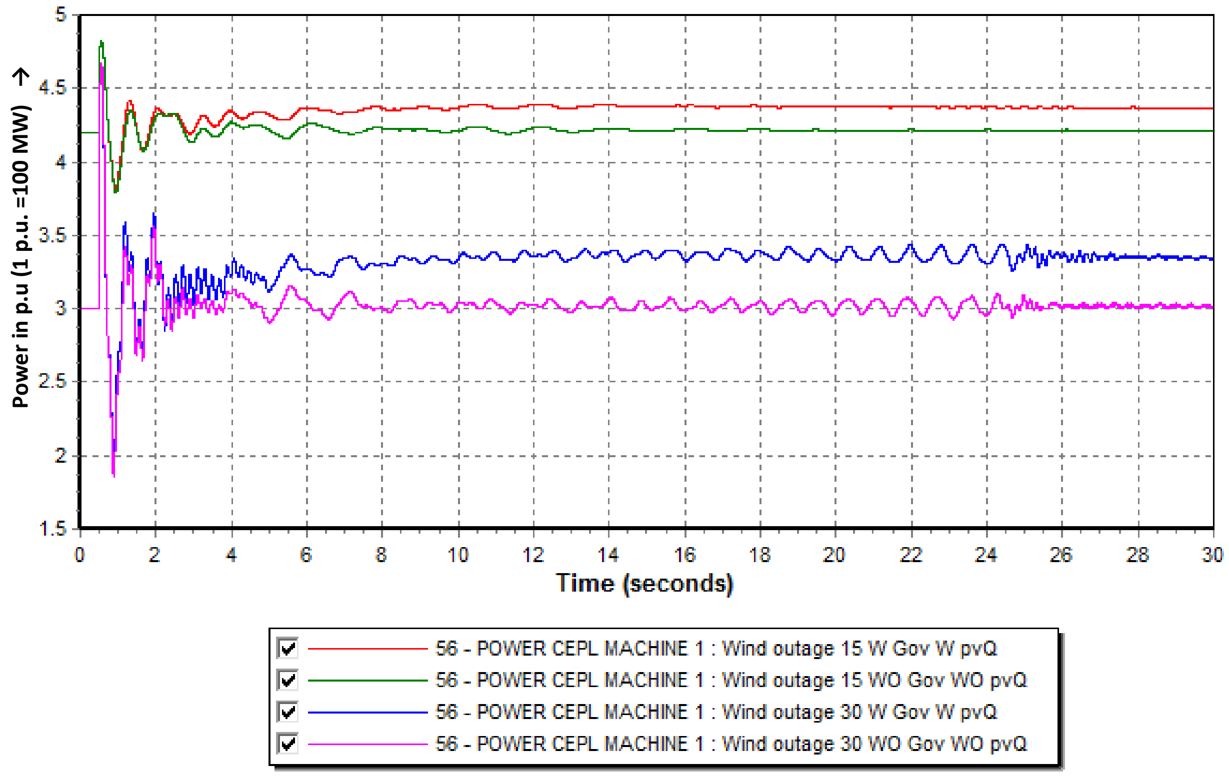


Figure 98: Generated Power of machine 1 of CEPL UMPP (Southern region)

Apart from the regional case studies, few cases have been performed with the combination of enabled all India generator governor action, reactive power support from solar PV plants and LVRT compliance of Solar and Wind (only Type 3 and 4) plants.

With Limited governor action and with & without LVRT compliance:

As Low voltage ride through (LVRT) compliance is an important requirement for RE generators, a case has also been simulated to see the impact of LVRT compliance with limited governor response (majorly hydro). The plot of frequency variation in case of grid disturbance with limited governors as well as LVRT compliance is as under:

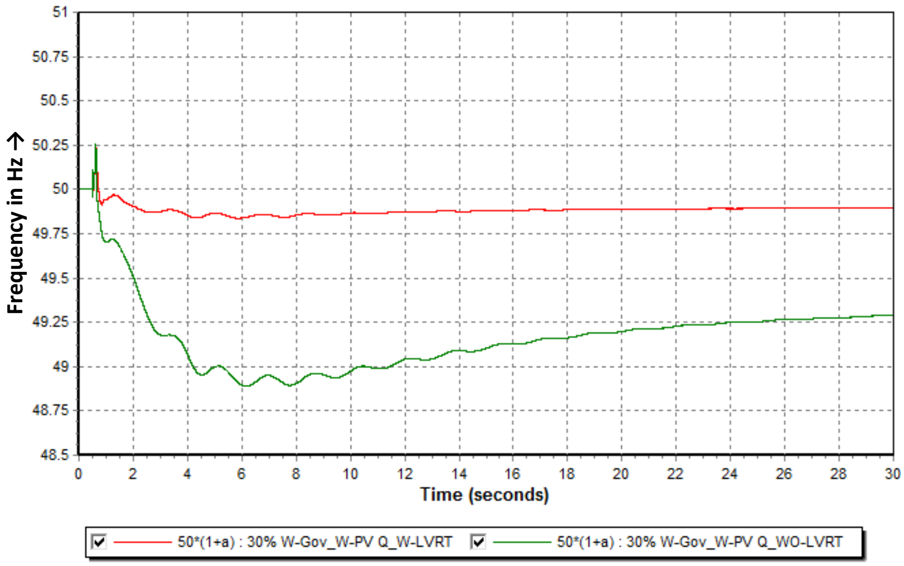


Figure 99: Grid Frequency

From above results it may be seen that LVRT compliance reduces the quantum of generation outage due to under frequency which in-turn helps the system in maintaining frequency in IEGC band during a major grid fault. In addition, if governor action of all thermal and hydro generators is considered, the steady state frequency will rise further in 49.90-50.05 Hz band.

Without LVRT compliance and with & without all India governor action:

In CERC order dated 13.10.2015 in matter of "Roadmap to operationalize Reserves in the country" governor action in form of primary control for frequency containment drop or rise is mandated for all generating units as per IEGC provision. Further, secondary reserves through Automatic Generation control (AGC) need to be operationalized from 1st April, 2017. So, an additional case has been studied in which all the thermal generators have been considered with governor response. The plot of frequency variation in case of grid disturbance with governors enabled but without LVRT compliance is as under:

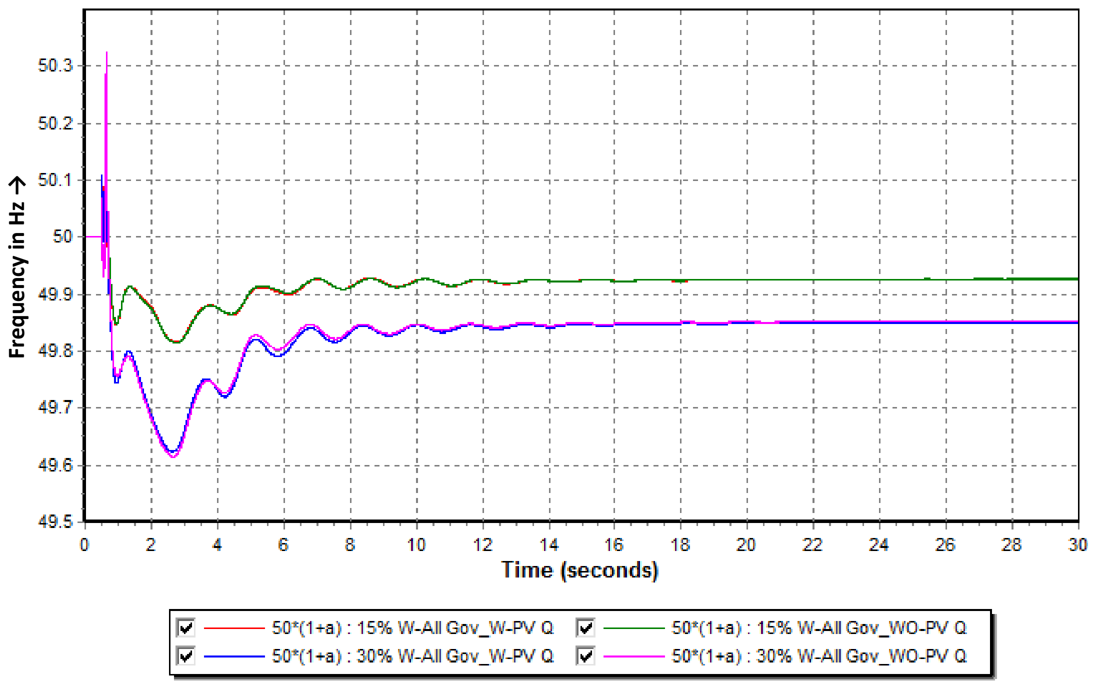


Figure 100: Grid Frequency

The above plot shows that the availability of governor response in thermal generators improves grid frequency response in case of severe faults and maintains frequency stability both in 15% as well as 30% RE capacity penetration case event without LVRT compliance. Also, as concluded earlier in RE balancing chapter that there is a shortfall in balancing reserve in case of 30% RE penetration scenario, above graph confirms the same.

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CHAPTER 5

REGULATORY FRAMEWORKS

Chapter-5

Regulatory Frameworks

In orderto facilitate implementation of higher penetration of RE, it is proposed that following actions may be taken up respectively by the Regulator, Statutory Authorities/MNRE, and CTU/STU etc.

S no.	Activities	Role/Responsibility
1	Technical Standards and protection requirement for renewables and Implementation	CEA/CTU/STU/RE Generators
2	Implementation of frequency response regulation	CERC/ ALL Generators
3	Forecasting & Scheduling regulation at Inter and Intra-state level	CERC/SERC/NLDC/RLDC/SLDC/ REMC/RE Generator
4	Ancillary Service regulation at Inter and Intra-state level	CERC/SERC/NLDC/RLDC/SLDC/ REMC/RE Generator
5	Regulation for Flexible Generation and Generation Reserves	MOP/CERC/SERC
6	Research in Forecasting technologies	IMD/FSPs
7	Capacity Building of SLDC particularly in RE rich states.	FOLD/POSOCO/States
8	Policy & Regulation for development of transmission system for Single window clearance/ RE zones etc.	MOP/MNRE/State Govt/CERC

- **Technical Standards and protection requirement for renewables and Implementation:** CEA have formulated technical standards in its "CEA (Technical Standards for connectivity to the Grid) Amendment regulations, 2013" for connectivity of Wind generating Stations and generating stations using inverters. In the regulation, it mandated that

  Power Factor Provision-(B2 (1)) *"The generating station shall be capable of supplying dynamically varying reactive power support so as to maintain power factor within the limits of 0.95 lagging to 0.95 leading."*

  Operating Frequency Provision-(B2 (2)) *"The generating units shall be capable of operating in the frequency range of 47.5 Hz to 52 Hz and shall be able to deliver rated output in the frequency range of 49.5 Hz to 50.5 Hz."*

  LVRT/FRT compliance: All the wind connected at 66kV and above are required to comply with the Low Voltage Ride Through (LVRT) or Fault Ride Through (FRT) capability.

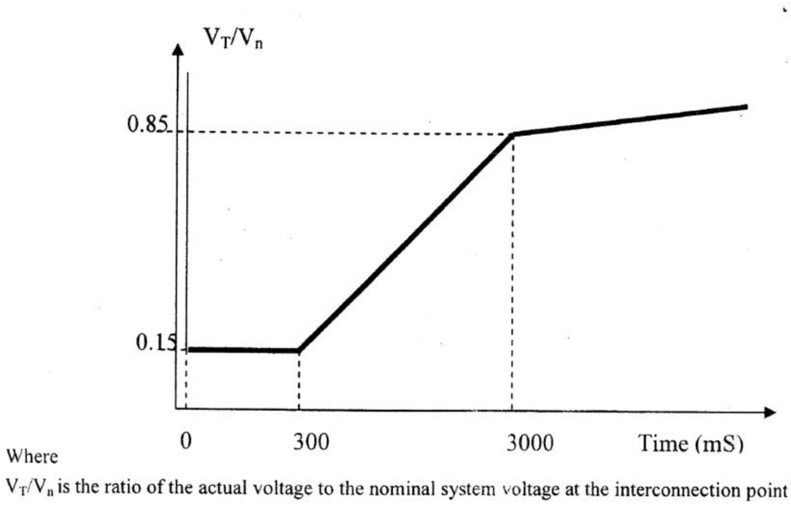

Figure 101: Wind LVRT

It is also required from the generating units that "*…during the voltage dip, the generating station shall maximize supply of reactive current till the time voltage starts recovering or for 300 ms…"*

The compliance to these regulations can be ensured at CTU/STU and RE generator level only. CEA needs to formulate similar LVRT/FRT compliance and reactive power supply regulation for Grid Connected Solar Parks/Stations also.

For older machines above regulation states" *…meet the standards specified in (B1) and (B2) subject to technical feasibility."* The regulation mandates for power factor and operating frequency compliance only. However, LVRT/FRT compliance through retrofitting of machines wherever possible should be mandated.

- **Implementation of frequency response regulation:** IEGC Regulations, 2010 mandates that "All thermal generating units of 200 MW and above and all hydro units of 10 MW and above, which are synchronized with the grid, irrespective of their ownership, shall have their governors in operation at all times…". Regulation also mandates that "All generating units shall normally have their automatic voltage regulators (AVRs)in operation."

  The compliance to above regulations helps power system in maintaining grid stability in case of generation outages. However, recent grid disturbance events have shown that majority of generators are non-complaint to these regulations which imposes a great threat in case of high RE penetrated power system.

  To address the grid stability issue due to lack of spinning reserve, Honourable CERC has issued an Order in the matter of Roadmap to operationalize reserves in the country dated 13.10.15, a committee under the chairmanship of Shri. A. S. Bakshi Member CERC examined the technical and commercial issues in connection with spinning reserves and evolved regulatory interventions in this context.

- **Ancillary services regulation at Inter and Intra-state level**: Ancillary Services need to be put in place as complementary support services for reliable operation of the electricity grids. Ancillary Services provide a framework for operationalizing the spinning reserves and the modalities of scheduling, metering and settlement of the reserves. It would address congestion management issues and facilitate optimization at Regional & National Level and thereby facilitate integration of renewables too. Ancillary services are being implemented at the inter-state level and a similar framework needs to be implemented in the States.

  CERC Draft Ancillary Services Operations Regulations, 2015 were floated for stakeholder consultations on 01st May, 2015. A public hearing on the draft regulations was held on 12th June, 2015. The Regulations have since been notified on 19thAugust 2015 and need to be operationalized at the earliest. NLDC would be the nodal agency for implementing this Regulation through the RLDCs. Statement of Reasons (SoR) was issued by CERC on 17th September, 2015. NLDC floated Draft Detailed Procedure for CERC Ancillary Services Operations for stakeholder consultations on 29th September, 2015. Stakeholder Workshops were conducted in every region to discuss the draft and obtain the suggestions/comments of stakeholders, after which the draft procedures have been submitted for approval of CERC. The Detailed Procedure for Ancillary Services Operations has been approved by CERC in March, 2016. The Ancillary Services have been rolled out for implementation in April 2016.

- **Forecasting & Scheduling regulation at Inter and Intra-state level**: Forecasting (both Load, RE generation as well as Net Load) is essential for ensuring resource adequacy during operation and grid security. Suitable regulatory framework for Forecasting, Scheduling and Imbalance Settlement for RE generators at both inter-state and intra-state level needs to be in place. Such a framework at inter-state level has already been put into place by the Central Commission and be used as a reference for intra-state framework. Aggregators should be introduced to coordinate with several RE generators and be responsible for scheduling, real time operation and settlement of imbalances with the State/Regional Pool and RE generators.

  In order to deal with variability of renewable generation forecasts are crucial for resource adequacy during operation and grid security. Forecasting is an essential pre-requisite for scheduling of the RE generation. There is a need for both centralized and de-centralized forecasting systems. The centralized forecast is done by concerned System Operator primarily for grid security. The de-centralized forecast done by respective RE generator essentially for scheduling and this has commercial implications for the RE generator. It is well recognized that while fixing the deviation limits, the size of the state and the quantum of renewable generation the state is having, also need to

be kept in consideration. However, as large quantum of RE Generation is going to be integrated with the grid, keeping in view the security of the grid, the Forecasting and Scheduling for RE Generators is a key pre-requisite. The granularity of forecast should be with a 15 – minute resolution so that it can be seamlessly integrated with existing scheduling and despatch framework. CERC IEGC, 2010- Regulations 5.3(e) stipulate estimation of demand at SLDC for daily operational use for each 15 minutes block.
Also, in this direction, CERC, vide order in the suo-motu petition No. 11/SM/2015 dated 13th October, 2015, has issued the roadmap to operationalize reserves in the country. A regulated framework has been provided for identification and utilising of spinning reserves and implemented with effect from 1st April, 2016 till 31st March, 2017. Also, it is envisaged that a market based framework is required for efficient provision of secondary reserves from all generators across the country for implementation by 1st April, 2017.

- **Regulation for Flexible Generation and Generation Reserves:** Flexibility in existing fleet of conventional generation as well as Pumped Storage Plants, Demand Side Management may be utilized for meeting changing load profile and maintaining system stability. Regulatory intervention is required to incentivize flexibility of conventional generation. Flexibility requirements should encompass the minimum and maximum generation level as well as the ramp up / down rates. The introduction of Flexible Generation Planning and Obligation may be explored in the future.

  For ramp up/ramp down rates, the Indian Electricity Grid Code (IEGC) clause 5.2 (i) states that 'The recommended rate for changing the governor setting, i.e. supplementary control for increasing or decreasing the output (generation level) for all generating units, irrespective of their type and size, would be one (1.0) per cent per minute or as per manufacturer's limits. However, if frequency falls below 49.7 Hz, all partly loaded generating units shall pick up additional load at faster rate, according to their capability'

  CEA (Technical Standards for Construction of Electrical Plant and Electric Lines) Regulations, 2010 Part B, S.No. 7 (4) for coal fired stations states that 'The design shall cover adequate provision for quick start up and loading of the unit to full load at a fast rate. The unit shall have minimum rate of loading or unloading of 3% per minute above the control load (i.e. 50% MCR).'

  Draft Central Electricity Regulatory Commission (Indian Electricity Grid Code) (Fourth Amendment) Regulations, 2015 had been notified vide public notice No. L-1/18/2010-CERC dated 02nd July, 2015 which laid out provisions for Technical Minimum Schedule for operation of Generating Stations.

  The relevant provisions are quoted as follows: "…6.3B – Technical Minimum Schedule for operation of Generating Stations

1. The technical minimum schedule for operation in respect of ISGS shall be 55% of MCR loading of unit/units of generating stations.

2. A generating station may be directed by concerned RLDC to operate below 85% but at or above the technical minimum schedule on account of grid security or due to the less generation schedule given by the beneficiaries

3. Where the generating station regulated by this Commission is directed by the concerned RLDC to operate at technical minimum schedule, the generation station may be compensated subject to the prudence check by the Commission in due consideration of average unit loading based on forced outages, planned outages, PLF, generation at generator terminal, energy sent out ex-bus, number of start-stop, secondary fuel oil consumption and aux energy consumption etc. on an application filed by the generating company duly supported by relevant data verified by RLDC/SLDC.

Along with the above mentioned technical frameworks, required commercial frameworks/regulations like market design in case of high RE capacity generation in total power generation portfolio, incentivizing flexibility in conventional generation need to be addressed by MoP/CEA/CERC.

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CHAPTER 6

WAY FORWARD

Chapter-6

Way Forward

During a grid contingency, stability of the grid is primarily maintained by primary response of governor action of generators, reactive power support by FACTS devices, solar inverters etc. as well as frequency restoration with the support of secondary reserves. On occurrence of fault, some amount of RE generation is lost due to under voltage relay triggering; resulting in load generation imbalance. This imbalance is filled by the governor action of available generators which tries to bring up the generation as per governor-droop settings to balance the system. Even though, it is a slower process than inertial response, it helps to recover the frequency of the system. Thereafter, secondary reserves take over to bring back frequency to normalcy.

Study cases have been performed with combination of LVRT compliance of Solar and Wind (only Type 3 and 4) plants and all India thermal and hydro generator governor action to study their effects. It has been found that if all India governor action which is mandated by CERC and LVRT compliance of renewable generating stations are taken into account, the Indian grid will be able to operate in IEGC mentioned frequency band under any grid disturbance.

In case of solar plants, whenever there is a voltage dips at point of interconnection, the inverter starts supplying reactive power by converting available solar power instantly to bring up the grid voltage. It tries to bring up the bus voltage and hence tries to prevent loss of generation due to under-voltage relay triggering. It is to mention that, the reactive power contribution by solar is instantaneous to reduce the voltage dip whereas contribution by governor action is slow and it tries to reduce the net loss of generation. However, impact of reactive support is more on distant located generator which faces relatively less voltage dip during the fault.

Angular stability is found not to be the limiting constraint for studied levels of RE penetration. From the results, it may be concluded that the overriding requirements for the grid security in case of large Scale RE penetration will be governor action, LVRT compliance and reactive support from grid scale PV power plants. Inter-area oscillations are also present in most of the tie lines which can be suppressed with the help of Power System Stabiliser (PSS) tuning. However, to balance variability of wind and solar power generating units in 30% renewable penetration scenario, availability of balancing reserve is assessed to be inadequate.

Therefore, from above study results it may be concluded that to accommodate 30% RE penetration, governor response of all generating units as well as LVRT compliance will be a must requirement.

From the **Balancing studies**, it was observed that with increase in the RE Penetration the Balancing Resource and Ramping Resource requirement also increases.Net load plays an important factor in balancing resource assessment. From the balancing and Ramping resource assessment it was found that the peak ramp rate required in both 15% and 30% scenarios can be met easily with the given flexible resource composition (based on envisaged capacity addition programmes) through hydro (including PSP and reservoir type),gas and super critical thermal generation.

The given flexible resource composition is likely to match the balancing requirements in 15%scenario but not adequate in 30% scenario. Further if balancing assessment for specific states/regions is considered, they may themselves fall short even in 15% case as in Tamil Nadu present case due to which they have to resort to RE curtailment. Hence, more flexible resources along with strong interconnections in the grid are required to accommodate 30 % RE penetration scenario.

Demand response can be used as an additional source of power system flexibility to compensate for the variability and uncertainty of RE generation. The gap between generation and demand can be reduced by careful planning on demand side. Contrary to load curve of developed nations developing nation has peak load in evening time. During peak load hours solar generation is not available and it reduces the effective utilisation of renewable energy sources. The Time of Day tariff mechanism can be very effective way to manage demand and shift evening peak to afternoon when solar generation is at max. In smart grid and smart cities, Demand Response (automatic/manual load control) will be an additional measure to balance renewable generation. Consumers may be incentivised to participate in automatic demand management system.

Real Time Dynamic State Measurement: To address better supervision and control of Indian electricity grid, nationwide installation of Phasor measurement units (PMU) was initiated through Unified Real Time Dynamic State Measurement (URTDSM) programme. Under this project, Phasor Measurement Units (PMUs) would be placed at all HVDC, 400kV and above substations and generating stations including at 220 kV level.

Synchronized PMUs will facilitate improved monitoring, visualization and enhanced situational awareness of the grid events on real time. Further, it will enable implementation of Wide Area Protection & Control Systems, which will improve grid reliability, reduce probability of blackouts and minimize their impact.

Electrical Energy storage, due to its tremendous range of uses and configurations, may assist RE integration in any number of ways. These uses include, inter alia, matching generation to loads through time-shifting; balancing the grid through ancillary services, load-following, and load-levelling; managing uncertainty in RE generation through reserves; and smoothing output from individual RE plants.

The battery energy storage system (BESS) and Pumped hydro units are can be used to shift the load from peak hours to off-peak hours by consuming RE power during off-peak hours and delivering energy during peak hours.

Also, to handle variability and intermittency of RE generators, RE power plants have to be dispersed over a wide geographic area.

Apart from the stability concerns, to facilitate the better functioning of power grid in case of high RE penetration scenario, many technical and financial regulatory framework/guidelines must be in place. In order to facilitate implementation of higher penetration of RE and address above mentioned issues, it is proposed that following actions may be taken up.

- Provision of increased balancing reserves of about 5 GW by 2019 through various measures including regulatory initiatives at the intra state hydro level
- Enforcement of primary, secondary and tertiary reserves in line with CERC order "Roadmap to operationalize reserves in the country."
- Enforcement of governing action in all eligible generating plants.
- Technical Standards and protection requirement for renewables and Implementation
- Implementation for frequency response regulation Need for LVRT regulation for large scale grid connected Solar Plants as well as HVRT requirement for wind & solar both.
- Implementation of Time of Day (ToD) tariff as a part of demand side management for all major categories of consumers.
- Demand Response (automatic/manual load control) as an additional measure to balance renewable generation
- Enforcement of power plant operation at technical minimum at 55% as mentioned in Central Electricity Regulatory Commission (Indian Electricity Grid Code) (Fourth Amendment) Regulations, 2015 with similar dispensation at the intra state level.
- Explore the possibility of further bringing down the technical minimum from 55% to 40% in case of some coal fired units for bringing about additional flexibility
- Policy & Regulation for development of transmission system for Single window clearance/ RE zones etc.
- Forecasting & Scheduling regulation at Inter and Intra-state level
- Regulation for Flexible Generation and Generation Reserves
- Research &Skill development in forecasting technologies
- Capacity Building of SLDC particularly in RE rich states.
- Introduction of PSS tuning in all eligible generating units.
- Deployment of Phasor Measurement Units in grid for better real time monitoring of power system health
- Establishment of new Pump storage plants identified by CEA as a balancing source and ensuring operation of existing PSPs in pumping mode.

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Annexure-1

1. Wind Turbine Type 1 Model Parameters

162274	'WT1G1'	W1			
	0.84600	0.0000	3.9270	0.17730	0.0000
	0.10000	1.0000	0.30000E-01	1.2000	0.17900 /
162274	'WT12T1'	W1			
	5.3000	0.0000	0.91800	5.0000	1.0000 /
162274	'WT12A1'	W1			
	0.1500E-01	0.1000	0.1500E-01	0.1000	0.1000
	0.1000	0.9000	0.2500 /		

2. Wind Turbine Type 2 Model Parameters

4004	'WT2G1' 1	0.12602	6.8399	0.18084	0.44190E-02	
	0.10994	1.0000	0.0000	1.2000	0.0000	
	0.0000	0.21700E-01	0.89880	0.90000	0.90500	
	0.0000	0.54000E-02	0.20000E-01	0.40000E-01	0.10000	/

4004 'WT2E1'10.50000E-01 0.500E-01 1.00 1.000 0.9900 0.5000E-01 /

4004 'WT12T1' 1 3.4600 0.0000 0.8101.500 0.3000 /

4004 'WT12A1' 1 0.1500E-01 20.0 1.000 0.1000.100 0.100 1.000 0.250 /

3. Wind Turbine Type 3 Model Parameters

162216 'WT3G2' V1 100
0.0000 0.0000 0.0000 0.0000 0.10000
1.0000 0.50000 0.90000 1.0000 1.2000
2.0000 1.0000 0.20000E-01 /

162216 'WT3E1' V1 0 1 2 0 0 '1 '
0.15000 18.000 5.0000 0.0000 0.50000E-01
0.0000 0.60000 1.1200 0.40000E-01 0.43600
-0.43600 1.6400 0.20000E-01 0.45000 -0.45000
5.0000 0.18600 0.90000 1.1000 117.40
0.50000 1.1870 0.50000E-01 0.50000E-01 1.0000
0.30000 1.1000 1.1000 1.1000 0.74000
1.2000 /

162216 'WT3T1' V1

1.2500	4.9500	0.0000	0.70000E-02	21.980
0.0000	1.8000	1.5000	/	

162216 'WT3P1' V1

0.30000	150.00	25.000	3.0000	30.000
0.0000	27.000	10.000	1.0000	/

4. Solar Model Parameters

512001	'REGCA1'		S	1	2.00E-02	10	0.9	0.4	1.22	1.2
	0.8	0.4	-1.3	2.00E-02		0.7	999	-999	1	/

512001	'REECB1'		S	0	0	1	1	0	-99.00	99.00
	0.00	-0.05	0.05	0.00	1.05	-1.05	0.00	0.05	0.40	-0.40
	1.10	0.90	0.00	0.10	0.00	10.00	0.02	99.00	-99.00	1.00
	0.00	1.70	0.04	/						