FLEXIBILITY ANALYSIS OF COAL BASED THERMAL POWER STATION WITH RENEWABLE ENERGY

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Submitted by

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CANDIDATE’S DECLARATION

I ROHIT THAKUR, 2K16/RET/006 student of M Tech. (Renewable Energy Technology), hereby declare that the project Dissertation titled **“Flexibility Analysis of Coal Based Thermal Power Station With Renewable Energy”** which is submitted by me to the Department of Mechanical, Production and Industrial Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement of the degree of Master of Technology is original and not copied from any source without any citation. This work has not previously formed the basis for the award of any Degree, Diploma Associate-ship, Fellowship and other similar title and recognition.

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I hereby certify that the project Dissertation titled **“FLEXIBILITY ANALYSIS OF COAL BASED THERMAL POWER STATION WITH RENEWABLE ENERGY”** which is submitted by **Rohit Thakur (2K16/RET/06)** to Department of Mechanical, Production and Industrial Engineering, Delhi Technological University, Delhi in partial fulfilment for the award of Master of Technology in Renewable Energy Technology, is a record of the project work carried by him under my supervision. To the best of my knowledge this work has not be submitted in part or full for any Degree or Diploma to this university or elsewhere.

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ABSTRACT

Due to huge cost reductions in renewable energy sources especially solar and wind power over the last decades, these sources are contributing more and more to the decarbonization of power systems around the world. However, these power sources are variable in nature and these technologies challenge electricity systems and thereby decreasing the reliability of the entire electrical grid. More variable power generation requires the enhancement of the flexibility requirements of the overall power system, both on the supply and demand sides. To compensate this variable nature of the renewable energy sources, fossil fuels operated especially coal-fired power plants are required to balance power grids. To meet such operational requirement, high flexibility of coal-fired thermal power plant is being required, in terms of possessing resilience to frequent start-ups (cold, warm and hot), meeting base and peak load changes (ramp up & ramp down), and providing frequency control duties. However, existing conventional power plants, especially coal power plants, cannot easily couple with the variable nature (weather-dependent generation) of wind and solar power. As a result, there is a rising level of renewable energy curtailment in some power systems. However, my work will be focused on making existing power plants more flexible in technically and economically way. Since flexibility is the standard that shapes modern power systems, by making system flexible its reliability increases and it can be operated either base load or peak load plant to meet the variability nature of the RE sources .

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NOMENCLATURE

CEA	Central Electricity Authority
CERC	Central Electricity Regulation Commission
CO	Carbon monoxide
CO_2	Carbon Dioxide
FGD	Flue-gas desulfurization (FGD)
GOI	Government of India
GW	Giga Watt
GWh	Giga Watt hour
HP	High Pressure
MNRE	Ministry of New Renewable Energy
MW	Mega Watt
NDC	Nationally Determined Contributions
Nox	Oxides of Nitrogen
NTPC	National Thermal Power Plant
PLF	Plant Load Factor
Pmin	Minimum Load
Pnet	Net Power
Pnom	Nominal Power
PPA	Purchase Power Agreement
RE	Renewable Energy
RES	Renewable Energy Sources
RPO	Renewable Purchase Obligation
SCR	Selective Catalytic Reduction
SHP	Small Hydro Power
TPP	Thermal Power Plant
TPS	Thermal Power Station
UMPP	Ultra Mega Power Project
VRE	Variable Renewable Energy

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The Paris agreement in December 2015 changed the international climate policy significantly. The objective of limiting global warming to well below to 2°C can only be achieved if energy systems are almost completely decarbonized over the longer term [1]. The decarburization of the power system is essential in this regard, as fossil fuels remain the dominant source of power generation worldwide, and are responsible for a large share of global greenhouse gas emissions. Renewable energy such as wind power and solar photovoltaic are playing a fundamental role in the transformation of the power system. These technologies have experienced tremendous cost reductions in recent years and are becoming cost-competitive with conventional technologies for new investment. However, renewables are characterized by variable and uncertain output, thereby increasing the need for flexibility in the power system. Indeed, integration of higher shares of renewable energy is possible by enhancing proper supply and demand-side flexibility [2].

Once the development of renewable energy reaches a certain level, concerns grow that existing conventional power plants cannot be operated with required flexibility. As a result, it will limit the addition of new variable renewable energy to the system [3]. One clear problem that is connected to this issue is the high level of renewable energy curtailment that occurs in certain power systems – for example, On Sunday, May 8, 2016, Germany produced so much of electricity that prices were actually negative. As a result, customers got paid to use the electricity. Therefore, it is prerequisite to make existing conventional power plants more flexible for higher integration of renewable energy effectively. Existing coal power plants can technically provide that kind of flexibility to meet the variable nature of renewable. However, in the long run, to meet the international emission-reduction targets fossil-fuel power plants, especially coal-based power plants, will need to be replaced altogether with less CO_2 intensive technologies.

Together with other flexibility measures, improving the flexibility of coal-based thermal power plants can enable higher penetration of variable renewable energy during the transition to a decarbonized power system [4]. Flexibility does not make coal clean, but making existing coal-based plants more flexible enables the higher penetrations of variable renewable energy in the system.

1.2 INDIA'S ENERGY SCENARIO

In past few years availability of electricity in India has both increased and improved and at the same time the peak deficit also got reduced, peak deficit in 2008-09 was 12.7 % which comes down to 2 % in 2017-2018 as shown in Fig. 1.1[4]. The energy requirement grows from 830.54 BU in 2008-09 to 1203 BU in 2.017-18 with a deficit of 0.7 % as shown in Fig 1.2. India's electricity generation is predominantly coal-based as shown in Fig.1.3, almost 80% of electricity generation comes from coal. With increased sourcing of power from the power sources which are variable and intermittent in nature, the need of flexible generation will also increase. Flexible generation sources will help counter the variability and intermittency of generation output of the renewables. Since India has limited pump storage and insufficient gas sources, coal-based generation is the major option to meet and match the fluctuating requirements of the grid.

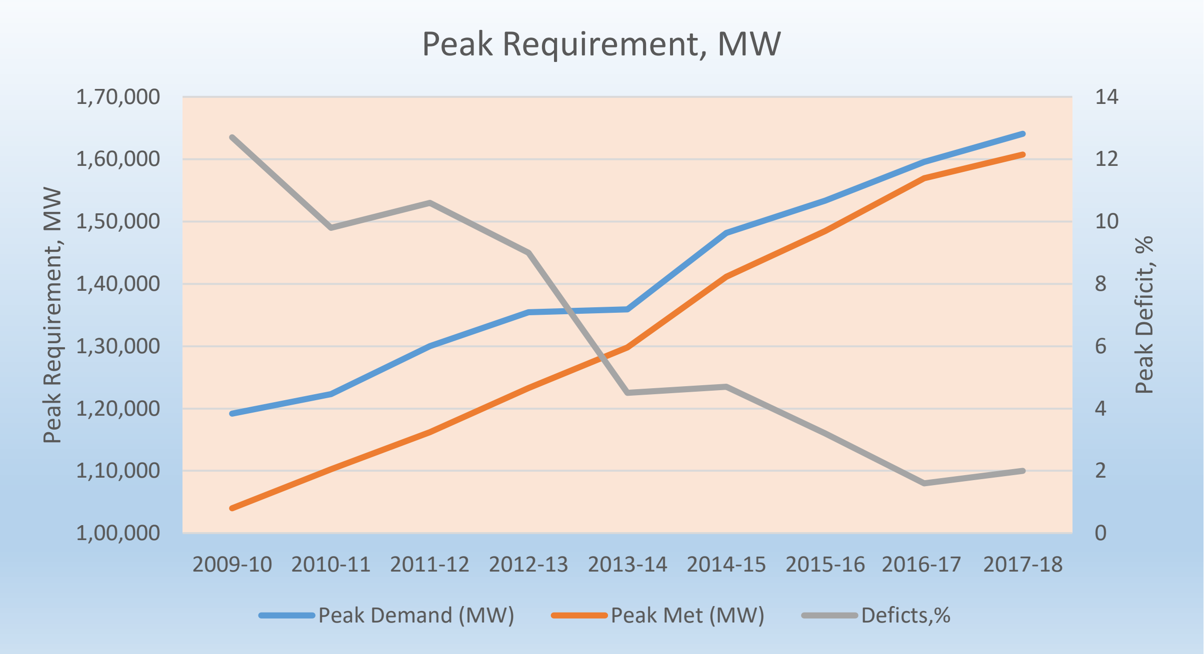

Fig. 1.1: Peak Demand, Peak Mer, and Peak Deficits [5]

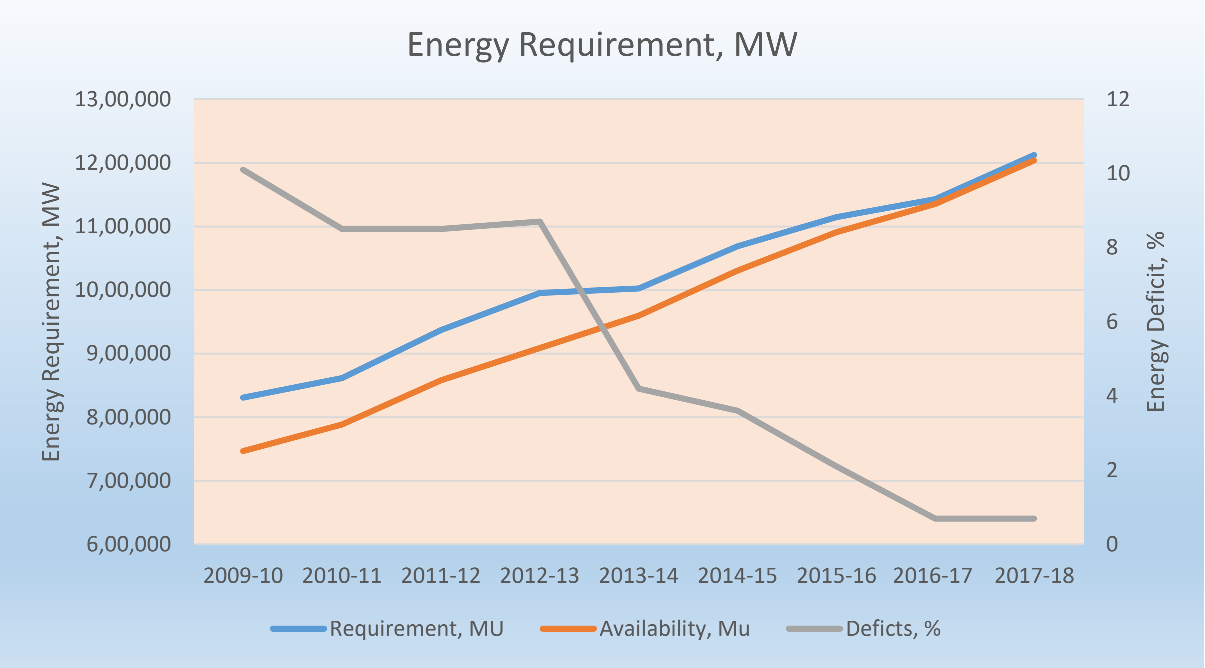

Fig. 1.2: Energy requirement, availability, and deficits [5]

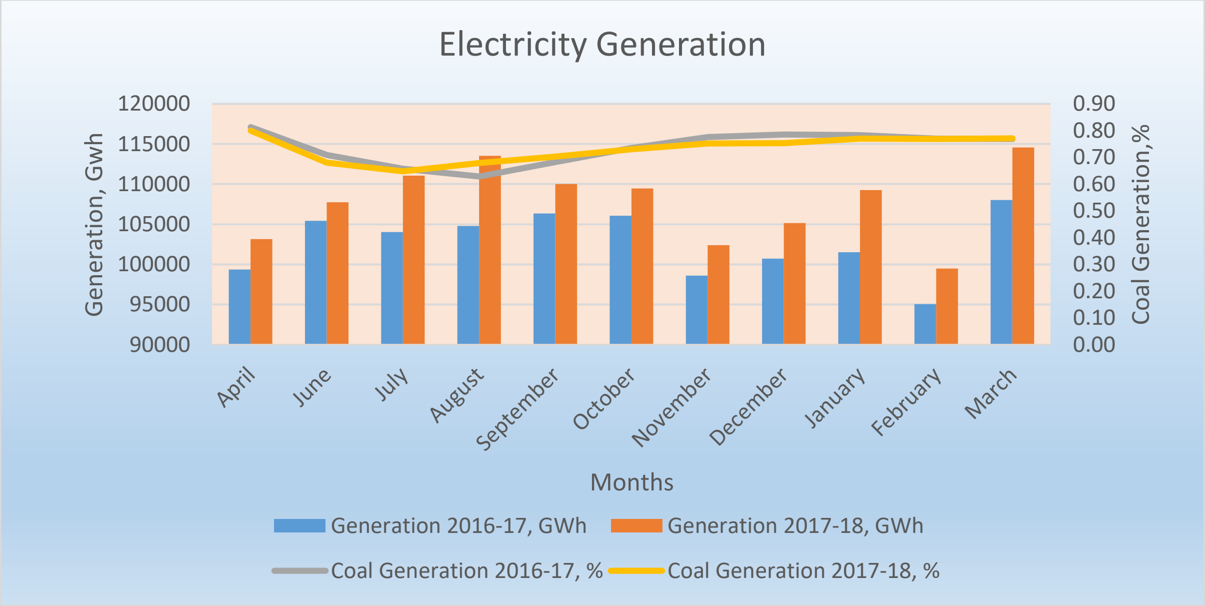

Fig. 1.3: Electricity generation form coal and other sources [5]

India’s renewable energy generation capacity has more than doubled during the past eight years. The renewable energy installed capacity as on 31.03.2018 is 69.022 GW. Wind energy accounts for 49.32% of the renewable energy capacity, with 34.046 GW of installed capacity, making India the world’s fifth-largest producer of wind energy. Small hydropower (4.4 GW), bio-energy (8.7 GW) and solar (21.65 GW) constitute the remaining capacity. With a total installed capacity of India reaching 344002.39 MW, it makes renewable capacity share around 20 % of the total capacity [5]. This is a fairly big number in comparison to the renewable share that exists a few years back. With Government of India target of 175 GW renewable power installed capacity by the end of 2022, this share will further increase [6].

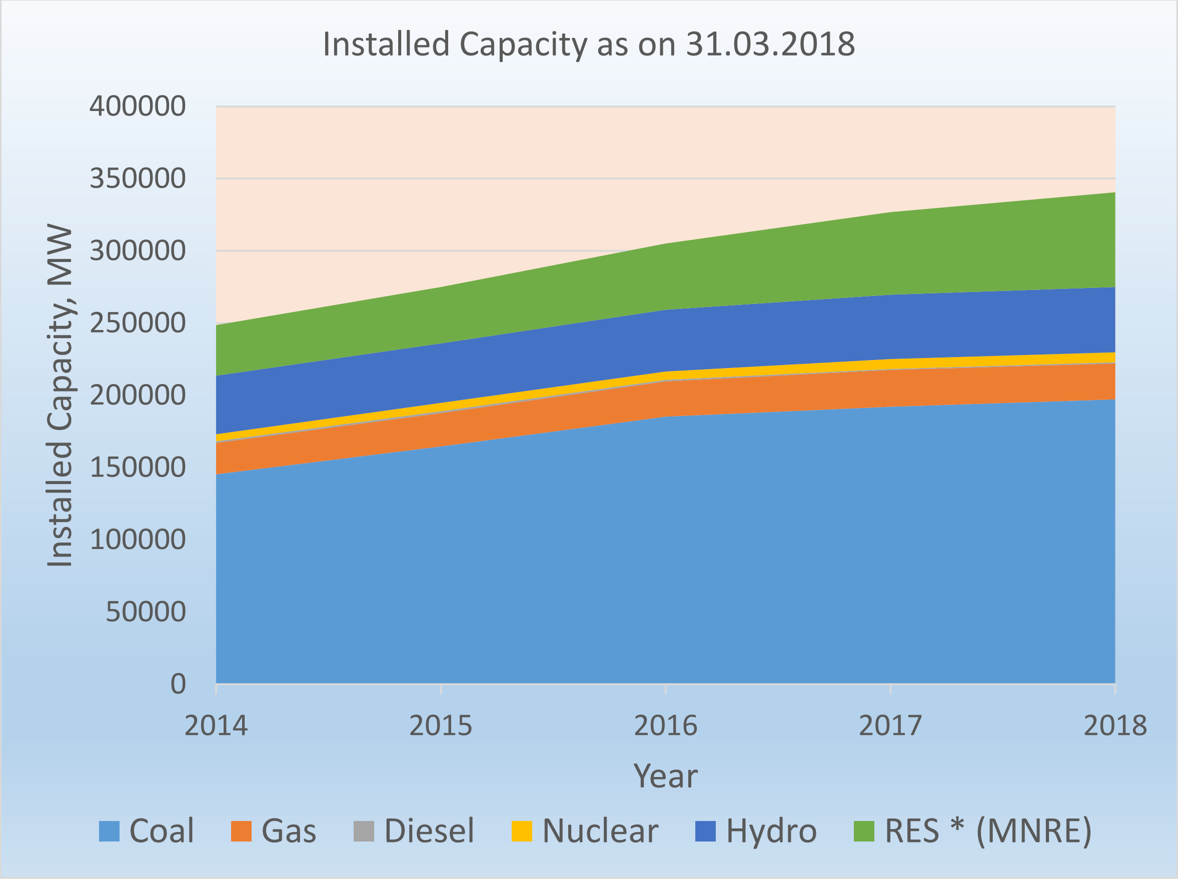

Fig. 1.4: Installed capacity of India as on 31.03.2018 [5]

India is blessed with the vast potential of solar and wind generation. However, generation from renewable energy sources especially solar and the wind is variable in nature and therefore, requires huge balancing capacity in the system [7-8]. Another big challenge faced by Indian power sector now and in the future is how to integrate higher shares of renewable energy with the grid. There are many elements attached to the grid integration challenge and solution lies in implementing a multilevel approach to tackle such a situation.

1.2.1 RENEWABLE ENERGY STATUS

In the electricity sector, renewable energy accounted for 20% of the total installed capacity (69.02 GW) as of 31.03.2018. Wind energy installed capacity is 34,046 MW as of 31.03.2018, making India the fourth-largest wind power producer in the world.

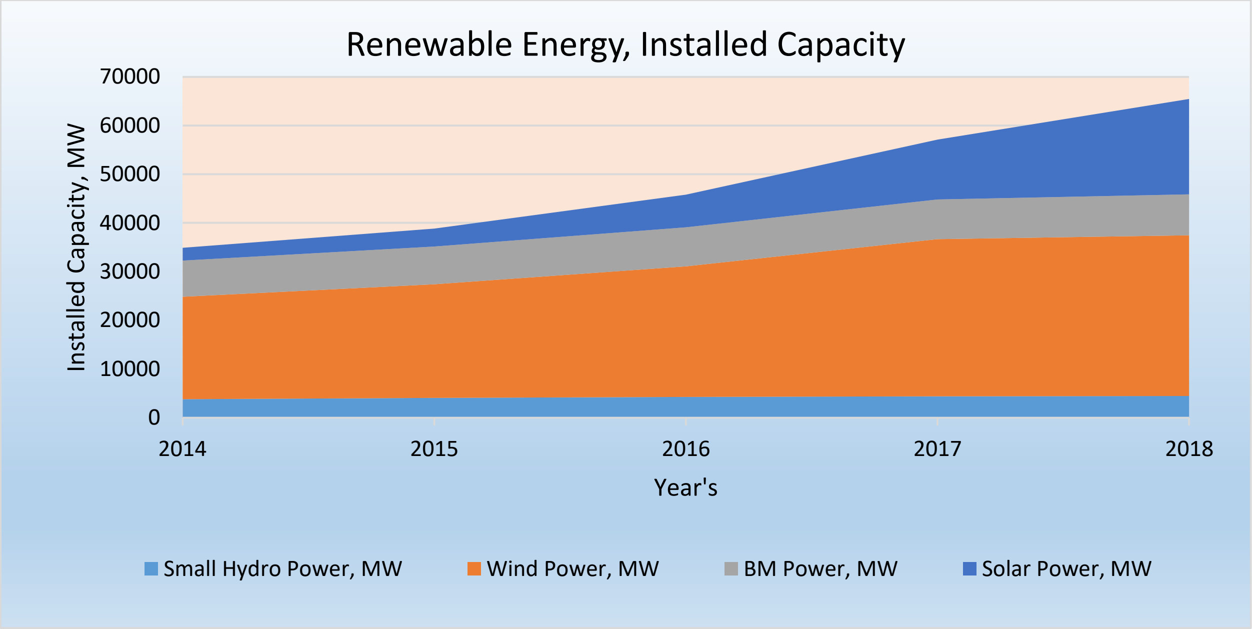

Fig. 1.5: Renewable energy installed capacity of India as on 31.03.2018 [5]

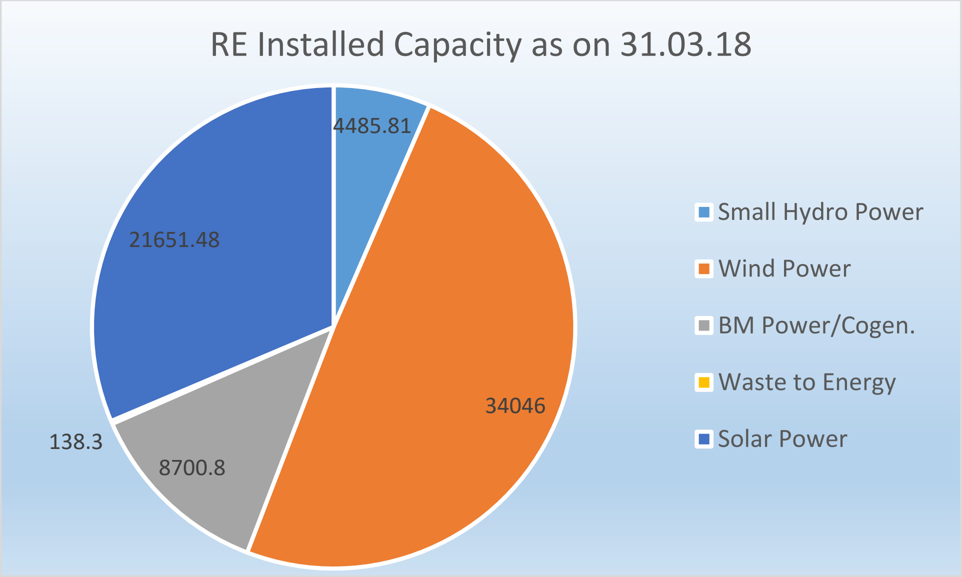

Fig.1.6 RE Share as on 31.03.2018 [5]

Table 1.1: Tentative State-wise break-up of Renewable Power target to be achieved by the year 2022 [6]

State/UTs	Solar Power (MW)	Wind (MW)	SHP (MW)	Biomass Power (MW)
Delhi	2762			
Haryana	4142		25	209
Himachal Pradesh	776		1500	
Jammu & Kashmir	1155		150	
Punjab	4772		50	244
Rajasthan	5762	8600		
Uttar Pradesh	10697		25	3499
Uttrakhand	900		700	197
Chandigarh	153			
Northern Region	**31120**	**8600**	**2450**	**4149**
Goa	358			
Gujarat	8020	8800	25	288
Chhattisgarh	1783		25	
Madhya Pradesh	5675	6200	25	118
Maharashtra	11926	7600	50	2469
D. & N. Haveli	449			
Daman & Diu	199			
Western Region	**28410**	**22600**	**125**	**2875**
Andhra Pradesh	9834	8100		543
Telangana		2000		
Karnataka	5697	6200	1500	1420
Kerala	1870		100	
Tamil Nadu	8884	11900	75	649
Puducherry	246			
Southern Region	**26531**	**28200**	**1675**	**2612**
Bihar	2493		25	244
Jharkhand	1995		10	
Orissa	2377			
West Bengal	5336		50	
Sikkim	36		50	
Eastern Region	**12237**		**135**	**244**
Assam	663		25	
Manipur	105			
Meghalaya	161		50	
Nagaland	61		15	
Tripura	105			
Arunachal Pradesh	39		500	
Mizoram	72		25	
North Eastern Region	**1205**		**615**	
Andaman & Nicobar Islands	27			
Lakshadweep	4			
Other (New States)		600		120
All India	**99533**	**60000**	**5000**	**10000**

1.3 EFFECT OF RENEWABLE ENERGY ON TPS

As the share of renewable energy (Wind and PV) increasing, it directly affects the operation of conventional coal-based thermal power stations. To counteract this effects, these power stations need to operate more flexibly i.e., they have to ramp up and down more quickly and frequently, operate often at part loads to provide higher operating range and have to be shut-down and startup with greater regularity. An increasing share of renewables also decreases the market profitability of conventional generation due to the so-called Merit-Order Effect [9]. In addition, integration of high renewable energy has indirect impacts on conventional power plants, as it increases the demand for balancing and congestion management in the power system. The following are the effects of renewable energy on thermal power stations:

1.3.1 INCREASING REQUIREMENTS FOR FLEXIBLE OPERATION

A power system, which is characterized by increasing integration of variable renewable energy generation, requires flexible operation of existing conventional power plants. The main cause of an increased need for flexibility is the variable nature of renewable energy sources. Both Wind and PV generation depend on weather conditions, daily and seasonal changes, and therefore cannot generate required “on demand” like conventional power plants. Furthermore, renewables have almost no marginal costs. This means that they produce “for free” whenever the primary resource is available. These factors lead to the fundamental transformation of power systems, as it increases the requirements for the flexible operation because of the need to respond flexibly to variation in renewables integration.

Currently, several options are available to provide more system flexibility for the integration of renewables. First one is to by Encouraging demand-side flexibility. Second is to promote grid development, so that electricity can be transmitted with greater ease between regions and countries. The third option is to store electricity using conventional storage technologies (Pump Storage) or new technologies (Batteries). The fourth available option is to increase conventional power plant flexibility.

Generally, conventional power plants especially coal-based power plants have been designed to serve electricity demand pattern that is characterized by relatively low variability. In the absence of variable renewables, this leads to an optimal generation mix with a high share of base-load power plants. However, renewable generation is highly variable, and to some extent less predictable. With a high share of variable renewables, a large proportion of conventional generation can no longer operate as base-load capacity and must be run with greater flexibility.

1.3.2 THE IMPACT OF RENEWABLES ON THE COST AND UTILIZATION OF EXISTING THERMAL POWER PLANTS

The increased integration of VRE has an effect both economic as well as utilization of conventional power plant and their profitability too. The flexible operation of coal-based power plants is technically possible, yet reducing the utilization of capital-intensive technology has negative impacts on profitability.

In general, when additional capacity is introduced to a power system whether it is wind, solar, or any other type of power plant the output and revenues of other existing power plants tend to be reduced [10]. In contrast to coal-based power plants, wind and solar power plants produce electricity only in the presence of effective wind blows and the sun shines. This means that their output is variable in nature and does not react to changes in demand for electricity. The reduced average utilization of the coal-based power plants leads to higher specific generation costs. This effect is important for generation technologies like coal-based power plants that are capital intensive.

1.3.3 THE MERIT-ORDER EFFECT

VRE has a direct impact on the utilization of thermal power plants and renewables also impact power plant earning in the wholesale market due to the Merit-Order Effect. The merit order effect may be defined as a way of ranking available sources of energy based on their ascending order of price together with the amount of energy that will be generated. In a centralized management system, the ranking is based on lowest marginal costs and those plants which are having minimum generation cost are brought online first to meet the requirement. Dispatching generation in this way minimizes the cost of production of electricity. Sometimes generating units must be started out of merit order, due to transmission congestion, system reliability or other reasons.

In contrast to coal-based power stations, wind and PV have no variable costs. Therefore, RE integrates at the beginning of the merit order, pushing conventional technologies further out on the merit order. This has two effects: 1) the utilization rate of conventional power plants tends to decrease during times of high RE availability and low demand. 2) the average market clearing price decreases as more expensive technologies are less frequently used.

1.3.4 BALANCING POWER

Renewable generation is mainly weather-dependent and is subjected to forecasting errors too. Forecasting errors can increase balancing costs, as it increases the need for maintaining and activating balancing reserves. Balancing power is necessary for the frequency stability of electrical grids, which is done by balancing in real-time power generation and consumption. If the power system is undersupplied, positive control power has to be added, in case if the power system is oversupplied negative control power has to be added.

The causes of balancing power demand are various. In systems without RE generation, the primary causes are unplanned power plant outages, load forecasting errors and load noise. In systems with VRE, errors in forecasting wind and PV production must be added to the list. The magnitude of forecasting error depends totally on the quality of the forecasting tools used and the time horizon for which the forecast is made.

1.4 OPERATIONAL FLEXIBILITY

The flexibility of a power plant can be described as its ability to adjust the net required power fed into the grid without affecting its stable working conditions and the time required for the same should be as low as possible.

Overview of flexibility characteristics:

- Minimum Load
- Start-Up time
- Ramp rate

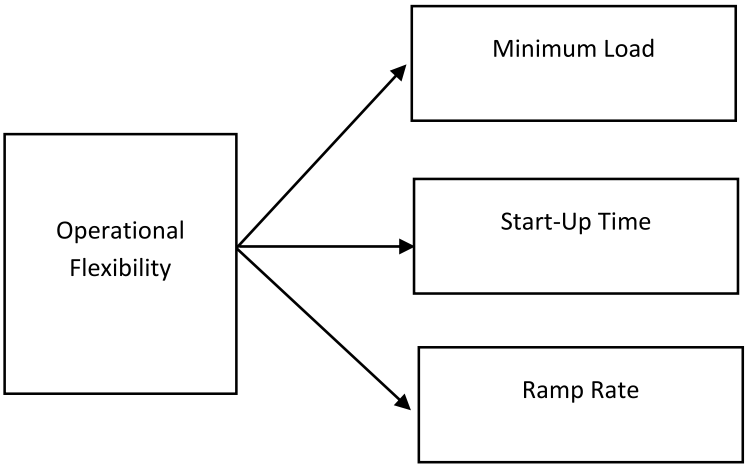

Fig. 1.7. Flexibility Characteristics

1.4.1 MINIMUM LOAD

The minimum load (P_{min}), is the lowest possible net power a power plant can deliver under stable operating conditions. It is measured in percentage of nominal load, %P_{nom}. The net power P_{net} fed into the grid, ranging from minimum load to nominal load. There are some advantages and disadvantages of lowering the minimum load. The advantages of lowering the minimum load of a coal-based power plant, it allows to increase the range of generation capacity and a lower minimum load also avoid expensive start-ups and shutdowns. The disadvantage of lowering the minimum load, is at minimum load the power plant operates at lower efficiency and specific CO_2 emissions also increased at low load. There are certain limitations of reducing the minimum load as the load of a power plant reduces it is difficult to ensure a stable combustion without supplemental firing.

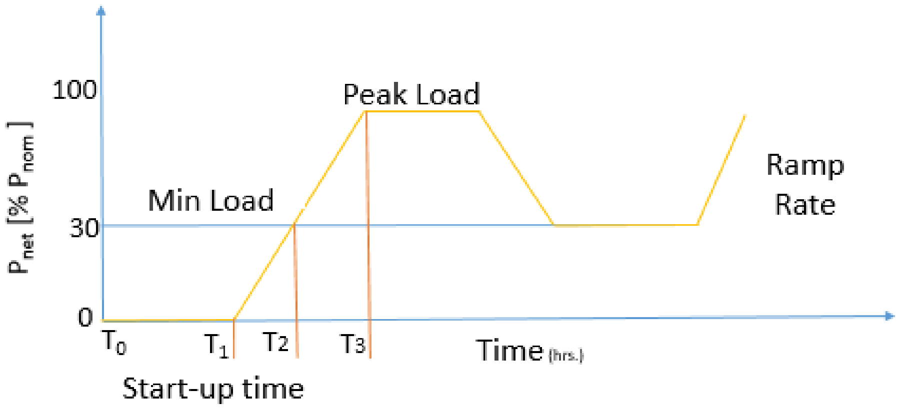

Fig. 1.8 Qualitative representation of key flexibility parameters of a power plant

1.4.2 START-UP TIME

The start-up time for a power plant is defined as the period from starting plant operation until reaching minimum load. The start-up time for a power plant is a function of different generation technologies and it varies significantly from technology to technology. Other factors influencing the start-up time are downtime i.e., a period when the power plant is out of operation and cooling rate. Fig. 1.8 shows the time for a simplified start-up.

After start-up initiation (t_0), no power is fed into the grid until t_1. After t_1, the net power gradually starts to increase until the minimum load is reached (t_2). Generally, steeper load curve slopes translate into shorter start-up time. The start-up time for a thermal power plant can be categorized as hot, warm and cold start-up. If the power plant has been out of phase for less than 8 hours, then start-up initiated is known as hot start-up. If the power plant has been out of phase for around 48 hours, then the start-up initiated is known as warm start-up. If the power plant has been out of operation for more than 48 hours, then the start-up initiated is known as cold-start-up. Generally, a cold start puts a larger strain on plant components than a hot start due to the greater temperature differences that occur during the start-up. The advantages of reducing the start-up time is the shorter the start-up time, the quicker a power plant can reach minimum load. The disadvantages of reducing the start-up time is faster start-up times put greater thermal stress on plant components, thereby reducing their lifetime.

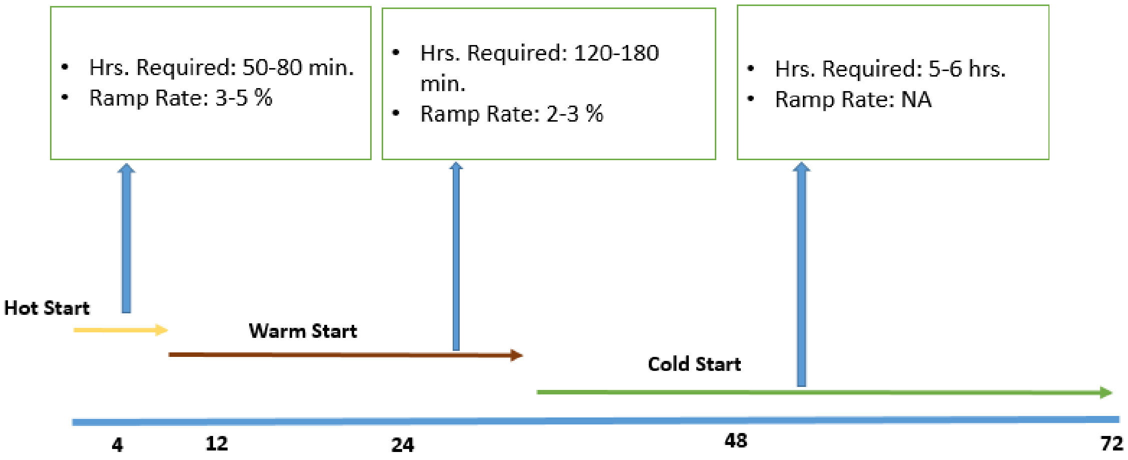

Fig. 1.9 Hours of the plant in shutdown

1.4.3 RAMP RATE

The ramp rate describes how fast a power plant can change its net power during operation. It is a function of generation technology. Mathematically ramp rate is represented as a change in net power with respect to time. It is represented as MW/Min or %P_{nom}/min.

$$\textit{Ramp rate} = \Delta Pnet/\Delta t$$

The advantages of higher ramp rate is, it allows a power plant to adjust net power more rapidly to meet changes in power demand. If the coal-based power plants have high ramp rate, then it can accommodate high variable renewable energy. The disadvantages of having high ramp rate is, it increases the thermal stress as there is rapid change in firing temperature occurs.

Table 1.2 Comparison of most commonly used and state-of-the-art power plants for each generation technology with regard to flexibility [13].

Property	OCGT	CCGT	Hard coal-fired power plant	Lignite-fired power plant
Most commonly used power plants				
Minimum load (% Pnom)	40-50 %	40-50 %	25-40 %	50-60 %
Average ramp rate (% Pnom per min)	8-12 %	2-4 %	1.5-4 %	1-2 %
Hot start-up time (min or h)	5-11 min	60-90 min	2.5-3 h	4-6 h
Cold start-up time (Min or h)	5-11 min	3-4 h	5-10 h	8-10 h
State-of-the-art power plants				
Minimum load (% Pnom)	20-50%	30-40%	25-40%	35-50%
Average ramp rate (% Pnom per min)	10-15 %	4-8 %	3-6 %	2-6 %
Hot start-up time (Min or h)	5-10 min	30-40 min	80 min - 2.5 h	1.25 -4 h
Cold start-up time (Min or h)	5-10 min	2-3 h	3-6 h	5-8 h

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Flexibility being a prized characteristic in any power system with significant power coming from variable renewable energy, it mandates that there should be adequate financial compensation for flexible operation by coal-based plants. An effort is also made during this work to analyze the various factors which should be considered in the compensatory framework for the flexible operation of coal-fired power plants. In several countries, the development of renewable energy is hampered after reaching a certain penetration level, because of the belief that the existing power system cannot cope with the weather-dependent generation of wind and solar power. As a result, VRE curtailment increases in various power system and the priority is given to the base-load operation of conventional generation. For conventional power system, it is true that they are not built to adjust frequent load changes, to integrate VRE with conventional power, the conventional power plant must be operated flexibly. There are many potential sources of flexibility are available which is presented in the following literature review.

2.2 LITERATURE REVIEW

Maken et al. presented a report on existing flexibility capabilities for Tamil Nadu, Rajasthan, and Gujarat. For Gujarat, from hourly basis analysis for the year 2014, they found that the maximum increase in residual load between two successive hours is 1258 MW, which means 16% ramp-up will be required to meet the peak. Also, the maximum decrease in the residual load in any two hours is 1531 MW, Which requires a 14% ramp down in an hour. For Tamilnadu, monthly plant generation data for April 2015-March 16 and daily plant generation data for 20th June 2015 is analyzed. The outcome of the analysis shows that there is a variation from 40% to 95% in the monthly PLF of the various thermal stations in Tamil Nadu. Thus, this proves some flexibility in the present scenario. For Rajasthan, Kota and Suratgarh STPS are analyzed on an hourly basis from May to Aug 2014. The outcome of the analysis shows that minimum hourly load factor was 42% and maximum hourly load factor was 95%. This shows that these plants are already ramping up and down with a range of 40 % of the total load variation [11].

Sharma et al. conducted a study for enhancing the flexible operation of coal-based thermal power plant. They conducted their study on two NTPC (Dadri (210 MW) & Simhadri 500 MW)) power plants. The goal of the study was to investigate the flexibility required for two power plants which are operated by NTPC – Dadri (210 MW) and Simhadri (500 MW). The study is performed in three different scenarios i.e., for a minimum load of 50%, a minimum load of 40% and a minimum load of 25%. The task force recommends for implementation of 50% minimum load operation in all stations including Central, State & IPPs. This can be achieved by proper monitoring and maintenance of TPS, and not involve any financial assistance. 40% minimum load operation can be implemented in phases and it will require some retrofitting to the stations. The cost for implementing a 40% minimum load operation will be around INR 7.8-17.5 crores per unit. As per task force committee report a 25% minimum load operation is not feasible because of the poor quality of coal [12].

Agora Enegiewende presents a study report on possible flexibility measures for coal-based thermal power plants. They have considered technical and economic factors related to increasing the flexibility of coal-based thermal power plants. The following are outcomes of this report: (i) As per Paris agreement, decarbonization of the power sector has become a top priority for many developing countries. To meet this requirement renewable generation must expand. As RE expand, the flexible operation required for power system increases as RE is Variable in nature. (ii) Generally, coal-based power plants are designed for base-load operation. However, coal-based power plants can improve their efficiency and flexibility by adopting retrofitting measures.(iii) By managing, demand-side requirements and interconnection between grids will also lead to flexible operation of the power system. (iv) The economics of retrofit for existing coal-based power plants influence the availability of remuneration options for flexibility. (v) Coal-based plants operate as baseload consumes a high amount of coal. If coal-based plants can increase the flexibility of their operation, coal consumption can be reduced, further emissions can also be reduced [13].

Henderson et al. presents a report on how to increase the flexibility of coal-based thermal power plants. Flexibility for coal-based thermal power plants can be achieved by improving or retrofitting some features of plants. These include: (i) Boiler firing systems – by changing the size and number of mills and fitting of modern burners to achieve lower fuel feed rates to reduce the number of shut-downs; introduction of lignite pre-drying (efficiency improved); installation of hoppers and associated pipework to achieve indirect firing (efficiency at part load improved), (ii) Boiler pressure parts – use of alloys of improved strength to permit thinner section components; installation of external steam preheating to reduce start-up time; reducing minimum load through means such as modified evaporator designs, economiser water-side bypasses together with feed-water recirculation, and increasing the mass flow in the evaporator to achieve greater stability, (iii) Ensuring emissions control systems remain effective – installing means to maintain SCR exit temperature within specification at part load to avoid catalyst blocking and damage to the air heater; minimising shut-downs and start-ups of FGD systems, and modernising control systems to reduce energy demand; for dust separation devices, ensuring adequate temperatures to avoid moisture condensation on particles, (iv) Turbine and water-steam systems – To manage the rate of steam temperature change as the boiler is starting up and staring down a turbine bypass can be provided to reduce thermal stresses; use of a steam-cooled turbine outer casing to allow thinner sections for faster start-up; use of sliding pressure boiler-turbine systems for better control of turbine temperatures and reduced stresses; adding feed-water heater bypasses for greater load range; providing condensate throttling, feed-water heater bypass or HP stage bypass for frequency control; adding thermal (feed-water) storage systems for greater load range or frequency control [14].

As part of Nationally Determined Contributions (NDC), GOI has already committed to installing a 40% of non-fossil fuel sources by 2030 of its total installed capacity. In the year 2016, GOI has introduced the concept of flexible use of coal. This policy allowed a power generation company to use coal in a most efficient manner such that unnecessary coal transportation is avoided and cost of power generation could be reduced. GOI purposed flexibility in a generation so that Discoms are able to meet their RPO without facing any extra financial burden. By providing this kind of flexibility to the generating stations, to generate RE power and supply power under existing/future contractual agreements will ensure Discoms to procure RE power within their existing PPA and meet their RPO. Thus RE power shall replace the thermal power of any of the thermal generating stations of the generating company, wherever found feasible by the generating company, this leads to balance RE power and reduce emissions [15].

GOI has made international commitment (INDC) to have 40% cumulative electric power installed capacity from non-fossil fuel energy sources by the end of 2030 and to reduce the emissions intensity of its GDP by 33% to 35% by the year 2030 from year 2005 level. GOI has set a target of 175 GW of RES by March 2022. In this report, two scenarios have been studied by considering INDC's Targets and another by considering a boost to hydropower. The studies show that even with 125 GW installed capacity from RES (100 GW during 2017-22 and 25 GW during 2022-27) and committed capacity addition from Hydro and Nuclear, INDC targets can be achieved. Another scenario has been carried out by considering higher Hydro installed capacity of 80 GW by 2027.It has been found that in the latter scenario, 60% of the installed capacity would be from the non-fossil fuel and 40% from the fossil fuel. With 175 GW of installed capacity from RES by the year 2021-22, it is estimated that the ramping requirement will increase with the maximum positive ramping requirement of around 400 MW/min. With the existing and proposed capacity addition, this ramping requirement can be achieved, if all generating stations exploit their inherent ramping capability and are flexible to operate. In case of high RE integration, hydro and gas-based generation can efficiently and effectively provide balancing and ramping requirements of the Grid [16].

Saidur et al. found that huge amount of energy is wasted through high-temperature flue gas and exhaust of the boiler. This loss of energy can be identified by performing energy audit. The major losses from the boiler are stack gas loss, this cannot be eliminated however can be minimized by recovering waste heat from the boiler exhaust. Heat loss due to the conduction and radiation occurs from the uninsulated surface of the boiler, fouling, and scaling which hinders heat transfer from high-temperature combustion product to the water, due to incomplete combustion. They also suggested by using variable speed driven ID fan excess air could be maintained, this enable to consume less amount of energy as well as optimized excess air will reduce stack gas loss by reducing the amount of stack gas. Heat recovery technologies can be used to recover waste heat from boiler exhaust and exploit that recovered heat to generate electricity or refrigeration effect. Recovered heat also can be used to preheat combustion air or feed water within the system. Proper maintenance of boiler also helps to save energy and to run the boiler at its maximum efficiency [17].

Oko et al. developed a detailed dynamic model of a 500 MW coal-fired subcritical power plant using gPROMS. This developed model was validated against actual plant measurements and the relative error was less than 5%. The developed model is able to predict plant performance reasonably from 70% load level to full load. The result of the analysis showed that implementing load changes through ramping introduces fewer process disturbances than a step change. The model was first simulated at full load with the governor valve fully opened and the fuel burn rate at 52.2 kg/s. After validation, the results show that relative error in model predictions is within <5% [18].

Soonee et al. presented a report on flexibility requirement for Indian power system. The rapid growth in renewable energy installed capacity without a proportionate increase in the loads, spatially during the off-peak hours has brought a change in the operation pattern of coal-based power stations. Earlier 100% plant load factor of thermal power stations is considered to be the performance indicator of thermal power plants. The changing shape of load curve has led to a situation where 100% PLF would be an exception. The main objective of this work is to identify the need for flexibility spatially of the Indian power system. To integrate RE generation into grid possess difficulty as it is variable in nature. To counter this issue one way is to have flexible generation sources with high ramping capabilities. As Indian electricity generation is coal-dominant, thermal generation needs to be operated more flexibly to balance the RE integration into the grid [19].

Moghaddam et al. presented a report on flexibility requirement in future power systems with high renewables penetrations. For decarbonization the power system, variable renewable energy is the best available option, however, at the same time, the large percentage of renewable integration can cause some problems for conventional generation system. The main aim of this work is to identify the flexibility required for the future power system. For their study, they have considerd the abilities, barriers and inherent attributes of the power system which has potential to deal with high VRE integration in the future power system [20].

Dagoumas et al. studied impact of penetration of renewable on flexibility needs. The main objective of this work is to identify the impact of the penetration of VRE on the flexibility needs and their price signal. For the power system planning, they used a generic Mixed Integer Linear Programming (MILP) model with a Unit Commitment (UC) model, which performs the simulation for the day ahead electricity requirement. This model evaluates the need for flexibility requirement under different penetrations level of renewable energy. The analysis of the model shows that the main flexibility needs concern the sunset effect for the months with an increased rate of growth. They found that the flexibility needs depends on the technology of the generation and the characteristics of the generation system [21].

Coker et al. presented a paper on increasing thermal power plant flexibility in a high renewable energy system. The main aim of this work is to examine the available option for flexibility enhancement. They found that to reduce the variability of the power system we must focus on the available alternatives, such as energy storage, demand-side management or interconnection of the system. They have also considered the operational and technical modifications for an existing coal plant. From this study, they found that system have the greatest saving, which is achieved by lower stable coal generation, increased carbon emissions due to the reduced efficiency of the partially operated plant [22].

Moritz et al. presented a paper on optimization of start-up for coal based thermal power plant. The main aim of this work is to develop a model for simulation of a coal-based power plant for start-up optimization considering the VRE growth in the energy system. They have developed a dynamic simulation model which includes process equipments such as boiler, water-steam circuit, and control system of a power plant. The model is able to identify constraints for faster start-ups, less fuel consumption, and less emission while keeping the thermal and mechanical stress, caused by higher ramp rates. The approach of dynamic simulation allows risk-free testing conditions under a different set of constraints and further allows to gain a comprehensive understanding of the complex process [23].

Peerapat et al. studied the operational flexibility of future generation portfolios with high renewables. The main objective of this study is to develop a model for different generation portfolios for Australian National Electricity Market (NEM). As the level of VRE increases, thermal power plants are subjected to frequent cyclic loading. They found that many coal and gas power plants have operational constraints. The combined effect of ramp rate, minimum load, and start-up costs was around 0.01-3% of the total annual cost. If the VRE penetration is increased by 40 % it has a significant effect on the energy system [24].

Lund et al. presented a review paper on energy system flexibility measures to enables a high level of variable renewable energy. This work provides reviews on different approaches, technologies, and strategies to integrate large-scale installation of variable renewable electricity such as solar and wind power. For their study, they have considered both demand

and supply-side measures. They found that the number of options available to improve energy system flexibility is large and the energy system has inherent capabilities to incorporate large share of VRE, without requiring massive change. However, in the long run, attention must be paid to dedicated flexibility products [25].

Miguel et al. presented a paper on operational flexibility and emissions of gas and coal-fired power plants in a future with growing RE. In this study they have studied six cases: heavy duty gas turbines in simple and combined cycle, aero-derivative gas turbines, large-scale supercritical coal power plants and small- and mid-scale subcritical coal power plants. They found the most critical operational processes and emissions associated with these plants. Their study shows that gas power plants are more efficient and their response rate towards load is also fast and it is generally less polluting than coal-based plants. However, at their respective minimum load, gas plants are less flexible and produced more NOx and CO emissions. The results show that, on average, an improvement of 50 %- 100 % on-ramp rates, minimum load, and start-up-time can be achieved [26].

Groot et al. presented a report on the effects of VRE on energy efficiency & full load hours of fossil-fired power plants in the European Union from 1990-2014. The outcome of this report is, average full load hours are found to be decreasing since 2006. The decrease is the most in the group with highest VRE penetration of 53 %. For medium penetration of VRE decrease was found to be 34% and for low VRE penetration, it was 32 %. These VRE penetration groups were then analyzed based on full load hours and energy efficiency and compared to each other. The decrease in full load hours in this study is 3000 h for natural gas and 2000 h for coal plants [27].

Kopiske et.al. studied the value of power plant flexibility in the power system considering high RE penetrations. They found the value of flexibility is determined by a combination of required flexibility and the available flexibility of the power system. VRE is only one factor among those, which include the flexibility of the power plant and availability of the other flexibility options. They also suggested that flexibility improvements for combined heat and power plants as well as the impact of other flexibility options such as Demand Side Management, E-Mobility, Power-to-Heat etc. would prove beneficial to achieve an even more comprehensive understanding of the value of flexibility [28].

Venkataraman et al. studied the operational and cost-benefit of retrofitting thermal power plants for flexibility. The main objective of this study the operational and cost-benefit analysis for retrofitting thermal power plants for flexibility. They found that with retrofit these plants can provide increased operational flexibility in terms of faster start-up, better turndown, and higher ramp rates. By retrofitting units, the cost of generation can be reduced [29].

Kondziella et al. studied flexibility requirement of the renewable energy based system. As contribution form, variable energy sources increases the system faces increasing flexibility requirement to avoid curtailment. The main aim of this work is to categorize the approach used for flexibility demand. Their study shows that the German and European energy system has enhanced technical, economic and market potential of their energy system. They have also purposed a framework to identify the market potential of the current flexible technologies [30].

Cochran et al. presented a report on flexibility requirements in 21st-century power systems. The main aim of this report is to find the flexibility required in 21st-century power systems. In the current scenario, all energy systems have some inbuilt level of flexibility which is designed to balance supply and demand requirements. However, it is difficult to integrate VRE generation. As power systems are to be fed more renewable energy into the grid and responsive demand, regulators and system operators have to identify the flexibility across all elements of a power system that is flexible generation, flexible transmission, Flexible demand-side management and flexible system operations. These practices help exact flexibility out of the existing system, such improved use of wind and solar forecasting [31].

Jaquelin Cochran et al. presented a report on flexible coal: Evolution from base load to peaking plant. As the RE penetration in the power system increases, it will favor resources that have low operating cost and provide some level of flexibility to the system. This transformation of the power system will require an increased proportion of the power generation fleet that is flexible in operation. By changing the operational practices such as monitoring and managing temperature ramp rates; creating a proper maintenance program for inspection of all affected equipment, and continual training to reinforce the skills needed in monitoring and inspections [32].

Annaluru et al. presented a paper on managing the power grid ramping challenges critical to the success of India’s RE target. As India is pushing ahead with its ambitious goal of integrating large amounts of renewable energy into the system, the grid side challenges of maintaining generation load balance with such large amounts of VRE sources remain. The aim of this work is to develop a model that can quantify the Ramp Up/Down rate requirements with three different levels of VRE penetrations. They found that ramp requirement to be 101 GW on the lower side and 134 GW on the higher side in 2027 [33].

2.3 SUMMARY OF LITERATURE

It is clear from the above literature review that as the integration of VRE increases, it requires flexible operation of conventional power plants to avoid the curtailment of RE. Many researchers have reported that the penetration of high VRE into the grid requires high ramp rate, as VRE is variable in nature and integration of high VRE into the grid has a direct impact on utilization and cost of generation on conventional power plants. The literature indicates that integration of high VRE into the grid also reduces the full load hours of the conventional power plant, which in turn reduces the plant load factor of coal-based power stations. In order to integrate high VRE, a conventional power plant need to be operated flexibly by controlling, three flexibility characteristics i.e., minimum load, ramp rate and start-up time. The first option for operating a conventional power plant flexibly is to reduce minimum load of the coal-based thermal power plant, by reducing minimum load high VRE can be easily integrated to the grid. The second option for flexible operation is to optimize the start-up time of the conventional power plant and the third one is to increase the ramp rate.

2.3.1 LITERATURE GAP

From the above referred literature it is clear that limited work has been done on developing the framework for the flexible operation of thermal power plants. There is not much literature available for technical aspects of ramp rate improvement and start-up optimization and their effect on the operation of thermal power plant. Limited work has been done on the effect of the flexible operation on emission.

2.3.2 OBJECTIVE

The objective of the present research work is:

1. Comprehensive literature survey

2. Determination of actual generation for different subcritical and supercritical thermal power plant.
3. Determination of flexibility index for different subcritical and supercritical thermal power plant.
4. Determination of ramp rate for different subcritical and supercritical thermal power plant.
5. Analysis of results
6. Study of the available retrofit option to enhance the flexible operation of subcritical and supercritical thermal power plants.
7. Study of the impact of flexibility on coal-based thermal power plants.

CHAPTER 3

FLEXIBILITY INDEX ANALYSIS

3.1 FLEXIBILITY INDEX FOR THERMAL POWER PLANTS

Flexibility Index for the thermal power plant is defined as the ratio of the difference between Maximum generation and Minimum Generation to the maximum generation. The value of flexibility index varies from 0 to 1, for flexibility index to be 1 thermal power plant need to be operated at a constant load.

$$\text{Flexibility Index} = \frac{\text{Maximum Generation} - \text{Minimum Generation}}{\text{Maximum Generation}}$$

Flexibility Index indicates, how much flexibility is present in the current system:

- The lower flexibility index indicates low flexible operation i.e., low range of operation.
- The higher flexibility index indicates higher flexible operation i.e., high range of operation.

3.2 METHODOLOGY

For analysis of flexibility Index for thermal power plants, the maximum generation and minimum generation during 96 blocks of 15 minutes is required. Fig. 3.1 shows the methodology adopted for flexibility index analysis. This analysis is performed for 19540 MW of installed capacity for both supercritical and subcritical technology based plants.

Assumptions for Flexibility Index and Ramp Rate Calculations:

- Maximum generation is considered as the actual maximum generation during 96 blocks of operation, in MW.
- Minimum generation is considered as the actual minimum generation during 96 blocks of operation, in MW.
- For calculation of Ramp rate two successive blocks of 15 min. is considered.

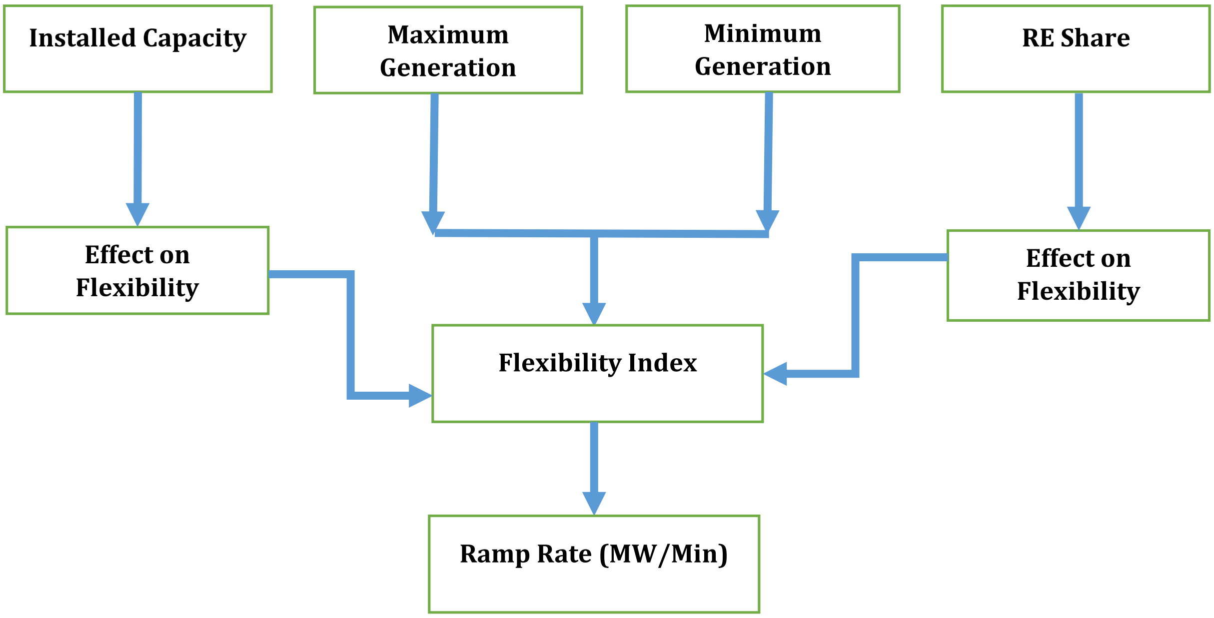

Fig. 3.1 Methodology for Flexibility Index Analysis

3.3 FLEXIBILITY INDEX ANALYSIS OF CGPL MUNDRA

Coastal Gujarat Power Limited (CGPL) is a Tata Power owned subsidiary and installed capacity of 4000 MW (800 x 5 units). This is India's first 800 MW Ultra Mega Power Project based on supercritical technology. It is a sub-bituminous coal-based power plant, the coal for the power plant is imported from Indonesia. The source of water for the power plant is seawater from Gulf of Kutch. Compared to other subcritical plants in India, It uses 1.7 million tonnes of less coal per year while generating the same quantum of energy.

For CGPL Mundra, 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week during 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 varies from 2180.00 MW to 2291.43 MW, the average schedule generation Varies from 1977.79 MW to 2280.57 MW and the actual generation varies from 1976.96 MW to 2270.85 MW. Fig.3.2 shows the declared capacity, Schedule and actual generation for CGPL Mundra. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 11.50 MW/Min and the Maximum Ramp down rate is 13.81 MW/Min. Fig. 3.3 Shows the ramp rate for CGPL Mundra.

By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.12 to 0.34. Fig. 3. 4 Shows the flexibility index for CGPL Mundra.

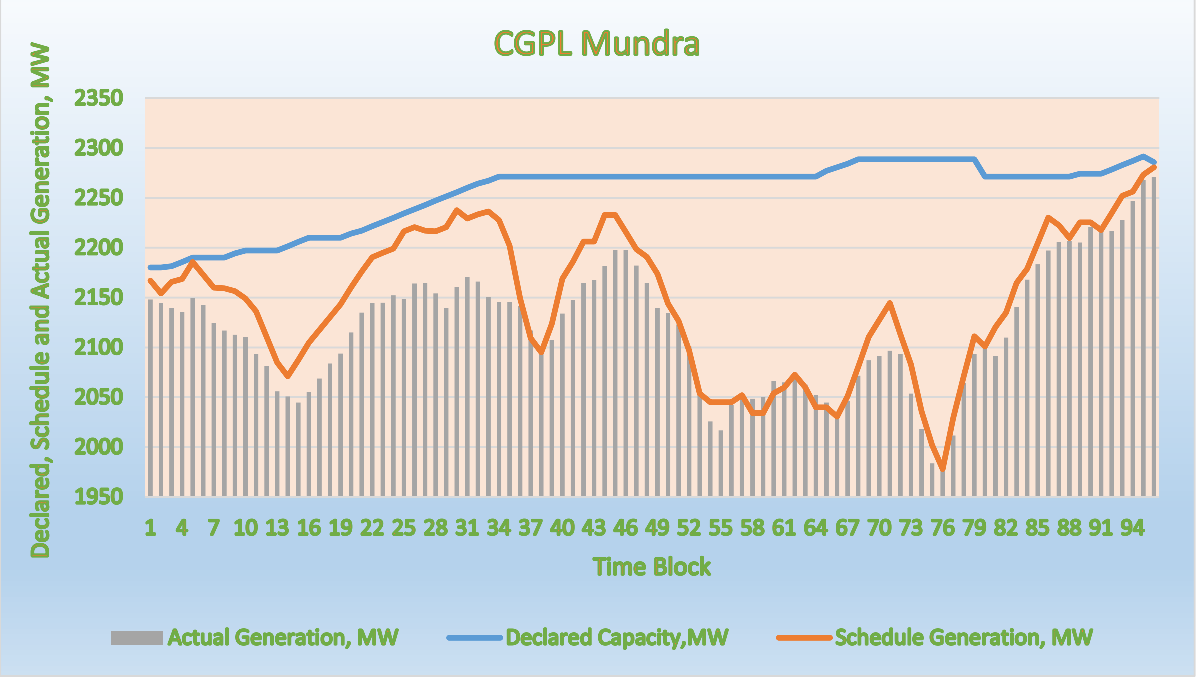

Fig. 3.2 CGPL Mundra: Declared Capacity, Schedule and Actual Generation (MW)

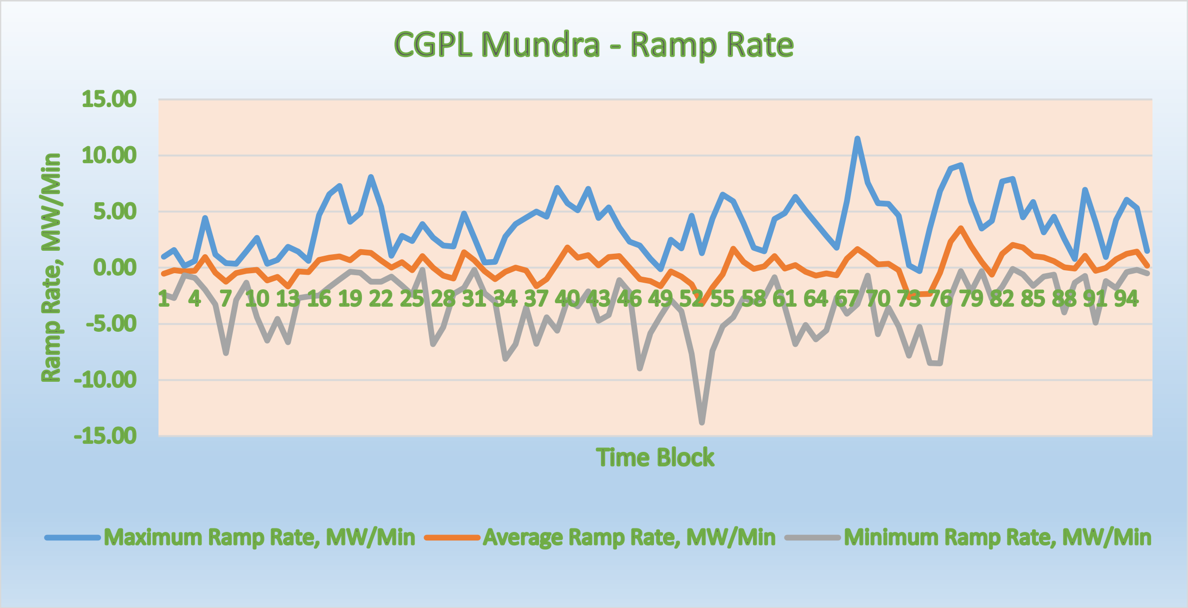

Fig. 3.3 CGPL Mundra: Ramp Rate (MW/Min)

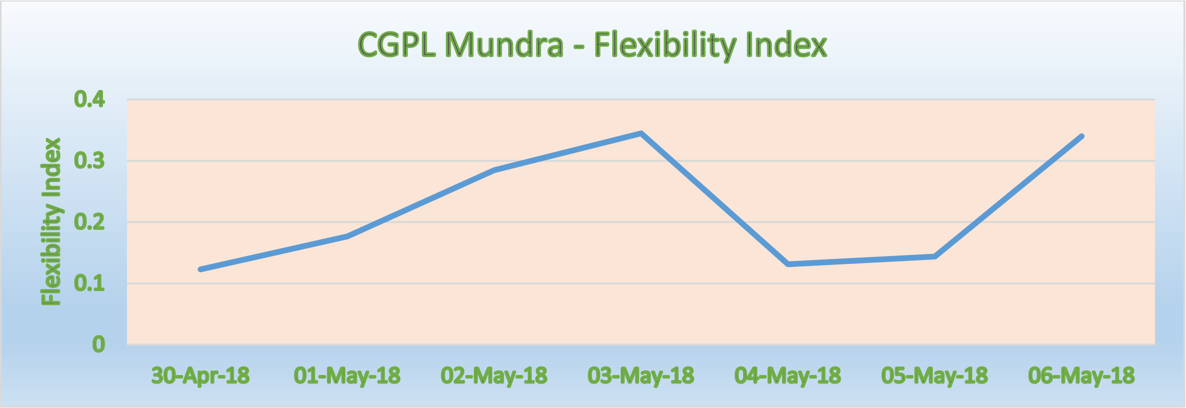

Fig. 3.4 CGPL Mundra: Flexibility Index

3.4 FLEXIBILITY INDEX ANALYSIS OF DADRI TPP

NTPC Dadri has installed capacity of 1820 MW (210 x 4 units + 490 x 2 Units). This project is installed in two stages. In 1st stage (210 x 4 Units) were installed and in 2nd stage (490 x 2 Units) were installed. The source of water for the power plant is Upper Ganga Canal and Mat Branch. The source of coal for the power plant is Piparwar Mines, Jharkhand.

3.4.1 DADRI TPP STAGE-1

For Dadri stage-1 (840 MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week during 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 is 768.6, the average schedule generation Varies from 425.40 MW to 613.05 MW and the actual generation varies from 478.44 MW to 590.613 MW. Fig.3.5 shows the declared capacity, Schedule and actual generation for Dadri Stage-1. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 7.89 MW/Min and the Maximum Ramp down rate is 6.08 MW/Min. Fig. 3.6 Shows the ramp rate for Dadri Stage-1.

By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.06 to 0.44. Fig. 3. 7 Shows the flexibility index for Dadri Stage-1.

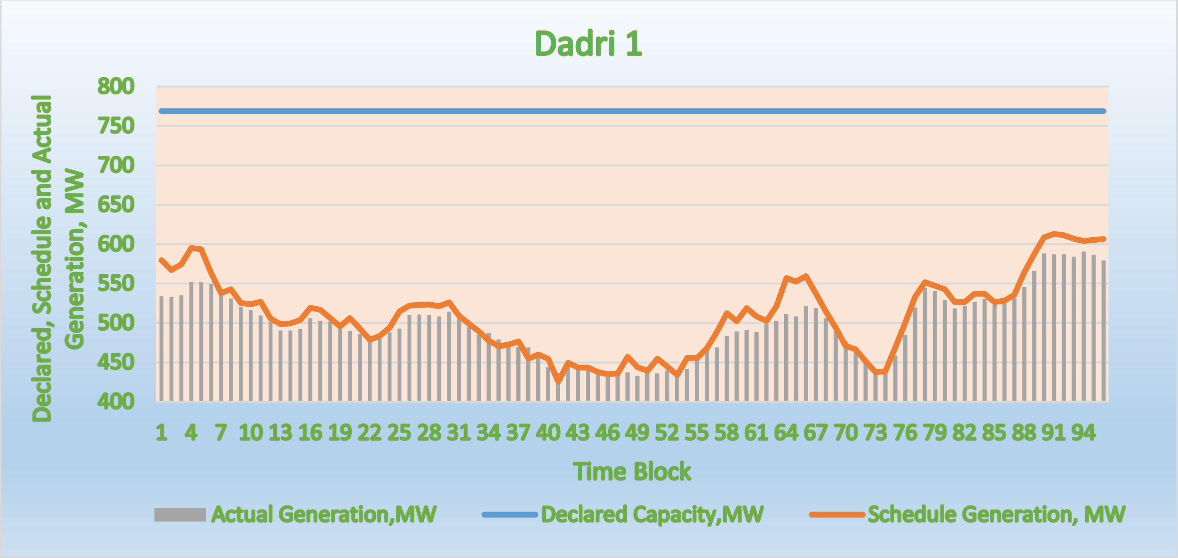

Fig. 3.5 Dadri Stage-1: Declared Capacity, Schedule and Actual Generation (MW)

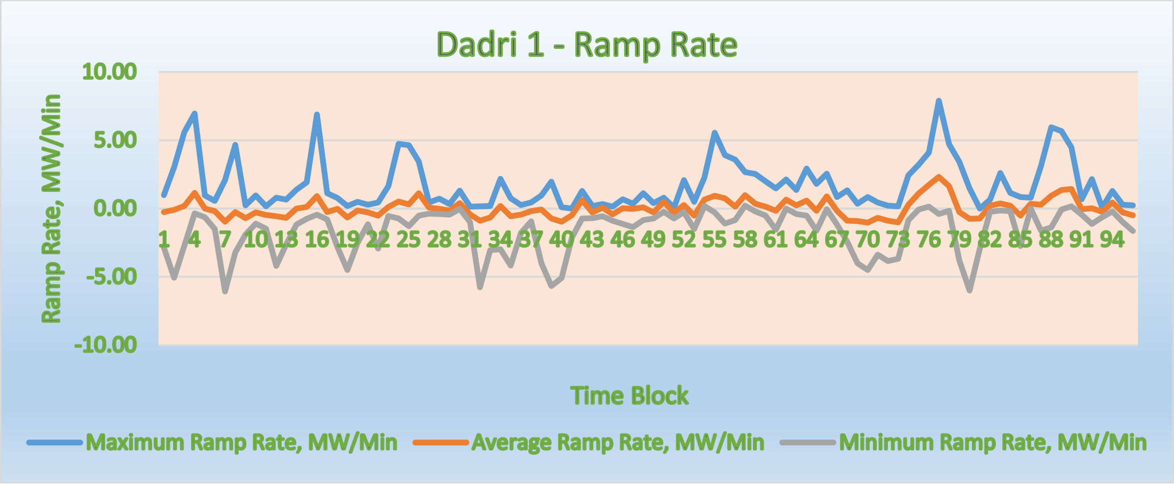

Fig. 3.6 Dadri Stage-1: Ramp Rate (MW/Min)

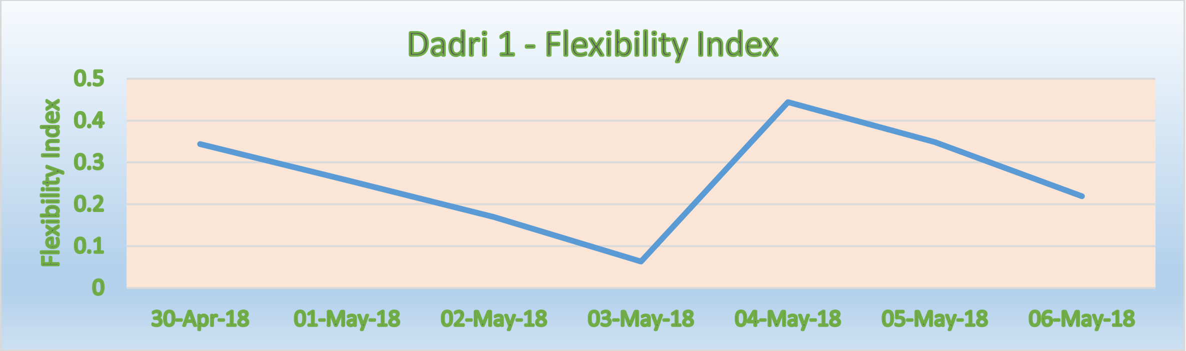

Fig. 3.7 Dadri Stage-1: Flexibility Index

3.4.2 DADRI TPP STAGE-2

For Dadri Stage-2 (980MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week during 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 varies from 862.22 MW to 928.55 MW, the average schedule generation Varies from 647.68 MW to 876.51 MW and the actual generation varies from 643.87 MW to 821.65 MW. Fig.3.8 shows the declared capacity, Schedule and actual generation for Dadri Stage-2. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 10.46 MW/Min and the Maximum Ramp down rate is 16.34 MW/Min. Fig.3. 9 Shows the ramp rate for Dadri Stage-2. By considering the actual generation, the flexibility index is also calculated for the same. The Flexibility Index varies from 0.11 to 0.55. Fig. 3. 10 shows the flexibility index for Dadri Stage-2.

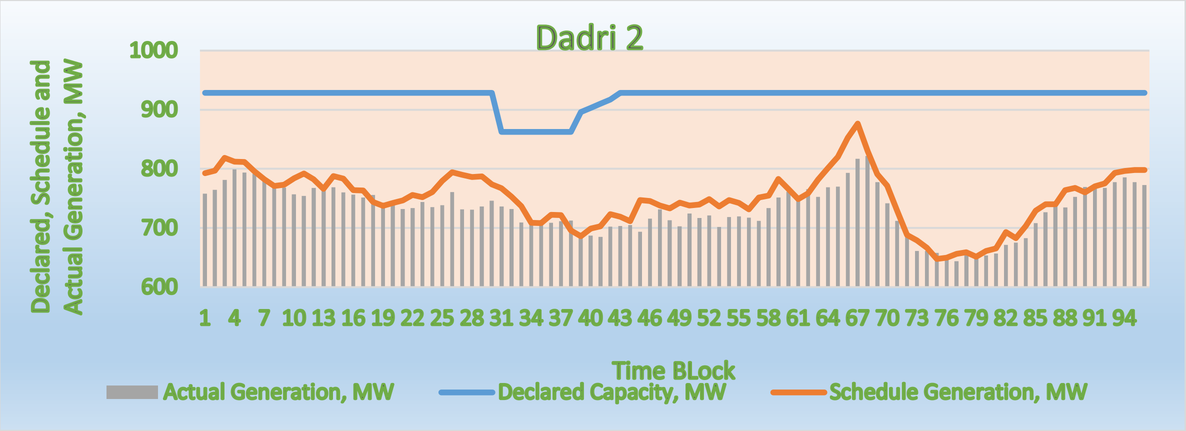

Fig. 3.8 Dadri Stage-2: Declared Capacity, Schedule and Actual Generation (MW)

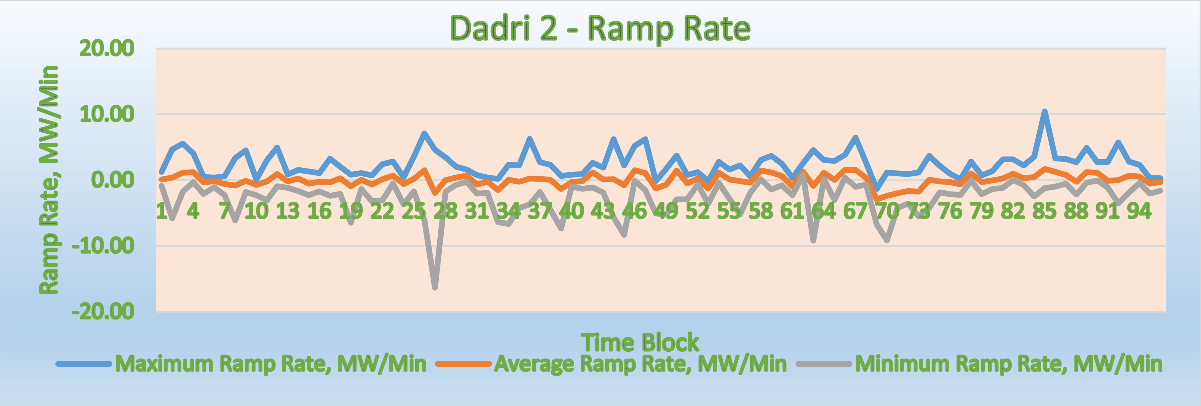

Fig. 3.9 Dadri Stage-2: Ramp Rate (MW/Min)

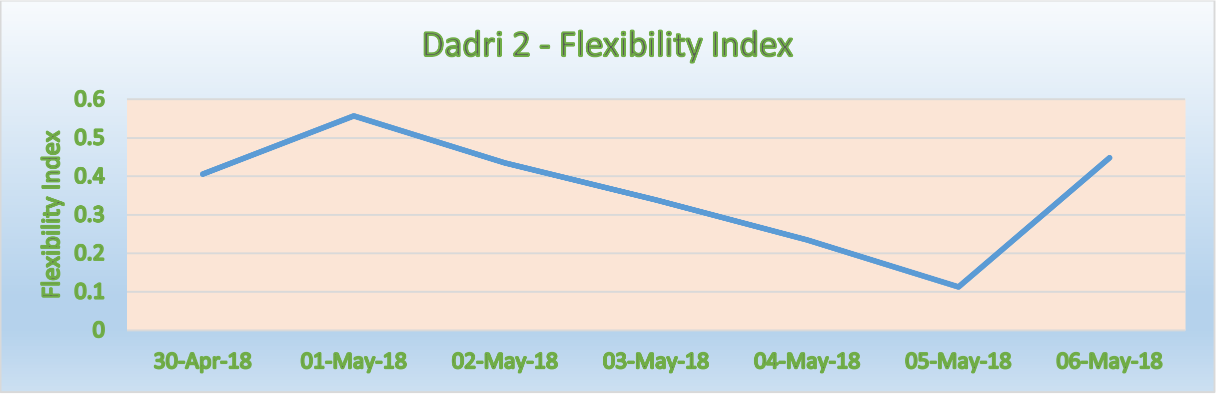

Fig. 3.10 Dadri Stage-2: Flexibility Index

3.5 FLEXIBILITY INDEX ANALYSIS OF RIHAND TPP

NTPC Rihand has installed capacity of 3000 MW (500 x 6 Units). This project is installed in three stages. In 1st stage (500 x 2 Units) were installed, in 2nd stage (500 x 2 Units) were installed and in 3rd stage (500 x 2 Units) were installed. The source of water for the power plant is Rihand reservoir. The source of coal for the power plant is Amlori mines & Dudhichua mines & Amloric Expansion mines.

3.5.1 RIHAND TPP STAGE-1

For Rihand Stage-1 (1000MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week during 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 varies from 561.96 MW to 632.32 MW, the average schedule generation Varies from 490 MW to 615.79 MW and the actual generation varies from 501 MW to 582.4 MW. Fig.3.11 shows the declared capacity, Schedule and actual generation for Rihand Stage-1. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 8.21 MW/Min and the Maximum Ramp down rate is 20.81 MW/Min. Fig. 3.12 Shows the ramp rate for Rihand Stage-1.

By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.08 to 0.60. Fig.3. 13 Shows the flexibility index for Rihand Stage-1.

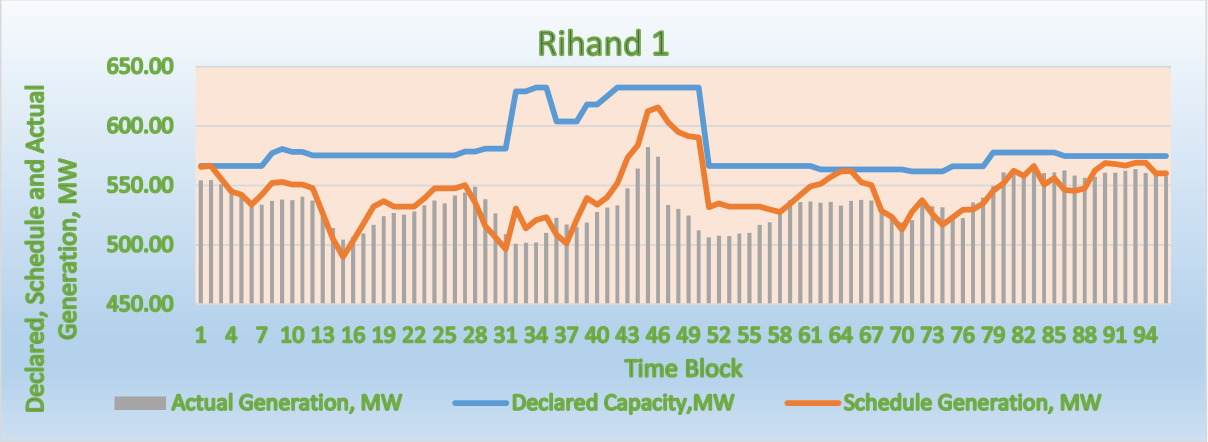

Fig. 3.11 Rihand Stage-1: Declared Capacity, Schedule and Actual Generation (MW)

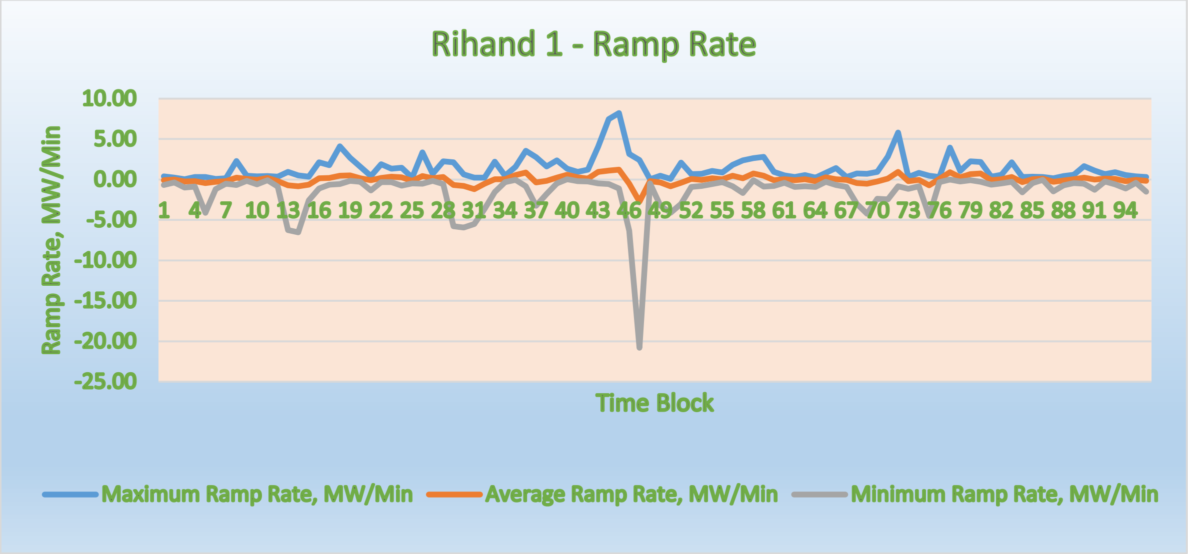

Fig. 3.12 Rihand Stage-1: Ramp Rate (MW/Min)

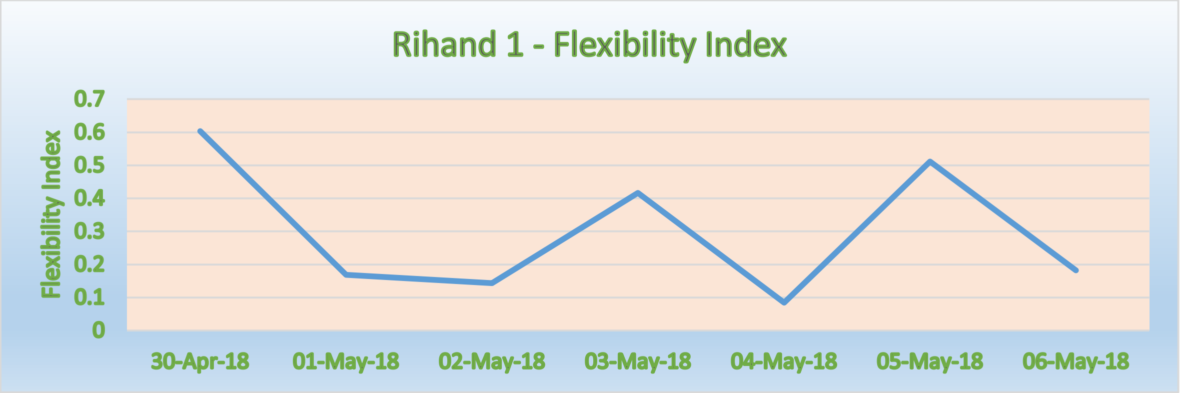

Fig. 3.13 Rihand Stage-1: Flexibility Index

3.5.2 RIHAND TPP STAGE-2

For Rihand Stage-2 (1000 MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week during 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 is 942.5, the average schedule generation Varies from 792.01 MW to 939.26 MW and the actual generation varies from 822.03 MW to 949.04 MW. Fig.3.14 shows the declared capacity, Schedule and actual generation for Rihand Stage-2. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 6.82 MW/Min and the Maximum Ramp down rate is 9.59 MW/Min. Fig. 3.15 Shows the ramp rate for Rihand Stage-2.

By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.07 to 0.61. Fig.3. 16 Shows the flexibility index for Rihand Stage-2.

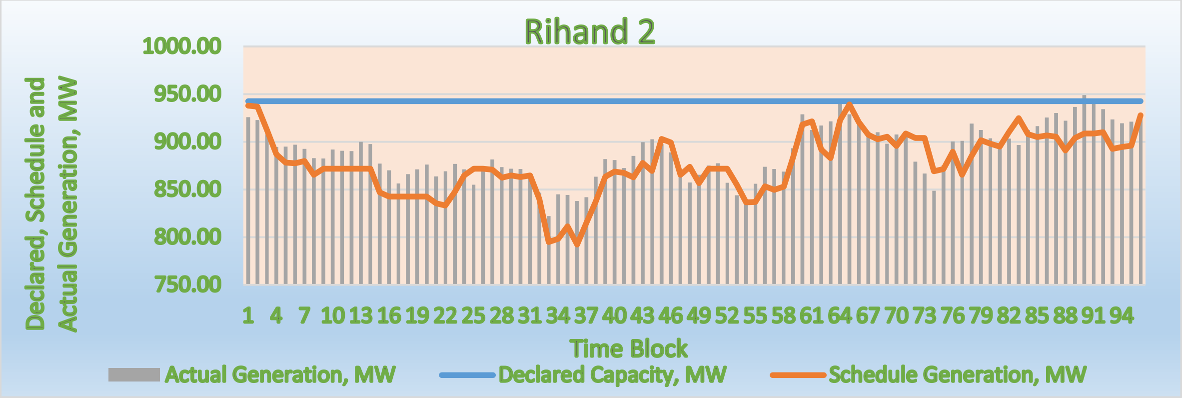

Fig. 3.14 Rihand Stage-2: Declared Capacity, Schedule and Actual Generation (MW)

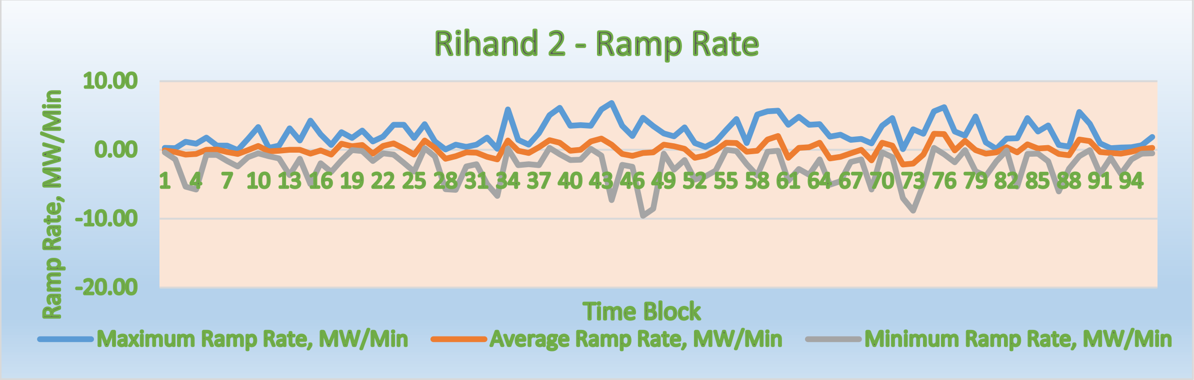

Fig. 3.15 Rihand Stage-2: Ramp Rate (MW/Min)

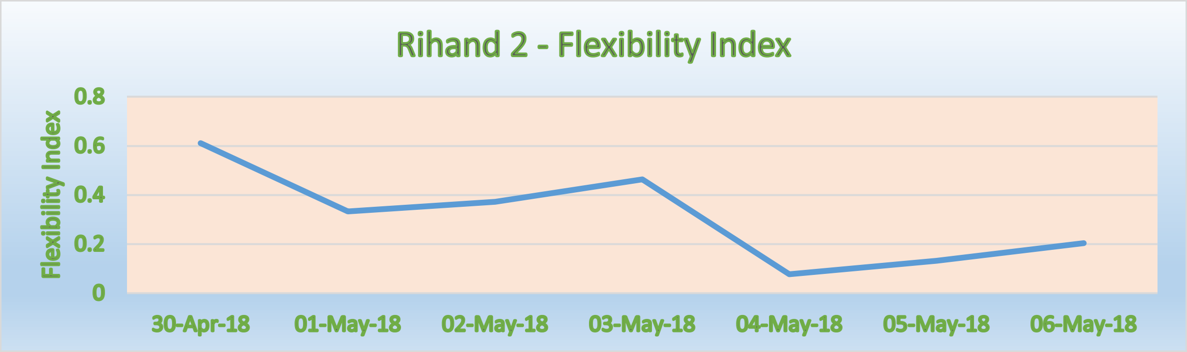

Fig. 3.16 Rihand Stage-2: Flexibility Index

3.5.3 RIHAND TPP STAGE-3

For Rihand Stage-3 (1000 MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week during 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 is 942.5 MW, the average schedule generation Varies from 763.67 MW to 925.16 MW and the actual generation varies from 830.54 MW to 930.5 MW. Fig.3.17 shows the declared capacity, Schedule and actual generation for Rihand Stage-3. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 7.09 MW/Min and the Maximum Ramp down rate is 5.99 MW/Min. Fig. 3.18 Shows the ramp rate for Rihand Stage-3.

By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.02 to 0.32. Fig.3. 19 Shows the flexibility index for Rihand Stage-3.

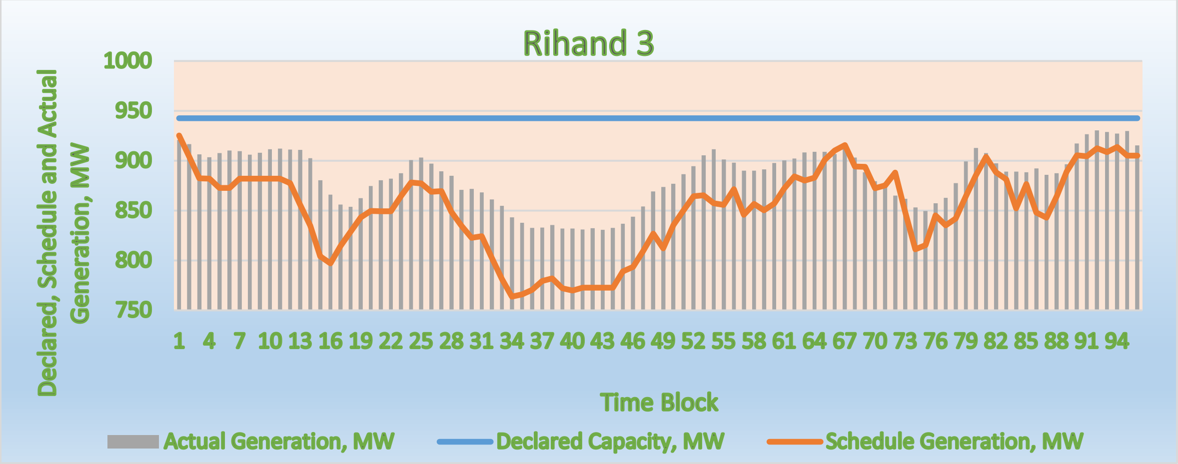

Fig. 3.17 Rihand Stage-3: Declared Capacity, Schedule and Actual Generation (MW)

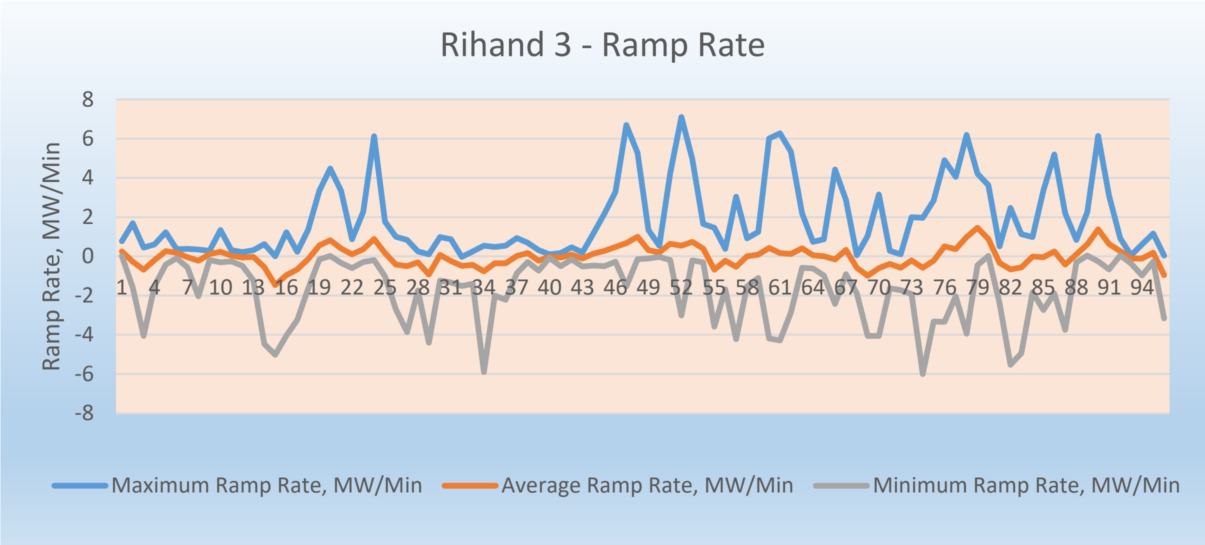

Fig. 3.18 Rihand Stage-3: Ramp Rate (MW/Min)

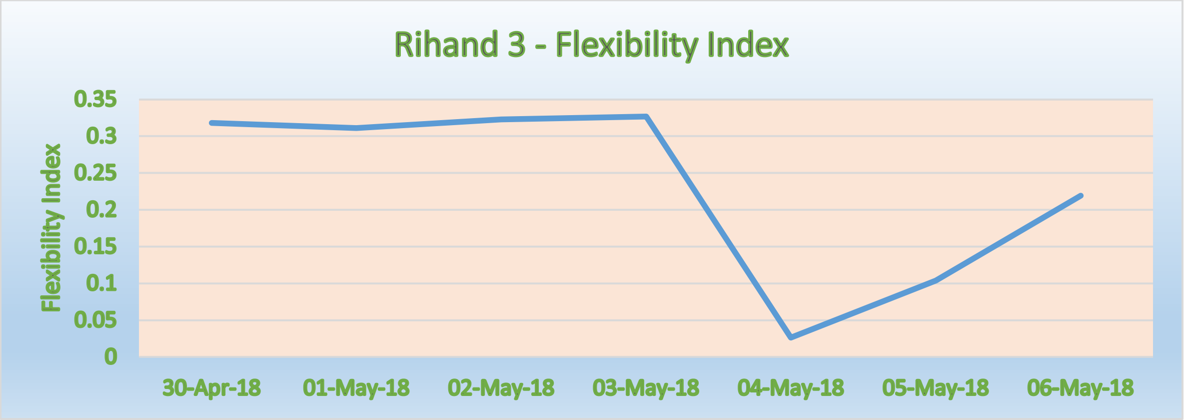

Fig.3.19 Rihand Stage-3: Flexibility Index

3.6 FLEXIBILITY INDEX ANALYSIS OF SASAN UMPP

Sasan Ultra mega power project is operated by Sasan power ltd. a wholly owned subsidiary of Reliance Power. Sasan UMPP has installed capacity of 3960 MW (660 x 6 Units). Sasan UMPP is a pit-head power project and has been allocated three captive coal mine blocks – Moher, Moher Amlori extension, and Chhatrasal.

For Sasan (3960 MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week during 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 varies from 3690.343 MW to 3695.686 MW, the average schedule generation Varies from 3418.3 MW to 3695.68 MW and the actual generation varies from 3444.057 MW to 3806.893 MW. Fig.3.20 shows the declared capacity, Schedule and actual generation for Sasan UMPP. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 19.87 MW/Min and the Maximum Ramp down rate is 16.85 MW/Min. Fig. 3.21 Shows the ramp rate for Sasan UMPP. By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.03 to 0.36. Fig.3. 22 Shows the flexibility index for Sasan UMPP.

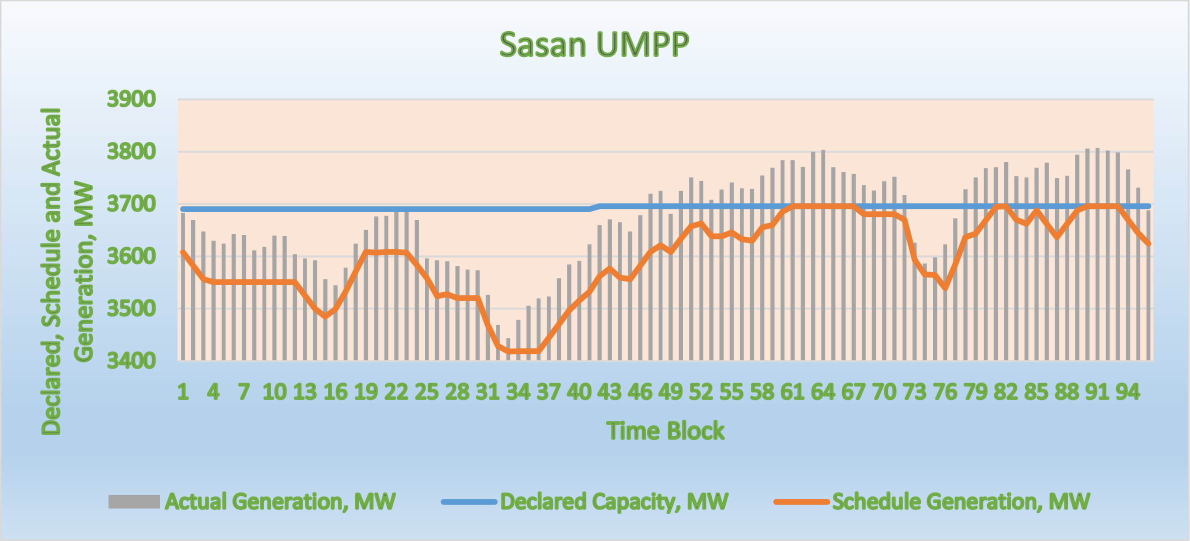

Fig.3.20 Sasan UMPP Declared Capacity, Schedule and Actual Generation (MW)

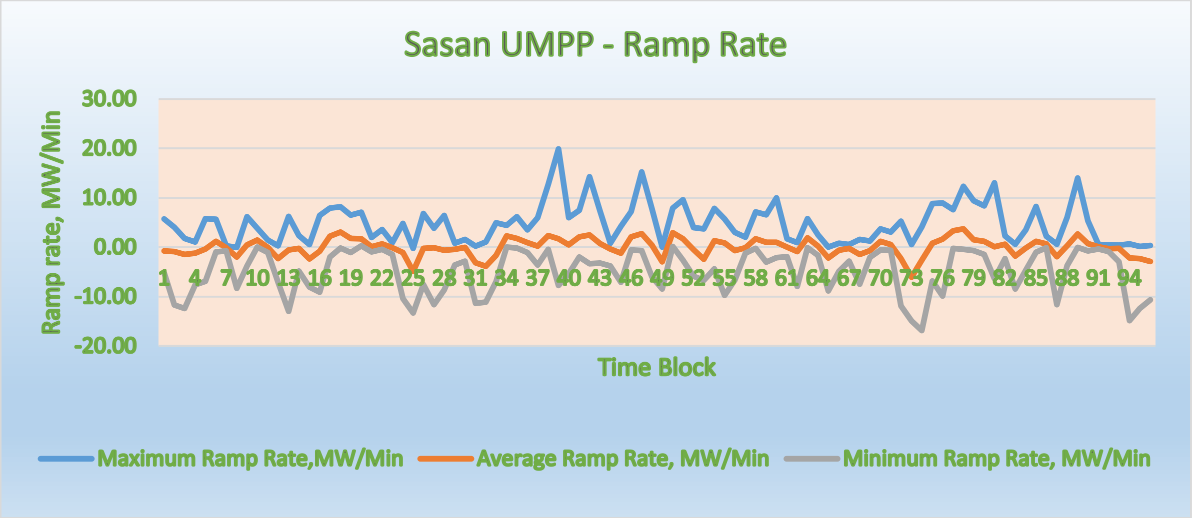

Fig.3.21 Sasan UMPP Ramp Rate (MW/Min)

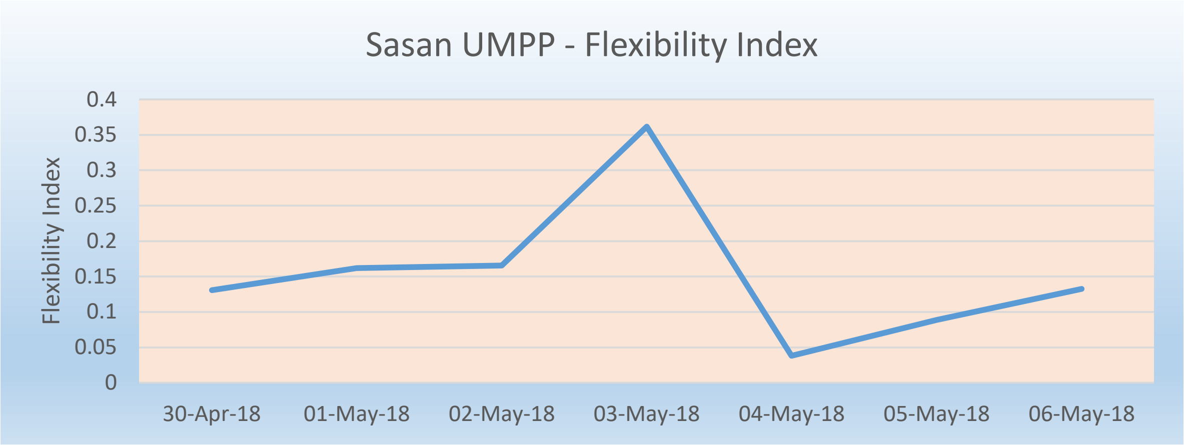

Fig. 3.22 Sasan UMPP Flexibility Index

3.7 FLEXIBILITY INDEX ANALYSIS OF VSTPS

NTPC Vindhyachal super thermal power station has installed capacity of 4760 MW (210 x 6 units + 500 x 2 Units + 500 x 2 Units + 500 x 2 Units + 500 x 1 unit). This project is installed in five stages. In 1st stage (210 x 6 Units) were installed, in 2nd stage (500 x 2 Units) were installed, in 3rd stage (500 x 2 Units) were installed, in 4th stage (500 x 2 Units) were installed and in 5th stage (500 x 1 Unit) were installed. The source of water for the power plant is Discharge canal of Singrauli Super Thermal Power Station. The source of coal for the power plant is Nigahi mines.

3.7.1 VSTPS STAGE-1

For VSTPS Stage-1 (1260 MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week from 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 varies from 900.00 MW to 910.741 MW, the average schedule generation Varies from 758.71 MW to 885.71 MW and the actual generation varies from 761.88 MW to 887.42 MW. Fig.3.23 shows the declared capacity, Schedule and actual generation for VSTPS Stage-1. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 8.85 MW/Min and the Maximum Ramp down rate is 9.98 MW/Min. Fig. 3.24 Shows the ramp rate for VSTPS Stage-1. By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.03 to 0.4. Fig.3. 25 Shows the flexibility index for VSTPS Stage-1.

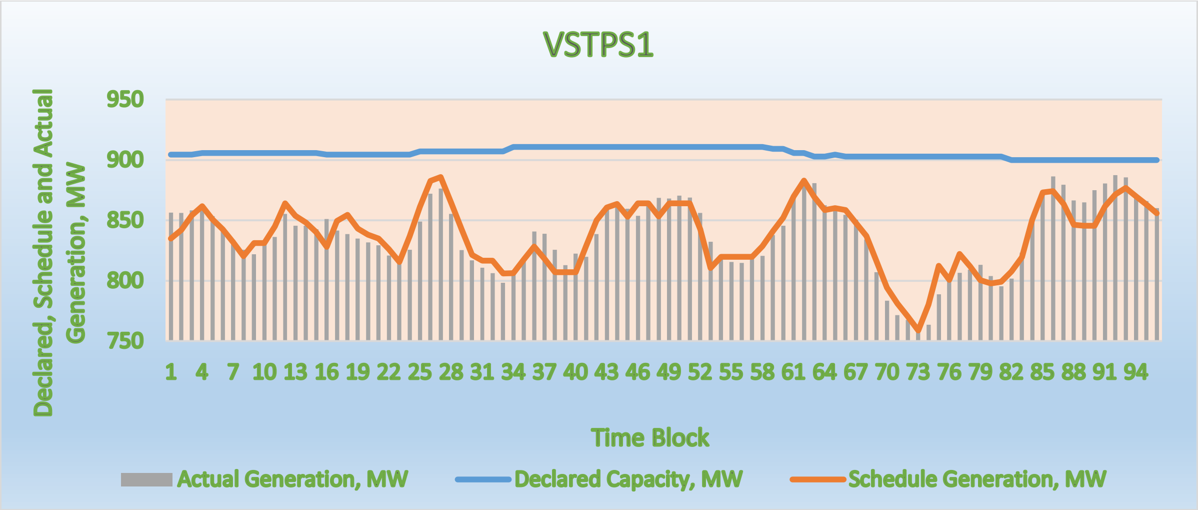

Fig. 3.23 VSTPS Stage-1: Declared Capacity, Schedule and Actual Generation (MW)

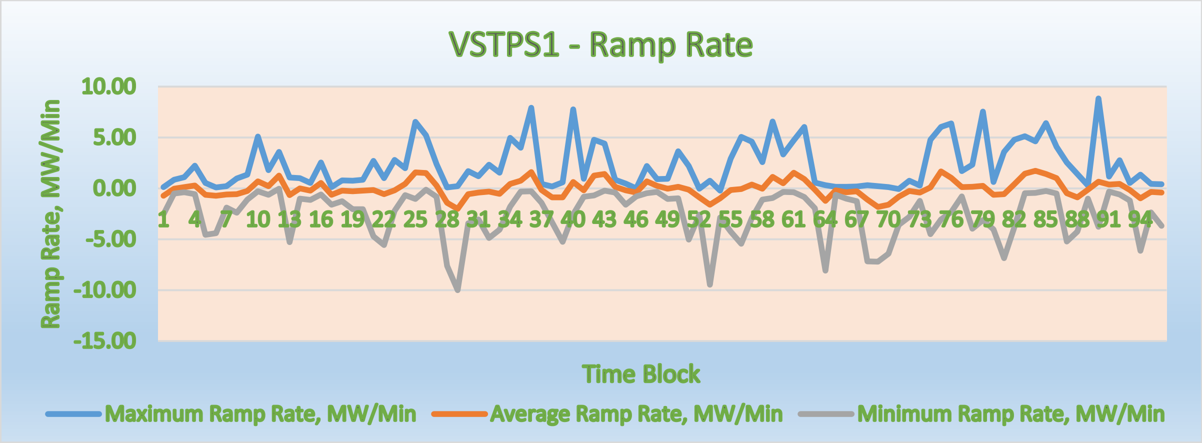

Fig. 3.24 VSTPS Stage-1: Ramp Rate (MW/Min)

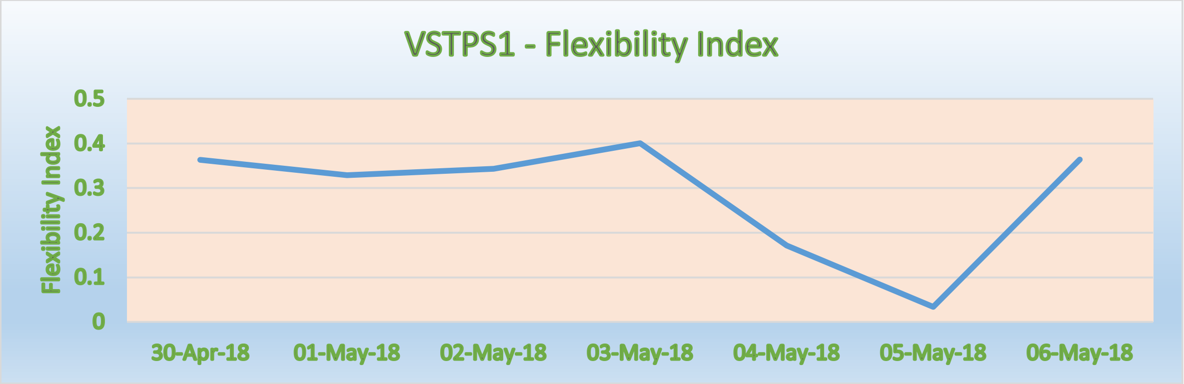

Fig. 3.25 VSTPS Stage-1: Flexibility Index

3.7.2 VSTPS STAGE-2

For VSTPS Stage-2 (1000 MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week from 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 varies from 935.35 MW to 942.5 MW, the average schedule generation Varies from 854.47 MW to 938.57 MW and the actual generation varies from 832.80 MW to 942.60 MW. Fig.3.26 shows the declared capacity, Schedule and actual generation for VSTPS Stage-2. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 7.77 MW/Min and the Maximum Ramp down rate is 8.93 MW/Min. Fig. 3.27 Shows the ramp rate for VSTPS Stage-2. By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.023 to 0.38. Fig.3. 28 Shows the flexibility index for VSTPS Stage-2.

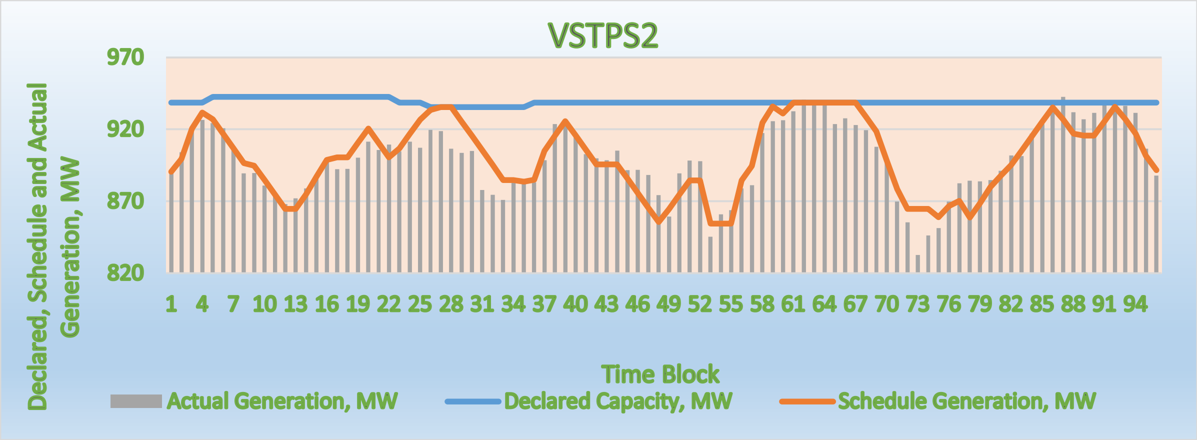

Fig. 3.26 VSTPS Stage-2: Declared Capacity, Schedule and Actual Generation (MW)

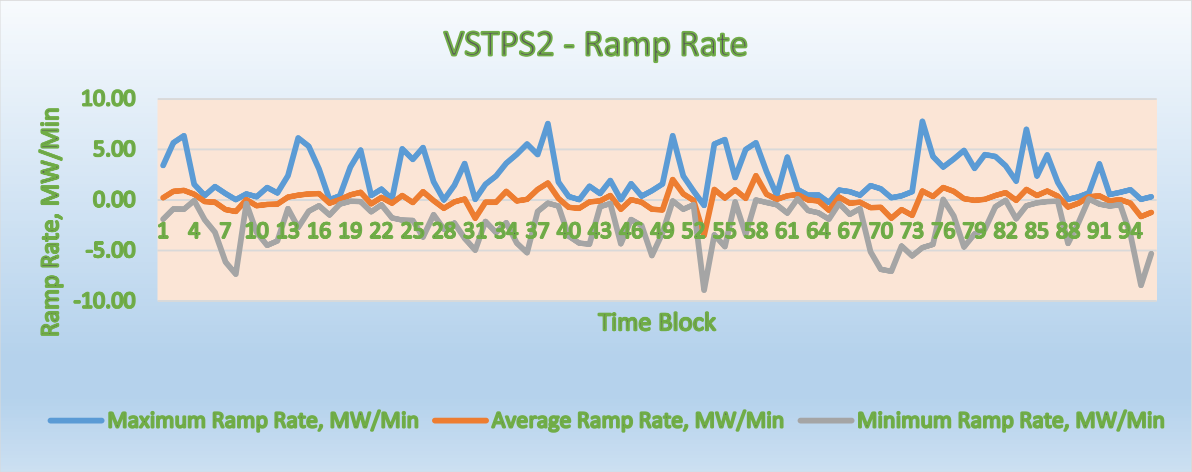

Fig. 3.27 VSTPS Stage-2: Ramp Rate (MW/Min)

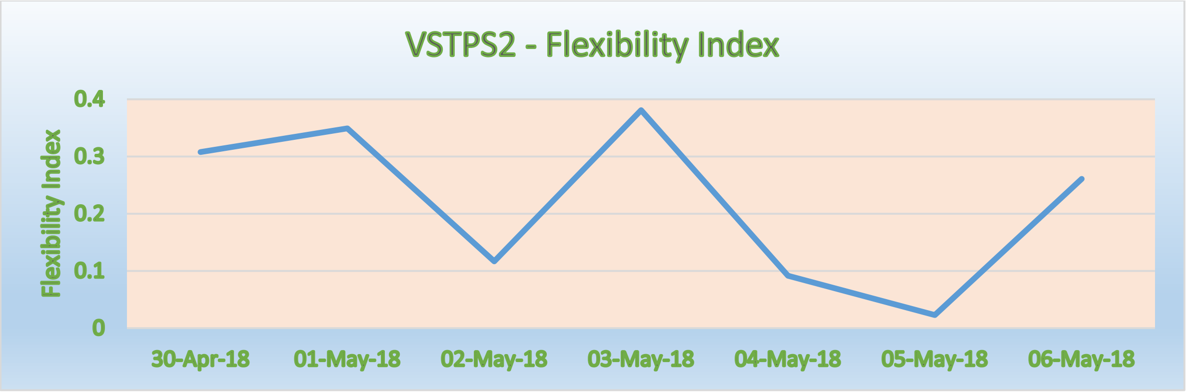

Fig. 3.28 VSTPS Stage-2: Flexibility Index

3.7.3 VSTPS STAGE-3

For VSTPS Stage-3 (1000 MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week from 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 varies from 882.14 MW to 942.5 MW, the average schedule generation Varies from 814 MW to 942.5 MW and the actual generation varies from 804.43 MW to 960.71 MW. Fig.3.29 shows the declared capacity, Schedule and actual generation for VSTPS Stage-3. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 8.66 MW/Min and the Maximum Ramp down rate is 10.14 MW/Min. Fig. 3.30 Shows the ramp rate for VSTPS Stage-3. By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.02 to 0.49. Fig.3. 31 Shows the flexibility index for VSTPS Stage-3.

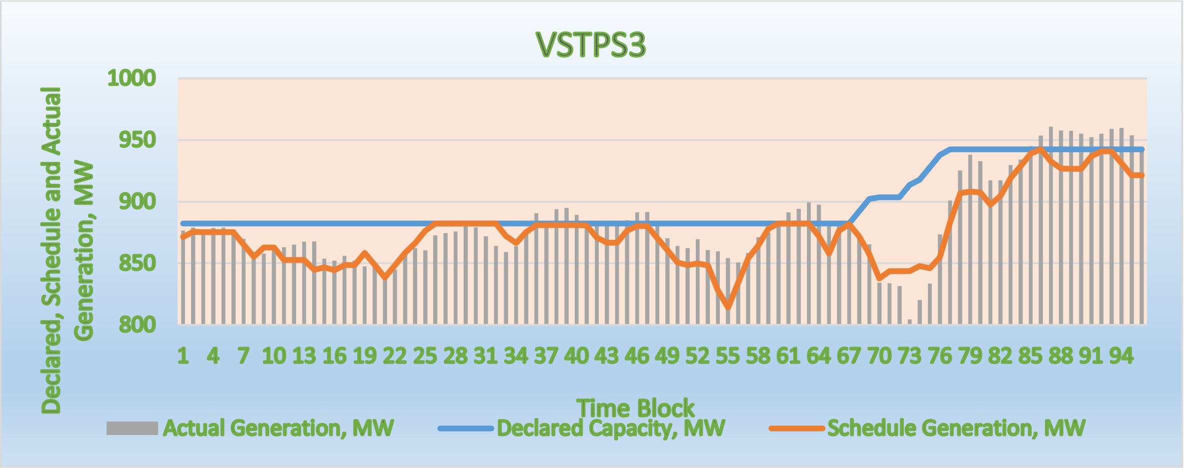

Fig. 3.29 VSTPS Stage-3: Declared Capacity, Schedule and Actual Generation (MW)

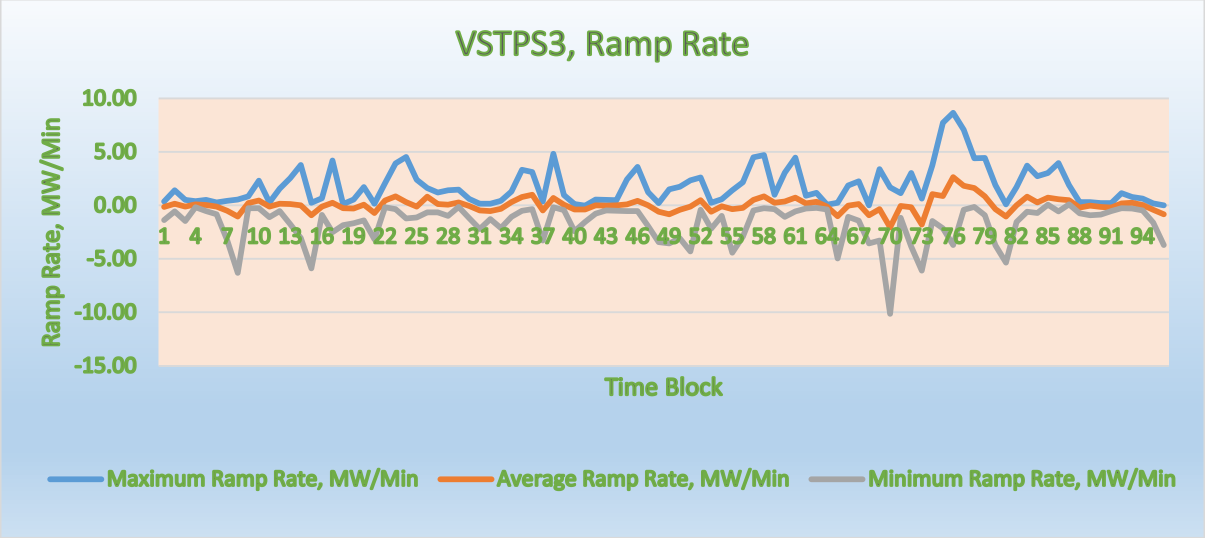

Fig. 3.30 VSTPS Stage-3: Ramp Rate (MW/Min)

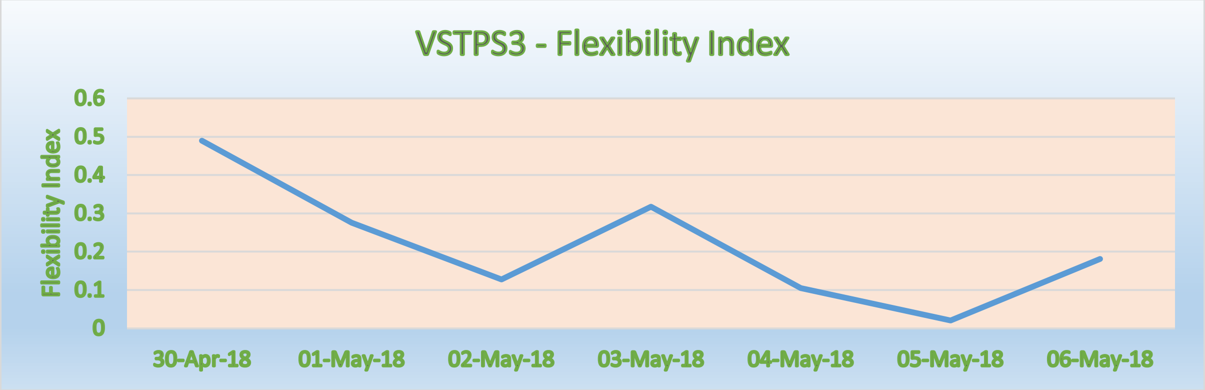

Fig. 3.31 VSTPS Stage-3: Flexibility Index

3.7.4 VSTPS STAGE-4

For VSTPS Stage-4 (1000 MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week during 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 is 942.5 MW, the average schedule generation Varies from 869.48 MW to 942.5 MW and the actual generation varies from 855.56 MW to 954.68 MW. Fig.3.32 shows the declared capacity, Schedule and actual generation for VSTPS Stage-4. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 9.10 MW/Min and the Maximum Ramp down rate is 6.28 MW/Min. Fig. 3.33 Shows the ramp rate for VSTPS Stage-4. By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.024 to 0.36. Fig.3. 34 Shows the flexibility index for VSTPS Stage-4.

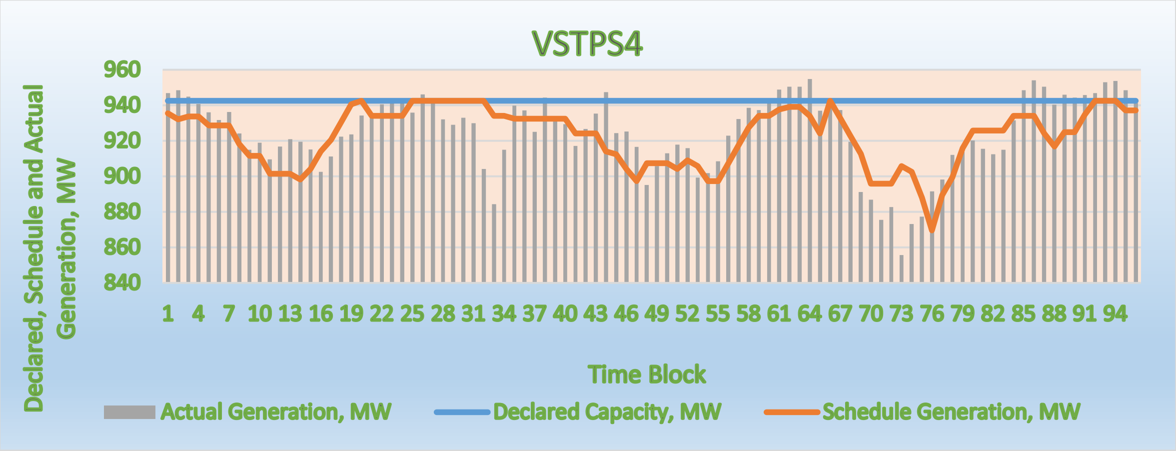

Fig. 3.32 VSTPS Stage-4: Declared Capacity, Schedule and Actual Generation (MW)

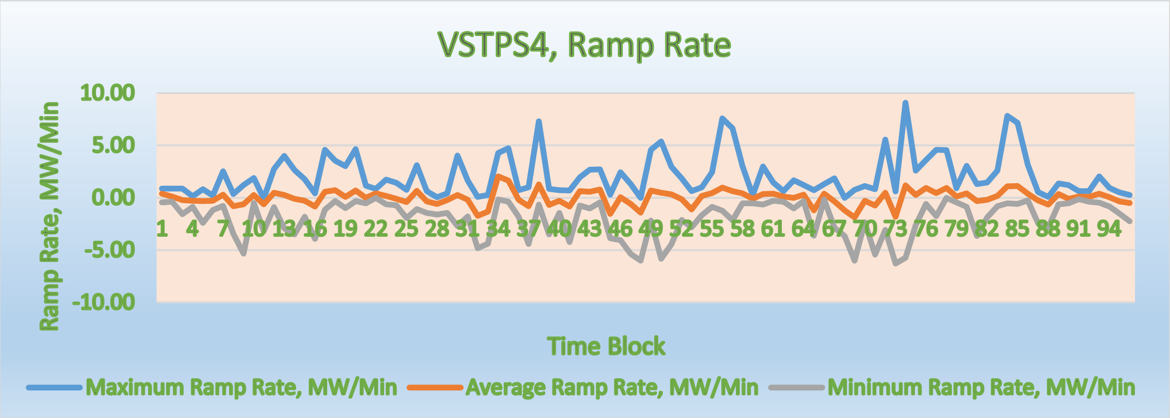

Fig. 3.33 VSTPS Stage-4: Ramp Rate (MW/Min)

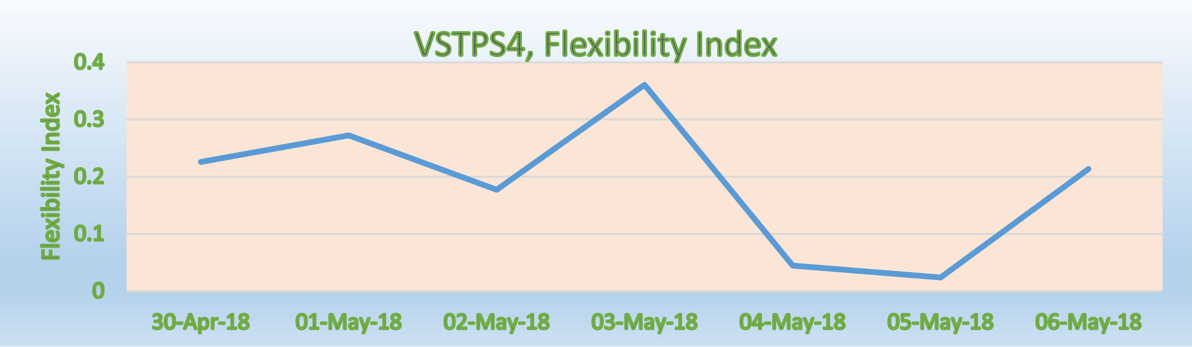

Fig. 3.34 VSTPS Stage-4: Flexibility Index

3.7.5 VSTPS STAGE-5

For VSTPS Stage-5 (500 MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week during 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 is 471.25 MW, the average schedule generation Varies from 401.84 MW to 465.83 MW and the actual generation varies from 380 MW to 477.75 MW. Fig.3.35 shows the declared capacity, Schedule and actual generation for VSTPS Stage-5. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 5.02 MW/Min and the Maximum Ramp down rate is 6.42 MW/Min. Fig. 3.36 Shows the ramp rate for VSTPS Stage-5. By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.04 to 0.43. Fig.3. 37 Shows the flexibility index for VSTPS Stage-5.

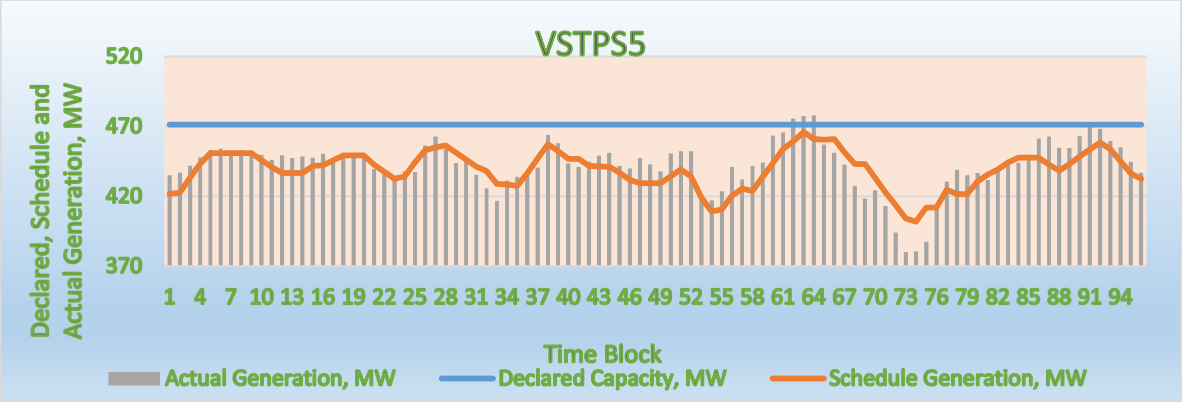

Fig. 3.35 VSTPS Stage-5: Declared Capacity, Schedule and Actual Generation (MW)

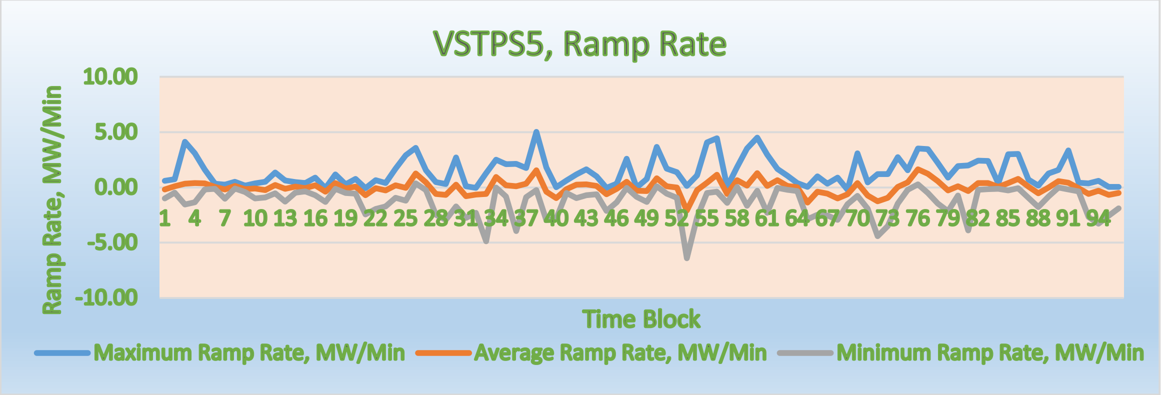

Fig. 3.36 VSTPS Stage-5: Ramp Rate (MW/Min)

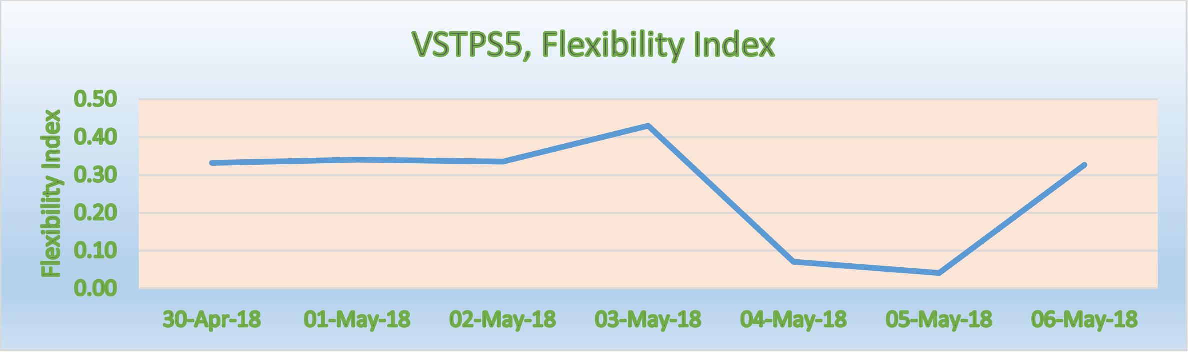

Fig. 3.37 VSTPS Stage-5: Flexibility Index

3.8 FLEXIBILITY INDEX ANALYSIS OF SINGRAULI STPS

NTPC Singrauli super thermal power station has installed capacity of 2000 MW (200 x 5 units + 500 x 2 Units). This project is installed in two stages. In 1st stage (200 x 5 Units) were installed and in 2nd stage (500 x 2 Units) were installed. The source of water for the power plant is Rihand Reservoir. The source of coal for the power plant is Jayant/Bina Mines.

For Singrauli (2000 MW), 15 minute basis (96 Block in 24 Hrs.) analysis had been performed for one week during 30th April 2018 to 6th May 2018 and from this analysis we found that the average declared capacity during 30th April 2018 to 6th may 2018 varies from 1177.143 MW to 1252.85 MW, the average schedule generation Varies from 1054.42 MW to 1237.58 MW and the actual generation varies from 1067.12 MW to 1227.25 MW. Fig.3.38 shows the declared capacity, Schedule and actual generation for Singrauli. On the basis of actual generation, Ramp Up/Down Rate is calculated. The Maximum Ramp up Rate is 10.30 MW/Min and the Maximum Ramp down rate is 12.47 MW/Min. Fig. 3.39 Shows the ramp rate for Singrauli.

By considering the actual generation, the flexibility Index is also calculated for the same. The Flexibility Index varies from 0.037 to 0.354. Fig.3. 40 Shows the flexibility index for Singrauli STPS.

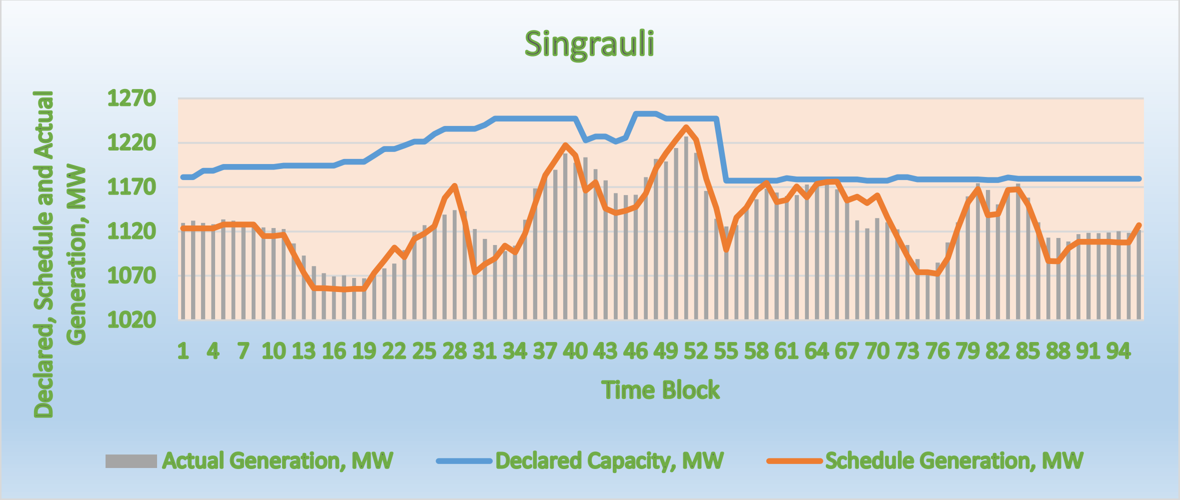

Fig. 3.38 Singrauli: Declared Capacity, Schedule and Actual Generation (MW)

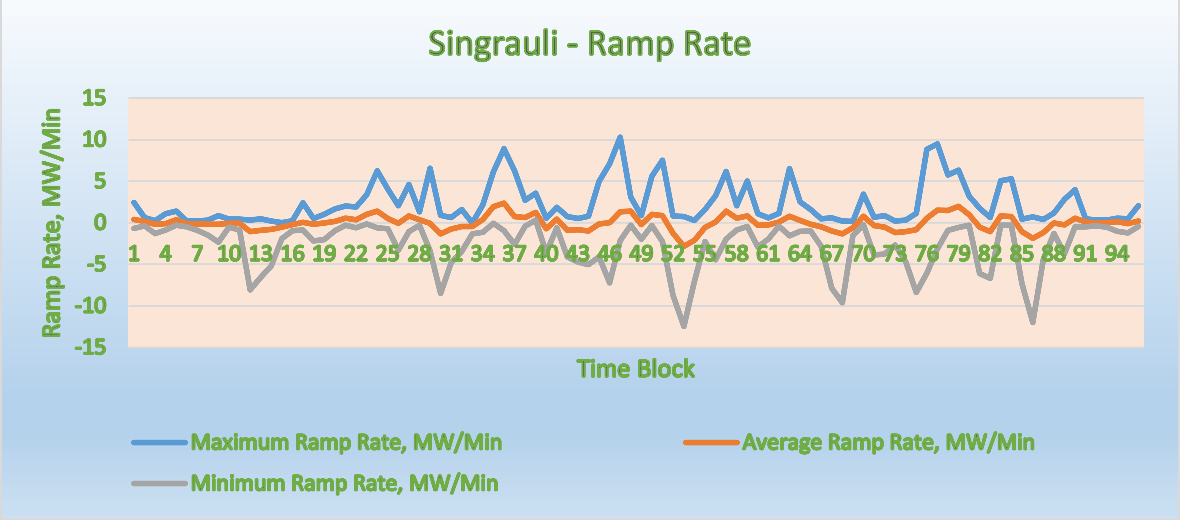

Fig. 3.39 Singrauli: Ramp Rate (MW/Min)

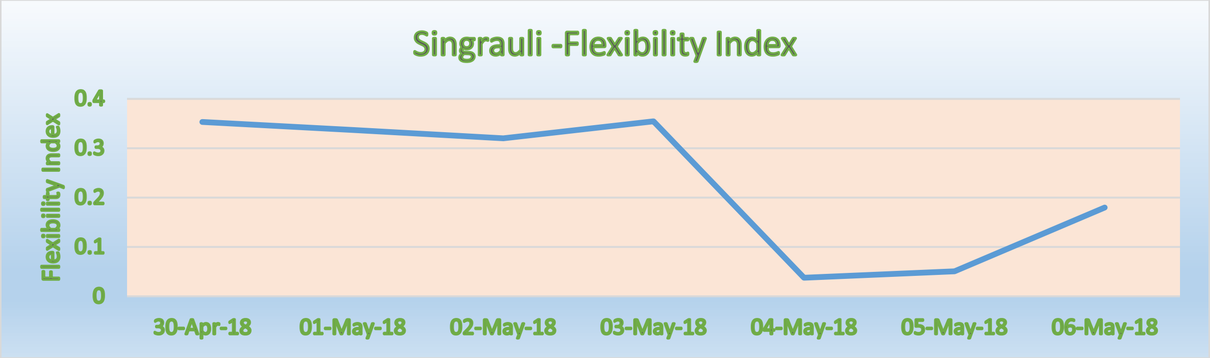

Fig. 3.40 Singrauli: Flexibility Index

CHAPTER 4

RETROFIT REQUIREMENT TO INCREASE FLEXIBILITY

4.1 RETROFIT

Retrofit is defined as a modernization or up gradation of power plant components or subsystems. Retrofit is performed as part of a major overhaul and it requires a power plant to be a standstill for multiple weeks depending upon the installed capacity of the power plant. Retrofits of Thermal power plants are done for various reasons, such as extending the lifetime of the components, improving plant efficiency and increasing flexibility.

4.2 MAJOR COMPONENTS FOR RETROFITS

To get a better understanding of coal-based power plant operation, it is useful to look at its subsystems. Fig 4.1 shows a schematic view of a coal-based power plant which is divided into 20 subsystems. Each subsystem fulfills a crucial role in the power plant. Research has shown that retrofits on the following subsystems are the most effective means for increasing coal-based power plant flexibility:

3 - Control and communication system

Control and communication system is the operating system of the power plant and it consists of all components for control and communication between other subsystems. It enables the control of the temperature and pressure inside the boiler.

5 – Oil and fuel supply for ignition

To initiate coal combustion, the air volume inside of the boiler needs to be brought to a certain pressure and temperature. This is generally achieved by burning auxiliary fuels, such as oil or gas. This subsystem plays a vital role during the start-up of coal-based power plants.

8 – Boiler

The main task of the boiler is to convert feed water into steam. Therefore, it also known as the steam generator. Nowadays, steam is generally generated in a single-pass using once through boiler.

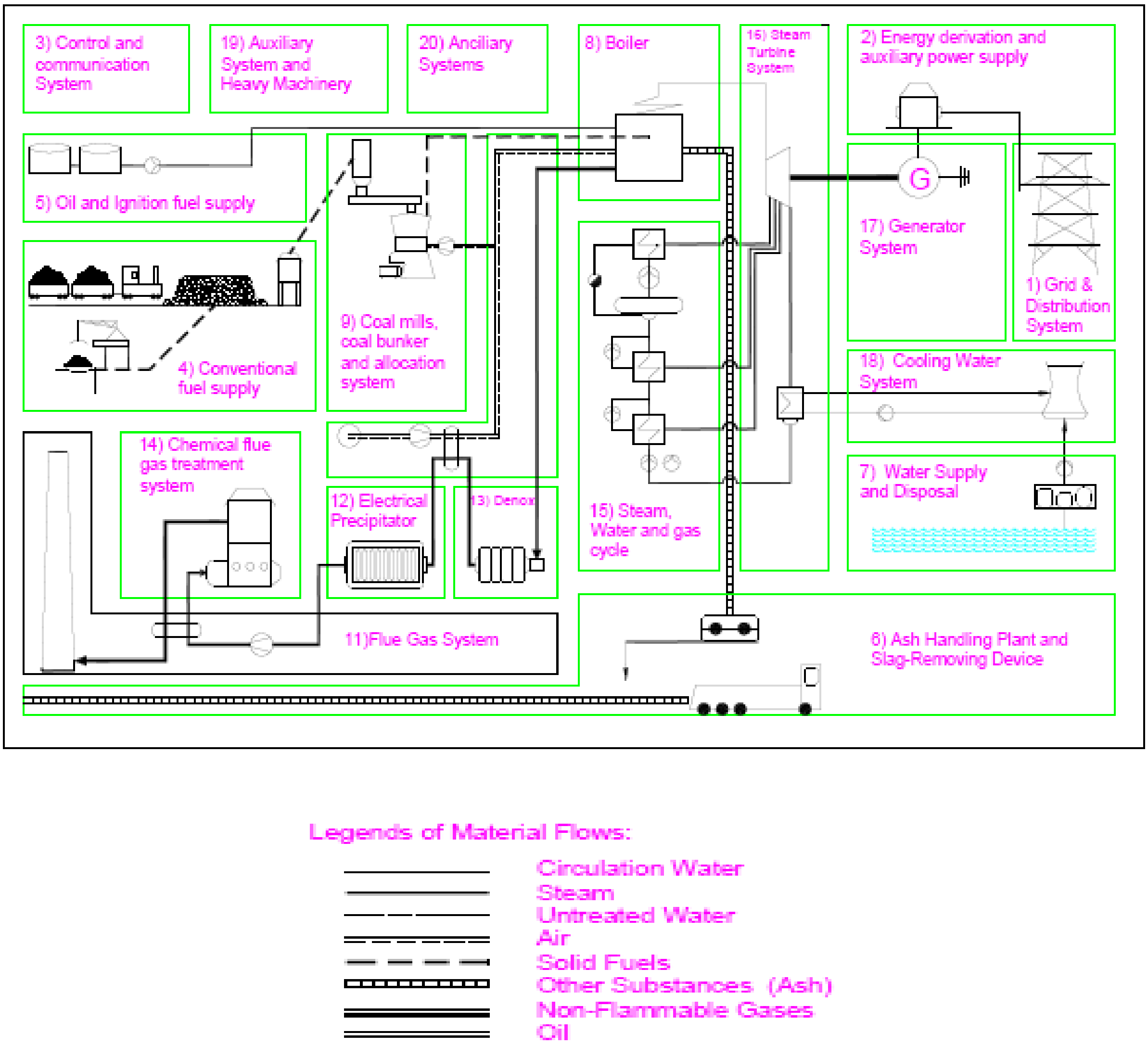

Fig: 4.1 Subsystems in a coal-based Thermal Power Station

9 – Coal mills, coal bunker and allocation system

In this subsystem, the raw coal is milled into pulverized coal (PC). For lignite-fired power plants, the coal is milled by using beater-wheel mills and dried with hot flue gas (up to 1,000 °C). For hard coal-fired power plants, the vertical roller or bowl mill is used to produce pulverized coal. Since the water content of hard coal (2–7 %) is significantly lower than lignite (45–60 %), the drying process of hard coal consumes less energy. For drying of hard coal, a hot air stream is sufficient enough to drive out remaining water. After the milling process, coal dust is blown into the boiler. In general, tube mills are more flexible than beater wheel mills.

15 - Steam, water and gas cycle

Steam, water and gas cycle is closely linked with the boiler and the steam turbine. Its main function is to pre-heat feed water before the feed water enters the boiler it is preheated by different heat exchangers. Generally, this is accomplished by extracting hot steam from the steam turbine and cooling it in the heat exchangers. The temperature of the feed water increases as it flows through the heat exchangers. Pre-heating the feed water is an important process in optimizing power plant efficiency.

16 - Steam turbine

The steam turbine converts pressure energy and thermal energy into mechanical energy. Unlike gas turbines, which rotate in a hot flue gas flow, steam turbines rotate in vaporized water. In large power plants, steam turbine systems contain high-pressure, intermediate-pressure and low-pressure sections. The steam turbine is mounted on a common shaft connected to the generator, which transforms mechanical energy into electrical energy.

4.3 OPTIONS TO DECREASE MINIMUM LOAD

Decreasing minimum load of a coal-based thermal power plant is beneficial because it provides a larger range of generation capacity. By decreasing the minimum load of a coal-based plant, operators can maintain operation when power demand is low and eliminates expensive start-up and shutdown procedures [34]. Reducing the minimum load of coal-based power plants allows a greater penetration of renewables by avoiding potential RE curtailment [35]. Reducing the minimum load of coal-based power plants has certain technical limitations, these limitations are fire stability, flame control, ignition, unburned coal and carbon monoxide emissions.

Fire instability can occur for various reasons, such as sudden changes in firing rate or fuel quality, improper air-fuel ratios or uneven flows of pulverized coal. In low load operations, if the hot flue gases do not completely ignite the inflowing pulverized coal it can result in fire instability. Under those circumstances, the minimum load of a coal power plants with dry ash removal is limited to 25–40 % of Pnom. For slag-tap firing systems, as the temperature required to maintain the flow of liquid ash is higher the minimum load is around 40 % of Pnom. For lignite-fired power plants, the minimum load is between 40–50 % as lignite must be dried during the milling operation. To eliminates such technical limitations several retrofit options are available, such as:

4.3.1 INDIRECT FIRING

Indirect Firing: IF involves the use of a pulverized coal storage facility, also known as dust bunker, this dust bunker is placed between coal mills and burners. This decouples the direct connection between coal mills and burners.

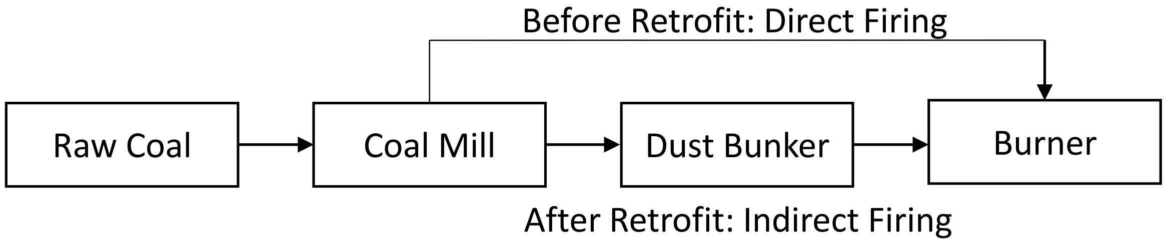

Fig. 4.2 Indirect Firing

This retrofit results in a reduction in the inertia of the firing rate due to reduced milling rate and burner feed rate. Indirect firing also stabilize the combustion process and avoid the need for oil support as start-up fuel. When indirect firing is installed in conjunction with flexible burners it allows the minimum firing rate to be as lowered as below 10 % of maximum continuous rating (MCR) of the boiler [36]. Part load efficiency is also improved at low load as mills can continue to operate in their optimum range of power consumption.

Effects of Indirect Firing:

- stabilize the combustion process at low load
- reduced net power consumption as coal mill operate at a nominal level during low load
- high ramp rate can be achieved, due to reducing the time lag between coal mills and burners

With direct firing, mills must reduce their load during a low load operation. With indirect firing, mills can run at nominal load even if the pulverized coal is not immediately required because it can be stored in the dust bunker. This allows the auxiliary power needed for milling to ramp up when the load is low. By maintaining nominal mill operation when the load is low, this reduces the net power fed into the grid. Direct firing requires coal mills to operate under partial load during periods of low load operations of coal-based power plants. These results drop in efficiency which leads to an increase in specific CO_2 emissions. By using indirect firing, coal mills can be operated at nominal load with optimal efficiency and as a result, it reduces specific CO_2 emissions.

Table: 4.1 Effects of Indirect Firing

	Direct Firing	Indirect Firing
Minimum Load	25-30%	<10 %
Ignition fuel	100%	5%
Excess air	15%	<12%
Grinding Process	Mills operating at partial load	Mills operating at optimal load

4.3.2 SWITCHING FROM TWO-MILL TO SINGLE-MILL OPERATION

Coal mills grind lignite or hard coal to pulverized coal (PC). The PC is transported via air stream (primary air) to the burners, where it is then combusted inside the boiler. In the direct firing configuration, reducing the net power of a power plant requires the burners and the coal mills to both runs at part load. At a certain firing rate, the fire becomes unstable, requiring the power plant controller to limit the low load operation in order to avoid damaging pressure pulses that can occur inside the boiler. The fire stability typically represents the lowest threshold for the low load operation [37].

At a certain net power output, it is feasible to shut down some of the mills and have the remaining mills operate closer to their design point. Since coal mills typically supply a single burner stage with PC, turning off a mill leads to a boiler operation with a reduced number of burning stages.

Fig. 4.3 shows a technical drawing of a mill/burner arrangement in a boiler of a hard coal-fired power plant. The purple crosses mark mills that are turned off. The pink arrows illustrate the flow of air conveying the pulverized coal from mill 4 to the burner stage 4, where it is blown into the interior of the boiler.

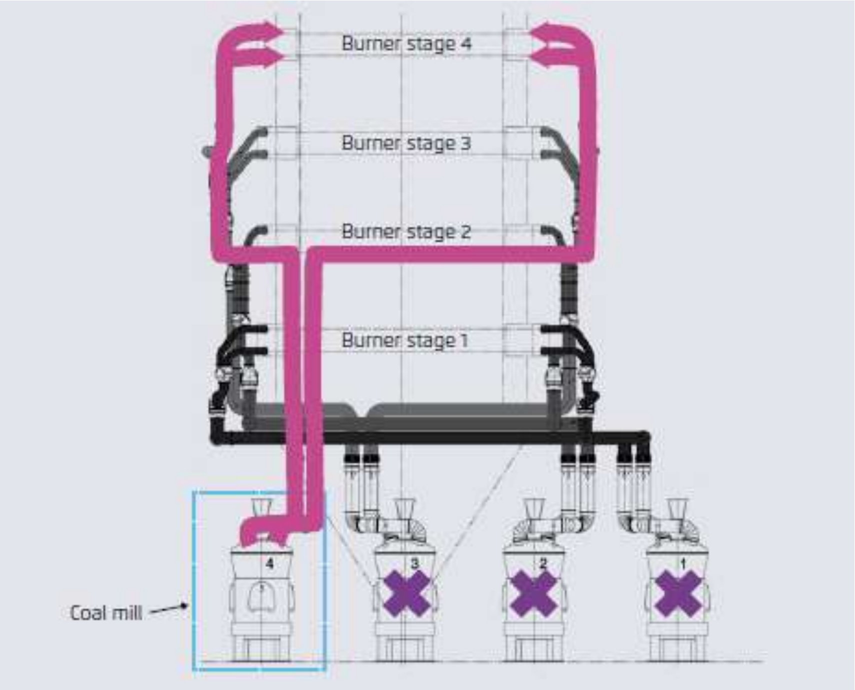

Fig. 4.3 Single mill operation

In single-mill operation, only the highest burner stage is operated for the benefits of releasing heat higher in the boiler as shown in the fig. 4.4. Operating the highest burner with combination of high air excess, compensates lower steam and flue gas temperature.

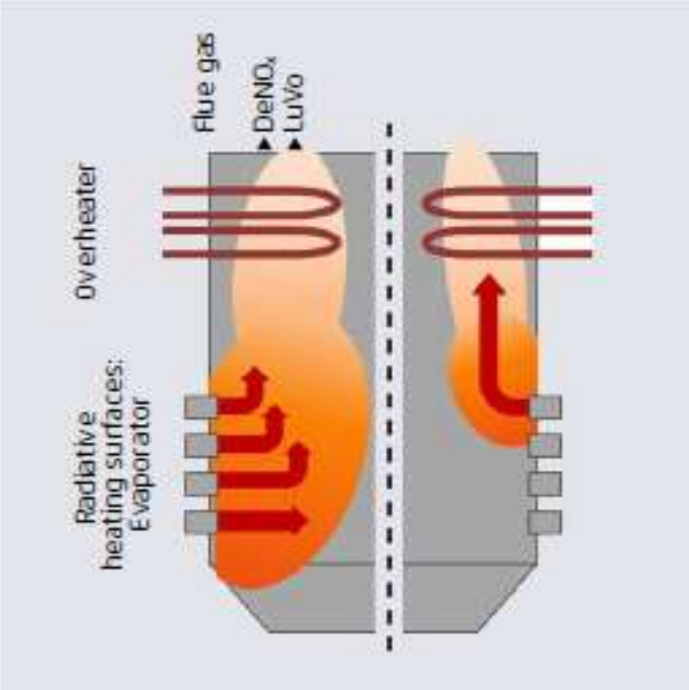

Fig.4.4 Comparison of four-mill and single mill operation

Relative to the two-mill operation, the single-mill operation can significantly reduce the minimum load while increasing operational stability.

4.3.3 UPGRADE OF A CONTROL SYSTEM IN COMBINATION WITH PLANT ENGINEERING UPGRADES

Control technology plays a crucial part in power plant operation. It allows navigation between different loads and ensures stable operation by adjusting all relevant process variables. In the context of coal-fired power plants, the control system monitors and controls the temperature and pressure inside the boiler, the feed-water mass flow in the water-steam circuit, the load point of the coal mills and the turbine valve positions.

An upgrade of the control system improves precision, reliability, and speed of control. For instance, it allows operation closer to the material limitations of important components, such as the boiler. This can mean operation at very high temperatures without significantly reducing material lifespan. An upgrade of the control system is usually combined with plant engineering upgrades, such as retrofits of the boiler or the turbine or other components.

4.3.4 AUXILIARY FIRING WITH DRIED LIGNITE IGNITION BURNER

Auxiliary firing describes the process of stabilizing the fire in the boiler by combusting auxiliary fuels, such as heavy oil or gas, in addition to the PC-fired main burners. This allows for an overall lowering of the stable firing rate in the boiler. Auxiliary firing can also be used for rapid increases to the firing rate, which have a positive influence on the ramp rate.

Since fire stability in the boiler usually limits the minimum load, auxiliary firing can support the minimum load reduction. By operating, the dried lignite ignition burner for auxiliary firing reduced the minimum load from 36 % to 26 % Pnom. Another advantage of operating the burner with dried lignite is that it reduces the need for high quality and expensive fuels, such as heavy oil or gas.

4.3.5 THERMAL ENERGY STORAGE FOR FEED WATER PRE-HEATING

Thermal energy storage can be used to store heat and release it at a later point in time. It presents an interesting concept for influencing net power without changing the firing rate in the boiler. In a typical configuration, the feed water is preheated in a heat exchanger with steam extracted from the steam turbine. This increases the overall efficiency of the power plant and offsets the loss of turbine power caused by the steam extraction.

Releasing or absorbing heat to or from the feed water has, therefore, a direct influence on net power because it influences the amount of steam extracted from the turbine. The operation of a storage system consists of charging and discharging cycles. Charging is done by transferring heat from the feed water to the storage system. To maintain a constant feed water temperature, more steam must be extracted from the steam turbine, leading to a reduction in net power. Crucial for reducing the minimum load is that charging take place during periods when loads are low. The minimum load achieved during the charging process is lower than in the normal configuration. It is important to note that the reduction of net power has no influence on the firing rate in the boiler.

4.4 OPTIONS FOR DECREASING START-UP TIME

Power plant operators want to decrease start-up time because it enables a more rapid response to power demand. Start-up procedures are complex and expensive since they usually require auxiliary fuel, such as oil or gas, during the ignition period.

There are various technical factors that limit the reduction of start-up time. Thick-walled components allow higher operating parameters which increase efficiency. But quick temperature changes in thick-walled components induce thermal stress, which acts as a limiting factor for the start-up time. With “thinner” component designs, flexibility can be higher but efficiency is usually lower. Several options exist for shortening start-up time in power plants that have not been built with flexibility in mind. Four of these retrofit options are described in the following section: repowering, predictive boiler operation, advanced turbine design and enhanced turbine start-up.

4.4.1 REPOWERING

Repowering involves placing a gas turbine upstream of the water-steam circuit in coal-fired power plants as shown in fig. 4.5. The thermal energy in the exhaust stream of the gas turbine is then transferred to the feed water via heat exchangers. Gas turbines can ramp up significantly faster than coal-fired power plants. Repowering increases the gross output of the power plant, improves total efficiency and start-up performance and increases ramp rate. An increase in gas turbine power output directly increases the heat transfer to the feed water of the water-steam circuit. This reduces the steam extraction needed from the steam turbine, which translates into higher steam turbine output.

In sum, repowering

- increases the net power of the coal-fired power plant;
- improves flexibility; and
- increases efficiency, which leads to lower specific CO_2 emissions.

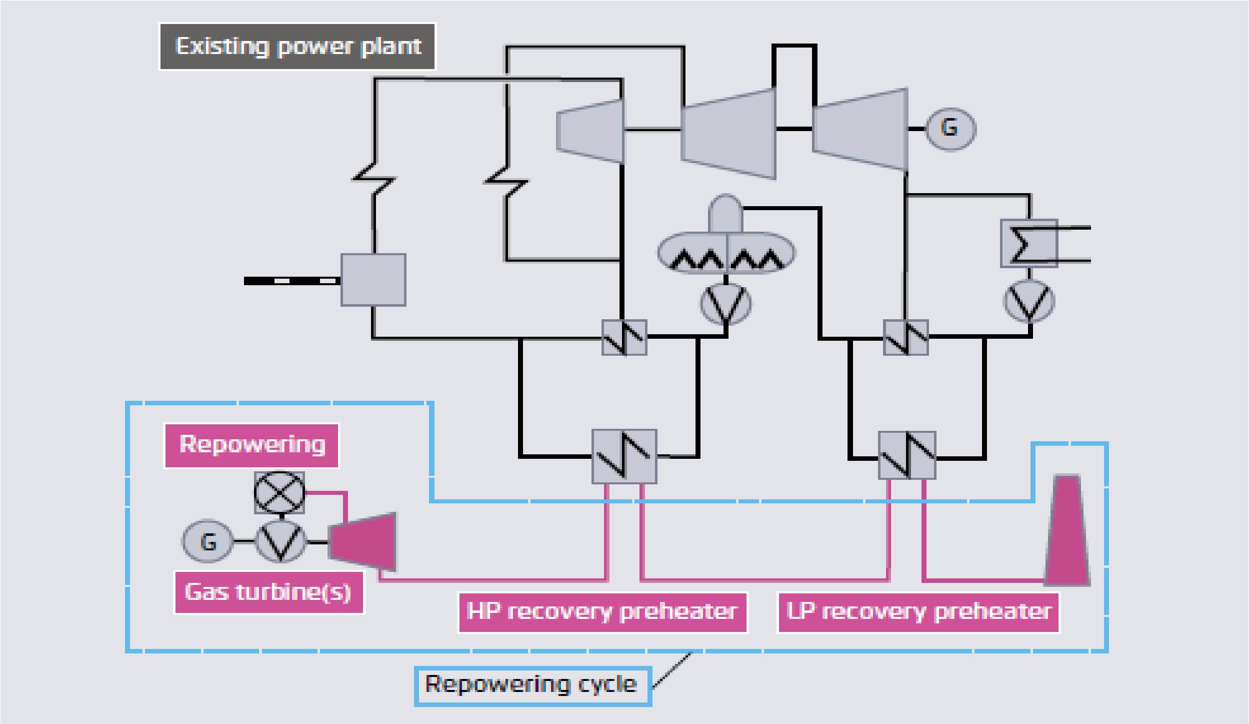

Fig. 4.5 Repowering

4.4.2 OPTIMIZED CONTROL SYSTEMS

Predictive controller solutions such as ABB’s BoilerMax are used for the online optimization of start-ups. Such control systems use dynamic optimization, which beat the performance of conventional control systems. BoilerMax optimizes several parameters to shorten boiler start-up time (Fig. 4.6).

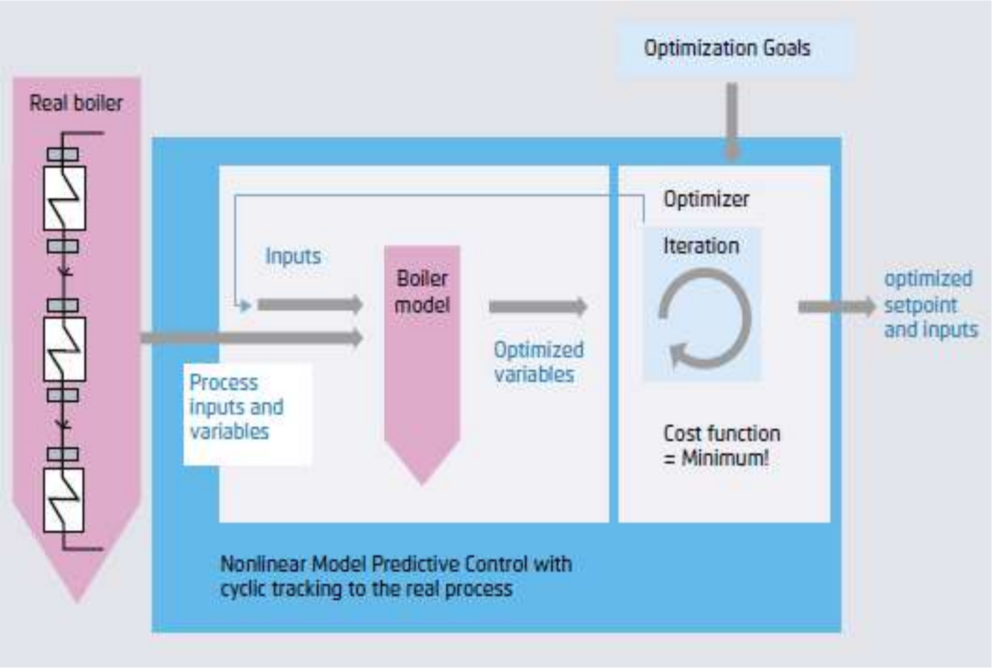

Fig. 4.6: Basic principle of Boiler Max Optimization Control System

The parameters include among others fuel costs and thermal stress on thick-walled components. Once installed in the control system, BoilerMax allows plant operators to shorten plant start-up time. A shorter start-up time normally implies higher thermal stress for the materials. The tool also provides plant operators with the opportunity to choose between different start-up options, allowing them to adjust the specific start-up to the current market situation.

4.4.3 THIN-WALLED COMPONENTS/SPECIAL TURBINE DESIGN

The quicker a start-up, the faster the temperature of thick-walled components rises. Thermal stress on thick-walled components of the boiler system, such as headers, limits temperature fluctuations. For quicker start-ups, the wall thickness of thick-walled components needs to be reduced. This can be achieved by using high-grade materials such as ferritic-martensitic steel P92, which can better cope with thermal stress, or by using special designs.

When designing a power plant, future operators need to evaluate if they want the power plant to be more flexible or more efficient. Plant operators need to decide if they want power plant components to be rather thick- or thin-walled. With thick-walled components, steam temperature and pressure can be higher than power plants that have thin-walled components.

This increases efficiency but decreases flexibility. With a “thin-walled” component design, power plant flexibility is higher but efficiency decreases because steam temperature and pressure are lower.

4.4.4 TURBINE START

In most cases, steam turbine start-ups require a steam temperature that is higher than the metal temperature. Due to its mass, the steam turbine cools down fairly slowly. If the power plant has been out of operation for only a couple of hours, the restart must be delayed until the steam temperature reaches the turbine temperature. In the past, steam turbine start-ups followed the static performance curves of the boiler and did not take ramp rates into account. As a result, the “hot” turbine hindered overall hot start performance.

To solve this problem, a new dynamic approach was introduced: allow “cold” steam to enter the steam turbine as quickly as possible after shutdown. This enables the turbine to start with the boiler while it's still ramping up. This approach can reduce the hot start-up time by 15 minutes.

4.5 OPTIONS FOR INCREASING RAMP RATE

Power plant operators are interested in increasing ramp rates because it allows dynamic adjustments to net power. This is especially important in power systems with rising shares of renewables.

4.5.1 REPOWERING

The repowering option has important implications for the ramp rate. Repowering involves installing a gas turbine in a coal-fired power plant upstream of the water-steam circuit. Heat exchangers transfer the thermal energy in the exhaust stream from the gas turbine to the feed water.

Usually, the ramp rate is limited by the allowable thermal stress for thick-walled components. Additional limitations are caused by the fuel quality and the time lag between coal milling and turbine response present in the direct firing configuration. In a normal coal-fired power plant, burning coal provides the only heat source for the water-steam circuit. With the repowering option, a second heat source can be used to pre-heat the feed water. This makes it possible to achieve a greater change in heat input per time, which translates into a faster ramp rate.

With repowering, the ramp rate is greater (hence the steeper slope) because an additional heat source is available to pre-heat the feed water. This means that after an equivalent period of ramping up a larger net power can be reached with the turbine than with the traditional configuration. The difference in net power between the two configurations is given by the net power of the gas turbine, PGT, and the difference in ramp rate, ΔRR.

4.5.2 REDUCING THE WALL THICKNESS OF KEY COMPONENTS

As discussed earlier, the wall thickness of components is an important parameter because it influences the allowable temperature change rate. The temperature change rate describes the change in temperature per change in time at a specific location in the wall in Kelvin per minute, K/min. Since temperature changes induce thermal stress, each material is assigned a maximum allowable value. Exceeding this value reduces the material’s lifespan.

In general, reducing wall thickness increases the allowable temperature change rate. This translates into a faster start-up by boosting the ramp rate. Wall thickness can be reduced by using superior materials or by increasing the number of specific components.

4.5.3 AUXILIARY FIRING WITH DRIED LIGNITE IGNITION BURNER IN BOOSTER OPERATION

The ignition burner can also be used during operation to increase firing power and increase net power and ramp rate. This type of operation is referred to as booster operation. It requires a dust bunker to be independent of the inertia of the milling process. Booster operation helps reduce the time lag between the rise in the firing rate and turbine response. Normally, the lag is around 20–60 s for hard coal-fired and 30–60 s for lignite-fired power plants.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

The present study was done on an installed capacity of 19540 MW to determine the flexibility available for coal-based power plants to integrate high RE into the grid. The main objective of the study was to collect the declared capacity, schedule generation and unscheduled interchange form different regional load despatch center to calculate the flexibility index, ramp rates and to study the different available retrofits and their effects on coal-based thermal power plants for flexible operation.

5.2 ACTUAL GENERATION FOR FLEET OF 19540 MW

For calculation of actual generation, block wise data collected for a week were analysed. One block is equal to 15 minutes and for 24 hrs. there are 96 blocks. The analysis had been performed for a fleet of 19540 MW to determine the actual generation. Table 5.1 shows the comparison between maximum, minimum and average actual generation for the same fleet for 96 blocks.

Table 5.1: Comparison of maximum, minimum and average actual generation, MW

	Declared Capacity, MW	Schedule Generation, MW	Unscheduled Interchange, MW	Actual Generation, MW
Maximum	15579.62	14966.99	149.50	15116.49
Average	15464.79	14382.90	79.63	14462.53
Minimum	15339.03	13775.23	-60.93	13714.30

For a fleet of 19540 MW the declared capacity varies from 15339.03 to15579.62 MW and the average declared capacity during 96 blocks was found to be 15464.79 MW. The scheduled generation varies from 13775.23 to 14966.99 Mw and the average schedule generation was 14382.9 MW. The unscheduled interchange varies from -60.93 to +149.50 MW and the average unscheduled generation was +79.63 MW. The actual generation varies from 13714.30 to 15116.49 MW and the average actual generation is 14382.9 MW. Fig. 5.1 shows the comparison between declared capacity, schedule generation and actual generation. From the above analysis it is clear that there is a huge difference of 1402.18 MW between maximum and minimum generation. This indicates that the current fleet of 19540 MW can be operated flexibly to integrate high RE generation.

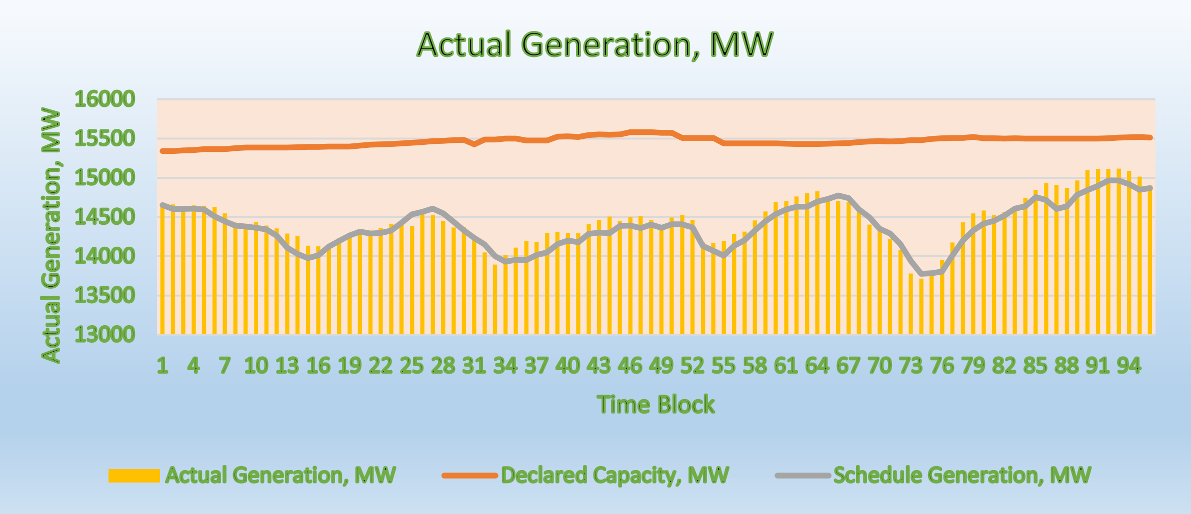

Fig. 5.1: Comparison between declared capacity, schedule generation and actual generation

5.3 COMPARISON OF FLEXIBILITY INDEX FOR DIFFERENT POWER PLANTS

Flexibility Index may be consider as a parameter which provides the actual operating range of a thermal power plants. Flexibility Index for a thermal power plants is calculated as the ratio of the difference of actual maximum generation actual minimum generation to the actual maximum generation. The flexibility index analysis for 19540 MW fleet is performed by considering 96 blocks for 7 days. Table 5.2 shows the flexibility index for different power plants.

Table 5.2: Flexibility Index for different for power plants

TPS	Installed Capacity, MW	Technology	Flexibility Index
CGPL Mundra	4000.00	Supercritical	0.13
Dadri 1	840.00	Subcritical	0.13
Dadri 2	980.00	Subcritical	0.22
Rihand 1	1000.00	Subcritical	0.14
Rihand 2	1000.00	Subcritical	0.13
Rihand 3	1000.00	Subcritical	0.11
Sasan UMPP	3960.00	Supercritical	0.10
Singrauli	2000.00	Subcritical	0.13
VSTPS1	1260.00	Subcritical	0.14
VSTPS2	1000.00	Subcritical	0.12
VSTPS3	1000.00	Subcritical	0.16
VSTPS4	1000.00	Subcritical	0.10
VSTPS5	500.00	Subcritical	0.20

From the above analysis it is clear that the flexibility index varies from plants to plants. For Sasan UMPP and Vindhyachal super thermal power stage-4 flexibility index was found to be 0.10, which implies that these power plants have low operating range. For CGPL Mundra, Rihand stage-1, Vindhyachal stage-3, flexibility index was found to be 0.13, 0.14 and 0.16 respectively, which implies these power plants have medium operating range. For Vindhyachal stage-5 and Dadri stage-2 flexibility index was found to be 0.20 and 0.22 respectively, which implies these power plants have high operating range. Fig. 5.2 shows the comparison of flexibility index for different power plants. For a fleet of 19540 MW, the average flexibility index was found to be 0.14, which indicates the current fleet can be operated flexibly.

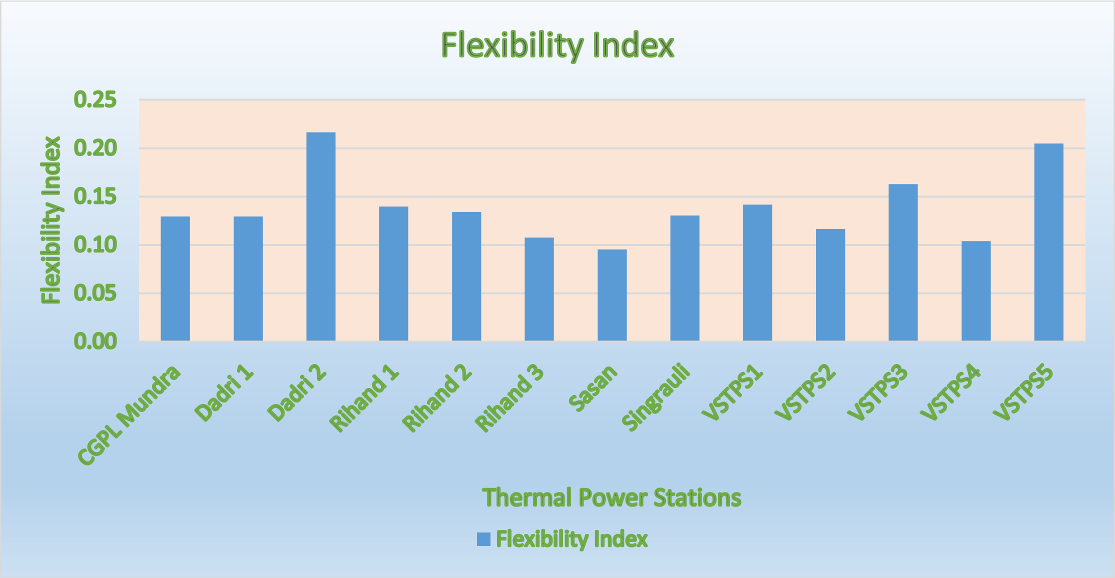

Fig. 5.2: Comparison of flexibility index for different power plants

5.4 COMPARISON OF RAMP RATE FOR DIFFERENT POWER PLANTS

Ramp rate is one of the characteristics of the operational flexibility of power plant and it is consider as a parameter which may allow high integration of high RE. Ramp up/down for a power plants is calculated as the ratio of the difference of two consecutive generation block to the time duration of one block (15 Minutes). The ramp rate analysis for 19540 MW fleet is performed by considering all 96 blocks for 7 days. Table 5.3 & 5.4 shows the actual ramp up rate and ramp down rate for different power plants.

Table 5.3: Actual ramp up-rate (MW/Min) for different power plants

TPS	Installed Capacity, MW	Technology	Ramp Up rate, MW/Min	% Ramp Up	Ramp Rate as per CERC (3%)
CGPL	4000.00	Supercritical	11.50	0.29	120.00
Dadri 1	840.00	Subcritical	7.89	0.94	25.20
Dadri 2	980.00	Subcritical	10.46	1.07	29.40
Rihand 1	1000.00	Subcritical	8.21	0.82	30.00
Rihand 2	1000.00	Subcritical	6.82	0.68	30.00
Rihand 3	1000.00	Subcritical	7.09	0.71	30.00
Sasan	3960.00	Supercritical	19.87	0.50	118.80
Singrauli	2000.00	Subcritical	10.30	0.52	60.00
VSTPS1	1260.00	Subcritical	8.85	0.70	37.80
VSTPS2	1000.00	Subcritical	7.77	0.78	30.00
VSTPS3	1000.00	Subcritical	8.66	0.87	30.00
VSTPS4	1000.00	Subcritical	9.10	0.91	30.00
VSTPS5	500.00	Subcritical	5.00	1.00	15.00

Table 5.4: Actual ramp-down rate (MW/Min) for different power plants

TPS	Installed Capacity, MW	Technology	Ramp Down Rate, MW/Min	% Ramp Down	Ramp Rate as per CERC (3%)
CGPL	4000.00	Supercritical	13.81	0.35	120.00
Dadri 1	840.00	Subcritical	6.08	0.72	25.20
Dadri 2	980.00	Subcritical	16.34	1.67	29.40
Rihand 1	1000.00	Subcritical	20.81	2.08	30.00
Rihand 2	1000.00	Subcritical	9.59	0.96	30.00
Rihand 3	1000.00	Subcritical	6.00	0.60	30.00
Sasan	3960.00	Supercritical	16.85	0.43	118.80
Singrauli	2000.00	Subcritical	12.48	0.62	60.00
VSTPS1	1260.00	Subcritical	9.98	0.79	37.80
VSTPS2	1000.00	Subcritical	8.93	0.89	30.00
VSTPS3	1000.00	Subcritical	10.14	1.01	30.00
VSTPS4	1000.00	Subcritical	6.28	0.63	30.00
VSTPS5	500.00	Subcritical	6.42	1.28	15.00

From the above analysis it is clear that the ramp rate varies from plants to plants and it’s depend on the installation capacity too. As per CERC norms each thermal power plants can ramp up/down by 3% of installed capacity, however as per above analysis no plant is nearby of this limit. As per the above analysis the highest ramp up rate is 1.07 % of installed capacity (10.46 MW/Min) for Dadri stage-2 and 1.0 % of installed capacity (5 MW) for Vindhyachal stage-5.

Other power plants have very low ramp up rate and it varies from 0.29 to 0.80 % of installed capacity. The highest ramp down rate was found to be 2.08 % of installed capacity (20.81 MW/Min) for Rihand stage-2 and the lowest ramp down rate was found to be 0.35 % of installed capacity (13.81 MW/Min). Fig. 5.3 & 5.4 shows the ramp up and ramp down rate for different power plants respectively.

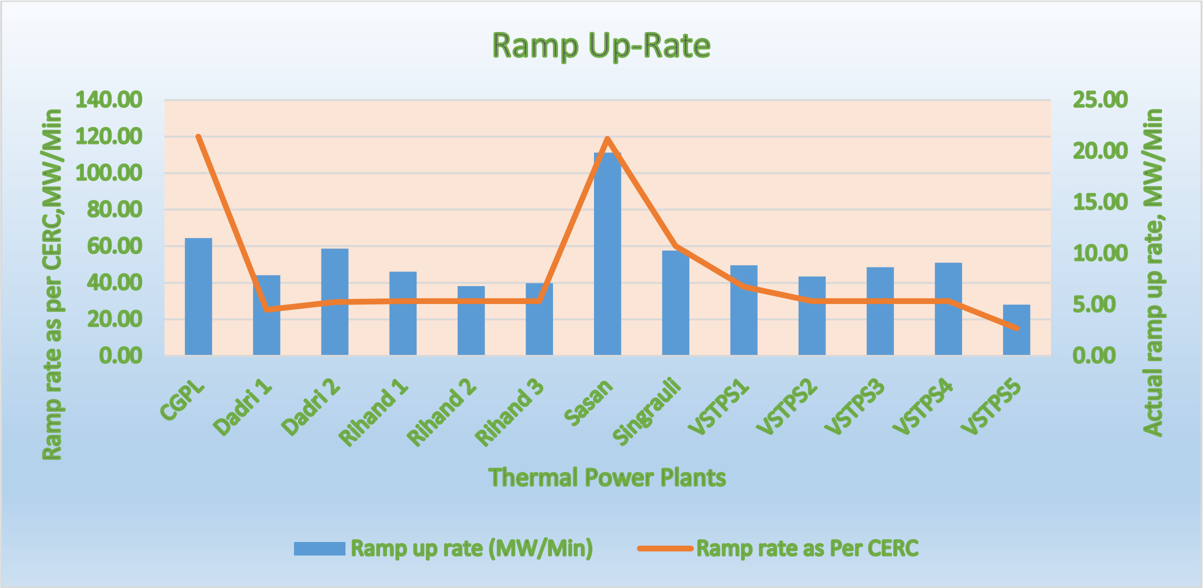

Fig. 5.3 Ramp up-rate for different power plants

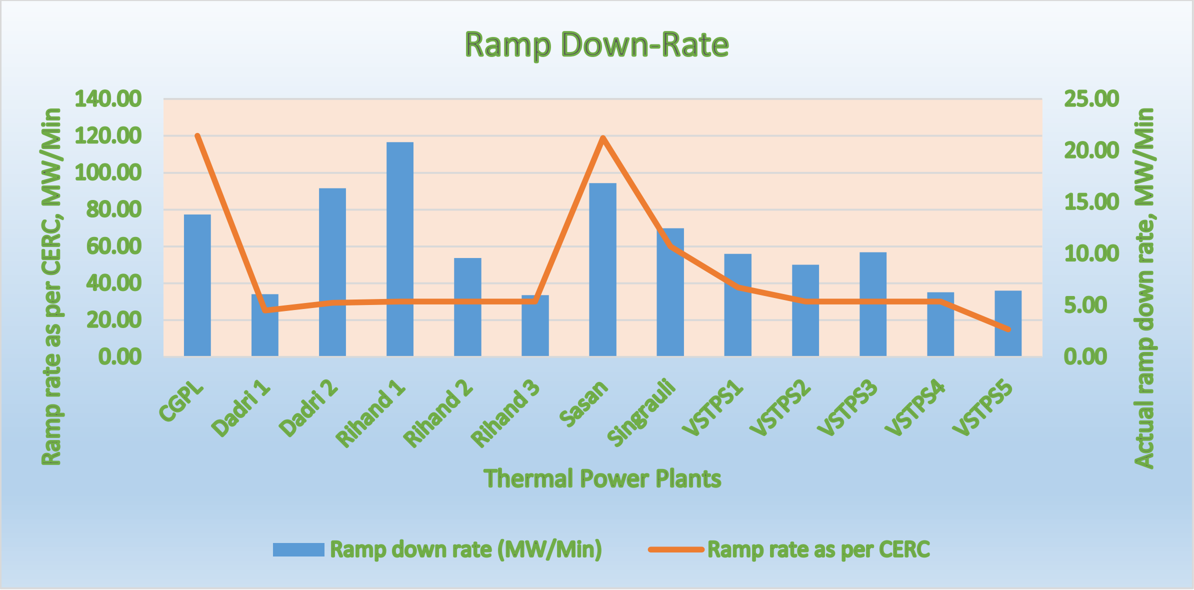

Fig. 5.4 Ramp down-rate for different power plants

5.5 RETROFITS AND THEIR EFFECTS

Form the above study it is clear that flexibility retrofits are an important way of improving coal-fired power plants for increasingly variable power demand. Retrofit measures do not have any negative effect on efficiency of the thermal power plants. In many cases, retrofits used to increase flexibility improved plant efficiency. However, lowering the minimum load can reduce the efficiency of the power plant at very low load, increasing specific CO_2 emissions at low load operating points. The flexibility gained by thermal power plants outweighs in most cases the drawbacks of CO_2 emissions at low operating points, and this advantage will only grow as the share of renewables increases. Table 5.5-5.8 shows different available retrofits, their potential and their limitations.

Table 5.5: Available retrofit options for different flexibility characteristics and their limitations

Option	Minimum Load	Start-up Time	Ramp Rate	Limitations
Indirect Firing	▨		▨	Fire stability
Switching from two-mill to single-mill operation	▨			Water-steam circuit
Monitoring & Optimization of combustion				NA
Control system and plant engineering upgrade	▨		▨	Fire stability/ thermal stress
Auxiliary firing with dried lignite ignition burner	▨		▨	Fire stability and boiler design
Thermal energy storage for feed water pre-heating	▨			NA
Repowering		▨	▨	NA
Optimized control system		▨		Thermal stress
Thin-walled components/special turbine design		▨		Mechanical and thermal stresses
“New” turbine start		▨		Turbine design
Reducing wall thickness of key components			▨	Mechanical and thermal stresses

Table 5.6: Summary of retrofit options for reducing the minimum load

Retrofit options for reducing the minimum load		
Option	Potential	Limiting Factor
Indirect Firing	A reduction of minimum stable firing rate from 25–30 % to 10 %.	Fire stability
Switching from two-mill to single-mill operation	On average, these retrofits reduced minimum load from 23 % to 12 % of Pnom.	Water-steam circuit
Control system and plant engineering upgrade	On average, these retrofits reduced minimum load from 71 % to 47 % of PNom.	Fire stability/ thermal stress
Auxiliary firing with dried lignite ignition burner	This option reduced the minimum load from 36 % to 26 % of PNom.	Fire stability and boiler design
Thermal energy storage for feed water pre-heating	A reduction of the minimum load by 5–10 % employing a hot water storage system that can operate for 2–8 hours is deemed realistic.	NA

Table 5.7: Summary of retrofit options for reducing start-up time

Retrofit options for reducing Start-up Time		
Option	Potential	Limiting Factor
Repowering	In general, repowering has a positive influence on start-up behavior, as the gas turbine can ramp significantly faster.	NA
Optimized control system	This retrofit reduced start-up time by 33 % (15 minutes).	Thermal Stress
Thin-walled components/special turbine design	Utilizing superior materials allows for thinner walls in components such as headers. Thinner walls allow faster start-ups.	Mechanical and thermal stresses
“New” turbine start	This retrofit reduced the hot start-up by 15 minutes.	Turbine Design

Table 5.8: Summary of retrofit options for reducing ramp rate

Retrofit options for reducing Ramp Rate		
Option	Potential	Limiting Factor
Repowering	Repowering has been shown to increase ramp rates. Modern power plants achieve ramp rates of up to 6 % PNom/min.	NA
Control system and plant engineering upgrade	These retrofit options increased ramp rates by +6 MW/min (600 MW PNom) and +10 MW/min (600 MW PNom) at Neurath and Weisweiler.	Thermal stress
Reducing the wall thickness of key components	This retrofit increased the ramp rate by 3 %.	Mechanical and thermal stresses
Auxiliary firing with dried lignite ignition burner in booster operation	Increasing the firing rate at constant boiler load with booster operation has the potential for rapidly increasing net power.	Boiler design, booster operation

CHAPTER 6

CONCLUSIONS AND FUTURE RECOMMEDATIONS

6.1 CONCLUSIONS

The present study was done on an installed capacity of 19540 MW to determine the flexibility available for coal-based power plants to integrate high RE into the grid. The following conclusion can be made from this study flexibility index for a fleet of 19540 MW, varies from 0.13 to 0.22, which indicates that current fleet is having very high operating range. From the analysis, the lowest ramp-up rate was found to be for CGPL Mundra i.e., 0.2875 % of installed capacity and the highest for Dadri Stage-2 i.e., 1.067% of installed capacity. However, as per CERC norms (3%), it is much lower and shows potential for improvement. For ramp down rate analysis, the lowest ramp down rate was found to be for CGPL Mundra i.e., 0.3452% of installed capacity and the highest for Rihand stage-1 i.e., 2.081 % of installed capacity. However, as per CERC norms (3%), it is much lower and shows potential for improvement. Generally, coal-based power plants are designed for base-load operation. However, coal-based power plants can improve their efficiency and flexibility by adopting retrofitting measures. Coal-based plants operate as baseload consumes a high amount of coal. If coal-based plants can increase the flexibility of their operation, coal consumption can be reduced, and further relative emissions can also be reduced.

6.2 FUTURE RECOMMENDATIONS

From the various studies, it is found that the current Indian power system is having the high operating range and high ramp rate capacity with penetration of 60 GW of VRE generation. However, there is no available framework for the flexible operation of conventional power plants, by developing the framework for the flexible operation we can easily identify the indexes which can be handy for achieving flexible operation. While all the studies show that start-up time can be optimized, however, for analyzing the thermal stress and other effects require an accurate numerical model. For ramp rate improvement studies shows that a higher ramp rate can be achieved by retrofitting some equipment's, however, higher ramp rates can affect the normal operating conditions of the turbine, for analyzing such effects we require an accurate numerical model.

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