Integration and flexibilization of steam power plants with growing renewable energy systems

Increasing the flexibility of conventional power plants is one key challenge for the massive integration of highly volatile renewable energy resources into the Indian power system. Flexible power plants ensure the security of supply by compensating fluctuations in the electrical grid caused by intermittent renewable energy production from wind and sun.

In this paper, the future development of the Indian electricity market is predicted and evaluated in terms of the future flexibility demand of coal and Lignite-fired power plants.

As the flexibility measures for coal-fired power plants generally use inherent capabilities of the existing power plant systems, they are usually restricted by limiting factors. Here, the limiting factors for reducing the minimum load and increasing load change rates are discussed and potential measures to mitigate their influence are presented.

An alternative way to increase the flexibility lies in properly integrating thermal energy storages. Integrating this storage concept the electrical minimum load can be reduced while simultaneously increasing the load change rate.

Keywords: *Integration and flexibilization, future development, renewable energy systems, energy mix.*

I.0 Introduction

The world energy scenario is undergoing a major transformation especially the year 2021, which has set the pace for various economies to redefine their strategies towards energy security, sustainability and energy mix. The Indian economy with its high growth potential will guide the corresponding energy demand growth.

India has set for itself a renewable energy target of 175 GW by 2022 and gradual reduction in contribution of thermal power, particularly coal based power in its energy mix. At present coal accounts for 59% of total capacity of 330 GW and the renewables are at 17%. By year 2022 the share of coal will reduce to 41%, while the renewables will increase to 36%. This roadmap for moving to low carbon economy ushers well with India's overall commitment of meeting more than 50% demand from renewables by year 2030.

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Table 1: Installed grid interactive renewable power capacity (excluding large hydropower) in India as of 31 October 2017 (RES MNRE)

Source	Total installed capacity (MW)	2022 target (MW)
Wind power	32,715.37	60,000.00
Solar power - ground mounted	14,751.07	100,000.00
Solar power - rooftop	823.64	
Biomass power (biomass and Gasification and bagasse cogeneration)	8,181.70	*10,000.00
Waste-to-power	114.08	
Small hydropower	4,399.35	5,000.00
Total	60,985.21	175,000.00

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At present coal accounts for 59% of total capacity of 330 GW and the renewables are at 17%. By year 2022 the share of coal will reduce to 41%, while the renewables will increase to 36%.This roadmap for moving to low carbon economy ushers well with India‘s overall commitment of meeting more than 50% demand from renewables by year 2030. Need for integration of large scale renewables with thermal power is imerging. The introduction of large scale renewables in the emerging energy transition brings along with it a new set of challenges to be managed by the power sector. The variability and intermittency of solar power and wind power has to be managed and supplemented by other sources of energy in order to ensure the system stability and security.

With limited pump storage and with overall hydro potential of the country limited to 150 GW and gas sources being insufficient the coal based generation is the major option to meet and match the fluctuating requirements of the grid. In the absence of credible and affordable technologies for renewable energy storage and demand side response to pick up, the coal based power generation is likely to be the main stay in the foreseeable future and accordingly it has to adapt to the fluctuating load requirements as demanded by the system for its proper balancing and stability.

The process of integration of renewables with the thermal generation as per fluctuating renewables will become more and more crucial with further growth of renewables in the coming years. A recent study has projected that the difference between off peak demand and peak demand after discounting renewables will be 80GW. This implies that the available capacities (other than renewables) should be able to ramp up at rates exceeding 25 GW/hour. The adaption of coal based power plants to fluctuating renewables throws a new set of challenges for both existing and new thermal power plants. There is a pressing need for a total relook in the design and operational philosophies of the thermal power plants.

The PLF and efficiency are no more the key drivers and these are overruled by better flexibility of the power plants. This new requirement calls for thermal power plant to be subjected to frequent load changes, cycling and two shift operation leading to higher fatigue and creep induced stresses. Apart from the need for higher maintenance, these additional stresses can further lead to possible failures and reduced equipment and plant life. Some of the equipment and components which are adversely affected include boiler thick walled components, turbine rotor and blades, copper components of electrical equipment etc. The various plant performance parameters too get adversely impacted. For enhancing the flexibility of existing power plants, retrofitting and upgrading of boiler, turbine, control and instrumentation and certain auxiliary systems will be necessary to meet the new requirements.

This calls for the existing power plants which hitherto have been operating mainly on base load to undertake specific studies and undertake required modifications and as well redefine the operation and maintenance practices. This in turn calls for the need of having new set of expertise among the various power sector stakeholders.

This task of rejuvenating most of existing fleet of power plants is gigantic and the success of energy transition to renewables will also depend on the success of how effectively and efficiently the existing thermal power plants can be transformed into their new adaptation.

German experiences in flexibilisation of thermal power plants: The German power industry has much earlier witnessed the era of adaptation to renewable energy by flexibilisation of its thermal power plants and other measures like grid strengthening, demand side response, battery storage etc. Germany has already reached 50% of its total capacity from renewables. Also, the net consumption of renewable power has reached 33% of total annual power consumption. The flexibilisation of the thermal power plants has been under great focus with the intended aim of balancing and achieving stability of the power system. The potential measures have been implemented by most of the German utilities. These measures are dependent on class of technology, units size, type of fuel etc. The units are able to achieve, high technical and operational flexibility, achieving stable load as low as 20%, high operational gradients, short ramp up time, high number of start ups and load cycles, high efficiency at wide load range. The fuel flexibility has been also implemented as potential modifications to have better overall flexibility.

The collaborative efforts of utilities, research institutes and manufacturers have defined and established the systematic approach in achieving flexibilisation of German steam power plant on various measurable parameters. The new power plant designs have been developed for better flexibilisation and certain new concepts having been introduced and implemented.

The German power industry has gained extensive experience in enhancing flexibilisation of their thermal power plants. This experience is very relevant to the transformation of our thermal power plants to meet the new emerging scenario in the Indian power sector

In the current energy system, mainly flexible conventional power plants ensure the stability of the system by compensating fluctuations in the grid caused by intermittent renewable energy supply (PV and wind). Considering the increasing installation of these renewable energy sources, the demand for flexible power plants becomes increasingly important.

In summary the flexibility features to be provided by future power plants are:

- Optimized start-up procedure
- Reduced minimum load
- Increased load change rates
- (Increased) Provision of control power

As the majority of current power plants, especially coal-fired power plants, have been designed with a focus on stable operation, a considerable potential for increasing the flexibility can be presumed for existing power plants. Scientifically sound assessment of future flexibility demand of coal-fired power plants and possible flexibility measure are studied.

The future flexibility requirements for coal-fired power plants are predicted and summarizes possible flexibility measures and discusses typical limiting factors, focusing on reducing the minimum load and increasing the load change rates and to optimize the flexibility features of coal and lignite l-fired power plants. This paper also presents the integration of a thermal energy storage (TES) into the power plant model. Such an integration is one possible flexibility measure, aiming at the reduction of the electrical minimum load while simultaneously increasing the load change rate.

2.0 Future developments of the electricity market in the Indian contex

Conventional power plants are modelled blockwise for 8,760 hours per scenario year. The objective function is to minimize the total costs of electricity production for hour h from 0 to 8,760 and power plant p. The objective function is to minimize the total costs of electricity production and can be expressed as,

Minimum total costs = Σh,p [(Variable costs (h,p) + Start upcosts (h,p)]

Start-up costs arise if a power plant starts operating. The actual start-up costs are dependent on the power plant p as well as on the non-production duration (time steps since last time operating). The objective function is subject to typical electricity market restrictions like supply-demand balance which is

Σp production(p) +Σsm import(sm)– Σsm export (sm) = Σsm demand (sm) and holds for every hour h and every spot market sm. Here, import considers the electricity flow from other states (spot markets) to the respective one and vice versa for exports.

Further restrictions, such as grid capacity constraints, are implemented similarly. Details of technical flexibility are considered as to part load and full load efficiencies, minimum load, load change rates and start-up times. Techno-economic parameters include fuel costs, CO_2 costs and emission factors. Demand side management is considered as load shifting and shedding processes. Assumptions need to be made as to uncertain developments like installed capacity of conventional power plants and renewable resources, grid extensions, as well as for fuel and CO_2 prices. Based on the assumptions, fuel prices are expected to increase slightly while CO_2 prices increase almost linear in 2034. The main

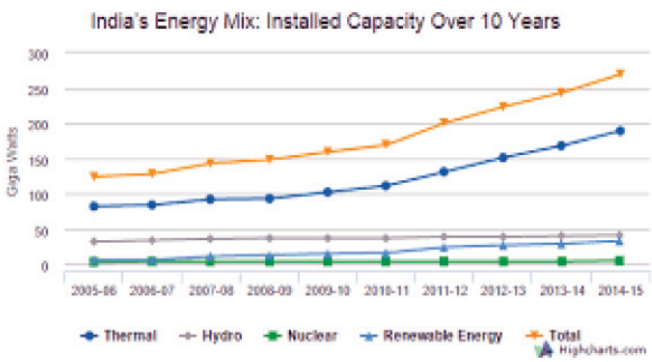

Fig.1

assumptions with respect to renewable capacities are visualized in Fig.1. The strong increase promotes the demand for flexibility.

Development of installed capacity of renewable energies: Results of the economic model the results give insights about the fundamental relationships of the cost-minimal fulfilment of the exogenous electricity demand. Under the exogenous capacity adjustments and market circumstances, the production in the German and India electricity market changes according to the availability of renewable energy sources.

Development of the German electricity production (water includes run-of-river and pumped storage): The share of renewable energies in power production increases while the conventional production decreases. The share of hard coal and lignite power plant production declines and will be compensated by gas power plants and renewable production. In future the price volatility is increased and the geneal price level is higher.

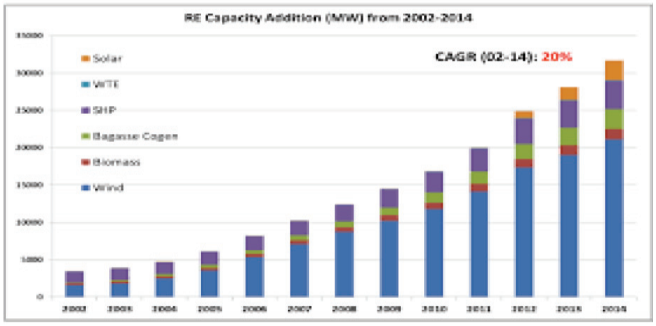

Fig.2

3.0 Exemplary development of variable costs of a coal-fired power plant

The increase in variable costs for coal-fired power plants is primarily driven by an increase in CO_2 costs and not fuel costs. Furthermore, the number of start-ups and full load hours which tend to decrease due to the merit order effect.

3.1 Development of operation of a typical coal-fired power plant

Scenario for the year the future number of start-ups, full load hours [h], number of total starts, number of cold starts, number of warm starts, number of hot starts

Here, hot or warm starts denote start-ups within 8 or 48 hours of downtime, respectively. Cold starts are started after more than 48 hours since last operation. The full load hours tend to decrease until 2034 with an increase in 2024 due to the introduction of renewable energy power plant sources. The decrease in full load hours comes with an increase in the total number of start-ups for a typical 7 coal-fired power plant. The number of starts is twice as much in 2034 compared to 2017. Among the starts, cold starts become more relevant. With respect to the future operation in different load levels of a typical coal-fired power plant, the hours operating in full load show a tendency to decrease

Compared to that, the share of hours operating at minimum load increases from 4.7% in 2017 to 11.2 % in 2034.

3.2 Development of operation hours at different load levels of a typical coal-fired power plant

Scenrio for the year the future operation at different load levels, full load hours [h], hours operating at full load [h], hours operating at minimum load [h].

Implications for the future flexibility demand to coal-fired power plants by the model results for the scenario years up to 2034, conventional power plants are still necessary to supply the electricity demand in a cost-minimal way and have a price setting behaviour in most of the analyzed hours. But compared to today, coal-fired power plants are less often infra-marginal and therefore more often price setting or extra-marginal. This implies that coal-fired power plants are still needed but are not used like today as a base load or mid load generator with a high share of full load hours. In comparison with present day, profitable situations for coal-fired power plants become less frequent and more often occur instantaneously. Therefore, coal-fired power plants need to operate more flexible. They need to perform more start-ups and stay at a minimum load level for longer periods. This is especially the case for an hourly operation of power plants, as it is optimized in flexibilization operation. When it comes to sub-hourly schedules also high load change rates are going to play an important role in the future. Higher load change rates enable power plant operators to trade electricity more flexibly in short-term markets, such as the quarter-hourly intraday market, and to gain additional profits. These implications are the reason for the following investigations how coal-fired power plants (as a representative of steam power plants) can increase their flexibility to cope with the future demand of electricity markets.

4.0 Flexibility measures for coal-fired power plants

4.1. Description of flexibility measures

Optimized start-up and reduced minimum load both optimized start-up and reduced minimum load have the same goal, namely, to reduce costs which would occur due to starting the plant [9]. On the one hand, the optimization of the start-up procedure aims at reducing the oil consumption during the start-up process and making the process reproducible in terms of timing until synchronization in order to avoid unnecessary waiting times.

On the other hand, reduced minimum load aims at completely avoiding the costs for start-up by bridging time intervals in which the plant would have been normally shut down due to low energy prices usually caused by a high energy in feed of renewables. Hence, if the minimum load is decreased, the loss due to operating the plant in these time intervals is decreased as well.

Increased load change rates and control power to counteract unpredictable events, such as outages of power plants or prediction errors regarding the energy consumption and the volatile energy production of intermittent sources, the current energy system offers services (control power) which are based on providing fast load changes by reliable energy producing units, i.e. flexible conventional power plants.

Consequently, substantial and expensive modifications of power plant components can be avoided. Limiting factors increasing the flexibility of conventional power plants is subject to limitations that define to which extent the respective flexibility strategies can be implemented.

With appropriate measures, such limitations can be overcome or at least be mitigated in order to improve the flexibility in a desired way. From a technical point of view, the aspects described in the following sections are particularly important for increasing the flexibility of coal-fired power plants in general. Here, apart from simply listing the limitations, potential measures to deal with these limitations are discussed as well. Please note that in this paper only some key issues are mentioned, focusing on reducing the minimum load and increasing load change rates. Several further restrictions or specific criteria may need to be considered.

Reduction of minimum load: In order to reduce the load, the firing rate must be reduced. At very low firing rates, the flame may become unstable and flame detection problems may occur. Also, the minimum air flow velocity must be taken into consideration in order to prevent backfiring. Potential measures are:

- Changes in the air/fuel proportion
- Increase of air swirl and turbulence
- Reduction of the cooling air of inactive burners
- Changes at the burner construction
- Changes in the mill operation (classifier and mill pressure)
- Transition to one mill operation
- Use of smaller mills
- (Partial) Indirect firing with pulverized dried coal.

In the water-steam cycle, a considerable reduction of the load requires the transition into circulation mode, in which a part of the feed water is not evaporated and is separated to the start-up vessel. For this, a reliable and stable operation in circulation mode during several hours is needed. This requires suitable actuators for the circulation water and the feed water and suitable, optimized control concepts. The turbine may be a limiting component due to insufficient steam flow.

This causes windage, also known as ventilation, which increases the steam temperature in the turbine. While to a certain extent the temperature may be reduced in the final stages of the low pressure turbine by spraying, ventilation can be a hard limit. The dynamic behaviour of power plants at very low loads is different from full load. The control loops and the supervisory unit control generally need to be revised and optimized to reach a satisfactory control performance and to eliminate oscillations. If the boiler load cannot be reduced further, a thermal energy storage may be used to reduce the electrical power output and to release the energy during higher loads. This flexibility measure will be evaluated with a dynamic simulation model of a coal-fired power plant.

Increase of load change rates considering the increase of the load change rates not only physical limitations have to be taken into account but also the dynamic behaviour of the components concerned. Generally, the following effects have to be overcome in order to get a faster response of the energy output of the power plant:

- Storage processes for mass and energy
- Delays and dead times due to transportation processes

The resulting limitations to be maintained by increasing the load change rate are:

- Thermal stress of primarily thick-walled components
- Thermal stress of generator windings
- Deterioration of actuators
- Cavitation.

As load change rates are usually restricted by rate limiters implemented in the control system of the power plant which are often set up in a conservative way, the increase of the load change rate can be achieved by accordingly adapting the control structure of the power plant. However, process variables which are related to the above-mentioned limitations need to be carefully monitored by (potentially) additional sensors to ensure that the plant will be driven within its physical bounds.

4.2 Dynamic power plant model

A. Dynamic simulation model of a coal-fired power plant dynamic power plant simulations could be a promising tool that can be used to calculate and optimize the transient operational behaviour of existing or newly-built power plants. The dynamic simulation model presented in the following was built up by means of the power plant simulation software. The dynamic simulation model consists of a combination of static and dynamic component models, the distinguishing criterion is the time response of the components to a change in the thermodynamic boundary conditions (e.g. a change in temperature). Dynamic components have relatively slow time constants in comparison with static components, which is accounted for by time derivatives in the balance equations for energy, mass and momentum.

4.3 Classification of power plant components into static and dynamic

Static components, dynamic components steam turbine, heat exchanger pump, steam pipe, valve mixing point compressor feed water tank, coal mill. The water-steam cycle of the dynamic simulation model includes turbine train, condenser, preheating line and feed water tank. Besides these components, a detailed dynamic model of the steam generator was built up consisting of coal-mills, air preheater, combustion chamber, nine heat exchangers and three injection coolers.

B. Power plant control system: Apart from the power plant process, also the control system has to be considered in the dynamic power plant model. The control system calculates set points and control variables for the operation of a power plant. The following control structures are implemented in the dynamic power plant model to achieve a sufficient accuracy of the simulation results:

- Unit control
- Feed water control
- Steam temperature control
- Recirculation control.

The main task of the unit control, for example, is to adapt the actual power output to the required power output which is given by the load dispatcher or the power plant schedule, respectively. To guarantee a stable and safe operation of the power plant, a step change of the power output target is transferred into a ramp signal with the maximum permissible rate of change Pperm (in MW/min) as its gradient.

Model validation: In order to validate the dynamic power plant model, the simulation results are compared to measurement data from the underlying coal-fired power plant. The trajectory of the power output is mainly influenced by the unit control. The power output target, represented by the black dashed line, is the only input variable to the dynamic power plant model. The results of the dynamic simulation model show a high correlation to the measured values during the load profile. The essential dynamic fluctuations in the gross electrical power output (e.g. between 5:00 and 6:00 due to the start-up of two coal mills) are also represented by the dynamic power plant model.

Comparison of simulated and measured power output additionally, shows the comparison of water-steam temperatures to prove the validity of the detailed dynamic steam generator model. The curves also show a good accordance. Due to the transition of the water-steam cycle to circulation mode, the economizer inlet temperature rises between 1:00 and 5:00 in measurement and simulation.

4.4 Integration of a thermal energy storage

Reduction of the (electrical) minimum load the integration of TES is one possible flexibility measure that can be evaluated by means of the dynamic power plant model. TES can have various effects on the flexibility, depending on concept, point of integration and capacity. They can be used to improve the power plant start-up and shut-down procedures, to provide control power or to increase the load change rates. Furthermore, TES can be used for a load shift between minimum load and full load. If a power plant is operated in minimum load - usually in times with a low spot market price - the storage can be charged with energy from the water-steam cycle. Charging the storage reduces the electrical minimum load. In times of high spot market prices the energy from the storage can be integrated into the preheating line, leading to an additional electrical power output at full load by the reduction of extraction steam for preheating. The integration of a TES concept for the load shift between minimum load and full load. The TES is charged with energy from an additional extraction of cold reheat steam. During discharge-mode, energy from the storage system is integrated between low-pressure preheater 3 (LP-PH 3) and the feed water tank (FWT).

5.0 Conclusion and outlook

The electricity market simulations show a significant reduction of full load hours, an increased number of start-up processes and an increased share of minimum load operation for a typical coal-fired power plant for the future due to an increasing share of renewable energies in power production. Consequently, steam power plants face increased flexibility requirements to provide the residual load and ensure security of supply also in the future. The consideration of limiting factors and potential measures to overcome these limitations indicate that increasing flexibility is not limited to newly-built coal-fired power plants. In fact, since the control algorithms currently implemented in existing power plants are generally designed to guarantee stability without focusing so much on the transient behaviour, many flexibility measures can be implemented by adapting the automation of the power plant. Consequently, the chances for successfully implementing these measures also in existing power plants are generally promising. Furthermore, the integration of TES could be a promising measure for the flexibilization of steam power plants.

5.1 Power plant reference power plant with TES

The results of the detailed dynamic power plant model show a good accordance to operating data. First simulation studies about the flexibilization of the power plant process through a TES integration outline the possibility of a load shift between minimum load and full load as well as the increase of the load change rates.

Outlook: Further development of the electricity market simulations towards the intraday market (quarter-hourly products) and the consideration of the balancing market are planned, to allow the economic evaluation of flexibility measures regarding load change rates and the supply of control energy. Regarding the TES integration, additional simulation studies are planned that focus on the supply of control energy and/or the start-up process. Moreover, further flexibility measures will be evaluated like adapting control structures as well as changes in the power plant process (e.g., the retrofit of an indirect firing system).

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