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Improvement in performance of primary frequency response of generating units in Indian power system

Chandan Kumar, Raj Protim Kundu, Saibal Ghosh, Shabari Pramanick, Chandan Mallick, Saurav Kumar Sahay, Surajit Banerjee
POSOCO
India

SUMMARY

Frequency Control in any power system is a continuum starting from seconds to a period of less than an hour. Beyond this time horizon, the frequency stability is maintained through forecasting, unit commitment, scheduling and despatch. Large imperfections in this area would lead to off-nominal frequency or a large quantum of generation reserves requirement which may be suboptimal. The first stage of frequency response is the inertial response which is immediate and comes from rotating generators and loads. This is followed by primary frequency response from generating units through their governor response.

Primary frequency response is essential in a power system as it directly impacts the nadir point. It comes from the free governor response through their droop characteristics during any frequency event. The Primary Frequency Response (PFR) implemented in the Indian power system is different from the classical free governor mode of operation (FGMO). In the Indian power system, it is implemented as a restricted governor mode of operation (RGMO). The RGMO detects sudden fall/rise in frequency events only and responds.

There has been difficulty in the implementation of RGMO/FGMO by generating plants in the Indian power system. This paper provides an overview of primary frequency response requirements and associated regulatory provisions in the Indian power system. It further highlights the restricted governor mode of operation logic, challenges observed in assessment of response, concerns and reasons related to generator control and logic adopted in providing an adequate response. This paper also highlights how these challenges can be mitigated with remedial measures. This improvement over the years has been discussed through frequency response by generators with the help of several practical cases. Overall, the paper provides an outlook on the improvement in the primary frequency response in the Indian power system focusing on the eastern regional grid.

KEYWORDS

Distributed control system (DCS), Frequency response characteristics (FRC), Indian Grid, Inertia, Phasor measurement units (PMUs), Primary Frequency response (PFR), Restricted governor mode of operation (RGMO)

chandan@posoco.in, rajprotim@posoco.in

1. Introduction

Frequency reflects the balance between generation and load in power system. With imbalance between load and generation, grid frequency starts to deviate from its nominal value. Rate of change of frequency depends on amount of imbalance and the inertia of the grid. With retiring of old thermal generating units and addition of new renewable generating units, grid inertia is reducing [1]. As per study done by Central Electricity Authority (CEA), around 60% of total installed capacity will be from the renewable power sources by 2030 [2]. With such an increase in RE penetration and reduction in grid inertia, frequency will change at a faster rate with contingencies like tripping of generating units or sudden load reduction. To arrest the frequency change, frequency response is to be provided by the other generating units which are already in running condition. In normal power system operation, frequency control by generating units is of three types: primary, secondary and tertiary frequency control, depending on time window [3]. Another type of control is emergency control which is basically a defence mechanism. It is achieved by tripping of generating unit in case of high frequency and tripping of load during low frequency on under frequency load shedding (UFLS) defence scheme [4].

Primary frequency response (PFR) is provided by the available units on bar through droop control. This frequency control should be fully deployed within 30 seconds from when it is activated and remain active till secondary frequency control comes into action [5]. Governor of running generating units which are mandated to provide primary frequency response monitors the grid frequency and changes the plant output if any change in grid frequency is observed by their controller. The provided response depends on the droop characteristics of the unit and change in grid frequency.

In the Indian power system, PFR provided by the generators have been observed to be inadequate and inconsistent on several occasions, with the required mandate. Such responses were found to be having issues in terms of response quantum, duration, withdrawal rate, logic and setting, ripple factor and other factors. A massive exercise was taken by Indian grid operators for improvement of primary frequency response through a set of exercises in coordination with generating plants. This paper presents the issues, actions taken, and improvement observed in primary frequency response.

2. Primary frequency response in Indian power system

In Indian grid, the allowable grid frequency band is 49.90 Hz to 50. 05 Hz as per the Indian electricity grid code (IEGC),2010. It mandates primary frequency control for coal and lignite-powered thermal generating units having a capacity of 200 MW and more. In case of Hydro powered generation, generating units with a capacity of 25 MW and more and with more than 3 hours of pondage are required to provide primary frequency response. In addition, Open Cycle /Combined Cycle generating stations having gas turbines with capacity of more than 50 MW are also mandated to provide PFR. [6]. In Eastern region of the Indian power system, 48 regional generating units (~17 GW capacity) are under the purview of primary frequency response. PFR of these generating units are being monitored by the Eastern regional load despatch centre (ERLDC). Further, PFR of more than 80 generating units within state control area with (~21 GW) are also being monitored by respective SLDCs and reviewed by RLDCs. Thus around 34 GW capacity out of 60 GW installed capacity in the entire eastern regional grid is mandated to provide PFR. This number is further high in terms of all India grid level.

The primary frequency response in the Indian power system is different from the free governor mode of operation (FGMO). In the Indian power system, it is implemented as restricted governor mode of operation (RGMO). The RGMO detects sudden fall/rise in frequency events only and provides a response. For this ripple factor of ±0.03 Hz is provided for governor action, and it is required that governor should not respond if frequency variation is gradual and within this ripple factor limit. PFR under RGMO/FGMO to be provided by generating units as per IEGC is shown in table 1.

To provide this response several other regulatory mandates have been provided in various regulations and standards by Central Electricity Regulatory Commission (CERC), State Electricity Regulatory Commissions (SERCs) and CEA. These include droop setting range specification, disallowing any valve wide open (VWO) operation and any additional control or deadband that hinders primary frequency response.

Table 1: RGMO/FGMO Criteria for Generators as per IEGC

Condition	Grid frequency increases	Grid frequency decreases
When frequency < 50 Hz	No change in power output; Governor should not respond	In case of sudden drop in frequency, power output will increase as per droop characteristics of the unit. Unit should respond as per its capacity and then its output will come down to original level at ramp rate less than 1% of unit machine continuous rating per minute.
When frequency > 50 Hz	As per droop characteristics of the unit.	As per droop characteristics of the unit i.e. FGMO

In order to ensure primary frequency response, the first measure is to evaluate the PFR provided by the generating unit for past events. This will provide the performance indicator and thereafter assessment of issues observed in providing the PFR by generating units [7]. The next section provides a detailed overview of PFR evaluation methodology.

3. Evaluation of primary frequency response

For evaluation of PFR provided by generating plants, SCADA data were earlier used at control centres which updates at every 4-10 seconds interval. The SCADA data is skewed in nature as it is not time synchronised. However, PFR of generating units starts to get deployed within from 4-5 seconds and it gets fully deployed in next 30-45 seconds [8]. Thus, SCADA data may not be able to provide adequate performance details. Figure 1 shows one example of SCADA data based evaluation of primary frequency response of generating units.

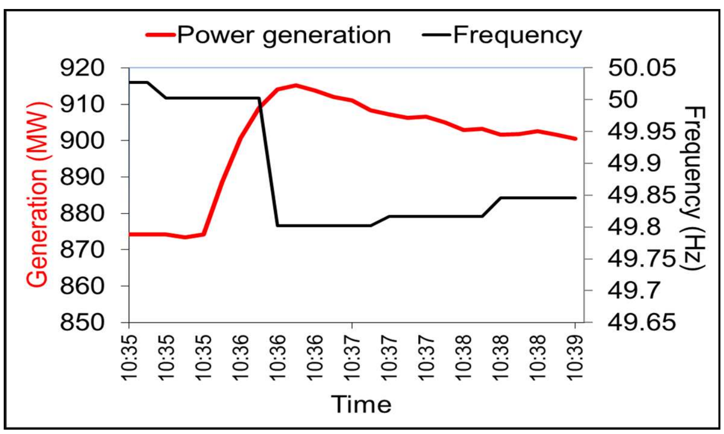

Figure 1:Variation of grid frequency and unit generation captured through SCADA during a grid event

In the Indian power system, synchrophasor technology was deployed in the year 2010 on a pilot basis and by the year 2015 large scale phasor measurement units (PMUs) were installed under URTDSM project. To overcome the inherent resolution and time synchronization related issues of SCADA data, PMU data have also been utilised. The resolution of PMU data is very high and is captured at a rate of 25 frames per second (40 ms resolution) with time synchronization. However, at present PMUs are installed at very few generating unit terminals in Eastern Region. To overcome this limitation, PMU data from all outgoing feeders from the generating stations can also be used to estimate total power output from the generating station. This will provide the entire power plant's PFR during any frequency event. For example Figure 2 shows the network connectivity of the generating station whose response evaluated from SCADA data is shown in Figure 1. Generating station Gen G is connected to substations A and B through 400 kV double circuit transmission lines. PMUs are installed on these lines at substations A and B. Hence with the help of PMUs, total incoming power flow from Gen G to substations A and B can be measured. Now it can be observed that total power generation at Gen G will be the negative of summation of power flow measured by PMU installed at substations A and B for incoming feeders from Gen G including auxiliary and other power consumption at Gen G and Power flow loss through feeders from Gen G to substations A and B [9].

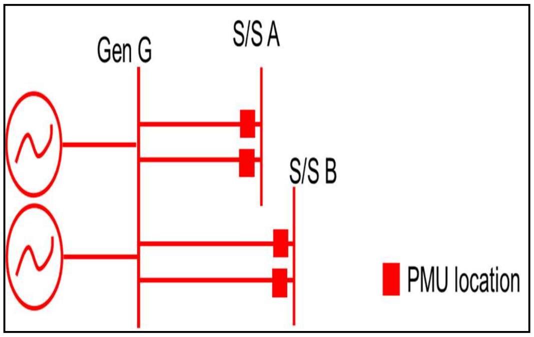

Figure 2: Network connectivity of the generating station whose response is shown in figure 1.

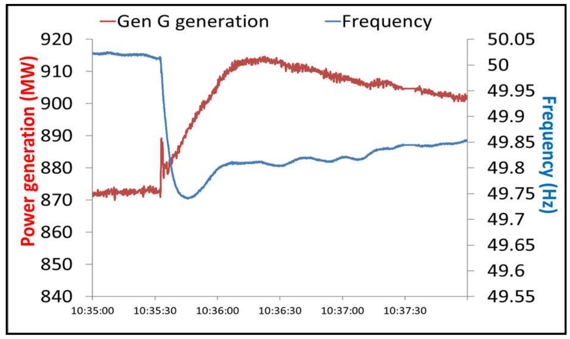

Figure 3: Measurement of power generation at Gen G shown in Error! Reference source not found. **with the help of PMU at S/S A and S/S B.**

Gen G here is a thermal power plant, auxiliary and other power consumption at Gen G and power loss in transmission lines are very less compared to its total power generation. Further, auxiliary power consumption and power loss do not vary with frequency. So, these can be ignored and thus power flow summation of outgoing lines measured at remote ends provides a better overview of the total power generation from the power plant. The PFR evaluation for the same event using PMU data is shown in Figure 3. It is clear from Figure 1 and Figure 3 that steady-state change in frequency and power generation are captured in SCADA, as well as PMU data however transient variation, has been captured with PMU measurement.

In Eastern Region, PMUs are not available at all feeders and transformers connected to generating stations. Hence PMU based analysis is not possible for all generating stations. Moreover, due to the non-availability of PMU at generating unit terminal, unit-wise response cannot be evaluated based on PMU data. To overcome this problem, generators have been asked to share unit-wise generation and frequency/speed data whenever a sudden change in frequency is observed. As these data are captured at generating unit terminal, approximation for unit auxiliary consumption and loss are not required to be taken care of during evaluation. However, the analysis of the performance shown by any generating unit depends on the resolution of data shared by the plant. It can be observed in Figure 4 that though the resolution of unit distributed control system (DCS) data is better than the SCADA data, however, the initial perturbation of generating unit power output (captured in PMU data and shown in Figure 3) is not captured in generating unit DCS data (Figure 4).

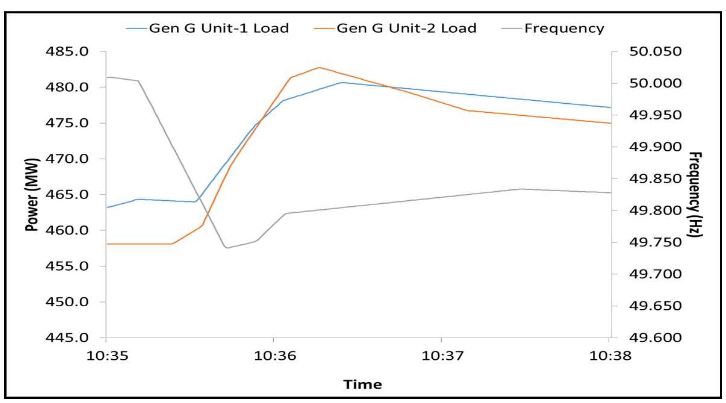

Figure 4: Unit wise Power flow and frequency variation captured at DCS data for event shown in Figures 1 and 3.

In addition to this, while evaluating primary frequency response, observing transient behaviour of generating unit, particularly at the time of sudden frequency change is extremely important. During this time, generating unit's' electric power output may induce some low frequency oscillation which cannot be captured by SCADA data or unit DCS data. These low frequency oscillations may be detrimental when the system is in a stressed condition. To monitor the performance of generating unit, it is recommended to install PMU devices at generating unit terminal also.

4. Type of unsatisfactory responses observed and their reasons

Generally, the mechanism of response of the hydropower plants is relatively less complex and is done by simply using extra water flow. Therefore, the performance of hydro units is relatively more stable and consistent. Hydro units run with overload capacity only during high hydro season to harness green hydro energy to the fullest possible and are exempted from providing PFR as per Indian Electricity Grid Code. However, thermal units provide a primary response from the energy stored in steam and therefore the steam pressure control loop also interacts with the primary frequency response loop. It increases the complexity of the process and response varies widely and needs regular tuning based on past performance. Performance of Eastern Region thermal generating units are analysed for primary frequency response for various frequency events. Generator electrical power output variation is evaluated based on the variation captured in frequency or rotor speed. Based on the detailed analysis, types of unsatisfactory responses observed are as follows:

A. Non-adequate primary frequency response: It is well established that electric power output from any generating unit should vary based on its droop characteristics and change in frequency. However, it was observed that primary frequency response in some of the units/plants is much less than the ideal response required as per IEGC. Some reasons identified for non-adequate primary frequency response are as follows:

- **Improper droop setting:** As per IEGC, the droop setting of generating units should be between 3% and 6%. But in some cases, droop setting of generating units were kept at more than 6%. As a result, the primary frequency response of those generating units was very less. After evaluation of performance, same was intimated to generating units and droop setting was corrected in accordance with IEGC.
- **Valve wide open operation of thermal generating units:** As per IEGC, thermal generating units should not be operated in valve wide open operation mode at any instant. But in some cases, it was observed that due to various technical reasons, generating units were operated at valve wide open operation. As a result, adequate margin for primary frequency response was not available. The said generating stations were notified regarding the violation of IEGC and advised not to run the units in valve wide open operation.
- **Unit generation more than maximum continuous rating (MCR):** As per IEGC, generating units are not allowed to be scheduled at more than 100% of maximum continuous rating (MCR) to ensure margin for primary frequency response. In some cases, it has been observed that generating units were operated at more than MCR. This resulted in depleting the PFR margin and the response of the plant was not adequate during the events. Such generating plants have been advised not to run the generating units at more than MCR so that sufficient margin for primary frequency response can be ensured.
- **Type of governing system:** There are some generating units where restricted governor mode of operation (RGMO) cannot be deployed as governors are of old electromechanical type. Those generating units have been advised to run in free governor mode of operation (FGMO) with manual intervention as per IEGC. In case of inability to provide any type of primary frequency response, generating stations have been advised to retrofit their governing system.

B. Non sustained primary frequency response: In some cases, the response of thermal generating units was adequate as per the droop setting recommended in IEGC. However, the initial response did not sustain for adequate time. Figure 5 shows the variation of a 500MW thermal generating unit output during an event of a sudden frequency drop. The response is withdrawn within 10 seconds due to drop in steam pressure. It was learned that the unit was being run without sufficient throttle pressure. As per IEGC, after providing governor response, power plant can withdraw the response at a rate less than 1% of unit capacity per min in case of the event with sudden frequency dip. Hence the generating station was advised to keep sufficient margin in steam pressure and tune the governor system so that primary frequency response can sustain for 3-5 min and unit output can step back to its original MW level at a rate not more than 1% of unit capacity per minute.

C. **Longer time taken to provide full primary frequency response:** For providing primary frequency response, unit power output should change immediately (within 5-6 seconds) during the event of a sudden frequency change. However, during some events, the time taken to provide adequate response for some of the generating units was observed to be high and frequency improved before the unit provided full response. Figure 6 shows the variation of power output of a generating unit with variation of its turbine speed. Though the response of unit was adequate as per its droop setting, yet around 2 minutes were taken for providing desired frequency response and the frequency got restored to almost its pre-event value within this period.

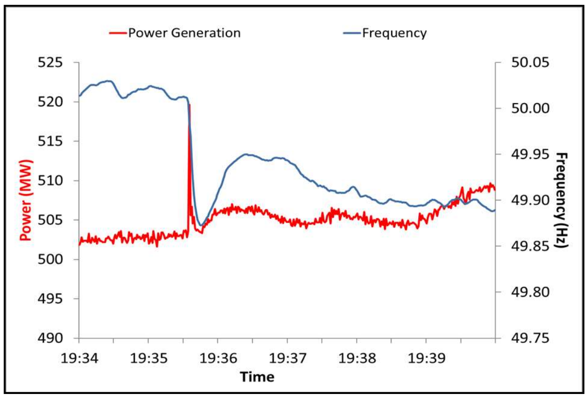

Figure 5: Response of 500 MW generating unit during the event of sudden frequency dip.

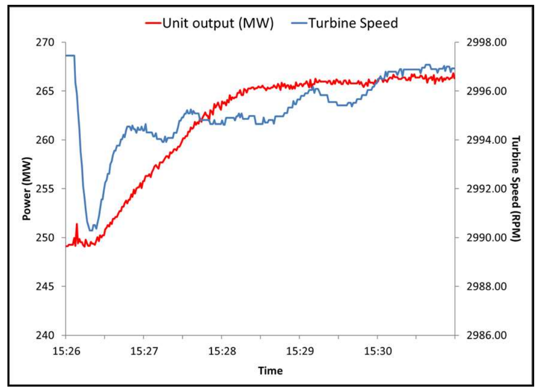

Figure 6: Variation of unit output with turbine speed indicating delayed full response.

During the analysis, it was observed that the setting of governor was as per normal ramping value which was quite low leading to delayed response. Based on this, the generating station was advised to tune the governor so that unit could provide its full response within 30 seconds.

D. **Oscillatory primary frequency response:** Figure 7 shows that PFR of generating unit was adequate as per droop setting. However, power output from the generating station was oscillatory in nature due to controller malfunction. Mode of oscillation was in controller mode range i.e., less than 0.2 Hz. Generating station was advised to tune their governor to prevent generator hunting while providing the primary frequency response.

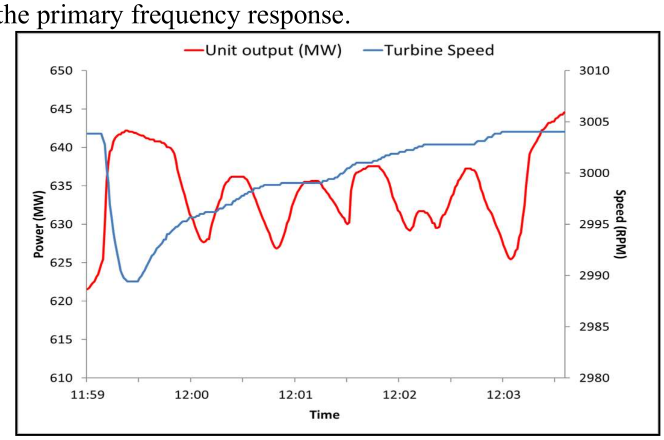

Figure 7: Oscillatory power output from generating units while providing primary frequency response

E. **Inability to detect the event of sudden frequency change:** As per the regulatory provisions, generating units are mandated to increase their power output instantly when frequency falls suddenly. In order to prevent governor hunting for small frequency variation, ripple filter of +/- 0.03 Hz is to be implemented in RGMO logic. Initially, few generating stations faced difficulty in detecting events of sudden frequency change. After frequent consultations with stakeholders and knowledge sharing with generating stations, this problem has been overcome.

Discussed case studies in this section and their associated analysis and finding suggested to review methods used by generating stations to detect sudden frequency change. This is required in order to check inherent issues with logic, any change required for improving the primary response. These logics are explained in the following section.

5. Technique used for implementing RGMO logic in generating plants

5.1. Methods used by generating stations to detect sudden frequency change

For RGMO, governor control tracks the grid frequency whenever frequency is below 50 Hz and acts only when a sudden change in frequency is detected. Following techniques are used by generating stations for detection of any sudden change in frequency in order to implement restricted governor operation (RGMO) logic for compliance with the regulatory provisions.

A. **Moving average of system frequency:** Some generating stations use moving average of system frequency or speed of the turbine. In case there is sudden change in frequency, moving average will also change. In such cases time to sense sudden frequency change will depend on time period of moving average. Thus, shorter the time period, quicker will be the detection of frequency change for the governor to act. However, sensitivity of the governor also increases with the reduction in the time period. Thus, with a shorter time window, generators may also respond to frequency change caused by normal load variation and switching of lines nearby the generating stations. Further, the resolution of data used to calculate moving average is also important as lower resolution data may not be sufficient for detection of frequency change. Generating stations are required to tune both the time window and resolution of the data so that the governor doesn't respond to transient frequency variation by load/generation variation and network switching.

B. **Measuring Rate of change of frequency (RoCoF df/dt):** Some generating stations use df/dt to detect the event of sudden frequency change and below as per designated level. Again, with the change in the inertia of the grid, df/dt at generating stations will change for loss of same load/generation. Hence governors of generating units are to be tuned continuously so that correct df/dt can be obtained. Further, the time period for which df/dt is to be calculated is of significance importance. This need to be tuned based on experience as df/dt is susceptible to noise/vibrations as well as voltage transients depending on the measurement signal source.

5.2. Methods used by generating stations to hold response when frequency increases towards 50 Hz after the dip

Generally holding of response when the frequency is improving from a lower value towards 50 Hz is done by the use of a soft hold timer logic. Many plants especially thermal plants use 5 min fixed hold time, and some plants reset the hold timer and withdraw the response if the frequency crosses 50 Hz and starts increasing towards the upper side. It is first important to have sufficient steam pressure for providing adequate response and subsequently they can withdraw as per unit capacity. It has been observed that thermal units can provide a sustained response with adequate pressure available if not running in valve wide open mode.

6. Improvement of primary frequency response of generating units

Initially, the primary frequency response provided by generating units was not adequate for most of the generating stations. As a result, post-event frequency remained the same as Nadir frequency. Continuous consultations with generating stations were conducted at different levels. Generating stations shared the challenges they were facing and remedial action they took to overcome those issues. Frequency Response Characteristics (FRC) is used to measure frequency response contribution by any control area [7]. Figure 8 shows FRC of the Indian grid which increased almost five times only in the last 8 years. It increased from 6500 MW/Hz in 2014 to 35000 MW/Hz in 2022. During some incidents, the FRC of the Indian grid was recorded as high as 55000 MW/Hz also.

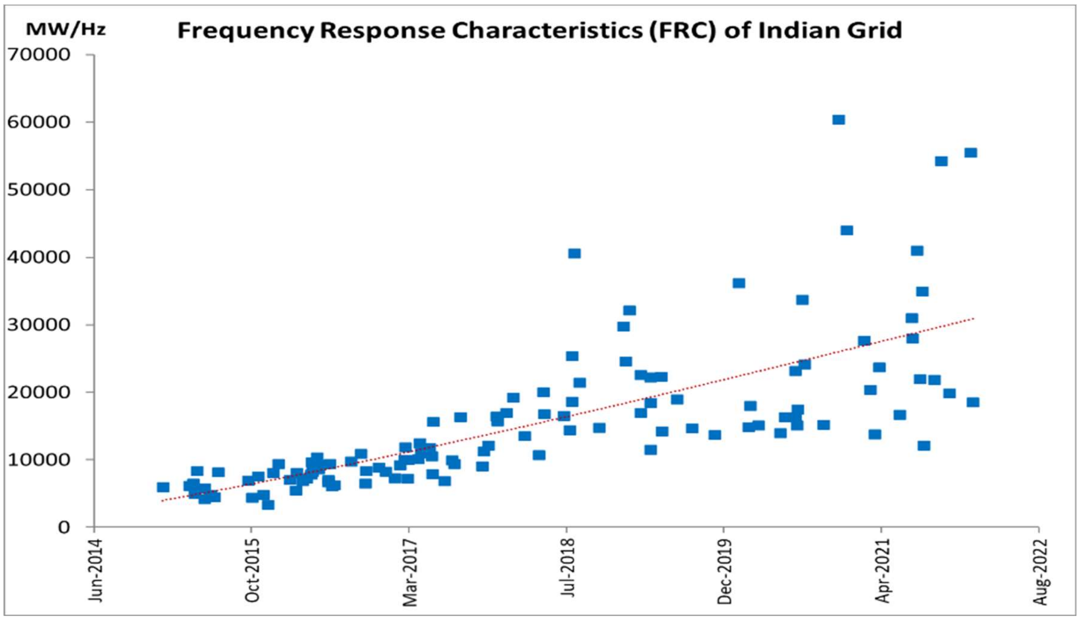

Figure 8: Frequency response characteristics (FRC) of Indian grid

This improvement in FRC is due to two major contributing factors out of which the first factor is the correction in logic and resolution of identified challenges for FGMO response by generating plants. Regulatory commission through grid code has now mandated frequency response testing of regional generating units by third party agency [10]. Primary frequency response testing of generating units also helped to correct PFR logic and improve PFR of generating units. At the same time, there has been significant addition of synchronous generating units in the system. This improvement in frequency response is going to help the Indian power system in better frequency control. With increasing RE penetration, having an adequate primary response is essential to meet the frequency stability criteria.

7. Summary

The paper provides an overview of primary frequency response requirements and associated regulatory provisions in the Indian power system. It further highlights the restricted governor mode of operation logic, challenges observed in evaluation of response, issues and reasons related to generators in providing adequate response and required remedial measures taken in their improvement. The paper highlights the improvements observed over the year in the frequency response by generators with the help of several practical cases. Overall, the paper provides an outlook on the improvement in the primary frequency response in the Indian power system focusing on the eastern regional grid.

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