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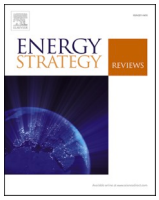

Role of hydro generation in Indian power grid to challenge the uncommon load patterns during crisis

Kannadasan Raju [a], Venkatesan Chandrasekaran [a], Mohammed H. Alsharif [b], Mun-Kyeom Kim [c,*], Jamel Nebhen [d]

[a] Department of Electrical and Electronics Engineering, Sri Venkateswara College of Engineering, Sriperumbudur, Chennai, Tamilnadu, 602117, India
[b] Department of Electrical Engineering, College of Electronics and Information Engineering, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul, 05006, South Korea
[c] Department of Energy System Engineering, Chung-Ang University, 84 Heukseok-ro, Dongjak-gu, Seoul, 156-756, South Korea
[d] Prince Sattam bin Abdulaziz University, College of Computer Engineering and Sciences, P.O. Box 151, Alkharj, 11942, Saudi Arabia

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ABSTRACT

Recently, the Indian Prime Minister Appeals to switch off the Light by people during the corona outbreak for 9 min. It also provides a significant challenge to the Indian power grid. A small malfunction of the power system may lead to a huge disaster that may worsen the daily activity of the 100 million people along with the pandemic. This review work discusses the actions of Indian power grid operation during the challenge when all the domestic Light loads are switched off for 9 min from 21:00 Hours. POSOCO (Power system Operation Corporation) of India handled the difficulty using effective actions and logged the total reduction in all India demands of about 31,089 MW (31 GW) during the event. Before the event, Indian power demand started dropping from 20:45 Hours and reaches 85,799 MW at 21:10 Hours. Subsequently, after the event, the demand begins inclined and settled around 114400 MW at 22:10 Hours. During this complete process, the grid frequency remained between 50.26 Hz and 49.70 Hz. On the other hand, the preliminary mock exercise was conducted by POSOCO before the day of the actual event and reported the expected load reduction of 15085 MW. It was anticipated by summation of SLDCs (State Load Dispatch Centers) which was half value with reported load reduction during the actual event and shows higher variance. This article also interpreted the reports of POSOCO and estimated that the actual Load reduction of this event was about 27452 MW taking place for 15 min. From the discussions, it is observed that the hydro generation schedule have the potential to minimize the havoc of the power system during steep increase and reduction of load demand during unexpected natural or artificial calamities.

1. Introduction

COVID-19 emerged at the end of 2019. It has already established its potential to create volatile epidemics in confined locations and cross borders following human mobility patterns [1–3]. Initially, it is a health calamity and enforced governments to take extraordinary actions to shield people's lives [4]. Later it becomes a massive crisis for monetary markets and vulnerable industries globally.

In India, the Coronavirus spread across the country and collapses the complete system because of the lockdown laid by the government. It affects the Indian economy in all sectors because about 1.3 billion people are self-locked within their homes [5]. Therefore, the power demand pattern picks a reverse trend, i.e. residential demand takes the upper hand while industrial and commercial demand decline significantly. Consequently, Distribution companies in India are in a massive loss of revenues due to the steep reduction of power demand from both industrial and commercial customers [5]. The power system corporation (POSOCO) of India faces more challenges to meet the diverse change in the daily loads. Additionally, the Indian Prime Minister called the Indian people to challenge the darkness spread by the Coronavirus by switching off their lights and lighting their candles for 9 min from 21:00 Hours on 5th April 2020 [6]. It tossed a new task for the POSOCO because the load reduction due to this event would be enormous; millions of people are confined in their homes due to the lockdown. Moreover, POSOCO does not have any standard database/guidelines to estimate the Load

* Corresponding author.
E-mail address: mkim@cau.ac.kr (M.-K. Kim).

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List of abbreviations

D/C	Double circuit
ER	Eastern region
ERLDC	Eastern RLDC
HVDC	High voltage Direct Current
NER	North-Eastern region
NERLDC	North-Eastern RLDC
NLDC	National Load Dispatch Center
NR	Northern region
NRLDC	Northern RLDC
POSOCO	Power system Operation Corporation
Q/C	Quad circuit
RESs	Renewable energy sources
RLDCs	Regional Load Dispatch Centers
S/C	Single circuit
SCADA	Supervisory control and data acquisition
SLDCs	State Load Dispatch Centers
SR	Southern region
SRLDC	Southern RLDC
STATCOM	Static compensators
SVCs	Static VAR Compensators
UHVAC	Ultra-high voltage alternating current
WR	Western region
WRLDC	Western RLDC

reduction for the upcoming event (Switching off lighting loads alone across the country). The Indian power grid is one of the largest and most intricate networks in the world comprising millions of consumers integrated through various Load dispatch centers for the entire country therefore maintaining the stability of the grid becomes a tough task. This complex context may offer a severe disturbance during the event. A small collapse in operation during the event may turn into a complete Blackout, as happened in July 2012 [7–9] which may stretch an additional burden on the country and people along with the Corona crisis.

Globally, several technical failures are recorded in the power system network worldwide. At an extreme point, it results in a blackout that has the potential to cause severe economic losses and brought trouble to people. Moreover, it has direct waves on modernization, financial, political, and social features. There are many technical reasons logged for this failure such as overloading, line tripping, voltage drop, malfunction in power components, mechanical failures, cyber-attacks, etc. However, the most common reason for this failure is a load-generation imbalance. Because this power imbalance between load and generation causes severe frequency instability and the reactive power imbalance has a direct relationship with voltage uncertainty. Globally, hundreds of such glitches in power systems were recorded by various countries in recent times notably on 10th January 2018 in Sudan; 3rd July 2018 in Azerbaijan; 21st March 2018 in Brazil; and 20th December 2018 in Canada (BC) [10]. Most of the events discussed above are unanticipated and tedious to handle and have separate counter-operations required to maintain the stability of the power system. Some other works reported the anticipated event which is similar to the 9-min event proposed by the Indian prime minister. Notably, Sarah et al. accumulated 274 computations of observed variations in power demand produced by Earth Hour occasions in 10 countries for six years. It was observed that this event reduced power consumption by an average of 4%. It also9 recorded that the range of variations is +2% (New Zealand) to −28% (Canada) [11]. The attained sharp peaks and drops result in incompetent generation necessities and potentially lead to grid failure. This event was executed to demonstrate the significance of short-term behavior on energy demand and possible applications to energy policies. Meier et al. reported about 6 GW of electricity demand was fallen on a weekday, notably at 12:00 noon, and returned to the pre-lunch trend at 13:00 in Japan. The authors investigated the reasons for Japan's 6 GW lunch break and it was found that the Industrial users and residential consumers are not responsible for this event; instead, a blend of practices and behaviors in the commercial segment seems to be accountable for the drop in electricity use [12]. Relating all these inferences to the light-off event, the probability of technical failure occurrence is more for the Indian grid during the actual event taking place [13].

Further, this article discusses the various activities of the POSOCO carried out to handle the event successively and organized as follows: Section 2 discusses the overview of POSOCO comprising the particulars of national, regional, and International power transactions. Subsequently, Section 3 presents the complete mock exercise carried out by POSOCO before the event like the estimation of all-India lighting load, the estimation of expected all-India Load reduction, the algorithm for Generation scheduling, operating margins, and voltage measures. Further, Section 4 demonstrates the actual event, and Segment 5 interprets the event reports. Section 6 discusses the lesson learned from the light-off event from a global view. Lastly, Section 7 concludes by highlighting the various processes of the event.

2. POSOCO (Power System Operation Corporation)

2.1. National grid

POSOCO is an Indian government agency under the Ministry of Power implemented for nationwide power operation via NLDC (National Load Dispatch Center). NLDC is located in New Delhi functioning for optimum scheduling and dispatch of electricity among the Regional Load Dispatch Centers (RLDCs) [14]. The critical functions of POSOCO are depicted in Fig. 1.

Further, NLDC also acts as an apex body to guarantee the integrated operation of nationwide power operation through Regional Load Dispatch Centers (RLDCs). For reliable operation, these RLDCs have been divided into five centers, namely SRLDC (Southern RLDC), NRLDC (Northern RLDC), ERLDC (Eastern RLDC), WRLDC (Western RLDC), and

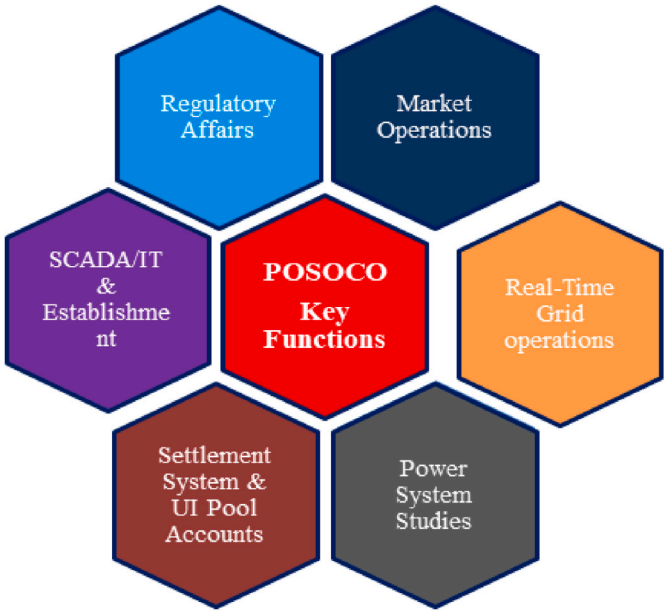

Fig. 1. Key functions of POSOCO(data retrieved from Ref. [14]).

NERLDC (North-Eastern RLDC) [9,15]. The operational scale of the Indian power system Operation Corporation is presented in Table 1(dated February 2020) [16].

The total all-India demand observed from the above figure is about 174 GW with a peak shortage of 606 MW i.e. 0.347%. Besides, the overall frequency profile on a specific day is logged as 50.05 Hz which warrants the power balance between the load and generation. The breakup of total installed capacity and actual generation by the Indian power grid (source-wise) is illustrated in Fig. 2.

From the figure, it is listed that the majority of the Indian power demand is met with a Coal-based generating station, i.e. 73% of generation contribution versus 54% of installed capacity. It continues the dominant though the installed capacity of Renewable energy sources (RESs) based generation takes place at about 23% of installed capacity. Furthermore, Hydro and RES are contributing about 18% [17] though their installed capacity attains 35%.

2.2. Regional grids

As it is stated earlier, NLDC comprises five RLDCs such as NR (Northern region), WR (Western region), SR (Southern region), ER (Eastern region), and NER (North-Eastern region) [15,18,19]. The complete grading of POSOCO is represented in Fig. 3.

Also, SLDCs are integrated with various generating stations, Substations, Load centers, protective and measuring equipment within the state, and communicating the grid data with respective RLDCs. The demand patterns and their scale in each region are represented in Fig. 4. WR integrates with five SLDCs and has the highest demand scale of about 32% of the total Indian demand, but it contributes to the grid about 40% (Fig. 5) of the whole generation [6,16]. Similarly, the generating capacity of ER (five SLDCs) follows the same trend which has a demand of about 10% but generation extents of about 13%.

It is stated previously, WR generation plays a significant role in the Indian power sector as it displays a good trend in all sources of generation except Lignite (Fig. 6). The regional generation scale also maintains the same trend as the Coal-based generation lead plot (Fig. 7). The Utilization of alternative energy resources is not showing good figures in all regions except SR. RES integration policies have a superior impression and value in the SR compared to other parts of RLDCs.

To transact the power between the regions, a high power transfer capacity of Transmission lines are essential. POSOCO handles the power transaction using 765 kV, 400 kV, 220 kV, and 132 kV transmission lines comprising Single, Double, and Quad circuits. Also, ten HVDC transmission lines are used. The nature, topography, and quantity of the Transmission lines are given in Table 2.

2.3. International transactions

The Indian power sector has implemented and operated with higher capacity HVDC and UHVAC systems successfully, and it connects the neighboring countries electrically through transmission lines. POSOCO transacts the power from/to three neighboring countries, namely Bhutan, Nepal, and Bangladesh [20]. The nature of the transaction is displayed in Fig. 8.

Table 1
Scale of Indian power systems Operation Corporation (data retrieved from Ref. [16]).

Parameters	Unit	Values
Peak demand	MW	174,625
Peak shortage		606
Energy met	GWh	3683
Hydro generation		332
Wind generation		115
Solar generation		157
Frequency profile	Hz	50.05

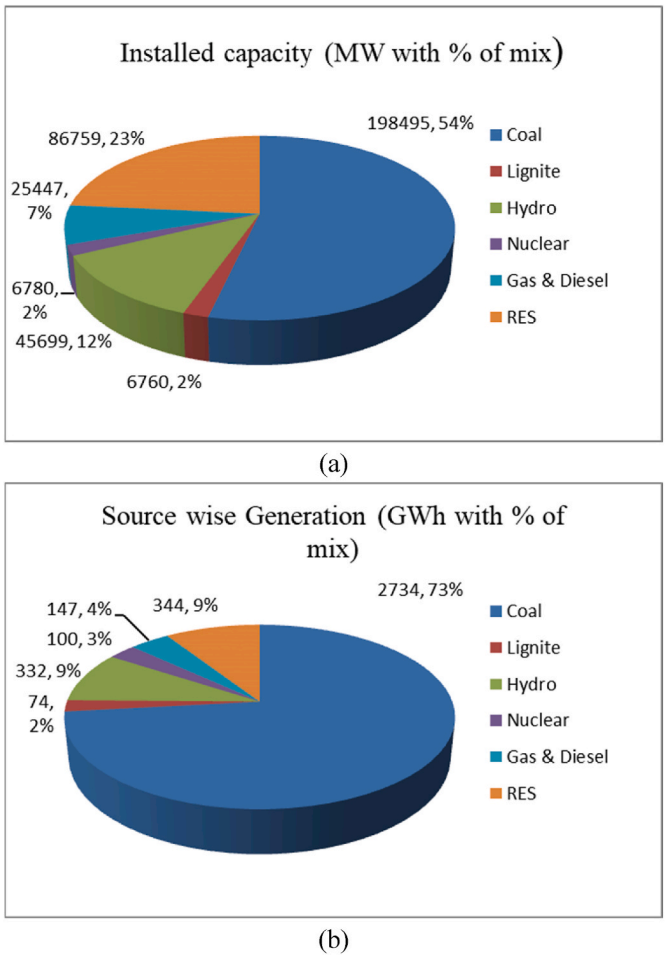

Fig. 2. Breakup of (a) total Installed capacity (MW with % of source mix) and (b) actual generation (GWh with % of source mix) (data retrieved from Ref. [17]).

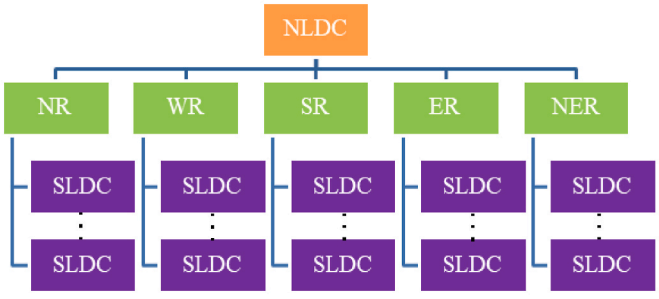

Fig. 3. Structure of Indian Load dispatch centers.

The positive scale represents the importing of Power from other countries, i.e. Bhutan. The negative range represents the exporting of power from the Indian grid to neighboring counties, i.e. Nepal and Bangladesh.

3. Mock exercise

The core reason for this article cope with the appeal of the Hon'ble Prime Minister of India to the citizens to switch off their lights and light lamps/candles at 21:00 Hours for 9 min on 5th April 2020 to challenge the darkness extent of the Coronavirus (COVID-19) crisis [6]. To guarantee reliable and secure grid operation during this event, POSOCO did a

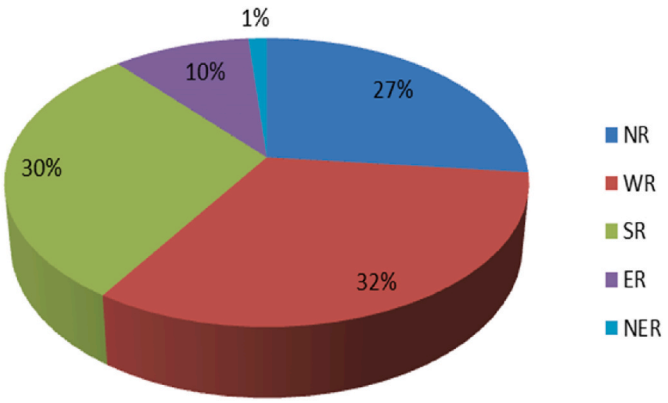

Fig. 4. Regional power demand breakup (%).

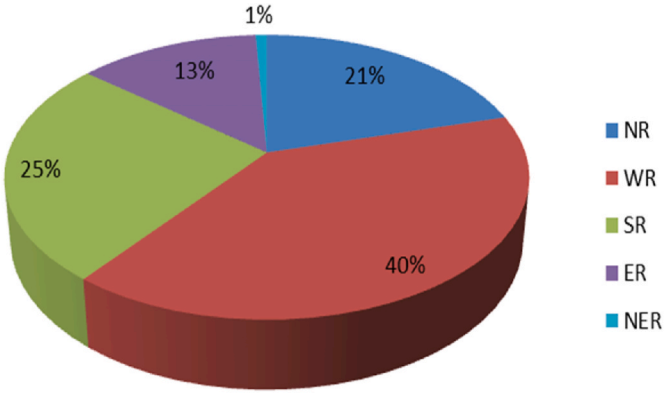

Fig. 5. Regional power generation breakup (%) (data retrieved from Ref. [6]).

mock exercise on the 4th of April 2020 night and the 5th of April 2020 morning with hydro ramping [21]. In connection with this, an attempt was made to estimate all India Lighting load and Load reduction for the upcoming event using two steps. The comprehensive course of the mock exercise is discussed below.

3.1. Estimation of all India lighting load

The Lighting load from all India Demand was estimated based on the evening demand pattern of 29th March 2020. As the considered date has fallen on Sunday, it was assumed that the commercial loads were not involved. The lowest demand rate of 101207 MW was taken as the reference at 18:07 Hours as shown in Fig. 9 [21].

Further, demand increased and obtained a peak value at 19:10 Hours. Subsequently, the demand rate declined and obtained 112551 MW at 21:00 Hours (the actual time of the upcoming event). Hence, it was anticipated that the total lighting load during the actual event might be the difference between the time 18:07 and 21:00 Hours, i.e. 11344 MW.

3.2. Estimation of all India load reduction

In addition to the above, another exercise was carried out to estimate all India lighting load reductions based on the number of domestic/household consumers at the grid level as given in Table 3 [21].

The estimated value reflected at the grid level was about 12452 MW. These load reduction trends between the regions are shown in Fig. 10 [21].

From the above analysis, it was inferred that the total all-India load reduction would be between 12 and 14 GW and might happen for 2–4 min. It might recover after 9 min by taking 2–4 min. The gird frequency might be around 49.50–50.5 Hz during the diverse household lighting loads. This inverse steep load reduction and steep recovery would be unparalleled; hence, this event would be effectively handled through Hydro and Gas generating stations.

3.3. Algorithm/steps for generation scheduling and frequency control

The most difficult aspect of dealing with the event was to coordinate the sharp pace of progress of demand with matching change in generation across the country. The expected abrupt changes in load were wanted to be overseen through high ramping resources (Hydro generation) with cyclic capacity. The timetable of these high-ramping resources was painstakingly organized to accomplish the greatest adaptability during the event. Vital arrangements in other generation sources, for example, slow-sloping coal-fired stations alongside the wind farms were additionally guaranteed to get the ideal generation alleviation. Further, the advantageous voltage profile alongside the dependability of the transmission network was guaranteed by taking adequate

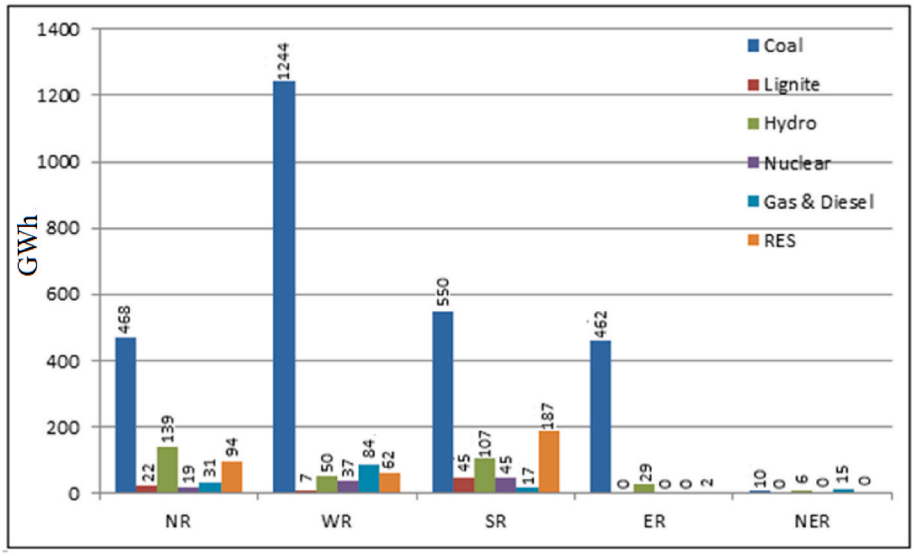

Fig. 6. Regional power generations GWh (source-wise).

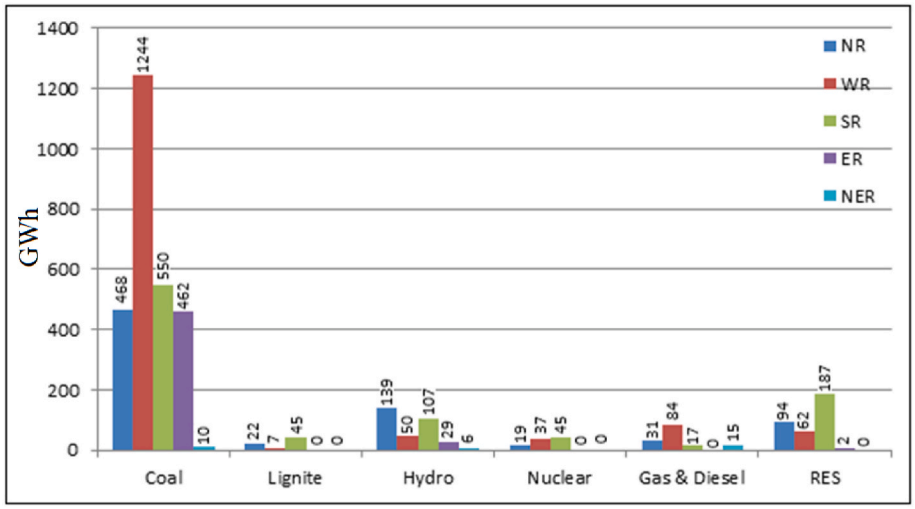

Fig. 7. Source-wise generations GWh (Region wise) (data retrieved from Ref. [6]).

Table 2
Transmission lines and their voltage ratings between regions (data retrieved from [16]).

Lines b/w		HVDC	765 kV			400 kV			220 kV		132 kV
			S/C	D/C	Q/C	S/C	D/C	Q/C	S/C	D/C	S/C
ER	and NR	2	2	1	–	2	4	1	1	–	4
	and WR	–	–	2	1	–	1	1	1	1	–
	and SR	2	–	1	–	–	1	–	1	–	–
	and NER	–	–	–	–	–	2	–	–	1	–
NER	and NR	1	–	–	–	–	–	–	–	–	–
WR	and NR	3	2	4	–	3	1	–	4	–	1
	and SR	2	–	2	–	–	2	–	1	2	–
Total		10	4	10	1	5	11	2	8	4	5

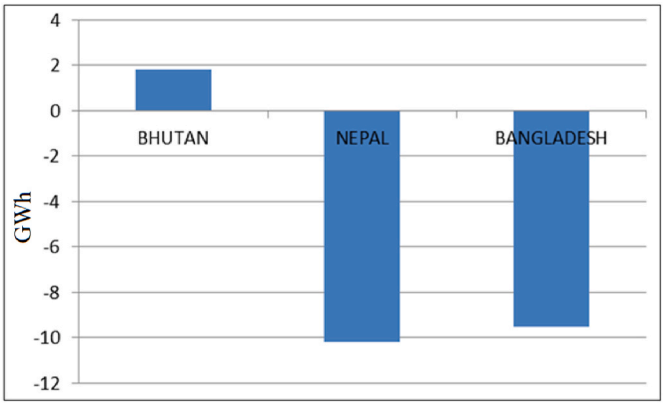

Fig. 8. International transactions in GWh (data retrieved from Ref. [20]).

preparation in view of the load flow simulations and other laid-out inputs.

The general procedure for generation schedule and Frequency control is given in Fig. 11. The actual steps followed by the POSOCO to conduct the mock exercise are as follows,

Step 1. Synchronized all the generating station clocks in IST (Indian Standard Time)

Step 2. Hydro generation was reduced and conserved from 18:10 to 20:00 Hours. Simultaneously, thermal and gas generation was scheduled to meet the demand.

Step 3. Before 5 min of the event, Interstate generating stations (ISGS) were reduced gradually by about 60%. Simultaneously, Hydro generations were ramped up to meet the demand.

Step 4. During the event, lighting loads started to reduce, and hence Hydro and Gas generations were ramped down to match the grid frequency. Hydro generations were kept rolling between 0 and 10% of the rating and Gas generations were ramped down to the minimum level.

Step 5. After the event, Thermal machines were committed gradually. Additionally, hydro generations were ramped up to meet the demand.

Step 6. After stabilization, Hydro generations were utterly withdrawn from the grid using under-frequency relays.

Step 7. At 21:30 Hours, the grid frequency increased to more than 50.2 Hz. Hence, Wind generating plants were disconnected from the grid using over-frequency settings.

Precautionary measures and expected post-actions:

- For better ramping of resources, SCED (Security constrained economic Dispatch) might be stopped from 18:00 Hours onwards and resumed after the event.
- Grid frequency might be kept at the lower side of the band about 49.90 Hz from 23:00 onwards.
- Grid frequency on the higher side might be 50.15 Hz around 21:09 Hours.
- At 12:00 Hours, the droop setting of hydro plants might reduce from 4-5% to 1–2%. It would be reversed on the next date of the event.
- Ensured the healthiness of all protective mechanisms, namely under frequency relays, df/dt relays, and automatic demand management systems.

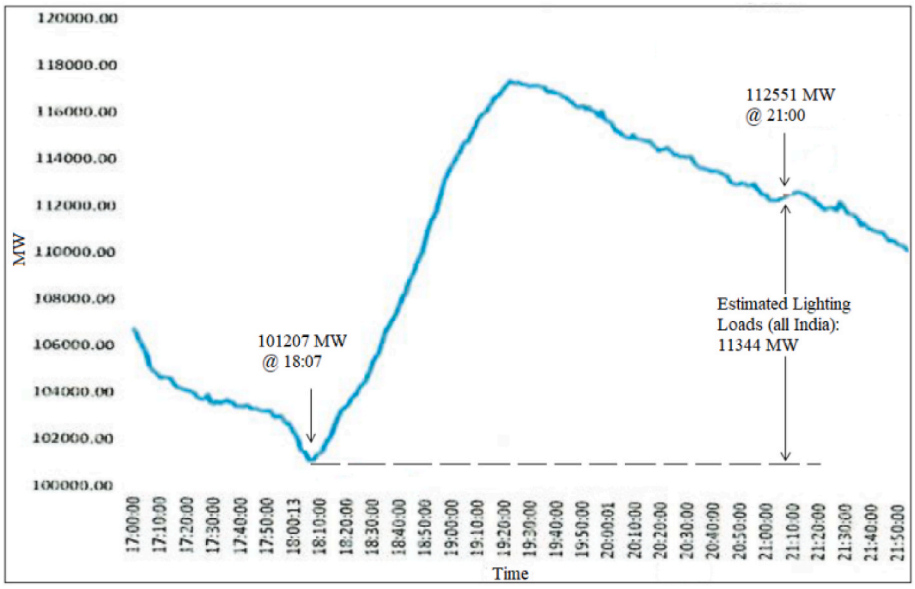

Fig. 9. All India Demand pattern (29th March 2020) [21].

Table 3
Estimation of total lighting load reduction (data retrieved from Ref. [21]).

Region	A	B	C	D	E	F	G	H
NR	42293470	13214064	2115	1321	1692	1057	2749	3054
WR	35669904	19020928	1783	1902	1427	1522	2948	3286
SR	43854642	4668665	2193	467	1754	373	2128	3407
ER	41183918	4515705	2059	452	1647	361	2009	2168
NER	8362568	1689177	418	169	335	135	470	537
Total	171364502	43108539	8568	4311	6855	3449	10303	**12452**

Where,
A-Total no of rural household consumers (data obtained from state electricity boards).
B-Total no of urban household consumers (data obtained from state electricity boards).
C-Estimated load of rural in MW = 50*A (50 W of lighting load was assumed for each rural consumer).
D-Estimated load of urban in MW = 100*B (100 W of lighting load was assumed for each urban consumer).
E-Expected rural load reduction in MW = 0.8*C (People response factor of 0.8 was assumed).
F-Expected urban load reduction in MW = 0.8*D (People response factor of 0.8 was assumed).
G-Expected load reduction (consumer level) in MW = E + F (Summation of rural and urban loads).
H-Expected total load reduction (grid level) in MW = G/0.9 (Load reduction factor of 0.9 was assumed).

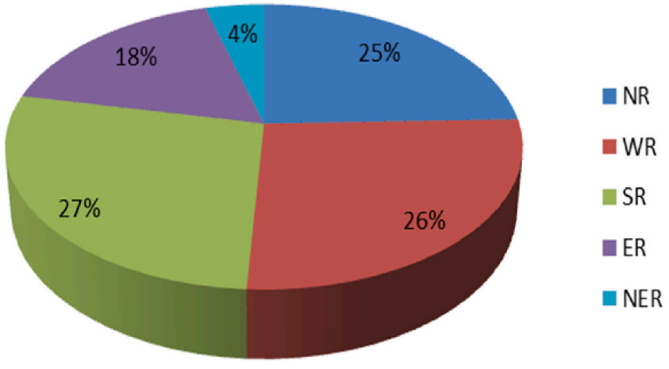

Fig. 10. Estimated lighting load reduction between the regions (%) (data retrieved from Ref. [21]).

3.4. Operating margin of hydro and gas generation

It is stated above, hydro and gas ramping was adopted to meet the steep reduction and steep rise of load demand during the mock exercise. Fig. 12 displays the maximum, minimum, and flexible power capacity of Hydro and Gas generating plants during the mock exercise and is expected the same for the upcoming event on April 5, 2020 at 21:00 Hours [14].

All India figure shows that the maximum and minimum possible generation would be 30924 MW and 11532 MW respectively (Hydro and Gas) with flexible power generation of about 19392 MW.

3.5. Voltage control measures

To maintain the voltage level in all higher voltage buses within the limit, some precautionary actions were made to overcome the overvoltages. Firstly, voltages rating of 400 kV and above transmission lines about 220–240 lines were kept in an open condition for voltage control. On the other hand, switching operations were made for transmission lines, line reactors, and bus reactors at 20:00 Hours to retain the voltages around 760kV/400 kV. Additionally, all reactors were committed to service at required locations at 20:00 Hours. Static compensators (STATCOM) and Static VAR Compensators (SVCs) were kept in voltage control mode with reference to 400 kV. The distribution level Capacitors were withdrawn in service to avoid overvoltage. Further, thermal and hydro units were allowed to absorb/generate reactive power as per the capability curve. However, POSOCO pointed out seven 765 kV and nineteen 400 kV buses which might face overvoltages during the actual

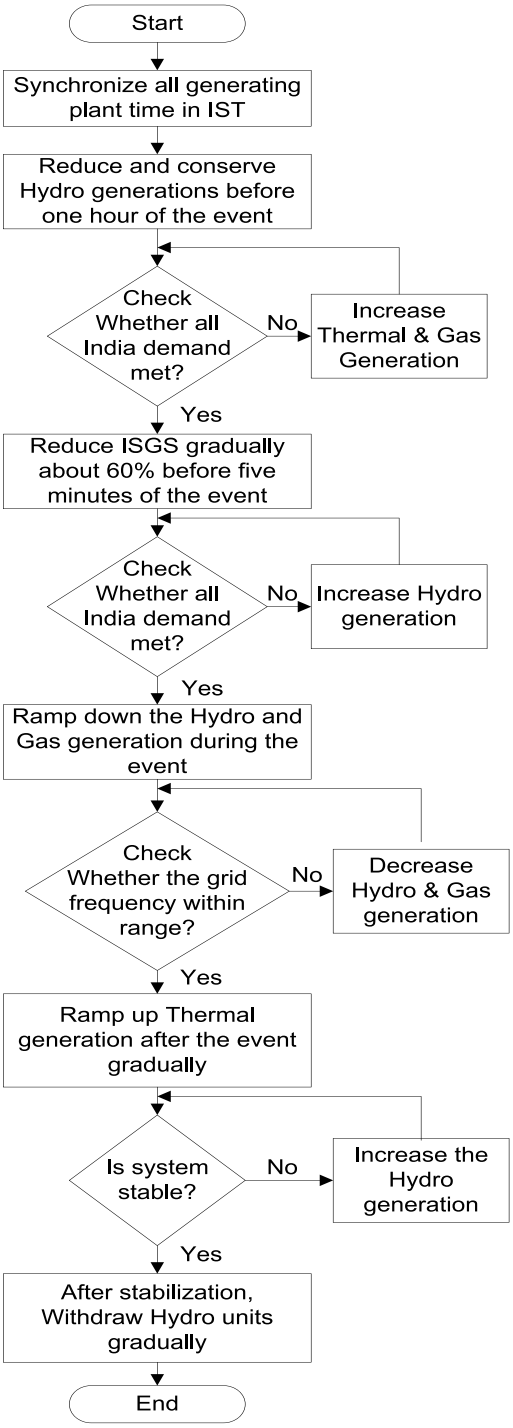

Fig. 11. Complete process of the event-general case.

event [14].

The list of buses where the voltage profile is expected to rise (recorded during mock exercise) more than 0.01p.u. is shown in Fig. 13.

4. 9 p.m.-9-Minutes event

POSOCO reported that the net reduction in all India demand logged during the event (on 5th April 2020 between 21:00 to 21:09 Hours) was about 31089 MW. It started plummeting from 20:45 Hours. The minimum demand of about 85,799 MW was noted at 21:10 Hours; consequently started picking up from 21:10 Hours and settled around 114400 MW at 22:10 Hrs. Moreover, grid frequency played a significant role

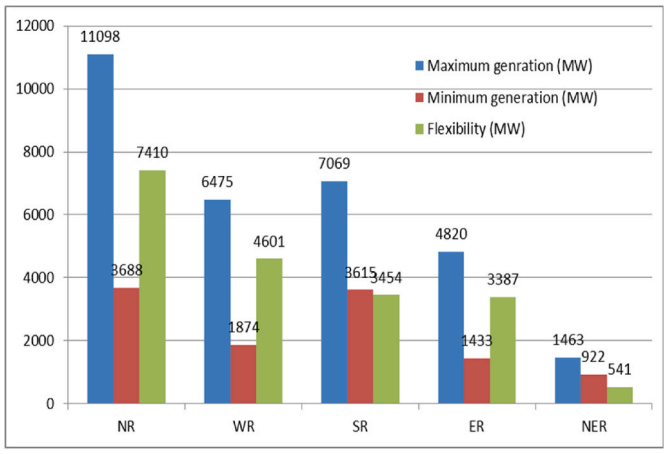

Fig. 12. Generation pattern of Hydro and Gas during a mock exercise (data retrieved from Ref. [14]).

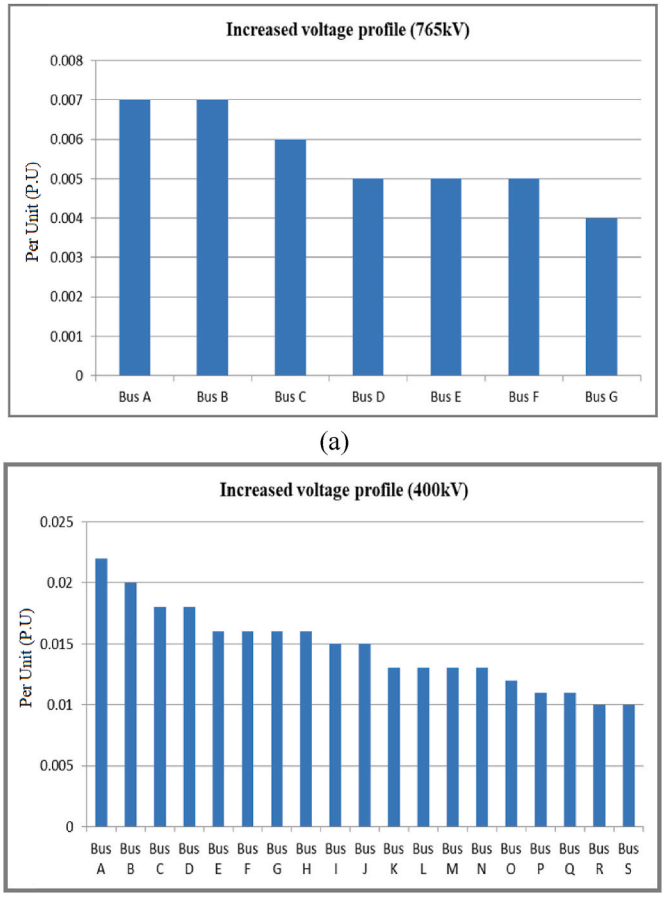

Fig. 13. Increased voltage magnitudes in p. u. (a) 765 kV (b) 400 kV (data retrieved from Ref. [14]).

during the event and was maintained between 50.26 Hz and 49.70 Hz. The maximum and minimum grid frequencies were recorded at 20:49 Hours and 21:08 Hours respectively [21].

It was estimated earlier during the mock exercise that the grid level load reduction would be about 12452 MW. But, the actual load reduction during the actual event was about 31089 MW. It is observed that

there is a massive difference between the mock exercise and actual load reduction notably about 19 GW. The reason for this immense deviation might be assessed by the utility after the actual event but not disclosed in an open forum due to restrictions in official protocols. However, it is essential to derive a rationale for this huge deviation that may support other utilities in the future when facing a similar kind of event. The following are the reasons assumed that may be rectified in future crises if any:

- The state electricity board might consider the consumers which have not participated in the official service connections (consumers getting free electricity connections).
- The load demand assumptions per consumer for rural and urban might be doubled i.e., 50 W–100 W, and 100 W–200 W for rural and urban consumers, respectively.
- The response factor (0.8) might play a small role in the huge deviations.
- The political influence of the Prime minister in specified states of India might be considered a factor.

The above-mentioned reasons represent the future activity that any utility may adapt to tackle similar kinds of events. However, a detailed study needs to be carried out considering the technical and non-technical parameters of the power system.

4.1. Operation of POSOCO and generation schedule

Steps have been followed as stated in the mock exercise (Section 3). The short process of the event is depicted below.

Step 1. Before the event, Hydro generations across the country were maximized by 20:45 Hours and their contributions were about 25559 MW. Further, the demand pattern started to decline.

Step 2. During the event, Generation reductions were carried out using Hydro from 25559 MW to 8016 MW between 20:45 Hours to 21:10 Hours to match with demand reduction of 31089 MW.

Step 3. After the event, Hydro generations were again ramped up from 8016 MW to 19012 MW from 21:10 Hours to 21:27 Hours to match the increasing demand.

In addition to the above, a total of 10950 MW reductions were attained through other sources likely 6992 MW from Thermal, 1951 MW from Gas, and 2007 MW from Wind generation between 20:45 Hours to 21:10 Hours. The extreme rate of variation in a generation was −4312 MW/Min and +2839 MW/Min with a supreme ramp rate of −2728 MW/Min and +1977 MW/min provided by hydro generators. It would be extremely tedious to attain the optimum scheduling of generation to match the huge demand variations using hydro generation as ramping up and ramping down time of the generators were not feasible for short-term high-scale load variations. The dynamic behavior of Generating stations (source-wise) and their contributions are given in Fig. 14. It characterizes that the hydro generation (Inverted V curve) has been adopted effectively to meet the All India load reduction. Also, hydro generation during the event is compared with the previous day of the event (Fig. 15) [21] which shows the same trend as observed in Fig. 14.

As stated earlier, prior actions were taken before the event such as committing the reactors, switching off transmission lines, altering Static VAR Compensators, Static Compensators, HVDC set points, etc. to maintain the voltages and line loading within the defined band.

4.2. Regional operations

The integrated operation of the national grid reflects the summation of five regional grids. Hence, this section discusses the regional operation of the load centers with their contributing scale. Fig. 16 shows that the demand pattern of SR leads the plot with a larger scale in all three stages, i.e. before, during, and after the event [14]. Beneath that, WR draws a larger scale of power compared with ER and NER which shows the usual trend. The magnitude of the inverted V curve of the SR is not great compared with others.

Table 4 clearly explains the variation in demand among the regions [21]. Although the demand rate of SR takes the upper hand, the total load reduction was not significant during the event. It declined sharply but with a low magnitude of about 6262 MW. Hence, the percentage response of SR shrunk to 17.74% which was minimal compared with other regions. On the other hand, ER and NER show a better response of about 41.22% and 46.66% respectively.

The overall percentage response for the event across the country attained about 33.03%. This region-wise trend clearly explains how the people of India responded to the PM's appeal to challenge the darkness spread by the COVID-19 crisis.

4.3. Frequency profile

Grid frequency directly reflects the power balance between

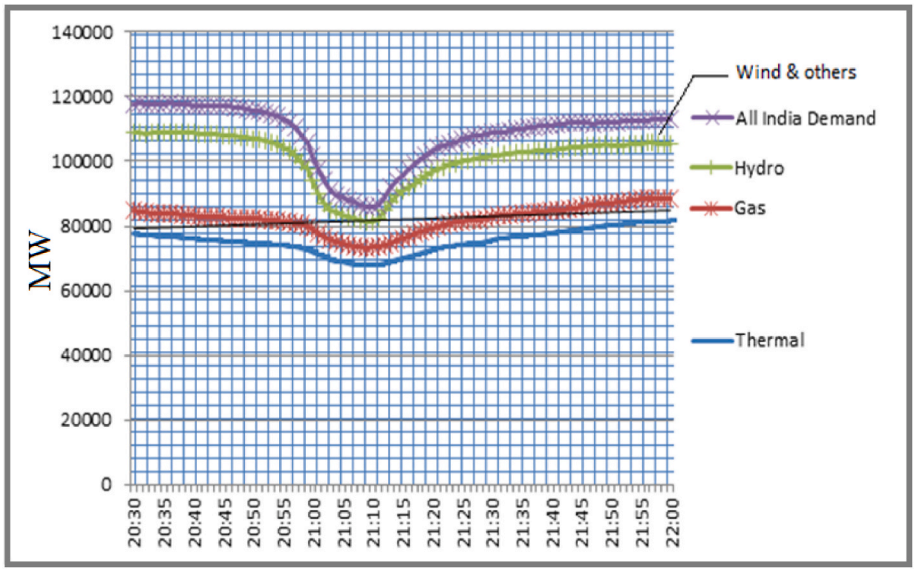

Fig. 14. Source-wise generation and All India demand met (MW) [21].

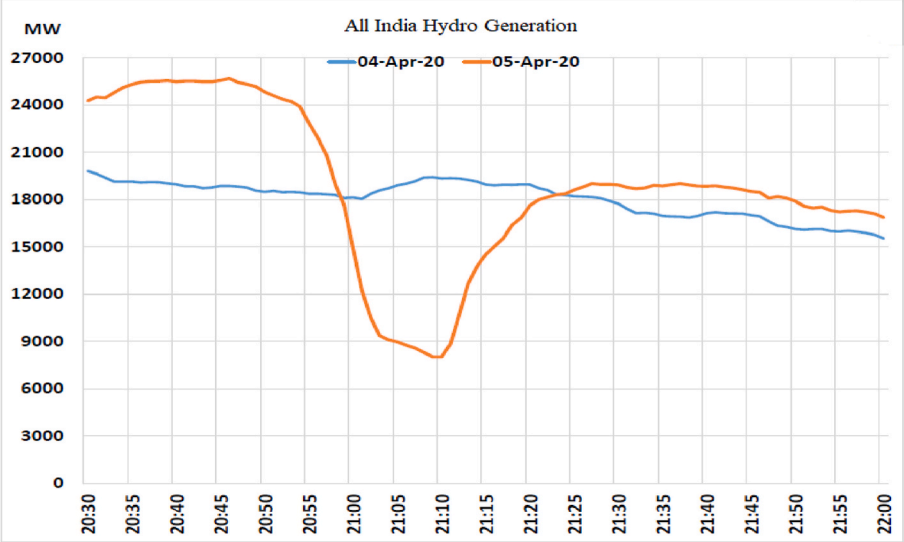

Fig. 15. Trend of All India Hydro generation [21].

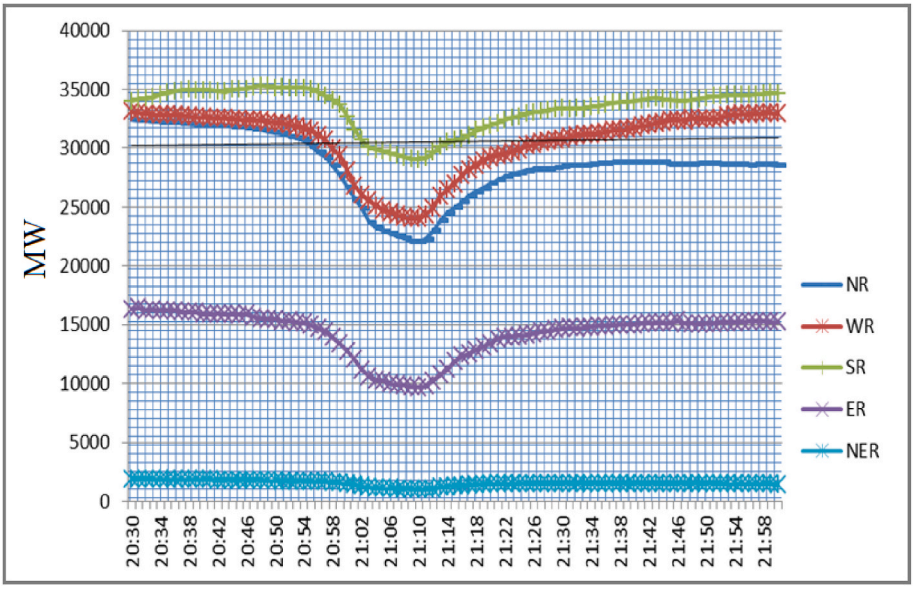

Fig. 16. Demand pattern in MW (Region wise) (data retrieved from Ref. [21]).

Table 4
Maximum and minimum reduction (Region wise) (data retrieved from [[21]]).

Parameters	NR	WR	SR	ER	NER
Maximum MW	32438 @20:30Hours	33122 @20:30Hours	35296 @20:48Hours	16468 @20:31Hours	1903 @20:30Hours
Minimum MW	22045 @21:09Hours	24010 @21:10Hours	29034 @21:10Hours	9679 @21:10Hours	1015 @21:10Hours
Net reduction in MW	10393	9112	6262	6789	888
% Response for the event	32.03	27.51	17.74	41.22	46.66

generation and load at a particular instant. To ensure the quality and security of the power grid, power frequency plays a significant role, and it has to be maintained within the specified range to guarantee the safe and reliable operation of the power system.

The nominal frequency in the Indian grid is 50 Hz and the tolerable frequency band stated by the Indian Electricity Grid Code (IEGC) is between 49.5 Hz and 50.2 Hz [22]. Fig. 17 displays the frequency range of the entire day (5th April 2020) which shows the violation of the frequency band during the event (operative zone indicated in the plot). The detailed version (zoom-in) of the operative zone is depicted in Fig. 18. The analysis shows that the frequency within the band is fair i.e. 10.86%.

5. Interpretation of the event report

POSOCO (acts as a responder) synchronized all RLDCs, SLDCs,

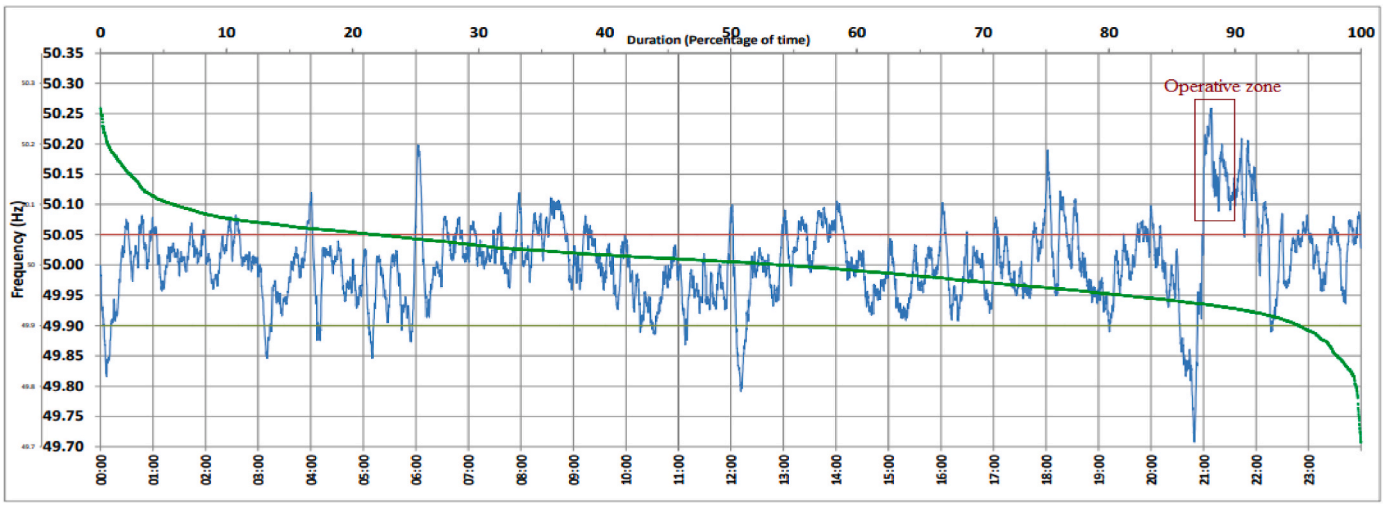

Fig. 17. Frequency trend of the entire day [14].

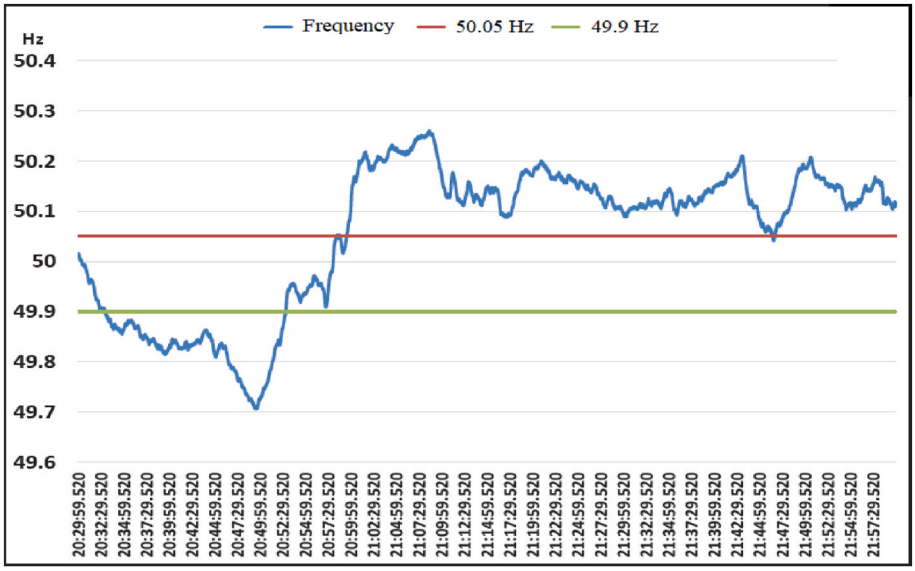

Fig. 18. Frequency trend during the event [14].

substations, and generating plants with IST (Indian standard time). It is an impossible task to synchronize among the people who act as a commander for this event. People might switch off their lights diversely before or after 21:00 Hours. To compute the total all-India Load reduction due to this event, finding an actual start of the event and end of the event is essential though PM's call clearly stated to switch off the lights at 21:00 and switch them on at 21:09 Hours [6]. This section interprets the available data [14,21] and attempts to find the following parameters.

- *Actual start time of the event.*
- Actual end time of the event.
- Actual Load reduction.
- Recovering time.
- Operative zone of the hydro generation for the demand.

Fig. 19 displays the demand pattern of the event date (05.04.2020) [21] and the previous date (29.03.2020) [14]. It clearly shows that the intercepting point on the left side represents the actual start of the event (20:55 Hours), the intercepting point on the right side specifies the recovering point (21:35 Hours), and the tip of the inverted V curve indicates the end of the event (21:10 Hours). Further, shaded/colored areas demonstrate the operation of Hydro generation based on the demand reduction by maintaining the grid frequency within the band. The complete interpreted results and POSOCO reports are compared in Table 5. In a nutshell, the total all-India load reduction would be 27452 MW and the event might take place for 15 min.

6. Lesson learnt-global view

Though the light-off event handled by the Indian utility was anticipated; but, maintaining the power balance between the steep decline and incline of massive load demand was a challenging one. Because the mock exercise of the utility resulted in a net load reduction of about 11,344 MW. However, the actual event was recorded as 31,088 MW unexpectedly. Moreover, the interpreted results show the net load reduction was 27,452 MW and took place very steeply. It is known that the Indian powder grid is the third-largest network in the world after China and the United States which produces net energy of about 2,561,100 GWh (as of November 2019) [23]. A small malfunction in the system during this event may cause severe technical failure and economic losses which worsen the daily activity of the people along with

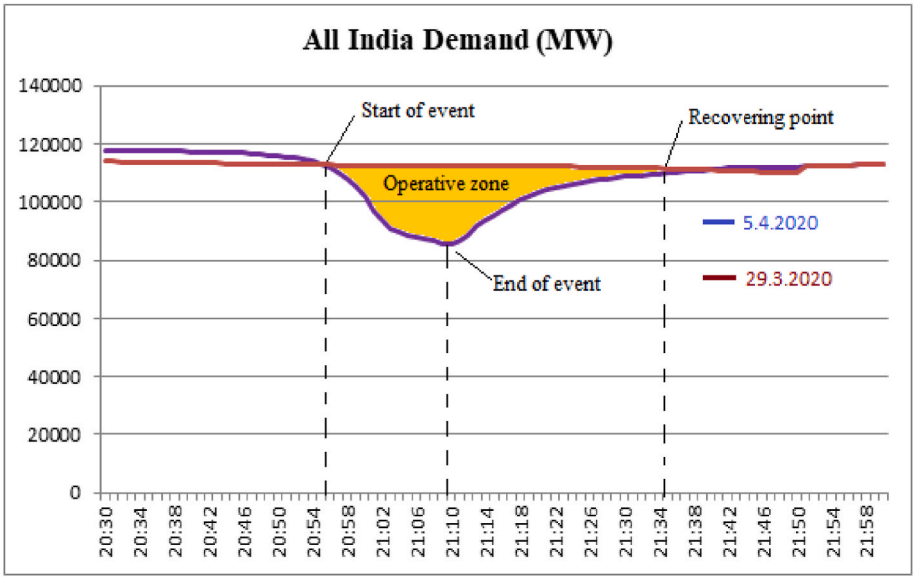

Fig. 19. Interpreted plot between regular (29.03.2020) and event load demand (05.04.2020) (data retrieved from Ref. [21]).

Table 5
Comparison of Interpreted and POSOCO reports.

Parameters	Interpreted report		POSOCO report [17]	
	Time	Power (MW)	Time	Power (MW)
Start of event	20:55 Hours	113251	20:45 Hours	116887
End of event	21:10 Hours	85799	21:10 Hours	85799
Load reduction	15 min	27452	25 min	31088
Recovering point	21:35 Hours	109712	22:10 Hours	114400

the COVID pandemic. Nonetheless, the ramping up and ramping down the procedure of hydro generation matches the load and generation precisely. As per the interpreted results, the steep load reduction of 27452 MW takes place for 15 min, and the hydro generations from various state grids are coordinated optimally to match the declining all-India demand by means of ramping down accurately. After 15 min, all India loads started to incline steeply from 85799 MW to 109712 MW within 25 min. Accordingly, the coordinated state hydro generations were ramped up to match the continual increase in demand.

This event was scheduled for 9 min which affect the power grid directly with steep reduction and inclination. This sharp load reduction with extremely high magnitude may happen to any utility worldwide due to several reasons specifically natural or artificial calamities. Under these circumstances, the recommended procedures depicted in this exertion using coordinated hydro ramping can help to overcome grid failures globally. Every grid event leaves a lesson that delivers both self-assurance and familiarity which is manageable for the future and this event was no exception for the global electric grid. The key learnings from the event are enumerated below:

- The grid should ensure the availability of flexible generating resources in the form of hydro, gas, and pumped storage plants that have a strong potential for sharp variations in demand during any short time event.
- It is essential to make available of whole country's transmission system with flexible resources using HVDCs, and FACTS devices such as STATCOMs and SVCs. These arrangements ensure the congestion-free arrangement and accessibility of reactive power regulating schemes for better voltage control. Under these circumstances, the entire grid is a solitary control zone exclusively for the drive of frequency control.
- The electric grid should have a robust regulatory framework in the form of the Electricity Grid Code and other protocols guaranteeing healthy scheduling, monitoring, secretarial, and settlement mechanism.
- A new arrangement like the Pilot scheme on Fast Response Ancillary Services and training on hydro elasticity done over and done with the forum of load dispatchers assisted in improved indulgent hydro elasticity.
- The global utilities should ensure the accessibility of tools for real-time monitoring, visualization, and situational awareness in various dispatch centers of the nation.
- Strong modules of communication substructure are required to maintain the grid between control centers, generating plants, and transmission licensees.

7. Conclusions

This review work discussed the complete actions of the POSOCO for the Indian PM's appeal to switch off the Lights across the country for 9 min. Firstly, the structure of POSOCO and its mock exercise was presented. From this, computation of expected all India lighting load and load reduction (for the actual event) was carried out and observed as 11344 MW and 12–14 GW respectively. On the other hand, POSOCO reported that the total load reduction in all India demand during the actual event was 31 GW, it started at 20:45 Hours and ended at 21:10 Hours (Load reduction happened for 25 min). Also, Grid Frequency oscillated between the ranges of 50.26 Hz–49.70 Hz.

Nevertheless, the computed load reduction during the mock exercise was far away from the observed value during the actual event as per the POSOCO report. Additionally, interpretations of the report have been carried out with the available data. It shows that the total all-India load reduction that happened during the event was about 27452 MW, and the actual event started at 20:55 Hours and ended at 21:10 Hours, i.e. 15 min, not 25 min.

In nutshell, the estimated load reduction during the mock and actual load reduction during the event has great dissimilarity. However, POSOCO handled the circumstance optimally using Hydro ramping with its flexible generating capacity and maintaining the frequency profile within the tolerable band. This procedure may be adopted globally during similar situations and the lessons learned from the event were listed that help global electric utilities in the future. Also, this work provided a strong research gap that needs a comprehensive study to

assess the actual reasons for the huge deviation of load reduction between the mock exercise and the actual event.

Credit author statement

Kannadasan Raju: Conceptualization, Methodology, Writing – original draft & review, Venkatesan Chandrasekaran: Software, Data curation, Mohammed H. Alsharif: Investigation, Formal analysis, Mun-Kyeom Kim*: Writing – Editing Editing, Supervision, Jamel Nebhen: Visualization, Data curation

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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