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# Dynamic Modeling and Cascade Failure Analysis of the Mumbai Grid Incident of October 12, 2020

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**ABSTRACT** The Mumbai region in India experienced a massive outage on October 12, 2020, due to cascade failure. The event taught some serious lessons to the grid operators and highlighted the need for energy security and reliability. In this incident, the cascade tripping of the external transmission network resulted in an unexpected island containing Mumbai city isolating it from the rest of Indian power grid. Although the Mumbai islanding scheme was operational, it failed to survive due to high rate of change of frequency (ROCOF). Globally, such blackouts occur due to low probability, high impact events. Major blackouts are caused by a set of triggering events that are usually preceded by some incidents that weaken the power system. Further, the failure of important security mechanisms and protections can compound the effect of disturbances. In view of this, the paper focuses on the consequences of cascading events that led to several blackouts in history. This paper analyses the October 12, 2020, Mumbai power grid failure by recreating various scenarios that resulted in the blackout through dynamic modelling on the PSS/E platform. The results were validated using data collected from phasor measurement units (PMUs) and SCADA. In this article various challenges faced during unfolding of the event are presented. Lessons learnt such as appropriate settings and tuning were identified to ensure the survival of islanding scheme. Assessment of Mumbai power system's transfer capability is done to facilitate the optimal mix of imported and embedded generation.

**INDEX TERMS** Blackout, cascade failure, critical infrastructure, islanding, power system modelling and simulator for engineering (PSS/E), rate of change of frequency (ROCOF), smart grid, under-frequency load shedding.

## NOMENCLATURE

| | |
|---|---|
| **ADTPS** | Adani Dahanu Thermal Power Station. |
| **AEML** | Adani Electricity Mumbai Limited. |
| **AEML-D** | Adani Electricity Mumbai Limited - Distribution. |
| **APM** | Administrative Price Mechanism. |
| **ATL** | Adani Transmission Limited. |
| **BEST** | Brihanmumbai Electricity Supply and Transport Undertaking. |
| **BPSU** | Bhira Pumped Storage Unit. |
| **BFV** | Butterfly Valve. |
| **CB** | Circuit Breaker. |
| **CCGT** | Combined Cycle Gas Turbine. |
| **COVID-19** | Coronavirus disease 2019. |
| **CT** | Current Transformer. |
| **df/dt** | Rate of Change of Frequency. |
| **DG** | Distributed generation. |
| **DR** | Disturbance Recorder. |
| **DTPS** | Dahanu Thermal Power Station. |
| **EHV** | Extra High Voltage. |
| **EMS** | Energy Management System. |
| **ESD** | Emergency Shutdown System. |
| **IEGC** | Indian Electricity Grid Code. |
| **GAIL** | Gas Authority of India Ltd. |
| **GC** | General Challenges. |

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| | |
|---|---|
| **GR** | General Recommendations. |
| **GTPS** | Gas Turbine Power Station. |
| **LTS** | Load Trimming Scheme. |
| **LSR** | Load Shedding Relay. |
| **LLMB** | Lessons Learnt from Mumbai Blackout. |
| **LP** | Low Pressure. |
| **MERC** | Maharashtra Electricity Regulatory Commission. |
| **MMR** | Mumbai Metropolitan Region. |
| **MSEDCL** | Maharashtra State Electricity Distribution Company Limited. |
| **MSETCL** | Maharashtra State Electricity Transmission Company Limited. |
| **MSLDC** | Maharashtra State Load Despatch Centre. |
| **ONGC** | Oil and Natural Gas Commission. |
| **PLCC** | Power Line Carrier Communication. |
| **PMU** | Phasor Measurement Units. |
| **PSS/E** | Power system simulator for engineering. |
| **PV** | Photovoltaic. |
| **RLNG** | Regasified Liquefied Natural Gas. |
| **ROCOF** | Rate of Change of Frequency. |
| **RPUF** | Reverse Power Under Frequency. |
| **RTCA** | Real-Time Contingency Analysis. |
| **SCADA** | Supervisory Control and Data Acquisition System. |
| **SLDC** | State Load Despatch Centre. |
| **SOP** | Standard Operating Procedure. |
| **SPA** | standing power angle. |
| **SPS** | Special Protection Schemes. |
| **TBC** | Transfer Bus Coupler. |
| **TCSC** | Thyristor Controlled Series Compensator. |
| **TPC** | Tata Power Company Ltd. |
| **TPC-D** | Tata Power Company Ltd-Distribution. |
| **TPC-T** | Tata Power Company Ltd-Transmission. |
| **UF** | Under Frequency. |
| **UFR** | Under Frequency Relay. |
| **UFLS** | Under Frequency Load Shedding. |
| **USA** | United States of America. |
| **WR** | Western Region. |

## I. INTRODUCTION

Electric power grids are increasingly becoming complex to operate with the interconnection of multiple utilities, integration of renewable energy resources, and complexity of operating protocols among several utilities created due to the restructuring of the power sector. Power grids being highly dynamic, experiences stability challenges in case of severe faults, loss of sizable generation or imports, and also oscillatory stability issues due to loading of transmission at its limits [1]. These stability issues can easily lead to a critical situation.

Cascade failure is defined as a series of correlated failures that gradually undermine the power system [2]. These failures can occur as a result of a variety of factors including natural disasters, technical failure, human error, and deliberate sabotage [3]. Various selected blackouts due to cascade failure reported acrose the world, along with its initiating event and affected population has been summarized in Fig. 1. It can be seen that the majority of the major power grid blackouts were caused by cascade failure. The most widely discussed blackout in the literature is the August 2003 USA-Canada blackout, which affected 50 million people and resulted in a massive financial loss of 6 billion dollars [4]. During this event, some trippings occurring in one TSO area were not visualized in the control center of the neighboring TSO area. Multiple line trips along with voltage collapse and power swings in the inter TSO transmission network resulted in the collapse of major parts. Whereas the two consecutive major blackouts of Indian power grid on July 30 and 31, 2012, affected a huge population of 620 million people [5]. This blackout is the biggest ever recorded in terms of the number of people impacted [6]. This blackout initiated due to maloperation of relay caused by inappropriate settings (hidden failure) in the backdrop of severe transmission outages. Several 400 kV lines tripped as a result of power swings/load encroachment. The need for visualization and situational awareness [7], [8] is one of the most important lessons to be learnt from these disturbances.

**TABLE 1. ROCOF issues in recent blackouts.**

| Blackout | Date | ROCOF |
|---|---|---|
| UK | Aug 9, 2019 | 1880 MW loss of generation led to ROCOF above 0.125Hz/s |
| Sri Lanka | Aug 17, 2020 | Failure of 300 MW oil-fired Kerawalapitiya power station led to ROCOF above 2 Hz/s |
| India | Oct 12, 2020 | Failure of the transmission network led to ROCOF above 3.5 Hz/s |

Recent developments in modern power systems have raised concerns about frequency stability. Sudden loss of generation or demand can create the issue of high ROCOF [9]. As illustrated in Table 1 key issue in some of the most recent blackouts was very high ROCOF. These blackouts include disturbances that occurred in the UK on August 9, 2019, because of faults occurring on lines during a thunderstorm leading to an 1880 MW loss of generation. This led to a rapid fall of frequency at high ROCOF, causing an under-frequency load shedding scheme [10] at 48.8 Hz to operate even before turbine governors could react. The high ROCOF was attributed to a decrease in system inertia due to the large-scale addition of renewable energy generation.

A major blackout occurred in Sri Lanka on August 17, 2020, when the 300 MW oil-fired Kerawalapitiya power station providing 50% of Sri Lankan electricity supply failed for around 7 hrs. A Three-Phase bus fault at Kerawalapitiya power station was cleared in 154 ms (instead of 30 ms), leading to a 50% voltage dip at another power station Lak Vijaya and all units tripped at both power stations, causing a rapid fall of the frequency of more than 2 Hz per second which led to frequency dropping to 47 Hz in 1.9 seconds [11].

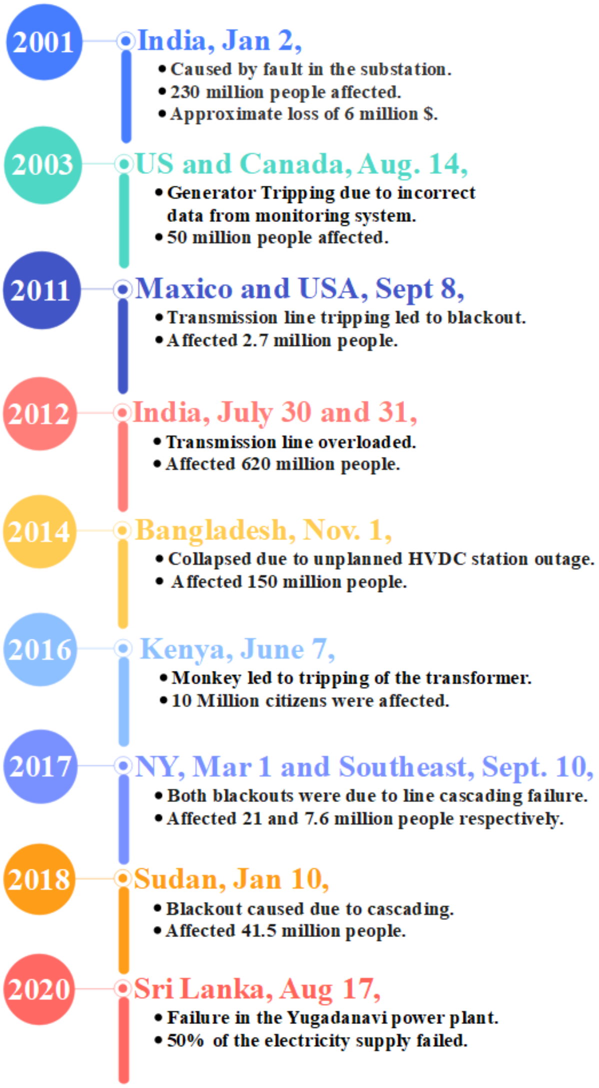


**FIGURE 1.** Major blackouts caused by cascade failures.

Significant research has been conducted in recent years to determine the impact of cascading on the sustainability of electrical grid [12]–[14] and analysis to anticipate critical moments in order to respond appropriately at a preliminary stage [15]–[17]. To systematically investigate blackout scenarios various tools are used [18]. Major blackouts and cascade failures, their root causes, and lesson learnt from these blackouts are studied in [19], [20].

The Mumbai region in India experienced a massive outage on October 12, 2020, due to cascade failure, that affected a population of around 20 million, urban transport, and industrial production for more than 12 hours [21]. One of the most critical security mechanisms, the Mumbai Islanding scheme [22], [23], which was implemented in 1981 to isolate Mumbai from spreading blackouts caused by the external network, also failed to prevent the city from a major power failure, and the city was forced to undergo nearly 12 hours of blackout.

Islanding schemes are a sub-set of special protection schemes [24] employed to protect important urban areas or power stations from major disturbances occurring outside the island to ensure continuity of power supply or to secure some generation that can help in the restoration of collapsed parts. Typically the protective relays sense disturbance outside the island by sensing reverse power, Under Frequency (U/F), ROCOF, out-of-step conditions [25], or a combination of above to actuate special protection schemes (SPS) for isolating the island from the main grid [26]. To secure the island from frequency instability and voltage instability, tripping of loads through U/F and U/V relays, auto restoration of loads using over frequency and over-voltage conditions, generation rejection, actuation of generation control schemes like- HP/LP bypass, Load Trimming Schemes (LTS) for controlling transformer and line overloads, etc. are actuated [27].

The key issues of islanding schemes are:

- When to island?
- How to island?
- How to secure the island once formed?
- When and where to reconnect the island with the main grid?

The islanding schemes use data from SCADA, EMS, synchrophasor, Real-Time Contingency Analysis (RTCA) protocols, etc., and state-of-the-art communication schemes to enable wide-area operations. The complexity and nature of disturbances throw a huge challenge for islanding schemes in choosing the proper settings, tuning protection settings, tuning remedial actions. This paper analyzes the October 12, 2020, Mumbai power grid cascading failures. This event is analyzed using dynamic modelling on the PSS/E platform by recreating various scenarios. The following summarises the significant contributions of the paper:

- Formulation of the large system model in a stronger and worldwide accepted platform of Siemens Power System Simulation for Engineering (PSS/E).
- Development of static and dynamic models for this large complex realistic system by utilizing actual parameters and data.
- Validation of findings of simulation using representative actual information acquired from situational awareness systems to validate the accuracy of the dynamic models developed for this system.
- This paper also discusses the need for islanding in important urban areas, the modus operandi of islanding schemes, securing islands once they are formed, critical issues that affect the formation of islands using SPS, etc.
- In the backdrop of a major disturbance that occurred in Mumbai ( commercial capital of India) and outlying urban areas around it on October 12, 2020, the study of operation of Mumbai islanding scheme has been performed.
- Primary contribution of the paper is a comprehensive investigation of the various challenges encountered during such a large-scale system failure. Not only does the research outcome include recommendations for MMR,

but it also makes some general recommendations / suggestions for preventing similar incidents in the future.

This research paper is organized into six sections. Section II sketches the electricity network of Mumbai Metropolitan Region (MMR) with major power sources and important Tie-lines for power pooling. The Mumbai islanding scheme is presented in detail, as the blackout on October 12, 2020, had a significant impact on the city. Section III contains a detailed description of the blackout on October 12, 2020, a timeline of events, the islanding and failure of the Mumbai system and key issues that contributed to the disruption, structural inadequacies, and so on. Section IV details the development of the dynamic simulation model in PSS/E as well as the recreation of operational scenarios. Section V provides the simulation of the Mumbai grid cascade failure, the analysis of the results regarding Mumbai grid failure. Section VI suggests lessons learned during this blackout and significant recommendations. Conclusions and recommendations are discussed in Section VII.

## II. BRIEF DESCRIPTION OF AFFECTED POWER SYSTEM AND MUMBAI ISLAND

Mumbai city is a part of the state power grid of Maharashtra with 42491.72 MW of installed capacity and 24960 MW of peak demand. Maharashtra is in the inturn part of the Indian power grid. As shown in Table 2 Tata Power Company Limited (TPC) owns 1377 MW of embedded generation in Mumbai, while Adani Electricity Mumbai Limited owns 500 MW (AEML) [28].

**TABLE 2. Embedded generation capacity of Mumbai [28].**

| Sr. No | Description | Capacity (MW) on bar | Actual Generation (MW) |
|---|---|---|---|
| 1 | TPC Unit 5 | 500 | 454 |
| 2 | TPC Units 7A & 7B | 180 | 182 |
| 3 | TPC Unit 8 | 250 | 0 (Not in Service) |
| 4 | AEML DTPS | 2×250 | 485 |
| 5 | TPC Hydro | 447 | 228 |
| **Total** | | **1877** | **1349** |

The city is divided into three distribution companies: Brihan Mumbai Electricity Supply and Transport Company (BEST), TPC-D, which serves south Mumbai, and AEML-D, which serves north Mumbai. Company-wise demand for the Mumbai area is shown in Table 3.

**TABLE 3. Demand on distribution companies in Mumbai [28].**

| Sr. No. | Description | Demand (MW) |
|---|---|---|
| 1 | TPC-D | 1633 |
| 2 | BEST | |
| 3 | AEML-D | 957 |
| **Total** | | **2590** |

The transmission network is operated by Maharashtra State Electricity Transmission Company Limited (MSETCL), TPC-T, and AEML-T. The peak load of Mumbai city is around 3600 MW, but during the period of disturbance, the demand was only around 2590 MW due to partial lockdown in the city during the pandemic situation. Mumbai city usually imports around 2000 MW from the MSETCL grid and import on the day of disturbance was around 1470 MW. The city is supplied by an external grid via two 400 kV sources: Padghe via the Padghe-Kalwa D/C line and Talegaon via the Talegaon-Kalwa S/C line, Talegaon-Kharghar-Kalwa S/C line, as illustrated in Fig. 2. Additionally, the city receives power from 220 kV interconnections of MSETCL at the Kalwa, Trombey, Boisar, and Borivali substations. Power is imported on the outskirts of Mumbai and distributed via a 220/110 kV transmission network to load centers in the city. The load centers in the city are not directly connected to the 400 kV MSETCL network due to Right-of-Way (ROW) problems caused by dense population and sea on three sides of the city. Mumbai has the import capability of 2000-2200 MW from the MSETCL network.

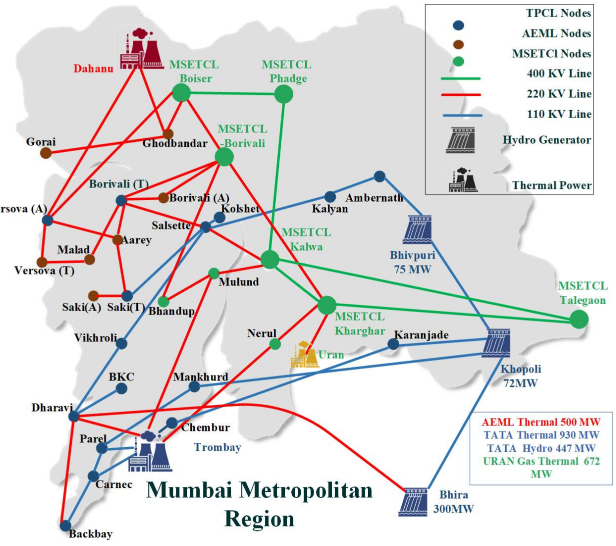


**FIGURE 2. The geographical power map of MMR [29].**

The outer periphery of the city is also highly urbanized, and these parts along with Mumbai city are known as Mumbai Metropolitan Region (MMR), which includes 400 kV substations of Kalwa and Kharghar and 220 kV substations exporting power to Mumbai city as well as Uran power station (CCGT) of 990 MW capacity as shown in Fig. 2. The MMR region other than Mumbai is heavily industrialized and meeting load of 1300 MW and Uran generation of 270 MW at the time of disturbance on October 12, 2020.

## III. THE BLACKOUT ON 12.10.2020 IN MUMBAI

### A. ANTECEDENT CONDITIONS

The geographical power map of Mumbai city with Tie-lines used for import of power from Maharashtra is shown in Fig. 2. The islanding scheme for Mumbai was conceived in 1981 to improve reliability in the city, and it has been revised several

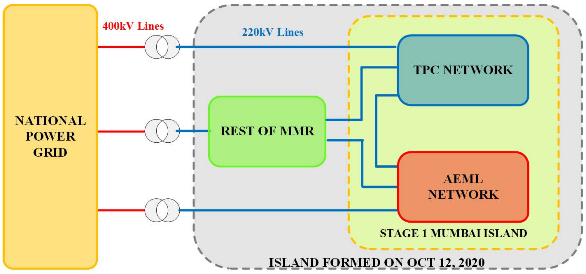


**FIGURE 3.** Formation of MMR Island on October 12, 2020.

times in response to changes in the network, both internal and external, generation and import profiles, and so on. Although Mumbai initially had a single island scheme for both TPC-D and AEML-D areas, two distinct islands were designed for both licensees to establish greater responsibility. At present as depicted in Fig. 4, Mumbai city is designed to island from MSETCL network at Tie-points of 220 kV Trombay, 110 kV Trombay, 220 kV and 110 kV Salsette, 220 kV and 110 kV Borivali (TPC), 220 kV Borivali (AEML), 110 kV Kalyan, 220 kV Gorai, 220 kV Ghodbunder, 220 kV Versova, 220 kV Chembur, 220 kV Aarey and 220 kV Dahanu based on reverse power under frequency (RPUF) and simple under frequency relays (UFR) set at 48 Hz and 47.9 Hz respectively. The reverse power condition implies a disturbance outside Mumbai, whereas under frequency condition implies a severe disturbance and a point of no return except for disconnecting from the rest of the grid and implementing dynamic load shedding (calculated in real-time) to compensate for the loss of imports, as well as a small amount of additional load shedding (20 MW) to enrich the island generation.

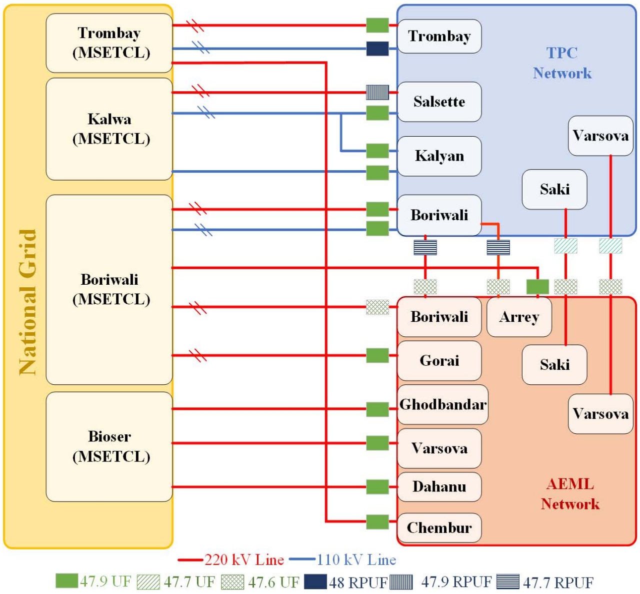


**FIGURE 4.** Representation of relay setting in interconnected Mumbai Grid [23].

In case of further fall in frequency in Mumbai island or flow of power from TPC-D to AEML-D, the Mumbai island splits into two sub-islands of TPC-D and AEML-D. The formation of sub-islands takes place at 47.7 Hz on reverse power (TPC to AEML) or 47.6 Hz only in case of under frequency and no reverse power. Fig. 4 depicts the locations where islanding is triggered to separate from MSETCL and the locations where islanding is conceived for sub-islands.

The key factors are that frequency following island formation should recover back to 50 Hz, and at the time of island formation, the frequency transient due to loss of import should not decay below 47 Hz to avoid U/F tripping of generators, specially Trombay Units 7A and 7B which are gas turbines. However, thermal units at Trombay and Dahanu have U/F settings at around 46.5 Hz. Meanwhile, hydro generators of TPC at Bhira, Bhivpuri, and Khopoli converted the island to a hydro island at a frequency of 46 Hz, with U/F tripping at 45 Hz. To compensate for the loss of import load shedding done using ROCOF and U/F relays - in AEML set at 49 Hz, 0.5 Hz/sec and at 47.9 Hz with no intentional delay and in TPC through U/F relays were set at 47.9 Hz with 150 msec intentional delay. Some additional load shedding is carried out to make island generation rich. In the case of unit trippings within Mumbai operating in islanded mode, additional U/F load shedding and high-frequency automatic restoration of loads are provided as a survival strategy.

The island was meeting a load of 2,590 MW with 1349 MW embedded generation and 1241 MW import. In the surrounding MMR area, the load was 1303 MW, and generation at Uran of 270 MW. The important 400 kV lines corridor which pools power to the Mumbai area are shown in Fig. 5.

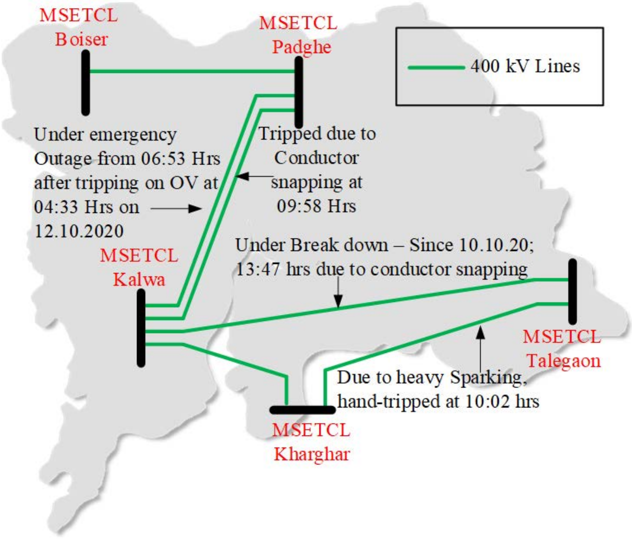
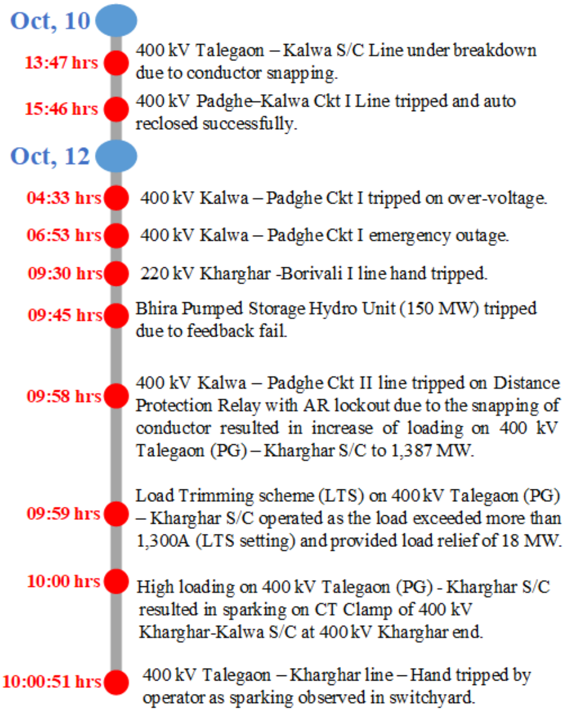


**FIGURE 5.** 400 kV lines bringing power to Mumbai area [28].

As illustrated in Fig. 5 the network has weakened due to the non-availability of two important 400 kV lines. The attempt to increase embedded generation to improve transmission reliability margin (TRM) by bringing Trombay Unit 8 (250 MW), Bhira pump storage (150 MW), and hydro generation pick up at Khopoli failed due to various constraints, as detailed in Fig. 6. Prior to the grid failure on October 12, 2020, Mumbai island was meeting a load of 2,590 MW with 1349 MW embedded generation and 1241 MW import. The load in the surrounding MMR region was 1303 MW, while generation at Uran was 270 MW. The critical 400 kV lines that supply electricity to the Mumbai area are depicted in Fig. 5. The network has weakened as a result of the non-availability of two important 400 kV lines, as shown in Fig. 5. The attempt to increase embedded generation to improve the transmission reliability margin (TRM) by bringing Trombay Unit 8 (250 MW) and Bhira pump storage (150 MW) online, as well as starting up hydro generation at Khopoli, failed due to various constraints, as described in Fig. 6.


Oct, 10

13:47 hrs 400 kV Talegaon – Kalwa S/C Line under breakdown due to conductor snapping.

15:46 hrs 400 kV Padghe–Kalwa Ckt I Line tripped and auto reclosed successfully.

Oct, 12

04:33 hrs 400 kV Kalwa – Padghe Ckt I tripped on over-voltage.

06:53 hrs 400 kV Kalwa – Padghe Ckt I emergency outage.

09:30 hrs 220 kV Kharghar -Borivali I line hand tripped.

09:45 hrs Bhira Pumped Storage Hydro Unit (150 MW) tripped due to feedback fail.

09:58 hrs 400 kV Kalwa – Padghe Ckt II line tripped on Distance Protection Relay with AR lockout due to the snapping of conductor resulted in increase of loading on 400 kV Talegaon (PG) – Kharghar S/C to 1,387 MW.

09:59 hrs Load Trimming scheme (LTS) on 400 kV Talegaon (PG) – Kharghar S/C operated as the load exceeded more than 1,300A (LTS setting) and provided load relief of 18 MW.

10:00 hrs High loading on 400 kV Talegaon (PG) - Kharghar S/C resulted in sparking on CT Clamp of 400 kV Kharghar-Kalwa S/C at 400 kV Kharghar end.

10:00:51 hrs 400 kV Talegaon – Kharghar line – Hand tripped by operator as sparking observed in switchyard.

**FIGURE 6.** Sequence of events before the disturbance [28].

As illustrated in Fig. 6, even the 220 kV network was weekend due to several trippings. Efforts to reduce imports through embedded generation were also unsuccessful.

### B. SEQUENCE OF EVENTS

Failure of the 400 kV network led to the rushing of power over the 220 kV network bringing power to Mumbai city and adjoining MMR areas. The 220 kV transmission lines connecting MSETCL sources to the MMR region (including Mumbai) tripped in cascade as a result of the operation of over-current relays set to trip on overload rather than fault currents. The LTS schemes at Kharghar and Boisar did not provide adequate load relief as per the defined scheme.

The aforementioned trippings resulted in the formation of an island at 10:05:07:400 hrs (not conceived), which got separated from the Indian grid at unexpected locations. This island included Mumbai city loads and generation, 1303 MW of load in the adjoining MMR region, and 270 MW generation at Uran. The island formed had a 4142 MW load with 1619 MW generation, and such adverse load-generation imbalance led to steep decay of frequency with ROCOF of around 3.5 Hz/sec. from the pre-fault frequency of 49.77 Hz. Adverse load generation balance in the formed island led to a fall of frequency to 47.79 Hz when the Mumbai islanding got triggered. However, the actual separation of Mumbai city would require another 250 msec delay (150 msec of intentional time delay and 100 msec inherent measurement time delay attributable to the measurement of 5 cycles). Mumbai island was unable to eliminate the excess MMR load at this time. As frequency went down to 46.88 Hz, the AEML system separated at 10:05:08:400 hrs due to the operation of the AEML islanding scheme set to separate at 47.6 Hz. The frequency continued to decay until 10:05:08:440 hrs when TPC islanding and MMR load isolation were completed. The isolation of MMR load coupled with U/F load shedding relieved the overload on the TPC island, which resulted in frequency improvement to 46.70 Hz. However, prior to this improvement, U/F tripping of Trombay unit 7A and 7B actuated at 46.4 Hz. These trippings of trombay units resulting in steep fall of frequency which lead to the tripping of Trombay unit 5 (setting of 46 Hz). The isolation of MMR load coupled with U/F load shedding relieved the overload on the TPC island and frequency improved to 46.70 Hz, but at 46.4 Hz, U/F tripping of Trombay unit 7A and 7B actuated, resulting in steep fall of frequency leading to tripping of Trombay unit 5 (setting of 46 Hz). These trippings led to a fall of frequency to 46 Hz and below, resulting in islanding, and the tripping of hydro units in accordance with the scheme. This led to collapsed of TPC island while AEML island survived due to faster-load shedding through ROCOF relays and faster disconnection from MMR loads. The sequence of trippings/formation of various islands is shown in Fig. 7 based on synchrophasor data available at a few sub-stations.

The key issues are the formation of MMR island, including Mumbai and adjoining areas at unexpected locations, and creating adverse load-generation balance, which led to a steep decay of frequency with ROCOF around 3.5 Hz/sec. In addition, due to intentional time delays, the load shedding in the TPC area operated later than in the AEML area; lingering an additional load of 1303 MW with TPC for a few milliseconds caused a frequency drop below the generator U/F settings.

## IV. DEVELOPMENT OF DYNAMIC SIMULATION MODEL AND RECREATING GRID DISTURBANCE

The Indian western region grid was modeled in PSS/E Software for dynamic simulation studies to recreate grid disturbance and identify the challenges faced on October 12, 2020. The model includes:

- Creation of network file with 3290 buses, 858 generating nodes (all conventional and renewable generating nodes), 3887 branches, 2751 transformers, and

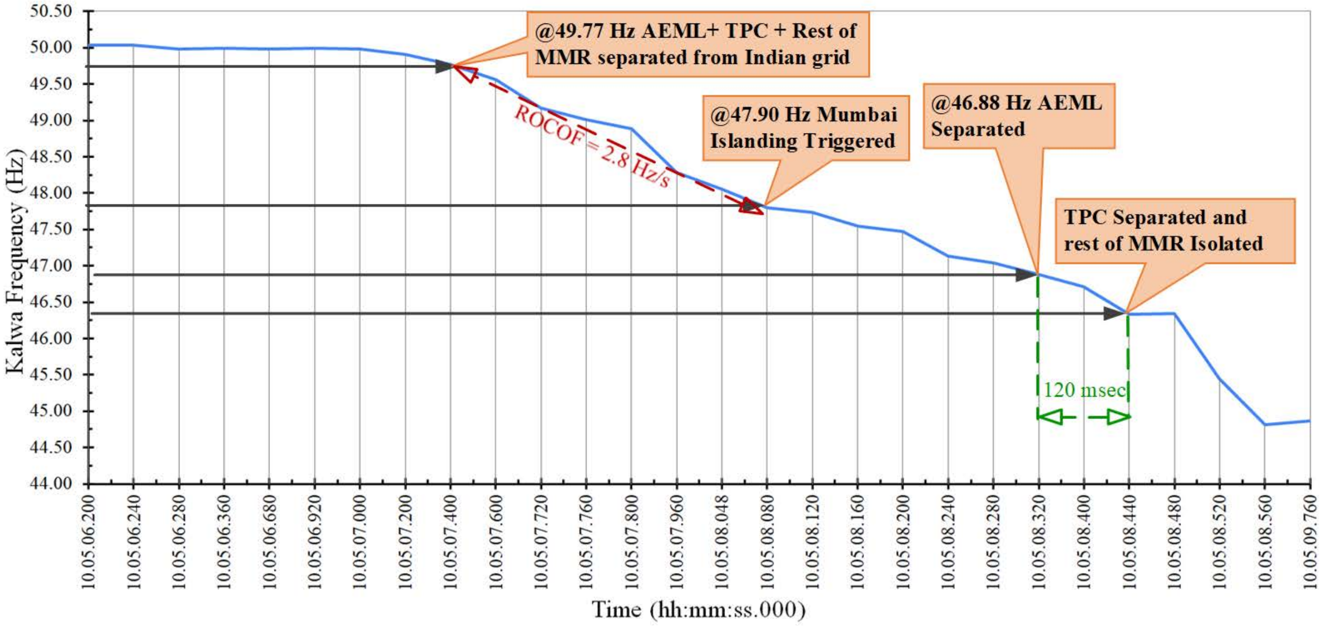


**FIGURE 7.** 400kV Kalwa PMU Data on October 12, 2020.

1614 load buses, that represents all generators and networks up to 22 kV level and clean up data errors in the power flow model.

- Creation of valid.sav,.seq, and.sld file for indian western region grid and testing of the case for its convergence, and voltages within criteria.
- PSS/E dynamic data file (DYRE file) and snapshot file preparation for the event. Assign dynamic models of the machine, exciter, and turbine governor with typical parameters depending on the fuel type. Generic and actual modeling are carried out using available data of elements such as
  - Generator models for thermal is ‘GENROU’ and for hydro is ‘GENSAL’ [30].
  - For exciter models used are ‘IEEET1’, ‘SEXS’, ‘ESST1A’ and SCRX [31].
  - For Governor models: ‘HYGOV’, ‘TGOV1’ and ‘IEEEG’ [32].
  - For stabilizers ‘PSS2A’.
  - Dynamic models used for different RE sources are [33]:
    - ∗ Wind Turbine: Generator- WT3G1, Electrical- WT3E1, Mechanical- WT3T1, Pitch- WT3P1.
    - ∗ Solar PV: Generator- PVGU1, Electrical- PVEU1.
- Dynamic models used in simulation of embedded generation of Mumbai are as shown in Table 4.
- To test the rationality, we used known contingencies including the Mumbai Blackout.
- To investigate the effects of the events that transpired on October 12, 2020, the actual tripping sequence was initiated by modeling the appropriate relay settings for the TPC and AEML islanding schemes, along with the U/F and ROCOF load shedding to mimic the Mumbai islanding scheme operation.
- Additionally, the simulation results were validated using PMU data collected from several substations and frequency plots extracted from numerical relays and SCADA data.

**TABLE 4.** Dynamic models used in the simulation of embedded generation of Mumbai.

| Generator | Type | Generator Model | Exciter Model | Governor Model | Stabilizer Model |
|---|---|---|---|---|---|
| Trombay 8 | Thermal | GENROU | IEEET1 | TGOV1 | PSS2A |
| Trombay 7A 7B | Thermal | GENROU | IEEET1 | TGOV1 | PSS2A |
| Trombay 5 | Thermal | GENROU | IEEET1 | TGOV1 | PSS2A |
| Khopoli units | Hydro | GENSAL | SEXS | HYGOV | PSS2A |
| Bhira units | Hydro | GENSAL | SEXS | HYGOV | PSS2A |
| Bhivpuri units | Hydro | GENSAL | SEXS | HYGOV | PSS2A |
| DTPS units | Thermal | GENROU | IEEET1 | TGOV1 | PSS2A |

MMR region’s representative transmission network is shown in Fig. 8.

## V. SIMULATION STUDIES

The purpose of this research is to replicate the grid disruption that occurred on October 12, 2020. Furthermore, it looks at the following aspects of Mumbai’s islanding scheme:

1) To conduct a review of the cascade failure as it transpired on October 12, 2020.
2) To investigate the effects of events using a 48.4 Hz U/F relay setting for load shedding.
3) To examine the effects of the same occurrences during peak demand - a coincident 3,691 MW peak demand.

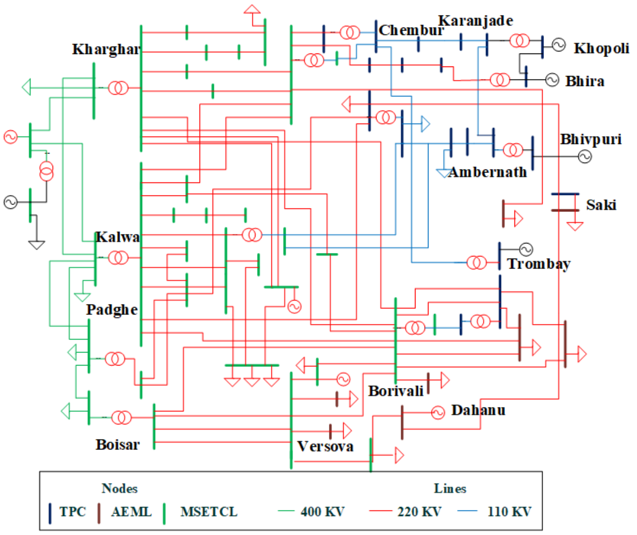


**FIGURE 8.** MMR region's representative transmission network.

4) The simulation studies also examine the reason behind the cascade failure of 220 kV lines supplying power to the MMR region. Moreover, the transfer capability criteria were analyzed in light of various contingencies.
5) To determine the optimum embedded generation in the Mumbai network to improve its chances of survival (especially in the case of transmission bottlenecks and to ensure N-1 compliance).

## A. ANALYSIS OF SIMULATION RESULTS FOR DEMAND SCENARIO OF OCTOBER 12, 2020

### 1) SIMULATION OF MUMBAI DISTURBANCE (TOTAL DEMAND OF 2590 mW)

As shown in Fig. 9, the simulation was carried out with 250 msec total time delays (measurement delay of 100 msec + 150 msec of intentional delay), for the relay setting of TPC in Mumbai. It is performed to examine the feasibility of intentional time delay if any were incorporated in the U/F setting of TPC and to examine the implication of measurement time. As illustrated in Fig. 9, the simulation results indicate that the AEML network separated first at 46.88 Hz, resulting in the continuation of MMR loads on the TPC network until the frequency dropped to 46.52 Hz, at which point TPC islanding was completed. TPC was isolated from the MMR load of 1,303 MW and Uran generation of 270 MW. This resulted in the TPC network's frequency falling below 47 Hz and down to 46.5 Hz (and below), triggering Units 7A, 7B (120 MW and 60 MW), and Bhira Unit 2 (24 MW) [28]. TPC shed 880 MW of load, while AEML shed 550 MW. Additionally, due to the continued decline in frequency, Trombay Unit 5 tripped and the hydro generation was islanded. As a result, the TPC system failed, while the AEML system survived.

The frequency of the AEML network dropped to 47 Hz, however, the delay (4 seconds) on its generator U/F trip relay prevented the tripping of this unit, ensuring AEML survival. The plot also shows the collapse of the TPC and MMR systems. It is observed that while considering an intentional delay of 250 ms the simulation results as shown in Fig. 9 are similar to the PMU data collected at 400 kV Kalwa line as depicted in Fig. 7. PMU data shows ROCOF from the separation point of Mumbai grid with national grid till the point when Mumbai Island is triggered is 2.8 Hz/s. The same can be observed from Fig. 9 where ROCOF is approximately 2.75 Hz/s. As can be seen in Fig. 7, the time difference from the point of separation of AEML and the point where TPC and rest of MMR separate from each other is approximately 120 msec, whereas Fig. 9 shows the separation is approximately 125 msec.

It can be observed that key events are similar such as AEML separates/separating first from 'TPC + rest of MMR' in PSS/E simulation plot as well as PMU data plot.

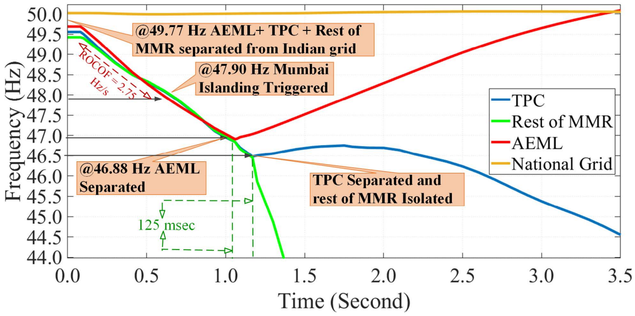


**FIGURE 9.** Frequency Plot for Mumbai islanding scheme.

The main reason for the non-survival of the TPC island is the overload of 'Rest of MMR' hanging on for a longer period. Shedding of the 'Rest of MMR' part or full load with the initiation of Mumbai islanding would help in the survival of Mumbai islanding. Further, it is observed that shedding load to make island generation rich at a higher frequency level or using ROCOF relays appears to be the key for survival as demonstrated in the case of AEML. The frequency fall is significant with the loss of import coupled with the overload of MMR. ROCOF relay can only take early action as compared to plain U/F relays.

### 2) LINE LOADING DURING DISTURBANCE (TOTAL DEMAND OF 2590 mW)

Table 5 shows the value of active power P (MVA), reactive power Q (MVAR), and voltage V (kV) of important 220 kV lines just before the cascade tripping of 220kV transmission lines and just before operation of Mumbai islanding. As per IEGC [34], the minimum acceptable voltage during normal operation for 220 kV and 110 kV are 198 kV and 99 kV respectively. As can be seen from the values, there was no voltage issue during the disturbance, and as the voltage is directly affected by the reactive power imbalance, it can be inferred that issue of reactive power imbalance was not the reason behind this event.

**TABLE 5.** Line loading and Voltage of 220 kV lines prior to the islanding.

| 220 kV lines | Before 220kV line tripping | | | Before Islanding operation | | |
|---|---|---|---|---|---|---|
| | P | Q | V | P | Q | V |
| Boisar- Ghodbndar | -382.6 | -53.2 | 206.7 | 0 | 0 | 0 |
| Boisar-Versov(A) | -244.2 | -0.5 | 205.3 | 0 | 0 | 0 |
| Boisar-Dahanu | -78.5 | 28.8 | 215.2 | 0 | 0 | 0 |
| Borivali(M)-Aarey | -111.7 | -6.2 | 204.9 | -143 | -5.4 | 188.5 |
| Borivali(M)-Borivali (A) | -147.8 | -14.4 | 205.1 | -149.3 | -15.3 | 189 |
| Borivali(M)-Gorai (A) | 21.5 | 11.9 | 205.5 | -67.5 | 18.3 | 189.3 |
| Borivali(M)- Borivali(T) | -197.3 | -14.3 | 205.1 | -198.5 | -16.4 | 189 |
| Kalwa-Salasette | -100.8 | 36.3 | 204.5 | -199.4 | 45 | 188.5 |
| Trombay(M)-Chembur | -26.1 | -1.5 | 206.8 | -26.7 | -1.6 | 191 |
| Trombay(M)-Trombay(T) | -53.2 | 66.4 | 206.9 | -80.5 | -64.5 | 191.5 |
| Salasette- Kalyan(110 kV) | -46.1 | 36.6 | 101.2 | 0 | 0 | 0 |

### B. OPTIMAL EMBEDDED GENERATION

Higher embedded generation in the Mumbai area helps in reducing the impact of cascade tripping under high import scenarios. In case of transmission depletion in the MSETCL network bordering the Mumbai island and catering power to Mumbai, N-1 compliance is the minimum criteria to be complied with as one more tripping is highly probable and such an eventuality should not lead to a cascading event. Import should be reduced to enforce N-1 compliance by bringing in standby generation after picking up available spinning margins and to keep hydro units ready by spinning in a vacuum and if required, shed some load as the last resort. In the study to compensate for the effect of loss of import, Unit 8 (250 MW) was taken into service. However, this would not fully compensate for the excess MMR load falling on the TPC network. In this case reduced load shedding of 630 MW was considered, the load shedding in the TPC network is less by 250 MW as compared to the load shedding that was done on October 12, 2020. As illustrated in Fig. 10, because the minimum frequency was greater than 47.6 Hz, the TPC network survived.

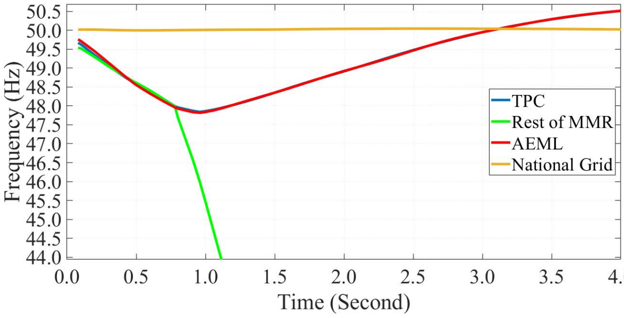


**FIGURE 10.** Frequency Plot for 250 MW increase in Mumbai generation.

If Unit 8 of Tata Power would have brought into service before 10:00 hrs on October 12, 2020, (under zero scheduling and synchronized at 14:00 hrs), MSLDC would have ensured N-1 compliance, and the disturbance could probably have been averted. Further, the tripping of Bhira PSP (150 MW) also hampered further operations. The survival of the islanding would have been possible and AEML and TPC would have stayed together if the under-frequency tripping of generators were on the lower side or had a minor time delay.

### C. REVISION OF U/F SETTINGS FOR LOAD SHEDDING

As shown in Fig. 11, when the load shedding settings were changed to 48.4 Hz U/F the islands were formed successfully. Both the islands could survive as sufficient time for load relief and frequency improvement was present in this case, therefore AEML and TPC stayed together and survived.

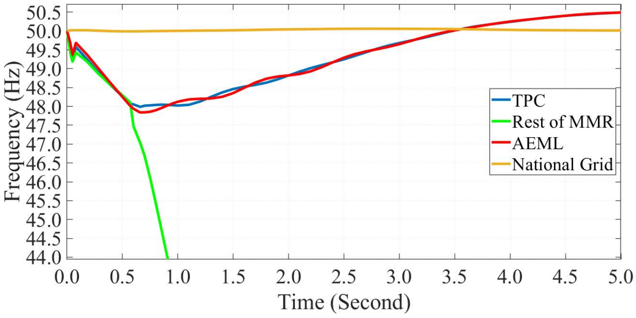


**FIGURE 11.** Frequency Plot with 48.4 Hz U/F Load Shedding.

### D. ANALYSIS OF SIMULATION RESULTS FOR PEAK DEMAND SCENARIO

A peak demand case for coincident Mumbai peak of 3,691 MW was considered and the generation in TPC and AEML made full with the import of 1,814 MW from MSETCL. The simulation was carried out with a similar set of initial disturbance events. The U/F load shedding for both AEML and TPC was considered at 48.4 Hz(the new revised settings) and the islanding settings remained the same. The minimum frequency touched was 47.8 Hz therefore AEML and TPC stayed together and survived. However, it may be noted that no increase was done in the MMR load which was kept at 1,303 MW.

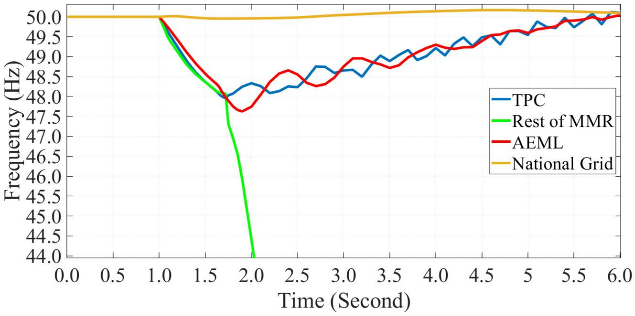


**FIGURE 12.** Frequency plot for coincident peak demand.

It is also found that in the coincident peak demand case, as shown in Fig. 12, oscillations are observed between the AEML and TPC network. These oscillations can be damped out by proper tuning of the Power System Stabilisers.

## VI. LESSONS LEARNT

In light of the event of October 12, 2020, this section explains the general challenges (GC) faced during the major disturbance. In addition, the section describes the experience of the event and the lessons learnt from Mumbai Blackout (LLMB). Some general recommendations (GR) are proposed based on the experience of this major grid disturbance to minimize the problems and difficulties experienced by system operators in the event of future grid disturbances.

### A. TRANSMISSION CONSTRAINTS

**GC:** The issue of installation increment of the transmission line to deliver power in a megacity like Mumbai is a big problem.

**LLMB:** The last blackout in Mumbai occurred ten years ago on November 19 and 21, 2010, and subsequent to this blackout, transmission augmentation in the external network for delivering power to Mumbai was planned to address the future load growth, However, due to ROW problems in a densely populated city no actions could be taken up, and the limitations on the import of power to Mumbai city continue to linger.

**GR:** Extensive study and plannings are required before transmission augmentation in the external network considering the future load growth.

### B. VIOLATION OF TRANSFER LIMITS

**GC:** Cascading failure occurs frequently in power systems when one line fails (totally or partially) and transfers its load to the surrounding line. During cascade failure balancing the transfer, capability limits are the main challenge to all grid operators.

**TABLE 6.** **TTC/ATC of 400 kV Network.**

| Import TTC | Import ATC | Actual Import | Remarks |
|---|---|---|---|
| (in MW) | | | |
| **Base Case** | | | |
| 2531.5 | 2030 | 1490 | Import must be restricted to 2030 MW |
| **Tripping of Talegaon- Kalwa S/C** | | | |
| 1610 | 1540 | 1490 | No emergency measures required except close monitoring |
| **Tripping of Kalwa-Padghe Circuit 1** | | | |
| 1454 | 1200 | 1490 | Increase 190 MW generation or load shedding |
| **Tripping of Kalwa-Padghe Circuit 2** | | | |
| 1400 | 1150 | 1490 | Increase 240 MW generation or load shedding |

**LLMB:** The transfer limits -TTC/ATC were computed with all 400 kV lines in service with the external network used to import power and under each cumulative contingencies using PSS/E are as shown in Table 6. The balancing protocol required is to bring up embedded generation (Hydro/standby thermal) and shed load consistent with transfer capability requirements.

**GR:** Timely balancing considering (N-1) compliance and transfer capability limits would have probably averted the disturbance.

### C. OVER VOLTAGE CONTROL

**GC:** In general, it is difficult to find a good trade-off between over-voltage protection and voltage support to maintain voltage profile.

**LLMB:** Inadequate over-voltage control at important 400 kV substations in the external system led to the tripping of an important 400 kV line under already depleted transmission.

**GR:** While forming islands or while getting connected back to the grid, maintaining voltage profile can be achieved by proper coordination between various controllers and compensators used in the network.

### D. ECONOMIC DISPATCH CONSIDERATIONS

**GC:** At times, reliability considerations are ignored due to economic considerations like merit order dispatch, promotion of trading due to open access, difficulties encountered in building transmission networks in certain pockets, and importing a sizable amount of power to growing urban areas. As the generators get scheduled based on the daily load requirements, some of the units may be off at the time of disturbance. In such circumstances, it is not always possible to get them started for helping the grid to strain off its overloading.

**LLMB:** One of the important generators was shut down due to lack of demand and also economic dispatch considerations in Mumbai embedded generation. The unit was unable to be brought into operation due to its zero scheduling, despite the fact that transmission exhaustion necessitated import restrictions.

**GR:** With due respect to the economic load dispatch schedules, reliability always remains a serious concern in case of emergencies like cascading. Depending on start-up time of the units, the backup plans should be prepared. Alternately, rather than taking units off, increased spinning reserves should be worked out for getting a trade-off solution for reliability and economical solutions to fulfill efficient normal operation as well as it will provide strong support at the time of cascading.

### E. HIDDEN FAILURES

**GC:** During any blackout event in large grid infrastructures like India and the US it is observed that there are various hidden failures in these events either due to inefficient planning or due to improper execution.

**LLMB:** During blackout event, multiple hidden failures were observed some of them are

- On 220 kV lines, the overcurrent relay settings were supposed to be revised to enable tripping in the event of a fault but not overloading. However, this was not the case.
- At Kharghar, one of the significant load trimming schemes (LTS) provided only 18 MW of load relief, falling short of the 302 MW of committed relief of 320 MW.

- For maintenance purposes, the communication equipment used to implement remote load shedding was bypassed.
- At the power station end, the Uran power station islanding scheme trip settings were bypassed, however the remote end tripping settings were not bypassed.
- The feedback relay monitoring the butterfly valve at the Bhira pump storage plant malfunctioned, resulting in the triping of the 150 MW unit, which the operators were attempting to synchronize in order to reduce grid import.
- Attempts to increase the generation capacity of khopoli to 75 MW were unsuccessful, and only 7 MW was added. These factors contributed to the failure of efforts to reduce the import of power.

**GR:** Planning must be done for more than N-1 contingencies at least for megacities like Mumbai as there is a huge financial loss during the blackout of even smaller duration.

### F. HIGH ROCOF

**GC:** High ROCOF is very significant in current grid infrastructures due to adverse embedded load generation balance in megacity islands and high integration of renewable sources of power, which reduces the inertia of the system leading to high ROCOF.

**LLMB:** The ROCOF of the order of 3.5 Hz/sec. and above was observed for the first time in the recent past as the unexpected formation of MMR island which had adverse load generation balance. This high ROCOF affected the islanding operation as minimum frequency touching 47.68 Hz, leading to tripping of embedded generators in the TPC area under frequency trip settings.

**GR:** The frequency of high ROCOF has become significant in recent days, so there is a need for smart relays (A synchrophasor based smart relay can be made to operate by sending an additional signal from WAMPAC control center to operate bypassing the base frequency and to trip much earlier in case of very high ROCOF than the set value or Hybrid UFLS relays can be implemented which will be using a combination of under-frequency, ROCOF and voltages) to cope up with this situation.

### G. ISLANDING SETTINGS

**GC:** The inherent time delays provided with under-frequency relay settings for islanding can not be further decreased to avoid maloperations. These delays affect the success of islanding during high ROCOF.

**LLMB:** As increasing demand of the Mumbai city will require more embedded generation to ensure load generation balance during islanding. To cater upcoming demand of embedded generation via fossil fuel is impractical due to space constraint and environmental issue. Following option to redesign the islanding scheme can be implemented considering the increasing demand of Mumbai city:

- There is a requirement of an adaptive islanding scheme for the Mumbai grid based on various permutations and combinations of generation load imbalance and all islanding schemes must use the ROCOF setting considering high ROCOF in all recent blackouts.
- Survival chances of current islanding scheme can also be increased significantly if the embedded load generation imbalance can be catered. Some of this increased demand can be catered by renewable generation and battery energy storage system (BESS) which can also serve as an emergency control mechanism to contain the ROCOF during islanding as full capacity of BESS can be switched in sub-seconds time span.
- In comparison to the peak demand of Mumbai city, importing 1900 MW power would be a more cost-effective option than investing in embedded generation and and the TPC island should be reduced to a single unit at Trombay power station with radial load, while the AEML island should also be reduced to a single unit at Dahanu with a radial load. These mini islands will help in survival of critical loads, generation and faster restoration.

**GR:** Comprehensive adaptive islanding scheme needs to be developed considering the future growth of load and renewable generation.

### H. SETTINGS FOR LOAD TRIMMING SCHEME

**GC:** Need to prioritize the load during a disturbance to save at least the critical loads like Hospitals, Transportation, etc. Implementing appropriate LTS to minimize the stress on the power network.

**LLMB:** The U/F load shedding planned within the Mumbai island to address frequency instability and raise the frequency to 50 Hz, proved insufficient shortly after the formation of island. The reason behind this failure was due to lower frequency settings, intentional delays provided in the U/F relays, and the absence of ROCOF relays in the TPC area.

**GR:** The periodical updating of LTS scheme and frequency settings of relays as per the changes in the network and power quality are recommended to minimize the downtime and size of the affected cascading span.

### I. VISUALIZATION AND SITUATIONAL AWARENESS

**GC:** Despite several widespread grid disturbances in the past and especially a major blackout in 2012 in India, still visualization tools, dynamic security analysis tools are yet to be used to carry out control system operations. Sometimes, the lack of synchrophasor data, Dynamic Security Analysis (DSA) tools to visualize the state of the system makes it difficult to operate and control the system performance within a given short time span of cascading.

**LLMB:** Due to the lack of telemeter data on the Mumbai city boundary in SCADA/EMS systems of TPC and AEML control centers, the trippings and transmission depletion and power flows in the external network are not visualized to take early actions and to have proper state estimation. Lack of synchrophasor data, Dynamic Security Analysis (DSA) tools to assess the situation awareness is a major handicap for TPC and AEML control centers. Security Constrained Economic Dispatch (SCED), and Unit Commitment (SCUC) would help inappropriately executing balancing protocol for import vis à vis embedded generation/load shedding under different operating scenarios and emergency conditions.

**GR:** To have better visibility in the network, it is recommended to opt for the DSA tool, Security Constrained Economic Dispatch (SCED), and Unit Commitment (SCUC).

### *J. CASCADE TRIPPING OF 220 kV LINES*

**GC:** Occasionally, an operator gets panicked during the disturbance, which may result in ending up with a wrong decision, which may lead to a huge economic loss.

**LLMB**: Even though several 220 kV lines bring power to MMR, they are all tripped in cascade due to the O/L trip setting of O/C relays. Further, while planning a new system and system strengthening, the transfer capability considerations are more important than augmenting mere capacity, especially at lower kV systems which are in parallel to 400 kV / 765 kV corridors. Some of these 220 kV lines needs to be considered for reconductoring/ re-rooting etc., to increase thermal loading. Another important issue is that several 220 kV lines were hand tripped to control overloading on some 220 kV lines, leading to the weakening of the 220 kV system. The load trimming schemes (LTS) should trim the loads by shedding through relays rather than trip lines to control overloadings on other lines. This was one of the major handicaps in the operating protocols. Using phase shifters to divert the power flow or load shedding could be the better option.

**GR:** Regular training of the operator and enhancing their decision-making ability. It is also advised for opting for automatic adaptive LTS to reduce further failure due to human error.

## VII. CONCLUSION AND FUTURE SCOPE

Each blackout is one-of-a-kind and will never be repeated due to its unique dynamics, but the lessons to be learned have more in common. Blackouts usually occur due to low probability high impact events compounded by various hidden failures. All recent blackouts demonstrates the fallout effect on essential supplies. The power failures increasingly have a devastating effect in urban cities due to over-dependence on power.

A blackout occurred in and around Mumbai city on October 12, 2020, at 10:05 hrs. The paper analyzed this event in great detail by developing static and dynamic models utilizing the PSS-E platform. The sequence of events was confirmed by simulation studies, which concluded that the AEML was separated first from TPC and the rest of MMR. The simulation studies enabled tuning of settings for the islanding scheme, U/F load shedding, and transfer capability limits. This article also used the Mumbai grid blackout to explain general challenges faced during the major disturbance, lessons learned from it, and recommendations to develop alternative operating scenarios, which can be useful for other utilities all over the world.

The way forward to ensure reliability of highly dynamic grid under such events is to incorporate DSA tool to visualize the state of the system to detect the fast paced events for early response. The frequency of high ROCOF has become significant in recent days, so comprehensive adaptive islanding scheme needs to be developed considering the future growth of load and renewable generation.

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