EXPERIENCE OF BLACKOUTS AND RESTORATION PRACTICES IN WESTERN REGION OF INDIA

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1 INTRODUCTION

Maintaining security of large power grids is an onerous task especially in the Indian context. In India, five regional power grids have been operating. Due to severe shortages of power in almost all the regions, the operational discipline is on low ebb and the grids are operating with adverse frequency and voltage profiles coupled with over and under drawals by one or other states. Transmission constraints and critical loadings of equipment are also not unusual. The pre-fault conditions can have far reaching effect on the extent and duration of the grid disturbances.

Generally, the initiating causes such as tripping of a heavily loaded line/ transformer, a bus fault or a line fault with a stuck breaker could trigger a disturbance. Due to operation of the high speed protection systems, the faults would be cleared discriminately and thus get localized. However, at times, factors such as power swings on transmission lines, relay mal-operations, tripping of equipment on overload etc., could spread the disturbance affecting larger areas. Due to system splitting and formation of islands, the pockets with adverse load generation balance collapse. This was mainly due to the non-implementation of the agreed upon Automatic Under Frequency Load Shedding Scheme. However, the islanding schemes operate at 47.6 Hz and some parts of the grid can be saved from collapse.

Even though, restoration of the grid following a major blackout is done as per the preplanned Black start proceedings, some unanticipated problems can cause considerable delay in restoration. On occasions, even the restored parts collapsed due to restoration of load in bulk, tripping of black started units while energizing large motors driving the power plant auxiliaries and large phase angle mismatches while synchronizing etc. The delays in restoration are also due to problems along the restoration paths, communication problems etc. However, the experience of blackouts helps in preparing restoration plans in more detail.

An attempt has been made to analyze significant features of various blackouts and restoration problems encountered during the several grid disturbances in Western Region (India) during the period 1988-2003.

2 OVERVIEW OF WESTERN REGIONAL GRID

- Western regional grid comprises the power systems of the States of Maharashtra, Gujarat, Madhya Pradesh, Chattisgarh, Goa; Union Territories of Daman & Diu and Dadra & Nagar Haveli; the Central Sector power stations owned by National Thermal Power Corporation (NTPC) & Nuclear Power Corporation(NPC); the inter state transmission system owned by POWERGRID and power systems owned by the private utilities such as Tata Power Company(TPC), Bombay Suburban Electric Supply (BSES) Ltd, Bombay Electricity Supply &Transport (BEST), Ahmedabad Electricity Co.Ltd (AE.Co.), etc. The installed capacity as on 1.10.2003 is 31464 MW. The region is catering to a peak demand of around 22500 MW. The daily energy consumption is 530 Mus. The region has hydro-thermal mix of 14:86. The region has been facing power shortage (peak) of 18% and energy shortage of 11%. The transmission network of the region comprises 19500 ckt. Kms of 400 kV lines and 30000 ckt. Kms of 220kV lines. 500 kV bipolar HVDC link between Chandrapur and Padghe connects Eastern & Western Maharashtra systems. The region is connected to Northern Region and Southern Region asynchronously through HVDC back-to-back links at Vindhyachal and Bhadravati respectively. The Eastern, North Eastern regions operate in synchronization with Western Region.

- The region is having full-fledged Supervisory Control & Data Acquisition (SCADA) systems since 1984 with fair amount of information available for monitoring the grid. All the State Load Despatch Centres (SLDCs) and Regional Load Despatch Centre (RLDC) are equipped with SCADA facilities and Energy Management Studies (EMS) functions are to be provided shortly.

- The defense mechanisms constitute Automatic Under Frequency Load Shedding (AUFLS) and islanding schemes. The AUFLS with discrete relays provided at 48.2 Hz and 47.9 Hz, is expected to give 2500 MW relief and the frequency trend relays are expected to give load relief of 4778 MW. However, due to very high shortages, the under frequency load relief actually observed is around 350 MW only. Due to continuous operation around 48 Hz for prolonged periods, the under frequency relays at 48.2 Hz are mostly bypassed or its settings are lowered. The U/F relays at 48.0 Hz are also bypassed in case of repeated operations. Some of the feeders connected to U/F relays are also used for manual load shedding. Due to this, the AUFLS is ineffective at certain times.

- Number of islanding schemes has been provided to operate at 47.6 Hz. Many of these islanding schemes successfully operated during major grid disturbance in the past. The islanding schemes enable partly survival of the system and also help in faster restoration.

- Due to high levels of power deficit, load generation balance is achieved through demand control. This is one of the major operational planning exercise jointly carried out by the State Electricity Boards and Western Regional Load Despatch Centre (WRLDC). The scheduled load shedding is planned to take care of long term shortages. The quantum of scheduled load shedding in the region is as high as 2500 MW in July (requirement of 3500 MW during June to Sept.) and requirement of about 4500 MW from October onwards (Oct. – May). The distress load shedding is also planned one day in advance and fine tuned on the day of despatch. The distress load shedding takes care of fluctuations in availability arising out of forced outages, partial outages and constraints like coal shortage etc. However, the constituents have a tendency to overdraw from the grid by not fully implementing the scheduled and distress load shedding due to social pressures.

- The voltage profile is by and large satisfactory except in the Rabi season from October to December. The considerable amount of load shedding especially in the rural areas enabled good voltage profile.

3 BLACKOUTS IN THE PAST – AN OVERVIEW

3.1 List of major occurrences (Category-A) during 1988-2003

NO.	DATE	TIME	COLLAPSED PARTS
1.	11.10.88	09:23	Western Madhya Pradesh (MP)
2.	28.12.88	10:34	Western Maharashtra, part of Gujarat
3.	14.8.89	15:26	Eastern MP
4.	17.8.89	16:35	Western Maharashtra including Bombay
5.	31.7.90	11:24	MP
6.	24.11.90	08:37	Western Maharashtra and Bombay
7.	16.3.91	12:43	Western Maharashtra
8.	25.10.91	10:51	Bombay + Western Maharashtra + Gujarat + Western MP
9.	12.2.92	16:12	South Bombay + parts of Western Maharashtra
10.	31.3.92	15:03	Western Maharashtra + Bombay
11.	15.6.92	19:25	Western MP, Gujarat, Maharashtra and North Bombay
12.	28.5.93	21:45	Western Maharashtra, parts of Goa
13.	19.4.95	18:02	Western Maharashtra, Gujarat, North MP and parts of Goa
14.	1.5.95	15:46	Western Maharashtra, Bombay, North MP and parts of Goa
15.	10.11.95	11:08	Entire grid except Bombay, parts of Eastern MP excluding Korba Super Thermal Power Station(KSTPS), Vindhyachal Super Thermal Power Station(VSTPS), etc.
16.	14.11.95	08:40	Maharashtra system excluding Bombay
17.	9.12.95	07:36	Entire grid except few islands – Bombay collapsed
18.	11.12.96	16:02	Western Maharashtra
19.	28.2.97	20:51	Western Maharashtra & Tata Power Company
20.	23.10.97	08:13	Eastern MP including KSTPS & VSTPS
21.	26.10.97	23:55	Maharashtra, TPC islanded & survived.
22.	16.12.98	10:55	Maharashtra & MP system

23.	14.10.00	04:41	MP system collapsed except Indore area.
24.	18.05.02	06:36	Western Maharashtra & Goa
25.	23.05.02	06:13	Western Maharashtra & Goa
26.	23.05.02	08:54	Western Maharashtra & Goa
27.	29.05.02	02:09	Western Maharashtra & Goa
28.	30.07.02	20:11	Entire Western Grid except Mumbai
29.	06.10.03	10:39	Western Maharashtra & Goa

3.2 Summary of events related to major occurrences during 1988-2003

NO.	DYNAMICS	A
	PRE-FAULT	
1.	Low frequency	5
2.	Low voltage	7
3.	Transmission inadequacy	14
4.	Transformation capacity inadequacy	4
5.	Low generation / overdrawals	4
6	High voltage	-
	INITIATING EVENT	
1	Equipment failure	3
2	Mal-operation of protection scheme	2
3	Overload tripping of lines / Inter Connecting Transformers (ICTs)	6
4	Bus faults	7
5	Tripping of ICTs or lines on faults	5
6.	Natural disasters	1
7.	Voltage collapse	2
8.	Sudden bulk load shedding	1
9.	Operation of Islanding Schemes at low frequency	1
10	Others	3
11.	Unknown	1
	COMPOUNDING FACTORS	
1.	Operation of Reverse Power Under Frequency (RPUF) / inter-trip of tie lines	8
2	Mal-operation of protection schemes	6
3	Trippings on overload	11
4	Tripping on power swing	17
5	Simultaneous faults	3
6	Over voltage	3
7	U/F tripping of generators	1
	SYSTEM OPERATION	
1.	System splitting	23
2.	Partly Collapse of main system	23
3.	Islanding of Bombay	15
4.	Survival of Bombay island	9

In 1983, one major disturbance affecting total power supply in the entire Western Region occurred on 13.7.1983. Thereafter, though several major grid disturbances took place, the extent of interruptions on power supply was only in one or more areas. This was due to adoption of various defence schemes and the islanding schemes by the constituents. During occurrences that took place on 10.11.95, 9.12.95 and 30.7.2002, the entire grid was affected except a few islanded parts that survived.

The pre-fault conditions have a bearing on the extent of the grid disturbance as these influence the compounding events. In most of the blackouts, prior to the system disturbance, grid was operating in an alert state. In most of the cases, transmission inadequacy and in some of the cases, low frequency or low voltage and combination of the above are the contributing factors for alert operation of the grid. Persistence of low frequency also led to bypassing of certain defence mechanisms like AUFLS scheme. Low voltages prior to disturbance can lead to tripping of some lines due to load encroachment or power swings in the event of tripping of an already over loaded line. The voltages at some nodes may also further sink and may lead to voltage collapse. The transmission inadequacy can lead to tripping of lines on load encroachment/power swing during disturbances and can lead to system splitting. Power swings, after the disturbance initiated, led to compounding of the disturbance as more lines had tripped in most of the occurrences leading to system splitting. Mumbai system had islanded from grid and survived on several occasions. However, on certain occasions, the Mumbai island could not sustain due to problems in control system of 500 MW units. However, the survival rate improved significantly since 1992. Whenever, system splitting took place, the Western Maharashtra system collapsed due to severe load generation imbalance and inadequate Under Frequency Load Shedding. Gujarat system survived number of times after separation from the rest of the grid due to reliable AUFLS. The Eastern parts have surplus generation as compared to loads and number of units trip on high frequency and stabilize thereafter. Non-implementation of Free Governor Operation is a major constraint.

4 RESTORATION POLICIES

4.1 Approaches

Both the island and core/sequential approaches are employed. The former is employed due to existence of several islanding schemes (designed) as well as black start facilities in the region mainly in Gujarat, Madhya Pradesh & Chattisgarh. The black started units are mainly hydro or gas units. However, in Maharashtra, due to lack of black-start facilities and pre-conceived islands, the sequential approach of restoration is employed.

In India, three power systems are operating asynchronously Central grid (ER+WR+NER), Southern grid (SR) and Northern grid (NR). The asynchronous interconnections between these three regions are through HVDC back-to-back links with provision to connect the regions synchronously during restoration using AC bypass links. The advantage of availability of external assistance is fully utilized as the assistance available from external sources could enable provision of start up power to number of power stations as well as restoration of essential loads. Further, the grid restored would be connected to the external systems which are stronger and probability of restored grid surviving would be higher.

4.2 Hierarchy of responsibilities

WRLDC is directly involved in restoration of Central Sector transmission and generation as well as getting assistance from external sources (other regions), re-integration of various islands and delinking of the restored parts of Western region from other regions apart from the responsibilities of frequency control and monitoring the line loadings. The SLDCs are mainly involved in restoring their own state systems.

4.3 Generation securing

- High priority is given to ensure the survival of islands that have been created either by design or by chance. One Engineer is assigned to each of these islands to monitor frequency control aspects as well as re-integration aspects.
- The power available from black started units is to be extended based on defined priorities. Highest priority will be accorded for supplying of survival power to the generating stations followed by to those units capable of hot start up, units capable of rapid restart and essential loads like traction etc. Normally, hydro and gas units are provided with black-start facilities. In case of non provision of black start facility or failure to black-start, hydro and gas units are given start-up power as these can come up with full load in about 10 minutes.
- The black start procedures require that thermal units island on house load. However, except for the Trombay units (TPC) and Kakrapar (nuclear) units, the islanding on house loads is not generally successful.

4.4 Restoration path

The restoration procedures prepared and made available at SLDCs and RLDC define restoration paths for extending start up power to each power station clearly along with alternative paths and priorities of paths. The priorities are generally based on short line sections and lower voltage lines.

4.5 Synchronizing locations

The islands are re-connected/re-integrated at pre-defined locations and the substation/generating station engineers in Western region are well conversant with the procedures as well as synchronization of islands.

4.6 Standing Phase Angle (SPA) problems

SPA problems have been encountered during restoration while re-integrating islands or re-connecting the state grids with each other. Normally, the state grids are reconnected after sufficient level of stabilization. The SPA problem is handled by generation re-scheduling based on the advice of RLDCs.

4.7 Frequently encountered restoration problems

The restored parts failed number of times during restoration or restoration delayed due to the following:-

a) Frequency control in islands with low stiffness.
b) Start up of large motors (auxiliaries) of thermal plants from black started gas units. Normally when thermal power stations’ auxiliaries are energized from black started gas units, minimum auxiliaries essential for start up have to be energized. Out of the various auxiliaries as far as possible and based on the

startup sequence the largest motor has to be started first. The other motors are started thereafter one by one in a sequential manner. (with larger ones preceding the smaller ones)

c) While supplying start up power from small hydro units over 132kV/220kV, hunting of hydro units were observed number of times.
d) While extending start up power, high voltages were encountered. The generating units supplying start up power are operated with excitation voltage as low as possible (much less than 1 p.u.). The non availability of radial load near some power stations (black started) is coming in the way of extending start up power to other stations due to high voltage (e.g. Koyna). In case of high voltage problems, we are restoring some loads along the restoration path usually of low power factor.
e) Mixing of supplies when start up power is provided from two different sources.
f) Difficulties were also encountered in delinking from the external systems as the tie-lines have to be operated with almost zero active and reactive power for sometime.
g) Ensuring of discipline when start up power is extended from one utility to other utility. Due to lack of adequate monitoring and control, some substation operators tend to restore more loads resulting in either overloading of start up path or unmanageable frequency variations.
h) The substation operators have no documentation regarding load variations on various feeders over the day.
i) Cold load pick up leading to tripping of black start units as well as line/transformers restored.
j) Due to black out, some industries declare lay-off for the day. In such cases, seeking load for generation maximization as well as for HV control is a concern.
k) The traction loads in the islands cause severe frequency fluctuations.
l) The generator under frequency trip settings at 47.5 Hz, instantaneous is also a concern in case of large frequency variations during load restoration (cold load pick up).
m) Restoration of unbalanced loads like traction loads.
n) Failure of Lightening Arresters (LA) due to high voltage.
o) Operation of Over-Fluxing relays, Over Voltage (O/V) relays
p) Communication problems

5 CASE STUDIES – IN BRIEF

5.1 Case Study of 30.7.02 blackout

A grid disturbance occurred on 30.07.02 at 20:11 hrs. The entire grid except some islanded parts collapsed. Prior to the occurrence, one of the states was overdrawing from the grid at very low frequency of 48 Hz. Low frequency operation persisted due to severe shortages on account of number of units on planned maintenance (a regular practice during monsoon) coupled with the onset of agricultural demand due to failure of monsoon. Due to lack of resources to control frequency, frequency persisted around 48 Hz and even dipped to 47.6 Hz. at 19:32 hrs when frequency improved due to some distress load shedding carried out by Gujarat. Continuous low frequency operation had resulted in bypassing of vital defense mechanism like U.F relays. At 20:11 hrs, when frequency dipped to 47.6 Hz and remained there for more than 200 milliseconds, several islanding schemes designed to operate at 47.6 Hz with some time delay operated. The operation of islanding schemes resulted in further deprivation of about 180 MW to the rest of the grid and frequency fell sharply (no primary response and UF load shedding) to 47.5 Hz where several thermal and nuclear generators are set to trip on UF protection of the turbo generator. Several generators tripped in cascade and the entire grid collapsed.

The restoration of the entire grid took around 22½ hours. The start up power to various generating stations and essential loads was obtained from some black-started units; survived islands and external sources such as from inter regional connection points (NR & SR). During restoration, part of the grid restored through SR interconnection collapsed twice i.e. at 01:00 hrs on 31.7.02 and at 10:20 hrs.

Generation in the Eastern part could not be picked up due to reduced loads. On one occasion, restored part of Western Maharashtra connected to Gujarat collapsed due to opening of inter-connecting line by Gujarat due to sudden restoration of loads in Western Maharashtra.

Some of the islands in Gujarat were interconnected and enlarged. However, tripping of one large thermal unit led to collapse of enlarged island. Delays were also experienced while extending start up power from a black-started hydro station (Koyna) due to high voltage problems and non-availability of radial loads. One black-started Gas Turbine (GT) tripped due to sudden restoration of load-higher than the response rate of the GT (7.2 MW/minute). Another black-started GT tripped while extending start up power to a thermal station and when a large motor was started. Some of the small hydro units which were black-started (Pench, Gandhisagar, Bargi, Bango) experienced power and voltage oscillations while supplying start up power over long restoration paths. One restored island (Koyna-Uran) tripped due to improper restoration of load and led to tripping of the units on UF protection (should it be bypassed?). Difficulties were experienced in synchronizing the partly system in the East due to large phase angle differences.

5.2 Case Study of 14.10.2000 blackout

On 4.10.00 at 04:41 hrs, a grid disturbance occurred in Western region resulting in collapse of M. P. system except Indore area. The occurrence was triggered by phase-to-ground line fault on 400kV Bhilai-Korba Single Circuit (S/C) line. Even though the fault was cleared by breakers at both the ends, the B-phase pole of the breaker connected to bus-2 of 400kV Bhilai substation (one and half breaker scheme) started hunting pneumatically. Due to hunting action, this breaker (ABCB) performed one close and one trip operation in 100 milliseconds and this cycle repeated 29 times in 2.9 seconds after which the breaker stuck up permanently and the fault could not be cleared. LBB protection could not operate till 2.9 seconds leading to tripping of all the 400kV lines from remote ends. The diversion of power on 220/132kV network led to tripping of these lines on power swing. Diversion of Korba power through another 400kV corridor (Vindhyachal-Asoj corridor) resulted in tripping of several 400kV lines on power swing. This blackout underlines the need for a protection to detect pneumatic hunting and initiates early tripping of LBB protection so as to protect the breaker.

The regional grid split into two parts; one part comprising Maharashtra and Gujarat system survived due to UF load shedding and pick up of reserve generation.

Other part comprising M. P. system along with Korba and Vindhyachal further split into two islands with both parts collapsing due to load generation mismatch.

The restoration of the grid took around 9-hours. The restoration commenced from black-started hydro units (Bargi, Pench, Bursinghpur, Bango) and power supply extended to thermal power stations of M. P. Satpura power station got start up power from 400kV Indore (survived along with Gujarat) using 220kV startup path. M.P system initially was restored in two parts and both the parts were later integrated. Korba & Vindhyachal power stations availed start up power on HVDC bypass link at Vindhyachal. The restored Vindhyachal-Korba island collapsed while disconnecting the restored parts from NR interconnection at Vindhyachal.

6 FUTURE SCENARIO

Government of India has promulgated Electricity Act, 2003 which is bringing forth restructuring and reforms in all the States by June 2004. The Act also provides for mandatory open access. The introduction of Availability Based Tariff (ABT) in all the regions in the bulk power market has already led to spurt in trading with number of bilateral contracts among the utilities. The surplus power in Eastern region is being utilized by deficit regions like Western region. With the likely introduction of ABT at intra-state level and implementation of open access by Central Electricity Regulatory Commission (CERC), some of the unutilized resources like surpluses in captive power plants are also likely to be utilized. In India, significant generation addition did not take place during the nineties and particularly in Western region the capacity addition during the last decade is inadequate whereas the demand for electricity has grown up leading to current levels of deficit in Western region as high as 6000 MW even with 2000 MW power imported by Western region from other regions without any addition to the transmission network. With IPPs also making a comeback and growing competition among utilities coupled with utilities seeking cheaper power would lead to multiple transactions taking place on the existing transmission corridors. So far, the transmission planning in India is based on regional basis. Now the boundaries have opened up and utilities may opt for power from distant generators, often requiring wheeling by third parties. This changed scenario is causing constraints in certain corridors and in most of the corridors the line loadings are closer to the loadability limits. The lack of operating margins is a major threat with dynamic instability (both angle and oscillatory) and voltage collapse looming large. Already Western region has faced occurrences on 5th & 7th November 2003.

In the restructured environment, frequency control, voltage control and control of line loadings are major challenges. Due to inadequate margins in generation/operating reserve, frequency control has to be done mostly through shedding loads and it is essential to implement load shedding through automatic means in order to avoid blackouts. The automatic under frequency load shedding scheme (AUFLS) and primary response through turbine governors become major defense mechanisms in the restructured environment. Due to increased line loadings, voltage control at various nodes along major corridors is required to be maintained in order to ensure stability and to prevent voltage collapse. In order to maintain line loadings with adequate margins, re-scheduling of various transactions need to be done to manage constraints in some corridors. To manage large power grids in the restructured environment, state-of-the-art power system analysis software tools both for real time applications (EMS) and for off-line planning are required. A very good optimal power flow software is required by the grid operators to manage the complex scenario – cheaper power versus safe operating margins and to optimize the transactions. Without automations and power system analysis tools, blackouts in restructured environment are more likely and more extensive. Western region is in the process of revamping SCADA, EMS and communication facilities by February, 2005.

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