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Comparative Analysis of Grid Failures in Recent World History

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Abstract: *On August 14, 2003 a cascade tripping initiated in the North Eastern America and Canada affected 50 million people, on September 28, 2003 major portion of Italy was pitch black due to fault in a transmission line, on May 17, 2005 blast in the series capacitor in one of the transmission line in Vietnam led to cascade tripping of its entire system, on July 30 - 31 of 2012 saw the cascade tripping in Northern and Eastern states of India. This paper contains the summary of major events which led to above mentioned grid failures along with the recommendations are given by the investigating committee of the respective countries. These blackouts as indicated in the respective reports have tremendous economic consequences, and hence it becomes crucial to investigate and study them. This paper includes a comparison between the number of technical and non-technical factors which played a critical role in the initiation of the blackout.*

Keywords: *Blackout, Grid Failure, Power System Stability, Power System Control, Power System Dynamic Performance*

I. Introduction

The dynamic performance of the power system is becoming more and more unpredictable due to increasing use of power electronic devices, load growth, etc. To cope with this unpredictability more controlling devices are employed to ensure failure-free operation of the system. One fault may not lead to grid failure but the accumulation of human errors, real-time information deficiencies, wear and tear of the protective devices over a period may lead to uncontrolled cascading of the system.

The general flow of the cascading can be given by the following figure [1]:

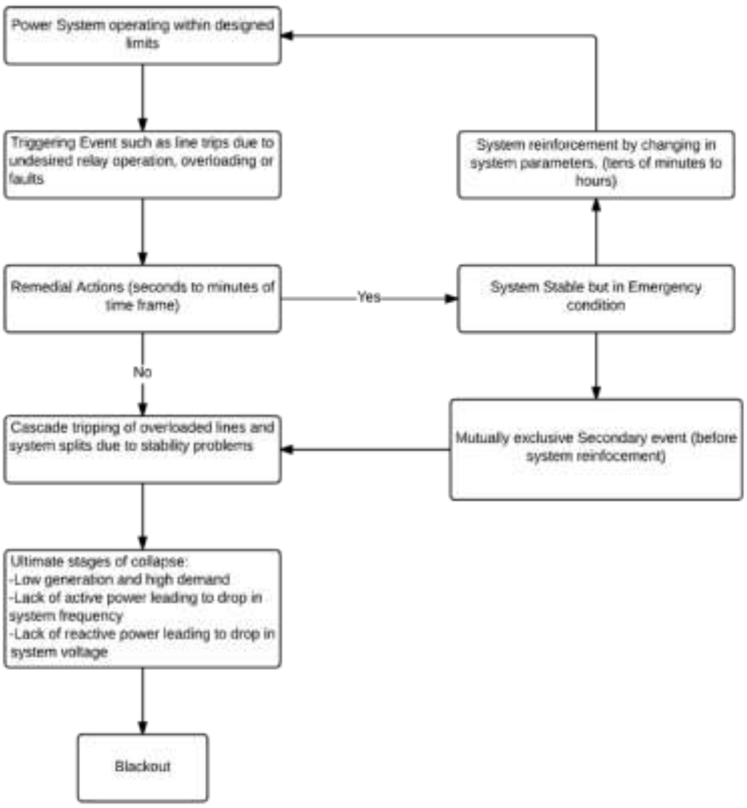

Figure 1: General Flow of a Blackout

II. Summary Of Grid Failure

A. Grid Failure of August 14, 2003 in North Eastern America and Canada

At around four p.m. on August 14, 2003, a cascade tripping was initiated which affected approximately 50 million people and 61,800 MW of electrical loads [3] in the North Eastern States of America and two provinces of Canada. During this cascade tripping over 400 transmission lines, 531 generating units and 261 power plants tripped [4]. The total estimated loss incurred in the US was around 4-10 billion dollars while in Canada it was estimated to be around 2.3 billion dollars [3].

The three major events which were not directly related to the grid failure but could have prevented it were tripping of Conevile Unit 5 at 12:05 (A), tripping of Greenwood unit 1 (B) at 13:14 and tripping of Stuart – Atlanta line (C) due to bush fire under the line. The fact which added intensity to this failure was the inoperativeness of the Midwest ISO’s (MISO) state estimator and Real Time Contingency Analysis software. The failure of this critical software rendered MISO inaccurately estimating the current state of the system. In spite of losses mentioned above, the post-blackout analysis done by the North America Electric Reliability Council (NERC) showed that the system was in obedience to the NERC operating policies up until 15:05.

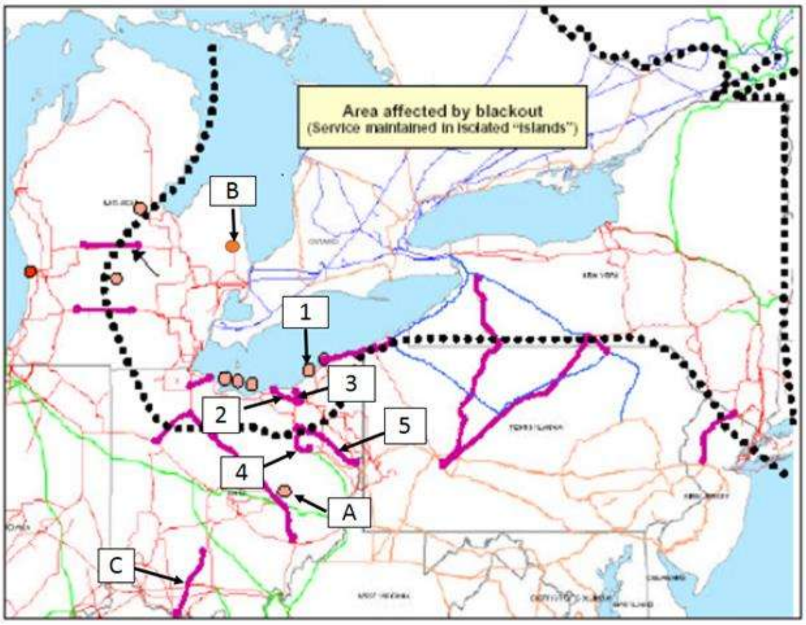

Figure 2: Area affected during U.S. – Canada Blackout

Tripping of two crucial generating stations overloaded other generators nearby. August 14 being a hot summer day the reactive power demand was at its peak value. Due to high reactive power generation, at 13:21 Eastlake Unit 5 (1) of FirstEnergy (FE) tripped as the operator attempted to restore automatic voltage control which was tripped to manual because of over excitation. At 15:05 and 15:32, Chamberlin – Harding 345 kV (2) and Hanna – Juniper 345 kV lines (3) which were loaded only to 44% and 88 % respectively of its emergency rating tripped due tree contact. Furthermore, at 15:41 Star - Canton 345 kV line (4) tripped owing to tree contact. Tripping of three 345 kV line resulted in overloading of other lines. Due to high reactive power demand and sagging voltage, at 16:05 Sammis – Star line (5) tripped as the operating point entered zone 3 of its impedance relay [2].

It is important to note that up until the tripping of Sammis – Star line the cascade tripping could have been avoided by selective tripping of load and hence releasing the load off the overloaded lines. But no mitigating actions were taken by any of the parties involved because of lack of situational awareness. After the 16:05 trip the situation got out of hands as low voltage line started overloading and tripping leaving no way to stop it. By the time tripping stopped it had affected 8 U.S. states and 2 Canadian provinces [3].

Primary causes of the blackout as outlined in NERC report were [2]:

i. Loss of functionality of critical monitoring and controlling tools: During the entire blackout the alarm system which could have made FE's operators aware of the current situation was not operational. Moreover, FE failed to predict and understand the functioning of its Energy Management System.

ii. Lack of situational awareness: Apart from the lack of awareness due to monitoring and the controlling tools failure, the FE's operators were unable to take hint and predict the current operating situation of the power system by the information provided by the neighbouring ISOs and reliability coordinators (RC).
iii. Improper management of vegetation growth in rights-of-way: Post-blackout inspection revealed ill managed vegetation in the rights-of-way of the transmission lines. Had the tripping due to this overgrown vegetation be avoided, cascading tripping would not have occurred.
iv. Inadequate support from reliability coordinators: As there were no proper guidelines specifying when and how to coordinate a security limit violation, there was inadequate information sharing between PJM, MISO and FE.

B. Grid Failure of September 28, 2003 in Italy and Switzerland

In 2003, the energy price in Italy was much higher than European market due to the absence of nuclear power plant and public resistance to the building of new thermal plants. High power demand created pressure to keep the very high level of power import from foreign countries (France, Switzerland, Austria, and Slovenia) to Italy through the interconnection lines. Because of this Italian system experienced for first time a blackout on 28th September 2003, which affected the whole country except the islands of Sardinia and Elba [5].

Italian blackout began when a single line to ground fault occurred on major tie line (Lukmanier line 380 kV) between Italy and Switzerland due to a tree flashover. The connection was not re-established because the circuit breaker didn't auto reclose as the phase angle difference became too large due to the heavy power import into Italy. This line is connected in Lavorgo to the 380 kV interconnection line to Musignano, where a large pumped storage plant is located. The single line to ground fault changed the power flow incoming in Musignano from about 1250 MW to 550 MW, and Sils-Soazza line (interconnection between Italy and Switzerland) was 110% overloaded. The overload of the Sils-Soazza was sustainable for about 15 minutes [4].

After that the power deficit in Italy was such that Italy started to loose synchronism with the rest of Europe and the lines on the interface between France and Italy tripped due to distance relays. The same happened for the 220-kV interconnection between Italy and Austria. Subsequently, the final 380-kV corridor between Italy and Slovenia became overloaded, and it too tripped. These outages left the Italian system with a shortage of 6400 MW of power, and also the frequency of Italian system started to fall. Thus, the entire Italian system collapsed causing a nation-wide blackout. This was the worst blackout in the history of the nation and affected approximately 56 million people [4].

C. Grid Failure of 2005 in North and Central Parts of Vietnam

The Vietnamese power system is segregated into three prime regions: North, Central and South. The transmission is done at 500kV, 220kV and 110kV. The 500kV grid is crucial for healthy power supply to the three regions of Vietnam. Hòa Bình substation received power from the hydro power plant with a capacity of 1920 MW and from South via a 500kV transmission line. The prime purpose of Hòa Bình substation was to supply to North Vietnam. 500kV Hà Tĩnh and Đà Nẵng substation fed power to Northern and Central Vietnam respectively. Pleiku substation received power from Ialy hydro power plant with a capacity of 720 MW. Pleiku substation supplied for the southern part of Central Vietnam and Northern part of South Vietnam. 500kV Phú Lâm substation supplied for South Vietnam; Phú Lâm substation also got power from Phú Mỹ power plants centre with rated power more than 3000MW [7].

The event of blackout occurred on May 17, 2005, initiating from Đà Nẵng substation due to the overloading of the series capacitors. Later, the series capacitor at Hà Tĩnh end of Hà Tĩnh - Hòa Bình line exploded which lead to tripping of all the three phases due to power swing protection feature of the distance protection relay. This separated the power system of Vietnam in two parts from the circuit breaker of Hà Tĩnh substation. Such a large power loss in the Hà Tĩnh - Hòa Bình line led to the overvoltage at 500 kV bus at Hà Tĩnh and Đà Nẵng bus. Thus, circuit breaker at Hà Tĩnh end tripped due to overvoltage [8].

The frequency of northern region dropped to 47.65 Hz and frequency of southern and central region rose to 51.45 Hz because of tripping of Hà Tĩnh - Hòa Bình 500 kV line. Thus, the northern Vietnam got power only from the northern power plants and not from the 500kV grid anymore. Automatic load shedding was done by under-frequency relays. Transmission lines between Đà Nẵng, Pleiku, PhúMỹ tripped because of overvoltage protection. Various generating stations tripped in South Vietnam due to over-frequency operation leading to a blackout [7].

D. Grid Failures of 2012 in North Eastern India

i. July 30, 2012

Disturbance occurred in the Northern India electricity grid at 02:33 a.m. of July 30, 2012 led to a blackout in nearly the entire Northern region (NR) covering all the 8 States. The frequency just before the incident was 49.68 Hz. The total import by NR at 02:30 a.m. is 5759 MW from Western Region (WR), Mundra- Mahendergarh HVDC line and Eastern Region (ER) [9].

There was extremely heavy over-drawl by the constituents of NR grid and heavy under-drawl/over- injection by the constituents of WR. The power to Northern Region was flowing via the available WR-NR Inter regional links as well as via the WR-ER-NR route. The inter-regional links between the Western and Northern Region were constrained due to forced/planned outage of certain transmission elements. Efforts were being made to reduce the heavy import by Northern Region as well as to reduce the heavy export by Western Region [10].

220 kV lines from Badod-Modak, Gwalior (PG)-Gwalior (MP)-2, 220 kV Gwalior (PG)-Malanpur-1
tripped due to successive overload, thus transferring the load on 220kV Auraiya substation which is in the Northern region. The entire load of Rajasthan was then supplied by 400 kV Zerda-Bhinmal due to tripping of 220 kV Bhinmal (PG)-Sanchore and 220 kV Bhinmal-Dhaurimanna lines. 400 kV Gorakhpur- Muzaffarpur-1, 400 kV Biharshariff-Balia-1, 400 kV Biharshariff-Balia-2, 400 KV Patna-Balia-1, 400 kV Patna-Balia-2 lines tripped due to power swing. Thus, by above tripping, the Northern region got isolated from the Western and North-eastern region.

The northern region frequency dropped down to 47.5 Hz; thus generators started tripping due to under - frequency protection. A load of about 10,000 MW was shed using under-frequency relays and df/dt relays. The frequency of Western and North-eastern grid rose to 50.92 Hz which leads tripping of various transmission lines and generating stations in this region.

ii. July 31, 2012

There was large amount of unscheduled power transfer between WR (3000MW export) and NR (2500
MW import). 400kV Bina-Gwalior-Agra-2 was under up gradation to 765 kV from 400kV since 28th July, 2012.

400kV Zerda-Bhinmal, 400kV Zerda-Kankroli and 400kV Bina-Gwalior-Agra-1 were tripped due to faults and load encroachment [9].

Due to tripping of Suratgarh unit 1 in Rajasthan, the power flow between the Northern and Western regions accelerated a bit but before the flow could be controlled 220kV lines between Madhya Pradesh systems to Rajasthan double circuit lines. 400kV Gwalior-Bina-1 and 220kV Bina-Gwalior D/C lines tripped within four minutes span. This led to more stress on Eastern region when the tie-lines between the Northern and Western region tripped. After the tripping of 400 kV Bina- Gwalior-1, the system collapsed within seconds and was beyond the control of the operator. The power flowing from West to North took a longer path via Eastern Region.

Due to power transfer through the Eastern region, a sudden voltage dip was experienced there even though the voltages before were normal. 400kV lines of Jamshedpur-Rourkela-1, Ranchi-Maithon, Rourkela- Sterlite-2, Ranchi-Sipat, Raigarh-Rourkela-3 lines tripped between Western grid and Eastern grid. The Eastern and North-Eastern grid should have survived the blackout due to under frequency relays and df/dt relay load shedding. Interestingly, it did survive the blackout for about one minute but later collapsed because the load shedding wasn't enough to ensure frequency returning to the tolerable limit of 49.5 Hz. In the Western Region also, the frequency rose to 51.4 Hz and four generating units and five 400kV lines tripped.

III. Comparison

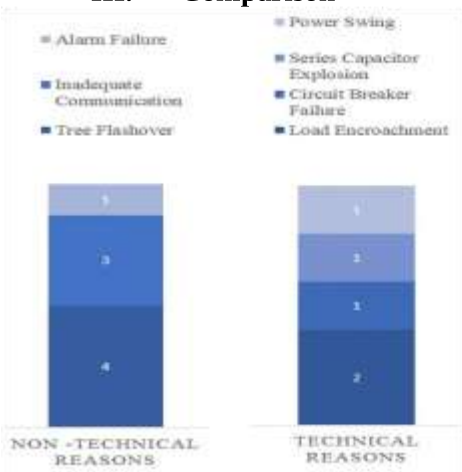

Figure 3: Number of Technical and Non – Technical reasons for above mentioned blackouts

IV. Recommendations

By NERC and Joint US-Canadian Task Force for North American Blackout:

i. Implement rigorous training of the reliability and system operators.
ii. Adoption of real-time monitoring tools.
iii. Employ automatic load shedding.
iv. Formulate rules to protect the operator who initiates load shedding from liability.
v. Proper management of vegetation in rights-of-way.
vi. Solve the problems related to the zone 3 operation of the relays.
vii. Clarify the roles, functions and responsibilities of the system and reliability operators.

In case of Vietnam Blackout:

i. Proper calibrations in the distance relay to prevent their operations during power swing conditions.
ii. Tightening of frequency tolerance of the system to make load shedding faster.
iii. The regions should resort to wilful islanding to ensure their survival and make restoration process faster.

In case of Italy – Switzerland Blackout:

i. N-1 Criteria rule suggested by UCTE should be followed – The N-1 criteria requires that all loads should be able to be restored if any single component fails (i.e. N-1 components still are available). Note that this does not mean no short-term outage should occur, only that the load should be quickly restored [6].
ii. Improve the calibration of recording instruments (DACF), especially in establishing time synchronization [4].
iii. Implementation of appropriate load-frequency control strategies and also dynamic improvement of the existing wide area measurement system (WAMS) [4].
iv. Fully utilize the capabilities often available in modern HVDC and FACTS equipment to directly examine system response to test inputs [6].

By enquiry committee submitted to CERC for Indian blackout:

i. Tightening of frequency tolerance of the system [10].
ii. Better policies should be designed for non-scheduled power transfers between the states [9].
iii. Improving the defence mechanism such as under frequency relays, the rate of change of frequency relays and islanding schemes of northern and eastern regions.
iv. Active power flow should be judiciously managed by load shedding to ensure that the frequency doesn't drop below desired levels.
v. Reactive power sources of appropriate ratings should be added to make sure voltage doesn't drop when the line is overloaded.
vi. Resorting to wilful islanding will make sure that restoration is faster, and the concerned region survives the blackout.
vii. Tripping due to load encroachment can be avoided by using quadrilateral characteristics of distance relay.
viii. Use of HVDC lines for inter-regional tie links.

V. Conclusion

The operation of large power grids is a complex task as the variables of control are dependent upon various factors. The possibilities of blackout can never be ruled out; it can be avoided by the recommendations made in the context. We have seen in the above blackouts that better communication and prompt action could have saved the regions from the blackout. Inefficient use of the existing technology and lack of technical know- how of the personnel can also lead to problems sometimes.

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