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PHYSICAL AND TECHNICAL ENERGY PROBLEMS

OPERATIVE AND TECHNOLOGICAL MANAGEMENT OF SUPER-LARGE UNITED POWER GRIDS: LESSONS OF MAJOR WORLD'S BLACKOUTS

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Power system (PS) blackouts still persist worldwide, evidencing that the existing protective structures need to be improved. The discussed requirements and criteria to be met for joint synchronous operation of large and super-large united PSs should be based on close co-ordination of operative and technological management of all PSs involved in order to ensure secure and stable electricity supply and minimise or avoid the threat of a total PS blackout. The authors analyse the July 2012 India blackout – the largest power outage in history, which affected over 620 million people, i.e. half of India's population and spread across its 22 states. The analysis is of a general character, being applicable also to similar blackouts that have occurred in Europe and worldwide since 2003. The authors summarise and develop the main principles and methods of operative and technological management aimed at preventing total blackouts in large and super-large PSs.

Keywords: *interconnected PSs; blackout prevention, protection systems*

1. INTRODUCTION

Despite notable achievements in the field of electricity production and continuous modernisation of power systems (PSs), total blackouts persistently occur worldwide. Disruption of power supply in large territories – especially in major cities – fully disorganises their life. The restoration of normal operation after a PS blackout is an involved task; depending on the PS's specifics, this may last from several hours to several days thus inflicting heavy damage [1].

It is known that the protection against blackouts is structurally based on the evaluation of emergency events and specifics of protective devices. Therefore, for analysing different blackouts a unified methodological approach is required.

Indeed, the causes of two blackouts of 2012 in the Indian PS [2] are quite similar to those of total blackouts in Italy, USA and Canada in 2003 as well as of the total blackout of 2006 in Italy that split up the synchronous power system of Europe into three asynchronous parts.

There are good grounds to believe that the Indian power engineers were aware of the previous blackouts as well as of their symptoms and possible risks.

Every super-large interconnected PS possesses definite elements of global management structure, so the local structural principles and techniques could be insufficient to operate it. To run a super-large interdependent PS, hierarchical operative and technological management structures are required that would ensure stable operation of the united grids and safe power supply, and would preventively remove the risks of total blackouts.

2. METHODS OF ANALYSIS

In the description of both the Indian blackouts (30 and 31 July, 2012) one can see the inconsistency and absence of coordination between the operative and technological management systems. The disproportionate preventive disconnection of multiple 400 kV transmission lines (TLs) which generated additional reactive power and raised voltage above the allowed limit considerably reduced the active power within the weakened electric sections in compliance with the inequality [3]:

$$P_m \leq (E_1 \cdot E_2 / Z) \cdot \sin(d_1 - d_2), \tag{1}$$

where Z is the complete equivalent resistance between two sources of equivalent voltage in two PSs, $(E_1 - E_2)$;

$d_1 - d_2$ is the angle difference between equivalent voltage sources in two PSs, $(E_1 - E_2)$.

If $d_1 - d_2 = 90^0$, then active power P_m reaches its maximum, i.e. its positive boundary value that can be transmitted over a weakened electric section from a PS with equivalent E_1 to a PS with equivalent E_2. At the same time, at $d_1 - d_2 = 90^0$ the synchronising torque is:

$$T = (E_1 \cdot E_2 / Z) \cdot \cos(d_1 - d_2) = 0. \tag{2}$$

This means that there might be a risk of stability loss in the electric section if the required total active power $\sum P_m$ is greater than P_m, i.e., at

$$\sum P_m - P_m = \Delta P_2, \tag{3}$$

where P_m is the maximum active power transmitted over the electric section at $(d_1 - d_2 = 90^0)$;

ΔP_2 is the power deficit in a PS with equivalent E_2.

The power deficit (ΔP_2) causes asynchronous operation, but at the angle $d_1 - d_2 > 180^0$ the direction of active power flow changes: the power from a PS with equivalent E_2 starts flowing in the direction to a PS with equivalent E_1. At $d_1 - d_2 = 270^0$ the power reaches its maximum negative value.

In the PS with equivalent E_2 the total deficit of active power arises:

$$\Delta P \sum = 2P_m + \Delta P_2. \tag{4}$$

The frequency deviation can be calculated from the end of the first cycle of nominal asynchronous operation:

$$\Delta F_2 = S_2 \cdot F \cdot \Delta P\Sigma / P_2, \tag{5}$$

where S_2 is the droop in a PS with equivalent E_2;

P_2 is the consumer capacity in the PS with equivalent E_2 before stability loss;

F is the frequency in the electric grid before stability loss.

It is known [4] that at the angle $d_1 - d_2 = 180^0$ in the electrical network the electric oscillation centre (EOC) is formed in which the voltage reduces to zero (similar to a three-phase short circuit).

In all power stations that are close enough to the EOC a voltage dip occurs, with actuation of the devices forcing voltage excitation in the generators. If the stability loss between two major PSs with a generation capacity greater than 20 000 MW has already happened, the frequency difference between them (ΔF) can be rather small (0.02 ÷ 0.1 Hz). The forcing devices are intended for use up to a short-circuit disconnection (6 ÷ 7 s); due to that, at the asynchronous operation with a one-cycle duration of 20 ÷ 30 s there will be automatic disconnection of the generator from the protection against excitation overload.

At nuclear power plants the technological protection of the turbo-generator is provided, which starts operating at fast load decrease; this results in operational tripping of the turbo-generator. It should also be taken into account that at the asynchronous operation the oil pressure is reduced gradually up to an impermissible limit in the rotation governor of hydro-generator, which leads to its automatic disconnection.

It is clear that after each asynchronous operation cycle in the deficient PS with equivalent E_2 the number of generating sources decreases, which causes immediate voltage and frequency collapse with the total disconnection of all electricity consumers.

3. ANALYSIS OF THE FIRST TOTAL BLACKOUT IN THE INDIAN UNITED PS (THE NORTHERN REGION)

Report on the Indian Power System's blackout [2] reads as follows.

On the 30th July, 2012, at approximately 2:33:12 cascade-wise disconnection of the Northern region from the Indian United power system started. The generating power in the Northern region was 32 636 MW, consumption was 38 322 MW, and import was 5686 MW.

Electrical connection Bina-Gwalior of the electric section North-West 400 kV was tripped at 1450 MW of active load and voltage 374 kV, at that, the distance protection equipment of the 3rd zone was actuated. After 2 seconds, the next 400 kV electrical connection of the same electrical section, Jamshedpur-Rourkela (one of the two-phase transmission lines) was tripped, but 70 ms later – also the second of two-phase transmission lines after the distance protection (DP) of the 3rd zone had worked.

The Bina-Gwalior electrical connection of the North-West 400 kV section was switched off at 1450 MW active load and 374 kV voltage; at that, distance protection equipment of the 3rd zone actuated due to operation of the relevant DP. After two seconds, the next 400 kV link of the same electrical cross-section, Jamshedpur-Rourkela (one of the two-phase TLs) was disconnected but 70 ms later also the second of two-phase TLs was tripped after the 3rd zone DP had operated.

To ensure blocking of the 3rd zone's distance protection its resistance setting on the characteristic curve should be smaller as compared with the load surge resistance in the least convenient regime of the electrical power network. It seems that the setting value was selected only to ensure the required sensitivity during short-circuit at the end of the reserve zone.

The up-to-date DP foresees solutions aimed at ensuring its non-operation at the load surge in the network, e.g., with the characteristic curve cut along the R-axis, with the characteristic curve cut narrowing along the R axis, etc.

Inoperative state of DP at the asynchronous operation can only be ensured with its blocking at electric oscillations. One of the most often applied techniques is here using the characteristic curve for launching the resistance that would overlap the DP 3rd zone resistance characteristic curve by ~ 10%. At short-circuit, the resistance value transition from the launching one to obtain the DP 3rd zone's characteristic curve practically occurs without time delay; due to that, the DP operation will not be blocked. On the contrary, at the asynchronous operation the above-mentioned resistance value transition proceeds with time delay; as a result, the DP operation will be blocked for a definite time.

Returning to the Indian blackouts, after some time in the electric section between the Northern and Western+ Eastern regions an asynchronous operation started (see Fig.1), during which five 400 kV electrical connections of the mentioned electrical section were tripped in a cascade way as a result of action of the protective devices meant for avoiding asynchronous operation.

All the 220 kV electrical connections were also tripped. In one of them, distance protection of the 1st zone occurred, which pointed to the launch of asynchronous operation since the electrical oscillation centre (EOC) was located in that electrical connection.

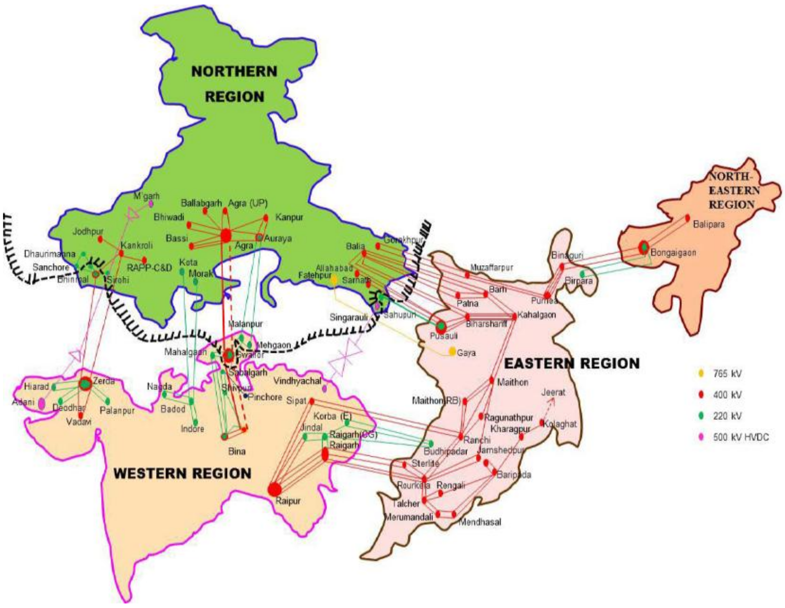

Fig.1. Cross-section of the Northern region PS disconnection.

In the time interval from the 5th second to the 25th second after the first 400 kV Bina-Gwalior connection had been tripped, more than 20 electrical connections (220 kV and 400 kV) were tripped – including two electrical connections in the Northern-Western region and Northern-Eastern sections.

In the time of asynchronous running, in the Northern region the cascading frequency drop and voltage decay started, which resulted in the loss of 36 000 MW electric load. It is worth noting that since the 27th July, 2012 one of the 765 kV TLs had been in the planned disconnection regime, while two other 765 kV TLs as well as twenty eight 400 kV power TLs had been disconnected gradually starting from the 15th July, 2012 and finishing on the 30th July, 2012, with the purpose to decrease the surplus of reactive power in the electrical network. The voltage limitation in the 400 kV network was the decisive factor for the operative personal to disconnect more than thirty six 400 kV TLs in the whole Indian united electric grid.

Comparing the causes of previous total blackouts in Europe and USA with those of the first total blackout in the India united PS, one can see their similarity, though with the difference that in the overloaded electric section in Europe and USA a short-circuit had occurred in a power TL followed by its cut-off; this, in turn, caused cascade-wise tripping of other TLs and asynchronous operation in the remained electrical connections.

The restoration of power supply in the India Northern region was dragged on till the Monday evening. It goes without saying that the restoration of power supply is a very complicated process, since in this case the balance between the generation and the consumption of electric energy has to be observed uninterruptedly. Therefore, first of all the "islanding" was to be done, and only then, synchronising the "islands", a joint operation of the PS had to be restored. It must be admitted that the cooperation and understanding between the operative management dispatchers in the hierarchical management system of India were insufficient.

4. ANALYSIS OF THE SECOND TOTAL BLACKOUT IN THE INDIA UNITED PS (BY REGIONS)

Figure 2 depicts the united power system of India, with the following installed generation capacities in its regions: Northern – 56 000 MW; Western – 67 000 MW; Eastern – 26 000 MW; Southern – 53 000 MW; and North-Eastern – 2400 MW [2].

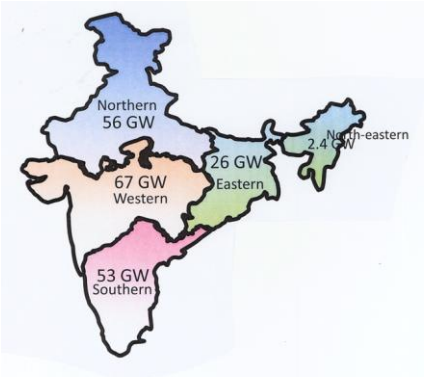

Fig.2. Installed capacities in the regions of India (2012).

On the 31st July, 2012 at 13:00 the 400 kV Bina-Gwalior line (the same that was disconnected on the previous day) first tripped after the 3rd zone distance protection operated at the 1254 MVA full power and the 362 kV voltage.

Then power failures cascaded through the network, disconnection of the 220 kV and 132 kV TLs occurred, after that also the 400 kV Jamshedpur-Reurkela 1 transmission line in the Eastern region, Jamshedpur-Reurkela 1 failed (at the current 1.98 kA and voltage 362 kV). About four seconds later, an asynchronous operation between the Northern+Eastern+North-Eastern and Western+Southern regions started. Within about 30 seconds, 67 transmission lines of different voltage were disconnected, including three 400 kV TLs.

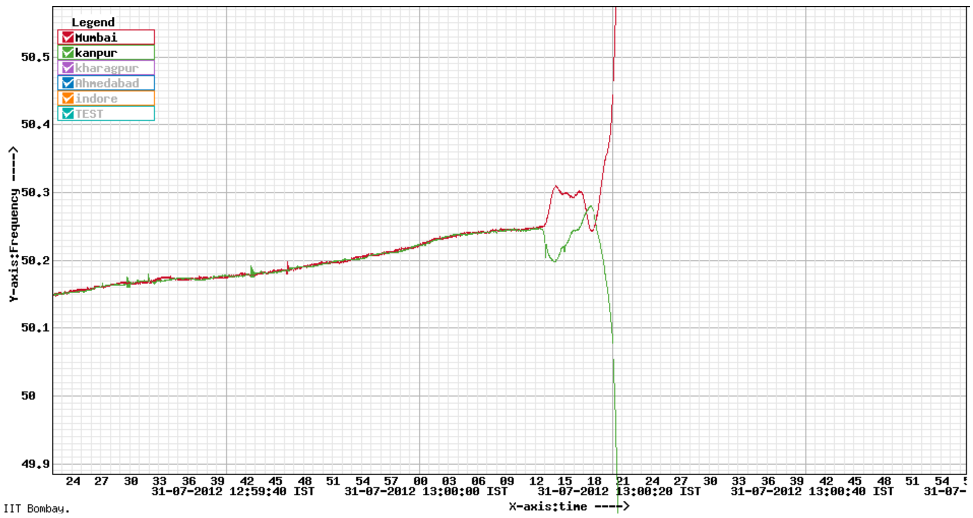

Fig. 3. Frequency deviation during the second 2012 blackout in the Indian PS.

From the frequency deviation curves (Fig.3) it can be seen that within about five seconds the asynchronous operation with one-cycle time (from 10 s to 30 s and longer) occurred. So, it is easy to understand why the 1st, 2nd and 3rd zone DPs operated during the sustained asynchronous operation. Approximately five seconds later, the frequency (specified in the Northern region (Kanpur)) rapidly decreased but in the remaining united Indian PS it rapidly increased and reached the value of 51.4 Hz. To decrease the frequency, the power generation of more than 3000 MW was switched off in the power stations, including 600 MW by using frequency increasing automatics.

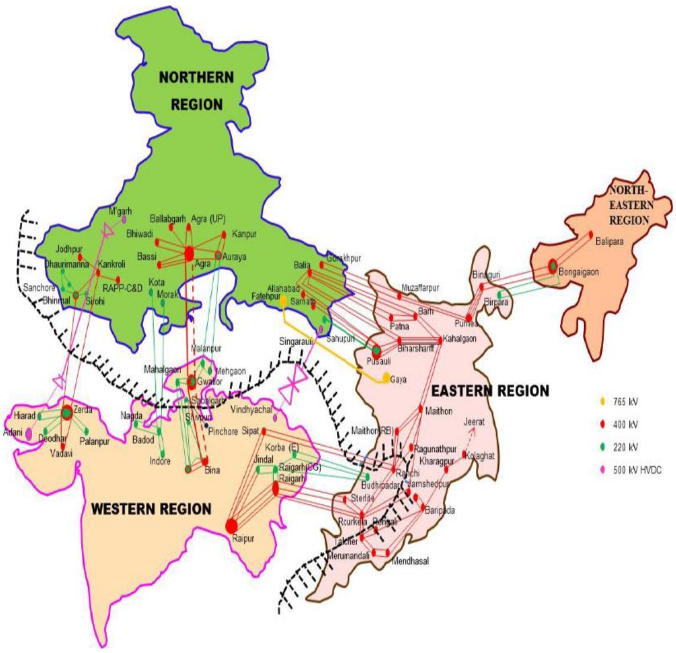

Fig.4. Separation border of the 2nd blackout in India (2012).

Figure 4 shows the border separating the regions affected by the 2nd 2012 blackout in India. In the affected regions about 600 million people were left without electricity: the demand of 48 000 MW was not met. The capital of India, Delhi, and the following states: Punjab, Haryana, Uttar Pradesh, Himachal Pradesh, Rajastan, West Bengal, Bihar, Orissa and Jharkhand were affected worst. More than 300 intercity passenger trains and commuter lines were shut down. The Delhi Metro suspended service on all six lines, and had to evacuate passengers trapped in the trains. Traffic signals were non-operational on the streets, which caused heavy traffic jams, etc.

Thanks to the experience gained in the previous total collapse restoration, the united power system was restored within eight hours.

5. DISCUSSION: LESSONS OF THE INDIAN PS BLACKOUTS

After the information about the first and the second blackouts had been summarised, the investigation committee concluded that the restoration of power stations took too much time (16 hours in the first blackout case). The committee recognised that to ensure the PS operation, a voltage-sensitive relay based distribution schema had to be developed as well as isolated islands had to be created to maintain electricity supply for priority objects in the power system.

The committee also discussed the issue of independent system supplier development in India as well as the issue of training and obligatory certification of the system operators. The inference was that, while planning load regimes, a potential overload of transmission lines and especially intersystem overload (most probable under the conditions of free energy market) is to be prevented.

The committee recognised that the use of phase measuring units (PMU) in India enabled performing better studying of the entire process of total blackout, system clearness and evaluation. It was admitted that issues related to the frequency automated regulation have to be solved urgently using emergency and regulation power resources. Increased attention should also be paid to the use of collapse prevention automatics.

In the committee report it is noted that the previous disconnection of multiple 400 kV transmission lines performed in order to ensure the allowable voltage level was a wrong decision. Instead, the installation of the static and dynamic reactive power compensators had to be planned. It is emphasised that the compensation of reactive power was to be started immediately by using generating power sources that could work both in the regimes of reactive power export and import. To avoid potential overloads, the reinforcement of inter-state electrical connections should have been implemented. In the power stations, it is necessary to work out standard procedures aimed at preparing and launching the forcing generator.

The committee also concluded that in the Indian national electrical power system the philosophy of system management needs to be changed, because the existing organisation and technological management structure of dispatcher centres cannot provide the stability and safety of energy supply; also the energy laws have to be revised.

6. CONCLUSIONS

1. The main cause of the total blackouts in the world is underestimation of the existing risks and of the criteria whose occurrence probability is comparatively low.

2. Operative and technological management structures of super-large power systems call for the development of proper legislation and administrative rules that would be obligatory for daily use.

3. Even a highly branched and developed electrical power network is not immune against the total blackout unless the principles of operative and technological management are estimated and effectively applied.

4. The calculation-based choice of distance protection devices can ensure their secure and efficient work under complicated operational conditions in the electrical grid.

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SUPERLIELU APVIENOTU ENERGOSISTĒMU OPERATĪVĀS UN TEHNOLOĢISKĀS VADĪBAS SISTĒMAS IZSTRĀDES METODOLOĢIJA

K. Briņķis, V. Krēsliņš, A. Mutule

K o p s a v i l k u m s

Neskatoties uz sasniegumiem elektroenerģētikas jomā un energosistēmu nepārtrauktu modernizāciju, pasaulē regulāri notiek sabrukumu avārijas. Rakstā apskatīti lielu un superlielu energosistēmu apvienību savstarpējas sinhronas darbības nodrošinājuma prasības un kritēriji, kas pamatojas uz operatīvās un tehnoloģiskās vadības ciešu koordināciju starp energosistēmām. Savstarpējas sinhronas darbības nodrošinājuma prasībām un kritērijiem ir izšķiroša nozīme, lai panāktu elektroapgādes drošumu un stabilitāti katrā energosistēmā, kas darbojas apvienotas energosistēmas sastāvā. Šo prasību un kritēriju ievērošana sekmē totālo avāriju izcelšanās iespēju samazināšanu un to novēršanu. Indijas 2012.gada totālo avāriju un citu analogo avāriju Eiropā un Amerikā analīze un izvērtējums laika posmā no 2003.gada, deva iespēju apkopot un izstrādāt lielu un superlielu energosistēmu operatīvās un tehnoloģiskās vadības principus un metodoloģiju, lai novērstu vai ierobežotu totālo avāriju izcelsmes iemeslus.

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