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Article

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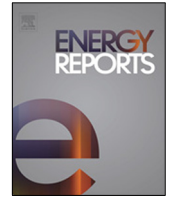
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Research paper

North Africa grid interconnection weakness: Impact on the Tunisian PES emergencies

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ABSTRACT

On August 31, 2014, a generalized power outage impaired the Tunisian power system. This event was particular in the time frame of the cascaded failures, where weak cross-border grid interconnection stood out as a determinant factor. North African interconnections did not support the Tunisian system during emergency. This paper presents a diagnostic review of the event based on an analysis of the precondition operational profile of the system. The chronological sequence of the blackout events are detailed and supported by real operator recording. North African power exchange assets are reviewed in view of the event. Hidden failure of protection system apparatus was particularly a triggering factor. The post-fault analysis revealed system isolation risks, corrective controller limitations. Countermeasures are proposed to enhance the system power supply reliability.

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1. Introduction

The Tunisian power electrical system (PES) has experienced two major power outages during the last two decades, the latest was a generalized blackout dating August 31, 2014 ([The Independent Commission of Inquiry on the Blackout, 2014](#); [Rapport de la commission, 2002](#)). Investigating the causes of the event revealed that it was triggered by severe lightning strikes affecting the transmission grid in the central area of the system, ten kilometers from the coastal city of Sousse (SSE) ([The Independent Commission of Inquiry on the Blackout, 2014](#)). These atmospheric discharges triggered a multi-phase short-circuit on one of the main power evacuation lines from Sousse power station, which comprises six generating units. An unfortunate misoperation of the protection system prevented the fault clearance, which led to the tripping of all generators of SSE power plant, totaling about 800 MW. The event cascaded subsequently to the trip of the Tunisia (TN)–Algeria (ALG) interconnection, and loss of generators in the south. The automatic load shedding procedure was fully deployed, but uncontrolled further generation loss led to the blackout ([The Independent Commission of Inquiry on the Blackout, 2014](#)).

In view of the event, a hidden failure in the protection system cascaded into a generalized power outage. Indeed, hidden failures

have been recognized as a contributing factor in spreading power system disturbances and even causing system blackouts ([Salim et al., 2011](#); [Zhao et al., 2015](#)). For example, in view of the general security assessment in off-line and on-line, the current practice generally assumes that protection systems are perfect, and the effects of protection system hidden failures are ignored. A key factor is that a protection system may have an undetected defect that remains inert until an abnormal operating condition is reached.

Nonetheless, triggering factors are not necessarily the fundamental causes of an electric system failure. Causes are characterized as structural, operational, and apparatus malfunction or failure ([Pourbeik et al., 2006](#); [Atputharajah and Saha, 2009](#); [Abdelaziz and Youssef, 2011](#); [Andersson et al., 2005](#)). [Fig. 1](#) reveals the recorded power exchange on the TUN-ALG interconnection during the event. We can note the interconnection tripped at an early phase, withstanding the faulted system for only 2.195 s [Fig. 2](#) summarizes the main chronological phases of the event, which point out the early trip of the TUN-ALG interconnection. In some prospects, the interconnection loss further loaded the system and accelerated to load shedding scheme. North African interconnections were insufficient to support the Tunisian system during its emergency operating conditions.

This paper presents a diagnostic review of the Tunisian 2014 blackout based on an analysis of the precondition operational profile of the system. The chronological sequence of the blackout events are described and supported by real operator recording. North African power exchange assets are reviewed in view of the event. The impact of hidden failure of system protection

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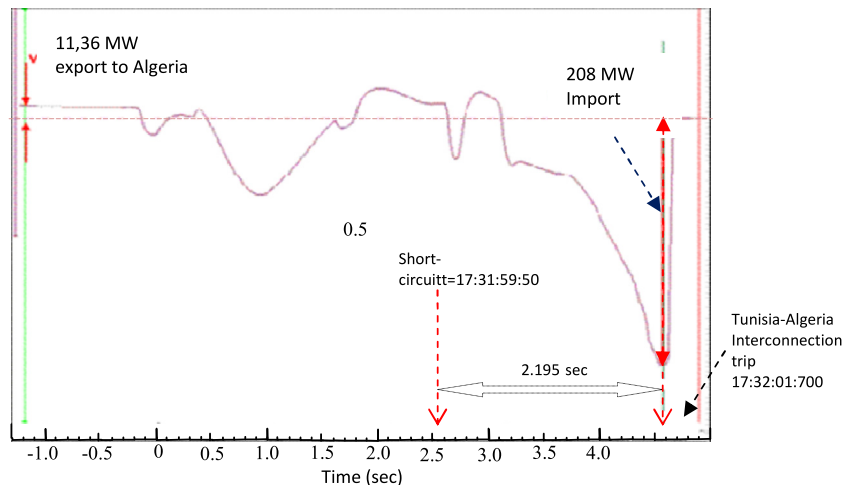


Fig. 1. Recorded power exchange on the TUN-ALG interconnection during the blackout of 2014.

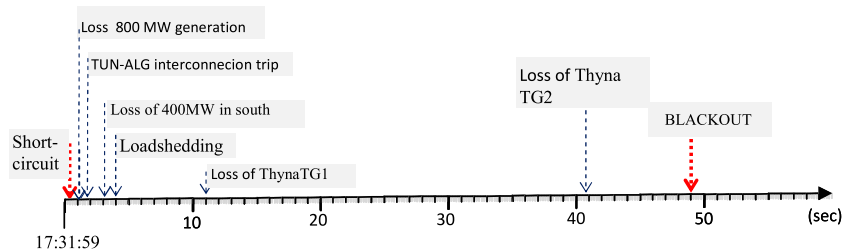


Fig. 2. Chronology of the main phases of the Tunisian blackout of 2014.

apparatus is demonstrated. The post-fault analysis reveals system isolation risks, corrective controller limitations. A set of counter-measures is proposed to the utility in order to enhance the power supply reliability.

2. North Africa interconnections

North Africa consists of seven countries at the northernmost part of the continent: Algeria, Egypt, Libya, Morocco, Sudan, Tunisia, Western Sahara. With desire to improve supply security through the diversification of energy supply resources, particularly in the context of the interregional programs for the development of renewable wind and solar resources, electric interconnections between countries have and continue to develop (Duhamel and Beaussant, 2011). The existing and planned electrical interconnections between the countries are illustrated in Fig. 3.

The Maghreb regional interconnection, which includes Morocco, Algeria, and Tunisia was initiated in the 1950s and evolved into multiple high-voltage transmission interconnections between the three countries. In the late 1990s, Morocco was connected to Spain via an AC interconnection, and thus Algeria, and Tunisia are now all synchronized with the European high-voltage transmission network. For the HVAC interconnection of Tunisia-Libya, although built since 2002, it is currently not operational. Synchronization tests with the Union for the Coordination of the Transmission of Electricity (UCTE) have failed to date, with the last test being conducted in April 2010 (Duhamel and Beaussant, 2011). The effectiveness of the connection with the existing but non-operational Libyan network is reduced by the non-compliance of this network with the requirements of the European network, to which it is connected via Morocco, Algeria and Tunisia.

Though the Maghreb electrical interconnections have existed for some time, and have been reinforced in capacity, electricity trade among countries has remained at modest levels. For example, although Tunisia is tied to Algeria via 5 tie lines of transmission capacity totaling 1760 MW, only 200 MW exchange is allowed. Fig. 4 depicts the volume of energy exchanges during the period 2010–2014 in the North African region. Power exchange merely changed during these years, increased in 2014 to values way below the net transfer capability of the interconnection. Weak transactions between countries may be related to the limited generation reserve margins, the absence of a harmonized regulatory framework with clear rules governing electricity trade, and institutional weaknesses at both the national and regional levels.

3. The Tunisian blackout of August 2014

The following succinct description of the event is based on (The Independent Commission of Inquiry on the Blackout, 2014).

3.1. Situation before the blackout

On Sunday August 31, 2014 at 17:30, the Tunisian power system was operating at steady state conditions corresponding to a low consumption day. The total system load was about 2400 MW, the recorded frequency was about 49.9 Hz, and the situation before the blackout was not exceptional. All transmission lines were in service, except for the 400 kV Tunisia-Algeria tie line which was open for maintenance. The remaining four transmission lines tying the Tunisian network to the Algeria, recorded only some MWs of power import, noting that the maximum power transfer limit was set to 200 MW. The power supply topology is shown in Fig. 5.

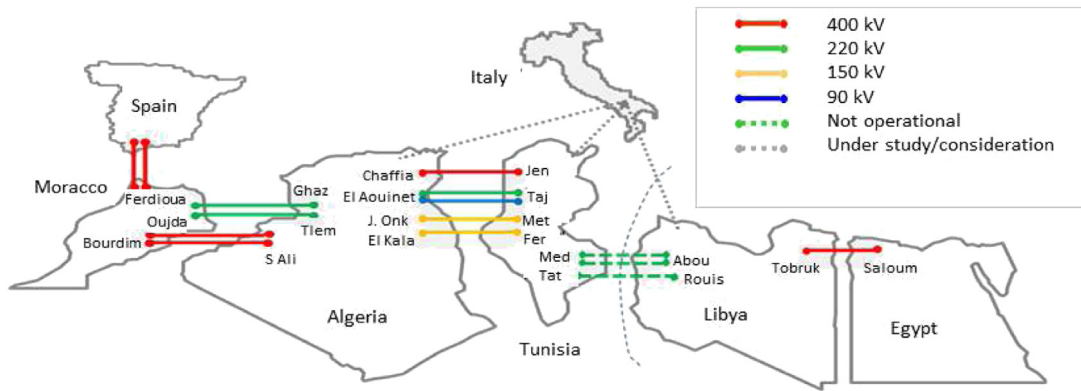


Fig. 3. Electric interconnections in the North African region.

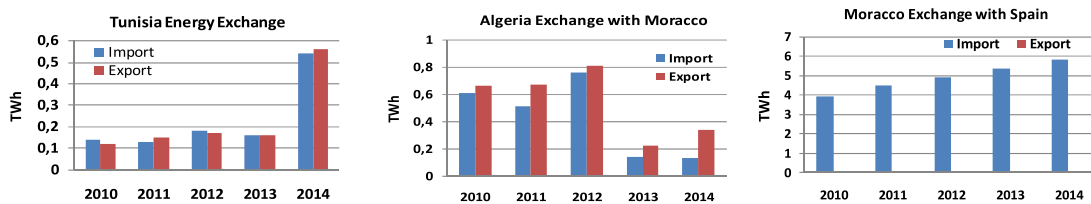


Fig. 4. The volume of energy exchanges during the period 2010–2014 in the North African interconnections.

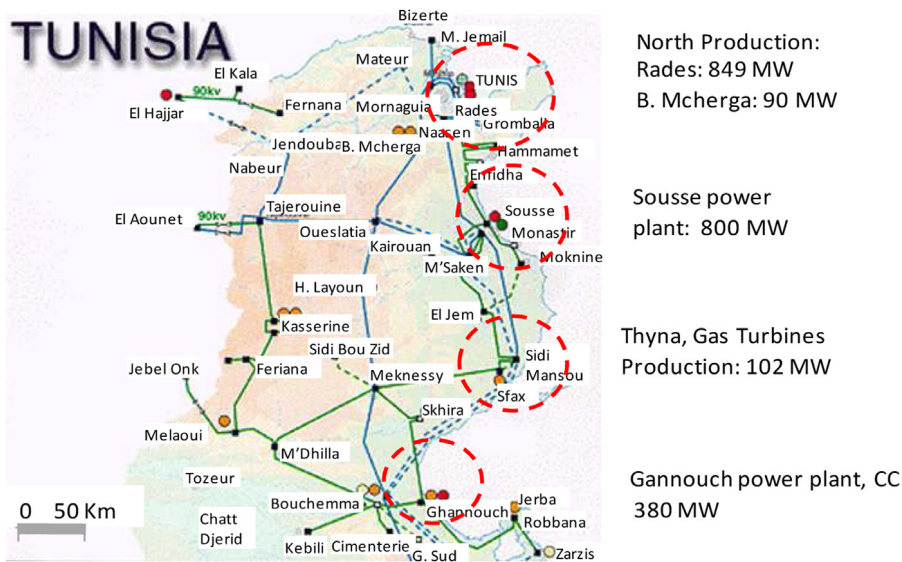


Fig. 5. Main power plants generation on 31/08/2014, prior to the blackout.

3.2. Sequential phases of the blackout

3.2.1. Phase 1: short-circuit on the 225 kV line SSE-MSN-1

- At $t_0 = 17:31:59:505$ – a discharge strikes the 225 kV line SSE-MSN-1, causing the optical ground shield wire to break. A single-line to ground fault on phase (B) occurred on the 225 kV overhead line SSE-MSN-1, at about 11 km from the 225 kV substation of Sousse as depicted in Fig. 6. The maximum short-circuit current measured at the Sousse substation on phase (B) reached 6450 A, as depicted in Fig. 7.
- At $t_0 + 0.110$ s : the 225 kV line SSE-MSN-1 tripped on the 225 kV side of the substation of MSN by the opening of the circuit breaker of the MSN substation feeder.

- At $t_0 + 0.221$ s: Opening of the three phases of the circuit breakers CB10 and CB8 (all three phases were opened) and the opening of phase (B) pole of CB12, as represented in Fig. 7, so the fault on phase (B) was cleared.
- At $t_0 + 0.470$ s: suddenly a second single line to ground fault on phase (A) appeared on the same 225 kV SSE-MSN-1line. The maximum short-circuit current measured in Sousse substation on phase (A) reached 9600 A, as depicted in Fig. 7.
- At $t_0 + 2600$ s: tripping of the 225 kV NAS feeder at Sousse substation by distance relaying, and opening of circuit breaker CB13.
- At $t_0 + 3.050$ s: tripping of the 225 kV SSE feeder at NAS 225 kV substation by distance protection and isolation of the fault, 2.8 s after its occurrence.

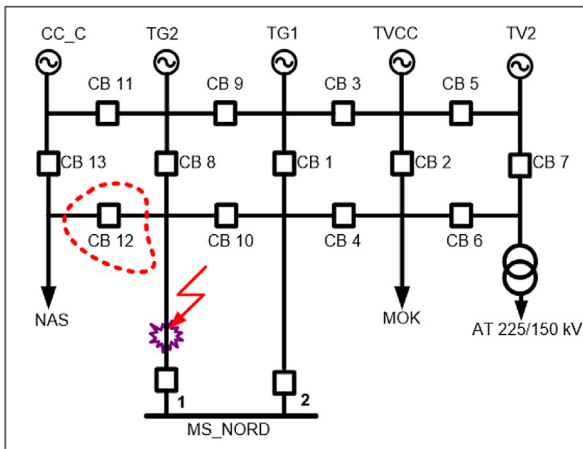


Fig. 6. Configuration of the Sousse 225 kV substation.

- 17:31:59: 618 — the circuit breaker CB12 was blocked in closed position. the fault not eliminated at the 225 kV ring-bus Sousse substation, as represented in Fig. 7, which depicts the recorded current variations on the 225 kV SSE-MSN-1 line during the incident.

Unfortunately, a dysfunction of the protection system installed in the 225 kV substation of Sousse happened. This dysfunction consists in not opening the circuit breaker CB12 and a transient state of circuit breaker alarm has been signaled. In this case, the Breaker Failure Protection should trip the circuit breakers adjacent to CB12. This protection was defective and did not function, so the short-circuit remained powered. Indeed, the opening of circuit breaker CB13 represented in Fig. 6 would have eliminated the fault.

3.2.2. Phase 2: Loss of the entire Sousse power plant

The malfunctions recorded on the protection system installed in the 225 kV Sousse substation prevented the disconnection of the faulted line (SSE-MSN-1). The persistence of the fault led to the protection systems operation at the 225 kV power plant in Sousse, such as zero-sequence over-current protection, alternator over-current protection, excitation failure. Therefore, five generation units were shutdown on the 225 kV Sousse-substation which then supplied about the third (800 MW) of the total system load.

3.2.3. Trip of the Tunisia-Algeria interconnections

The generation loss of Sousse power plant instantly called for an increased power import from the Algerian network, exceeding the set-transfer limit of 200 MW. The two networks disconnected automatically by watt-metric protection set at 200 MW. Thus, the Tunisian power system was isolated from the rest of the Maghreb power system, and the frequency began to decline rapidly, as illustrated in Fig. 8.

3.2.4. Phase 4: Loss of the southern CC generator

At 17:32:03 — as shown in Fig. 8, the largest power plant in the southern region, a combined cycle turbine, supplying 440 MW, tripped by excitation failure and the generator exceeding the normal operating limits. As a result, the Tunisian power system lost nearly 1250 MW within few seconds, while being disconnected from the Algerian network, and the power demand still at the level of 2400 MW, much higher than generation reserves of the power plants remaining in operation.

At 17:32:04 — the frequency fell to a minimum value of 47.766 Hz (Fig. 8), activating the automatic under-frequency load shedding scheme. This scheme sheds a preset amount of load when the system frequency falls below certain threshold values with the aim of balancing generation-demand. Further load shedding is performed if the system frequency continues to drop, according to seven stages (Ben Kilani et al., 2017). All seven load shedding

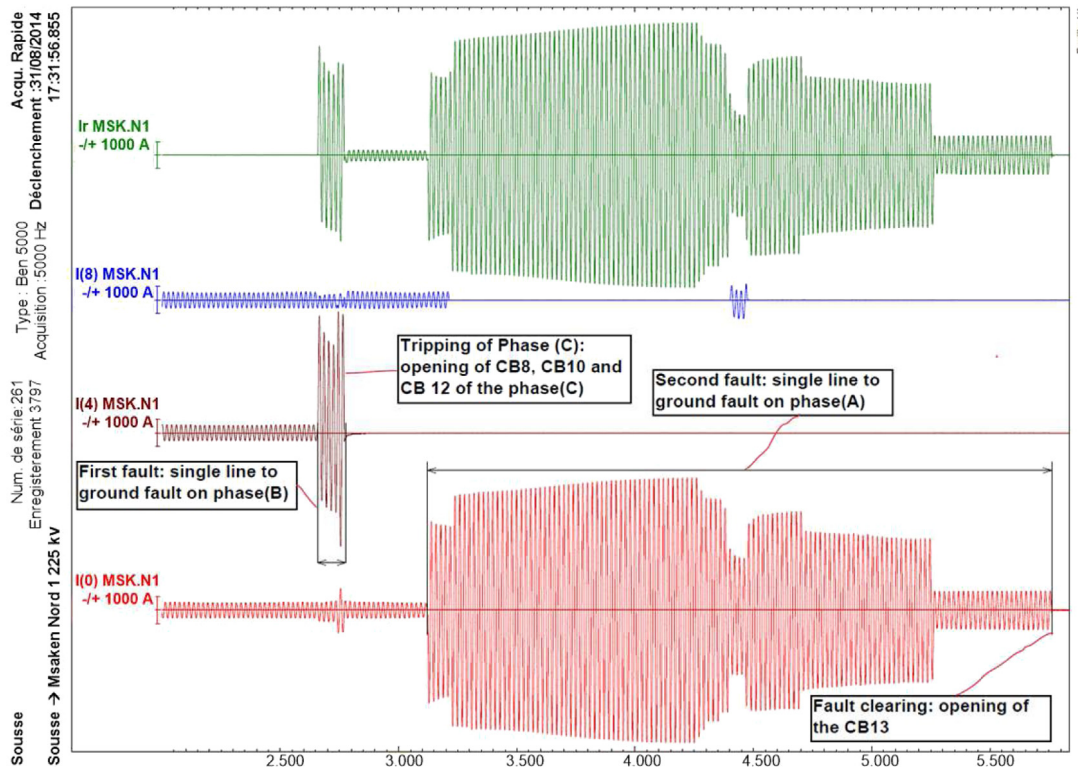


Fig. 7. Recording of the fault-current on the 225 kV line SSE-MSN-1.

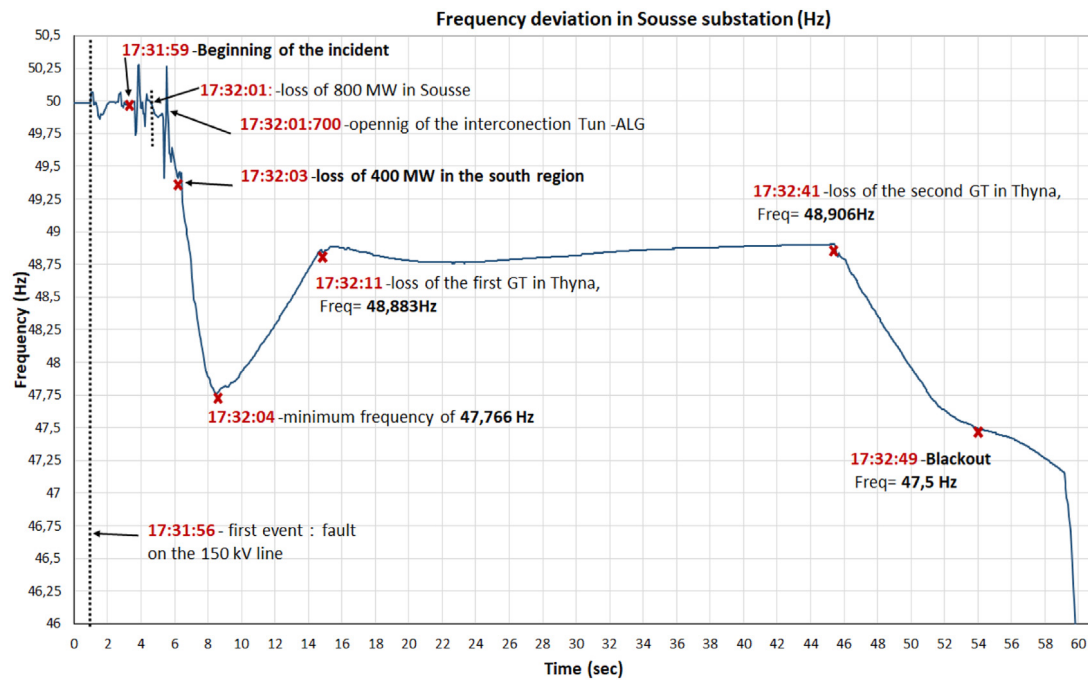


Fig. 8. Frequency response during the Tunisian blackout of August 2014 (The Independent Commission of Inquiry on the Blackout, 2014).

stages were deployed, shedding 997 MW of load. For the primary operating reserves allocated in Thyna gas turbines, they were fully deployed. As a result, frequency drop stopped, and the frequency raised to 48.9 Hz at 17:32:11, as shown in Fig. 8.

3.2.5. Phase 4: loss of two gas turbines in Thyna

At 17:32:11 – the gas turbine GT2 of Thyna power plant with a power generation of 100 MW was tripped as a consequence to an excitation protection failure (The Independent Commission of Inquiry on the Blackout, 2014), as shown in Fig. 8. At 17:32:41, after 30 s of the tripping of the first GT1 in Thyna, the second gas turbine of Thyna power plant tripped, which at that time was supplying almost 105 MW, by over fluxing protection (V/f - Protection). Over fluxing can, therefore, occur either due to increase in voltage or decrease in-frequency (Bhatt et al., 2016).

At 17:32:49 – as shown in Fig. 8, the activation of the load shedding system, could no longer balance the 1250 MW load that was still called, as the remaining operating generators could only supply 997 MW. The frequency fell below 47.5 Hz, which is the limit of safe operation of the power system. At this level of frequency, all the generation units were shutdown and a generalized blackout of the Tunisian network happened.

4. Causal analysis

4.1. Protection hidden failure

Short-circuits are common incidents on electrical networks. Protection systems feature selectivity functions, normally able to isolate the faulted circuit. The blackout would not normally have occurred if there were not other defects, malfunction or weak points. Hidden failures of system apparatus and excitation system performances were particularly determinant factors, added to the topological profile of the system: The faulted SSE-MSN-1line was protected by a breaker suffering from a hidden defect which was revealed due to the vibration following the operation of the circuit-breaker, after the detection of the short-circuit. This weak point in the protection system has contributed directly to the blackout, but it would not have occurred if a second defect had

not manifested itself at the same time and at the same place, at the Sousse substation. The latter evacuates to the national power system the power produced by 5 generating units via a substation of “ring” structure. The organization of its protection is based on a selectivity logic where fault elimination is based on a coordinated action of 3 circuit breakers: if one of the circuit breakers does not function correctly, information is passed onto neighboring 2 breakers to isolate the affected branch. The operation delays vary according to the fault distance. Each fault occurring on the power system can cause the activation of 4 breakers that should come into play in a coordinated way and with variable delays, depending on the configuration of the fault. These operation delays must be precisely coordinated.

4.2. Power supply infrastructure

The Tunisian Company of Electricity and Gas (STEG) has given a great importance to the electric production cost, favoring thereafter large production, such as single shaft combined cycles with power ratings higher than 400 MW (Tang et al., 2013; Andersson et al., 2004). Such large capacity power plants are characterized by a low specific fuel cost and a very high efficiency. However, their integration presents a critical inconsistency between the power system total load and the installed power plants size. With the limitation of the active power transfer on the interconnections, the loss of such production units triggers automatically the interconnection and leads to a frequency drop to critical levels, activating thereafter the automatic load shedding scheme.

4.3. Load shedding limitation

For the outcome of the load shedding, it could not save the system. Such emergency control action is still based on best-guess settings, which typically yield excessive or insufficient load shedding, counteracting the desired fast relief. Faster and optimal load shedding systems using actual operating conditions should be used (Société Tunisienne de l'Electricité et du Gaz, 2014, 2015).

4.4. Weak inter-regional interconnection

The interconnection with Europe via Algeria and Morocco, did not prevent the blackout because of its power limitation. Its capacity, currently set to 200 MW, is limited apparently by the Algerian-Moroccan connection. The interconnection with the Libyan power system is currently non-operational for its non-compliance with the requirements of the European standards. A connection with Europe from Tunisia, via Italy, could however particularly be helpful in such emergency situations.

5. Conclusion

This paper presents a diagnostic review of the Tunisian power system blackout of August 31, based on an analysis of the pre-condition operational profile of the system. North African power exchange assets are reviewed in view of the event. Lessons learned from this specific event:

The under-frequency load shedding based on preset levels demonstrated a drawback, as it may result in over or under-shedding of load. Splitting the load shedding scheme into smaller blocks is advantageous in diminishing over load-shedding but this may make the scheme less-effective if larger amount of loads has to be shed to save the system from frequency instability. The use of an intelligent load shedding makes it possible to optimize the amount of load to be shed with faster frequency recovery.

In off-peak load operating hours, and in order to secure the system from contingent critical disturbances, preventive measures ought to be taken such as: the limitation of output power of large units, the integration of smaller units, the optimization of the under frequency load shedding, and the allocation a sufficient amount of fall reserves.

Preventive countermeasures are rather more desirable in power system operation. If initially operated at unfavorable and vulnerable conditions, a power systems may be very close to its stability limits. It is necessary to shift the operating system to stable side in advance by preventive control, so that the system can be stable even if some severe faults occur. Short and mid-term preventive countermeasures include the following:

- Regular maintenance operations are crucial factors for blackout prevention. The improvement of existing substations and other equipment through replacement of critical components is vital for the prevention of cascading events.
- Ensuring the redundancy and reliability of control devices, by testing their performances, especially when subjected to large scale contingencies, including excitation systems and power system stabilizers.
- Improving the current load shedding scheme to optimize the amount of load to be shed with faster frequency recovery.
- Reinforcement of the system interconnections by enhancing the power exchange with Algeria, restoring the interconnection with Libya, and building of HVDC interconnection with Italy.

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