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Review of PES Failures and Lessons Learned from the Tunisian Blackout of August 2014

This paper presents a review of the blackout that impaired the Tunisian power system on august 31, 2014. This event is particular in its time frame of the cascaded failures leading to generalized power disruption. First, the paper reviews the operational profile of the system: topological layout, generation topology, power demand profile, grid interconnection assets. Many stability issues are addressed: angular stability, fault critical clearing time, frequency recovery, and PSS performances. Corrective controllers performances are assessed: load shedding scheme for variable primary operating reserve quantities, in off-peak and peak loading conditions. Then, the chronological sequence of the blackout events are detailed and supported by real operator recording. Hidden failure of system protection apparatus and excitation system performances were particularly determinant factors, added to the operational constraints profile of the system. The simulations revealed fall reserve requirements, system isolation risks, corrective controller limitations. A set of countermeasures is proposed to the utility in order to prevent its reoccurrence and reinforce the power supply reliability.

Keywords: Tunisian blackout of August 2014; frequency stability; transient stability; short-circuit; hidden failures; operational profile; load shedding; primary reserve.

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1. Introduction

The power grid is an infrastructure system comprising a netting of interconnected components in interaction. The interdependent dynamics of such systems make their stability a challenging issue, especially in severe fault situations. Verily, power system instabilities and collapses have commonly impaired electric networks around the world. We may recall the blackout in North America of July 1977, the blackout in Japan of July 1987, the multiple major blackouts of 2003 around the word, the European interconnected grid blackout of November 2006, and the blackout in India of July 2012 [1]-[4]. Elaborate investigations of these events have shown that the major causes emanate from lack of transient stability, mainly angle and voltage stability [4]. The outage of overloaded lines is one of the most important mechanisms in power system blackouts. Following such large disturbances, the transient system dynamics from milliseconds to seconds represent inductive factors to further outages. Generally, after a severe fault, the corrective controls

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attempt to stabilize the system, by directing its trajectory towards a new stable operating point. These control actions may or may not save the system from impairment, depending on other factors related to its operational profile.

For the Tunisian electrical system, two major power outages have been observed on its network during the last two decades, the latest was a generalized power outage dating August 31, 2014 [5]-[6]. Investigating the causes of the event has 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 [6]. These atmospheric discharges triggered a severe short-circuit on one of the main power evacuation lines from Sousse power plant, which comprises six generating units. This fault was not cleared timely, which led to the tripping of all the generators feeding the 225 kV Sousse substation totaling about 800 MW. The consequent power unbalance caused the frequency to decline. The event cascaded to subsequent loss of generators in the south, and the trip of the Tunisia-Algeria interconnection. The automatic load shedding procedure was fully deployed, but tripping of more generators led to the blackout [6].

In order to comprehend the blackout mechanism, multi-faceted diagnosis ought to be followed [7]-[8]. The challenge is to understand the complex dynamics of power systems components and their interactions with different controls and protections, in their respective time frames. Blackout causes are characterized as structural, operational, and apparatus malfunction or failure [9]. For example, for 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. However, hidden failures have been recognized as a contributing factor in spreading disturbances and even causing system blackouts [9]-[10]. A key factor is that a protection system may have an undetected defect that remains inert until an abnormal operating condition is reached. A hidden failure is undetectable during normal operation but will be revealed as a direct consequence of other system disturbances, which might cause a relay to incorrectly and inappropriately disconnect circuit elements. That is, if one line trips, then all the lines connected to its ends are exposed to the incorrect tripping. Such cascading misoperation of protection relays ought to cause system disturbances.

In this paper, we present a causal analysis of the 2014 blackout of Tunisia by highlighting the various operational constraints that led to the event. The aim is to expose the industrial experience on how the constraints of the system affect its operation. The aspects presented on the Tunisian power system transient stability are drawn from the operational experience of the network. A succinct description of the pre-fault system operation and the main events that triggered the blackout are presented. The chronological sequence of the blackout events are detailed, identifying some of the main causes that resulted in the cascaded failure. The causes are classified as structural/topological, and operational, hidden failure of protection system. A set of countermeasures is proposed to the utility in order to prevent its reoccurrence and reinforce the power supply reliability.

2. Operational Constraints

The system operational profile is defined by the constraints governing the system both in steady conditions and during severe fault transients. The main topological and operational constraints pertain to the system interconnection assets and power exchange capacities [11], generating units characteristics, load-curve profile, load shedding scheme, and primary operating reserves. The Tunisian electrical network is part of the Maghreb power system which is interconnected to the European network via an AC interconnection between Morocco and Spain. For over two decades, this electrical system has rapidly been evolving due to the increase in electric energy demand. The developments of the system concerned mainly the power plant types and installed capacities, and the extension of the electric transmission network [11]-[12]. In the following, we describe the main topological and operational properties of the Tunisian network.

2.1 System interconnections

Although the countries of northern Africa seem to be well interconnected, several of these interconnections are not currently operational or have very limited power transfer threshold settings: The Tunisian electric system has only one interconnection with its neighboring Algerian network, limited to a maximum net transfer of 200 MW [11]-[12]. Upon reaching this maximum threshold, this single interconnection is tripped and the Tunisian system becomes isolated. Such an event may lead to an imbalance between generation and load, followed by frequency decline and the activation of under-frequency protection relays.

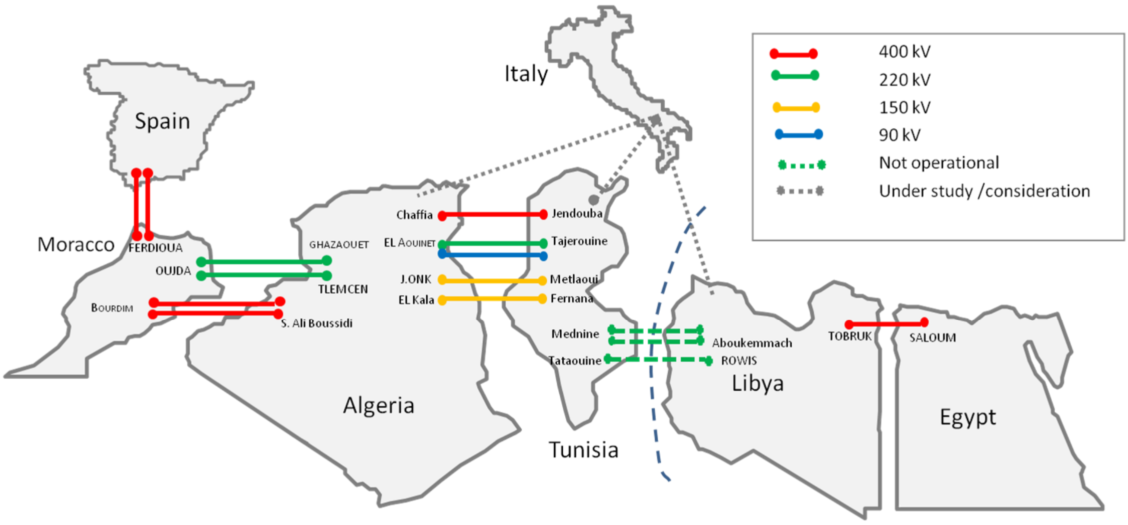

Fig. 1. Electric interconnections of the Tunisian network

2.2 Power plants characteristics

The Tunisian Company of Electricity and Gas (STEG) has given a great importance to the electric production cost, favoring thereafter large production units, such as single shaft combined cycles with power ratings higher than 400 MW [13-14]. Such large capacity power plants are characterized by a low specific fuel cost and a very high efficiency. However, the integration of such large size generation units presents a critical inadequacy between the system load and the size of installed power plants. 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.

An additional topological constraint shaping the Tunisian power system is the geographical distribution of the power plants: they are concentrated on the coastal regions, forming three main generation clusters: northern, central and southern, as indicated in Fig. 2. Such topology makes the system vulnerable to the onset of oscillations between areas. Indeed, inter-area oscillations have been experienced between the generator groups, especially between the southern and the central areas. Dynamically, an incident in the central area such as the trip of a generating unit, may cascade to subsequent loss of generation in the southern area by the onset of undamped coupled oscillations.

Fig. 2. Geographical distribution of power plants in the Tunisian power system

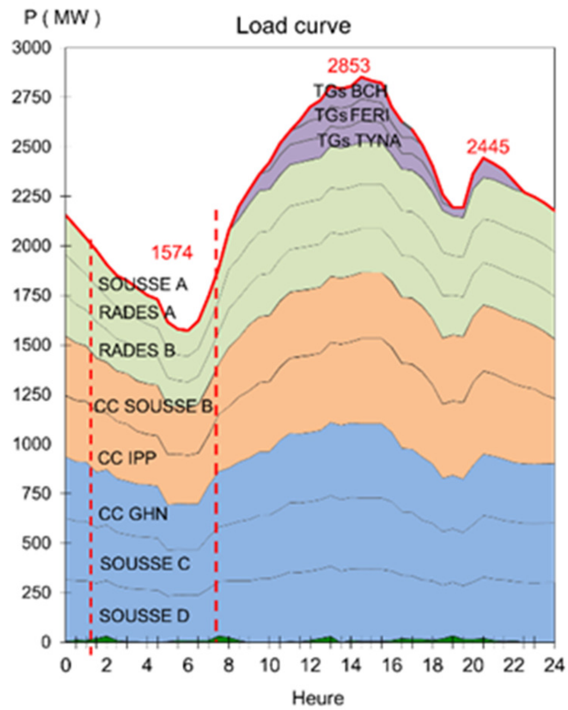

Fig. 3. Typical load curve of the Tunisian power system

2.3 Daily load profile

The Tunisian daily and seasonal load curve profiles are characterized by a large gap between the peak and off-peak load levels. Fig. 3. depicts a typical average load curve of the system. While the maximum peak demand reaches 2.85 GW, the off-peak load is as low as 1.57 GW. This discrepancy makes the generation-load balancing problematic. Two situations represent the extreme operational states of the electrical system where the generation units are very close to their technical upper or lower generaion limits, denoting exhaustion of either active or reactive reserves [15]. For example, a single generating unit of 400 MW capacity presents up to 12%, 18% and 30% of total generation during peak load, average load and minimum system load, respectively. In the particular scenario of minimum load conditions, a 400 MW-generator outage would lead to a trip of the single interconnection with Algeria, system isolation, frequency drop, and the activation of load shedding process. Sufficient amounts of active reserves ought to be allocated to help frequency recovery to nominal, both in fall or rise of frequency situations. In peak load conditions, the system operator must ensure sufficient active spinning reserves to overcome the frequency decrease and minimize the amount of eventual load shedding. Likewise, sufficient reactive reserves must be allocated on production units or by means of reactive power compensation to avoid voltage drop. In minimum load conditions, the generating units operate close to their technical minimums, the loss of load may lead to an over-frequency. Hence, the system operator must ensure sufficient fall reserve in order to reduce the power generation and retrieve the generation-demand balance.

All the cited constraints pose a set of challenges to the system operators, on how to maintain the stability of the network under the various operating scenarios.

3. Dynamic performance of the system

3.1 Fault Critical Clearing Time

We propose to determine the critical clearing time for a three phase short-circuit on the line tying the central production pole to the rest of the Tunisian transmission system. It is the 225 kV line SSE-MSN between *SSE* and *MSN* substations depicted in Fig. 5. The fault is applied with different fault clearing times (FCT), from FCT=0.250 s to FCT=0.470 s with an incremental time step of 0.050 s. The resulting rotor deviations of the central machines are shown in Fig. 4. It can be seen that for clearing times less than 0.470s the system is stable, beyond, the rotor angle deviated. Thus, the CCT is about 0.470 s. The simulations are carried out using the Power System Simulator for Engineering (PSS/E) [16].

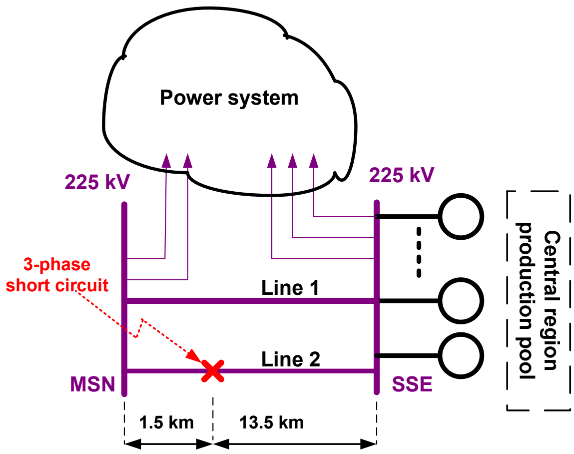

Fig. 4. Short-circuit on the 225 kV line SSE-MSN in the central production pole

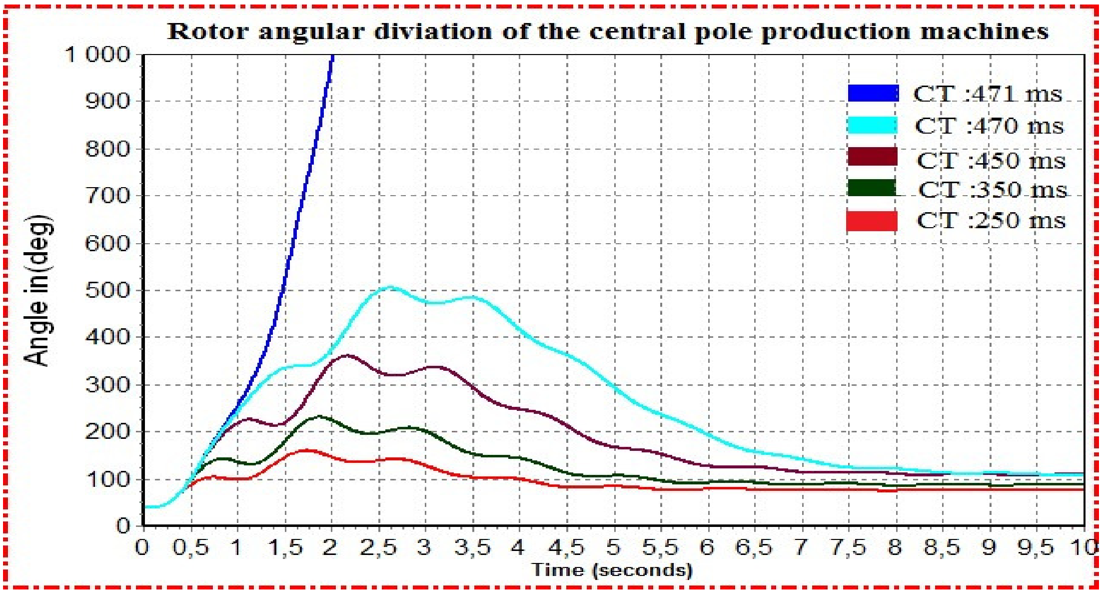

Fig. 5. Angular rotor variation function of fault clearing time.

If the fault clearing time is higher than the CCT, the rotor angle will increase without bound as shown in Fig. 5. The voltage variation at the SSE 225 kV substation is depicted in Fig. 6 for fault clearing times of 0.470 s and 0.471 s. We can observe that the voltage dynamics at SSE substation exhibit undamped oscillatory response for FCT= 0.471s, which confirms the conclusion that the CCT is 0.470 s.

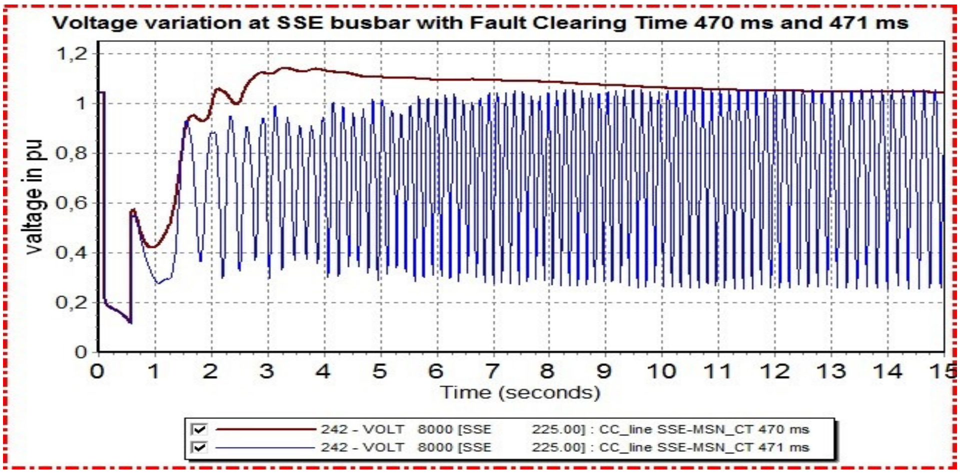

Fig. 6. Voltage variation at SSE substation with different fault clearing times

3.2 Frequency control

According to the IEEE/CIGRE Task Force, frequency stability is the ability of the power system to maintain steady state frequency, following a significant imbalance between generation and load [17]. Many disturbances may lead to the lack of system frequency stability, such as sudden changes in generation or load. Power systems featuring weak interconnections or islanded grids are more vulnerable to frequency instability. Generally, the lack of frequency stability is associated with several problems, such as poor coordination of operation control, protection devices, equipment performance weakness, and deficiency in generation reverse [18].

If a generator trips, the frequency declines. Depending on the prime mover and spinning reserves, the frequency will eventually regain its nominal. However, if the frequency drops drastically, the under frequency relays may trigger load shedding to stop frequency drop. If the generation loss is greater than the available spinning reserve, the frequency could eventually stabilize at a new value below nominal (50 Hz). In practice, under-frequency relaying is used to re-establish the balance between demand and the available generation. If the frequency decline is excessive, the generating units can automatically trip off causing an additional decline of frequency, and possible collapse of the power system. It is very important to coordinate system under-frequency load shedding with under-frequency protection of the generators. An early generator tripping before system load shedding achievement can lead to a blackout [19].

Conversely, the frequency rises in case of load decrease. The frequency stability can be seriously affected if there is no sufficient spinning reserve in the decline direction, mainly on off-peak load and when generators operate close to their lower limits.

3.2.1 Impact of generation loss

Generation loss is a contingency which threatens power system frequency stability. Three hierarchical control actions are deployed: primary control, secondary control and tertiary control. Theoretically, the primary reserve must be sufficient to cover the worst case generation loss [20]. However, this condition is not often satisfied because of its economic drawback. For the Tunisian power system, a generation loss greater than 200 MW leads to the trip of the interconnection with Algeria, isolating thereafter the Tunisian system. The main frequency thresholds and operating limits of the system are depicted in Fig. 7. This load shedding scheme sheds a preset amount of load when the system frequency falls below certain threshold values. The under-frequency load shedding plan adopted in the Tunisian power system is given in Table 1 which shows the different frequency thresholds and the approximate load shed. We propose to study the effect the largest generation loss on frequency stability of the Tunisian power system in the case of peak load (3500 MW) and off-peak load (1500 MW) conditions. Table 2 illustrates the different study cases. The main objective of these simulations is to analyze the impact of primary reserve and the load shedding on the frequency stability of the system.

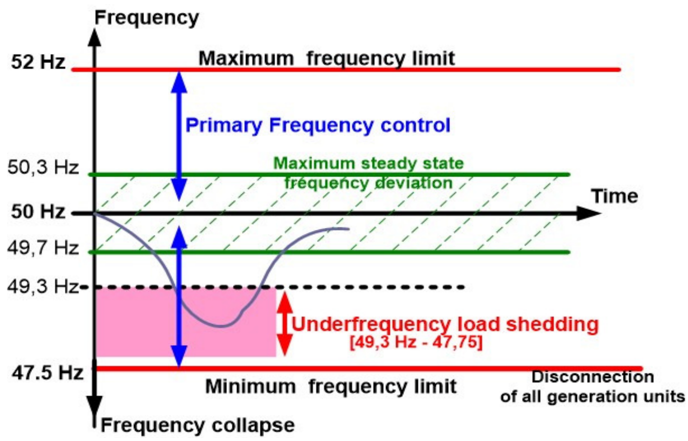

Fig. 7. Main frequency thresholds and operating limits of the Tunisian power system.

Table 1. Tunisian under-frequency load shedding plan

Stage Number	**Frequency (Hz)**	**Load Shed** (%)
1	49.30	3.3
2	49.00	4.4
3	48.7	4.5
4	48.5	9.5
5	48.25	11
6	48.00	9

Table 2**.** Study cases and simulation conditions

Load condition	Off-Peak (1500MW)		Peak load (3500 MW)	
Generation loss	250 MW		400 MW	
Cases	Primary reserve (MW)	Load Shedding	Primary reserve (MW)	Load shedding
Case 1	60	*Yes*	60	*yes*
Case 2	120	*Yes*	120	*yes*
Case 3	60	*No*	60	*no*
Case 4	120	*No*	120	*no*
Case 5	0	*Yes*	0	*yes*

Table 3**.** Loss of 250 MW Generation in off-peak load.

	Frequency deviation		**Load shed**	
Cases	Minimal Value (Hz)	Value after 30 sec (Hz)	Stage No.	Power (MW)
Case 1	48.49	49.2	4*th*	219.9
Case 2	48.69	49.5	3*rd*	167.4
Case 3	45.15	45.15	□□	□□
Case 4	46.6	46.6	□□	□□
Case 5	48.24	50,75	5*th*	324.9

Based on the simulation results illustrated in Table 3 and Fig. 8 relative to the loss of 250 MW of generation in the Tunisian network in off-peak load, we note that the larger the primary reserve, the lower the frequency fall and the smaller the load shedding amount (cases 1, 2 and 5). However, the generation loss of 250 MW without the under-frequency load shedding and with an amount of primary reserve less than the amount of production loss (cases 3 and 4), leads to a frequency collapse. For the fifth case, the load shedding quantity exceeded the generation power lost (over shedding). It caused the rise of frequency over nominal value (50.75 Hz). This is a drawback of the under-frequency load shedding based on preset levels. The use of an intelligent load shedding makes it possible to optimize the amount to be shed and also reach the nominal frequency [21]. To save the power system from fatal outcomes in low load period, many conditions must be respected, such as the limitation of output power of the large units, the optimization of the under frequency load shedding and the allocation a sufficient amount of primary reserve.

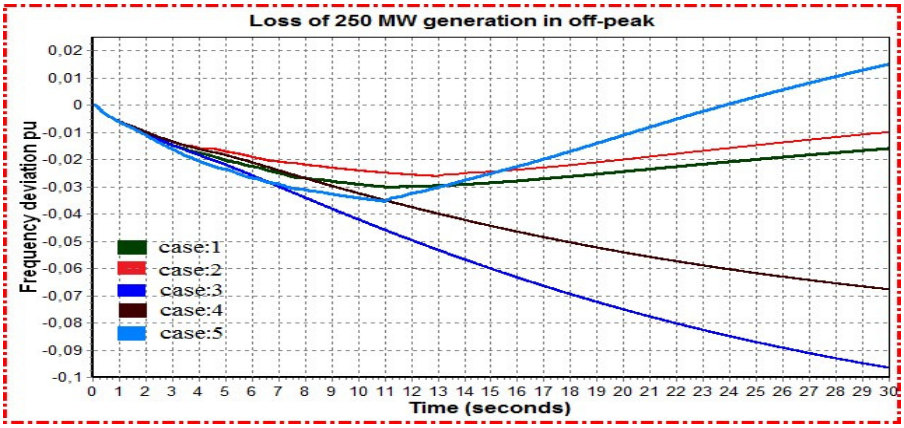

Fig. 8. Frequency deviation in off-peak load after loss of 250 MW.

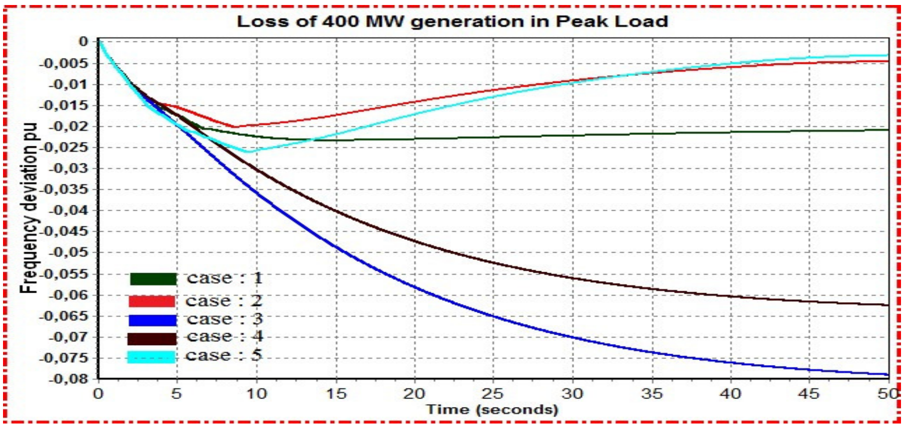

Fig. 9. Frequency deviation in peak load after loss of 400 MW.

From the simulation results in Fig. 9 and Table 4, we note that the larger the primary reserve, the lower the frequency fall and the smaller the load shedding amount (cases 1, 2 and 5). However, the generation loss of 400 MW without the under-frequency load shedding and with a quantity of primary reserve less than the amount of production loss (cases 3 and 4), leads to a frequency collapse and blackout. We note from these simulations that the optimization between the amount of load shed and the primary reserve deployed yields a better frequency control in the event of a large disturbance in peak or off-peak load conditions.

Table 4. Loss of 400 MW Generation during peak load.

Cases	Frequency deviation		Load shed	
	Minimal Frequency (Hz)	Frequency after 30 sec (Hz)	Stage	Power (MW)
Case 1	48.85	48.98	2*sd*	255,5
Case 2	49.00	49.55	2*rd*	255,5
Case 3	46,5	46,5	□□	□□
Case 4	47,2	47,2	□□	□□
Case 5	48.69	49,5	3*rd*	402,5

3.2.2 Impact of loss of load

During the off-peak load period (1500 MW), the generation units operate at their lower operating limits. Often, there is not enough fall reserve on these units. Hence, any load loss may trigger the interconnection Tunisia-Algeria and the frequency increase which affects the stability of the Tunisian electrical system.

We consider the loss of 100 MW load in off-peak load conditions with different amounts of reserve. The results are depicted in Fig.10. It shows the maximum values of frequency obtained after this loss with the variation of fall reserve deployed in generation units. The security zone is characterized by the maximum dynamic frequency below 50.8 Hz. It can be noted that without fall reserve, the 100 MW load loss leads to a frequency increase which may reach 53.55 Hz and might cause a blackout. Also, when the fall reserve is between 20 MW and 80 MW, the frequency varies from 52.8 Hz down to 50.6 Hz. Nonetheless, this fall reserve quantity is still not sufficient for frequency stabilization. The adequate fall reserve amount necessary to reach the nominal frequency equals 100 MW which yields a frequency of 50.3 Hz.

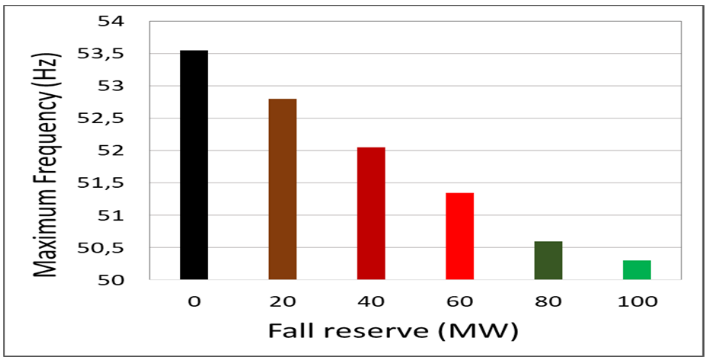

Fig. 10. Frequency histogram function of the fall reserve.

3.2.3 PSS Dynamic Performance

Power transfer capability in a transmission network may be limited by electromechanical oscillations with frequency ranging between 0.1 and 4 Hz. These oscillations can arise due to the lack of damping of the systems' mechanical mode. They are also generated due to the usage of high gain fast-acting automatic voltage regulators (AVRs). In order to provide the oscillations damping, supplementary excitation control subsystems have been developed. Among others, power system stabilizer (PSS) is frequently used for providing damping of the above mentioned power oscillations [22]. The PSS basic function is to apply an additional signal to the excitation system, creating electrical torque that damps out low frequency power oscillations [22]. After the installation of many large generation units in the Tunisian power system with power rating greater than 400 MW, an inter-regional oscillation between generation units in the central and the southern regions occurs. Indeed, after a loss of generation units of 400 MW in the central region, the largest unit in the south (400 MW) triggers immediately due to malfunction of its PSS. Two test case simulations were carried out to illustrate the impact of the loss of 400 MW in the center region on the voltage and the reactive generation in the southern units. Two scenarios were investigated: with PSS as shown in Fig. 11 and without PSS as depicted in Fig. 12.

In Fig. 11, the voltage of the largest generation unit in the southern region dropped under 0.9 pu, while the reactive generation of this unit decreases instead of increasing (to keep voltage in its normal value). This misbehavior is due to the malfunction of its PSS. In addition, in Fig. 12, without PSS, the response of the generation unit is acceptable.

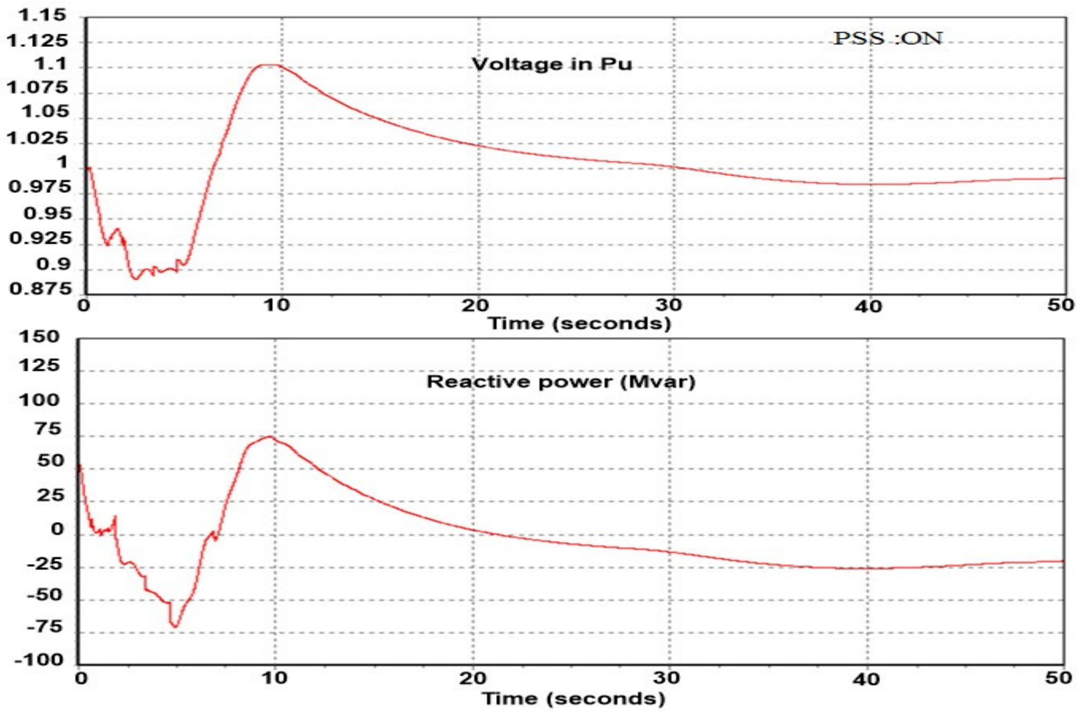

Fig. 11. Voltage and reactive power deviation in a southern unit, PSS: ON.

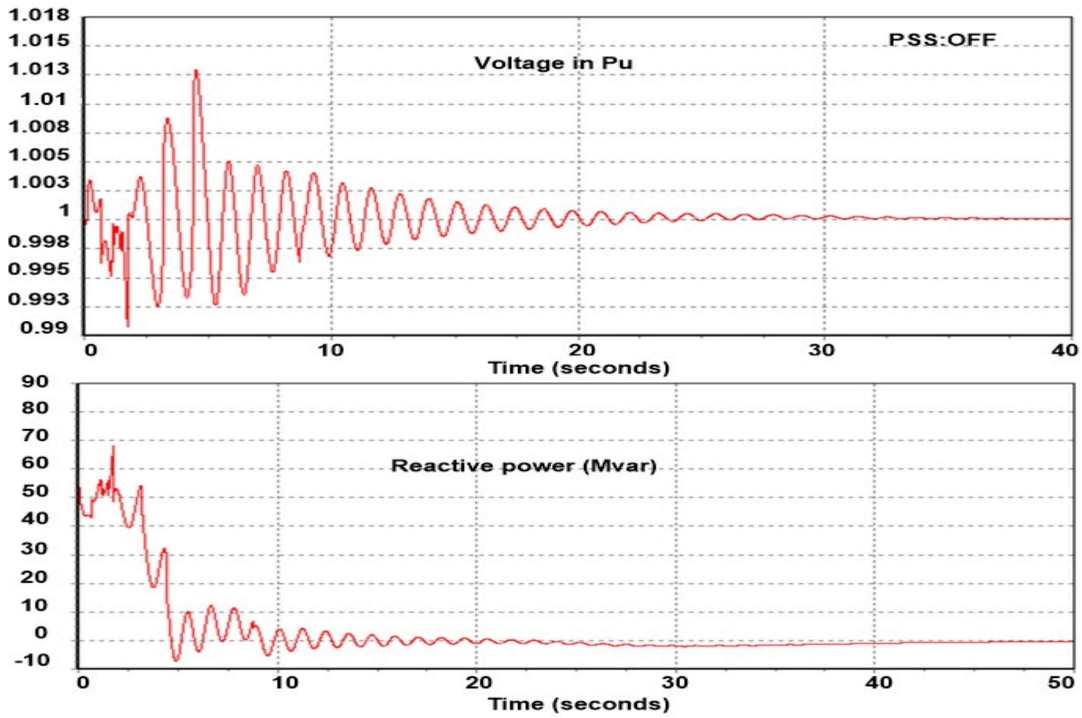

Fig. 12. Voltage and reactive power deviation in a southern unit, PSS: OFF.

4 The Tunisian Blackout of August 2014

4.1 Situation before the blackout

On Sunday August 31, 2014 and until 17:30, the Tunisian power system was operating at steady state operating conditions corresponding to a low consumption day, as it was a weekend. The total electric power demand was about 2400 MW, supplied by the scheduled committed generators. Geographically, the generation is mainly centralized along the costs of the Tunisian territory into northern generation group, central generation, and southern generation, as schematized in Fig. 13. The recorded operating frequency was about 49.9 Hz, and the situation before the blackout was not exceptional. All the transmission lines were in service, except for the 400 kV Tunisia-Algeria interconnection line which was open for maintenance. Four transmission lines tied the Tunisian power system to the Algerian system, recording only some MWs of power exchange, noting that the maximum exchange power transfer limit was set to 200 MW.

Around 17:31 a severe thunderstorm struck the Sousse region, where atmospheric discharges (lightning strikes) were recorded. At 17:31:56:855, a first lighting struck a 150 kV overhead transmission line in Sousse region causing the deterioration of an insulator, resulting in a single-line to ground fault about 10 Km from the 150 kV Sousse substation. The line protection relays functioned properly by isolating the faulted section.

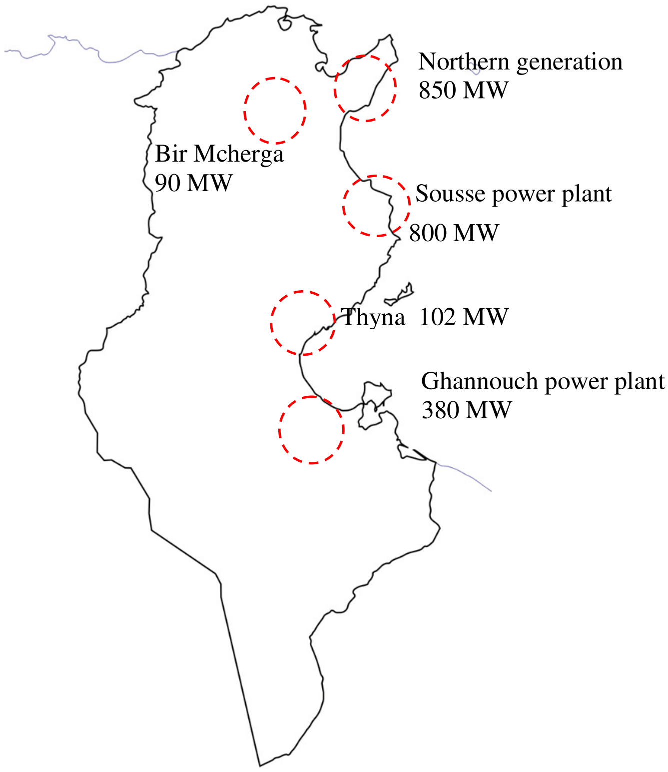

Fig. 13. Main power plants generation on 31/08/2014, prior to the blackout.

4.2 Sequential phases of the Blackout

4.2.1 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 breaking of the optical ground shield wire of the line. This wire is a conductor running parallel to the power conductors of the transmission line, and is placed at the top of the tower structure serving for earthling the lightning Strikes. After the breaking of the shield cablewhich is connected to earth through the pylons, a single-line to ground (LG) 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. 14. The maximum short-circuit current measured at the Sousse substation on phase (B) reached 6450 Amp, as depicted in Fig. 15.
- At t_0 + 0.110 s: the 225 kV line SSE-MSN-1 tripped on the side of 225 kV substation of MSN by the opening of the circuit breaker of the feeder in MSN substation.
- At t_0 + 0.221s: Opening of the three phases of the circuit breakers *CB*10 and *CB*8 (all three phases were opened) and the opening of the phase (B) pole of the *CB*12, as represented in Fig. 14 and Fig. 15, so the fault on phase (B) was cleared.

- At t_0 + 0.470s: suddenly a second single line to ground fault on phase (A) appeared on the same 225 kV SSE-MSN-1 line. The maximum short-circuit current measured in Sousse substation on phase (A) reached 9600 Amp, as depicted in Fig. 15.
- At t_0 + 2,600s: tripping of the 225 kV NAS feeder at Sousse substation by distance relaying, and opening of circuit breaker *CB*13.
- At t_0 + 3.050s: tripping of the 225kV SSE feeder at NAS 225 kV substation by distance protection and isolation of the fault after 2.8 second after its apparition.
- 17:31:59: 618 – the circuit breaker *CB*12 was blocked in closed condition. The fault not eliminated at the 225 kV ring-bus substation Sousse, as represented in Fig. 14 and Fig. 15, which depicts the recorded current variations on the 225 kV SSE-MSN-1 line during this 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 *CB*12 and a transient state of circuit breaker alarm has been signalized. In this case the Breaker Failure Protection (BFP) should trip the adjacent circuit breakers to *CB*12. This protection was defective and did not function, so the short-circuit remained powered. Indeed, the opening of circuit breaker *CB*13 represented in Fig. 14 would have eliminated the fault.

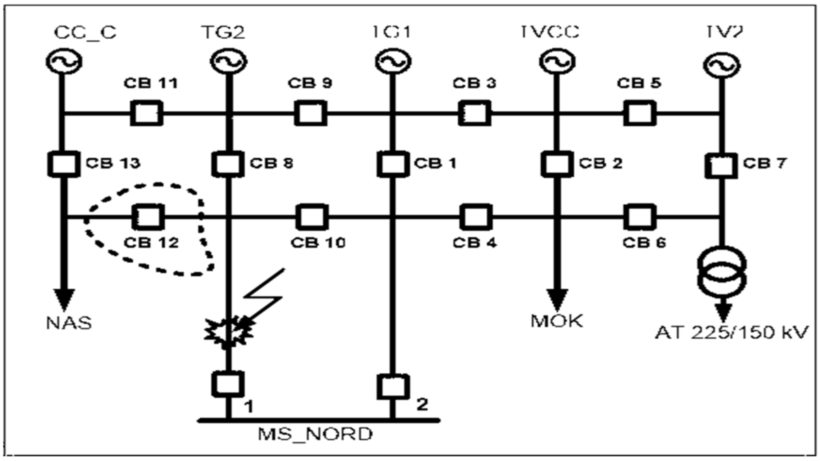

Fig. 14. Configuration of the Sousse 225 kV substation

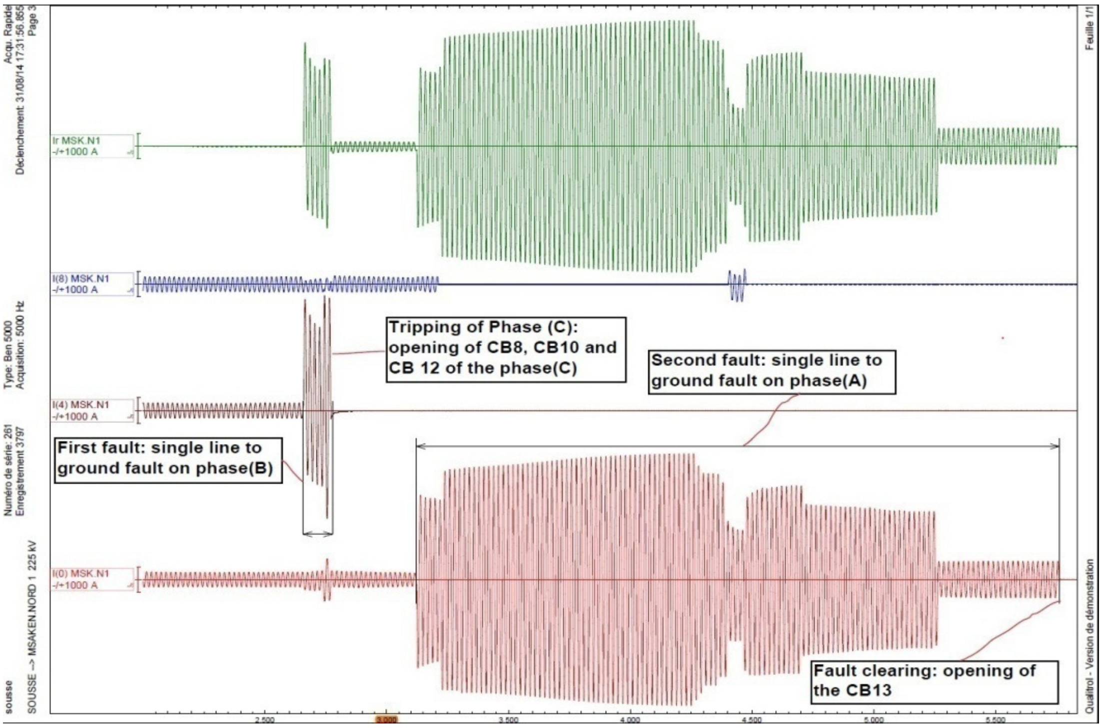

Fig. 15 Recording of the fault-current on the 225 kV line SSE-MSN-1

4.2.2 Phase 2: Loss of the entire Sousse power plant

The malfunctions recorded on the protection system installed in the 225 kV substation of Sousse prevented the disconnection of the faulted line (SSE-MSN-1). The persistence of the fault led to the operation protections systems 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 the third (800 MW) of the total system load. This 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 the frequency began to decline rapidly.

4.2.3 Phase 3: Loss of the southern CC generator

At 17:32:03– as shown in Fig. 16, almost at the same time of the generation trip in Sousse, at 250 km far from Sousse, and as a result of the voltage drop recorded on the grid, the largest power plant in the south region, with single-shaft combined cycle turbine, and supplying 440 MW, tripped by excitation failure and the generator exceeding the normal operating limits. The behavior of this generation unit following the short-circuit is commented below:

- The active power output increased from 380 MW in pre-fault reaching 440 MW at tripping time;
- The reactive power output increased from 67 MVAR in pre-fault to a maximum of 146 MVAR and then down to −34 MVAR at tripping time.

In this situation, the increase of reactive power generation is an expected response of generation unit since the short-circuit still not eliminated, and a deficit of 800 MW in the center region. Nonetheless, the change of the generator from reactive power supplier to a reactive power sink while the frequency is dropping, is an abnormal response of the excitation system, which should support the voltage by supplying instead of absorbing reactive power. As a result, the Tunisian power system lost nearly 1250 MW within one second, while being disconnected from the Algerian network, and the power demand still at the level of 2400 MW, much higher than the power that could be supplied by the remaining power plants (still in service).

At 17:32:04–the frequency fell to a minimum value of 47.766 Hz (Fig. 16), 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 [23]. All seven load shedding 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 the value of 48.9 Hz at 17:32:11, as shown in Fig. 16.

4.2.4 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 the excitation protection failure, as shown in Fig. 16.

At 17:32:41, after 30 seconds 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) in the step-up transformer. Over fluxing can, therefore, occur either due to increase in voltage or decrease in-frequency [24].

At 17:32:49 –as shown in Fig. 16, 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 power system. At this level of frequency all the generation units were shutdown and a generalized blackout of the Tunisian network happened. Fig. 16 summarizes the sequence of these events, marked with respect to the variation of the power system frequency:

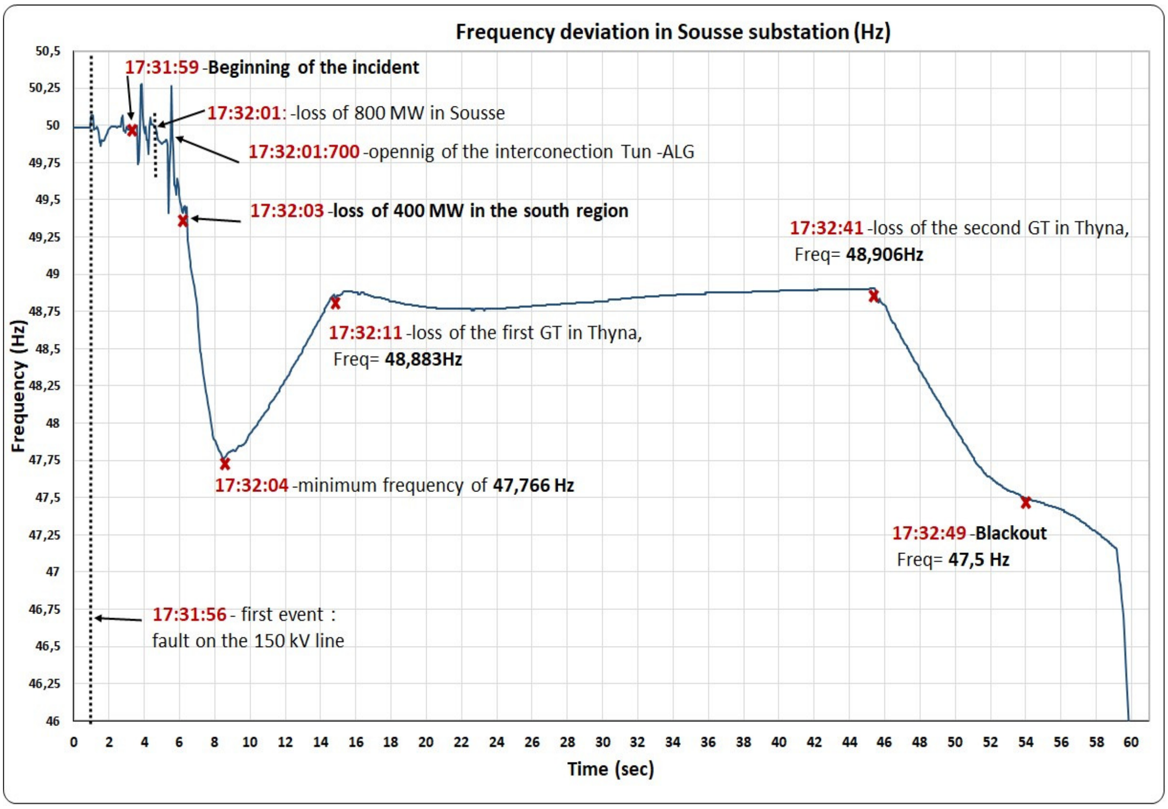

Fig. 16. Recording of the fault current on the 225 kV line SSE-MSN-1.

5. Causal analysis

In this section we point out some of the causes of the blackout from different aspects. The lightning strikes have certainly triggered the blackout of August 31, 2014, but it's not solely the root cause. Power grids are normally designed to withstand such incidents with no major damage. 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 weren't other defects, malfunction or weak points. Hidden failure of system apparatus and excitation system performances were particularly determinant factors, added to the topological profile of the system:

The faulted SSE-MSN-1 line 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 of the Sousse-Msaken_Nord_1 line. 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 substation of 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 thus 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.

Electric overload has tipped all groups of the Sousse power plant, as are stiffly coupled by the ring-structured substation. The trip was even accelerated under the effect of the voltage fall on the 225kV lines. The southern single shaft combined cycle power plant, has tripped about 1s after Sousse units, for low voltage grid, since its excitation voltage is supplied from the grid.

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 yields excessive or insufficient load shedding, counteracting the desired fast relief. Faster and optimal load shedding systems using actual operating conditions should be used [25]-[26].

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.

6. Conclusion

This paper reviewed the Tunisian power system blackout of August 31, 2014. First some aspects of the operational profile of the system were highlighted. The system profile features specific topological layout, generation topology, power demand profile with large discrepancy peak/off peak, limited grid interconnection assets, fixed-step load shedding scheme. These constraints pose a set of challenges to the system operators, on how to maintain the stability of the network under the various operating scenarios. Many severe disturbances have been simulated to investigate transient stability, frequency control function of primary reserve allocation, reserve fall in off-peak and peak loading conditions and corrective controllers performances.

A detailed description of the blackout sequences was presented, attempting to diagnose the main causal factors of the event. Hidden failure of system apparatus and excitation system performances were particularly determinant factors, added to the topological and operational profile of the system. Indeed, hidden failures may prevent power system operators from performing proper on line security assessments of the system.

Many lessons are 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:

- 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.
- Ensure 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 optimization the amount of load to be shed with faster frequency recover.
- Reinforcement of the system interconnections by enhancing the power exchange with Algeria, restoring the interconnection with Libya, and building of HVDC interconnection with Italy.

New challenges have been added by massive integration of renewable energy sources which feature new characteristics: variability, inertialess or weak inertia, and not fully dispatchable. A new Dispatching model incorporating multi-horizon forecast of renewable energy generation should be underway.

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