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Voltage Stability: Effect of the Load and Contingency Ranking

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ABSTRACT
The voltage collapse is a dynamic process that may take a few minutes which is called the slow voltage collapse or that may take a few seconds which is called the fast voltage collapse. These collapses can be avoided through preventives and curative measures. The load shedding activated by voltage criterion is a defensive mode that allows limiting the degradation of the voltage at unusable values. This load shedding by undervoltage must consider the dynamics of the voltage drop and irreversible degradation. In other cases, the voltage collapses may occur following the failure of the transmission network, related to the maximum power transmissible, to ensure the transfer of energy. Thus, a phenomenon of static stability loss is generally initiated. The study of voltage stability of the Tunisian network showed that the lines with highest index voltage stability, in normal situation, engender highest index voltage stability in N-1 situation. Therefore, these lines should be treated with caution during the planning phases of the electrical system.

Key words: Voltage collapse, voltage stability index, slow collapse, fast collapse, stability, static load, dynamic load

INTRODUCTION
In order to study the voltage stability of the Tunisian electric system, it is necessary to proceed in three steps; classification of nodes, simulation of scenarios of voltage collapse and the calculation of voltage stability indices. The classification of nodes consists of ranking of the all nodes in coherent areas by the voltage. This classification is based on the Kohonen method founded on automatic learning of artificial neural networks (Pandit *et al.*, 2001).

In the second step, a scenario of rapid collapse, caused by a negative behavior by the rotating load, following a short circuit (Chebbi *et al.*, 2005) is simulated. Also, a second scenario of collapse, caused by the successive increase of the load (Bouchoucha *et al.*, 2006) is simulated.

Finally, the voltage stability of different areas is studied with stability index to measure how close the system to instability and that in order to avert possible collapse and implement appropriate preventive measures in timely manner.

CLASSIFICATION AREA AND KOHONEN CARD
The Kohonen network is able to identify common features of input patterns which constitute the training set. It uses an unsupervised learning to change its internal state. The topology of the neural network is composed of two layers: a conventional input layer and one output layer at which

the neurons are fully connected in a plane. When data are presented to the network, one of the neurons of the output layer has the highest value. This is the number of that neuron, corresponding to a class, which will provide the information extracted by the Kohonen network (Pandit *et al.*, 2001).

The learning is to adapt, iteratively, the weights of connections in order to specialize the neuron in function of the types of signals presented in the network input. For this purpose, it is necessary to define a neighborhood around each output neuron, then to choose the neuron which has minimum distance and finally to modify the weights of connections of neurons in their neighborhoods. After reducing the neighborhoods, the iteration process (following Hebb's rule) start (Wehenkel, 1998). However, in all simulations, we take into account of a two-dimensional grid which is most the traditional and has a square shape (Wehenkel *et al.*, 1994; Kundur, 1996).

The rate of decline of the "radius" of the neighborhood is in the form:

$$r(t) = r_0\left(1 - \frac{t}{T}\right) \quad (1)$$

where, r_0 is the radius of the initial value, t is the current iteration, T is the total number of iterations or the parameter which determines the end of the organizational phase and the beginning of the phase convergence and r(t) is the scalar order neighborhood at t.

The Self-organizing Map (SOM) of Kohonen in our application includes three input vectors (Ne = 3) as follows:

- The couple (Pi, Vi): Table value of the PV curve
- The index in: Chosen to reflect the geographic distribution (two nodes which are meadows have indices close geographically)

Each of the output neurons of the Kohonen network has 3 connections to the inputs. For each neuron "i" is associated a weight vector $w_i^T = (w_{i1}, w_{i2}, w_{i3})$, that reflects its connections with the inputs. The Kohonen network is thus composed of three neurons in the input layer and 900 (30×30) neurons in the output layer. The Kohonen map has the dimension of 30×30.

The result of applying this algorithm for classifying the nodes according to coherent regions, viewpoint voltage, is given in the card format Kohonen SOM (Fig. 1).

At below to the right of the SOM map we find the Bizerte region ('Bizerte' in the map) which is surrounded by the Greater Tunis ('Grand Tunis' in the map) area and directly linked to the North West. In the middle of the map is the Central Est Region ('Centre Est' in the map) Linked to the central region. The central region ('Centre' in the map) is related to the Sfax region which is strongly linked to the south west region. Finally, the South West region ('Sud Ouest' in the map) is directly related to the Southern region.

In light of this class, we distinguish the following points:

- The North West region very far compares to other regions. This is explained by the large discrepancy between the values of various parameters of this region and those of other regions. Lambda values of this region are very low values compared to other regions at a given voltage

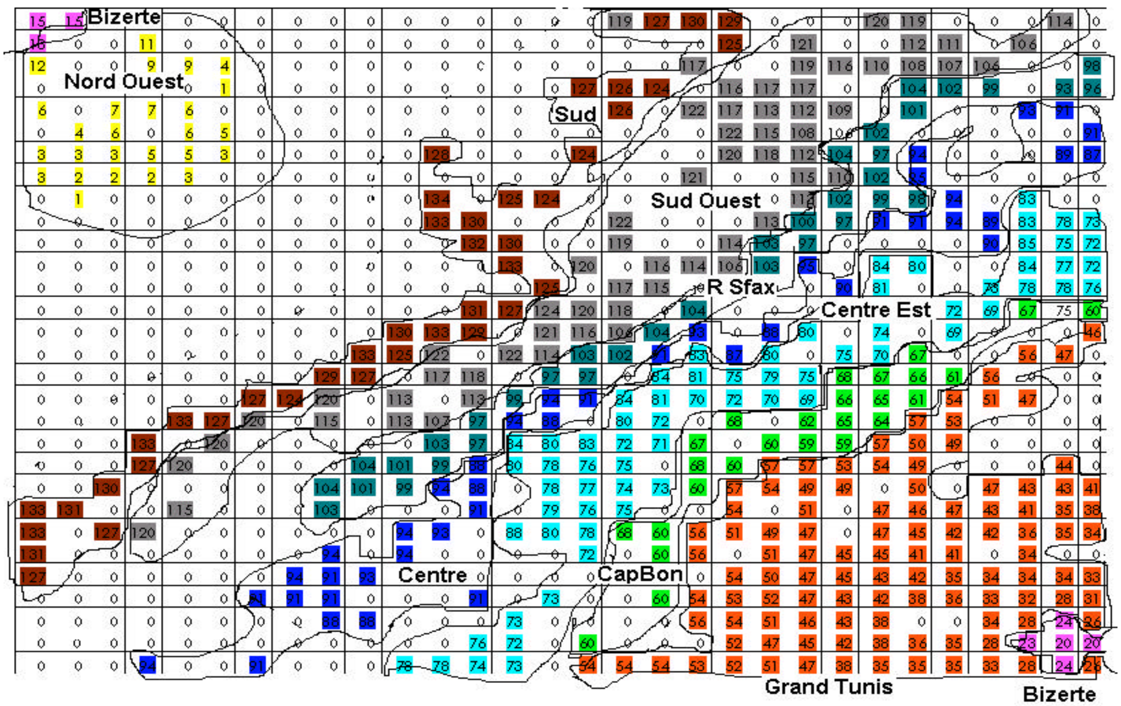

Fig. 1: Kohonen card of the Tunisian electrical system

- As described on the Kohonen map, the other 8 regions have very similar parameters so their location is very close
- The region of Bizerte is classified into two positions, with the Greater Tunis region and the other with the North West region, which is explained by the strong correlation of this region (Bizerte) with that of Greater Tunis and North West

VOLTAGE COLLAPSE AND DEFENSE ACTION

Load characteristic: It is difficult to make a model to a load in electrical systems because of their diversity as fluorescent and incandescent lamps, refrigerators, heaters, compressors, industrial engines, boilers, air conditioners, foundries, kilns arc, etc.

Therefore, the exact composition of the load is difficult to estimate. To this end, the overall model, which governs the actual behavior of the load, must indicate:

- Endogenous portion governing the behavior of the load at a given moment depending on variables internal electrical system, such that the voltage and frequency
- Exogenous portion including external factor system, in particular, time (hour, day, season), weather conditions and the state economy of the country

Fast voltage collapse: Causes and consequences

Rotating loads behavior during an isolation fault: The rapid collapse of voltage (Chebbi *et al*., 2005) is usually caused by a sudden increase in load due to the behavior of the latter, resulting in a rise in current consumption and thus an increase in consumption, such as induction motors and power converters continuous.

When an insulation fault (franc short circuit), voltage drop, therefore, in a highly motorized network (including a large percentage of engines), asynchronous engines request more reactive energy which aggravates further the fall, contributing to a rapid collapse of voltage. After fault clearance, the engine cannot re-accelerate since the electrical torque (which is proportional to the square of the voltage deteriorates during the short circuit) becomes lower than the mechanical torque. Under these conditions the engine stalls and absorb most of the current which causes the voltage drop further and other machines are wedged.

This phenomenon of Avalanche leads, in addition to the rapid voltage collapse to overload on the lines (which can cause the openings of transmission equipments by the overload protection) which contribute to the black out or partial collapse of the network.

Depending on the characteristics of the mechanical torque (constant, linear or quadratic) imposed by the load, we can consider whether or not an operating point during the short circuit. The variation of the mechanical torque (C_m) is of the form: $C_m = C_0(1+\Delta\Omega)^\alpha$ with α a scalar which defines the characteristic of the load (for example a fan $\alpha = 2$).

Scenario of fast voltage collapse in the Tunisian network: We have shown, by simulation on software PTI (PSSE), a scenario of rapid voltage collapse in the Tunisian network following fault isolation on a line that feeds the city (Greater Tunis). The simulated event is a three phase short-circuit normally eliminated by the main protections on both sides after 0.2 sec. The dynamic load introduced into simulation is a rotating load constituted by 80% of induction motors from the total load of greater Tunis (Fig. 2). The mechanical torque, load up the engine, is assumed constant. Indeed, for the rapid disturbance of the order of 2 to 3 sec, the change in mechanical torque is negligible and independent of the voltage.

The simulated event sequences are as follows:

- **0→0.5 sec:** Phase of initialization of variables starting with a static case of load flow
- **0.5 sec:** Isolation fault at the South Tunis substation on the line 90 kV South Tunis-Naassen
- **0.7 sec:** Cleaning of the fault at the side Tunis South (fault eliminated in the first stage of Tunis South side after 200 msec)
- **0.9 sec:** Cleaning of the fault at the side Naassen (fault eliminated in the second stage in 400 msec)

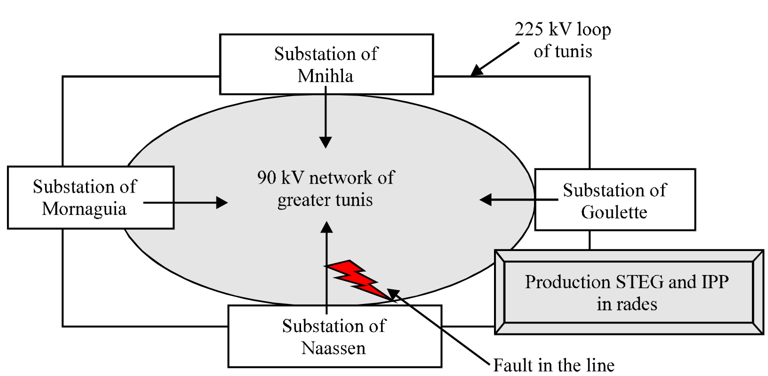

Fig. 2: Network of greater Tunis

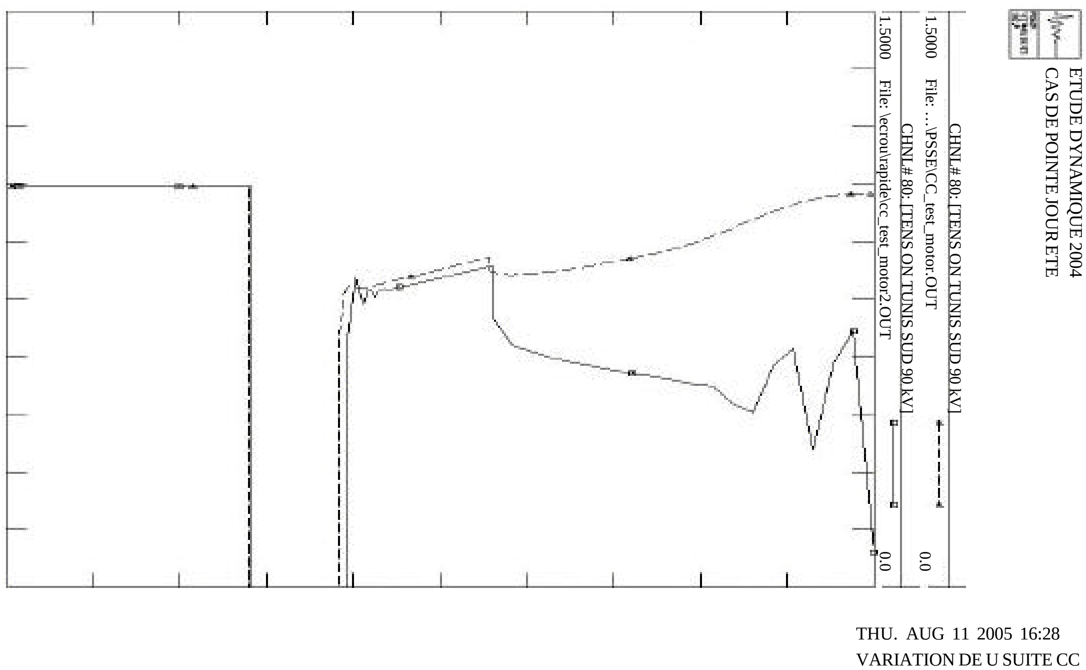

Fig. 3: Variation of the voltage in Tunis south substation for tow cases of load

Simulation results show that there is a rapid voltage collapse in Greater Tunis at 1.8 sec (that is to say 1.3 sec after the short circuit) as shown in Fig. 3.

To highlight the influence of the transient behavior of the dynamic load introduced in the simulations, we repeated the same sequence of events with a static load (constant current for active power and constant admittance for reactive power). Simulation results show that in this case (static load), there is a normal recovery of voltage. To this end, the dynamic and negative behavior of load is the cause of the rapid collapse of voltage.

The transient decrease in voltage at default has degraded the electrical torque developed by the engine knowing that we have a constant mechanical torque imposed by the load (Fig. 4). At the time of default (0.2 sec) that the engine stalls and absorbs more active and reactive power, leading to voltage drop further. And increasingly other engines stall and the call of active and reactive power increases until the voltage collapse. The elimination of the default after 200 msec of the first side and 400 msec of the second side is not able to avoid the collapse of the voltage, because during this time, there were many engine stall and require 4 to six times their nominal current to restart.

Curative defense action, which is still valid, is to put out of service the engines affected by the voltage drop. The engines must be equipped with an undervoltage protection and/or overcurrent for electric networks with high concentrations of rotating loads. These engines can be equipped with internal protection (integrated with engine) overcurrent or undervoltage in the manufacturing phase or in a manner outside the time of installation.

Scenario of the slow voltage collapse

Dynamics process of the collapse: The slow collapse said static voltage is a phenomenon that takes about ten minutes. It is characterized by a deterioration of the tension, aggravated by the entry into instability of certain settings, especially those of tap changers of transformers and

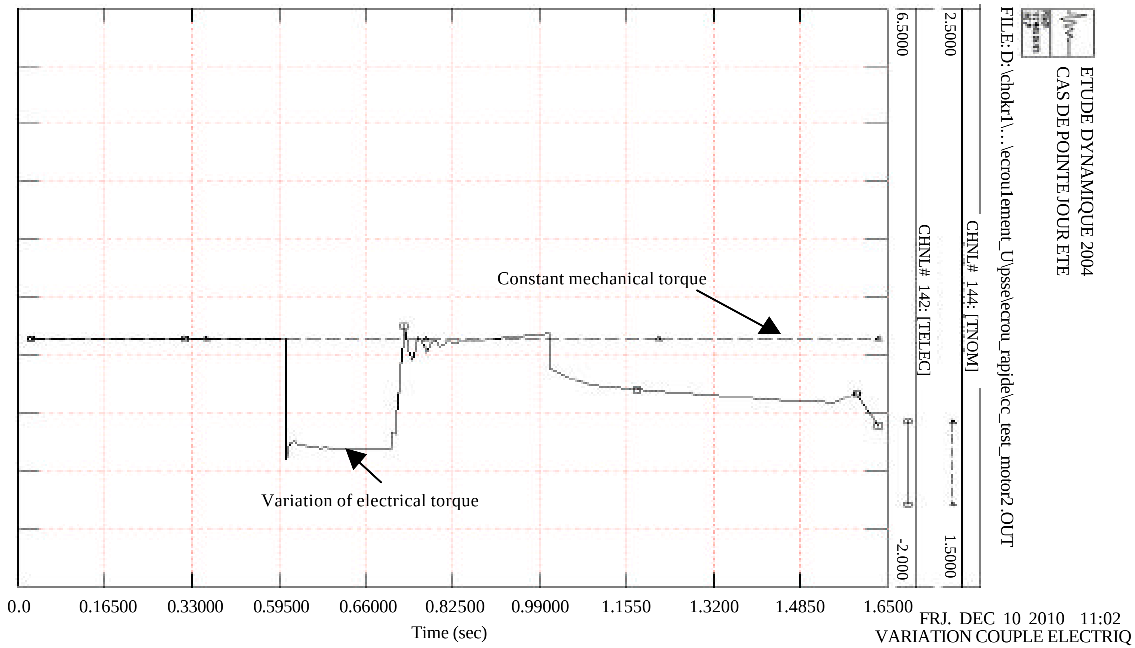

Fig. 4: Variation of the torque

saturation in reactive of some groups of production. The main cause of this phenomenon is a failure of the network through the holding voltage and reactive power compensation. The voltage drop in the high voltage network may lead to the development of events that exacerbate the process of collapse as the arrival of the alternators at the limit of their area of operation and therefore the voltage is no longer held in their location or the triggering of groups when the conditions for alimentation of accessories are no longer correct, resulting in a loss of production of active and reactive power.

The increasing of the load above the capacity of the electrical system causes the voltage collapse. The loss of a generator or line leads to increase of losses network and loss of reactive power that contribute in the voltage drop. The tap changers of transformers and autotransformers operate to restore the secondary voltage. The restoration of the secondary voltage produces an increase in the call of active and reactive power at high voltage network and generators will be overexcited.

After a few minutes, the limiters of the excitation current will restrict the generators to produce a certain limited amount of reactive power. The electrical system no longer supports the increase of the load and the active and reactive additional losses. Therefore, the voltage drops rapidly and a total or partial collapse of voltage occurs. The breakdown voltage and its dynamics depends crucially on the type of load, the reactive power margin maintained and the characteristics of the electrical system such that the control system or the limitation of production machines.

Study case in Tunisian network: We have shown by numerical simulation of a scenario of voltage collapse in the Tunisian network: corresponding to a gradual increase of the programmed exchange inter-country (Algeria-Tunisia), by decreasing the charge consumed in the Tunisian network and increasing the level of the Algerian network. The step of increase of the exchange was set at 30 MW/min. Starting from a zero exchange Tunisia-Algeria, we recorded a collapse of voltage

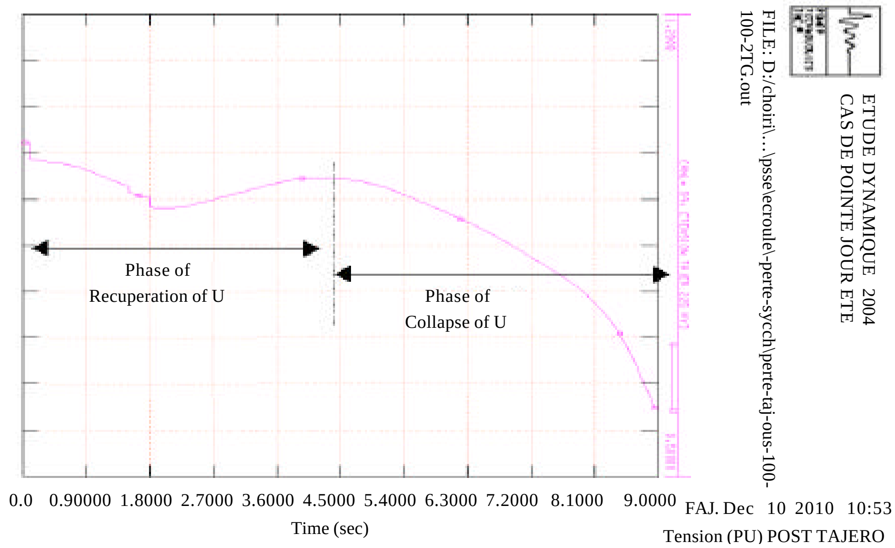

Fig. 5: Variation of the voltage at the Tunisia-Algeria interconnection

after 10 min corresponding to an exchange of 300 MW. This exchange is the maximum power transmitted Interconnection Tunisia-Algeria. The maximum power transmissible defines the maximum exchange capacity that can be exchanged between the two countries without losing stability. Once this maximum is reached the system loses stability which results in a voltage collapse.

Note here that there is a recovery of tension in the early stages of the collapse (from 1 to 6 min) through the voltage regulators of groups of machines nearby (combustion turbine plant of Kasserine). Then after a few minutes, limiters of exciter current, will restrict the generators to produce a certain limited amount of reactive power and voltage is not required, causing a collapse of the voltage (Fig. 5).

Defense plan for the slow voltage collapse: The slow voltage collapse can be avoided in most cases when we consider at the level of short-term planning and at the level of exploitation in real-time the voltage criteria, the normal operating range and N-i safety (Kundur, 1996; Hameyer and Belmans, 1999).

The forecast calculations help to ensure that a level of high voltage is sufficiently achievable by the means available. They also allow us to make arrangements accordingly. The management of the network must maintain the plan voltage by monitoring margins of security in order to avoid any appearance of dangerous situation. In cases where it occurs, energy measures would be to implement rapidly. These measures are harmful because they lead to a reduction in consumption, see the loss of customers. These measures are the only ones who can save the network to collapse.

The load shedding on voltage criterion is a defensive plan in curative mode that allows to limit the degradation of the voltage at unusable values (Matusz *et al*., 2004).

Load shedding by undervoltage must consider the following criteria:

- The dynamics of the voltage drop and the irreversible degradation
- The non-operation in the case of a normal short circuit

The first criterion will be respected by using a relay load shedding with a function dU/dt that reflects the dynamics of the drop. Indeed, the trajectory of the tension admits an almost vertical slope during insulation faults and light slope at the time of slow voltage collapse. To avoid spurious operation of load shedding, it makes sense to condition the operation of this relay load shedding by a threshold voltage set to voltage values outside normal operating limits. Thus the use of a relay undervoltage load shedding by mixed criterion (threshold of voltage and threshold of its derivative dU/dt) is recommended.

Correlation between voltage stability and inter-area oscillation: We simulated in this part, a scenario of the voltage collapse caused by the loss of a strategic link feeding the northwest region bordering interconnection with Algeria. The initial conditions were chosen so as to have a programmed exchange of 150 MW from Tunisia to Algeria and in the case of static modeling of the load (constant current for active power and constant admittance for reactive power) as the Fig. 6.

The voltage collapse (Bouchoucha *et al.*, 2006) was initiated by the loss of line of the strategic link that is the focus of the exchange scheduled Interconnection Tunisia and Algeria. This loss of line has changed the reactance of connection between the Tunisian and Algerian networks to higher values, which affects considerably to down on the maximum transmitted power (Pmax) of the interconnection in question. The initial exchange of 150 MW is no longer guaranteed and it is situated above the new Pmax. A rapid voltage collapse in the northwest region bordering interconnection has occurred. After 3 sec of the trip strategic link, an irreversible value of the voltage of 0,6 p.u. is reached which initiated an oscillation phenomenon of the voltage.

A modal analysis (Abdellaziz *et al.*, 2005; Abdellaziz and Kilani, 2005) of the voltage during the first 10 sec which consist to compose the signals S(t) in Fourier series (sum of two terms: an exponentially damped component or not and another sine) allows to determine the different eigenvalues excited in this phenomenon (real and imaginary parts).

Indeed the signal S(t) is decomposed as follows:

$$S(t) = \sum(A_i e^{\sigma i t}) + \sum(B_j e^{\sigma j t} \cos(w_j t + \phi_j)) \quad (2)$$

At each exponential term (i) associated a real eigenvalue (σi), while each sinusoidal term (j) associated is two conjugates eigenvalues (σj±ωj). Ai or (Bj, Φj) is the participation and the phase of each mode (exponential and sinusoidal).

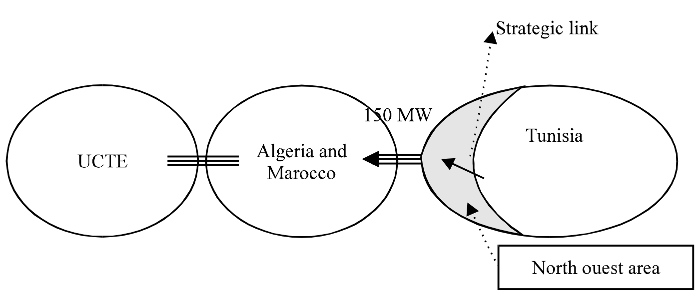

Fig. 6: Initial condition

Table 1: Modal analysis of the voltage at the border substation

	Eigenvalue			Vecteur propre		
N°	Real	Imaginary	Damping	Amplitude	Angle	Frequency (Hz)
1	2.18E-03	-	-	0.772370	-	-
2	-0.604244	6.15124	9.8	0.527660	108.68	0.979
3	-6.125150	-	-	0.181150	-	
4	-1.276290	7.77623	16.2	0.344690	-118.65	1.238
5	-1.272730	12.30430	10.3	6.28 E-02	-70.09	1.958
6	0.421621	7.70667	-5.5	2.86 E-02	-177.19	1.227
7	6.60E-02	13.74480	-0.5	8.51 E-03	80.68	2.188
8	0.174621	3.83769	-4.5	3.27 E-03	3.38	0.611
9	0.611736	15.41520	-4.0	6.10 E-04	98.34	2.453
10	-0.671276	26.96700	2.5	4.88 E-04	143.41	4.292
11	8.39E-03	20.83300	0.0	3.30 E-04	-123.00	3.316
12	0.369072	29.61060	-1.2	9.60 E-05	-16.64	4.713
13	0.614547	22.68820	-2.7	7.65 E-05	-159.50	3.611

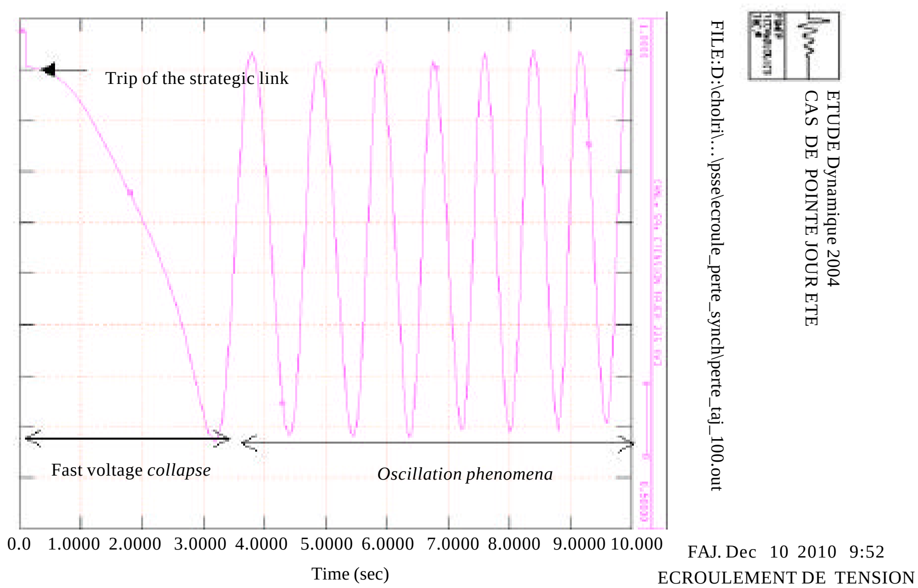

Fig. 7: Voltage at border substation

The stability criterion for linear systems is such that all eigenvalues of the system have negative real parts. Indeed, in response to a disturbance, there is an exponential associated with each eigenvalue. If the real part is positive, the exponential is infinitely increasing and the system is unstable. The results of this analysis during the time interval [3-10 sec] are summarized in the Table 1.

The results of modal analysis shows that the eigenvalues numbers 6, 7, 8, 9, 11, 12 and 13 have positive real parts and are therefore undamped sinusoidal modes. Confirming that the phenomenon observed in this period [3-10 sec] is a loss of static stability expressed in the voltage oscillation at the grid border substation (Fig. 7).

In light of this scenario we can conclude that the loss of the strategic link has caused in the first phase an irreversible voltage collapse (5 sec) and then in a second step the loss of static stability with undamped oscillations of the voltage (Houben *et al.*, 1997).

Index of voltage stability: The purpose of voltage stability index is to measure how close the system to instability. Index voltage stability are pre-calculated and for defining a scalar value which can be controlled as the modification of a system parameter. An index of voltage stability, to be useful and effective, must possess the following (Pandit *et al.*, 2001; Goharrizi and Asghari, 2007; Musirin and Rahman, 2002) qualifications:

- The index should be linked to the controllable parameters of a simple function
- Corrective measures can be derived from these indexes
- The index should be easy to calculate and low calculation cost

Fast voltage stability index (FVSI): This index of voltage stability, FVSI, can determine the point of voltage drop, the maximum permissible load (Wehenkel *et al.*, 1998), the lowest bus power system and the most critical line of the network. The FVSI can be calculated for any of the lines of the network and depends mainly on the reactive power. The line that has the index value closed to unity is considered the most critical line of the system. This index has a very simple mathematical formulation and uses the discriminator of the quadratic equation of the voltage to be equal to or greater than zero to guarantee stability. If the discriminator is less than zero, the roots will be imaginary, which can lead to instability of the system.

Consider the transmission line of the (Fig. 8) connecting the two bus of an elementary network, where in:

- **V_1 and V_2:** Module voltage at nodes 1 and 2, respectively
- **P_1 and Q_1:** Active power and reactive power at node 1
- **P_2 and Q_2:** Active power and reactive power at node 2

The apparent power at bus 2 is defined as:

$$S_2 = V_2 \times I^* \quad (3)$$

and

$$I = \left(\frac{S_2}{V_2}\right)^* = \frac{P_2 - jQ_2}{V_2 \times e^{-j\delta}} \quad (4)$$

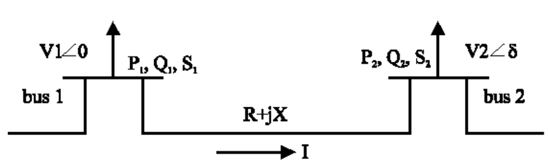

Fig. 8: Concept of the fast voltage stability index

In subsistent the 2 equations, we will have:

$$\frac{P_2 - jQ_2}{V_2 \times e^{-j\delta}} = \frac{V_1 e^{j0} - V_2 e^{j\delta}}{R + jX} \tag{5}$$

$$RP_2 + XQ_2 = V_1 V_2 \cos\delta - V_2^2 \tag{6}$$

The separation of the real part and the imaginary part in the 2 equations gives:

$$\begin{cases} RP_2 + XQ_2 = V_1 V_2 \cos\delta - V_2^2 \\ XP_2 - RQ_2 = -V_1 V_2 \sin\delta \end{cases} \tag{7}$$

And the act if power at the bus 2 as follow:

$$P_2 = \frac{RQ_2 - V_1 V_2 \sin\delta}{X} \tag{8}$$

The voltage at bus 2 is given by:

$$V_2^2 - \left(\frac{R}{X}\sin\delta + \cos\delta\right) V_2 V_2 + \left(\frac{R^2}{X} + X\right) Q_2 = 0 \tag{9}$$

The roots are as follows:

$$V_2 = \frac{\left(\frac{R}{X}\sin\delta + \cos\delta\right) V_1 \pm \sqrt{\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right) V_1\right]^2 - 4\left(\frac{R^2}{X} + X\right) Q_2}}{2} \tag{10}$$

The roots are real. With this intention, the discriminant must be equal or higher than zero:

$$\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right) V_1\right]^2 - 4\left(\frac{R^2}{X} + X\right) Q_2 \geq 0 \tag{11}$$

And the Fast Voltage Stability Index (FVSI) is:

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \tag{12}$$

where, Z is the line impedance, X is the line reactance, Q_2 is the reactive power at node 2, V_1 is the amplitude of the voltage at node 1.

If the value of FVSI is close to unity, it shows that their line is close to its instability point. If FVSI greater than 1, one of the buses, connected to a progressive and uncontrollable decline of voltage, leads to the collapse of the system. Therefore, the value of FVSI should be kept below one for a stable system operation.

Similarly we can define the index of stability line L_{mn} (line Stability Index). Calculating the current flowing in the line gives the primary expression of this index. Using the relationship between voltage and current of the transmission line, the stability index (L_{mn}) can be defined as follows:

$$\frac{4XQ_r}{[V_s \sin(\theta - \delta)]^2} = L_{mn} \le 1 \tag{13}$$

where, X is the reactance of the line, Q_r is the reactive power to receive end-Voltage, V_s is the sending-end, θ is the phase angle of the line impedance, δ is the phase difference voltage buses s and r.

Similarly, L_{mn} indicates stable operation of the load if it is strictly less than unity.

Line stability factor (LQP): LQP uses the same concept of FVSI and L_{mn}. It is derived from equations describing the power transfer system of Fig. 9.

In order to elaborate this index it is necessary to determinate first, the equation of the circulate current between nodes I and J:

$$I = \frac{V_i - V_j}{Z} = \frac{V_i - V_j}{R + j^X} \tag{14}$$

and

$$\frac{X}{V_i^2} Q_i^2 - Q_i + \left(\frac{X}{V_i^2} P_i^2 + Q_j \right) \tag{15}$$

The roots are as follows:

$$Q_i = 1 \mp \frac{\sqrt{\left(\frac{X}{V_i^2} \right)\left(\frac{X}{V_i^2} P_i^2 + Q_j \right)}}{2\left(\frac{X}{V_i^2} \right)} \tag{16}$$

The LQP index is defined by:

$$1 - 4\left(\frac{X}{V_i^2} \right)\left(\frac{X}{V_i^2} P_i^2 + Q_j \right) \ge 0 \tag{17}$$

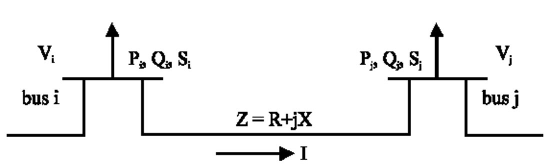

Fig. 9: Concept of the index of stability LQP

$$4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2+Q_j\right)\leq 1 \tag{18}$$

If:

$$L_{QP}=4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2+Q_j\right)\leq 1 \tag{19}$$

Finally:

$$L_{QP}=4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2+Q_j\right) \tag{20}$$

where, P_i is the real power at node I, X is the line reactance, Q_j is the flow of reactive power at node j, V_i is the voltage amplitude at node i.

When there is no load at node j, the value of LQP is 0. As the reactive power in the system increases, the value of LQP increases from 0 to 1. This value must be less than unity for the system is stable. Thus, more than the value of LQP, is higher the system is operating more near its margin of instability (Barbier and Barret, 1980).

Voltage stability of the network studied

Calculation of the collapse point: Here, we will study the voltage stability of Tunisia system. So, the stability indices FVSI, Lmn and LQP will be evaluated for different regions introduced in the first part. For each region we select a reference node that have the minimum short circuit power and it's not in radial configuration. With the aim of calculating the different indices of stability and the critical load and voltage, we proceed to load more and more (increase in active and reactive power at constant tgφ) these reference nodes (one at a time) to have the stability index FVSI equal to unity. At this time we also evaluate these other indices of stability Lmn and LQP and there is the critical line giving the highest index FVSI.

The Table 2 summarizes the results of simulations for different reference nodes of study areas.

The calculation of the collapses points of the different reference nodes presented in Table 2 fact of appearing nine (09) sensitive lines. Each sensitive line belongs to an area.

Thus, we can conclude that currently the Tunisian network is threatened by phenomena of voltage collapse in normal situation (all transmission apparatus in service). Just to announce that a critical power of 18% (P_{lmax}/P_{d0}) in the northwest region (Oued Zargua substation) is reached after 2 to 3 years later with no new setting in use (apparatus, substation, lines) in this region.

The maximum critical powers (ΔP_{load}) for the different regions are shown on the histogram in the Fig. 10. Regions North West and South West have the lowest margin of voltage stability. While the greater Tunis area has a large margin.

The Fig. 10 gives the classification of voltage stability of the different area while starting more fragile (North West area) on the left towards most stable on the right (Greater Tunis area).

Effect of the load model at the voltage stability: With the aim to study the influence of load model on voltage stability, we calculated the stability indices (FVSI, Lmn and LQP) for three cases:

Table 2: Different index of the voltage stability

Initial condition				Calculating of voltage collapse					
Area	Reference node	P_{d0} (p.u.)	Q_{d0} (p.u.)	P_{1max} (p.u.)*	Critical voltage (p.u.)	Sensitive line name	FVSI	Lmn	LQP
North west	O.Zarga	0,338	0,19	0.40	0.66	O.ZARGA-AROUSSIA	0.98	0.99	0.99
Bizerte	Mateur	0,346	0,192	2.52	0.54	MATEUR-MORNAGUIA	1.00	1.00	0.99
Greater Tunis	Zahrouni	1,118	0,63	4.90	0.55	ZAHROUNI-AROUSSIA	0.91	0.96	0.91
Cap Bon	Grombalia	0,716	0,4	2.85	0.79	KORBA-GROMBALIA	0.98	0.98	0.93
Central est	Enfidha	0,236	0,133	1.66	0.57	ENFIDHA-BOUFICHA	1.00	0.96	0.80
Central	Kairouan	0,508	0,286	2.98	0.74	SOUSSE-KAIROUAN	0.94	1.00	0.75
Sfax	Sfax	0,216	0,119	1.83	0.82	SFAX-THYNA	1.00	1.00	0.97
South west	Tozeur	0,212	0,12	0.601	0.71	TOZEUR-METLAOUI	1.00	0.97	0.79
South	S.Bouzid	0,296	0,171	0.623	0.63	S.BOUZID-MEKNASSI	1.00	0.97	0.81

*ΔP_{load}: P_{1max}-P_{d0} ΔQ load: Q_{1max}-Q_{d0}

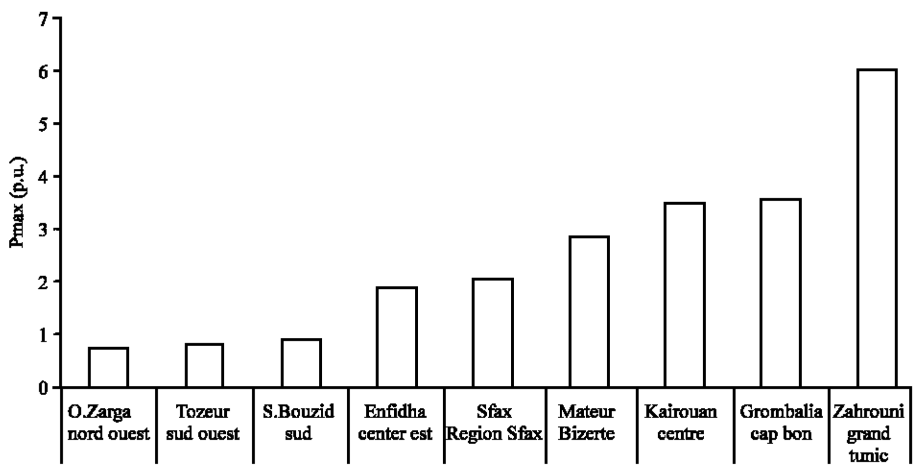

Fig. 10: Critical power at the different areas

- Constant static load model (P)
- Polynomial model in function of the voltage: Constant current (I)
- Polynomial model in function of the voltage: Constant admittance (Z)

For each reference node, we proceed to increase the active power more and more (and the reactive power at constant tg(φ)), one at a time, until the stability index FVSI equal to unity. At this time we evaluate the maximum power P_{1max} at the reference node and the sensitive line giving the highest index FVSI. The Table 3 summarizes the results of simulations.

Simulation results show that the model charge does not affect the list of lines giving the point of collapse. Also the critical power calculated depends on the load model. This dependence is dependent of a region to another. The Table 4 illustrates the variation of the maximum power (P_{1max}) as a function of load model.

The greatest variation in function of the load models (P, I, Z) is at the node O.Zarga (the most fragile area in voltage). While the smallest variation is at the node Zahrouni (the most stable area). Thus, the static model load significantly affects fragile areas in terms of voltage stability. However,

Table 3: Influence of load model in voltage stability index

Ranking stability	Area	Reference node	P_{lmax} (p.u.) Load model P	I	Z	Sensitive Line name	FVSI Load model P	I	Z
1	North west	O.Zarga (56)	0,400	0,480	0,530	O.ZARGA-AROUSSIA	0.98	0.99	1
2	South west	Tozeur (84)	0,601	0,670	0,720	TOZEUR-METLAOUI	1	1	1
3	South	S.Bouzid (81)	0,623	0,680	0,720	S.BOUZID-MEKNASSI	1	0.98	0.97
4	Central east	Enfidha (73)	1,660	1,700	1,700	ENFIDHA-BOUFICHA	1	1	1
5	Sfax	SFAX (78)	1,830	1,900	1,960	SFAX-THYNA	1	1	1
6	Bizerte	Mateur (48)	2,520	2,580	2,630	MATEUR-MORNAGUIA	1	0.99	1
7	Cap Bon	Grombalia (51)	2,850	2,990	3,000	KORBA-GROMBALIA	0.98	0.98	0.98
8	Central	Kairouan (99)	2,980	3,020	3,000	SOUSSE-KAIROUAN	0.94	0.93	0.93
9	Greater Tunis	Zahrouni (49)	4,900	4,980	5,040	ZAHROUNI-AROUSSIA	0.91	1	1

P: Constant power model, I: Constant current model, Z: Constant admittance model

Table 4: Maximum power at the reference nodes

Ranking stability	Reference node	P_{lmax} (p.u.) Constant power model (P)	Constant current model (I)	Constant admittance model (Z)	Max variation (MW)
1	O.Zarga	0,40	0,48	0,54	14,00
2	Tozeur	0,60	0,67	0,74	13,90
3	S.Bouzid	0,62	0,68	0,76	13,70
4	Sfax	1,83	1,90	1,96	13,00
5	Enfidha	1,66	1,72	1,78	12,00
6	Mateur	2,52	2,58	2,63	11,00
7	Grombalia	2,85	2,92	2,95	10,00
8	Kairouan	2,98	3,02	3,06	8,00
9	Zahrouni	4,90	4,95	4,96	6,00

regions with stability margin and high power of short-circuit are little sensitive to static characteristics of the load. The histogram in the Fig. 11a illustrates the sensitivity of the point of collapse depending on the load model. Variations in the maximum power according to load model were ranked in descending order on the graph in the following Fig. 11b.

Index of critical line stability: To enhance the stability index we performed the calculation of these indexes at initial conditions. To this end, for the initial operating point, called the base case of electrical systems, characterizing the initial conditions of voltage stability, we calculate stability index FVSI, Lmn and LQP for the various links of the Tunisian network. The Table 5 shows the first 30 index calculated in the base case and are classified in descending order.

In referent in Table 2, four sensitive lines (8, 17, 19 and 20) only were listed in the classification of first about thirty lines to high index of stability appear in the basic case (Table 5).

The table above (Table 5) has two families presented stability index:

- A first family that includes the nodes of production
- A second family that touches the high voltage transmission network

It is particularly interested to the transmission network. To this end, we classified the apparatus mentioned above by home region.

Table 5: First 30 index stability of critical lines

Ranking stability	Rank	Line N°	Bus 1	Name 1	Bus 2	Name 2	FVSI	Lmn	LQP
	1	138	52	Korba 90	12	Korba TG1	0,376	0,380	0,327
	2	137	52	Korba 90	11	Korba TG2	0,368	0,370	0,336
	3	139	72	Sousse 150	13	Sousse TV1	0,358	0,363	0,291
	4	144	78	Sfax 150	18	Sfax TG1	0,245	0,246	0,227
	5	145	78	Sfax 150	19	Sfax TG2	0,245	0,246	0,227
	6	133	112	Radès II 90	7	Radès II TG2	0,206	0,208	0,176
	7	136	113	Goulette 90	10	Goulette TG	0,203	0,204	0,189
6*	8	36	52	Korba 90	51	Grombalia 90	0,161	0,161	0,151
	9	171	129	Sousse 225	72	Sousse 150	0,158	0,161	0,219
	10	134	97	B.Mchergua 225	8	B.Mchergua TG1	0,151	0,153	0,097
	11	135	97	B.Mchergua 225	9	B.Mchergua TG2	0,151	0,153	0,097
	12	146	83	Thyna 150	20	Thyna TG1	0,144	0,146	0,090
	13	147	83	Thyna 150	21	Thyna TG2	0,144	0,146	0,090
	14	173	131	S.Mansour 225	77	S.Mansour 150	0,140	0,141	0,144
	15	56	114	Radès 150	71	Hammamet 150	0,137	0,147	0,152
	16	158	121	Mnihla 225	39	Mnihla 90	0,134	0,134	0,152
4*	17	65	80	Bouficha 150	73	Enfidha 150	0,132	0,132	0,125
	18	117	131	S.Mansour 225	133	Bouchemma 225	0,130	0,132	0,122
7*	19	157	119	Mornaguia 225	103	Mateur 225	0,130	0,130	0,145
9*	20	31	49	Zahrouni 90	107	Aroussia 90	0,127	0,131	0,002
	21	127	120	Radès 225	2	Radès TV1	0,125	0,127	0,072
	22	128	120	Radès 225	3	Radès TV2	0,125	0,127	0,072
	23	40	52	Korba 90	62	M.Temim 90	0,125	0,126	0,122
	24	163	71	Hammamet 150	104	Hammamet 90	0,124	0,124	0,123
	25	174	126	Bouficha 225	80	Bouficha 150	0,123	0,123	0,137
	26	76	83	Thyna 150	85	Maknassy 150	0,122	0,132	0,077
	27	62	72	Sousse 150	82	Monastir 150	0,122	0,125	0,130
	28	129	120	Radès 225	4	Radès TV3	0,121	0,123	0,076
	29	130	120	Radès 225	5	Radès TV4	0,121	0,123	0,076
	30	172	130	Msaken 225	116	Msaken 150	0,118	0,118	0,122

*Common line with Table 2

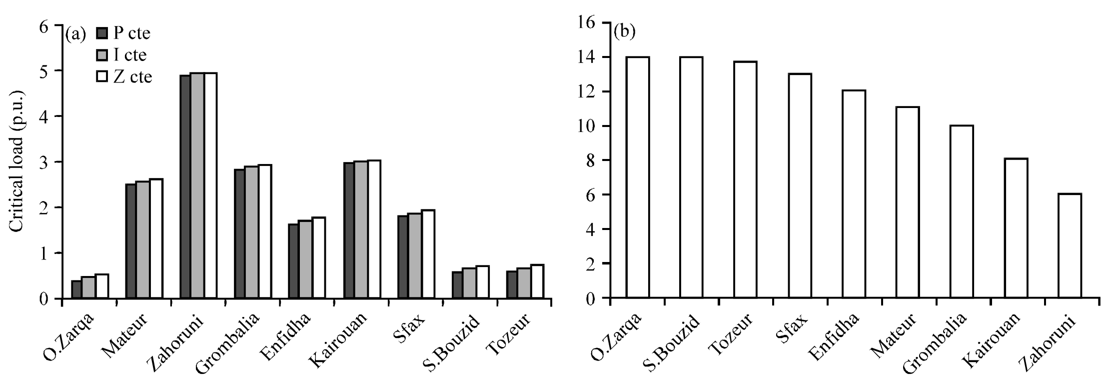

Fig. 11(a-b): (a) Effect of load model at the collapse point and (b) Maximum variation of the load modal

Table 6: Classification of the first index stability of critical line

Rank	Name 1	Name 2	Area	FVSI	Lmn	LQP
8	Korba 90	Grombalia 90	Cap Bon	0,161	0,161	0,151
23	Korba 90	M.Temim 90		0,125	0,126	0,122
24	Hammamet 150	Hammamet 90		0,124	0,124	0,123
25	Bouficha 225	Bouficha 150		0,123	0,123	0,137
9	Sousse 225	Sousse 150	Central	0,158	0,161	0,219
27	Sousse 150	Monastir 150		0,122	0,125	0,130
30	Msaken 225	Msaken 150		0,118	0,118	0,122
14	S.Mansour 225	S.Mansour 150	Sfax	0,140	0,141	0,144
16	Mnihla 225	Mnihla 90	Greater Tunis	0,134	0,134	0,152
20	Zahrouni 90	Aroussia 90	North west	0,127	0,131	0,002
15	Radès 150	Hammamet 150	Inter-area (greater Tunis-Cap Bon)	0,137	0,147	0,152
17	Bouficha 150	Enfidha 150	Inter-area (Cap Bon-central)	0,132	0,132	0,125
18	S.Mansour 225	Bouchemma 225	Inter-area (Sfax-South)	0,130	0,132	0,122
19	Mornaguia 225	Mateur 225	Inter-area (Greater Tunis-Bizerte)	0,130	0,130	0,145
26	Thyna 150	Maknassy 150	Inter-area (Sfax-Central)	0,122	0,132	0,077

In normal situations, the region most contained in the Table 6 are the Cap Bon region then the central region. We also note that five apparatus inter-region have high stability index in the Tunisian power system. The critical lines do not give a true and fair view of voltage stability. Indeed, the region most affected in viewpoint voltage is the North West (ΔP_{load} = 0.062 p.u.) and it appears only once, while the Cap Bon region (with ΔP_{load} = 2.13 p.u.) appears 4 times. However, the critical lines that have high stability index in normal situation may give useful information in disturbed situations (N-1).

For this purpose and in order to judge the critical states of these transmission equipments, we analyzed the voltage stability of Tunisian system at N-1 situation. We conducted at the disconnection of high voltage network links one by one and each time we calculate stability index (FVSI, Lmn and LQP). Table 7 illustrates the simulation results arranged in descending order of FVSI. In the first thirteen case, the load balancing algorithm does not converge indicating a voltage instability.

The nine sensitive lines (presented in Table 2) are again found among the thirty significant connections in N-1 situation. The appearance of these nine lines in Table 7 is in the same order as the voltage stability of the different areas. The first line which appeared (O.Zarga-Aroussia) belonged to the Western Northern area most significant in voltage, the second line (S.Bouzid-Meknassi) belonged to the second area (southern Est) and so on.

It should be noted that the critical lines with the highest stability index in normal situation have the highest stability index in N-1 situation. These critical lines should be treated with caution during the calculating phases of the electrical system (Moghavvemi and Omar, 1998).

In order to conclude on the voltage stability of the electrical system, it is necessary to evaluate the voltage stability index (FVSI) not only in the base case in normal situation but as well in N-1 situation. The study has also shown that there is a correlation between critical line outage obtained from contingency ranking and sensitive lines obtained from voltage stability analysis. The proposed contingency ranking technique has also identified the weak cluster based on the critical line outages in the system. The information obtained from the analysis combined with N-1 contingency could be used as an early warning system in the control centre so that proper monitoring can be done.

Table 7: Index stability of critical line in N-1 situation

Ranking stability	Rank	Line N°	Bus 1	Name 1	Bus 2	Name 2	FVSI	Lmn	LQP
	#	20	45	Kram 90	63	Gamart 90	NR	NR	NR
	#	26	46	M.Bourguiba 90	66	El Fouledh 90	NR	NR	NR
	#	30	48	Mateur 90	58	Ettaref 90	NR	NR	NR
	#	33	50	Bizerte 90	59	T.Acier 90	NR	NR	NR
	#	34	50	Bizerte 90	60	C.Bizerte 90	NR	NR	NR
	#	43	54	Tajerouine 90	61	C.Tajerouine 90	NR	NR	NR
	#	45	55	Jendouba 90	110	Barbra 90	NR	NR	NR
1*	#	48	56	O.Zarga 90	107	Aroussia 90	NR	NR	NR
	#	49	56	O.Zarga 90	108	S.Salem 90	NR	NR	NR
	#	50	57	Tabarka 90	109	S.Barrak 90	NR	NR	NR
	#	53	68	C.Feriana 150	89	Feriana 150	NR	NR	NR
	#	54	69	SNCFT 150	72	Sousse 150	NR	NR	NR
	#	55	70	C.Gabes 150	118	Bouchemma 150	NR	NR	NR
	1	62	72	Sousse 150	82	Monastir 150	0,627	0,603	0,460
2*	2	171	129	S.Bouzid 150	72	Meknessy 150	0,575	0,584	0,497
	3	138	52	Korba 90	12	Korba TG2	0,557	0,561	0,520
	4	137	52	Korba 90	11	Korba TG1	0,508	0,514	0,454
	5	174	126	Bouficha 225	80	Bouficha 150	0,479	0,484	0,426
	6	56	114	Rades 150	71	Hammamet 150	0,468	0,473	0,415
3*	7	139	72	Touzer 150	13	Metlaoui 150	0,402	0,406	0,351
	8	173	131	S.Mansour 225	77	S.Mansour 150	0,393	0,394	0,372
	9	129	120	Rades 225	4	Rades TV3	0,387	0,391	0,338
4*	10	136	113	Enfidha 150	10	Bouficha 150	0,386	0,390	0,337
	11	134	97	B.Mchergua 225	8	B.Mchergua TG1	0,386	0,390	0,337
	12	135	97	B.Mchergua 225	9	B.Mchergua TG2	0,386	0,390	0,337
	13	127	120	Rades 225	2	Rades TV1	0,386	0,390	0,336
	14	128	120	Rades 225	3	Rades TV2	0,386	0,390	0,336
5*	15	133	112	Sfax 150	7	Thyna 150	0,385	0,390	0,331
	16	117	131	S.Mansour 225	133	Bouchemma 225	0,385	0,391	0,317
	17	180	141	Randa	32	Randa 90	0,384	0,388	0,334
6*	18	179	140	Korba 90	31	Grombalia 90	0,384	0,388	0,334
	19	181	142	Kchabta	33	Kchabta 90	0,382	0,386	0,333
	20	158	121	Mnihla 225	39	Mnihla 90	0,382	0,386	0,333
7*	21	157	119	Mornaguia 225	103	Mateur 225	0,380	0,384	0,331
	22	146	83	Thyna 150	20	Thyna TG1	0,378	0,382	0,329
	23	147	83	Thyna 150	21	Thyna TG2	0,378	0,382	0,329
8*	24	76	83	Sousse 225	85	Kairouan 225	0,377	0,381	0,328
	25	144	78	Sfax 150	18	Sfax TG1	0,376	0,380	0,327
	26	145	78	Sfax 150	19	Sfax TG2	0,376	0,380	0,327
	27	163	71	Hammamet 150	104	Hammamet 90	0,363	0,368	0,296
9*	28	40	107	Aroussia 90	62	Zahrouni 90	0,357	0,362	0,291
	29	76	83	Thyna 150	85	Maknessy 150	0,357	0,361	0,292
	30	179	140	Abderrahmen	31	Abderrahmen 225	0,354	0,358	0,290

NR: Not resolved, *Common line with Table 2, #Voltage instability

RESULTS AND DISCUSSION

The study of voltage stability of the Tunisian electric system by the Fast Voltage Stability Index (FVSI) made it possible to classify the various areas. The lines sensitive calculated (Table 2) at the

Table 8: Influence of load model in voltage stability

Ranking stability	Area	Sensitive line	Voltage stability	Influence model of load
1	North West	O.Zarga-Aroussia	Weak	Large
2	South West	Tozeur-Metlaoui	Weak	Large
3	South	S.Bouzid-Meknassi	Weak	Large
4	Exchange Is	Enfidha-Bouficha	Average	Average
5	Sfax	Sfax-Thyna	Average	Average
6	Bizerte	Mateur-Mornaguia	Average	Average
7	Good Cape	Korba-Grombalia	Extremely	Weak
8	Exchange	Sousse-Kairouan	Extremely	Weak
9	Greater Tunis	Zahrouni-Aroussia	Extremely	Weak

point of collapse were FVSI = 1 (Subramani *et al*., 2011) are thus arranged in the same order that their areas mother. The static model of load influences considerably the fragile area presenting a weak margin of stability. The study makes show the following classification (Table 8).

The calculations of the stability index (FVSI) in the base case it possible to determine only 4 lines among 9 sensitive lines. However, the calculation of the FVSI in N-1 situation makes leave all the sensitive lines in the Tunisian electric system. Indeed, certain lines are of primary importance for the maintenance of the voltage stability but they present weak transits in normal situation and in consequence of weak indices FVSI. In addition their releases generate a voltage collapse and thus a strong index FVSI.

In the light of the study results of voltage stability of the real case, Tunisian electric system, it is necessary to evaluate index FVSI not only in normal situation but as well in N-1 situation in order to conclude on the voltage stability.

The drawn conclusions in several references (Mohamed and Jasmon, 1989; Musirin and Rahman, 2001; Subramani *et al*., 2009) miss precision concerning the practical application in the control centers of a monitoring system of the voltage stability in real time based on the calculation of the sensitive lines in normal situation and the correlation observed with the calculation of the indices in N-1 situation. Indeed, this work as well puts the light on the FVSI calculated in N-1 situation as on the computation results of the FVSI in normal situation and maximum loading. The calculation of the FVSI in normal situation and in the base case must take with prudence for the stability of voltage.

CONCLUSION

The voltage collapse is a dynamic process that can last several minutes: we talk about the slow collapse of the voltage or it can last a few seconds talking about the rapid collapse of voltage. These collapses can be avoided through preventive measures and curative measures. The load shedding on voltage criterion is a defensive measure in curative mode that allows to limit the degradation of the voltage to unusable values. This load shedding by undervoltage must consider the dynamics of the voltage drop and irreversible degradation.

In other cases, the voltage collapses may occur following the failure of the transmission network, related to the maximum power transmissible, to insure the transfer of energy. Thus, a phenomenon of loss of static stability is generally initiated.

It should be noted that the areas presenting of the sufficient margins of voltage stability are the seat of the fast voltage collapses (like the case of the area Great Tunis in the Tunisian system). However, the areas weakened in terms of voltage are the seat of the slow voltage collapses (like the case of the Western northern area in Tunisia). The study of voltage stability of the Tunisian network showed that the critical line that shows the highest index of stability in normal situation engender highest index of stability in N-1 situation. Therefore, these critical lines should be treated with caution during the calculating phases of the electrical system. In order to conclude on the voltage stability of the electrical system, it is necessary to evaluate the voltage stability index (FVSI) not only in the base case in normal situation but as well in N-1 situation.

Voltage stability is sensitive to the load characteristics and its location. Indeed, the static model of load significantly affects fragile areas in terms of voltage stability. On the other side, regions with stability margins and high short-circuit power are little sensitive to static characteristics of the load. However, they present risks of rapid voltage collapse. These collapses are caused by a sudden increase in load due to the behavior of the latter resulting in a rise of current absorbed and thus an increase in consumption, such as induction motors and DC converters.

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