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Voltage Stability Investigation of the Egyptian Grid With High Penetration Level of Wind Energy During Steady State and Transient

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Summary-The large penetration level of wind farms might have deleterious effects on the voltage stability of the electric network. This is because wind farms absorb reactive power from the transmission network and an observable drop in bus voltages occur. To mitigate this effect, system must be studied under steady-state and transient conditions.
The main objective of this study is to analyze the voltage stability of the Egyptian Electrical Network with large scale wind power under normal condition, under single contingency (N-1) and under transient condition. The single contingency is defined as the loss of any transmission line, transformer, or generator. In addition, the paper determines the size of reactive power compensation devices (capacitors or STATCOM) that should be installed at weak buses to prevent the voltage collapse during normal and transient states.

Index Terms - Voltage stability, PV analysis, QV analysis, voltage sensitivity, reactive compensation.

I. Introduction

Recently, wind power generation has been experiencing a rapid development in a global scale. The size of wind turbines and wind farms are increasing quickly; a large amount of wind power is integrated into the power system. The Egyptian authorities have ambitious plans to increase renewable resources, especially from wind in the national grid. The wind power penetration into the grid is expected to reach 7200 MW by the year 2020 [1]. This penetration level represents 12% of the total generation capacity. Most of wind farms are to be installed in the Canal Zone due to the high average wind speeds in this area. This large penetration level of wind farms might have harmful effects on the voltage stability of the Egyptian electric network, as these wind turbines absorb (or supply) reactive power from the transmission network.

This paper investigates the voltage stability of the Egyptian network in the presence of high penetration levels of wind energy. The analyses are carried out under normal condition, (N-1) contingency and under transient conditions to identify the weak buses in the electrical grid. Weak buses are characterized by low voltage profiles and high voltage sensitivity. Also, the study allows for the sizing of the reactive power compensation devices, such as capacitors and STATCOM devices that should be installed at the weak buses to prevent the voltage collapse.

II. VOLTAGE STABILTY

Voltage stability is the ability of a power system to maintain steady voltages of all buses in the system after being subjected to a disturbance [2]. Also, it is the ability of maintaining controlled voltage when load and power are increased. Voltage instability occurs in the form of a progressive fall or rise in the values of the voltages of some buses**.** A possible outcome of voltage instability is the loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages.

Power-Voltage (PV) curves and Voltage-MVAr (VQ) curves [2-4] generation are utilized to asses static voltage stability. These techniques are industry standard accepted generally by power system engineers worldwide.

A. PV Analysis

When considering voltage stability, the relationship between transmitted power (P) and receiving end voltage (V) is of interest. The voltage stability analysis process involves the transfer of P from one region of a system to another, and monitoring the effects to system voltages, V. This type of analysis is commonly referred to as a PV study. Using continuation power flow (CPF) or standard power flow algorithm, the load demand is increased incrementally, and the demand in MW and the bus voltage of focus are reported for the generation of the PV curve, Fig. 1. The PV curve is analyzed to identify the nose point or the voltage collapse point. The impact of a disturbance or reactive power compensation can be evaluated by looking at a PV curve as shown in Fig. 1. Details of PV methodology are given in References [5-7].

B. VQ Analysis

Voltage stability depends on how the variations in the reactive power (Q) and the active power (P) affect the voltages at the load buses. The influence of reactive power characteristics of devices at the receiving end is more apparent in a VQ relationship. It shows the sensitivity and variation of bus voltages with respect to reactive power injections or absorptions. Reactive power margin or deficit can be determined by generating the VQ graph, Fig. 2. The independent variable, bus voltage, is varied to compute the MVAr requirement which is the dependent variable. A dummy synchronous condenser is used for MVAr generation at the bus of focus, Fig. 2. Standards [5-7], detail the procedure for this area of static voltage stability.

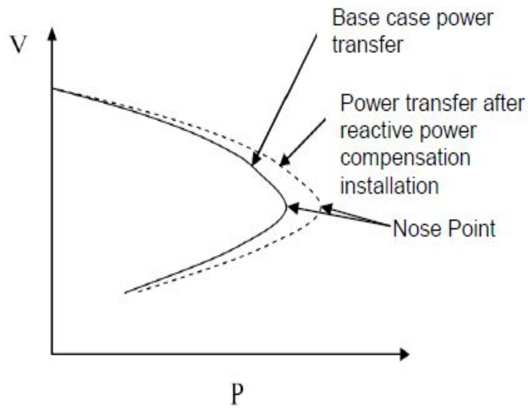

Figure 1 Power-Voltage Curve for Static Voltage Stability.

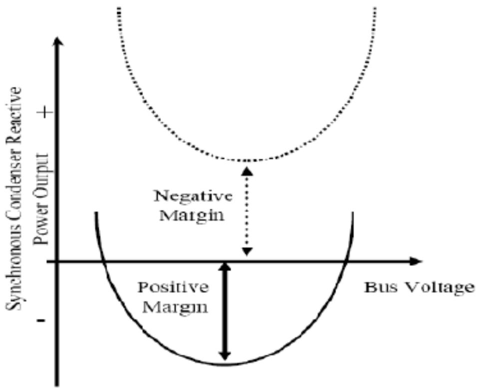

Figure 2 Voltage-MVAr (VQ) curve for Static Voltage Stability.

III. METHODOLOGY

The area under study is the Canal Zone where existing and future planned wind farms are included. The voltage stability of the grid is studied under normal operating conditions and (N-1) contingency using the PV and VQ analyses for the year 2017.

The PV analysis detects the slower form of voltage instability, which occurs due to the gradual increase in power transfer between a sending subsystem (source) and a receiving subsystem (sink). The VQ analysis is used to size the reactive power compensation devices required at relevant buses to prevent voltage collapse.

In PSS™E [8], the VQ curves are generated by artificially introducing a synchronous condenser, with high reactive power limits at a bus to make it a PV bus. As the scheduled voltage set point (bus voltage) of the PV bus is varied in steps for a series of AC load flow calculations, the reactive power output from the condenser is monitored. When the reactive power is plotted as a function of the bus voltage a VQ curve is obtained.

VQ curves are commonly used to identify voltage stability issues and reactive power margin for specific locations in the power system under various loading and contingency conditions. The VQ curves are also used as a method to size shunt reactive compensation at any particular bus to maintain the required scheduled voltage.

The aim of this study is to find the buses that have the lowest voltage profile and highest voltage sensitivity. The voltage sensitivity is defined as the ratio of the modulus of the total change in voltage to the total change in transmitted power $|dV/dP|$. The weakest bus is more sensitive to load changes, i.e., the load connected to this bus is highly affected by voltage reduction.

IV. DESCRIPTION, MODELLING, AND SIMULATION OF STUDY SYSTEM

Power flow analyses were performed using the PSS/E program for the complete Egyptian network. The peak generation capacity and peak load of the base case in 2017 of the Egyptian network are assumed to be 33833 MW and 33315 MW respectively.

Fig. 3 shows the electric network of the Canal Zone, which is a part of the Egyptian electric network, for the year 2017. In year 2017, the total generation capacity is assumed consisting of 1994 MW of wind energy and 5515MW of conventional generation, with a total of 7509 MW. The forecasted peak load of the year 2017 in the Canal Zone is assumed to be 5464 MW. The wind farms are installed at El-Zeit bus, which is used as the source subsystem in the PV analysis. The sink subsystem is represented by buses Sokhna, Economy and Ghard, which are load buses.

Five cases, including the base case, are presented and were formulated to solve voltage instability. These five cases are given in Table (1).

Table (1): Simulation Cases.

Case Number	Description
1	Base case - 2017 system

2	(N-1) single contingency - 2017 system
3	Connect a capacitor-2017 system
4	Connect a STATCOM-2017 system
5	Transient analysis with and without reactive power compensation

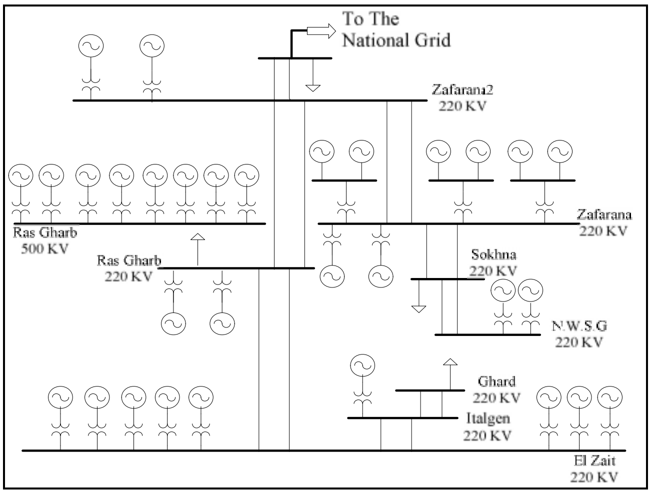

Figure 3 Year 2017 Canal Zone Study System

V. WIND POWER REPRESENTATION

In this section, a static model simulates the wind farm power production because the voltage stability problem is slow. The wind farm static model must simulate the reactive power demanded based on the active power and the power factor, WPF, at the wind turbine bus. The PSS/E represents the wind farm in the steady state as an equivalent generator connected to a generator bus. The active (P) and the reactive (Q) powers are specified to the load flow program (that computes the load ability curves). The P component is the rated power of the wind farm to be installed on a specific site and Q is computed based on a control mode option, WMOD, specified by the PSS/E software package [8] to indicate whether the equivalent machine is a wind machine, and, if it is, the type of reactive power limits to be imposed, such that [9]:

WMOD: 0 for a machine that is not a wind machine.

1 for a wind machine whose reactive power limits are specified by QT and QB.

2 for a wind machine for which reactive power limits are determined from the machine's active power output and WPF; limits are of equal magnitude and opposite sign.

3 for a wind machine with a fixed reactive power setting determined from the machine's active power output and WPF; when WPF is positive, the machine's reactive power has the same sign as its active power; when WPF is negative, the machine's reactive power has the opposite sign of its active power.

The wind turbine generator can be represented by the PQ load model by choosing WMOD = 3 and setting QT=QB = the set reactive power. This mode is used for fixed speed wind turbines (Type 1) and wound rotor (Type 2). On the other hand the wind turbine generator can be represented by the PV model by choosing WMOD = 2 and setting QT and QB to the upper and lower limits. This mode is used for doubly fed induction generators (Type 3) and full rated converter (Type 4).

VI. SIMULATION RESULTS

PV and VQ results are obtained for the base cases with all elements in service. Also they are obtained for cases of single contingencies (N-1) such as the loss of any transmission line, transformer or generator. These are often termed 'probable' or 'credible' contingencies.

Acceptable system conditions prior to and subsequent to the contingencies depend on the severity of the contingency. They should include voltages within defined normal or emergency limits. The contingency file used to run the PSS/E software package consists of:

1) Bus voltages are monitored below 0.95 p.u. or above 1.05 p.u. for normal and transient conditions

2) Bus voltages are monitored below 0.90 p.u. or above 1.1 p.u for (N-1) contingency condition.

The VQ curve is used to determine the reactive power injection required at a bus in order to maintain the bus voltage within the design criteria; typically between 0.95 and 1.05 p.u. Starting from the existing reactive loading at a bus, the voltage is increased in steps, until the power flow experience convergence difficulties indicating the proximity of a voltage collapse.

A. Results of 2017 Base Case:

The simulation results for the static voltage stability for the 2017 base case are shown in Fig. 4. The bus voltages are plotted versus the load parameter. As the load parameter is increased, voltages of load buses decrease as expected. The system would lose its voltage stability at the critical point, where the load parameter value is 437.5MW as seen in Fig. 4. The critical point can be taken as the voltage collapse point. The voltage of load buses becomes unstable beyond these points and voltage decreases rapidly due to the system requirement of reactive power.

The results of 2017 system show that the lowest voltage profiles are at Ghard, Italgen and El-Zeit buses. The voltage sensitivity at these buses are 0.000544, 0.00039, and 0.00038 respectively. Therefore, when Fig. 4 is examined it can be seen that the Ghard bus has the lowest voltage profile and the most reduction in bus voltage. Hence, it can be concluded that GHARD bus is the weakest bus in the Canal Zone. Fig. 4 shows that the voltage of GHARD bus is below 0.9 p.u. for the base case of 2017 when the load increment is 100 MW or more.

For the 2017 network, the VQ analyses Fig. 5 shows that, in order to maintain the Ghard bus voltage at 1 p.u., the required reactive power injections at this bus are 200 MVAr. When this reactive power is installed in the form of a STATCOM or a capacitor bank, the PV curves are improved as shown in Fig. 6. The STATCOM gives better results as compared to the capacitor bank. Adding a shunt capacitor or a STATCOM improves the voltage stability limit not only at Ghard bus but also in other system buses. Fig. 6 indicates an increase in the load parameter value at the critical points of 2017 base case. The loading parameters of the 2017 base case increase to 593.8 MW when a capacitor bank is utilized, and
1000 MW when a STATCOM is utilized.

The voltage support of the STATCOM is fair as its reactive power injection drops with the voltage V. On the other hand, the voltage support of the shunt capacitor bank is relatively poor as its reactive power injection drops with V^2.

B. Summary of Results for Cases 2-4:

The PV and VQ methods are applied to the 2017 system to determine the voltage stability sensitivity factors, bus voltage profiles and reactive power injections for the different several scenarios listed in Table 1. For brevity, the summary of the simulation results is reported in Tables 2-4.

It is noted that the (N-1) contingencies increase the sensitivity factors as shown in Table 2. This means that the voltage stability is negatively affected since the contingencies cause significant amount of reactive power requirement in both systems. The only exception is when the power factor of the wind farm is adjusted such that it injects reactive power into the system. When voltage sensitivity factors in Table 3 are compared to those of Table 4 (or to those of Table 5), it is noticed that the sensitivity factors of all buses decrease. This indicates an enhancement in voltage stability. In addition, when comparing the sensitivity factors of each individual bus, it can be concluded that the most enhancement in voltage stability occurs at Ghard bus. It is an expected result since shunt capacitor is connected to Ghard bus. In fact, it proves the importance of local compensation. Due to the requirement of reactive power in transmission lines, most of the time local compensation is preferred in order to improve voltage stability. The installation of a 200 MVAr STATCOM in the 2017 system at this particular bus provides more MW margin, Figs. 4, 6.

C. Summary of Results for Case 5:

The system response to the disturbance is simulated under a three phase fault in the middle of one line of the two lines connected Ghard and Italgen buses. This line is tripped after the incidence of the fault with simulation time 2 sec. The results of fault show that voltage limits are violated more than the criteria limit whereas voltages values decrease less than value (0.95 p.u.). This can be attributed to the lack of reactive power support in the Canal area, Figs. 7,8. It can be seen that installing 64 MVAr STATCOM enhances the dynamic stability. From these results, it can be concluded that the rating of the installed STATCOM at the weak bus can be determined at 0.95 p.u voltage from the VQ analysis, instead of 200 MVAr STATCOM installed in the steady state analysis at 1 p.u voltage, as shown in Figs. 9, 10. To achieve 1 p.u voltage in the steady state, capacitors can be installed and this will reduce the size of installed STATCOM which will be more economic.

VII. CONCLUSIONS

In this paper, PV and VQ methods, frequently used in voltage stability analysis of power systems, are presented and applied to the Egyptian network. Curves of voltage sensitivity factors (VSF) and bus voltages in the Canal area versus load parameter are obtained for several scenarios of base and contingency cases, by performing power flow calculations using the PSS/E software package. The study showed that with the increase in the penetration level of wind generation in this zone, voltage instability problems could be a major issue due to insufficient reactive power in this area. The effect of reactive power injection is discussed by installing shunt capacitors or STATCOM devices of different values at the weak buses defined in the study system. From results of transient analysis, installing STATCOM enhances the dynamic stability. Addition of these components injects suitable reactive power to the system. Hence, voltage values are within voltage criteria limits and the needed reactive power at the weak point is minimized. By this way, strong and enhanced system can be achieved.

Acknowledgement

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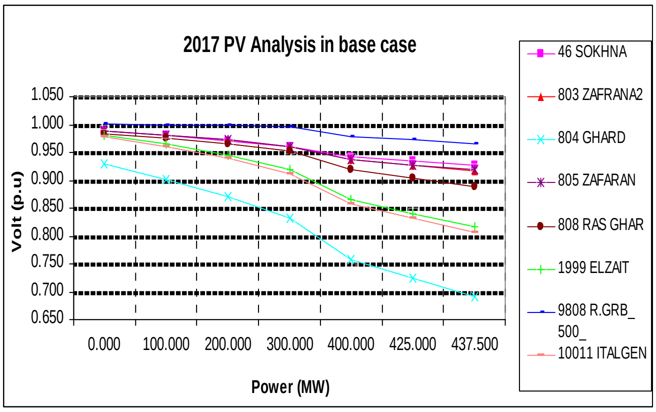


Fig. 4 P-V Curves For 2017 Base Case

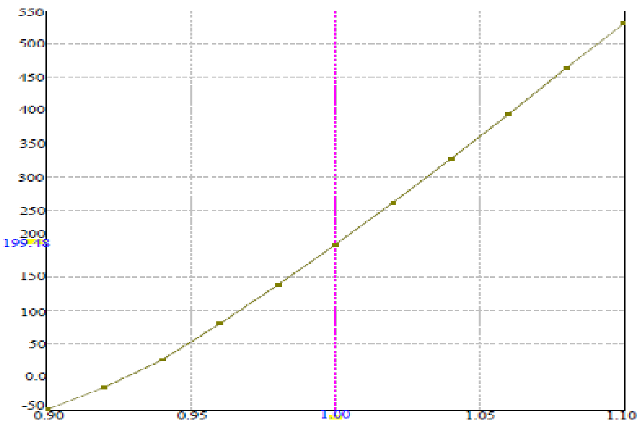
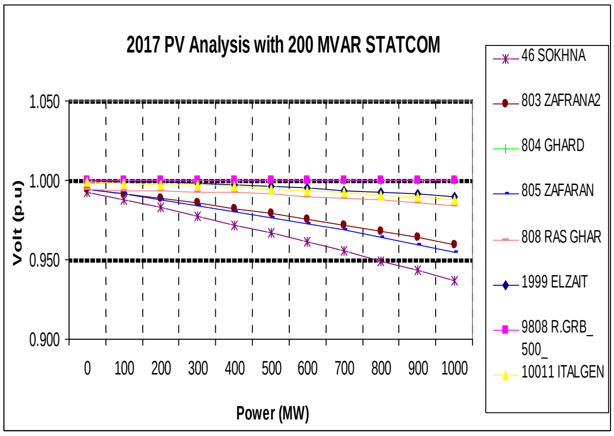


Fig. 5 Reactive Power Requirement to Maintain Ghard Bus Voltage at 1 p.u. – 2017 Base Case



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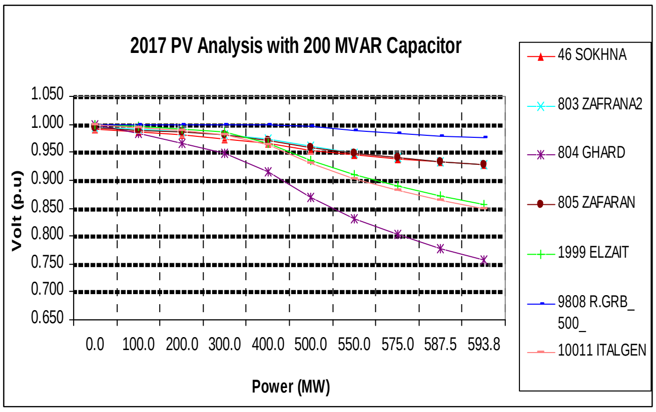

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Fig. 6 P-V Curves For 2017 Base Case with Reactive Power (a) 200 MVAr STATCOM (b) 200 MVAr Capacitor Bank

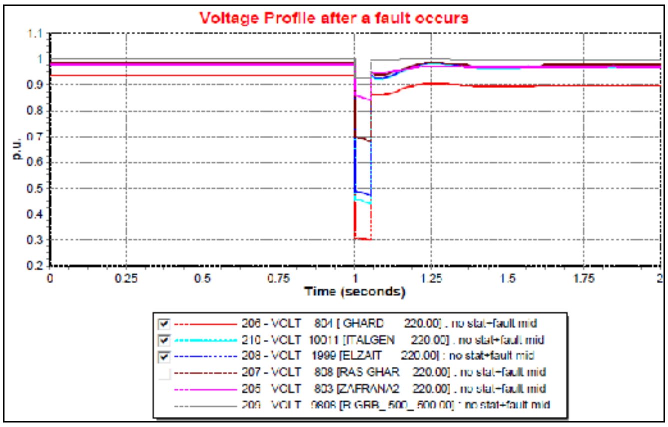

Fig. 7 Voltage Profiles in 2017 in case of a 3 phase fault at one line between Ghard and Italgen buses

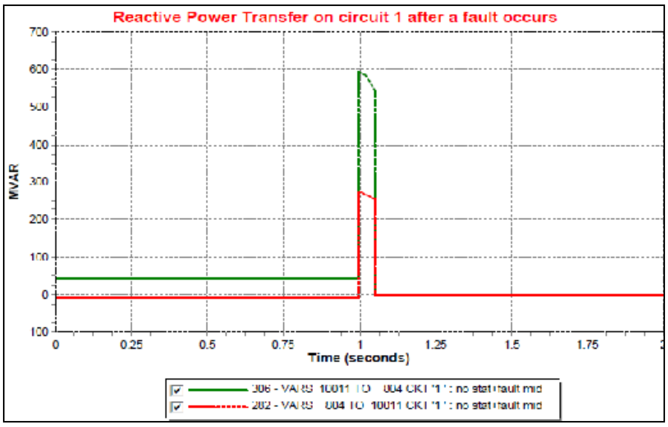

Fig. 8 Reactive Power Flow on one line between Ghard and Italgen buses in 2017 in the case of a 3 phase fault on the other line

Table (2): Aggregated wind farm generation data in 2017

Aggregated Generation	RAS GHAERB 20KV	ITALG EN 22KV	ZAIT 22KV	ZAF 22KV
PGen (MW)	910	90	570	424
Power Factor	0.98	0.98	0.98	1, 0.98
Generator Types	Variable Speed (Type 3,4)	Variable Speed (Type 3)	Variable Speed (Type 3)	Fixed Speed (Type 1,2) Variable Speed (Type 3)
WMOD	2	2	2	2, 3

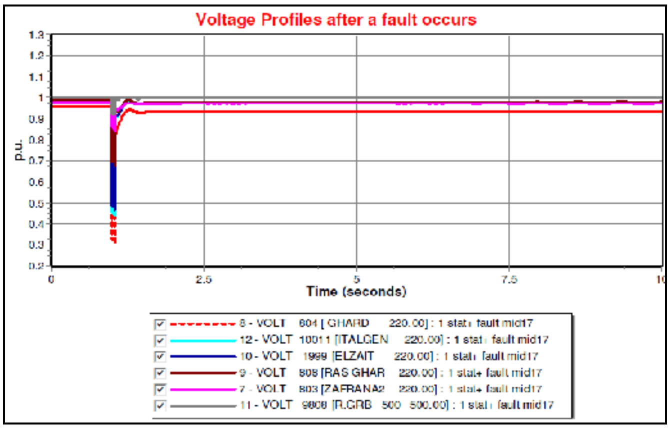

Fig. 9 Voltage Profiles in 2017 in case of a 3 phase fault at one line between Ghard and Italgen buses and 64 MVAr installed STATCOM

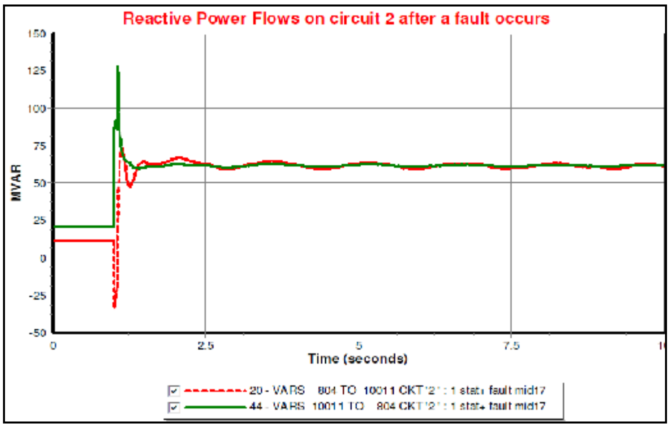

Fig. 10 Reactive Power Flow on one line between Ghard and Italgen buses in 2017 in the case of a 3 phase fault on the other line and 64 MVAr installed STATCOM

Table (3): Voltage Sensitivity Factors for Different 2017 Scenarios with No reactive Power Injection

Year 2017 without reactive power compensation (No voltage improvements							
Bus Number & Name	Voltage Sensitivity Factor │dV/dP│						
	Base case	Disconnect 1 generators	Disconnect 2 generators	Disconnect line 1999-10011	Disconnect line 804-10011	WF Injects MVAr (p.f = 0.85)	WF Absorbs MVAr (p.f = -0.85)
46 SOKHNA	0.00014	0.00016	0.0002	0.00014	0.00018	0.00012	0.00027
803 ZAFARAN2	0.000162	0.00018	0.000226	0.000162	0.00022	0.000136	0.00034
804 GHARD	0.000544	0.00055	0.000614	0.00055	0.00082	0.00043	0.00087
805 ZAFARAN	0.000162	0.00018	0.000226	0.00016	0.00021	0.000134	0.00033
808 RAS GHARB 220KV	0.00022	0.000235	0.00029	0.00022	0.0003	0.00018	0.00048
1999 ELZEIT	0.00038	0.00039	0.00045	0.00037	0.00048	0.00027	0.00069
9808 RAS GHARB 500KV	0.000178	0.000095	0.00013	0.000079	0.00014	0.00011	0.00034
10011 ITALGEN	0.00039	0.00041	0.000463	0.0004	0.0005	0.00029	0.0007

Table (4): Voltage Sensitivity Factors for Different 2017 Scenarios with reactive Power Injection (200 MVAr Capacitor Bank)

Year 2017 with reactive power compensation (voltage improvements) By using Capacitor 200 MVAr							
Bus Number & Name	Voltage Sensitivity Factor │dV/dP│						
	Base case	Disconnect 1 generators	Disconnect 2 generators	Disconnect line 1999-10011	Disconnect line 804 -10011	WF Injects MVAr (p.f=0.85)	WF Absors MVAr (p.f=-0.85)
46 SOKHNA	0.00011	0.00013	0.00016	0.000106	0.00013	0.000101	0.00019
803 ZAFARAN2	0.000113	0.00014	0.00017	0.000113	0.000138	0.000103	0.00023
804 GHARD	0.00041	0.00044	0.00048	0.00042	0.00062	0.00035	0.00062
805 ZAFARAN	0.000113	0.000133	0.00017	0.000113	0.000138	0.000103	0.00023
808 RASGHARB	0.00014	0.00016	0.00019	0.00014	0.000174	0.000124	0.00032
1999 ELZEIT	0.00024	0.00027	0.000312	0.00024	0.000293	0.000186	0.00046
9808 RAS GHARB 500KV	0.000042	0.000054	0.000073	0.000042	0.0000597	0.0000814	0.00023
10011 ITALGEN	0.00025	0.00028	0.000324	0.00027	0.000306	0.000197	0.00048

Table (5): Voltage Sensitivity Factors for Different 2017 Scenarios with reactive Power Injection (200 MVAr STATCOM)

Year 2017 with reactive power compensation (voltage improvements) By using STATCOM 200 MVAR							
Bus Number & Name	Voltage Sensitivity Factor │dV/dP│						
	Base case	Disconnect 1 generators	Disconnect 2 generators	Disconnect line 1999 -10011	Disconnect line 804-10011	WF Injects MVAr (p.f = 0.85)	WF Absorbs MVAr (p.f = -0.85)
46 SOKHNA	0.00006	0.000067	0.000095	0.000056	0.000062	0.000056	0.000084
803 ZAFARAN2	0.000036	0.000044	0.00007	0.000035	0.000044	0.000042	0.000075
804 GHARD	0.000	0.000	0.000	0.000	0.000	0.000	0.000
805 ZAFARAN	0.000039	0.000049	0.000078	0.00004	0.000048	0.000046	0.000077
808 RAS GHARB 220KV	0.00001	0.000014	0.000039	0.00001	0.00002	0.000022	0.000066
1999 ELZEIT	0.00001	0.000011	0.000029	0.00001	0.000027	0.000014	0.000053
9808 RAS GHARB 500KV	0.000	0.000003	0.000034	0.000	0.00006	0.000031	0.00009
10011 ITALGEN	0.000011	0.000013	0.000029	0.00013	0.000028	0.000015	0.000052