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Abstract- **The paper presents voltage and reactive power control in the Main Interconnected Transmission System (MITS) in the Sultanate of Oman. The objective is to improve voltage profile at substations supplying distribution companies and directly connected bulk customer. An objective function is used to maximize reactive power margin of generating units to maintain as much as possible reserves on different generators. The control parameters include existing voltage and reactive power control means, e.g. settings of generators' excitation/AVR, transformer tap-changing, and capacitor bank switching. The constraints include operational limits of the above control devices in addition to allowable limits of busbar voltages, loading of power equipment, and power exchange. The optimal power flow technique is used to determine the optimal settings of the control facilities. The main advantage of this technique is that its implementation does not require any new investments. A model of the MITS is developed and simulation results are presented to show the improvement in voltage profile. Practical measurements of power factor and voltage at substations are also presented to show the improvement in voltage.**

I. Introduction

The load on the Main Interconnected Transmission System (MITS) has been steadily increased with a high growth rate of about 10% during recent years [1], [2]. This has led to low voltage at some remote substations during summer peaks due to increased voltage drop in transmission lines. Studies have been performed to address the voltage issue [3]. The studies include steady-state and dynamic analyses to find short-term and long-term solutions. The short-term solution which is the subject of this paper concerns with the existing reactive power and voltage control means. These include generator excitation and automatic voltage control systems, transformer tap changing devices and capacitor banks switching control. A model of the MITS system is obtained [4] including representation of synchronous generator, units-transformers, transmission lines, grid station transformers with on load tap changers (OLTC), shunt capacitor banks with their switching controllers, and loads. The actual capability curves of the synchronous generators are used to define operational limits.
Optimal power flow is employed to determine the optimal control settings of generator voltages in addition to optimal tap settings of generator step-up transformers, substation step-down transformers, interconnection transformers, and shunt compensation capacitor banks at substations. The optimization process takes into consideration all operational and equipment constraints in addition to transmission security criteria [5] and Grid Code [6] requirements.

Section II describes the optimization process, Section III provides brief description of the MITS of Oman, Section IV describes the studied cases, and Section V presents the results. Section VI lists practical records of power factor and voltage at some substations. Finally, Section VII summarizes the main conclusions.

II. Optimization Process

The optimizations are performed by steady state optimum power flow calculations with the objective to verify that the MITS is able to achieve an adequate voltage profile through adequate generation reactive power injections, in addition to transformer tap-changer and switch on/off of the controllable shunt compensation means. In order to achieve that calculation, the following objective function is programmed in the IPSO OPF tool [7]:

Objective function:
Maximization of the individual reactive power margin of the generating units to maintain as much as possible reserves of reactive power on the different generators. This policy is referred to as "alignment" or maximization of individual reactive reserves. This is realized by the minimization of the generator reactive power deviation with respect to an attractor.

Control variables:
- Reactive power of synchronous generators;
- Status (discrete variables) of the compensation means mainly the 33 kV shunt compensation banks;
- Tap changers position (discrete variables) of all (on and off load, automatic and manual, local and remote);

The optimization of the system will a priori modify slightly the level of the losses. It is therefore needed to free the active power injection of at least one generator. Two generators have been chosen for that purpose. They are located at Barka II and correspond to the steam turbines.

Constraints:
The different constraints imposed to the optimization process reflect the various design and operational criteria:
- Voltage between limits in base case: V_N ±10% in 220 kV and 132 kV, V_N ±6% in 33 kV;
- Generators: MVAr generation must be between minimum and maximum reactive power limits Q_{min} and Q_{max};
- Shunt capacitors: MVAr is allowed to take only the possible discrete values of the number of banks connected.
- Transformer taps: must be between min and max tap

positions.

- Units apparent power must be between 0 and nominal apparent power value S_N ;
- Transfer on branches must remain under their related nominal apparent power values;

The interconnections of the MITS with the external systems are represented by injections of P and Q which are not allowed to change during the optimization process.

III. Transmission System Description

The transmission system extends across the whole of northern Oman and interconnects bulk consumers and generators of electricity located in the Governorate of Muscat and in the regions of Bureimi, Batinah, Dhahirah, Dakhiliyah and Sharquiya [4]. Figure 1 shows a geo-schematic diagram of the main transmission system of Oman. The OETC system model is composed of three voltage levels: 220 kV, 132k V and 33 kV. In general, the lines are fitted with double circuit except for the interconnection with Petroleum Development of Oman (PDO). The substations of 220/132 kV and 132/33 kV present an arrangement of two transformers in parallel. The 33 kV network is operated by the licensed electricity distribution companies, e.g. Muscat, Majan and Mazoon. Only the 33 kV primary substations pertaining to the 132/33 kV transformation are represented in the model. Together with the downstream load, they are represented by an equivalent load model. The bulk of the power transmitted through the main grid, is fed, through 220/132/33 kV, 132/33 kV and 132/11 kV grid stations, to the three distribution licence holders. A number of large private customers are connected directly to the transmission system either at 220 kV or 132 kV. Some customers have their own generation capability on site and can exchange electric power with the main transmission grid. The MITS has been interconnected with the Transco Abu Dhabi transmission system through a double-circuit 220 kV overhead line since November 2011.

IV. Studied Cases

In the simulation studies described in this paper, the MITS model of 2010 is employed to show the low voltage issue at that time. The 220 kV Mahdah-Ibri line, Barka-3 IPP, and Sohar-2 IPP were not exist in 2010. The following four cases have been considered:

Case 1: Intends to verify if the low voltage issues could be solved if the power producers allow the generators to inject reactive power as per their capability curve. The system is optimized as explained in section II and the reactive power limits (Q_{min} and Q_{max}) are set as per the capability curves.

Case 2: Intends to verify if the low voltage issues could still be solved if the power producers keep their policy of injecting limited reactive power. The system is optimized and the max reactive power limit (Q_{max}) is set as per the reactive power injected at the peak load of 2009, i.e. before optimization.

Case 3: Intends to verify if the low voltage issues could be solved if the distribution companies guarantee a load power factor at the 33 kV primary substations of at least 0.95 corresponding to the minimum requirement of the Grid Code. The system is optimized and the load reactive power is modified to achieve a power factor of 0.95. The loads at substations having already a capacitor bank are not modified. The reactive power generation limits (Q_{min} and Q_{max}) are set as per the capability curves.

Case 4: Intends to verify if the low voltage issues could be solved by adding to the system 5 small scale distributed generators connected to the 33 kV voltage level at the substations of: Sur (27 MW), Mudaibi (24 MW), JBB Ali (24 MW), Jahloot (22 MW), Mudairib (18 MW) adding together 115 MW. It should be recognized that the interconnection with UAE is not in operation in2010. The system is optimized and the reactive power generation limits (Q_{min} and Q_{max}) are set as per the capability curves.

In Case 3, the reactive power maximum limit has been determined based on the system snapshot of the peak 2009, i.e. before applying optimization. When available, the gross value of the injected reactive power has been used otherwise it was considered that the injected reactive power corresponded to 120% of the net value, taking into account the losses in the step-up transformer.

Indeed, only the capacitors located in the 33 kV substations directly connected to the 132 kV transformers are under the control of OETC LDC. Primary substation capacitors (all the other distribution substations) are controlled automatically. In particular, for primary substations equipped with 1, 3 and 6 MVA transformers (with off-load tap changers), the control is based on the voltage. In these substations, if the voltage level is acceptable at the peak, not all the capacitor steps are in service, even if the power factor does not reach the minimum required value of 0.95.

Globally, due to the present reactive power management in force, there exists potentially a certain reactive power capacity at the distribution level that is unused at the system peak. In the assumption that the distribution companies can align the total reactive power capacity of the capacitors (including capacitors connected at 11 kV), it should be possible to get nearer to (or possibly to reach) the grid code objective of a 0.95 power factor in all 33 kV primary substations. The new value of the load reactive power was calculated assuming that a necessary amount of capacitive reactive power would be added at the primary 33 kV substations to compensate the load to a power factor of 0.95. The difference of 475 MVAr corresponds to the minimum necessary to achieve the required power factor. However this value is not discretized in terms of capacitor banks with a specific number of steps and MVAr/steps. By doing so, the amount of reactive power capacity required would increase.

V. Results

A. Minimization of Reactive Rower Ranges

The generation reactive power margin is important in order to prevent the operation near to under- or over- excitation limits, coping as much as possible with system voltage instabilities whether in capacitive (normally light load) or in inductive system (normally peak load) operation.

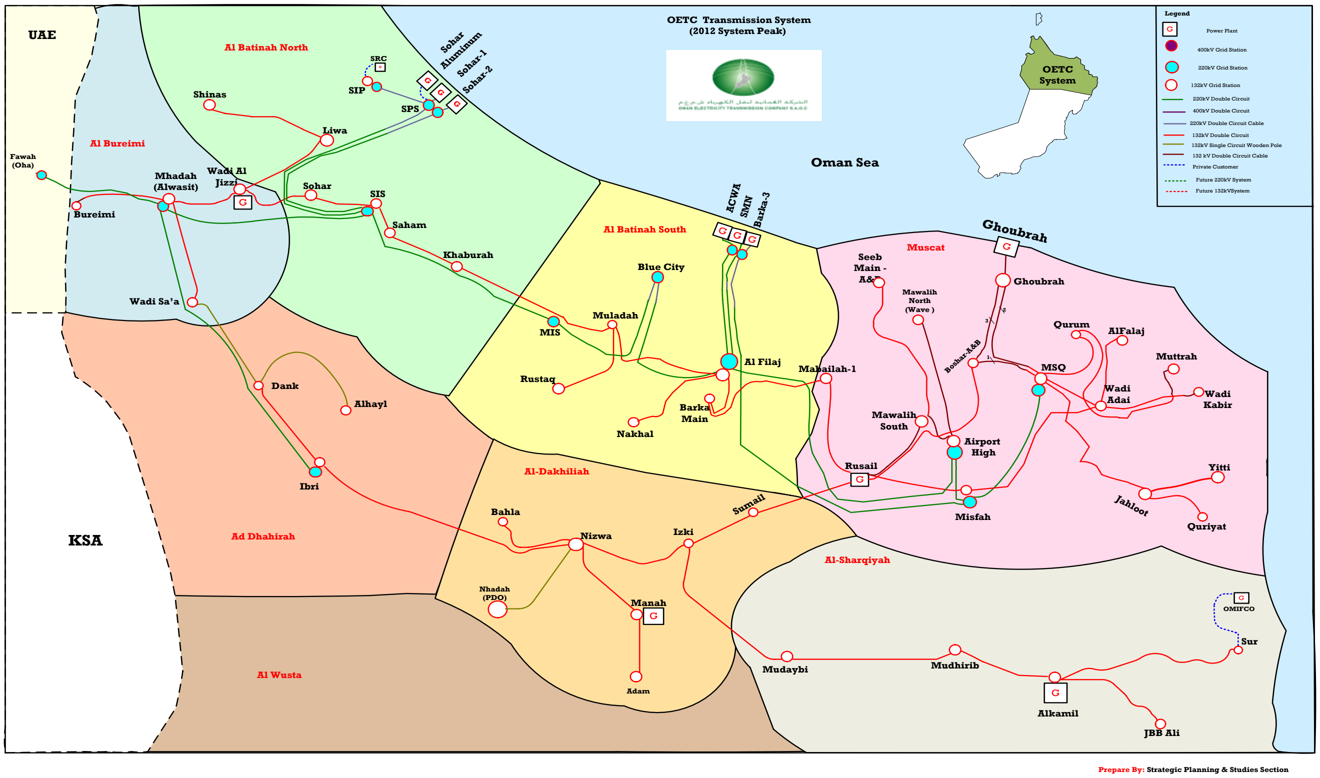

Fig. 1. Geo-schematic diagram of the main transmission system of Oman in 2012

A preliminary analysis has shown that in the initial load flow (before optimization) the generators had no suitable reactive power alignment: some generators had large reactive margins when others were reaching their maximum limit.

Normal conditions

The main result from the optimization process is the alignment of the reactive power injected by each generator around a given attractor, respecting the operating constraints (voltage and flow limits).

Analysis of Case 1 and Case 2

For Cases 1 and 2 the attractor has been set to 65% of the reactive power range. This value is below the average of the generators reactive loading found in the initial load flow and it is justified as it gives a reasonable margin of reactive power injection or absorption in case needed. The results from the optimization confirm that in steady state, the system is able to operate while respecting all operating constraints. The voltage profile is improved with respect to the initial load flow (green curve) in all voltage levels and no substations present voltage out of the acceptable limits as shown in Figure 2. The results from the optimization also confirm that it is possible to align most of the generators between 65 and 80% of the reactive power range. Figure 3 and Figure 4 present the reactive power injected by each generator in the initial load flow before optimization (in green), after the optimization with the reactive power generation limited as per the capability curves (Case 1 in red) and after the optimization with the reactive power generation limited as per the 2009 reference records (Case 2 in blue). The first conclusion that can be drawn is that it is possible to achieve an acceptable operating point independent of the reactive power limits imposed to the generators. In fact, the optimization process found a set of parameters (transformers taps and capacitor bank steps) that succeed to align the generators reactive power to the minimum possible. The result is that the reactive power that each generator should inject is considerably below the imposed limits and therefore Cases 1 and 2 present similar final results.

The results can be analyzed by groups of machines as follows. The power stations situated in the Batinah North and Bureimi regions (Wadi Jizzi, Sohar and Sohar Aluminium) are aligned between 60% and 70% of the reactive power range as the local needs in reactive power are not too important. Barka, Rusail and Ghoubrah that are situated in the Muscat and Al Batinah regions, where is also situated the most important consumption center, are not able to align around 65% of the reactive power range but find their optimal settings around 80% of the reactive power range. The power stations situated in Dakhiliah and Sharquiyah region (Al Kamil and Manah) are close to 90% of the reactive power range, showing that the only way to keep the substations in the vicinity with an acceptable voltage is by injecting a considerable amount of reactive power. As a final result for Cases 1 and 2, the optimization of the system operation leads to an increase of the reactive power margins of 270 MVAr and a reduction of losses of 11.1 MW and 223 MVAr with respect to the initial load flow.

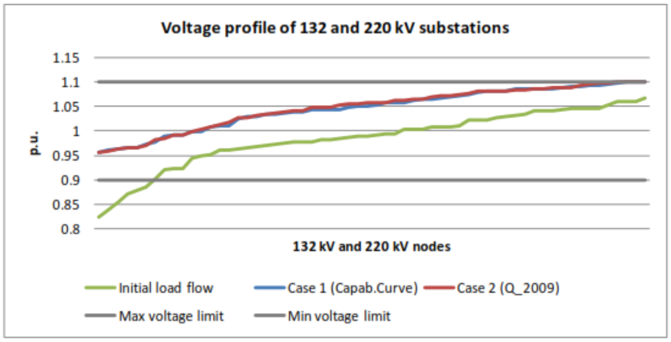

Fig. 2. Voltage as a function of accumulated number of nodes (Cases 1&2)

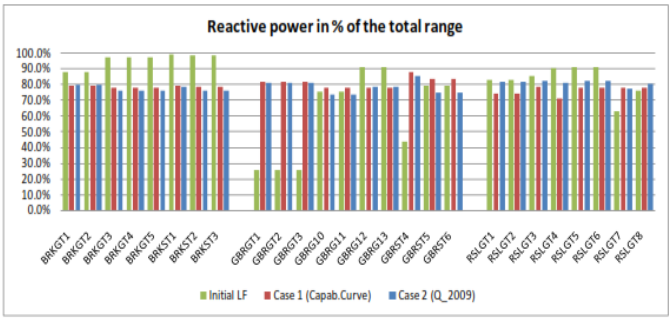

Fig. 3. : Reactive power of generators - part 1 (Cases 1&2)

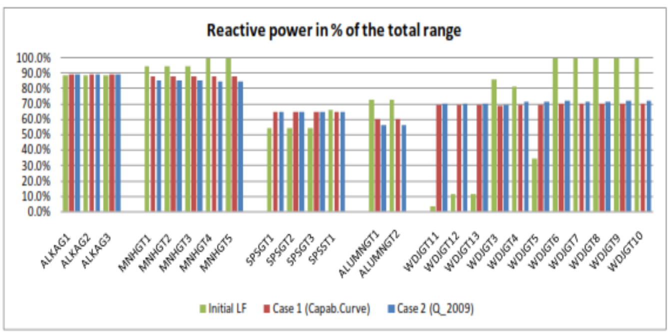

Fig. 4. Reactive power of generators - part 2 (Cases 1&2)

Analysis of Case 3

For Case 3 the attractor has been set to 55% of the reactive power range. This value is justified in a tentative to increase even more the generators reactive power margins once that reactive power means have been "put in action" at the distribution level to compensate the load to a power factor of 0.95. The results from the optimization confirm that in steady state, the system is able to operate while respecting all operating constraints. The voltage profile is improved with respect to the initial load flow (green curve) in all voltage levels and no substations presents voltage out the acceptable limits. The voltage profile of the 132 kV and 220 kV substations is presented in Figure 5. The results from the optimization also confirm that it possible to align most of the generators between 55 and 75% of the reactive power range. Figure 6 and Figure 7 present the reactive power injected by some generators in the initial load flow before optimization (in green) and after the optimization with the load compensated to a power factor of 0.95 (in purple).

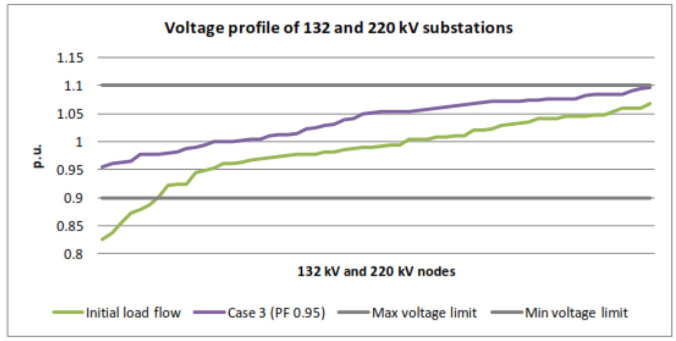

Fig. 5. Voltage as a function of accumulated number of nodes (Case 3)

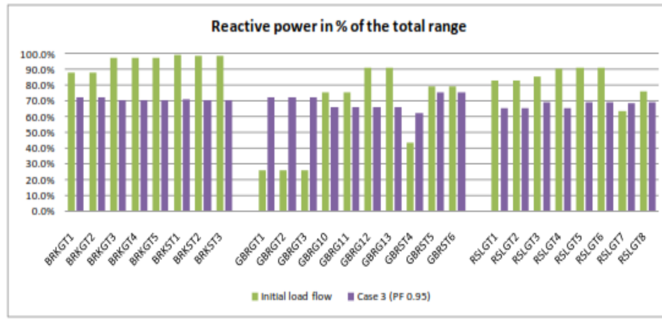

Fig. 6. Reactive power of generators - part 1 (Case 3)

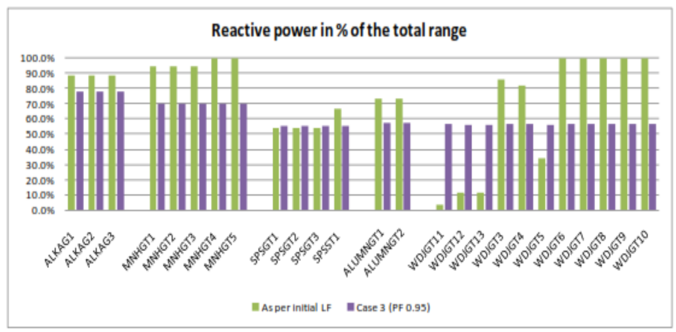

Fig. 7. Reactive power of generators - part 2 (Case 3)

The first conclusion that can be draw is that it is possible to achieve an acceptable operating point and increase the generators reactive power margins when compensating correctly the load. When analyzing by groups of machines, again the geographical location plays its role as follows. Wadi Jizzi, Sohar and Sohar Aluminium are easily aligned around 55%. Barka, Rusail and Ghoubrah, are not able to align around 55% but find their optimal around 70%. Manah and Al Kamil are aligned to 70% and 78% respectively. As a final result for Case 3, the optimization of the system operation leads to an increase of the reactive power margins of 795 MVAr and a reduction of losses of 14.7 MW and 293 MVAr with respect to the initial load flow.

Analysis of Case 4

Case 4 is similar to Case 1 with two main differences: (i) the addition of some distributed generators, (ii) the fact that the interconnection with UAE was not be in operation. The DGs are contributing with their nominal active power capacity.

The difference in reactive power will be rearranged by the optimizer among all the generators. In general the difference of active and reactive power capacity in the system did not change between Case 1 and Case 4, the attractor for Case 4 has also been set to 65% of the reactive power range. The results from the optimization confirm that in steady state, the system is able to operate while respecting all operating constraints. The voltage profile is improved with respect to the initial load flow (green curve) and it is similar to the results of Case 1. No substations present voltage out of the acceptable limits in all voltage levels. The voltage profile of 132 kV and 220 kV substations is presented in Figure 8.

The results from the optimization also confirm that it is possible to align all the generators between 65 and 85% of the reactive power range. When comparing Case 1 to Case 4 it is possible to observe that the generators of Wadi Jizzi, Sohar and Sohar Aluminum become a bit more loaded in Case 4 due to the lack of reactive power. It is also observed that the generators of Al Kamil and Manah become less loaded in Case 4 due to the additional DGs in the area of Sharquiya. The first conclusion that can be drawn is that it is possible to achieve an acceptable operating point without the contribution of the interconnection with UAE without major impacts on the reactive loading of the machines in the vicinity. In addition, the contribution in active and reactive power from the DGs alleviates the loading of the most critical power plants (Al Kamil and Manah). When analyzing by groups of machines, it can be seen that: Sohar and Sohar Aluminium are aligned around 65%, however Wadi Jizzi is aligned to 75%; Barka, Rusail and Ghoubrah, are not able to align around 65% but find their optimal between 70 and 80%; and Manah and Al Kamil are aligned around 80%. As a final result for Cases 4, the optimization of the system operation leads to an increase of the reactive power margins of 386 MVAr and a reduction of losses of 19.2 MW and 315.7 MVAr with respect to the initial load flow.

In a preliminary basis, it can be conclude that the four optimized cases improved the voltage profile over the whole network avoiding any substation to have voltages under the acceptable limits. Also, with the policy of generators reactive power alignment is was possible to increase their margins and reduce the system losses, as can be seen in Figure 9 and Figure 10. It was possible to observe that there are regions where the reactive power is more necessary to keep the voltage inside the acceptable limits as it is the case for Manah and Al Kamil.

Voltages not compliant to N-1 criterion

The four optimized system operating points are compliant to N-1 for almost all incidents considered here, for what concerns under voltage limits. In fact, there are five incidents that lead to low voltages at some 132 kV substations in the vicinity of Al Kamil. The loss of units 4 or 5 of Manah and the loss of one unit of Al Kamil are critical contingencies as they reduce the amount of reactive power in the south region making it harder to keep the voltage inside the acceptable limits. In Case 1 and 2, these incidents lead to the system voltage collapse and should be better analyzed in a dynamic simulation. In Case 3, these incidents lead to low voltages.

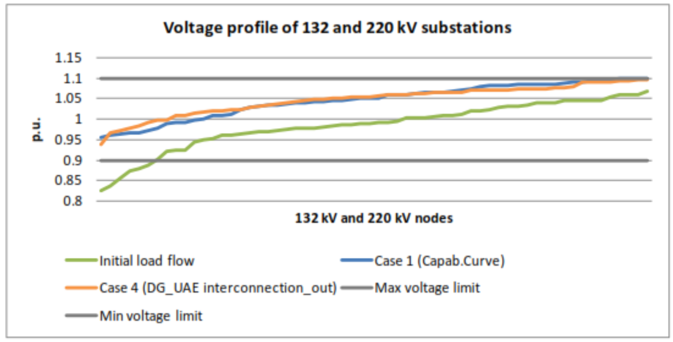

Fig. 8. Voltage as a function of accumulated number of nodes (Cases 1&4)

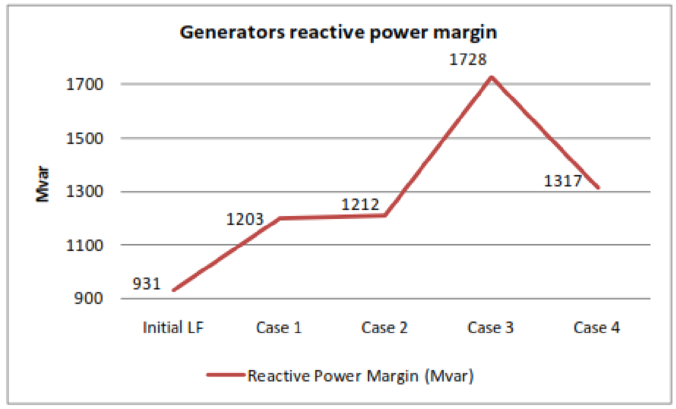

Fig. 9. Generators reactive power margin

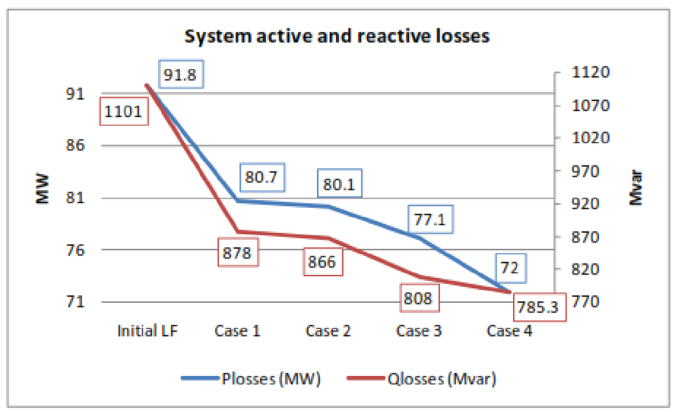

Fig. 10. System active and reactive losses

In Cases 1 and 2, the loss of one circuit of the double circuit lines connecting Al Kamil to Sur or to JBB Ali leads to low voltages at the ending substations as the losses increase and not enough reactive power reaches these substations. The same behavior happens with the loss of one circuit of the double circuit lines connecting Izki to Mudaybi. In Case 4, the problems of voltage collapse disappear due to the support of the DGs installed directly to the 33 kV voltage level supplying active and reactive power in the most critical areas of the system. It should be noted that the introduction of the new 2000 MW Sur IPP and associated 400 kV transmission lines in 2013-2014 will completely remove this low voltage issue in the MITS system.

VI. Practical Measurements

The following table lists the improved power factor recorded at some substations during the day of the last summer peak load (25 July, 2012). Figure 11 and Figure 12 show the measured voltage at some substations during the same peak load day. Clearly, the voltage profile has been significantly improved by implementing the optimum voltage and reactive power control settings.

TABLE I: MEASURED POWER FACTOR AT SOME SUBSTATIONS

Time	Substation					
	Falag	**Bousher**	**Sohar**	**Liwa**	**Rustaq**	**Sur**
0:00	0.94	0.98	0.99	0.94	0.97	0.94
1:00	0.95	0.99	0.99	0.94	0.98	0.94
2:00	0.95	0.99	0.99	0.94	0.98	0.94
3:00	0.95	0.99	0.99	0.94	0.98	0.94
4:00	0.94	0.99	0.99	0.95	0.98	0.94
5:00	0.94	0.99	0.99	0.94	0.98	0.94
6:00	0.95	0.99	1.00	0.95	0.97	0.95
7:00	0.94	0.99	1.00	0.95	0.98	0.95
8:00	0.93	0.99	1.00	0.95	0.98	0.95
9:00	0.93	0.99	0.99	0.94	0.98	0.95
10:00	0.93	0.98	0.99	0.94	0.98	0.95
11:00	0.91	0.98	0.99	0.94	0.98	0.94
12:00	0.91	0.98	0.99	0.93	0.98	0.94
13:00	0.92	0.98	0.99	0.94	0.98	0.93
14:00	0.92	0.98	0.99	0.94	0.98	0.92
15:00	0.93	0.98	0.99	0.94	0.98	0.94
16:00	0.93	0.98	0.99	0.93	0.98	0.92
17:00	0.93	0.98	0.99	0.94	0.98	0.94
18:00	0.94	0.98	0.99	0.94	0.98	0.97
19:00	0.93	0.98	0.99	0.94	0.98	0.94
20:00	0.94	0.98	0.99	0.94	0.97	0.92
21:00	0.93	0.98	0.99	0.94	0.97	0.92
22:00	0.93	0.98	0.99	0.94	0.97	0.92
23:00	0.94	0.99	0.99	0.94	0.97	0.93

VII. Conclusions

The calculations show that it is possible to achieve an acceptable operating point for the system in the steady state, independent of the reactive power limits imposed to the generators either capability curves or the practices of 2009 (before optimization). The optimal operating point is defined by a set of consistent settings (generator voltage set-points, transformer taps, and capacitor bank steps).

Compared to the old practice, the optimization of the system operation in all studied cases improves the voltage profile over the whole network (33 kV, 132 kV and 220 kV substations), avoiding any substation to have voltages under the acceptable limits in normal operation.

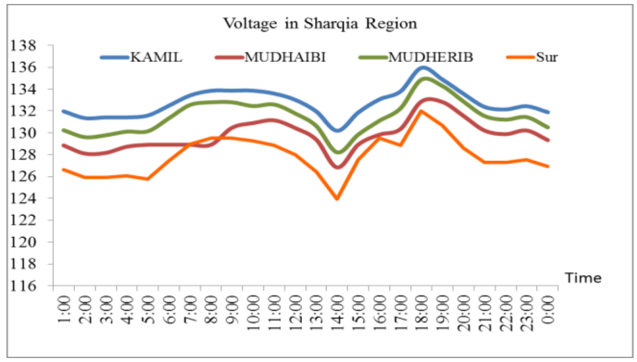

Fig. 11. Voltage in Sharqia during the 2012 summer peak load day

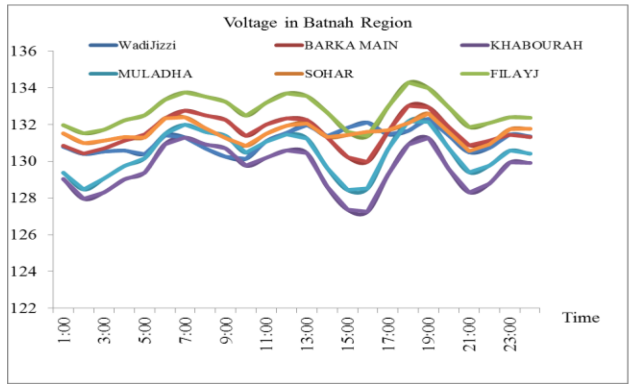

Fig. 12. Voltage in Batinah during the 2012 summer peak load day

The optimal operation policy enables also to increase the reactive power margins of the generators and to reduce the system losses. If the power factor is maintained at least at the 0.95 level corresponding to the Grid Code objective, the optimal policy could lead to an increase of the reactive power margin on generators and reduction in the active and reactive losses. The recorded power factor and voltage at substations during the 2012 summer peak load day prove the validity of the simulation results.

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