Voltage Stability Improvement and Transmission Loss Minimization for a 5-Bus Oman System based on Modal Analysis and Reactive Power Compensation

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Abstract:- The aim of this paper is to proposed a method to analyze and improve a technique to find out the ideal amount of reactive power as a compensation in order to reduce the power loss in electrical system and as well to develop voltage magnitude profiles. The first step is to calculate the required amount of reactive power and then it is injected to each load bus. Additional analysis is implemented in order to inject that amount of reactive power into certain buses. The proposed algorithm is implemented in Matlab for 5-Bus Oman selected grid and the obtained results are closed to that data which provided by Oman Electricity Transmission Company which helped to verified.

***Keywords**:- OETC, Oman Electricity Transmission Company. NR, Newton-Raphson load flow algorithm. RPC, Reactive Power Compensation.*

I. INTRODUCTION

There are various of techniques for reactive power compensation which help to improve and develop the operation of AC power systems, and this is called as the management of reactive power. The idea of reactive power management can help to solve system and end users' problems, especially those affecting power performance and quality. There are two sides which should be considered in RPC management; load compensation and voltage controllers (support). There are three objectives of load compensation which can be summarized as; compensation of voltage regulations, removal of current harmonic which produced by large loads and balance of real power. Voltage fluctuations at any terminal in power system can be manage by voltage controllers (support). The performance of power systems can be sustained and managed by using reactive power tools which will increase the transmission of real power. By maintaining the voltage profiles at all transmission levels, the performance of power systems will get better [1]. Therefore, the consumers can get better quality of power by good management of load bus voltages with their limits.

It is obvious from above that a concept of working on simple and useful ways to calculate the additional required reactive power RPC to maintain the voltage profiles and reduce the power loss in Oman 5- bus system.

II. REACTIVE POWER COMPENSATION STRATEGIES

In ideal power system, the power factor can be kept at unity with a constant voltage and frequency at any AC source and as well no harmonic. The power supply quality can be evaluated by the constancy of the voltage supply and frequency. The mentioned parameters cannot be affected by the end users loads. Moreover, consumer load could be manufactured to work at certain performance with various voltage range [2]. The possibility of interference between loads can be reduced by the current fluctuations.

A good quality of power supply and voltage levels with the threshold could be produced in well-designed power system. By keeping the sending terminal voltage as constant in power system grid, the end terminal (receiving load) can be influenced by fluctuations come from the magnitude and power factors only. If there is a large load, there will be smaller power factor and high variations in voltage. The variations in voltage represent unbalanced of reactive power which has been provided by certain source and used at load. If there is extra reactive power has not been consumed, there will be an increase in voltage and vice versa [3]. Thus, when there is voltage variations higher than threshold at any bus, it gives an indication of the instability of reactive power at that bus.

To make it more clear will take 2-bus system as an example as shown in fig.1, bus-2 is to be considered as load bus;

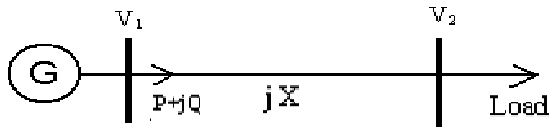

Fig 1:- Two-bus example system

The following three aspects are taken in account for aim of analysis:

- Keeping the V1 as a constant (by regulating the excitation in generator);
- Considering V1 as reference; and
- Because the resistance of line is negligible, so the transmission line is considered purely inductive.

So the following equations can be applicable:

$$V_2 = V_1 - IZ$$

$$V_1^* I = P - jQ \quad (1.1)$$

The line power is represented by (P +j Q), so the line current (I) will be given as:

$$I = \frac{P - jQ}{V_1^*} \quad (1.2)$$

Since, $V_1^* = V_1$, and V1 is the reference vector,

$$V_2 = V_1 - \left[\frac{P - jQ}{V_1}\right] jX \quad (1.3)$$

By making (1.3) more simplified, the V2 is obtained as:

$$V_2 = V_1 - \left[\frac{X}{V_1}\right] Q - j\left[\frac{X}{V_1}\right] P \quad (1.4)$$

The equation (1.4) can be shown as phasor diagram (see Fig.2).

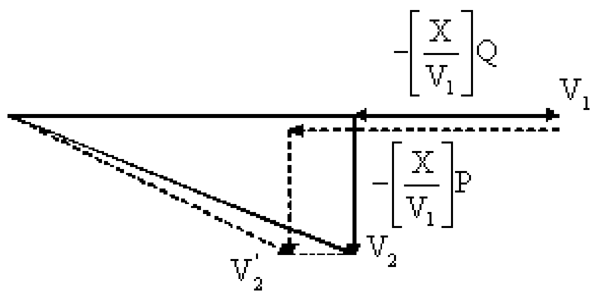

Fig 2:- Phasor diagram for load voltage

The analysis can be reached from Fig.2 is as following:

It can be seen that load P is perpendicular to the vector V1, hence there is a minor influence on V2; and any change at load Q, will affects the voltage drop phasor, which is in phase with V1. It is obvious that there is a proportional relationship between V2 and Q and the dotted line in figure 2 shows if there is change in V2 will affect the reactive load.

Assuming a negligible voltage drop due to real power, equation (1.4) can be simplified thus:

$$V_2 = V_1 - \left[\frac{Q}{V_1}\right] X \quad (1.5)$$

For a certain source voltage V1 and in order to keep voltage V2 as constant at particular destination, the ratio QX/V1 must be stationary and that ratio is called drop factor. It is clear that the only Q is changeable, therefore to ensure the constancy, reactive power need to be managed and controlled at loads.

From (1.5), there is another solution in order to keep V2 as constant for fixed V1 which is using series capacitances which will reduce the whole system's reactance [4].

III. DEVELOPMENT OF PROPOSED ALGORITHM

In order to get the expression for required amount of reactive power, load flow and line flow need to be discussed;

Load flow expression [5-6]: a certain system consists of number (n) of buses and have a magnitude V_i, and δ_i (phase angle) for a particular bus (i). so the complex power could be injected at that bus (i) can be given by:

$$S_i = P_i + jQ_i = (V_i I_i^*) \quad (1.6)$$

Then the underneath equation represents the performance of the system in terms of admittance;

$$I_{Bus} = Y_{Bus} V_{Bus} \quad (1.7)$$

Where I_{BUS}, V_{BUS} are the bus' current and voltage vectors and Y_{BUS} is the bus admittance matrix; From (1.7), for 'n' bus system, the current at bus i can be represented as:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad (1.8)$$

Using (1.8) in (1.7), the complex power at bus i, is shown by:

$$S_i = P_i + jQ_i = \sum_{j=1}^{n} \left| V_i V_j Y_{ij} \right| e^{j(\delta_i - \delta_j - \theta_{ij})} \quad (1.9)$$

Where $Y_{ij} = |Y_{ij}| \angle \theta_{ij}$ and δi and δ_j are the phase angle of voltages at bus-i and bus-j respectively. So the load flow equation can be indicated as below;

$$P_i = \sum_{j=1}^{n} |V_i V_j Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \qquad \text{For } i = 1, 2, 3 \ldots\ldots n \qquad (1.10)$$

$$Q_i = \sum_{j=1}^{n} |V_i V_j Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \qquad \text{For } i = 1, 2, 3 \ldots\ldots n \qquad (1.11)$$

Line flow equation [7]: the buses parameters need to be calculated first and then the line flows are calculated, the equation below gives the current flow from bus i to j;

$$I_{ij} = (V_i - V_j)Y_{ij} + V_i \frac{Y'_{ij}}{2} \qquad (1.12)$$

Where Yij is the admittance of line i-j and Y'_{ij} is its total line charging admittance. Thus, the power flow between bus' i and j are given by:

$$S_{ij} = P_{ij} + jQ_{ij} = V_i\left[(V_i - V_j)Y_{ij}\right]^* + V_i V_i^* \frac{Y'^*_{ij}}{2} \qquad (1.13)$$

$$S_{ji} = P_{ji} + jQ_{ji} = V_j\left[(V_j - V_i)Y_{ij}\right]^* + V_j V_j^* \frac{Y'^*_{ij}}{2} \qquad (1.14)$$

The loss in line i-j could be calculated by addition between (1.13) and (1.14), therefore the total system's loss can be calculated easily.

NR load flow algorithm [8]: by using the jacobian matrix for the Newton-Raphson load flow algorithm; the underneath matrix (1.16) will be reached

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \qquad (1.15)$$

$$= \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \qquad (1.16)$$

As shown above, ΔP represents the change in real power, ΔQ indicates the change in reactive power, Δδ value is the change in voltage angle at the bus, ΔV is the change in voltage profile or magnitude and the matrices J1-J4 represents the Jacobian matrix.

Required reactive power [9]: after load and line flow analysis with followed by NR method the required amount of reactive power can be obtained. In order to investigate the influence of reactive power in the system's stability, the ΔP needs to be considered as zero and getting the Q-V sensitives for different conditions of operations. Then, the matrix (1.16) can be rewritten as:

$$0 = J_1 \Delta\delta + J_2 \Delta|V| \qquad (1.17)$$

$$\Delta Q = J_3 \Delta\delta + J_4 \Delta|V| \qquad (1.18)$$

By substituting $\Delta\delta = -J_1^{-1} J_2 \Delta|V|$ in (1.18), the expression for required reactive power can be obtained as;

$$\Delta Q = \left[-J_3 J_1^{-1} J_2 + J_4\right] \Delta|V| \qquad (1.19)$$

IV. METHODOLOGY

In this proposed technique to get the required reactive power in selected 5-Oman grid, the difference between the aiming voltage magnitudes and voltage which calculated in base case-load flow is determined first in order to see the changes in voltage magnitudes in each load buses. Then, the change in reactive power is calculated for each load bus by using the equation (1.19). the calculated reactive power can be injected at each load bus in different combinations in order to reach desired voltage profiles and reduce real power loss as well. The following steps need to be performed in sequence;

1. Base-case load flow is calculated first, by using NR method;
2. Load voltages, power losses and reactive power limits are obtained and help to check the system performance. After checking the findings, if there is need to manage VAr compensation, so proceed to next step.
3. Using Jacobian matrix for NR method;
4. It is assumed that there is no change in real power (zero) and voltage magnitudes are unity, then the changes in load buses voltages are found;
5. Find the changes of required reactive power for each load bus;
6. Required reactive power for each load bus is modified; then
7. Line flow and load flow analysis is performed again and shift to step 2.

V. RESULTS AND DISCUSSION

Figure 3 below shows the 5-Bus system which is select by OETC where there is some voltage drop issues as appear in company annual report. It consists of two power stations and three load buses. Rusail (1) and Manah (2) power stations are considered as slack bus and generator bus respectively. Nizwa (5), Sumail (3) and Izki (4) are load buses. The bus and line data are shown in table 1 & 2 as given by company.

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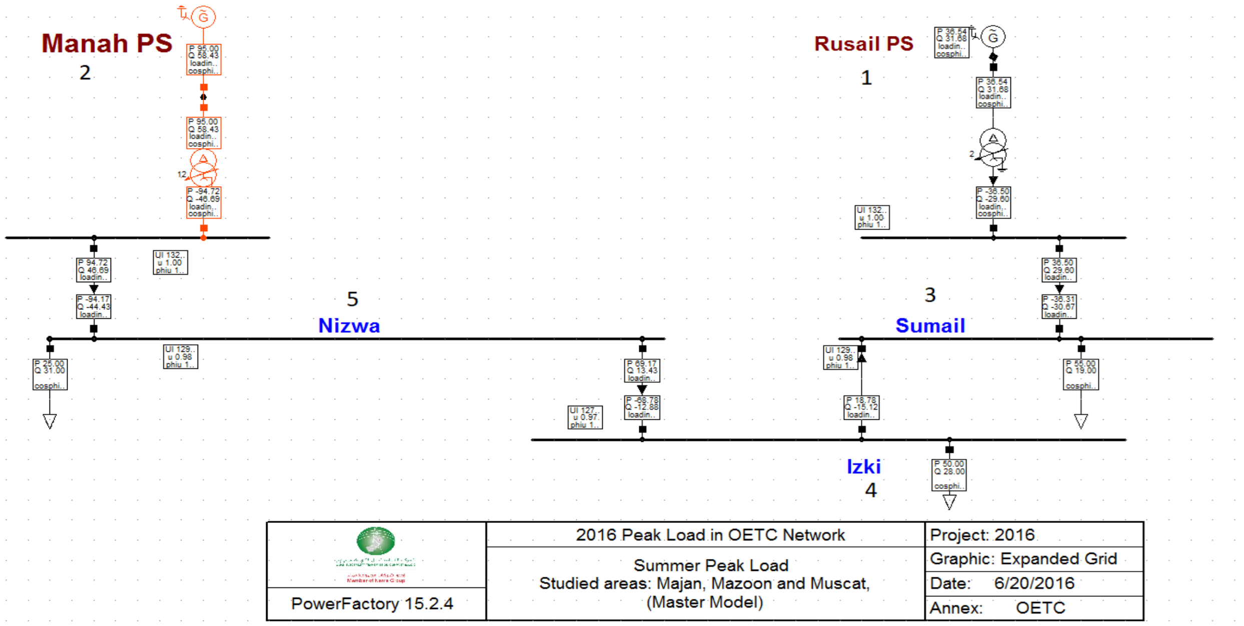


Fig 3:- 5-Bus Oman System [OETC]

Line No.	Bus Number		Length (km)	Total Impedances Ω/Length(km)		Total Impedances p.u/ Length(km)		Half line charging Admittance p.u	Tap ratio
	From	To		R	X	R	X	B/2	-
1	1	3	34.5	1.477	9.732	0.00848	0.05585	0.02392	-
2	3	4	60.8	2.604	17.151	0.01494	0.09843	0.04216	-
3	4	5	31	1.327	8.7451	0.00762	0.05018	0.02149	-
4	5	2	20	0.8566	5.642	0.00491	0.03238	0.01386	-

Table 1:- Line Data

Bus No.	Voltage		Generation		Load	
	V (pu)	Θ (deg)	P (MW)	Q(MVAR)	P (MW)	Q(MVAR)
1	1.00	0				
2	1.00	-	95	-	-	-
3	1.00	-	-	-	55	19
4	1.00	-			50	28
5	1.00	-			25	31

Table 2:- Bus Data

The analysis takes three various cases in order to reach the goal of this paper and results with description and observations are shown below:

➢ *CASE-1:*

As we can see in table 3, After the load flow analysis is implemented in Matlab for the selected network as shown in fig 3, the results for base case is found and power losses is **1.183** MW. The green cells in table 3 shows the voltage magnitudes for three load buses in p.u and could be converted in real unit (Kv) by multiply by 132 Kv which represent the rated voltage for power stations. After calculations, 129.624 kv for both bus Sumail and Nizwa and 128.172 kv for bus Izki. The red cell in table 3 shows the required reactive power need to injected on each load bus (totally = 84.08 MVAr) which will help to sustain voltage magnitudes at each load bus and the results are shown in table 3(case-1). In addition, the percentage of saving of the real power is much higher and reached 16.145%. As seen from obtained results, the proposed technique is more efficient and simple.

The obtained results are validated by the given results from Oman Electricity Transmission Company (OETC) as shown in appendix [A]. Table-4 illustrates the comparison between the both results and obviously the percentage of real power loss in proposed method is less than in DIGSILENT software.

Load Bus No.	Additional VArs Required to be Injected (MVAr)	Bus Voltages as per NR load flow analysis (p.u.)		
		Base Case load flow results	Proposed (Case-1)	Proposed (Case-2)
-	-	1.000	1.000	1.000
-	-	1.000	1.000	1.000
3	20.90	0.982	1.000	1.002
4	29.78	0.971	0.999	0.999
5	33.40	0.982	1.000	0.998
Real power loss (MW)		**1.183**	**0.992**	**1.000**
Saving as compared to base case		*Saving MW units*	0.191	0.183
		Saving Percentage	16.145%	15.47%

Table 3:- Results for the Proposed Method - 5-Bus Oman System

Bus No.	Bus Voltages as per NR load flow analysis (p.u.)	Bus Voltages as per DIGSLIENT
	Base Case load flow results	Voltage in p.u.
1	1.000	1.000
2	1.000	1.000
3	0.982	0.98
4	0.971	0.97
5	0.982	0.98
Real power loss (MW)	1.183	1.260

Table 4:- Comparison Results for Proposed Method - 5 Bus Oman Systems with Oman Electricity Transmission Company Results

➢ *CASE-2:*

In this case the required reactive power (84.08 MVAR) is injected equally on all three load buses and the results obtained as appear in table 3 above (case-2). It is obvious that the power loss is less than in base case but higher than in case-2, in addition the power saving percentage is less than in case-1 and the difference is 0.678%.

➢ *CASE-3:*

In this case, two various ways has been used to inject the required reactive power in load buses 3-5.

a. Total required reactive power (Q_{Total}=84.04 MVAr) is injected on any pair of load buses at same time and the results are as shown in table 5; and
b. Total required reactive power (Q_{Total}=84.04 MVAr) is injected on any pair of load buses at same time in ratio of 2:1 and the findings in table 6.

Load buses at which VArs (=QTotal/2) is injected	Total real power loss (MW)	Saving realized (MW)	Saving Percentage compared to base case value = 1.183 MW
Bus-3 & bus-4	1.078	0.105	8.875%
Bus-3 & bus-5	1.040	0.143	12.08%
Bus-4 & bus-5	1.018	0.165	13.95%

Table 5:- Total VArs injected into a pair of load buses at a time

Load bus at which VArs (=2:1) is injected	Total real power loss (MW)	Saving realized (MW)	Saving Percentage compared to base case value = 1.183 MW
Bus-3 & bus-4	1.116	0.067	5.66%
Bus-3 & bus-5	1.093	0.09	9.00%
Bus-4 & bus-5	1.044	0.139	11.74%

Table 6:- Total VArs injected in a 2:1 ratio to a pair of load buses at a time

As it obvious from table 5 & 6, the highest saving percentages in both cases happened at bus 4 and bus 5 which reached 13.95% in case-3(a) and 11.74% in case-3 (b), and as well for the power loss is lowest for the same buses in both cases. Comparing to case-1, the saving percentage is still higher as well for power loss is better in case-1.

VI. OBSERVATIONS

Based on the results obtained for the proposed systems under different scenarios, it is apparent that the voltage profile of the system is appreciably improved by compensation of the required load buses. The effectiveness of the results obtained as based on the proposed method is evident from Fig 4. and a comparison of the voltage profiles for the proposed method and the Oman Electricity Transmission Company's (DIGSILENT) [Appendix A] results are depicted in Fig 5.

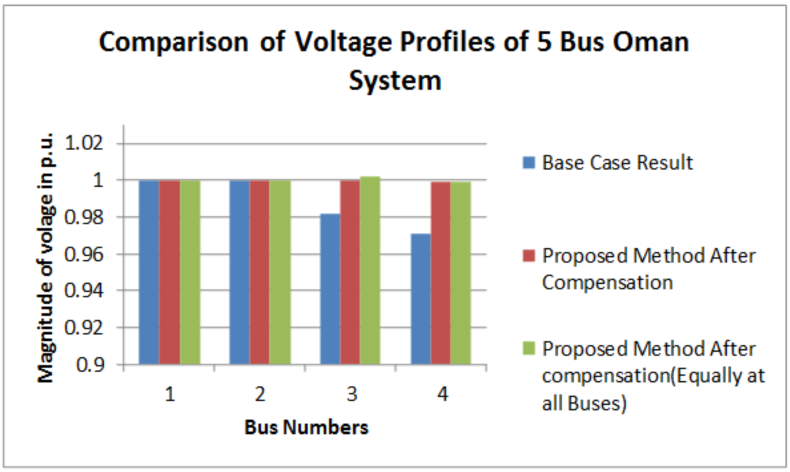


Fig 4:- Results for case 2

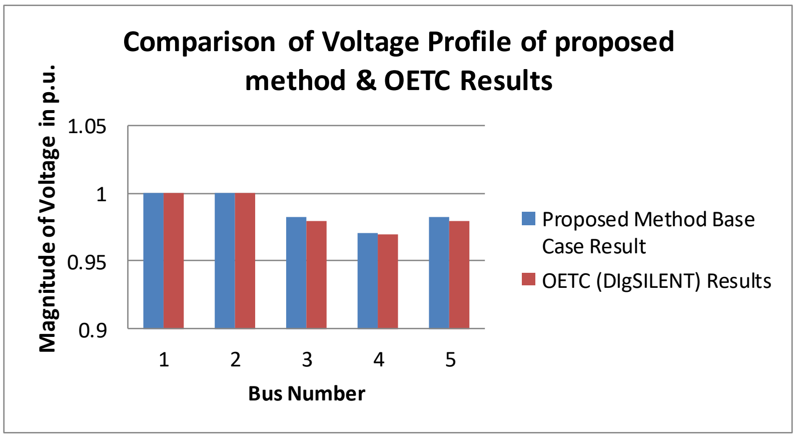
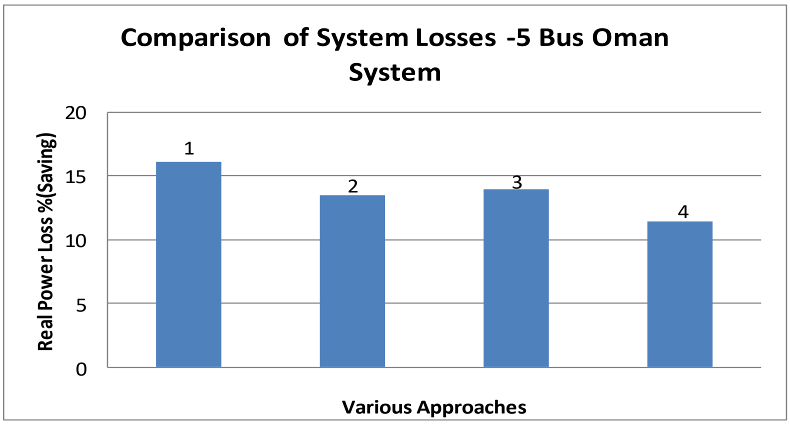


Fig 5:- Comparison of the Voltage Profiles for proposed method and Oman

➢ *Electricity Transmission Company (DIGSILENT) -5 Bus Oman System*

Furthermore, it is encouraging to note that the proposed method minimizes real power loss (see Table 3) in the example system, when comparing the results obtained with those provided by OETC [Appendix A]. In addition, the loss values corresponding to the various cases discussed using the proposed method are compared in Fig. 6. Here, as with Table 5 & 6, the largest value for real power loss has been considered.



1=Proposed method case (1) *3= Proposed method case(3-a)*

2= Proposed method case(2) *4= Proposed method case(3-b)*

Fig 6:- Comparison of System Losses – 5-Bus System

VII. CONCLUSION

In this paper, NR method is used to get analytical expressions for reactive power compensation in order to maintain voltage profiles and reduce real power loss at load buses. The proposed method would be useful and simple for electrical power system operators to make a proper decision to improve the voltage drop at any bus in electrical power system. In addition, it has been implemented on Oman 5-bus system and results have been validated. It can be used for larger systems since it does not depend on any form of linear programming analysis.

APPENDIX – A

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-----------------------------------------------------------------------------------------------------------------------
|                   |                                                                | DIgSILENT      | Company:OETC    |
|                   |                                                                | PowerFactory   |-----------------------------
|                   |                                                                |   15.2.4       | Date:   6/19/2016          |
-----------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                    Complete System Report: Substations, Voltage Profiles, Grid Interchange, Zone Interchange |
-----------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence          |    Automatic Model Adaptation for Convergence             Yes  |
|     Automatic Tap Adjust of Transformers          Yes  |    Max. Acceptable Load Flow Error for                        |
|     Consider Reactive Power Limits                Yes  |      Nodes                                            1.00 kVA |
|                                                        |      Model Equations                                  0.10 %   |
-----------------------------------------------------------------------------------------------------------------------
| Grid: Original              System Stage: Original         | Study Case: 2016 Max                    | Annex:           / 1 |
-----------------------------------------------------------------------------------------------------------------------
|        rated                                 Active Reactive Power                    |                                         |
|       Voltage       Bus-voltage             Power   Power   Factor Current Loading|              Additional Data            |
|        [kV]   [p.u.]     [kV]     [deg]     [MW]   [Mvar]    [-]    [kA]     [%]  |                                         |
-----------------------------------------------------------------------------------------------------------------------
|132kV Izki BB                                                                       |                                         |
|         132.00     0.97  127.85   148.32                                           |                                         |
|   Cub_8   /Lod         33kV IZKI                50.00    28.00   0.87    0.26         |Plo:     50.00 MW    Qlo:  28.00 Mvar          |
|   Cub_3   /Lne         132kV OHL Sumail-I       18.77   -15.52   0.77    0.11    8.59 |Pv:      85.35 kW    cLod:  4.00 Mvar L:  60.80 km|
|   Cub_7   /Lne         132kV OHL Izki-Niz      -68.77   -12.48  -0.98    0.32   24.66 |Pv:     394.88 kW    cLod:  2.04 Mvar L:  31.00 km|
|                                                                                    |                                         |
|132kV Manah BB                                                                      |                                         |
|         132.00     1.00  132.00   152.01                                           |                                         |
|   Cub_3   /Tr2         mnh GT4-5 TX            -94.72   -46.30  -0.90    0.46   74.01 |Tap:     13.00       Min:      1      Max:     17 |
|   Cub_7   /Lne         132kV OHL Nizwa-Ma       94.72    46.30   0.90    0.46   36.23 |Pv:     549.63 kW    cLod:  1.36 Mvar L:  20.00 km|
|                                                                                    |                                         |
|132kV Nizwa BB                                                                      |                                         |
|         132.00     0.98  129.43   150.35                                           |                                         |
|   Cub_16  /Lod         33kV Nizwa load(3)       25.00    31.00   0.63    0.18         |Plo:     25.00 MW    Qlo:  31.00 Mvar          |
|   Cub_10  /Lne         132kV OHL Nizwa-Ma      -94.17   -44.04  -0.91    0.46   36.23 |Pv:     549.63 kW    cLod:  1.36 Mvar L:  20.00 km|
|   Cub_15  /Lne         132kV OHL Izki-Niz       69.17    13.04   0.98    0.31   24.66 |Pv:     394.88 kW    cLod:  2.04 Mvar L:  31.00 km|
|                                                                                    |                                         |
|132kV Rusail BB                                                                     |                                         |
|         132.00     1.00  132.00   148.12                                           |                                         |
|   Cub_10  /Tr2         rsl GT1-2 TX            -36.51   -30.02  -0.77    0.21   36.76 |Tap:      2.22       Min:      1      Max:      5 |
|   Cub_30  /Lne         132kV OHL Rusail-S       36.51    30.02   0.77    0.21   16.67 |Pv:     195.67 kW    cLod:  2.34 Mvar L:  34.50 km|
|                                                                                    |                                         |
|132kV Sumail BB                                                                     |                                         |
|         132.00     0.98  129.31   147.08                                           |                                         |
|   Cub_4   /Lod         33kV SUMAIL              55.00    19.00   0.95    0.26         |Plo:     55.00 MW    Qlo:  19.00 Mvar          |
|   Cub_2   /Lne         132kV OHL Sumail-I      -18.69    12.08  -0.84    0.10    8.59 |Pv:      85.35 kW    cLod:  4.00 Mvar L:  60.80 km|
|   Cub_3   /Lne         132kV OHL Rusail-S      -36.31   -31.08  -0.76    0.21   16.67 |Pv:     195.67 kW    cLod:  2.34 Mvar L:  34.50 km|
|                                                                                    |                                         |
-----------------------------------------------------------------------------------------------------------------------
|                   |                                                                | DIgSILENT      | Company:OETC    |
|                   |                                                                | PowerFactory   |-----------------------------
|                   |                                                                |   15.2.4       | Date:   6/19/2016          |
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|     Automatic Tap Adjust of Transformers          Yes  |    Max. Acceptable Load Flow Error for                        |
|     Consider Reactive Power Limits                Yes  |      Nodes                                            1.00 kVA |
|                                                        |      Model Equations                                  0.10 %   |
-----------------------------------------------------------------------------------------------------------------------
| Zone Summaries                                          | Study Case: 2016 Max                    | Annex:           / 8 |
-----------------------------------------------------------------------------------------------------------------------
|      Generation   Motor     Load    Compen-  External                 Inter Area   Total    Load    Noload   |
|                   Load              sation   Infeed                     Flow      Losses   Losses   Losses   |
|        [MW]/      [MW]/    [MW]/    [MW]/    [MW]/                     [MW]/     [MW]/    [MW]/    [MW]/    |
|       [Mvar]     [Mvar]   [Mvar]   [Mvar]   [Mvar]                    [Mvar]    [Mvar]   [Mvar]   [Mvar]    |
-----------------------------------------------------------------------------------------------------------------------
| \awf.almamari\2016 Max Model from Ahmed Jun 2016\Network Model\Network Data\Zones\Mazoon                           |
|        95.00      0.00   130.00     0.00     0.00                    -36.31      1.31     1.26     0.05    |
|        58.36      0.00    78.00     0.00     0.00                    -31.08     11.44    18.14    -6.70    |
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Fig 7:- Digsilent Results As Given From Oman Electrcity Transmission Company(Oetc)

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