# IMPACT OF PHOTOVOLTAIC POWER GENERATION ON TECHNICAL LOSSES

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## ABSTRACT

The present research investigates the integration of photovoltaic (PV) power systems into the 33-kV transmission network of Sohar Grid, in the Sultanate of Oman. The 33 kV network characteristics were first described. Its associated substations, feeders, transformers and capacitor banks were presented in details. A single line diagram for the grid network suitable for studying PV integration was developed. The single line diagram was built on the basis of field measurements, equipment information and relevant data available from Majan Electric Company (SAOC). The obtained single line diagram was then used to simulate the grid in its existing configuration, i.e. without PV generation. Subsequent simulation runs were made by introducing the PV generation in various substations of the network. No network modification was made, except for the PV connection. Substation selection was made on the basis of losses and voltage criteria in the reference case. Both reference and subsequent simulation results were analyzed and discussed in the aim of finding the best PV generation location. Best location was judged based upon loss reduction and voltage improvement.

**Keywords-**losses, voltage index, voltage regulation, load flow, photovoltaics, substation.

## 1.0 INTRODUCTION

Conversion of solar energy to electrical energy has been technically possible since the late 1930's. The main difficulty is the high cost of photovoltaic systems. Additionally the power output is directly proportional to the surface area of the cells and footprint sizes are hence relatively large. Typical applications of photovoltaic cells include small installations on building rooftops or remote systems that can not be connected to the electricity grid. However, there are larger capacity systems being tested in Europe and the United States. In 2005 alone, the total US grid connected PV generation was 80 MW [1]. A study by EPRI (Electric Power Research Institute) estimated that distributed generation market in the US, including PV could reach 2.5 to 5 GW per year by 2010 [2].

When tied to the grid, the connection is usually made through an inverter and the grid accepts all power from the photovoltaic system. Energy storage is often required for periods when there is no sunshine. However, this component is still expensive.

In spite of their low efficiency, low capacity factor, and high capital costs, non conventional generations such as wind, PV power, fuel cells and hydroelectric power are considered by many countries as viable alternatives to meet environmental constraints, satisfy customers load and depend less on coal, gas, oil and nuclear fuels. Other benefits include peak load reduction, transmission and distribution cost savings, transmission upgrade deferral, wheeling charges, loss reduction on both transmission and distribution lines, and voltage support.

Abundant and numerous studies were done in which these benefits were quantified. According to these studies, grid connected PV generation has became an attractive option. This is due to technological advances in solar cell technology and DC to AC inverters. As a result, many large scale PV systems are now operating in a distributed fashion.

In this work, PV generation is chosen to be connected to Sohar 33 kV grid network, a part of the North Batinah Network, Sultanate of Oman. The addition of the PV was investigated in terms of voltage support, loss reduction, and load demand reduction. Throughout this paper, losses are the difference between the power drawn from the main grid and the total load. In percent, losses are defined by the following equation:

$$Losses(\%) = \frac{Grid\ Power - Total\ Load}{Grid\ Power} \times 100 \qquad (1)$$

Where

- The grid power is the power drawn from the main grid.
- The total load is the power drawn by the 11 kV distribution network.

Meanwhile, a voltage index (VI) is defined by equation (2), shown below, for the purpose of observing the effectiveness of the voltage correction in the network.

$$VI = \sum_{i=1}^{N} \left( \frac{V_b - V_i}{V_b} \right)^2 \qquad (2)$$

- N is the number of critical and marginal buses.
- $V_i$ is the voltage for bus i.
- $V_b$ is the base voltage (11 kV for secondary buses, and 33 kV for primary buses).

For this purpose, PV generation was connected to several 33/11 kV substations, one at a time. Then load flow studies were carried out. Obtained results were discussed and compared in the aim of finding the best substation location that would host the proposed PV system.

## 2.0 INTEGRATION OF PV GENERATION IN THE TRANSMISSION SYSTEM

Now that conditions are in favor of using grid connected PV systems, countries, with abundant sunshine and land should take advantage of this kind of renewable energy systems. Therefore, electric utilities must study the impact of grid connected PV generation on power quality, system losses, voltage regulation, power flow security, and other problems related to the PV technology and resources.

### 2.1 Sohar 33 kV Grid Network

Sohar Grid is a part of the North Batinah Network. As new industries such as oil refinery, aluminum smelter and petrochemical are under planning, power demand is expected to increase significantly and electric losses will increase as well. Therefore, a thorough study of the Sohar Grid Network is mandatory in terms of losses and voltage regulation. For this purpose two steps are involved. The first step is to understand the structure of the grid and the characteristics of its, feeders, transformers, and capacitors. The second step involves the optimal PV system placement. Therefore, feeders and transformers with significant losses and substations with high voltage regulations have to be identified. Once these substations are identified, the PV generation is connected to the network at each of these substations. The aim is to find the substation where PV generation yields most benefits.

### 2.1.1 North Batinah Network

The Northern Batinah transmission and distribution system consists of three stations-Khabourah, Sohar, and Shinas, each rated 132/33 kV. In addition, a new grid station in Sohar Port Area is under commissioning. North Batinah Region has a mean annual temperature of about 40°C. This high temperature has a strong effect on the electrical load demand, especially in the summer season, as more than 80% of the system load during summer is air conditioning. The rated voltages of the distribution networks are 33 kV, 11 kV and 0.415 kV. There is one 66 kV line, with 11/66 kV and 66/33 kV transformers in Wadi Al Jizzi Area. As shown in Figure 1, North Batinah region had a peak load of 224 MW in 2001, and 300 MW in 2005 [3].

### 2.1.2 Description of Sohar 33 kV Grid

The existing Sohar Grid Network consists of:

- 17 33-kV feeders,
- 19 33/11 kV substations.
- Transmission network: 375 km.
- 33/11.5 kV transformers: rated 0.5 to 20 MVA.
- Capacitor banks, installed in many substations for voltage enhancement and power factor correction.

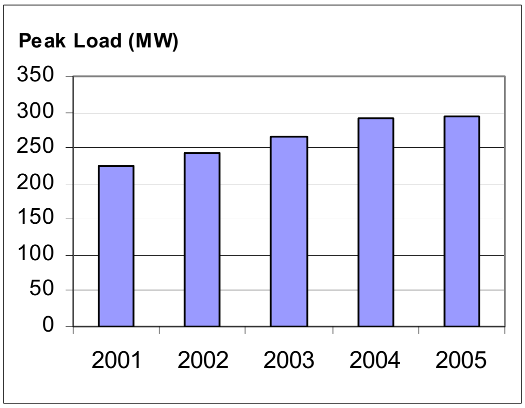

**Figure 1**. North Batinah peak loads: 2001- 2005.

Feeders' lengths and peak load currents are shown in Figures 2 and 3. According to Figure 2, Wadi Hibi is the longest feeder. It is 80-km long and it represents 21 percent of the transmission system. This feeder supplies 4 substations with power: Wadi Faras, Hail-Ashkarain, Wadi Ahin, and Wadi Hibi. The next longest feeder is Saham 3. This 63-km feeder connects Saham with Sohar Grid and feeds four substations: Al Huwail, Mahab, Fleij, and Saham Industrial. Saham 3 feeder is supported by two 35-km long feeders Saham 1 and Saham 2.

As shown in Figure 3, Sohar 1 feeder had the highest peak load of 404.6 A, followed by Multaqaa feeder with 397 A. Other peak loads were as low as 107.2 A. Figure 3 shows the peak load values used in this study.

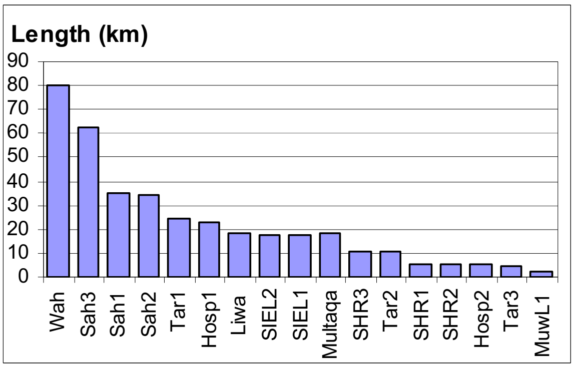

**Figure 2**. Sohar Grid feeders.

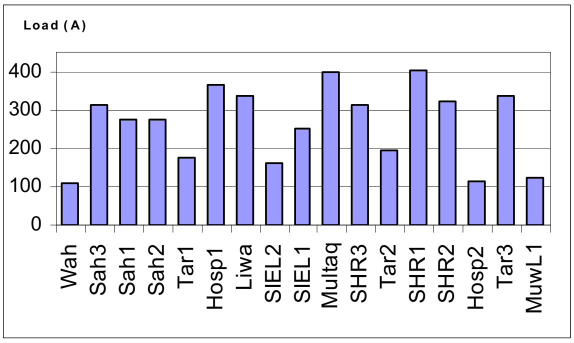

**Figure 3.** 33 kV feeders' peak loads for 2005.

# 3.0 CASE STUDIES

## 3.1 Reference Case

In order to determine the best location for the PV generation in terms of loss reduction, voltage improvement, conventional generation reduction, the authors studied the existing Sohar Grid 33 kV network without PV generation and would use the results as a reference for subsequent simulations. Subsequent simulations were performed, in which the PV generation was connected to six different substations, one at a time. No other changes were made.

### 3.1.1 33 kV Buses Voltages

Figure 4 displays the critical primary voltage level, in percent, for several 33kV sub-stations buses. The Figure 4 indicates that the worst voltage drop of 14.5 percent was for Saham 2 Bus and that the lowest voltage drops of 5.5 % and 6 % were for Wadi Faras and Hail-Ashkarain buses, respectively.

### 3.1.2 Technical Losses

As in table 1, the overall technical losses in Sohar Grid Network represent 5.36% of the total demand. Meanwhile, 90 % of losses were caused by the transmission network, with the remaining 10 percent were caused by transformers. Figure 5 shows that 6 feeders-Saham 3, Hospital 1, Saham 1, Saham 2, Liwa and Multaqa, were responsible for 67 % of the transmission losses

**Table 1.** Demand and total losses.

| | |
|---|---:|
| Total Demand (MW) | 213.941 |
| Transformers Losses (MW) | 1.144 |
| Transmission Losses (MW) | 10.321 |
| Total Losses (MW) | 11.464 |
| Total Losses (%) | 5.360 |

### 3.1.3 Concluding Remarks

For the reference case, there are four main conclusions. First, transmission losses account for 90 % of Sohar Grid Network losses, while transformers losses account for the remaining 10 %. Second, Saham 3 feeder has the highest losses in the network. Third, Sohar Town transformer 2 has the highest losses and it is overloaded. Finally, Al Huwail transformer 2 is significantly overloaded.

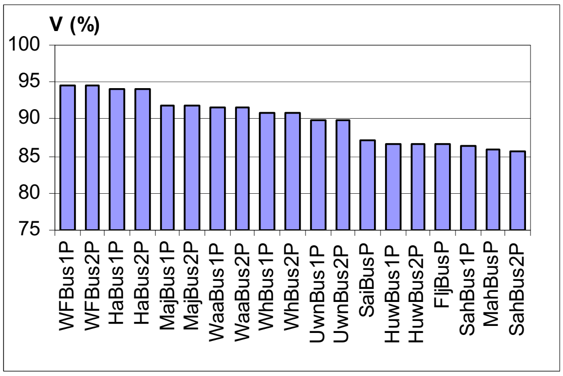

**Figure 4.** Percent Voltage for Critical 33 kV buses.

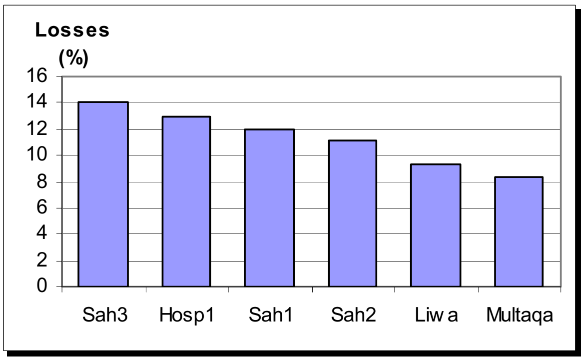

**Figure 5**. Feeders with significant losses.

## 3.2 Subsequent Studies

In order to find the best PV generation location, the authors proposed to connect the PV generation to the following six substations-Al Fleij, Al Huwail, Majees, Saham, Sohar and Wadi Hibi under the following assumptions:

- 2005 annual peak loads,
- A PV generation of 1 MW,
- A power factor of 85 percent for all loads.
- PV generation would provide both real and reactive power at an 85 percent power factor.

In this section, a total of 6 simulation runs were performed in which and their results are listed in tables 2 and 3. Several important observations are made:

- Connecting the PV generation to Saham substation resulted in lowest losses, lowest demand, and lowest conventional power.
- Connecting the PV generation to Al Fleij substation resulted in the lowest voltage index of 0.738, and the third lowest losses of 5.247 percent.
- Therefore, based on these preliminary results, the PV generation should be placed either in Saham or Al Fleij substation, with a preference is given to Saham substation since it has a higher load and more customers than at Al Fleij substation.

**Table 2.** Grid power, total losses and voltage index for all cases.

| Substation | Grid Power (MW) | Total Losses (MW) | Total Losses (%) | Voltage Index |
|---|---|---|---|---|
| Reference | 213.980 | 11.441 | 5.347 | 0.787 |
| Sohar | 212.970 | 11.406 | 5.331 | 0.787 |
| Wadi Hibi | 212.998 | 11.317 | 5.289 | 0.748 |
| Majees | 212.976 | 11.308 | 5.285 | 0.783 |
| Al Fleij | 213.016 | 11.228 | 5.247 | 0.738 |
| Al-Huwail | 213.017 | 11.226 | 5.245 | 0.741 |
| Saham | 212.954 | 11.217 | 5.243 | 0.776 |

**Table 3.** Changes in Grid power, total load and total losses and voltage index for the six substations.

| Substation | Grid Power Change (MW) | Loss Change (MW) | Loss Change (%) |
|---|---|---|---|
| Sohar | -1.010 | -0.350 | -0.3 |
| Wadi Hibi | -0.982 | -0.124 | -1.1 |
| Majees | -1.004 | -0.133 | -1.2 |
| Al Fleij | -0.964 | -0.213 | -1.9 |
| Al-Huwail | -0.963 | -0.215 | -1.9 |
| Saham | -1.026 | -0.224 | -2.0 |

## 4.0 THE PV GENERATION POWER FACTOR

Usually, PV generation is designed to operate at a unity power factor, providing only active power to the grid. However, PV generation may be operated so as to provide active power and limited reactive power to the grid. Most studies assumed a unity power factor. However, in other studies, the power factor varied between 0.6 and 0.90 [4]. In the first part of this study, a power factor of 85 % was assumed. This is in line with the utility regulations in some countries [5].

In order to assess the impact of the PV generation power factor on losses and voltage support, several scenarios were simulated. The power factor was allowed to vary from 40 % to 90 %. Keys results are shown in table 4, assuming that the PV generation is 1 MW and it is connected to Saham substation.

Results of table 4 indicate clearly that as the power factor increased, both losses and voltage index went up. However, the power drawn from the grid dropped. In both cases, the changes were not significant. In fact, comparing the results for the 40 % and the 90 % power factors reveals that the voltage index increased by a factor of 1.67 % for a 125 % power factor rise. In addition, for the same power factor increase, total losses increased by a small factor of 1.47 %.

## 5.0 CONCLUSIONS

This work was aimed at investigating the effects of introducing PV generation on losses and voltage profile for Sohar Grid 33 kV network. The present work showed that the location and the power factor of PV generation influence the transmission losses, transformers losses as well as on buses voltages. Results of the first part of the study indicate that introducing the PV generation at Saham substation resulted in lowest technical losses, lowest demand, and lowest grid power. Results of the second part reveal that if the PV generation is operating at low power factor, it provides enough reactive power to reduce both technical losses and improve system voltage. However, the impact of power factor on losses and voltage index was not significant. Therefore, using a power factor of 85 percent is recommended for the PV generation operation. Finally, an economic analysis should be made to compare the different schemes. Therefore, the optimal loss reduction scheme can be identified. This will be the subject of a future study.

**Table 4.** Grid power, total losses, voltage index for selected power factors at Saham.

| Power Factor | Grid Power (MW) | Total Losses (MW) | Total Losses (%) | Voltage Index |
|---|---|---|---|---|
| No PV generation | 213.980 | 11.441 | 5.347 | 0.787 |
| 0.40 | 213.043 | 11.070 | 5.172 | 0.764 |
| 0.45 | 213.023 | 11.094 | 5.183 | 0.766 |
| 0.50 | 213.009 | 11.114 | 5.193 | 0.768 |
| 0.55 | 212.997 | 11.132 | 5.202 | 0.769 |
| 0.60 | 212.987 | 11.149 | 5.210 | 0.771 |
| 0.65 | 212.979 | 11.163 | 5.217 | 0.772 |
| 0.70 | 212.972 | 11.177 | 5.224 | 0.773 |
| 0.75 | 212.965 | 11.191 | 5.230 | 0.774 |
| 0.80 | 212.960 | 11.204 | 5.236 | 0.775 |
| 0.85 | 212.954 | 11.217 | 5.243 | 0.776 |
| 0.90 | 212.949 | 11.231 | 5.249 | 0.777 |

## 6.0 ACKNOWLEDGEMENT

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