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Techno-Economic Studies for Connecting 1700MW Sohar-3 Power Station to Oman Grid

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Abstract—This paper presents techno-economic studies for grid connection of a new 1700MW generating plant in the vicinity of Sohar port area which is planned to be commissioned by January 2019. The objective is to justify the required capital expenditure on the basis of the submission of a full, complete and robust study, in the form of Pre-Investment Appraisal Document (PIAD), insuring the transmission system in Oman is planned, developed and operated in an efficient manner.

Five options for connecting the Sohar generating plant to the Main Interconnected Transmission System (MITS) have been assessed and the most efficient financially, technically and lower risk option is selected. The paper describes the assessment for each option from different aspects, technically, financially and risk of deliverability of the project. The assessment of each option has been carried out on the basis of the following performance considerations: compliance with the Transmission Security Standard (TSS), capital cost, Net Present Value (NPV), environmental considerations, safety and flood risk assessment. Power losses have also been considered in the NPV calculation. In addition, the paper describes the optimal generation connection design in accordance with the TSS criteria. The compliance with TSS requirements has been assessed by steady state and dynamic studies for both peak and off peak demand with full evacuation of the new Sohar power plant, using the DigsILENT professional software. The results include load flow analysis in N, (N-1), and (N-M-1) operating conditions, short-circuit levels, and transient stability.


I. INTRODUCTION

Connection of a generating plant to the main grid of any country requires technical and economic studies to insure compliance with the corresponding security standards and justifying the required investment cost. The analyses include also assessment of environmental, safety and risk. A comparison of methods used by different utilities in Europe for the connection of a large power station to the main grid is described in [1]. Major issues are discussed in [1] including principles of planning, site selection, and connection of a new power plant to the main electricity grid. Evaluation of economic and risk level of a large hydropower plant project in China is discussed in [2]. An overview of criteria and actions for connecting a hybrid solar - wind generation plant to grid is described in [3] in accordance with official documents in Bosnia and Herzegovina. Grid connection of large offshore wind farms through a gas insulated transmission line is explored in [4].

The Oman Electricity Transmission Company (OETC) has received a connection application from the Oman Power and Water Procurement Company (OPWP) [5] for the connection of a new generating plant in the vicinity of Sohar port area with a maximum capacity of 1700 MW by January 2019. In order to meet the Transmission Licence Conditions 8, 23 and 26 [6] and mitigate any risk associated with non-compliance of these obligations, OETC has to prepare a PIAD including technical and economic studies to assess a number of available connection options and recommend the most financially and technically suitable solution [7, 8]. Five proposed options have been assessed and compared. The preferred option providing a technically viable, deliverable and financially preferable solution is selected. This solution allows new generation at Sohar IPP to supply local industrial loads in the SFZ demand group with connections into the wider coastal and inland network corridors. Furthermore, the option aligns with the OETC master plan (2014-2030) [9]. The option presents a solution with manageable deliverability and safety risks.

The paper is organized as follows: Section 2 describes the existing transmission system in Oman. Section 3 presents the structure and contents of the PIAD for a new project. Section 4 presents Sohar generation site and surrounding transmission assets. Section 5 presents the technical and economic studies of connecting the 1700MW Sohar 3 IPP to the MITS and provides a comparison of the options. Section 6 presents full technical and economic studies of the preferred connection option. Section 7 summarises the main conclusions of the paper.
II. SYSTEM DESCRIPTION

The existing transmission system in northern Oman has three HV operating voltages, i.e. 400 kV, 220 kV and 132 kV while in Dhofar 132 kV is employed. The transmission system extends across the whole of northern Oman and interconnects bulk consumers and generators of electricity located in the Governorates of Muscat, Batinah South, Batinah North, Dhahirah, Buraimi, Dakhliyah, Sharquiya South and Sharqiya North as shown in Fig. 1. The present OETC transmission system of the MITS consists of [10]:

- 884 circuit-km of 400 kV OHTLs
- 1601.5 circuit-km of 220 kV OHTLs
- 3395 circuit-km of 132 kV OHTLs
- 67 circuit-km of 220 kV underground cables
- 153.83 circuit-km of 132 kV underground cables
- 8250 MVA of 400/220 kV transformer capacity
- 13630 MVA of 220/132 kV transformer capacity
- 320 MVA of 220/33 kV transformer capacity
- 16059 MVA of 132/33 kV transformer capacity
- 150 MVA of 132/11 kV transformer capacity
- Two 400/220 kV interconnection grid stations
- Two 400/220/132/33 kV grid stations
- Four 220 kV interconnection grid stations
- Three 220/132 kV grid stations
- One 220/33 kV grid station
- Eight 220/132/33 kV grid stations
- Forty Six 132/33 kV grid stations
- Two 132/11 kV grid stations

In addition, the present OETC transmission system at Dhofar consists of [10]:

- 504 circuit-km of 132 kV OHTLs
- 33.64 circuit-km of 132 kV cables
- 2062 MVA of 132/33 kV transformer capacity
- Eight 132/33 kV grid stations

III. PRE INVESTMENT APPRAISAL DOCUMENT

The PIAD is the principal document on which OETC bases their network investment planning [8]. It identifies the needs case and provide the business case for initiating a project to resolve a predicted non-compliance of the OETC system to the Grid Code [11] or Transmission Security Standard (TSS) [12]. PIADs are the principal means by which OETC seeks to ensure that its decisions on capital investment in the transmission system are necessary, soundly-based and cost-effective. Fig. 2 shows the contents of the PIAD.

PIADs are designed to present the Investment Appraisal Committee with a range of options designed to [8]:

a) Resolve the stress on the system which is predicted to experience as a result of load growth or new generation additions or other factors; and

b) Recommend the best and most feasible option that will, on the current information available to OETC, enable the system to comply with the Grid Code and the TSS. In addition, the PIAD is required to be sent to the Authority of Electricity Regulation (AER) for final capital allowance as it is part of the price control submission.
The OETC requires justification of capital expenditure on the basis of the submission of a full, complete and robust PIAD, demonstrating compliance with the Transmission and Dispatch Licence obligations. In particular OETC is obliged to demonstrate that the transmission system in Oman is planned, developed and operated in an efficient manner. PIAD is an OETC property official document which has a lifecycle starts from planning and ends with the projects. OETC is to receive a project needs through a connection application from OPWP or Distribution Companies (DISCOs). OETC is to submit a connection offer and the same shall be accepted by OPWP/DISCOs which trigger the PIAD process start-up [8].

IV. SOHAR 3 IPP GENERATION SITE AND SURROUNDING MITS ASSETS

The Sohar 3 IPP is proposed to be located in the south east corner of the Sohar port area approximately 1 km south east of the existing Sohar Power Station (SPS) facilities. The boundary of the Sohar port area where cable sealing ends connect the circuits to respective 220 kV overhead line circuit that connects SPS with SIP-A Grid Supply Point (GSP) and the route of the twin 132 kV underground cable connection from SIP-A to Sohar Refinery, within the Sohar port area as shown in Fig. 1.

With reference to PIAD 40/2013 for the new 220/132/33 kV Grid Station at Sohar Free Zone (SFZ)), it is expected that the OETC 220 kV double circuit lines from the Sohar-2 Power Plant will be ‘turned’ into the proposed SFZ GSP, as also will the existing double circuit 132 kV line to Liwa GSP from Wadi Jizzi GSP. The committed SFZ substation is also proposed as the connection point for a second 132 kV double circuit line to Shinas GSP [10].

At SFZ GSP, there are five spare 220 kV bays (two on the left and three on the right sections). Following the turn-ins of the 220 kV connections to Sohar-2 power plant, approximately 742 MW of peak generation output will be seen at this location. SFZ GSP is to be connected to SIS GSP through the turn-in of the Sohar-2 power plant 220 kV overhead lines. SIS also has 220 kV connections to Mahadha to the west, SPS (Sohar port area) and Khaborah to the south east. There are currently two 220 kV spare bays (one on the right and one on the left sections) at SIS. Mahadha substation is proposed to be upgraded to 400kV operation (as part of improved interconnection with the UAE) by 2017. Subsequently, no spare 220 kV bays are available although there is space to extend the busbar. At the 400 kV busbar, as this project is currently in planning stages, it can be assumed that space for additional 400 kV bays would be available.

V. TECHNICAL AND ECONOMIC EVALUATION OF OPTIONS

Five options were considered to mitigate the risks associated with non-compliance of Licence Conditions 8, 23 and 26 [6]. These options are summarized as:

Option 1: 220kV Connection
Option 2a: 400kV connection to Mahadha and SIS (via SFZ)
Option 2b: 400kV connection to Mahadha and SIS (bypass SFZ)
Option 3a: 400kV connection to SIS (via SFZ)
Option 3b: 400kV connection to SIS (bypass SFZ)

Each of the options is assessed on the basis of the following performance considerations:

i. Deliverability

All the associated circumstances on every option shall be assessed on terms of circuit routes, grid station location …etc.

ii. TSS Compliance

Transmission Security Standard that OETC implements for the planning and operation of its licensed transmission system. The TSS has been prepared in accordance with Condition 26 of OETC’s Transmission and Dispatch Licence [6]
iii. Capital cost
Every asset’s costs and civil works cost on every options shall be calculated thoroughly.

iv. Net present value (NPV)
Net present value is calculated for every option for 40 years.

v. Environmental considerations
As OETC is an ISO 14001 (EMS) “Environmental Management System” certified company, it is committed toward environment so all the environmental impacts of every project are considered.

vi. Flood Risk Assessment (FRA)
OETC maintains a check list that considers the location of all assets associated to every option to the nearest flood or valleys.

vii. Safety
As OETC is an ISO 18001 (OHSAS) “Occupational Health and Safety Assessment Series” certified company, it is committed toward safety so all the safety impacts of every project are considered.

vi. Flood Risk Assessment (FRA)

Table I provides a comparative summary of the options based on the key aspects assessed including financial, technical performance, deliverability, environmental considerations including FRA and safety aspects. Colour coding is provided for visual reference such that green indicates no issues, yellow indicates option feasibility but with some additional considerations, red indicates a non-feasible aspect which prevents the option from being considered further and black notes items in non-feasible options that have not been fully assessed due to a prior limitation.

As summarized in Table I, Option 1, Option 2b and Option 3b are not deemed feasible as a result of significant overloads being seen under N-M-1 assessments across a range of outage conditions which would require substantial additional reinforcements to mitigate. Option 2a and Option 3a are therefore provided as the remaining feasible options and a descriptive summary of the options and the relative merits of each are provided below:

Option 2a presents the most technically preferred solution, albeit at a marginally increased capital cost (4.6%) and NPV (5.5%) against Option 3a.

Option 3a presents the least cost solution on both capital cost and NPV basis. The option, although technically acceptable based on the studies conducted, presents a number of technical risks, particularly with regard to short circuit levels. It is seen that SIS 220 kV fault level is within 1% of rating and could be deemed to be within the margin for error which may require subsequent uprating of the existing equipment at the site or other network fault limiting solution should any switchgear derating or alternative network configuration / dispatch be considered. Furthermore, loading of SFZ and SIS transformers under contingency events is seen to be greater than 90%, suggesting further reinforcements may be required in the short to medium term to mitigate these emerging limitations.

Based on the comparison of the options presented above, Option 2a presents the technically preferred long term solution with a marginally greater cost and is therefore the preferred solution.

Subsequently, dynamic studies of the preferred option (Option 2a) relating to a three phase fault (maximum load N-1 and maintenance load N-M-1) of one of the 400 kV cables from Sohar 3 IPP to SFZ (resulting in a loss of the circuit), in addition to a generator trip at Sohar IPP3 have been conducted. It is concluded that there are no issues to report with regard to the dynamic assessment with all generators remaining stable under the conditions assessed.

VI. PREFERRED CONNECTION OPTION

A. Configuration

Fig. 3 shows a simplified connection of Option 2a. This preferred option mitigates the Licence Condition risks whilst providing the most technically preferred and deliverable solution through the construction of a 400 kV substation at Sohar 3 IPP, four 400 kV cables from Sohar IPP3 to SFZ, 400/220 kV substation extension at SFZ and SIS, 400 kV double circuit connection from SFZ to SIS (including 2x 50 MVAr shunt reactor) and a 400 kV double circuit from SFZ to Mahadha (including 4x 50 MVAr shunt reactor). The solution allows new generation at Sohar 3 IPP to supply local industrial loads in the SFZ demand group with connections into the wider coastal and inland network corridors.

This option involves the construction of a new 400 kV GIS double busbar and associated three 400/220 kV 500 MVA transformers at both SFZ and SIS to allow the connection of new 400 kV circuits to these locations (8.5 km and 31 km respectively) with suitable N-1 and N-M-1 transformer capacity. Further 400 kV circuits to Mahadha from SFZ (66 km) are proposed (400 kV GIS busbar, switchgear structure and two 400/220 kV transformers are assumed to exist at Mahadha by 2019 as part of the UAE interconnector upgrades).

B. Specifications
The outline specification of the works associated with the preferred option is as follows:

(1) Establish 400 kV Sohar 3 IPP Substation
- 20 x 400 kV GIS
- Associated civil, auxiliary and infrastructure works to support the above equipment

(2) Establish 400/220 kV SFZ Substation
- 15 x 400 kV GIS
- 5 x 220 kV GIS
- 3 x 500 MVA 400/220 kV Transformers
- Associated civil, auxiliary and infrastructure works to support the above equipment
<table>
<thead>
<tr>
<th></th>
<th>Option 1</th>
<th>Option 2a</th>
<th>Option 2b</th>
<th>Option 3a</th>
<th>Option 3b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost [R.O.]</td>
<td>N/A</td>
<td>90,098,447</td>
<td>N/A</td>
<td>85,913,029</td>
<td>N/A</td>
</tr>
<tr>
<td>NPV [R.O.]</td>
<td>N/A</td>
<td>-109,746,285</td>
<td>N/A</td>
<td>-103,716,355</td>
<td>N/A</td>
</tr>
<tr>
<td>Intact</td>
<td>N/A</td>
<td>No issues</td>
<td>No issues</td>
<td>No issues</td>
<td>Use of 750 MVA transformers at SIS required</td>
</tr>
<tr>
<td>N-1</td>
<td>N/A</td>
<td>No issues</td>
<td>Marginal overloading of SIS transformers</td>
<td>No issues</td>
<td>Fourth 750 MVA transformer at SIS required</td>
</tr>
<tr>
<td>N-M-1</td>
<td>N/A</td>
<td>No issues</td>
<td>Severe overloading of multiple areas of the network for multiple events – Not Feasible</td>
<td>No issues</td>
<td>Severe overloading of multiple areas of the network for multiple events – Not Feasible</td>
</tr>
<tr>
<td>Short Circuit</td>
<td>N/A</td>
<td>SIS 220 kV within 10% of rating</td>
<td>N/A</td>
<td>SIS 220 kV within 1% of rating</td>
<td>N/A</td>
</tr>
<tr>
<td>Losses (2019 Peak)</td>
<td>N/A</td>
<td>16.3 MW</td>
<td>N/A</td>
<td>16.7 MW</td>
<td>N/A</td>
</tr>
<tr>
<td>Deliverability</td>
<td>Constraints in the port area prevent five (possibly six) 220 kV cables to be installed – Not Feasible</td>
<td>Constraints in the port area.</td>
<td>Constraints in the port area.</td>
<td>Constraints in the port area.</td>
<td>Constraints in the port area.</td>
</tr>
<tr>
<td>Environmental</td>
<td>N/A</td>
<td>Initial route surveys indicate no limitations</td>
<td>Initial route surveys indicate no limitations</td>
<td>Initial route surveys indicate no limitations</td>
<td>Initial route surveys indicate no limitations</td>
</tr>
<tr>
<td>FRA</td>
<td>N/A</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Safety</td>
<td>N/A</td>
<td>No significant safety risk</td>
<td>No significant safety risk</td>
<td>No significant safety risk</td>
<td>No significant safety risk</td>
</tr>
</tbody>
</table>

**Fig. 3: Simplified configuration of Option 2a**
(3) Establish 400/220 kV SIS Substation
   - 9 x 400 kV GIS
   - 5 x 220 kV GIS
   - 3 x 500 MVA 400/220 kV Transformers
   - Associated civil, auxiliary and infrastructure works to support the above equipment

(4) Extend 400 kV Mahadha Substation by 2 x 400 kV GIS
   - 4 x 8.5 km of 400 kV 2500mm2 cable from Sohar 3 IPP to SFZ
   - 31 km of 400 kV quad yew overhead line double circuit from SFZ to SIS
   - 66 km of 400 kV quad yew overhead line double circuit from SFZ to Mahadha
   - 6 x 50 MVAr shunt reactors

C. Cost
The preferred option presented the highest long-term technical performance. The estimated capital cost for connection of the Sohar 3 IPP to the MITS is R.O. 90,098,447. The requested funding will be distributed over five years as follows:
   - 2015 – R.O. 221,100
   - 2016 – R.O. 18,019,689
   - 2017 – R.O. 31,368,632
   - 2018 – R.O. 31,368,632
   - 2019 – R.O. 9,120,395

D. Deliverability
The physical constraints in the Sohar port area with a number of traditional and innovative solutions investigated to overcome such constraints and are not considered further within this assessment. Investigation of the SFZ and SIS sites has indicated sufficient land availability to construct 400 kV infrastructures at these locations. Furthermore, the 400 kV structure at Mahadha is assumed to exist by 2019 as part of separate UAE interconnector upgrades.

In addition, preliminary surveys (with exception to a short section in the vicinity of Wadi Jizzi) have suggested no significant constraints to the consent and construction of the required 400 kV overhead lines to Mahadha (66 km) and SIS (31 km).

E. Technical Performance
A digital model of the MITS has been developed [13] using the DIgSILENT professional software [14]. The model has been updated to accommodate new assets to be added in studied years (2018 and 2019). The following simulation studies have been performed to assess the technical performance of the MITS with Option 2a of Sohar 3 IPP connection.

   - Intact Conditions

Intact system loadings indicate some 615 MW is offloaded at the SFZ substation onto the 220 kV network with an additional 370 MW provided to the location from Sohar 2 generation. Of this, 200 MW is demanded by local SFZ load at 220 kV, some 470 MW is demanded by 132 kV SFZ load with the remaining 315 MW being sent to SIS on the 220 kV network. Tables II and III show sample results in Sohar area. With respect to the 400 kV circuits to SIS from SFZ, ~700 MW is seen with the remaining 410 MW of generation on the 400 kV circuits from SFZ to Mahadha. These intact system power flows indicate a relatively even distribution of the generated power to local loads at SFZ and the corridors to SIS and Mahadha.

   - (N-1) Conditions

N-1 contingency analysis indicates no overloading issues in 2019 with this arrangement owing to the capacity available on the 400 kV circuits and 400/220 kV transformers under contingency conditions in addition to the redistribution of power available around the network from this option design.

<table>
<thead>
<tr>
<th>Asset</th>
<th>Type</th>
<th>Voltage (kV)</th>
<th>Peak (MW)</th>
<th>Off-Peak (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sohar 3 IPP to SFZ</td>
<td>4 x Cable</td>
<td>400</td>
<td>1722</td>
<td>1722</td>
</tr>
<tr>
<td>SFZ to Mahadha</td>
<td>OHTL</td>
<td>400</td>
<td>407</td>
<td>356</td>
</tr>
<tr>
<td>SFZ to SIS</td>
<td>OHTL</td>
<td>400</td>
<td>697</td>
<td>718</td>
</tr>
<tr>
<td>SFZ</td>
<td>3 x Transf.</td>
<td>400/220</td>
<td>615</td>
<td>645</td>
</tr>
<tr>
<td>SFZ</td>
<td>2 x Transf.</td>
<td>220/132</td>
<td>469</td>
<td>318</td>
</tr>
<tr>
<td>Sohar 2 to SFZ</td>
<td>OHTL</td>
<td>220</td>
<td>370</td>
<td>180</td>
</tr>
<tr>
<td>SFZ to SIS</td>
<td>OHTL</td>
<td>220</td>
<td>317</td>
<td>310</td>
</tr>
<tr>
<td>SPS to SIS</td>
<td>OHTL</td>
<td>220</td>
<td>57</td>
<td>166</td>
</tr>
<tr>
<td>Mahadha to SIS</td>
<td>OHTL</td>
<td>220</td>
<td>47</td>
<td>139</td>
</tr>
<tr>
<td>SIS to Khabarah</td>
<td>OHTL</td>
<td>220</td>
<td>640</td>
<td>720</td>
</tr>
<tr>
<td>SIS</td>
<td>3 x Transf.</td>
<td>400/220</td>
<td>696</td>
<td>717</td>
</tr>
<tr>
<td>SIS</td>
<td>2 x Transf.</td>
<td>220/132</td>
<td>364</td>
<td>281</td>
</tr>
</tbody>
</table>

   - (N-M-1) Conditions

N-M-1 conditions relate to a forced outage occurring during the periods of low demand, when another asset is already out for maintenance.

<table>
<thead>
<tr>
<th>Busbar</th>
<th>Nominal Voltage (kV)</th>
<th>Peak Demand Voltage (p.u.)</th>
<th>Off-Peak Demand Voltage (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sohar 3 IPP</td>
<td>400</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>SFZ</td>
<td>400</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>SFZ</td>
<td>220</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>SFZ</td>
<td>132</td>
<td>0.97</td>
<td>0.99</td>
</tr>
<tr>
<td>SIS</td>
<td>400</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>SIS</td>
<td>220</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>SIS</td>
<td>132</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td>Mahadha</td>
<td>400</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>SPS</td>
<td>220</td>
<td>1.03</td>
<td>1.02</td>
</tr>
</tbody>
</table>

The network configuration for the N-M-1 study reflects the maintenance period and OETC TSS requirements such that all 33 kV (and below) connected loads are reduced to 66% of
peak demand, whilst 132 kV connected (and above) customers remain at peak demand values. With regard to generation, the proposed generators at Ibri and Sohar remain at maximum output as these new generators are the focus of the assessment and the connection arrangement being assessed must be capable of full power evacuation under the N-M-1 condition.

The above arrangement provides a suitable network configuration to allow the N-M-1 studies to be conducted, representing a reduced load scenario in line with OETC TSS requirements (and practical network loadings in the maintenance period) in addition to a practical generation dispatch whilst maintaining maximum output at Ibri and Sohar. Sur gas turbines, as the reference machines, are seen to be at 40% output under this arrangement, indicating a practical balance of generation and demand.

N-M-1 contingency analysis in the vicinity of Sohar 3 IPP generation indicates no overloading. The loss of either of the double circuits to SIS or Mahadha result in power being rerouted to the remaining two circuits, or utilising the connection through SFZ. N-M-1 outage of the two 220/132 kV SFZ transformers is accommodated through power flows to Mahadha, through Wadi Al Jazzi to the SFZ 132 kV busbar, allowing continuous supply of demand at that location without overloads or substantial voltage drop.

- Short Circuit Levels

Three phase and single phase to ground intact system short circuit system levels (all generators on to provide worst case assessment) have been calculated (according to IEC60909 Standard) and are measured against equipment ratings for relevant substation locations in the vicinity of the new Sohar 3 IPP generation. The results of these studies are presented in Table IV.

<table>
<thead>
<tr>
<th>Site</th>
<th>Rated (kV)</th>
<th>Rated (kA)</th>
<th>3-Ph $I_{g}$ (kA)</th>
<th>1-Ph $I_{g}$ (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sohar 3 IPP</td>
<td>400</td>
<td>63.0</td>
<td>28.8</td>
<td>34.7</td>
</tr>
<tr>
<td>SFZ</td>
<td>600</td>
<td>63.0</td>
<td>28.7</td>
<td>34.5</td>
</tr>
<tr>
<td>SFZ</td>
<td>220</td>
<td>50.0</td>
<td>32.7</td>
<td>36.3</td>
</tr>
<tr>
<td>SFZ</td>
<td>132</td>
<td>40.0</td>
<td>24.2</td>
<td>30.2</td>
</tr>
<tr>
<td>SIS</td>
<td>400</td>
<td>63.0</td>
<td>22.1</td>
<td>21.1</td>
</tr>
<tr>
<td>SIS</td>
<td>220</td>
<td>40.0</td>
<td>37.7</td>
<td>36.1</td>
</tr>
<tr>
<td>SIS</td>
<td>132</td>
<td>31.5</td>
<td>26.1</td>
<td>27.3</td>
</tr>
<tr>
<td>Mahadha</td>
<td>400</td>
<td>63.0</td>
<td>21.3</td>
<td>18.2</td>
</tr>
<tr>
<td>SPS</td>
<td>220</td>
<td>40.0</td>
<td>23.4</td>
<td>26.7</td>
</tr>
</tbody>
</table>

Table IV illustrates that there is sufficient margin at each of the sites in the vicinity of the Sohar 3 IPP generator under this connection arrangement.

- Losses

Real power losses at 2019 peak demand have been calculated for this option to be included within the lifetime cost assessment and as a comparison to other feasible options. The real power losses have been calculated for the network in the vicinity of the Sohar 3 IPP generator which is directly impacted by the additional generation. Broadly this relates to the 400 kV, 220 kV and 132 kV network to Mahadha from SFZ and SIS, the 220 kV and 132 kV network from Sohar to Khaborah (via SIS) in addition to relevant transformers at these locations. An overview of the real power losses for Option 2a is presented in Table V.

<table>
<thead>
<tr>
<th>Location</th>
<th>Asset</th>
<th>(kV)</th>
<th>Losses (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sohar 3 IPP to SFZ</td>
<td>4 x Cable</td>
<td>400</td>
<td>0.4</td>
</tr>
<tr>
<td>SFZ to SIS</td>
<td>OHL</td>
<td>400</td>
<td>1.2</td>
</tr>
<tr>
<td>SFZ</td>
<td>3 x Trans.</td>
<td>400/220</td>
<td>0.3</td>
</tr>
<tr>
<td>SFZ</td>
<td>2 x Trans.</td>
<td>220/132</td>
<td>0.6</td>
</tr>
<tr>
<td>Sohar 2 to SFZ</td>
<td>OHL</td>
<td>220</td>
<td>0.2</td>
</tr>
<tr>
<td>SFZ to SIS</td>
<td>OHL</td>
<td>220</td>
<td>0.9</td>
</tr>
<tr>
<td>SPS to SIS</td>
<td>OHL</td>
<td>220</td>
<td>0.2</td>
</tr>
<tr>
<td>Mahadha to SIS</td>
<td>OHL</td>
<td>220</td>
<td>0.0</td>
</tr>
<tr>
<td>SIS to Khaborah</td>
<td>OHL</td>
<td>220</td>
<td>5.8</td>
</tr>
<tr>
<td>SIS</td>
<td>3 x Trans.</td>
<td>400/220</td>
<td>0.6</td>
</tr>
<tr>
<td>SIS</td>
<td>2 x Trans.</td>
<td>220/132</td>
<td>0.4</td>
</tr>
<tr>
<td>SFZ to Wadi Jizzi</td>
<td>OHL</td>
<td>132</td>
<td>0.2</td>
</tr>
<tr>
<td>Wadi Jizzi to Mahadha</td>
<td>OHL</td>
<td>132</td>
<td>1.7</td>
</tr>
<tr>
<td>Wadi Jizzi to SIS (via Sohar A&amp;B and Uwaynat)</td>
<td>OHL</td>
<td>132</td>
<td>1.2</td>
</tr>
<tr>
<td>SIS to Khaborah (via Saham and DAS)</td>
<td>OHL</td>
<td>132</td>
<td>2.4</td>
</tr>
</tbody>
</table>

The real power losses have been calculated for this option to be included within the lifetime cost assessment and as a comparison to other feasible options. The real power losses have been calculated for the network in the vicinity of the Sohar 3 IPP generator which is directly impacted by the additional generation. Broadly this relates to the 400 kV, 220 kV and 132 kV network to Mahadha from SFZ and SIS, the 220 kV and 132 kV network from Sohar to Khaborah (via SIS) in addition to relevant transformers at these locations. An overview of the real power losses for Option 2a is presented in Table V.

It is clear from Table V that the losses are dominated by the 132 kV corridors from Mahadha to Khaborah via Wadi Jizzi and SIS with a third of the losses seen on this part of the network. Approximately a third of the losses is also seen on the SIS to Khaborah 220 kV double circuit line. Subsequently, the total loss of this area of the network at peak load is seen to be 16.7 MW.

For the purposes of the lifetime financial assessment, the losses will be capitalized on the basis of 12 R.O./MWh utilizing a load loss factor of 0.3166. Subsequently, the 2019 annual losses for this area of the network directly impacted by the Sohar 3 IPP generation can be assumed to be 46,316 MWh, with a cost of ~R.O. 555,793. Anticipated peak demand growth of 9.5% will increase the level of losses proportionately year on year and have been considered within the financial assessment for the first five years. Beyond the five year period, no further growth in losses is assumed for the purposes of the assessment.

F. Financial Assessment

The capital cost assessment of this option in full, including five year spend phasing, and can be summarized as a total cost of R.O. 90,098,447. The NPV assessment has been carried out over 40 years using a discount rate of 5.65%. The NPV calculation includes the O&M costs for the option based on a flat rate of 3.31% of the asset’s capex value, determined from OETC’S Transmission Running Charge (TRC) statement. It is recognized that this is not fully representative of a whole-life cost modelling approach but is considered sufficient for the 40-year investment period given the information which is presently available to OETC. The resulting NPV of this option is provided as R.O. -109,746,285.
G. Environmental Considerations

This option would require the consent of two separate circuit corridors, one to Mahadha and one to SIS. Presently there is a 220 kV and 132 kV corridor to Mahadha and the construction of a third overhead line requiring a similar corridor could be constrained; however the visual impact would be limited in comparison to a new corridor requirement. Similarly, there are currently three 220 kV circuits to SIS from the west and the construction of a fourth overhead line in the vicinity could be constrained; however the visual impact would again be limited.

H. Flood Risk Assessment

A flood risk assessment for the Sohar 3 IPP has been performed. The assessment has illustrated that although the site is in close vicinity to the sea and infrastructure within the Sohar port, the risk is deemed acceptable, due to the sea defences that exist to protect the port area. The flood risk assessment for the Mahadha, SFZ and SIS substations is deemed to be acceptable considering these sites are currently in existence. A brief review of the location indicates that 400 kV extensions at SFZ and SIS should not represent additional flood risk. Furthermore, the 400 kV routes from SFZ to SIS and Mahadha will broadly align with existing 132 kV and 220 kV corridors and the flood risk is therefore deemed acceptable.

I. Safety

This option requires the construction of new 400 kV circuits in the vicinity of existing 132 kV and 220 kV circuits in addition to the offline construction of 400 kV infrastructure at SFZ and SIS in the vicinity of existing 220 kV and equipment. With respect to the substation expansion, the 400 kV equipment can be installed offline, adjacent to the existing structures and working within the confines of the existing site should not be required. Connections to the existing 220 kV infrastructure will be required, including extending the SIS 220 kV busbar to accommodate three transformers (existing spare bays for two only) which will require a limited amount of working in close proximity to live connections. Some safety risks do exist whilst working within the vicinity of live equipment, however standard construction practices should be suitable to avoid any risks and subsequently no significant safety risk is associated with this option.

J. Dynamic Studies

The compliance with TSS requirements has been assessed by steady state and dynamic studies for both peak and off peak demand with full evacuation of Ibri IPP power plant. The dynamic studies cover the rotor angle stability, voltage response and frequency response at both peak and off peak demands. Fig. 4 shows an example of the rotor angle response, at peak demand, to tripping Sohar GT1 (single unit) generator with associated power reduction of ST1 (around 50%) – resulting in a total loss of 323 MW.

Small-disturbance stability studies have been performed by calculating the system eigenvalues and the results indicated that the system is stable. Also, it is observed that there is no inter-area oscillations issue in the system with the selected option.

VII. Conclusion

This paper has described the assessment for each option from different aspects, technically, financially and risk of deliverability of the Sohar 3 IPP connection project. The assessment of each option has been carried out on the basis of the following performance considerations: deliverability, transmission security standard (TSS) compliance technical performance, capital cost, net present value, environmental considerations, safety and flood risk assessment. Power losses have also been considered in the NPV calculation. In addition, the paper describes the optimal generation connection design that is respected the TSS criteria. The compliance with TSS requirements has been proved by steady state and dynamic studies for both peak and off peak demand with full evacuation of Ibri IPP power plant.

The preferred Option 2a has shown to mitigate the licence condition risks whilst providing a technically viable, deliverable and financially preferable solution. It consists of construction of a 400 kV substation at Sohar 3 IPP, four 400 kV cables from Sohar 3 IPP to SFZ, 400/220 kV substation extension at SFZ and SIS, 400 kV double circuit connection from SFZ to SIS (including 2x 50 MVAR shunt reactor) and a 400 kV double circuit from SFZ to Mahadha (including 4x 50 MVAR shunt reactor). The NPV assessment of this option which accounts for lifetime costs associated with losses and estimated operations and maintenance costs over a 40 year period. The resulting NPV of this option has been calculated to be R.O. -109,746,285.

REFERENCES


Fig. 4: Rotor angle response to tripping GT1 with associated 50% of ST1 at peak demand.