Application of Fault Current Limitation Techniques in a Transmission System

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Abstract—The paper describes the applications of fault current limiting techniques to Oman electricity transmission system to overcome high short-circuit currents in some parts of the grid. These include splitting busbars at selected grid stations, regrouping generators at power stations, opening transmission lines at critical points, and introducing fault current limiters at strategic places in the network.

Computer simulation results, using DIgSILENT software package, are presented to show the effectiveness of these techniques in reducing the short-circuit currents at critical busbars. The results have shown that the calculated short-circuit currents can be reduced to be within the fault level capacity of the existing switchgears. Splitting busbars and regrouping generators are considered as short-term temporary solutions with no cost. Practical implementation of this technique at Rusail power plant is described. Employing fault current limiting reactors is considered as a long-term permanent solution.

Index Terms— Fault current limiter, Short-circuit currents, Splitting busbars, Transmission system.

I. INTRODUCTION

Continuous growth of electricity demand leads to upgrading transmission systems to increase the capability of power transfer. This results in the need for higher fault current capability. Interconnected systems with more parallel paths exhibit reduced source impedances and increased number of sources contributing to fault currents. Fault currents increase also with the introduction of new generation. To avoid damages or malfunctioning system assets and to increase reliability, it is crucial to properly manage increased fault currents [1]. High fault currents produce mechanical forces and thermal effects [2] that can damage or destroy substation equipment, circuit breakers, earthing grids, transmission lines and transformers. Protection and control systems can be badly affected by high fault currents [3]-[8].

Various methods and technologies of fault current limitation are discussed in [1] and [9]. These methods include splitting grids at strategic points, splitting busbars, introduction of higher-voltage levels, use of transformers with increased short-circuit impedance, and installing fault current limiting reactors. Technologies include conventional solid-state, and superconductor techniques.

This paper presents simulation studies and field applications of conventional techniques to the main transmission system of Oman in order to solve the high fault-current problem at some locations in the system. A short-term solution with no-cost is to split the HV busbars at grid stations directly connected to power plants. A long-term permanent solution is to install fault current limiting reactors at strategic locations in the network. A digital model of the system is developed based on the PowerFactory DIgSILENT software [10]. Simulation results are presented to show the reduction in fault levels achieved by using the proposed methods. Busbar splitting and generator re-grouping are successfully implemented at one power plant.

Section II and section III describe the system configuration and modeling, respectively. Section IV describes proposed splitting options. Section V illustrates the results of the proposed short-term temporary options. Section VI presents fault current limiting reactors as a long-term solution. Practical implementation and operational considerations are discussed in section VII. Conclusions are summarized in section VIII.

II. SYSTEM DESCRIPTION

The existing transmission system extends across the whole of northern Oman and interconnects bulk consumers and power plants [11]. Fig. 1 shows a geo-schematic diagram of the system. It has two operating high voltages, i.e. 220 kV and 132 kV. The present OETC transmission system consists of:

- 665 circuit-km of 220 kV overhead transmission lines
- 2829 circuit-km of 132 kV overhead transmission lines
- 12 circuit-km of 220 kV underground cables
- 50 circuit-km of 132 kV underground cables
- 6630 MVA of 220/132 kV transformer capacity
- 7488 MVA of 132/33 kV transformer capacity
- 150 MVA of 132/11 kV transformer capacity
- Two 220 kV interconnection grid stations
- Two 220/132 kV grid stations
- Five 220/132/33 kV grid stations
- Thirty one 132/33 kV grid supply point substations
- One 132/11 kV grid station

The transmission system is interconnected at 220 kV with the transmission system of the United Arab Emirates (UAE). This should provide increased security of supply and benefits to both countries in the form of cost savings from the sharing of reserve capacity and energy resources. The Oman-UAE interconnector will be brought into service when the Inter-Governmental agreement is signed. Internally, the main transmission system is interconnected with other systems such as Sohar Aluminum Company and Petroleum Development of Oman (PDO) [12].
The main transmission system is supplied with electricity generated from eight gas-based power stations located at Ghubrah (482MW), Rusail (684MW), Wadi Al-Jizzi (290MW), Manah (279MW), Al-Kamil (282MW), Barka AES (434MW), Barka SMN (683MW) and Sohar (590MW) [13].

The bulk of the power transmitted through the main grid, is fed, through 220/132/33 kV and 132/33 kV grid stations, to the three distribution licence holders, namely, Muscat Electricity Distribution Company, Mazoon Electricity Company and Majan Electricity Company, in addition to directly-connected large private customers. In summer 2009 the system peak demand of 3546 MW occurred at 15:00 hours on 31 May, which was an increase of 13% from 2008 peak demand.

III. SYSTEM MODELING

A digital model of the system is developed [10] based on a commercially available power system simulation package called PowerFactory DIgSILENT software [14]. In the following, modeling of the main components is summarized.

A. Synchronous Generators

The system comprises 56 synchronous generators of a round-rotor type in the 8 power stations. The rating of these turbo-generators ranges from 13.4 MVA for the smallest old unit to 280 MVA for the largest unit in the system. Each generator is represented by an 8th order model [15] based on the two-reaction theory. The stator has three windings ABC, and the round rotor has the field winding in the d-axis. Also, it is assumed that the rotor has one damper winding in the d-axis and two damper windings in the q-axis.

B. Transformers

The generating units in the 8 power stations are equipped with step-up transformers connecting the generators to the corresponding 132 kV or the 220 kV transmission network. Auto transformers of 500 MVA and 315 MVA are used at the interconnection substations between the 220 kV and 132 kV transmission systems. At connection points with the distribution companies, 132/33 two-winding transformers are used in the substations. Most of these transformers are 125 MVA rating; in some smaller substations 63 MVA, 40 MVA or 15 MVA ratings are used. Three-phase power transformers are represented by equivalent circuit models with parameters in ohms or in p.u. The models include representation of the magnetization reactance and iron loss admittance in addition to the leakage reactances and winding resistances. On-load tap changers with their automatic control facilities; and off-load tap changers are simulated in the transformer model. The representations include various connection types and vector groups of transformers. Earthing transformers with associated earthing resistors are also simulated in the model.

C. Transmission Lines

The system comprises 53 double-circuit transmission lines; most of them are overhead lines and only a few are cables. The majority of these lines are within the short length range; only a few are in the medium length range. Lumped-parameters π-equivalent circuit models are used to simulate the lines.

D. Loads

An electric power system normally includes residential, industrial and commercial main load types. These may be
represented as constant P & Q load, voltage dependant load or
dynamical load models. Selection of load representation
method depends on the objective of the study and availability
of accurate data. In the studies presented here, the load at each
substation is represented as constant P and Q model.
Contribution of induction motor loads to fault currents is
neglected.

E. Shunt Capacitors
A number of 132/33 kV substations are equipped with
capacitor banks at the 33 kV load side to provide reactive
power and voltage support. The capacitor banks are arranged
in a number of groups called steps (1 to 4); each has a capacity
of 5 MVAR. They are set to power factor control mode.

IV. SHORT-TERM FAULT CURRENT LIMITATION METHODS

Short-circuit studies have shown that, the fault currents
levels at Rusail, Ghubrah, and MSQ grid station busbars are
higher than the corresponding short-circuit ratings of the
switchgear. The rating of the 132 kV switchgear at Rusail and
MSQ grid stations is 31.5 kA. At Ghubrah, it is 31.5 kA for
section A and 26.5 kA for section B. It is observed that
single-phase-to ground fault currents are significantly higher
than three-phase fault currents at these busbars.

Four options are considered here to reduce fault currents.
All these methods are available for direct applications by the
system operator at no cost. They are considered as short-term
temporary solutions and described as follows:

Option 1: Disconnect Rusail- Mobella Line
The double-circuit transmission line between Rusail power
station and Mobella grid station is opened at both sides. This
results in eliminating the current coming to Rusail from Barka
Power Stations through Mobella when a short circuit fault
occurs at the 132 kV of Rusail.

Option 2: Splitting Bushars at Rusail Power Plant
The 132 kV busbars at Rusail power plant are split into two
groups:

Rusail Busbar Group A:
- Three generating units: GT1, GT2, and GT6
- Three transmission lines: Rusail-Boushar, Rusail-Sumail, and Rusail-Mobellah
- Four transformers: 75 MVA, 132/33 kV feeding Rusail distribution grid

Rusail Busbar Group B:
- Five generating units: GT3, GT4, GT5, GT7, and GT8
- Two transmission lines: Rusail-Mawaleh, and Rusail-Wadi Adai

Option 3: Splitting Bushars at both Rusail and Ghubrah
Power Plants
In addition to splitting the busbars at Rusail power plant as
shown in option 2, the 132 kV busbars at Ghubrah power plant
are split into two groups:

Ghubrah Busbar Group A:
- Seven generating units: GT4, GT5, GT6, GT10, GT11, GT12, and ST4
- One transmission line: Ghubrah-Bousher

Ghubrah Busbar Group B:
- Ten generating units: GT1, GT2, GT3, GT7, GT8, GT9, GT13, ST5, ST3, and ST6
- One transmission line: Ghubrah-MSQ

Fig. 2 and Fig. 3 show the connection diagrams of this part
of the network before and after splitting both Rusail and
Ghubrah busbars.

Option 4: Splitting Bushars at both Rusail Power Plant and
Madienet as-Sultan Qaboos (MSQ) grid station
In addition to splitting the busbars at Rusail power plant as
shown in option 2, the 132 kV busbars at MSQ are split into
two groups as shown in Fig. 4.

Fig. 2: Before splitting.
Fig. 3: After splitting Rusail and Ghubrah
V. SHORT-TERM FAULT CURRENT LIMITATION RESULTS

A. Short-Circuit Results

Table I and Table II show the results of three-phase and single-phase to ground faults, respectively. If no action is taken, the fault current levels are well higher than the short-circuit rating at Rusail, Ghubrah and MSQ grid stations. As shown in Table I, the three-phase fault currents at these busbars are 40.8, 33.0, and 31.8 kA, respectively. Table 2 shows that the single-phase to ground fault currents at the same busbars are much higher. The IEC fault current calculation method is employed.

<table>
<thead>
<tr>
<th>Grid Stations</th>
<th>Max 1-Phase Short Circuit Current (I_f) (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Action</td>
</tr>
<tr>
<td><strong>132 kV Busbar, 31.5kA Fault Rated</strong></td>
<td></td>
</tr>
<tr>
<td>Rusail</td>
<td>NA</td>
</tr>
<tr>
<td>Rusail Group-A</td>
<td>NA</td>
</tr>
<tr>
<td>Rusail Group-B</td>
<td>NA</td>
</tr>
<tr>
<td>Ghubrah</td>
<td>40.4</td>
</tr>
<tr>
<td>Ghubrah Group-A</td>
<td>NA</td>
</tr>
<tr>
<td>Ghubrah Group-B*</td>
<td>NA</td>
</tr>
<tr>
<td>MSQ</td>
<td>36.2</td>
</tr>
<tr>
<td>MSQ Group-A</td>
<td>NA</td>
</tr>
<tr>
<td>MSQ Group-B</td>
<td>NA</td>
</tr>
<tr>
<td>Bousher</td>
<td>29.6</td>
</tr>
<tr>
<td>Wadi Adai</td>
<td>28.7</td>
</tr>
<tr>
<td>Wadi Al Kabir</td>
<td>17.5</td>
</tr>
</tbody>
</table>

NA: Not Applicable * Fault Rated = 26.5 kA

Option 1 leads to significant reduction in fault current levels for both 3-phase and 1-phase to ground cases, but fault currents are still higher than the ratings of circuit-breakers, thus this option is not acceptable. Option 2, i.e. splitting the busbars at Rusail, provides better results than option 1. It makes the 3-phase fault current levels below short-circuit ratings except at Ghubrah bus section rated at 26.5 kA. However, with option 2, the 1-phase fault current level although significantly reduced at Rusail but it is still high at Ghubrah and MSQ.

With option 3, i.e. splitting the busbars at both Rusail and Ghubrah, the fault level currents are below the short-circuit ratings of the concerned switchgear. This is true for either three-phase or single-phase to ground faults. From the short-circuit point of view, option 3 is the best short-term temporary solution. Option 4, may provide an alternative solution.

B. Load Flow Results

Load flow studies are performed to determine the impacts of applying the busbar splitting method to Oman main power grid. The DiGSIILENT software is employed. Table III shows the voltage profile at concerned busbars. In general, the voltages at most busbars are improved with option 3. For example, improvements of 1% to 3% are achieved in Rusail Busbar Group A, Ghubrah A and B, MSQ, Wadi Adi, and Wadi Al Kabir grid stations. A reduction of 1% is observed at Rusail Busbar Group A, but the voltage level (0.95 p.u.) is still acceptable.

Table IV shows that there will no significant changes in the transformer loadings due to the application of busbar splitting techniques.
TABLE III
VOLTAGE PROFILE (P.U.)

<table>
<thead>
<tr>
<th>132 kV Busbars</th>
<th>Voltage Profile (p.u.)</th>
<th>No Action</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rusail</td>
<td>0.96</td>
<td>0.98</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Rusail Group- A</td>
<td>NA</td>
<td>NA</td>
<td>0.94</td>
<td>0.95</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Rusail Group- B</td>
<td>NA</td>
<td>NA</td>
<td>0.97</td>
<td>0.99</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>Ghubrah</td>
<td>0.94</td>
<td>0.95</td>
<td>0.92</td>
<td>NA</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Ghubrah Group- A</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.95</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Ghubrah Group- B</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.97</td>
<td>NA</td>
</tr>
<tr>
<td>MSQ</td>
<td>0.93</td>
<td>0.94</td>
<td>0.92</td>
<td>0.96</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>MSQ Group-A</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.97</td>
<td>NA</td>
</tr>
<tr>
<td>MSQ Group-B</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>1.00</td>
<td>NA</td>
</tr>
<tr>
<td>Bousher</td>
<td>0.94</td>
<td>0.95</td>
<td>0.91</td>
<td>0.94</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>Wadi Adai</td>
<td>0.93</td>
<td>0.94</td>
<td>0.91</td>
<td>0.96</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Wadi Al Kabir</td>
<td>0.92</td>
<td>0.93</td>
<td>0.90</td>
<td>0.95</td>
<td>0.98</td>
<td></td>
</tr>
</tbody>
</table>

TABLE IV
SAMPLE OF PERCENTAGE TRANSFORMER LOADINGS (%)

<table>
<thead>
<tr>
<th>132/33 kV Transformer</th>
<th>Transformer loading (%)</th>
<th>No Action</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rusail (1)</td>
<td>49.3</td>
<td>48.5</td>
<td>50.1</td>
<td>49.5</td>
<td>48.2</td>
<td></td>
</tr>
<tr>
<td>Ghubrah (2)</td>
<td>38.5</td>
<td>39.6</td>
<td>37.6</td>
<td>42.1</td>
<td>44.2</td>
<td></td>
</tr>
<tr>
<td>MSQ (3)</td>
<td>85.1</td>
<td>84.3</td>
<td>86.8</td>
<td>82.5</td>
<td>81.78</td>
<td></td>
</tr>
<tr>
<td>Wadi Adai (3)</td>
<td>52.7</td>
<td>52.4</td>
<td>53.7</td>
<td>51.2</td>
<td>49.5</td>
<td></td>
</tr>
<tr>
<td>Wadi Al Kabir (3)</td>
<td>57.7</td>
<td>57.2</td>
<td>58.6</td>
<td>55.8</td>
<td>53.9</td>
<td></td>
</tr>
<tr>
<td>Mawallah (3)</td>
<td>79.3</td>
<td>77.7</td>
<td>78.5</td>
<td>76.4</td>
<td>75.3</td>
<td></td>
</tr>
</tbody>
</table>

(1) 4 x 75 MVA Transformers
(2) 2 x 42 MVA Transformers
(3) 2 x 125 MVA Transformers

New 220 kV and 132 kV overhead transmission lines will be constructed, in addition to about 20 new grid stations. A number of existing grid stations will be upgraded by replacing old transformers with larger capacity units. Details can be found in [11].

VI. LONG-TERM FAULT CURRENT LIMITATION

As a long-term permanent solution for the short-circuit issue, fault current limiting reactors can be used. Various technologies are discussed in [16] and [17]. In fact, it has been already planned to introduce major developments in the main power system in Oman during the years 2010-2013 [11] and [13]. Three new power plants are planned to be in operation by 2013. These are Sohar-II IPP (750 MW), Barka-II IPP (750 MW), and New Ghubrah IWPP.

Table V shows that the percentage line loadings are not significantly changed.

TABLE V
SAMPLE OF PERCENTAGE LINE LOADINGS (%)

<table>
<thead>
<tr>
<th>Line</th>
<th>Lines loading (%)</th>
<th>No Action</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>132 kV Lines, 261 MVA Circuit Rating</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rusail-Bousher</td>
<td>13.1</td>
<td>18.0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Rusail Group A- Bousher</td>
<td>NA</td>
<td>NA</td>
<td>14.5</td>
<td>6.2</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>Rusail-Sumail</td>
<td>44.8</td>
<td>41.6</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Rusail Group A - Sumail</td>
<td>NA</td>
<td>NA</td>
<td>37.1</td>
<td>37.1</td>
<td>35.6</td>
<td></td>
</tr>
<tr>
<td>Rusail-Mobellah</td>
<td>33.1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Rusail Group A- Mobellah</td>
<td>NA</td>
<td>NA</td>
<td>29.2</td>
<td>28.0</td>
<td>15.1</td>
<td></td>
</tr>
<tr>
<td>Rusail-Wadi Adai</td>
<td>23.7</td>
<td>21.4</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Rusil Group B - Wadi Adai</td>
<td>NA</td>
<td>NA</td>
<td>36.3</td>
<td>29.5</td>
<td>25.4</td>
<td></td>
</tr>
<tr>
<td>Rusail-Mowalleh</td>
<td>68.7</td>
<td>67.1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Rusil Group B - Mowalleh</td>
<td>NA</td>
<td>NA</td>
<td>67.7</td>
<td>66.0</td>
<td>65.0</td>
<td></td>
</tr>
<tr>
<td>Barka Main- Mobellah</td>
<td>42.3</td>
<td>17.8</td>
<td>40.9</td>
<td>37.0</td>
<td>29.0</td>
<td></td>
</tr>
<tr>
<td>Ghubrah-Bousher</td>
<td>39.8</td>
<td>41.6</td>
<td>33.8</td>
<td>NA</td>
<td>43.2</td>
<td></td>
</tr>
<tr>
<td>Ghubrah Group A-Bousher</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>40.5</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Ghubrah-MSQ Group A</td>
<td>29.2</td>
<td>28.7</td>
<td>21.1</td>
<td>NA</td>
<td>19.6</td>
<td></td>
</tr>
<tr>
<td>Ghubrah Group B-MSQ</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>19.5</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>MSQ Group A- Wadi Adai</td>
<td>69.0</td>
<td>79.0</td>
<td>61.2</td>
<td>59.5</td>
<td>60.4</td>
<td></td>
</tr>
</tbody>
</table>

NA: Not Applicable
Simulations studies have shown that splitting the busbars is an effective method to reduce fault currents to be within the equipment short-circuit rating. Splitting the busbars at Rusail power plant grid station has been successfully implemented in the field at no cost.

The various short-term options described in the paper provide the system operator with flexible tools to select the most appropriate operational arrangement to avoid the problems of high fault currents.

The long-term option using fault current limiting reactors can provide a permanent practical solution to the high fault current problem in transmission networks.

REFERENCES