Synchronization Process of Oman and UAE Electric Power Systems

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Abstract - Before connecting two large power systems for the first time, it is necessary to perform simulation studies to ensure that the synchronization process can be achieved successfully. This paper presents simulation studies and practical records of the synchronization and operation of Oman and United Arab Emirates electric power systems. The synchronizing process consists of the step-by-step actions to be implemented by the operators in order to energize the new equipment and synchronize both systems in a successful and secure way, taking into account the capability of the installed and available equipment of the grid, power producers and consumers. Synchronizing scenarios are simulated with the EUROSTAG tool, assessing on the one hand, the adequacy of the ampacity of grids’ equipment and the voltage on each node with their operational limits, and on the other hand, the stability and the electromechanical behavior of the whole system after each step of the synchronization process. Simulations are performed at minimum load conditions. It is usually more critical than for peak load conditions since fewer units will be operated to absorb the reactive power generated by the energized interconnection and there is a lower synchronizing torque to secure and damp the synchronization transients. Based on the simulation results, recommendations are made for the settings of the synchro-check automaton installed in the interconnection substation (maximum voltage amplitude, voltage angle and frequency deviations). Practical records of system frequency and emergency power exchange are presented to demonstrate the improvement in system performance after interconnecting the two systems.

Index Terms - Oman-UAE Interconnection, Synchronization, Synchro-Check Settings.

I. INTRODUCTION

There has been a considerable interest in the development of the Gulf Cooperation Council (GCC) interconnection project during the recent three decades. Details of the progress of the GCC interconnection project can be found in the GCC Interconnection Authority (GCCIA) website [1]. Briefly, the project consists of three phases:

Phase I: interconnecting the GCC North Grid which includes the State of Kuwait, Kingdom of Bahrain and State of Qatar and Kingdom of Saudi Arabia through a HVDC back-to-back interconnector. Phase I is operational.

Phase II: interconnecting the GCC South Grid which consists of the electrical power systems in the Sultanate of Oman and the United Arab Emirates (UAE).

Phase III: interconnecting the GCC North and South Grids, thus completing the interconnection of the six Gulf States. Successful completion of phase III has been officially launched on the 20th of April 2011.

The objective of the GCC interconnection is to provide economical, operational and technological benefits to the GCC countries [1]. This will improve security of supply and system reliability. The interchange of energy among the interconnected grids will reduce the total operating costs. The interconnection facilitates sharing of power generation reserves and installed capacity which can lead to optimization of investments in power generation and grid infrastructures. The interconnection can provide alternative energy sources to support individual systems during emergencies.

The objective of this paper is to present simulation studies required to ensure successful and secure synchronization of Oman and UAE electric power systems before actual interconnection. The two systems were first interconnected on the 14th of November 2011, and after a testing period, they have been in commercial operation since the 2nd of May 2012. The synchronizing process consists of the step-by-step actions to be implemented by the operators in order to energize the new equipment and synchronize both systems in a successful and secure way, taking into account the capability of the installed and available equipment of the transmission grid, power producers and consumers. The EUROSTAG simulation software has been used to simulate and assess synchronizing scenarios. The aim is to assess the adequacy of the transmission system equipment and to determine if the voltage on each node is within its operational limits. Also, it is necessary to test the stability and the electromechanical behaviour of the whole system after each step. Simulations are performed at minimum load conditions as it is usually more critical than for peak load conditions. In this case, fewer generating units are normally being in operation, thus limiting absorption capability of reactive power in addition to availability of a lower synchronizing torque to secure and damp the synchronization transients. The simulation results presented in this paper are based on recent Oman-UAE interconnection studies performed by OETC and Tractebel Engineering [2].

Additionally, assessment of Oman system performance is presented to show the system behaviours before and after real
operation with the UAE system. The recorded system frequency values and deviations have shown the improvement in system performance after connecting the two systems. Records have shown that the two countries support each other when either side is subjected to sudden shortage in generation.

Section II presents the system description and modeling. Section III explains the physical phenomena during energization. Section IV presents the simulation results. Section V analyses the recorded data. Section VI summarises the main conclusions and recommendations.

II. SYSTEM DESCRIPTION AND MODELING

A. Oman Power System

The Main Interconnected Transmission System (MITS) is owned, maintained and operated by the Oman Electricity Transmission Company OETC. It extends across the whole north of Oman on about 130,000 km² and interconnects electricity generating stations and bulk consumers located in the Governorate of Muscat, Bureimi, Batinah (South & North), Dhahirah, Dakhiliyah and Sharquiya [3]. Fig. 1 shows a geo-schematic diagram of the MITS.

The MITS is composed of two voltage levels: 220 kV and 132 kV. In general, the lines are fitted with double circuit except for the interconnection with Petroleum Development of Oman (PDO) [4]. The substations of 220/132 kV and 132/33 kV present an arrangement of two transformers in parallel. The 33 kV network is operated by the licensed electricity distribution companies, e.g. Muscat, Majan and Mazoon. Only the 33 kV primary substations pertaining to the 132/33 kV transformers are represented in the model. Together with the downstream load, they are represented by an equivalent load model.

In 2011, the MITS consisted of:
- 835 circuit-km of 220 kV overhead transmission lines
- 2970 circuit-km of 132 kV overhead transmission lines
- 12 circuit-km of 220 kV underground cables
- 64 circuit-km of 132 kV underground cables
- 6630 MVA of 220/132 kV transformer capacity
- 9239 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 eight 132/33 kV grid stations
- One 132/11 kV grid station

The bulk of the power transmitted through the main grid, is fed, through 220/132/33 kV, 132/33 kV and 132/11 kV grid stations, to the three distribution companies. A number of large private customers are connected directly to the transmission system either at 220 kV or 132 kV. Some of these customers have their own generation capability on site. For the peak of 2011, some customers inject electric power to the MITS.

In 2011, the MITS was supplied from 8 power stations: Rusail IPP (687MW), Ghoubrah Power & Desalination Plant (469MW), Barka-1 IWPP (434MW), Barka-2 IWPP (681MW), Sohar IWPP (605MW), Wadi Jizzi PP (290MW), Manah IPP (279MW), and Al Kamil IPP (297MW). The locations of these power stations are shown in Fig. 1. In addition, a number of temporary diesel-engine driven generators were connected directly to the 33 kV voltage level at some grid stations to support central generation for the summer peak demand. New power stations [5] have been introduced to the system in 2012. Those which will be introduced in 2013 and 2014 are not included in this study.

The interconnection is a 220 kV, 46.7 km transmission line between Al Foah substation in Abu Dhabi and Al Wasit (Mahadah) substation in Oman. The line consists of double circuits with twin Araucaria 821 mm² AAAC per phase. The line has been already in service since the 14th of November 2011.

B. Abu Dhabi Power System

The Abu Dhabi power system is described in more details in [2] and [6]. Briefly, it is composed of the 400kV and 220kV voltage levels. Abu Dhabi Island has a meshed sub-transmission network operated with 132kV voltage level. The main load centers are Abu Dhabi Island and surrounding areas and Al Ain city. The transmission system is operated by Transco Abu Dhabi. The system is connected to the rest of Emirates’ systems to form the Emirate National Grid (ENG), which consists of the following systems:
- Abu Dhabi Water and Electricity Authority (ADWEA)
- Dubai Electricity and Water Authority (DEWA)
- Federal Electricity and Water Authority (FEWA)
- Sharjah Electricity and Water Authority (SEWA)

There are 16 power plants connected to the Transco system totaling an installed capacity of approximately 12.3GW. Six SVCs are in operation in the Abu Dhabi system allocated partly (50%) to voltage control during steady state and partly (50%) to dynamic stability to enhance the voltage recovery after fault clearing.

C. System Modelling

Details of Oman-UAE interconnected system model are reported in [2], [6] and [7]. A brief description is given here. Each generator is represented by a dynamic model based on Park’s equations. It is assumed that the rotor has one damper winding in the d-axis and two damper windings in the q-axis. All the generating units are equipped with automatic voltage regulator and over and under excitation limiters. Most generating units in Oman are driven by gas turbines in an open cycle basis. Some are driven by steam turbines and some use combined cycle (gas plus steam) [5] and [7]. In the combined cycle power plants, the frequency response is usually achieved through the speed governor of the gas turbine part. Standard IEEE models are used to represent generator exciters, automatic voltage regulators, turbines and speed governors.
Transformer models include 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.

In Oman, the main transmission system comprises 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 $\pi$-equivalent circuit models are used to simulate the lines.

The system dynamic behavior is highly dependent on the assumptions adopted for the load. The load model structure is composed of a step down transformer connected to an equivalent LV feeder supplying in parallel a rotating load and impedance. To match the load flow power factor, fixed shunt compensation is connected at the secondary of the service transformer.

### III. Physical Phenomena during Energization

#### A. Expected Physical Phenomena during the Energization

Different kind of problems can possibly arise while energizing grid elements:

1) **Ferranti effect**: A synchronous resonance phenomenon observed when a shunt capacitor (e.g. line or cable shunt capacitance) is energized over a series reactance (e.g. line, cable and/or transformer reactance). The voltage at the end of the line/cable can be considerably higher than at the sending end. Preventive counteractions are:
   - Lowering the voltage at the sending end to lower the voltage at the receiving end.
   - Absorbing the reactive power with shunt reactors at the receiving end to lower the voltage rise.

2) **Generator reactive power limit**: An energized open ended 220 kV line or cable generates a net quantity of reactive power that has to be absorbed by the sending grid. This could cause generators to absorb additional reactive power up to an unacceptable amount for the generator (heating of the rotor windings) and/or for the angular stability of the grid (an under-excited generator is less stable). Preventive counteractions are:
   - Adequately select the first energizing sending side;
   - Lower the 220 kV energizing voltage to lower the reactive power generated by the unloaded energized line or cable;
   - Spread the reactive power absorption over more generators to reduce the reactive power to be absorbed by each involved generator.

3) **Transient voltage dips**: Reactor or transformer inrush currents cause transient voltage dips which could cause
machine tripping. A preventive counteraction is to increase the electrical distance from the energized transformer or reactor limits the voltage dip at the machines.

4) **Transient over-voltages:** Depending among others on the precise moment within the 50 Hz cycle each phase is closed and/or on the remnant magnetism in the energized reactor or transformer transient voltages can occur. A preventive counteraction is to lower the voltage at the sending end to lower the transient over-voltages.

5) **Ferro-resonance:** Interaction between capacitances and non-linear saturation characteristics of iron cores of reactors or transformers can in case of a weak source (low Short Circuit Level - SCL) providing insufficient damping cause ferro-resonance. Preventive counteractions are:
   - Lowering the voltage lowers saturation and thus the risk of ferro-resonance.
   - Higher SCL enhances the damping effect of generators and avoids the risk of ferro-resonance.

B. **Anticipated Physical Phenomena during the Synchronization**

Connecting two systems gives rise to voltage angle and power exchange oscillations. When the amplitude of voltage angle oscillations becomes too large, power exchanges can exceed the interconnection capacity and/or synchronization could fail by loss of synchronism between the systems and out of step protection operation. The voltage oscillations can be minimized by:

- minimizing the voltage angle difference at closing time;
- minimizing the frequency difference at closing time;
- minimizing the impedance between the systems (all interconnecting elements in service to increase the synchronizing torque between the two systems);
- higher voltage profile in the grid at closing time to increase the synchronizing torque between the two systems.

To be successful, the synchronization should only be attempted under limited voltage angle and frequency differences between the two systems. The optimal synchronization sequence can be explicated by the following sequence of breaker closing indicated in the Fig. 2:

Step 1: Circuit breaker 1 (CB1) is first closed at Al Foah side.
Step 2: The interconnection is synchronized by closing the circuit breaker 2 (CB2) on Al Wasit side.
Step 3: The second circuit is energized by closing the circuit breaker 3 (CB3).
Step 4: The second circuit is put in service by closing circuit breaker 4 (CB4).

The following aspects justify the proposed synchronizing sequence at minimum load:

![Interconnection Diagram](image-url)

**Fig. 2.** Interconnection diagram showing the synchronization steps.

**Step 1:** Closing CB1 permits to absorb the reactive power on the UAE side instead of the Oman side that would force the few units in service in Wadi Jizzi and Sohar to absorb large amount of reactive power.

**Step 2:** Closing CB2 synchronizes the two systems. At minimum load it is preferred to the closing of CB3 that would increase the voltage on the UAE side and therefore the reactive power to be absorbed after synchronization. The following constraints might arise:

- Reactive power constraint on the Wadi Jizzi side that translates at minimum load into a voltage differential constraint to provoke a reactive power flow from Oman towards the UAE. Alternatively, it translates into the check that there is sufficient reactive power absorption capability at the Wadi Jizzi and Sohar power stations.
- Angle difference constraint: The acceptable level will be quantified in the next section;
- Speed difference constraints: The acceptable level will be quantified in the next section.

**Step 3:** closing CB3. If this step poses a reactive power problem, the voltage profile and reactive flow could be adjusted between CB2 and CB3 closing actions. This can be easily performed by action on the Al-Wasit 220/132 kV transformers and on the 400/220 kV Dahma transformers.

**Step 4:** closing CB4.

**IV. SIMULATION RESULTS**

This section determines the voltage (reactive power), angle and speed synchronization limits to secure a successful synchronization. The obtained results define the margin with respect to the recommended settings of the synchro-check devices. The voltage amplitude, voltage angle and frequency deviations for a successful synchronization have been simulated and the obtained results presented hereafter.

For each of the 6 considered scenarios, the voltage at both terminals, the current, the active and reactive power flowing in circuit 1 are studied together with the machine speeds and frequencies in both Oman and Abu Dhabi systems to verify the system stability during the synchronization transient.

A. **Difference in Voltage Amplitude**

The voltage amplitude difference between both systems before synchronization is analysed. Simulations are carried out starting from a deviation of 20% and decreasing it until the acceptable difference has been found.
Scenario 1: Voltage amplitude in Al Wasit is 10% higher than in Al Foah.

When the voltage is higher in the Oman side the maximum difference in voltage is 10%. It will lead to an amount of MVAR flowing from Oman towards UAE after the synchronization of the interconnection (98 MVAR when closing CB2 and 2 x 70 MVAR when closing CB4). Fig. 3 shows the voltage at both extremities of the interconnection lines, current and active and reactive power flow.

Scenario 2: Voltage amplitude in Al Foah is 10% higher than in Al Wasit.

When the voltage is higher on the UAE side, the maximum difference in voltage that both systems can withstand is 10%. However, to achieve a successful synchronization, the units in Oman (especially Sohar and Wadi Jizzi units) have to be sufficiently excited to absorb the reactive power from UAE (99 MVAR when closing CB2 and 2 x 70 when closing CB4). Approximately 80 MVAR must be absorbed by WDJ GT8, GT9, GT11, Sohar GT1 and ST1 at minimum load. Fig. 4 shows the voltage at both extremities of the interconnection lines, current and active and reactive power flow. Fig. 5 shows the Reactive power absorption of Wadi Jizzi and Sohar units.

B. Difference in Voltage Angle

The objective is to identify the maximum voltage angle difference between both systems before synchronization. Simulations are carried on starting with an angle difference of 30° and decreasing it until the acceptable difference has been found.

Scenario 3: Voltage angle in Al Wasit is 30° higher than in Al Foah.

With a voltage angle difference higher in Oman by 30°, a step of current and active power appears just after the synchronization. Fig. 6 indicates a current peak of 0.98 kA and an active power peak of 370 MW in the direction of ENG. These values are initial values of an adequately damped transient. Indeed, steady state is reached after 10 seconds.

Scenario 4: Voltage angle in Al Foah is 30° higher than in Al Wasit.

With a voltage angle difference higher in UAE by 30°, a step of current and active power appears just after the synchronization. Fig. 7 indicates a current peak of 0.98 kA and an active power peak of 366 MW in the direction of Oman. These values are initial values of an adequately damped transient. Indeed, steady state is reached after 10 seconds.

C. Difference in Frequency

The objective is to identify the maximum frequency difference between both systems before synchronization that permits to synchronize both systems. Simulations are carried out decreasing progressively the frequency difference from $f_{Oman} - f_{UAE} = 0.75$ Hz between the two systems until the maximum acceptable difference is found.

Scenario 5: Frequency in Oman higher than the UAE.

The maximum found frequency deviation between the two systems is 0.6 Hz. Such a value leads to a large amplitude current peak and active power swings just after the synchronization. Fig. 8 displays the current and active power peaks reaching 2.18 kA and 636 MW respectively. The post synchronization steady state active power flows stabilizes around 2 x 177 MW towards the UAE system. Fig. 9 shows the frequency at both systems.
D. Combination between the Three Factors (Maximum Voltage Angle, Amplitude and Frequency)

Scenario 6: Combines all the variables previously simulated in one single scenario:

This scenario includes the following:

- Max voltage amplitude difference $\Delta V = 10\%$ which is 22 kV at 220 kV level, ($V_{\text{Oman}} - V_{\text{UAE}}$)
- Max voltage angle difference $\Delta \phi = 30^\circ$
- Max frequency difference $\Delta f = 0.6$ Hz ($f_{\text{Oman}} - f_{\text{UAE}}$)

The results indicate that if the interconnection line was indeed synchronized with the mentioned conditions, the two systems would synchronize and the transient would stabilize after 10 seconds. The peak of current and active power would reach 2.3 kA and 675 MW, which is compatible with the interconnection line protection settings. The results are shown in Fig. 10 and Fig. 11.

V. PRACTICAL RECORDS

The two power systems of Oman and Abu Dhabi were first synchronized on the 14th of November 2011 at 11:28 am. Measurements and records have been collected at both sides. Tables I and II show recorded values and variations in Oman system frequency before and after actual synchronization, including 13-15 November 2011, 27 January 2012, and 4 June 2012. Clearly, with the two systems interconnected, the frequency measured at Oman transmission network becomes tighter to its nominal value of 50 Hz.
As shown in Table I, the average frequency is reduced to 50.03 Hz during the day on the 15th of November (i.e. with the two systems interconnected) compared to average system frequency on the 13th of November before interconnection. Both maximum and minimum values of the frequency are closer to the nominal frequency of 50 Hz, thus indicating improved system performance after interconnection. The last two columns of the table show the recorded frequency during the day of minimum winter load and peak summer load in 2012, respectively. Again, the frequency is tighter to its nominal value of 50 Hz.

The recorded frequency deviation is significantly reduced as shown in Table II. During almost all times of the day on the 15th of November, the frequency deviations remains within 49.9 Hz to 50.1 Hz, except for two minutes only the frequency deviation was within 50.1 Hz to 50.2 Hz range. Before synchronization on the 13th of November, the accumulated time during which the frequency deviation in this range was 238 minutes, i.e. about 4 hours. The frequency deviation records during the days of the 2012 minimum and maximum loading conditions listed in the last two columns of Table II confirms the improved achieved in frequency behaviour in Oman transmission system when it is interconnected with UAE grid.

### Table I

<table>
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<tr>
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<tbody>
<tr>
<td>Average frequency (Hz)</td>
<td>50.045</td>
<td>50.055</td>
<td>50.03</td>
<td>50.01</td>
<td>50.03</td>
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<tr>
<td>MAX of the day (Hz)</td>
<td>50.18</td>
<td>50.17</td>
<td>50.11</td>
<td>50.12</td>
<td>50.09</td>
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<tr>
<td>MIN of the day (Hz)</td>
<td>49.91</td>
<td>49.94</td>
<td>49.95</td>
<td>49.95</td>
<td>49.97</td>
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### Table II

<table>
<thead>
<tr>
<th>Frequency Deviation</th>
<th>Time in minutes</th>
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<tr>
<td>Below 49.5 (Hz)</td>
<td>0 0 0 0 0</td>
</tr>
<tr>
<td>49.5 to 49.8 (Hz)</td>
<td>0 0 0 0 0</td>
</tr>
<tr>
<td>49.8 to 49.9 (Hz)</td>
<td>0 0 0 0 0</td>
</tr>
<tr>
<td>49.9 to 50.1 (Hz)</td>
<td>1202 1291 1438 1436 1440</td>
</tr>
<tr>
<td>50.1 to 50.2 (Hz)</td>
<td>238 149 2 4 0</td>
</tr>
<tr>
<td>50.2 to 50.5 (Hz)</td>
<td>0 0 0 0 0</td>
</tr>
<tr>
<td>Above 50.5 (Hz)</td>
<td>0 0 0 0 0</td>
</tr>
<tr>
<td>Total minutes (24x60)</td>
<td>1440 1440 1440 1440 1440</td>
</tr>
</tbody>
</table>
Fig. 12. Recorded power flow in interconnections with the MITS during the 320MW tripping incident.

Fig. 13. Recorded frequency in the MITS due to the tripping incident.

Fig. 13 shows acceptable frequency response in Oman. At off-peak load, with the mentioned operating conditions, the maximum reactive power absorbed by the ENG system would be 2 x 29 MVAR. The peak of current and active power would be reduced to 0.78 kA and 302 MW. The power flow towards ENG would be limited in steady state to 2 x 63 MW. The above settings are in use by system operators who are successfully performing the synchronization process.

Practical records of frequency measured in Oman system indicate improvement in system performance after being interconnected with UAE grid. Both countries have benefited from the existing 220 kV interconnector by supporting each other when either side is subjected to a sudden shortage in generation.

VI. CONCLUSIONS AND RECOMMENDATIONS

The simulations results have shown that both systems are able to withstand the synchronization process with large difference of voltage amplitude (10% of the nominal voltage in the 220 kV), voltage angle (30°) and frequency (0.6 Hz). At minimum load, the Oman side generating units of Wadi-Jizzi and Sohar should be capable to absorb reactive power generated by the off load 220 kV interconnection lines. To avoid this problem, it is recommended to synchronize with a voltage at Oman side higher than the Abu Dhabi side and/or keep an absorption margin of 70 MVAR on the close located units connected to the Oman system (Wadi Jizzi & Sohar).

The following recommended synchro-check device settings permit to perform a satisfactory synchronization with an adequate margin and a limited stress imposed to the system:

- Max voltage difference $\Delta V=5\%$ which is 11 kV at the 220 kV level, $(V_{Oman}>V_{UAE})$.
- Max voltage angle difference $\Delta \varphi = 10^\circ$, and
- Max frequency difference $\Delta f = 200$ mHz.

At off-peak load, with the mentioned operating conditions, the maximum reactive power absorbed by the ENG system would be 2 x 29 MVAR. The peak of current and active power would be reduced to 0.78 kA and 302 MW. The power flow towards ENG would be limited in steady state to 2 x 63 MW. The above settings are in use by system operators who are successfully performing the synchronization process.

VII. REFERENCES