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DEVELOPMENT OF STABILITY PROTECTION FRAMEWORK IN OMAN ELECTRICITY TRANSMISSION SYSTEM

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Abstract

This paper discusses potential extreme scenarios which could result in unstable conditions on the main interconnected electricity transmission system of Oman. Case studies on loss-of-stability scenarios between different parts of the network are examined. The objectives of the study are to identify possible locations of the electrical centre of swing and to develop an approach for controllable system splitting. A controllable splitting approach has been proposed and sensitivity analysis has been utilised to identify potential locations for controllable system splitting. In the final recommendations, trade-off considerations should compare the introduction of a system-wide out-of-step protection framework and its associated potential complications versus alternatives (e.g. improved protection performance).

1 Introduction

The Oman Electricity Transmission Company (OETC) initiated the swing study project undertaken by Parson Brinckerhoff (consulting engineers) [11]. Extreme and complex contingencies are observed as rare events in power system practice. These can potentially bring disintegration of the system and other unpleasant consequences including stability concerns. Angular instability or unstable power swings can arise as an outcome of selected uncommon conditions. System analysis should reveal the actual possibility of occurrence of unstable angular swings. Controllable system separation has found an application in utilities around the globe as a surviving countermeasure, subject to the outcome of studies and practicalities.

The swing study project assessed the possibility and consequences of extreme and complex contingencies. Those can be caused for multiple reasons, resulting in unacceptable conditions including angular instability, or unstable power swings. The usage of controllable system islanding is a practice accepted by many utilities. It prevents a total system blackout and interrupts unstable conditions. This solution is referred to as a stability protection framework.

Extensive power system modelling was undertaken using DIgSILENT software and the dynamic models for multiple study years. The dynamic models of open and combined cycle gas and steam turbine generators have been utilised to show system dynamic performance under critical fault conditions.

The swing study project considered a range of extreme and complex scenarios applied to the OETC grid in order to address specific types of rare events. These include:

- Delayed clearance of a short circuit;
- Tripping of both faulted and un-faulted circuits;
- Interruption of a transmission corridor;
- Unexpected loss of a single power plant.

Section 2 of the paper describes the transmission system of Oman; Section 3 outlines system modelling; Section 4 analyses severe scenarios leading to angular instability (unstable power swings) in the 2011, 2013 and 2014 year configurations; Section 5 presents a splitting example; Section 6 addresses an influence of air conditioning; Section 7 discusses the instability protection framework issues relevant to the OETC grid; and Section 8 summarises the main conclusions and recommendations.

2 Oman Electricity Transmission System

The Main Interconnected Transmission System (MITS) of Oman extends across the whole of the northern region and interconnects bulk consumers and electricity generators located in the Governorate of Muscat and in the regions of Batinah, Dhahirah, Dakhliyah and Sharquiya [7]. Figure 1 shows a geo-schematic diagram of the system in 2013, with two operating high voltages, i.e. 220 kV and 132 kV. The MITS of the 2013 configuration will be supplied with electricity generated from 11 gas-based power stations namely: Ghubrah (317 MW), Rusail (687 MW), Wadi Al-Jizzi (256 MW), Manah (279 MW), Al-Kamil (282 MW), BarkaI (434 MW), Barka-II (679 MW), Barka III (750 MW), Sohar I (605 MW), Sohar II (750 MW) and Sur Phase I (500 MW). In 2014, the total generation at Sur will reach 2000 MW [7]. Rusail, Wadi Al-Jizzi, Manah and Al-Kamel power plants have open-cycle gas turbines. The remaining plants are of combined-cycle type; i.e. gas and steam turbines. The transmission system may import generation from direct connected customers such as Sohar Aluminum Company, Oman Mining Company, Sohar Refinery Company and Petroleum Development of Oman (PDO). The MITS of Oman is interconnected at 220 kV with the transmission system of the United Arab Emirate within the framework of the Gulf Cooperation Council (GCC) interconnection scheme. The Oman/UAE interconnection 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.

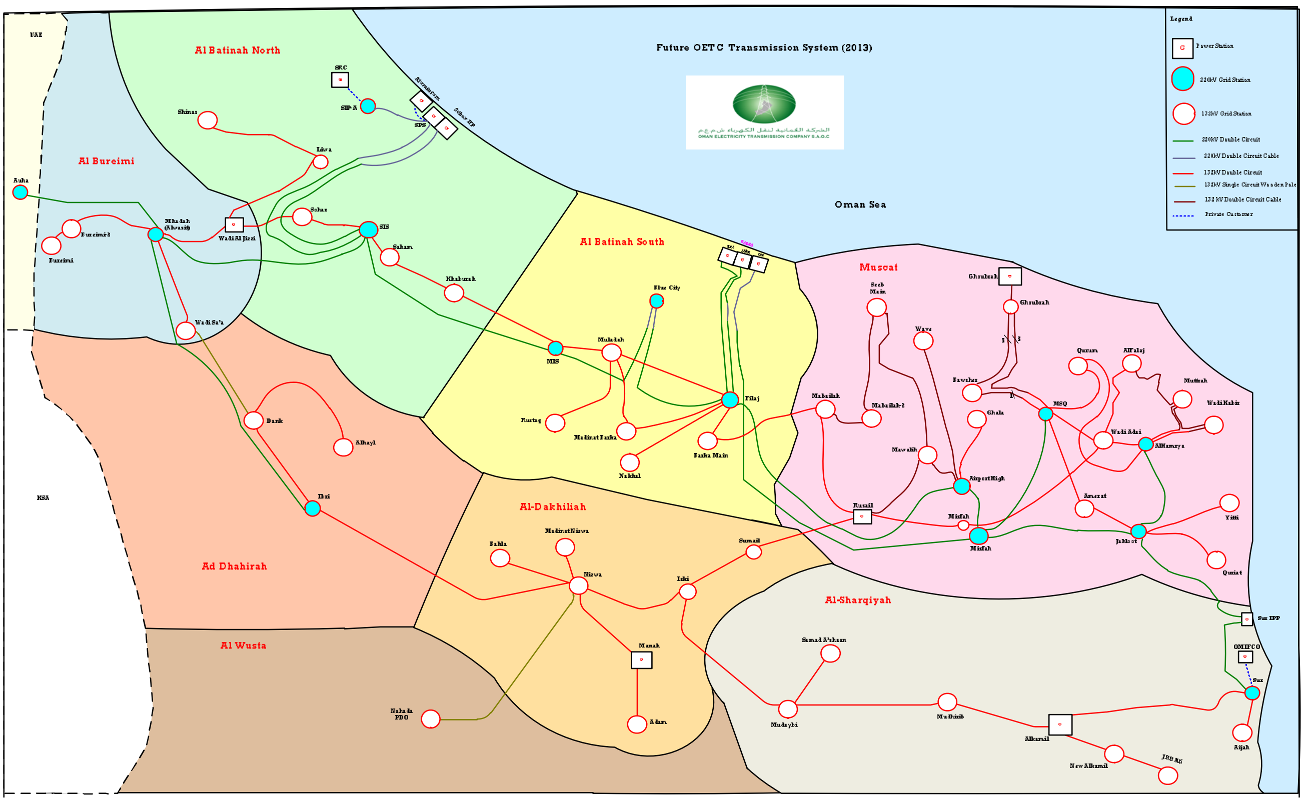

Figure 1. Planned Main Electricity Transmission System of Oman in 2013.

The bulk of the power transmitted through the main grid, is fed, through 220/132/33kV, 132/33kV and 132/11kV grid stations, to the three distribution license holders, i.e. Muscat Electricity Distribution Company, Mazoon Electricity Company and Majan Electricity Company. In addition to the distribution companies a number of large private customers are directly connected to the main transmission system at 220 kV or 132 kV level. In 2011 the system gross peak demand was 4000 MW occurred at 15:00 hours on 18 June 2011, which represented an increase of 10.68% from 2010 peak demand (3614 MW).

3 System Modelling

Extensive power system modelling was undertaken using DIgSILENT software and the dynamic models of excitation automatic voltage regulators, and turbine speed governor systems of the MITS for multiple study years. Modelling details are available in [8]; the main dynamic component models are briefly described as follows:

3.1 Synchronous Generators

The OETC power system comprises synchronous generators of a round-rotor type in the 11 power stations. The rating of these turbo-generators ranges from 13.4 MVA for the smallest old unit in Ghubrah IWPP to 425 MVA for the largest steam unit in Sur IPP. 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.

3.2 Prime mover and governor systems

Most generating units in the OETC system are driven by gas turbines in an open cycle basis. Some are driven by steam turbines and few use combined cycle (gas plus steam) [8]. These include conventional separate steam turbines or steam turbines as part of a combined cycle configuration. To achieve maximum efficiency, in the combined cycle power plant, the governor valve of the steam part is made insensitive to frequency variations, since the frequency response is usually achieved through the speed governor of the gas turbine part.

3.3 Excitation systems

Various types of excitation systems are employed to provide the DC field magnetization for the synchronous generators. These include rotating and static types [8]. The IEEE Type AC1 model is used to represent a brushless Permanent Magnet Generator (PGM) excitation system. It comprises a rotating diode system feeding the field of the synchronous generator from an AC exciter whose field is driven by a thyristor converter fed from a PMG. The second type of excitation systems (brushless ET) is similar to the first one mentioned above, but the converter is supplied from the generator terminals via an Excitation Transformer (ET).

3.4 External systems

Dynamic equivalents of Sohar Aluminium Power Plant (SAPP) and PDO system have been derived. These influence the stability processes in question and characteristic representation of equivalents has been included in the model. The UAE system dynamics are not represented in this study.

4 Swing Studies

An extensive range of system studies was carried out for the 2011 and 2013 OETC system configurations; selected issues for the year 2014 configuration were also addressed. Extreme scenarios included: estimation of critical clearing time (CCT), blackouts of a single power plant with simultaneous removal of multiple generators, the full opening of selected transmission corridors and, finally, the loss of stability of radially connected single power plants.

4.1 Critical Clearing Time (CCT)

The CCT for multiple 220 kV and 132 kV locations were calculated as follows:

Year 2011

- 220 kV: Sohar Interconnection substation (SIS) to Sohar Power Plant (SPS), Filaj to Barka and Musanna Interconnection (MIS) to SIS.
- 132 kV: Bousher – Ghubrah A and MSQ - Ghubrah B.

Year 2013

- 220 kV: Jahloot-Sur, Sur PS-Sur, Barka III-Cable Terminal, IPP Sohar-SIS, SIS-SPS and Filaj–Barka.
- 132 kV: Sur – Al Kamil, Old Ghubrah–New Ghubrah, and New Ghubrah–MSQ.

Year 2014

- 220 kV: Sur PS-Jahloot, and Barka–Filaj.

System configuration in 2014 is mainly concentrated on the uprating of the Sur PS power plant as a production centre of 2000 MW, interconnected primarily by two double-circuit lines, i.e. four circuits of quad Yew conductors in each phase. These lines are designed to 400 kV standards but operated initially at 220 kV level. This most important corridor is secured to (N-2) level, as it transmits bulk power from Sur PS to the load centre in Muscat area. A similar double-circuit line is also extended from Sur PS to Izki grid station.

The CCT for a 3-phase fault at 1% of Sur PS-Jahloot line is 270 ms, and at 1% of Barka-Filaj line 410 ms, the fault is cleared by disconnecting the corresponding faulted circuit.
Examination of CCT results has revealed that the year 2013 configuration demands smaller CCT values, resulting in the least stable margin compared with other study years. Further studies concentrated on largely on the year 2013.

4.2 Blackouts

A number of blackouts of a single power plant were examined for the year 2013 model including:

- Blackout of Barka IPP.
- Blackout of Sur PP, and
- Blackout of Sohar PP.

4.3 Interruption of transmission corridors

The interruption of transmission corridors examined the following connections for the 2013 configuration:

- The corridor between Filaj and Airport High.
- The corridor between Filaj and MIS.
- Circuits heading southwards from SIS to Al Wasit.
- The corridor between Jahloot and Sur PP, and
- All connection between Jahloot and MSQ and Misfah.

4.4 Radial mode

The radial mode and grid splitting analysis was based on a loss-of-synchronism scenario for radially connected Sohar and Sohar Aluminium power plants.

4.5 Stability matrix

The outcomes of the above swing studies were summarised in a single instability matrix as based on the 2013 configuration. Table 1 lists some selected fault scenarios for 2013 system configuration. Angular instability in the OETC grid is possible following extreme events only.

Faulted Circuits or Disturbance	System is Unstable – Instability Modes							System is Stable with Non-Acceptable Operational Conditions
	Single Power Plant Accelerates		Inter-machine		Inter-machine + 2 Groups in Loop Initially		3 Groups	
	Sur PS vs Others	Kamil vs Others	Barka-2 ST1-2	Ghubrah ST5-6	SPS ST1 **G1**: All others SPS, Sohar II, SAPP & Wadi Al-Jizi **G2**: Others	Barka-1 ST1 Barka-3 GT1 **G1**:Barka-2 ST1 **G2**: Others	**G1**: Kamil, Barka III (excl. Barka III GT1), Ghubrah & Sur **G2**: Rusail, Manah, PDO **G3**: Others	
220 kV								
Jahloot-Sur PS	270							
Sur PS-Sur	290							
SPS-SIS					320			
Barka-Filaj			360(*)			330(*)		
132 kV								
MSQ-Ghubrah				730				
Sur-Kamil	970(*)	740(*)						1500(*)
Blackout of Power Plant (Loss of generation)								
Sur 426 MW, Sohar 750 MW								Yes
Loop Interruption (Disconnecting complete corridor)								
Filaj-Airport High							W/o SC	
Filaj-MIS, SIS-Wasit or Sur-Jahloot								W/o SC

Table 1: Instability matrix based on 2013 configuration.
(*) Depending on short-circuit location; W/o SC Without application of short-circuits; the CCT in the table is in ms.

An example of such events is significantly delayed operation of relay protection – e.g. 270 ms clearing time versus 120 ms normal clearing times of Main-1 and Main-2 OETC protection policy. Blackouts of Sur PS with a dispatch of 426 MW and Sohar PP with a dispatch of 750 MW do not cause angular instabilities or significant oscillations in the summer peak 2013 configuration. Interruption of certain corridors leads to angular instability, e.g. the Filaj to Airport Heights corridor analysed in the 2013 configuration.
Other considered cases – SIS to Al Wasit, Filaj to MIS, Jahloot to MSQ (and Hamryah) and Sur to Jahloot 220 kV corridors in the 2013 configuration – bring stable but operationally unacceptable system conditions.

5 Splitting Example

5.1 Unstable case

A significantly delayed (325 ms) three-phase short circuit next to the 220 kV Sohar IPP and SIS busbars is to be followed by multiple incorrectly removed 220 kV circuits. Every 220 kV line originated from SIS lost one circuits; this is an extremely unlikely but severe outage. Figure 2 and Table 2 summarise the unstable radial case for SPS and SAPP.

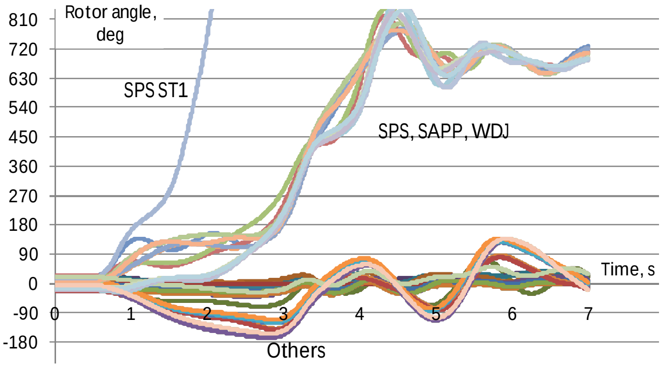

Figure 2: Rotor angle response - radial mode SPS & SAPP

Faulted and Tripped Circuits
SC: SIS to SPS 220 kV, circuit1, 50%, 325 ms. **Tripped:** SIS to SPS 220 kV, circuit 1, 325 ms
Initial Unstable Groups
3 Groups: 1. SPS ST1 accelerates. 2. SAPP, SPS, WDJ. 3. Others Up to time about 1 sec all Sohar II and SPS machines accelerate uniformly, with the same acceleration rates.
Location of ECS
Initial swing: Sohar IPP-SIS 220 Kv, SIS-SPS 220kV, ckt 2. **2nd swing:** Sohar II Tx GT1,2; Sohar II Tx ST1; MIS-SIS 220 kV_2; Nizwa-Ibri 132 kV, etc.
ECS Timing, sec
About 1.0-1.2 s, (first swing)

Table 2: Unstable radial mode for SPS and SAPP

5.2 Splitting case

The splitting strategy is based on a combined operation of a generator-dedicated pole slip protection with the grid-dedicated swing protection framework. The first one is an individual isolation of the SPS ST1 generator. An operation of a pole-slip protection associated with this machine was assumed at time 1.0 s. Then the remaining transiently unstable group of generators includes Sohar (I and II), SAPP and Wadi Jizzi power plants. They should be separated using an optimal surrounding splitting interface and providing the balance between generation and demand in the island.
An optimal location for controlled splitting was chosen based on tripping of six circuits, namely the 220 kV double circuit line MIS to SIS, 132 kV double circuit line Nizwa to Ibri, and MIS-Khaborah.
It was modelled as an action of the swing protection framework. Splitting timing is defined by observance of the 180° of angular difference between terminals of circuits where the Electrical Center of Swing (ECS) resides. Table 3 summarises the proposed splitting option. The resulting rotor angle diagram indicates a successful controllable tripping executed in two succeeding steps, as shown in Figure 3.

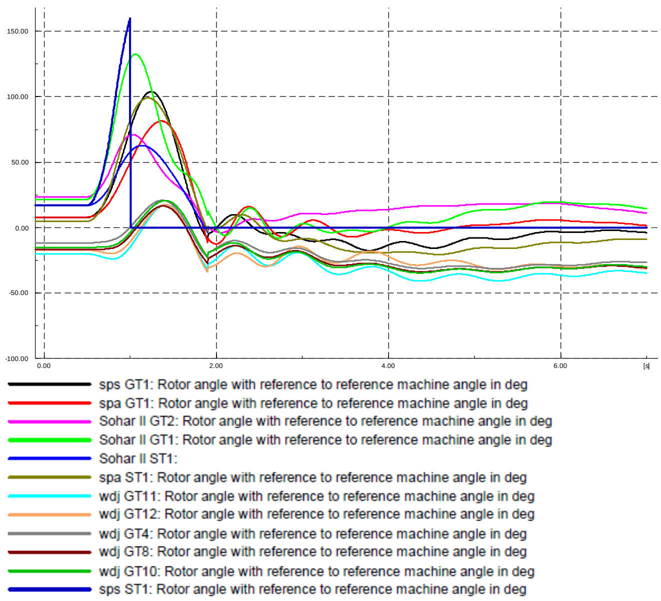

Figure 3: Response – with splitting of SPS & SAPP

Relay Protection Trips
SIS to SPS 220 kV, ckt 1, 325 ms
Out-of-Step (Swing) Protection Trips
SPS ST1: Pole-slipping protection, 1.0 s. 220 kV: MIS – SIS, ckt 1, 2: 1.8 s 132 kV: Nizwa – Ibri, ckt 1, 2: 1.7 s , MIS – Khaborah, ckt 1, 2: 1.9s
Islands
Unstable groups not detected. Two islands: - Sohar PP, Sohar II, SAPP, WDJ; - OETC.

Table 3: Splitting case for radial mode for SPS and SAPP.

The successful grid splitting interface was identified around Sohar and Wadi Al Jizzi (220 kV double circuit line MIS to SIS, 132 kV double circuit line Nizwa to Ibri, and MIS-Khaborah) demonstrated a potential surviving for the islanded parts of the OETC system. A possibility for earlier loss of synchronism exists for the Sohar steam generators in relation to other generators at the same power plant. Application of the pole slip protection for these machines is recommended.

6 Sensitivity Study – Air Conditioning

It was realised that air conditioning comprises a very significant proportion of the total consumption in the OETC system. A comparative study analysed influence of the induction motors on the unstable transients in OETC based on the 2013 model. Air-conditioning and motors were introduced as the rotating load extended with the static load modelling.
Different categories of consumers were modelled at distribution level of 33 kV, namely:

- Industrial.
- Industrial directly connected to the HV grid.
- Residential.
- Tourism.
- Commercial.
- Agriculture.
- Government.
- Auxiliaries and Desalination load.
- Aluminium industry.

A dedicated DIgSILENT model was established incorporating induction machines of small, medium and large sizes together with static demand on the individual node basis. Typical induction motor data were used; however, those are not suitable for simulations where motors stall.
Explicit representation of the induction motors leads to much complex and complicated unstable process just after first crossing of the 180° of angular difference between unstable groups of generators. Further transient will lead to the total collapse of the system from both the voltage and angle stability perspectives.
More detailed dynamic study addressing modelling of the high proportion of domestic air conditioning load would be beneficial in future.

7 Instability Protection Framework

7.1 Main driver

A high probability of encountering unstable conditions for a number of sequential years would be the main driver for the development of an instability protection framework. The probability of encountering an unstable condition is composed by a number of factors, namely: critical CCT values, rate of circuit breaker failures and rate of observance of extreme contingencies.
Continuous significant system improvements and good relay protection performance statistics would make the introduction of an instability protection framework less likely. This is supplemented by the fact that not every extreme contingency will trigger an angular instability phenomenon. Furthermore an account should take of the possibility of incorrect and missing operations from any new instability protection framework [3]. Re-engineering for UFLS would be needed to be efficient within each isolated island.

Finally, years spent on an instability protection framework development and implementation will effectively reduce the number of sub-sequent years when the framework might still be deemed necessary.

7.2 Guidelines

Guidelines for building an instability protection framework have been established to support OETC with an in-depth picture of the relevant specific issues. The OETC 220 kV and 132 kV network structure has been analysed from an instability perspective. The network structure for years 2011 to 2014 can be described as: *"A single loop structure with power plants and external equivalents connected radially to multiple nodes around the loop."*
The most general requirement states that any instability in the OETC system must be interrupted by splitting the most appropriate connections. Thus, if considered in future, the unified splitting framework should provide means to detect any unstable swings and split the system appropriately.
The following questions should be answered to facilitate the development process:

- Where to separate.
- When to separate.
- How to support islands.
- Is adaptive splitting feasible?
- How to make the framework less dependent on further extensive system studies.

Potential splitting subjects have been derived – the series circuits (legs) between generation busbars of the OETC loop as these border possible mutually unstable groups of generators. The year 2013 configuration holds eight legs: Filaj to SIS, SIS to Mhadah, Mhadah to Nizwa, Nizwa to Izki, Izki to Alkamil, Alkamil to Sur PS, Sur PS to Misfah (three different paths in parallel) and Misfah to Filaj as Figure 4 shows.

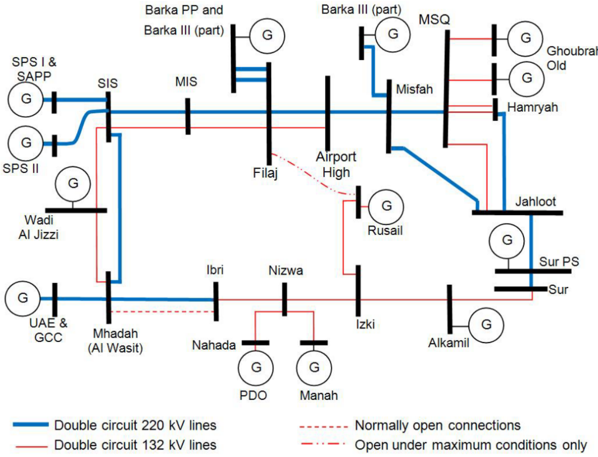

Figure 4: Structural diagram of the OETC network

The radial lines up to a particular power plant are probable splitting subjects also, subject to study results.

A combined analysis of the location of the electrical centre of swing (ECS) and modes of instability has been undertaken estimating study-based rather than potential splitting locations. This kind of examination is very useful in putting the basis for the out-of-step protection structure. The system studies recognised the splitting locations are wide-spread throughout the whole network.

It is recommended that the first swing protection concept be adopted, i.e. before the first angular difference of 180° in the system.

Analysis of dedicated splitting options has been undertaken demonstrating a successful example of a grid splitting interface. Studies showed the potential capability of separated islands to maintain stability, support voltages and frequency. System restoration plans should be in place to facilitate fast system restoration following controlled islanding.

7.3 Swing protection systems

Three technologically different groups of the swing protection systems could be considered for application in OETC:

1. Synchronised measurements of phasors in real time using Phasor measurement units (PMUs) and GPS satellite signals
2. Line differential protection technology, and
3. Based on the compensation (compounding) schemes.

The swing protection arrangement options can be summarised as follows: individual local devices, coordinated set of local devices, central control units and wide-area (or global) systems. The system response can be monitored in the following ways: behaviour confirmation, behaviour assumption and behaviour prediction [1,2,5,6,10].

The local systems can employ different monitoring approaches including the following: angle-based algorithms, $V\cos\varphi$ algorithm, energy function-based methods, incorporation into the differential protection technology, distance algorithms, detection of the pulsations, determination of existence of two or more frequencies and usage of artificial intelligence.

Opposing views exist in terms of trusting Phasor Measurement Units (PMUs) and synchrophasors to be a key element for out-of-step protection functionality [4, 9]. It is preferable for a utility to build a pilot project using PMUs in order to gain experience of their capabilities, e.g. monitoring and wide-area measurement systems (WAMS).

8 Conclusions

The OETC network structure is analysed from an angular instability perspective. The network structure for years 2011 to 2014 is described as: "*A single loop structure with power plants and external equivalents connected radially to multiple nodes around the loop.*" Series circuits (legs) between generation busbars of the OETC loop are effectively recognised as splitting subjects.

Angular instability in the OETC grid is possible only following extreme events. Examples of such extreme events are significantly delayed operation of relay protection or interruption of the Filaj to Airport corridor in 2013 configuration. Inter-machine loss of stability is also possible within a single power plant. Based on study results no development of an instability protection framework is recommended for the OETC power system up to year 2014.

A unified splitting framework could be developed based on clear functional and performance requirements, balanced against associated costs. Guidelines for the development of an instability protection framework have been elaborated. The most fundamental requirement to the framework is that any possible loss-of-synchronism case within the OETC network should be detected rapidly and system separation should be executed in the most suitable manner. However, a trade-off is possible between the most probable instability scenarios and all possible ones. It is recommended to adopt the first swing protection concept for OETC, i.e. detection and operation before the first angular difference of 180° in the system.

9 Acknowledgement

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