Innovative Approach of Improving Security of Electricity Supply of an Aluminium smelter against Power System Oscillations

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Abstract— A large industrial facility with their inhouse power generating sources, connected to the utility grid via high impedance interconnecting transformers, could experience low frequency oscillations when dispatch changes occur while having one of the interconnecting transformers offline for maintenance. Typical aluminium smelters have their own generators and substations along with high voltage grid connections, a detailed study for an aluminium smelter was conducted involving model reviews, operating condition replication, modal analysis, and RMS dynamic simulations to assess the risk of such oscillations and to analyze the possible measures under both normal and abnormal operating conditions in order to improve the Security of Electricity Supply to the smelter process. This paper presents the main outcomes of a case study and provides a number of recommendations including the need for better observability of oscillations via PMU's, ensuring a minimum level of system strength, installation of an Out of Step (OOS) Relay, Power Swing Blocking (PSB) and adhering to the system state limits such as maximum power transfer.

Index Terms – Low-Frequency Oscillations, Small Signal Stability, Out of Step protection, Power Swing Blocking, industrial facility network, Security of Electricity Supply (SoES).

I. Introduction

Low-frequency oscillations (LFOs), typically ranging from 0.1 to 2.5 Hz, pose a significant threat to the stability of modern power systems. These oscillations arise from electromechanical interactions among synchronous generators and are aggravated by long-distance power transfers, weak interconnections, and the increasing integration of converter-interfaced renewable energy sources. If not adequately damped, LFOs may lead to system instability, reduced power transfer capability, and even large-scale blackouts. The classification of LFOs typically includes local modes, inter-area modes, and control modes. Local modes involve oscillations of a single generator or plant, while inter-area modes occur between coherent groups of generators in different regions [1].

Emirates Global Aluminium (EGA) is one of the leading 'premium aluminium' producer in the world and is the largest industrial company in the UAE outside the oil and gas sector [2]. EGA-Jebel Ali (JA), together with the other main operating site, namely EGA-Al Taweelah (EGA-AT), have a combined production capacity of around 2.7 million tons per annum of hot aluminium metal.

For a short duration in an uncommon operating condition, one instance of an under-damped inter-area oscillation was observed at the smelter power system in Jebal Ali (JA). The defensive Special Protection System (SPS) deployed in the plant acted promptly to ensure avoidance of negative system impact. However, following this brief observation, EGA-JA proactively decided to identify any potential risks to their grid and to assess the possible mitigation measures against such power oscillations under normal and abnormal conditions, by conducting a detailed small signal stability study of the power system, also known as modal analysis, where eigenvalues and mode shapes are computed.

In the remainder of this paper, the main approach and outcomes of the analysis of this case study are further presented. In the next section, section II, the EGA network and the analysis of the observed oscillations within the case study are elaborated. The proposed corrective actions by means of adding an OOS relay at the interface of the facility is given in section III. Also, operational preventive actions are assessed which are discussed in section IV. Finally, section V outlines the main conclusions.

II. Case Study

A. The EGA-JA power system network

EGA-JA site has an installed capacity of approximately 3000 MW composed of 24 gas turbines, 6 condensing steam turbines and 2 back pressure steam turbines. Figure 1 presents the network layout highlighting the network configuration, generation & potline connections.

The network consists of three main 132 kV substations and three 33 kV substations connecting the different generation units. Between the 132 kV main busbars, series reactors are installed to limit the fault current levels. The High Voltage (HV) network of EGA-JA is connected to the utility network via two 400/132 kV Interconnecting Transformers (ICT) rated 300 MVA each. The potlines are all connected to the 132 kV bus bars of each respective substation within EGA-JA. Each potline is made of a recti-formers providing a constant DC current.

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At the LV end of the recti-former, the diode rectifiers deliver a DC voltage. A transductor adapts the commutation resistance of the recti-former to control the resulting DC current to the set value. This control is effective for small variations of the 132 kV voltage. For larger voltage variations, the DC current is restored to its set value through manual tapping of the regulating transformer by the operator. The recti-formers are interconnected to finally reach the nominal current required by the aluminum process.

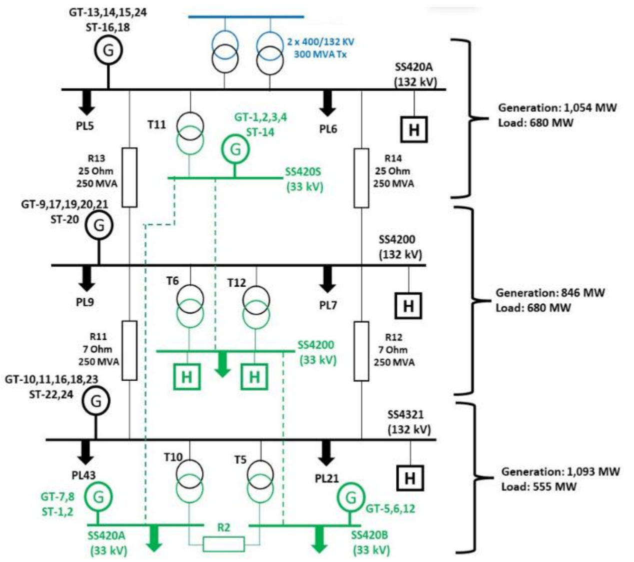

Figure 1 – EGA-JA Network (H represent the harmonic filters, dashed lines denote the 33 kV cable network)

B. Dispatch & network scenario description

Although, low frequency oscillations can occur in different operating conditions, the possibility increases during the night hours of the winter season, when the overall power grid remains lightly loaded, since major demand in the region is formed of air conditioning loads. For the case study under consideration, all the 132kV network elements were kept in service namely all the four series reactors, and all the bus sections of all three GIS substations, except one grid interconnector which was kept out of service to replicate a planned maintenance activity. However, as a result of multiple outages of the generating units, the fault level and voltage control at substation 420A was lower compared to usual operating conditions. Due to a weaker than usual system state and small changes in generation output, oscillations were observed and continued to grow. This continued until a number of equipment tripped due to the operation of the SPS whereafter the oscillations disappeared, and the system recovered.

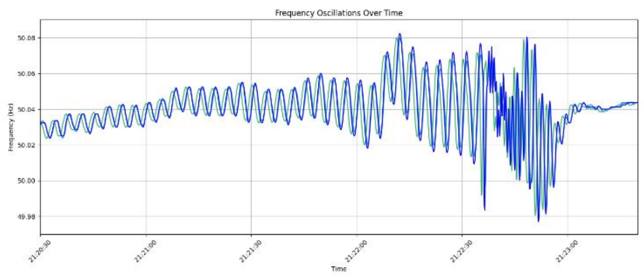

Figure 2 – Observed Frequency Performance

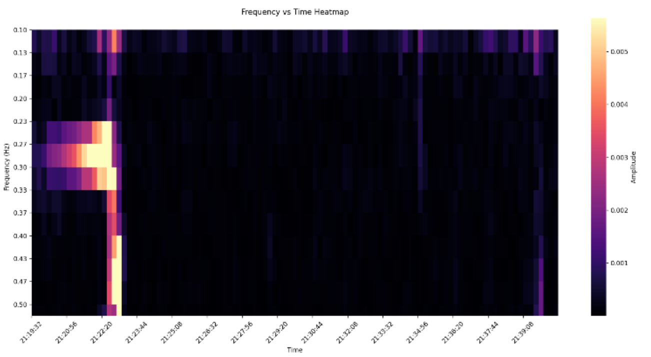

Figure 3 – Observed Frequency Performance via STFT

The oscillations observed on the simulated power system were of an Interarea mode of 0.26 Hz (period of 3.8 sec) during the negative damping phase, and mode of 0.47 Hz (period of 2.12 sec) during the positive damping phase after the set of disconnections.

The observed frequency during the case study is presented in Figure 2, while Figure 3 presents the Short-Time Fourier transform (STFT) spectrogram respectively.

C. System modelling & Modal analysis

The complete power system network of the EGA-JA as well as part of the external network have been modelled within the DIgSILENT Power Factory software tool. Next, using the method of Arnoldi-Lanczos, a small signal analysis was performed. This method makes it possible to determine the eigenvalues of a large system in the zone around the imaginary axis that is critical for the stability assessment.

The modes have been evaluated for the system state at the moment of change in the network (referred to as "case study") but also including the summer peak and winter minimum load states for year 2024 & 2025. Figure 4 presents the evolution of the inter-area mode with the 5, 10 & 15% damping lines presented.

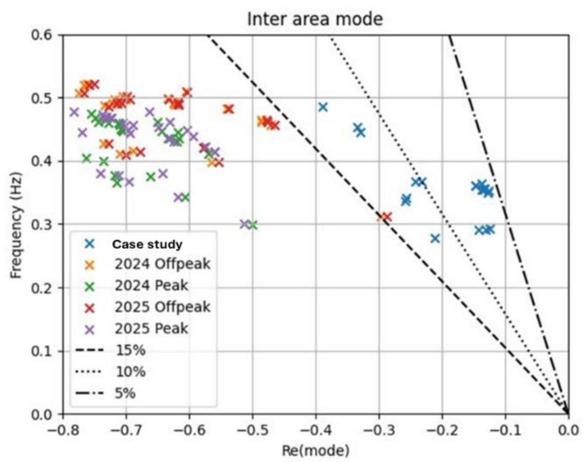

Figure 4 – Small-signal stability results for various system states

The frequency of the inter-area oscillatory mode resides in the region of 0.29 to 0.5 Hz. It can also be seen that the blue crosses, which correspond to the system state of the case study, show the closest frequency to the actual oscillatory frequency observed (0.26 Hz) as well as the worst damping.

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The participation factors of the inter-area mode have shown that the generating units of the smelter power system oscillate against the utility generating units.

III. Corrective Actions Applying Protection at Network Interconnection

A. *Power Swing Blocking (PSB) and Out of Step (OOS) protection*

Power swing blocking (PSB) is generally used in combination with a distance protection, where (certain zones of) the distance protection is blocked during (stable and unstable) power swings. The main philosophy of a power swing detection is to discriminate a power swing from a fault. This can be done by analyzing the impedance trajectory in the R-X plane. In particular, the rate of change of the positive-sequence impedance is the most used indicator to detect a power swing. This rate of change will be much slower during a power swing than during a fault. A logic with two blinders is illustrated in Figure 5 to discriminate a power swing from a fault. If the impedance seen by the relay stays between the inner and outer blinder longer than a predefined time, a power swing is detected, and the distance protection functions are blocked. By adding a functionality to the PSB in which protection functions are unblocked after a certain timeout period, a distinction can be made between a stable and an unstable swing. If after the timeout period the swing has still not stabilized, the block for selected zones can be released (unblocking), giving the opportunity to split the network.

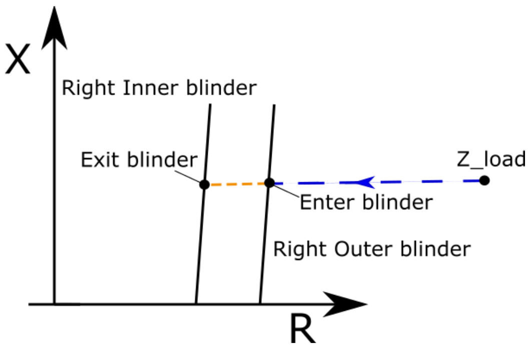

Figure 5 – Power swing detection with blinders

Another way of protecting the system is to apply Out of Step (OOS) Protection whose objective is to split the network in a controlled way in order to reduce the impact of unstable power swings. These relays must be placed at specific locations where it is possible to detect the Out of Step conditions. It is important to ensure that the split results in a number of coherent groups of units which are kept together in order to minimize the disturbances in each part of the separated network. To determine the best location for the Out of Step Protection, the coherent groups of machines must be determined as a first step. Therefore, identifying which machines belong to each group is a key step. The Electrical System Centre (or Swing Centre Voltage) needs to be identified as a second step. The voltage at the Electrical Centre will go to zero during a power swing and therefore analyzing the voltage profile allows to estimate it. It is illustrated in Figure 6 that the impedance seen by a relay close to the Electrical Centre or far from the Electrical Centre will be different. This emphasizes the benefits to install the Out of Step Protection relay as close as possible to the Electrical System Center.

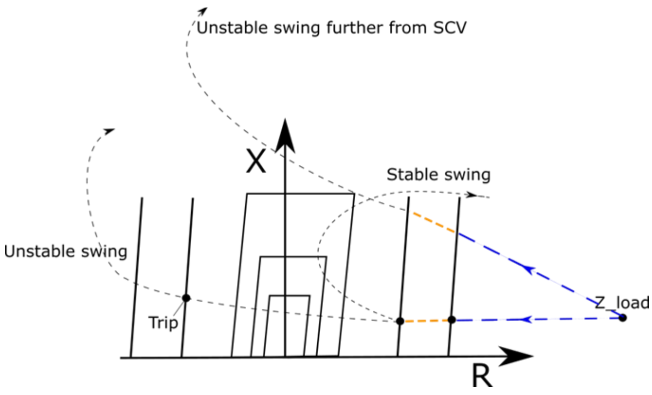

Figure 6 – Impedance trajectories that can be seen by a relay during power swings (SCV=Swing Center Voltage)

In this case coherency analysis has been performed by simulating three-phase faults successively at the interconnection and within the smelter power system with a duration leading to unstable power swings. When unstable cases are observed, the machines are grouped based on their rotor angle variations after the fault is cleared. From this analysis, it can be observed that most of the machines in the smelter facility remains coherent and will lose synchronism against the machines in the external network.

In order to determine the electrical center of the network under the given faults, the substation in which the minimum voltage occurred was identified for each unstable power swing. It can be observed that for the majority of the simulated cases, the voltage is the lowest at the EGA 420A 132 kV substation. This observation is valid for all simulated scenarios and is in line with the replication of the specific case study as presented in Figure 7. In this figure, it is clearly demonstrated that the units are becoming increasingly unstable as the oscillations grow which finally leads to an OOS situation. The potential actions of the SPS and generator/load protection within the EGA plant (which would have positive impact on the system behavior) are not simulated here and therefore represent the intrinsic behavior of the system.

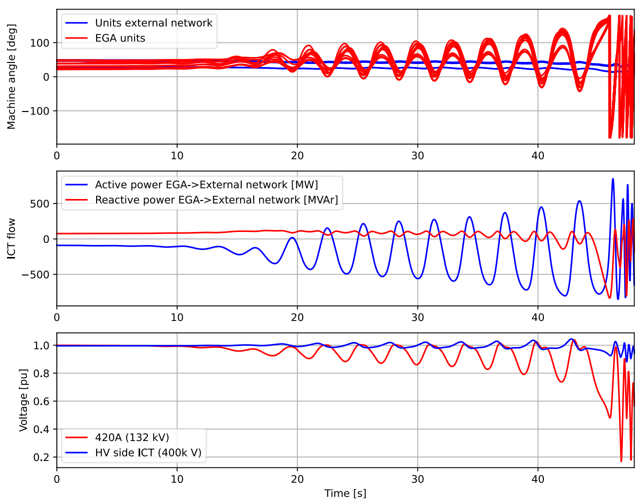

Figure 7 – Machine angles, ICT flow and voltage during unstable inter-area oscillation for the case study (Prior to the implementation of the PBS and OOS relay)

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B. Comparison of tripping based on OOS activation or unblocking PSB applied to the case study

Based on the analysis conducted, it has been recommended to install a dedicated out of step relay on the 132 kV cable bay at the 132 kV 420A substation. The different settings for the protection zones and blinders of the OOS and PSB functionality have been determined following the guidelines of the OEM. Two options remain:

Option 1: Have an alarm stage for sustained stable power swing oscillations via the Power Swing Blocking function and an action stage using the unblocking function after a certain timeout period. Tripping could take place before OOS detection.

Option 2: Have an alarm stage for sustained stable power swing oscillations via the Power Swing Blocking function and an action stage for unstable power swing oscillations via the OOS Protection function which trips the interconnection.

To compare the different options and to cross validate the operation of the out of step relay as well as its settings, power system simulations have been conducted using the simulation model replicating the state of the network of the case study. The goal is to ensure that as the inter-area mode increases in growing oscillations, the trajectory of the RX vector enters the associated zones, and the power swing blocking (PSB) or out of step (OOS) acts appropriately.

The RMS simulation results of option 1 are presented in Figure 8. It shows that, compared to the case without protection given in Figure 7, that after tripping, the inter-area oscillation is removed, and the external system recovers to a stable state. The protection within the smelter system should be able to also stabilize the islanded system (protection actions are not implemented, so simulations results after tripping are not representative).

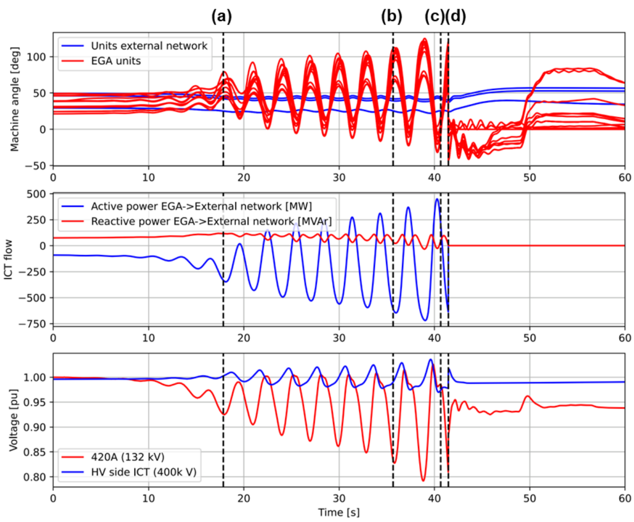

Figure 8 – Machine angles, ICT flow and voltage when option 1 is applied (Tripping is activated when PSB is released and RX trajectory enters impedance zone)

A step-by-step analysis of the RX trajectory is provided in Figure 9. At t=17.84s, the power swing enters for a first time the outer zone. The swing continues to grow and at 35.65s, the RX trajectory crosses also the inner zone (>25 ms to move from outer to inner zone, i.e. PSB timer setting to distinguish between fault and power swing). The relay is blocked for 5s (equal to the selected timeout period of the PSB functionality). At 40.65s, the relay is unblocked, and the RX trajectory finally enters the distance protection impedance zone at 41.45s at which a tripping signal is send. The main phase (a)-(d) are also highlighted in the corresponding time domain simulations of Figure 8.

In option 2, the PSB only trigger alarms in the control room when the growing oscillation is detected, and tripping is activated due to OOS protection. The simulation results are given in Figure 10. It shows that after tripping, the inter-area oscillation is removed, and the external grid recovers to a stable state.

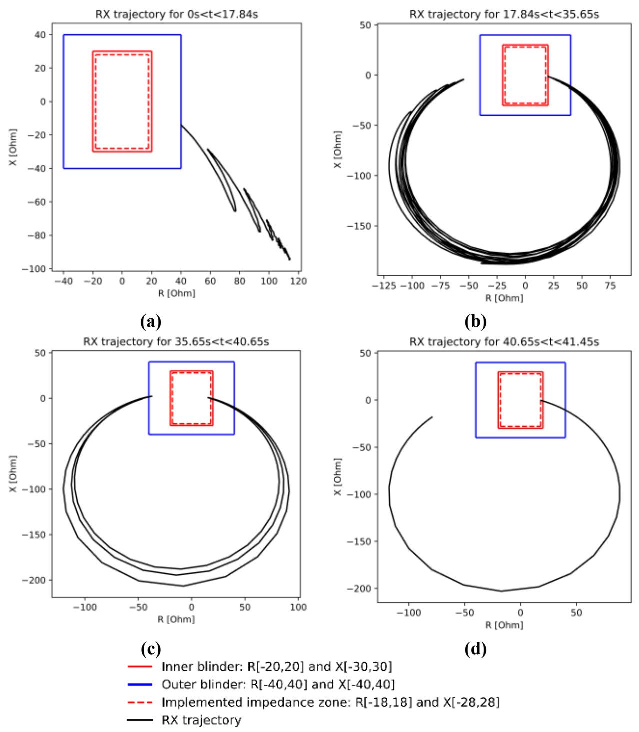

Figure 9 – Step by step analysis of RX trajectory for option 1

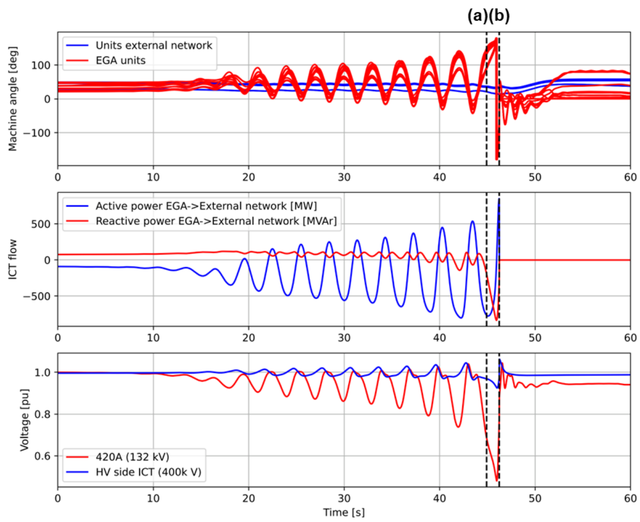

Figure 10 – Machine angles, ICT flow and voltage when option 2 is applied (Tripping is activated when OOS is detected)

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A step-by-step analysis of the RX trajectory is given in Figure 11. At t=44.93s, the power swing enters for a first time the inner zone at a positive R value and at t=46.24s the RX trajectory leaves the inner zone at a negative R value which results in a tripping signal. Compared to step-by-step analysis of the RX trajectory of option 1 in Figure 9, the tripping occurs later (46.24s instead of 41.45s).

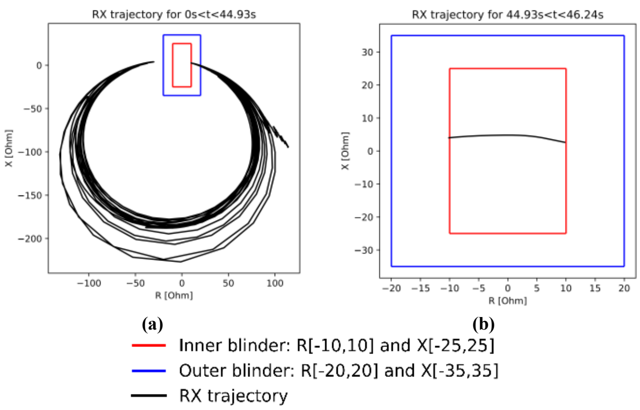

Figure 11 – Step by step analysis of RX trajectory for option 2

The main disadvantage of option 1 is that opening upon growing oscillations (depending on a fixed, predefined blocking period within the PSB function), might lead to unnecessary (i.e. too early) disconnection of smelter system before any of the potential defense actions taken by the SPS within the industrial network are activated which could safeguard the stability of the system. As negative damping leads to out-of-step conditions, the phenomena will be intercepted by the Out of Step protection anyway, therefore option 2 has been recommended.

The presence of a protection that can disconnect the smelter power system induces the need for smelter system to be prepared to operate in islanded mode and recover safely from the islanding transient in various possible operating conditions (export, import conditions). The system under this case study of the smelter power system has already been designed to operate in such island mode.

IV. Operational Preventive Actions to Reduce Risk of Undamped Oscillations

Besides corrective actions, a range of operating conditions have been further studied to analyze preventive operational measures to reduce the risk of undamped oscillations. The main recommendations are listed below:

- The analysis of the case study has demonstrated that the root cause is lack of system strength which led to poor damping during the specific operating conditions. Therefore, it is advised to keep a high level of short-circuit power at each substation and to ensure that both ICT transformers/series reactors are always in service, as this would reduce the impedance between smelter system and the external network. If this situation does not occur (due to a fault or planned maintenance condition) a clear notification should be given to both parties, and small signal stability assessment should be conducted based on the dispatch at that given time.
- To optimize operational decisions, and although not usual for industrial facilities with embedded generation, it is advised to increase the observability of such oscillations by using time synchronized recordings (PMUs) with high-resolution data at each 132 kV substation to monitor in real time the damping rate of the interarea, local and control modes. Early warning alarms of damping degradation should be issued in the control room to allow operators to take actions before the amplitude grows to unacceptable levels.
- It is advised to regularly revise the controllers in the plant i.e. mainly AVR & power system stabilizer to confirm that the damping factors display a positive margin for normal and worst credible operating conditions.

V. Conclusions

To address the potential stability concerns, which could aggravate due to growing low frequency interarea oscillations between the smelter facility and the external network, a study was performed to analyze the risk of frequency oscillations during different operating conditions as well as to provide countermeasures to mitigate these oscillations. This paper has presented a software based incident analysis of a case study as well as the approach applied to analyze the mitigation measures. By means of a small signal analysis on different operating points, a lack of system strength and reduced damping by the different machines has been observed in the case study resulting in recommending several preventive operational actions. As corrective measure, the focus was on analyzing the use of OOS relay with PSB function to send out alarms upon the detection of growing oscillations and disconnect as soon as OOS is observed. Both these operational and corrective measures have displayed great potential of improving Security of Electricity Supply of the Aluminium Smelter Power Supply System. RMS simulations were carried out to prove the effectiveness and accuracy of the applied relay settings.

VI. References

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