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Mitigating Extraordinary Events using Wide Area Monitoring Applications

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SUMMARY

Increased understanding of extraordinary events in the electrical power system is vital in order to develop and assign appropriate remedies to limit the presence and consequences of such events in the future.

In this paper extraordinary events are discussed in a generalised way, describing sequence and causes of historical events.
Results from a dynamic study of an improved description of the IEEE Reliability Test System 1996 are used to illustrate the importance of proper representation of a power systems dynamic behaviour in order to be able to study consequences of extraordinary events and the development of various remedial applications based on Wide Area Monitoring Systems.

KEYWORDS

System security – Extreme contingencies – Wide Area Monitoring Systems – Dynamic modelling

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1. INTRODUCTION

Power system operation and management requirements are escalating due to society's increased dependency on electricity as well as a continued evolution of the power system. A reliable supply of electricity is recognized as vital for the society, to which extreme contingencies pose a severe threat.

Reliability of a power system is composed by two aspects, adequacy and security, where adequacy relates to the ability of the system to satisfy the demand while security is related to the systems capability to withstand disturbances [1]. When addressing the reliability of power systems, the attention is often towards the steady state adequacy in supply and demand, rather than towards the dynamic robustness and contingency ride through capabilities of the system. Hence, many reliability assessment techniques are neglecting the dynamic aspect of reliability and only focusing on steady-state security and adequacy assessment of the power system.

Several security assessment techniques are available, with many of the online dynamic security assessment techniques described in [2]. There is, however, a need to further define security assessment indices, [3]. Challenges are also related to the modelling requirements for performing adequate dynamic analysis and to the assessment of consequences of extraordinary events from a simulation point of view.

This paper is organised as follows:

Section 2 includes a generalised description of extraordinary events. An introduction to wide area monitoring systems is given in section 3, and the results of a dynamic analysis are included in section 4. Planned further work is described in section 5.

2. EXTRAORDINARY EVENTS

Extraordinary events or extreme contingencies refer to disturbances in the power system with a potentially high societal impact and a low probability to occur. An extraordinary event often results in a wide-area interruption or a total blackout of the power system.

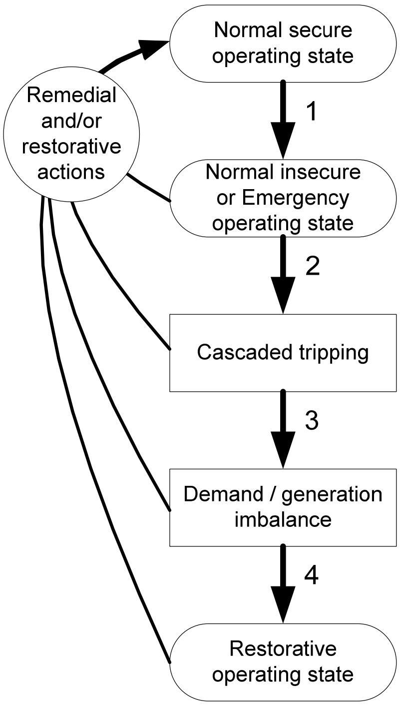
Due to the unpredictable nature of extraordinary events, difficulties arise to economically justify major reinforcements of the power system to prevent extraordinary events from occurring [3]. It is impossible to prevent all unforeseen event from occurring, there is however a potentially high economical incentive to limit the consequences of extraordinary events.

Increased insight into and understanding of these events is an important step in order to develop and assign appropriate remedies to limit the consequences of future events.

2.1 Sequence of events

Analysing the sequence of events of historical extraordinary events, several similarities can be found. The sequence of events depicted in Figure 1 corresponds to the generalised pattern described in [4]. A generalised sequence of events cannot be valid for all possible extraordinary events, nevertheless a generalised view is valuable when analysing remedial solutions to mitigate future extraordinary events.

As indicated in the figure, remedial actions are an important part at every stage of the event in order to limit consequences and to maintain integrity of the power system. Further discussion on generalised sequence of events can be found in [5] and [6].



1. The event is triggered by a failure with an unforeseen impact on the operation of the power system, moving the operation into an insecure state or even to an emergency state. Proper remedial actions are necessary to prevent the system from deteriorating.
2. In cases with insufficient preventive actions, the security of the power system is further declining and a fast cascaded tripping of lines and generation occurs due to overload and/or instability.
3. The power system gets sectioned into several islands, where the demand and generation experiences significant imbalance due to tripping of load and/or generation.
4. Inadequate emergency control or island operation lead to instability problems and partial or total blackout of the power system.

Figure 1: Generalised sequence of extraordinary events

2.2 Root causes

Root causes are the most fundamental aspects of an event, and are in [7] defined as: the cause that if corrected would prevent the recurrence of similar events. Hence, the identification of true root causes of historical events is an important task in order to mitigate future events.
Root causes are in general related to system operation, and analyses of historical extreme contingencies, e.g. [6, 8-9], describe several factors identified as root causes to the studied events. Two aspects of special importance recognised in [4] are: an insufficient situational awareness of the system operators and a general inadequacy of implemented schemes for controlled islanding.

3. WIDE AREA MONITORING SYSTEMS

Wide Area Monitoring Systems (WAMS) is identified as a field where applications could be efficiently utilised in order to increase the system reliability to extreme contingencies without major economical investments.
The breakthrough in wide area monitoring arrived with the development and installation of fast, reliable, and highly accurate Phasor Measurement Units, PMUs [10], utilised to supply a WAMS with time synchronised phasor data from a widely dispersed system. Typically WAMS have a relatively low time delay, providing almost real-time observability either of selected parts of the power system, such as vital transfer corridors, or of the entire power system if sufficient PMU installations are available.
The enhanced information made available by a WAMS enables improvements in many fields related to monitoring control and protection of the power system, two of them being: situational awareness and system integrity protection.

3.1 Situational awareness

Insufficient situational awareness is a common root cause in several historical events. The importance of situational awareness can be recognized from analysing the time available to take remedial actions, i.e. the time between triggering event and the instant when a wide-area interruption occurs. In several cases, this time can be considered long enough to implement manual emergency actions according to the operating practices. One of the reasons why sufficient actions were not taken in such cases could be the system operators' unawareness of the vulnerability of the situation. Hence, an improved monitoring system such as the WAMS could be utilised to increase the system wide situational awareness, with essential contributions to decrease the power systems vulnerability to extraordinary events.

3.2 System integrity protection schemes

In cases where the time period available for implementation of appropriate remedial actions is too short for manual actions, the need of automatic actions is called for. Applications for system control and/or protection to mitigate extraordinary events can be referred to as system integrity protection schemes, SIPS.

The main objective of a SIPS can be of two aspects, either to preserve the system integrity in case of emergency operation or to increase the system utilisation under normal operation. When designing a SIPS for either objective, it is important to consider the impacts the scheme might have on the other objective.

The input signals to SIPS are generally of a local nature and can be either event-based (detecting of predefined events) or response-based (measuring of electrical parameters). Commonly used SIPS, such as e.g. remote load shedding or generator rejection, tend to be event-based giving them the characteristics of being:

- fast and often related to the transient rotor angle stability and short-term voltage stability of the power system
- without protection against unforeseen events, implying that the consequence of the SIPS action might be hard to anticipate for all operating scenarios

Integration between wide area monitoring systems and SIPS is one possible solutions to decrease the vulnerability of unforeseen extraordinary events.

4. ANALYSIS AND RESULTS

In order to properly perform benchmark reliability assessment of various WAMS applications and extreme contingencies, the widely known IEEE Reliability Test System 1996 [11] is used. This is a test system designed for benchmark studies of reliability evaluation techniques. In the study model, an extended dynamic model has been used in order to more properly reflect the dynamic behaviour of a power system. The proposed extension of the IEEE Reliability Test System 1996 is described in [12].

The studied scenario corresponds to the peak load scenario and the system is studied after a sequential outage of four of the five transformers interconnecting the 230 kV and 138 kV transmission systems. Three different cases are studied:

- Case 1: no corrective actions taken after the outages of the four transformers
- Case 2: the fifth transformer is tripped 200 ms after the fourth transformer outage, separating the system into two islanded power systems
- Case 3: load shedding is performed to limit the deterioration of the system

The results displayed in the following figures are data which could be made available from PMU measurement and used as input to a system integrity protection schemes.

Figure 2, describes the bus voltage magnitudes before and after the outage of the fourth transformer. The curves marked with rings describe the voltages on each side of the last

remaining 230 / 138 kV transformer (bus 103 & 124). These voltages are of special interest in this study, since the link between the two sub-systems is very weak.
The left hand side of Figure 2 shows the voltages for Case 1. It is obvious that the system is on the brink of voltage collapse, and the integrity of the power system is severely threatened with voltages below 0.5 pu 300 ms after the outage of the fourth transformer.
The right hand side of the figure shows the voltages for Case 2. The system separation stabilises the islanded 230 kV sub-system, while the 138 kV sub-system island is further deteriorated towards voltage instability.

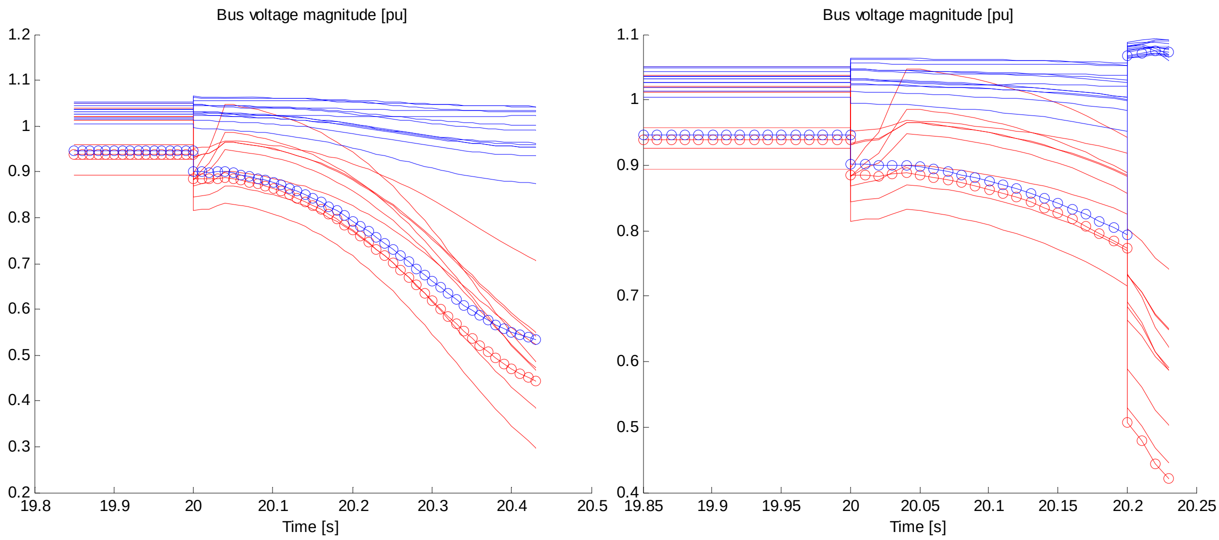


Figure 2: Bus voltage amplitudes [pu], left: Case 1, right: Case 2,
RED: 138 kV sub-system, BLUE: 230 kV sub-system

Figure 3 describes the system behaviour in Case 3. Here, load shedding is preformed in three stages sufficiently preventing further system deterioration and the system remains interconnected and returns to a new steady state.

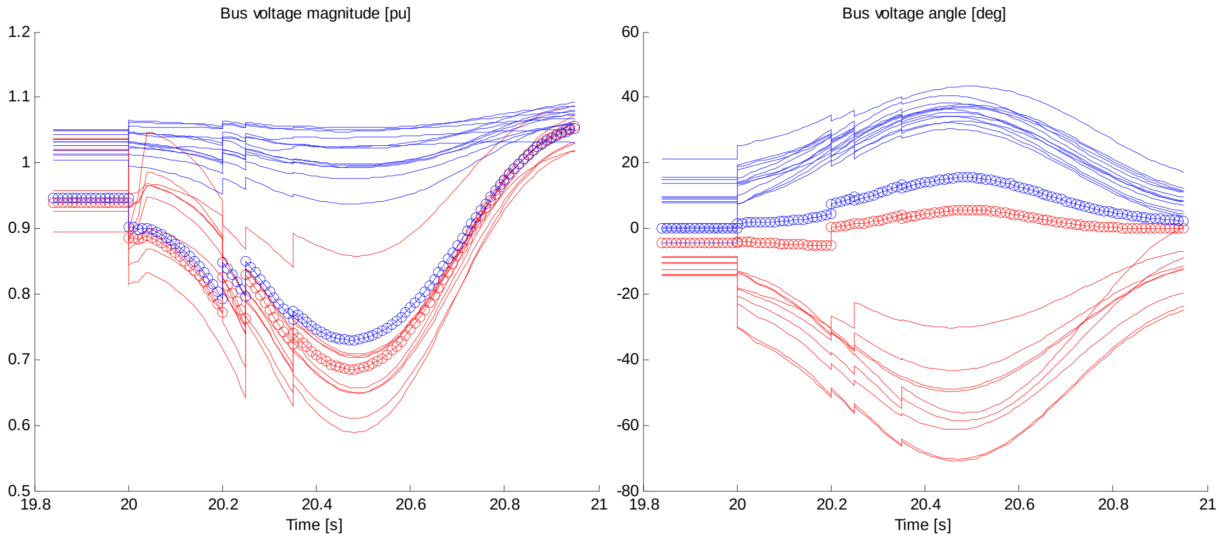


Figure 3: Bus voltage amplitudes [pu] (left) and angles [deg] (right), Case 3
RED: 138 kV sub-system, BLUE: 230 kV sub-system

Signals of special interest are shown in Figure 4, where the voltage vector differences of the high voltage buses and the frequency estimate are displayed.

Voltage vector differences are derived using bus 103 as a reference, $\Delta\overline{U}_i = \overline{\mathrm{U}}_\mathrm{i} - \overline{\mathrm{U}}_{103}$, and in the figure the magnitude of the voltage vectors differences are displayed using the sign of the angular difference to differentiate the voltage vectors, i.e.:

$$\Delta U_i = |\overline{\mathrm{U}}_\mathrm{i} - \overline{\mathrm{U}}_{103}| \times \frac{\mathrm{IM}\{\overline{\mathrm{U}}_\mathrm{i} - \overline{\mathrm{U}}_{103}\}}{|\mathrm{IM}\{\overline{\mathrm{U}}_\mathrm{i} - \overline{\mathrm{U}}_{103}\}|}$$

Local frequency estimates are calculated as the discrete time derivative of the bus voltage angles, $f_i = \frac{1}{2\pi}\frac{\Delta\theta}{\Delta t}$. In Figure 5, the estimated local frequency is displayed for a longer time interval showing the low damped oscillations in the 138 kV part of the transmission system. The frequency on the buses on each side of the last remaining 230 / 138 kV transformer (bus 103 & 124, displayed in green) are clearly distinguished from the other buses in the system.

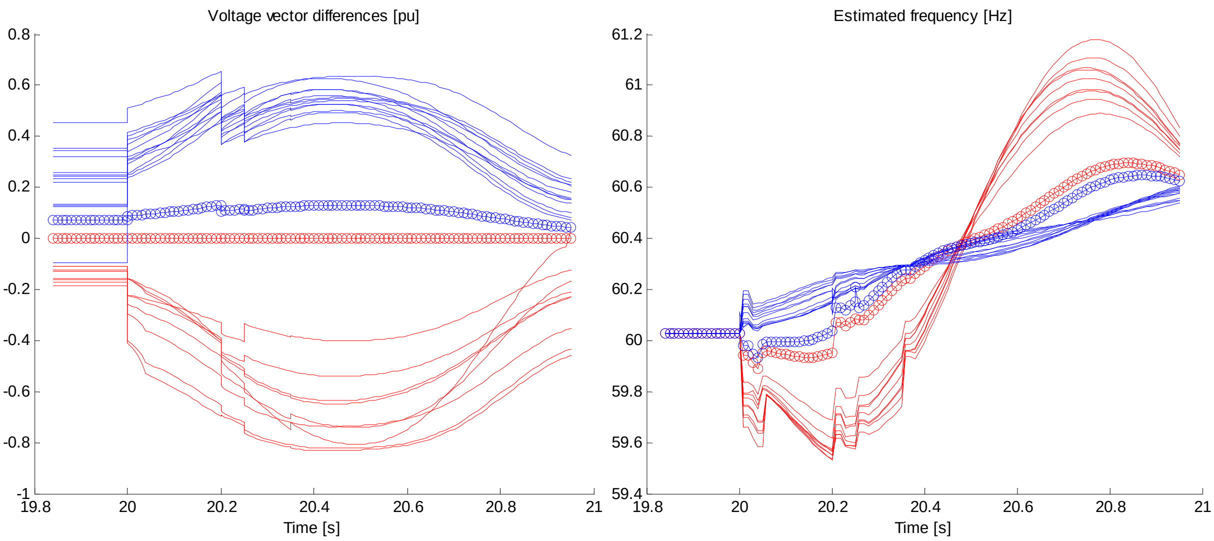


Figure 4: Bus voltage vector difference [pu] (rel. bus 103) and frequency [Hz], Case 3
RED: 138 kV sub-system, BLUE: 230 kV sub-system

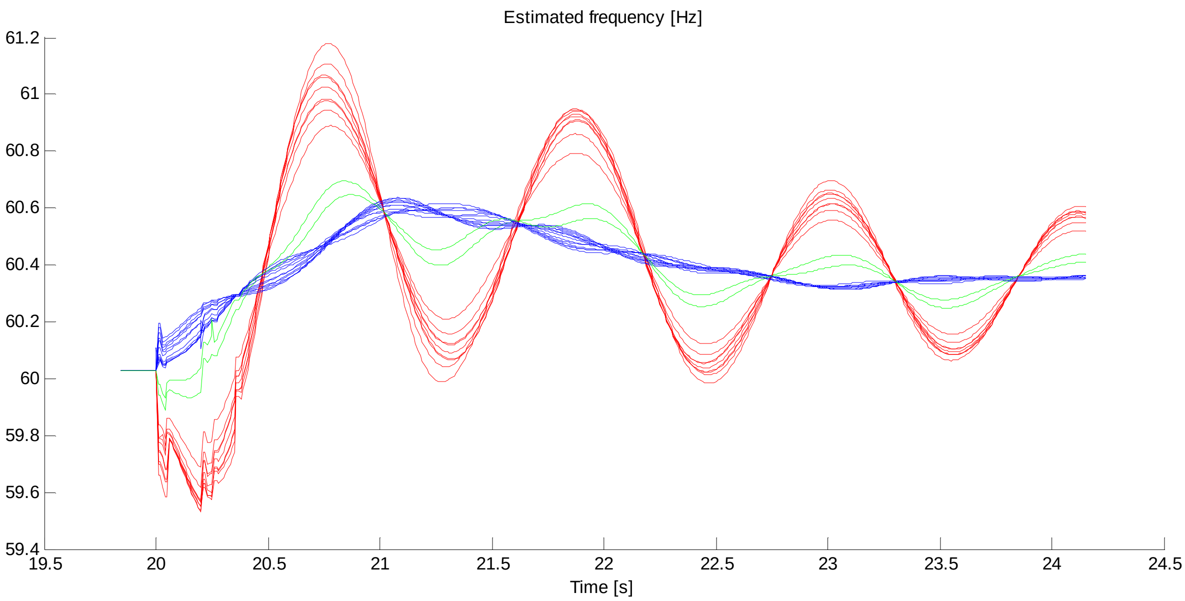


Figure 5: Estimated bus frequency [Hz], Case 3
RED: 138 kV sub-system, BLUE: 230 kV sub-system, GREEN: bus 103 & 124

5. DISCUSSION AND FURTHER WORK

Development of a wide area monitoring, protection, and control system is a topic of high interest. However, to properly assess the reliability impact of developed applications the R&D community need good power system models.

Further work includes specification of improved models describing dynamic behaviour of loads, reactive power compensation, power system stabilisers, tap-changer control and equipment protection of the IEEE Reliability Test System 1996.

Planned studies involve security assessment analysis of the impact of WAMS applications as well as HVDC interconnections between the areas of the IEEE Reliability Test System 1996.

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