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PHYSICAL AND TECHNICAL ENERGY PROBLEMS

APPLICATION OF SYNCHROPHASOR MEASUREMENTS FOR IMPROVING SITUATIONAL AWARENESS OF THE POWER SYSTEM

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The paper focuses on the application of synchrophasor measurements that present unprecedented benefits compared to SCADA systems in order to facilitate the successful transformation of the Nordic-Baltic-and-European electric power system to operate with large amounts of renewable energy sources and improve situational awareness of the power system. The article describes new functionalities of visualisation tools to estimate a grid inertia level in real time with monitoring results between Nordic and Baltic power systems.

Keywords: *dynamic parameter identification, phasor measurement, power system dynamics, wide-area monitoring*

1. INTRODUCTION

Power system operation is challenged by the “green shift”, which is characterised by more extreme variations, faster and larger changes and uncertainty in generation and demand. Stable and secure operation of the next generation common Nordic-Baltic-and-European (NBE) power system will need new information tools for monitoring, more advanced automatic control systems and wide-area monitoring solutions that are adapted to the variability and complexity of the future electric power system.

The fundamental changes of the power system due to the increasing number of renewable energy sources, small-scale photovoltaic, feeding into networks at various voltage levels require radically new control schemes that strongly rely on the availability of adequate monitoring infrastructure [1], [2]. Phasor measurement units (PMUs) are crucial tools for the monitoring of the transmission networks [3] and are likely be used in the future in medium- and low-voltage distribution grids as well [4]. The deployment of PMUs could allow achieving a wide range of control objectives required for the future power system.

The paper presents part of the study under the SAMBA (Synchronized Area Monitoring for BAltic states) project, the purpose of which is to attempt a leverage of unpresented benefit of Synchrophasor Technology (PMU technology) at different voltage levels (i.e., including needs of both Transmission System Operators (TSOs), Distribution System Operators (DSOs) and other stakeholders in the electricity system). The overall project aim is to facilitate the successful transformation of the NBE electric power system to operate with large amounts of RES and to develop the NBE energy system as a supplier and carrier of RES, providing solutions to local and global challenges. Local challenges are as follows: 1) From an operational point of view, they are related to balancing, power quality and maintaining security of supply, especially considering the outlook for nuclear power in the region. 2) The transfer capacity could exceed current transmission capacity values if the synchrophasor technology is combined with other assets such as continuous PMU-based monitoring and alarming, and fast-controls on power-electronics assets such as SVC and HVDC. Global challenges are as follows: 1) The traditional assumption that grid inertia is sufficiently high with only small variations over time is thus not valid for power systems with high RES shares. Frequency dynamics are faster in power systems with low rotational inertia, making frequency control and power system operation more challenging. 2) Focus is shifting towards a more decentralised power system, which results in a greater emphasis on monitoring of power system in real time and new control algorithms to allow the power system to operate closer to its capacity while maintaining system security.

2. MONITORING AND ANALYSIS OF SYNCHROPHASOR SYSTEM DATA

Synchrophasor systems are considered to be one of the enablers of Smart Grids. They are able to scan the system from a large number of measuring points at a high scanning rate and report highly accurate and time-synchronized voltage and current phasors measurements together with frequency at a very high rate of 50/60 messages per second compared to SCADA systems (less than 1 measurement per second). The PMUs utilise the IEEE C37.118.2 standard to stream out synchronous phasor measurements. The development and implementation of Wide-Area Monitoring, Protection and Control Systems that exploit synchronised phasor measurement data to provide coherent real-time data for enhancing power system reliability has seen a significant increase in the past few years. A real-time approach based on wide-area PMU measurements is envisioned as a means of providing operators with information and tools in order to keep the power system in stable and secure operation. The system generates a large quantity of data, which has to be analysed promptly and monitored. The operator should be alerted of any abnormal situation so that they may take appropriate action to avoid escalation of an abnormal situation. Several tools have been developed to fulfil this need. Some of the tools in use today include SEL-5078-2 SynchroWAVe Central, OpenPDC Power System Outlook, Real Time Monitoring System – SMART, Real Time Dynamics Monitoring System – RTDMS and Phasor Grid Dynamic Analyser – PGDA. Some of the useful indicators of the "health" of the grid that can be monitored using this technology are as follows [5]: Performance Metrics; Transient Stability; Stability Metrics; Composite Indicator of

Reliability; Interconnections between areas (Tie-lines); Interconnected Grid – the entire grid that operates in synchronism, i.e., at the same system frequency, e.g., Belorussia, Russia, Estonia, Latvia and Lithuania (BRELL); Local Level or Area (Local Control Area) – an area covered by a single TSO; Wide-Area Visualisation – the ability to see the critical operating parameters from all locations in the entire control grid (Fig. 1 presents visualisation of phasor measurements among asynchronous areas).

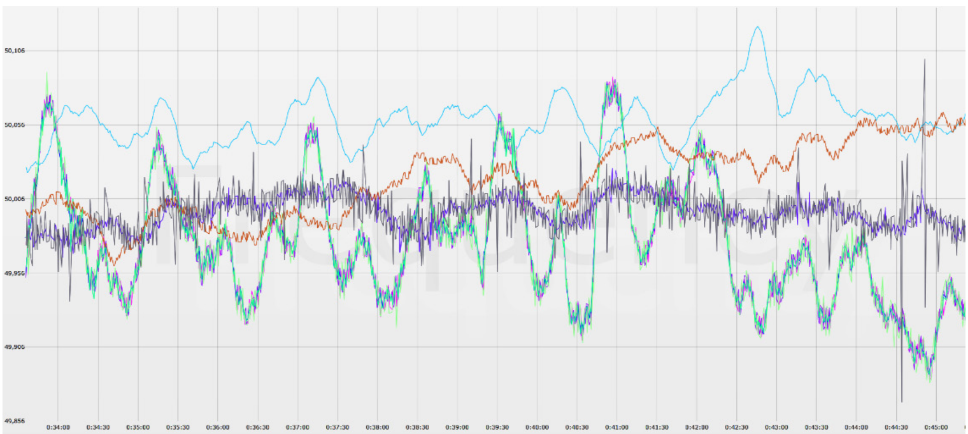

Fig. 1. Visualisation of frequency oscillations of four asynchronous areas by SEL-5078-2 SynchroWAVe.

In large interconnected power systems, wide-area situational awareness is critical to ensure reliable system operation. Synchrophasor visualisation tools provide wide-area situational awareness of the power system using geographic display of angle differences and colour-coded traffic light gauges for key metrics, including frequency, voltage, power flows and damping. This situational awareness overview of the entire interconnection and easy-to-use drill down menus enable operators to quickly pinpoint the location of a problem and better assist in formulating any corrective actions or mitigation measures.

It is envisaged to promote future development of synchrophasor analysis and visualisation tools with new functionalities for improving situational awareness of power systems, e.g., with dynamic line rating and grid inertia level estimations in real time.

3. INERTIA: RELATIONS WITH THE POWER SYSTEM

The energy stored in the power system and instantly available to be exchanged is stored as kinetic energy of the connected electric machines (synchronous and asynchronous generators and motors). Inertia is an inherent mechanical feature of rotating masses and it acts as an early intrinsic countermeasure against frequency deviation after perturbations due to load-generation imbalances. More precisely, the response of the present structure of the controlled power system to a sudden change in the active power balance can be divided into five stages [6], [7], the second of which is the Inertial Response (IR):

- First of all, the magnetic field of synchronous generators releases electromagnetic energy, for about 1/3 s, to contribute to maintaining synchronism;
- After the electromagnetic release, the IR acts, for a few seconds at most;
- Within a few seconds from the event, the primary frequency reserve is activated and stabilises frequency to a steady state;
- Within 15 minutes from the event, the secondary control reserve is deployed, to bring frequency back to its nominal value and free up the primary frequency reserve;
- The secondary control reserve is followed and supported by the tertiary control reserve.

When the active power balance in the power system undergoes large disturbance, both rotor angle and frequency stability have to be considered:

- IR is related to the rotor angle change in synchronous machines; namely, it contributes to keeping this angle within suitable bounds so that synchronism is preserved;
- IR is related to frequency stability because it affects both the ROCOF and the maximal frequency deviation: the former, in turn, influences the behaviour of protective relays.

Figure 2 reports the features of a typical frequency transient following power imbalance in the form of a large power step occurring at time $t=t_{pert}$.

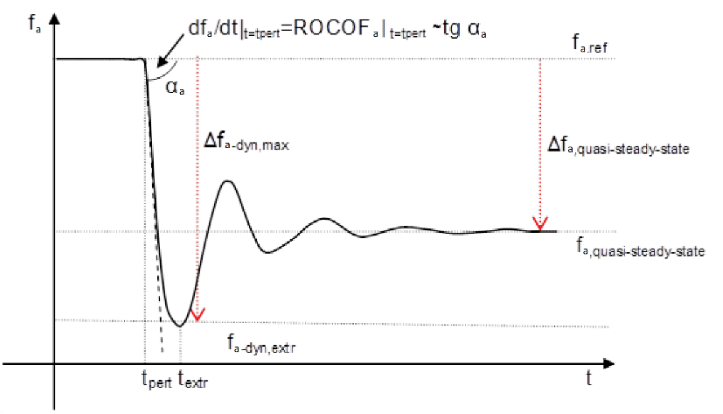

Fig. 2. A typical frequency transient due to a step power imbalance.

A set of quantities can preliminarily be envisaged as needed to study frequency stability in the power system [7], [8]: the (instantaneous) average frequency of each area, i.e., f_c (Hz); the rate of change $ROCOF_a$ (Hz/s) of the frequency of each area; the maximum deviation $|\Delta f_{a\text{-}dyn,max}|$ of the mentioned frequency due to a sudden and relevant change in power balance; the time interval t_{extr}-t_{pert}, where t_{extr} is the time instant for which $\Delta f_{a\text{-}dyn,extr}$ is attained; the maximal absolute value $|ROCOF_a|_{max}$ of the mentioned rate of change; the (quasi-)steady-state deviation of frequency $\Delta f_{a,quasi\text{-}steady\text{-}state}$ from its setpoint value $f_{a,ref}$, which can coincide with the frequency nominal value or be slightly different from it; the time interval, starting from t_{pert}, after which f_a reaches (quasi) steadily the value $f_{a,quasi\text{-}steady\text{-}state}$, namely after which

$|f_a\text{-}f_{a,quasi\text{-}steady\text{-}state}|<\varepsilon$, where the error value ε has to be quantified as well (10–20 mHz could be a starting point for the evaluation); the (physical) inertia constant H_i (s) of each synchronous generator in an area and "equivalent" inertia constant H_j (s) of each device that can be used to supply synthetic inertia; the overall inertia constant of each area, i.e., H_a (s) and the whole power system, i.e., H_{sys}; this could:

- be a combination, in terms of a suitable weighted average, of all physical and equivalent inertia constants of single machines and devices; in this combination, not only the individual H_i or H_j could be relevant, but also the electrical distance, or better impedance, of the lines connecting the machines or devices;
- be derived from area frequency measurement, assuming that the power system working point (in terms of active power injections and absorptions, inside the area and/or with respect to the neighbouring areas) is known and the perturbation is known, this measurement, in turn, can be made after a sudden and relevant change in power balance.

For inertia estimation the power system can be described in a simplified way by the following swing equation [9]:

$$M_{sys} \cdot \frac{df_{sys}}{dt} \simeq P_{m,sys} - P_{e,sys}\ [MW], \tag{1}$$

where $P_{m,\text{sys}}$ is the power system mechanical power and $P_{e,\text{sys}}$ – its electric power, M_{sys} – the power system mechanical inertia. In turn,

$$M_{sys} = \frac{2 \cdot H_{sys} \cdot S_{n,sys}}{f_n} = \sum_{i \in \alpha_G} \frac{2 \cdot H_i \cdot S_{n,i}}{f_n} \left[MW \cdot \frac{s}{Hz}\right], \quad H_i = \frac{J_i \cdot \omega_{n,i}^2}{2S_{n,i}}\ [s], \tag{2}$$

where $S_{n\ i}$ is the machine nominal apparent power, H_i – its inertia time constant, J_i – its moment of inertia, $\omega_{n,i}$ – its nominal rotational speed, f_n – the nominal frequency, α_G – a set of the Synchronous Generators connected to the network. To estimate the instantaneous ROCOF after power imbalance for the system:

$$\begin{aligned} ROCOF(t = pert^+) &= \frac{df_{sys}}{dt}(t = pert^+) \\ &\simeq \frac{P_{m,sys} - P_{e,sys}}{M_{sys}}\ [Hz/s] \end{aligned} \tag{3}$$

4. MONITORING APPLICATION AND OBSERVATION RESULTS

For situational awareness of power systems with grid inertia level estimation, the monitoring information from the Institute of Physical Energetics Smart Grid Research Centre has been used. After commissioning of NordBalt submarine power cable between Klaipeda in Lithuania and Nybro in Sweden at the end of 2015, connecting Nordic and IPS/UPS asynchronous areas by 700MW HVDC cable, ten sudden outages occured during 2016 and change power balances in Nordic and IPS/UPS power systems by 700MW. Figures 3–5 present a few power system frequency transients due to step power imbalances, where PMU measurements from both sides were used.

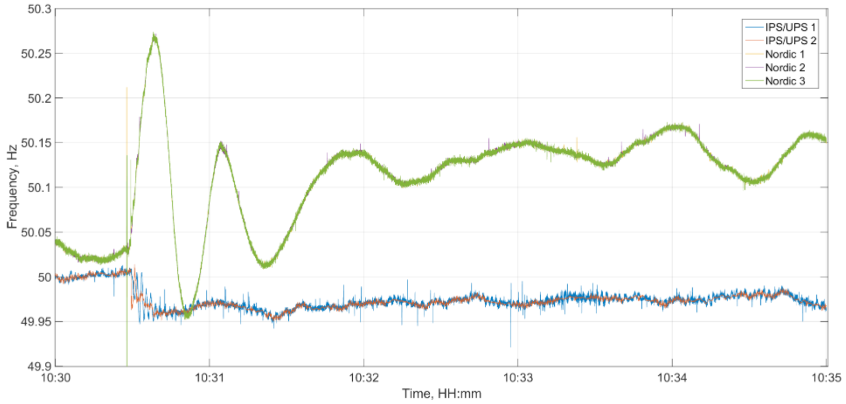

Fig. 3. NordBalt sudden outage – 700MW on Wednesday, 24/02/2016 at 10:30.

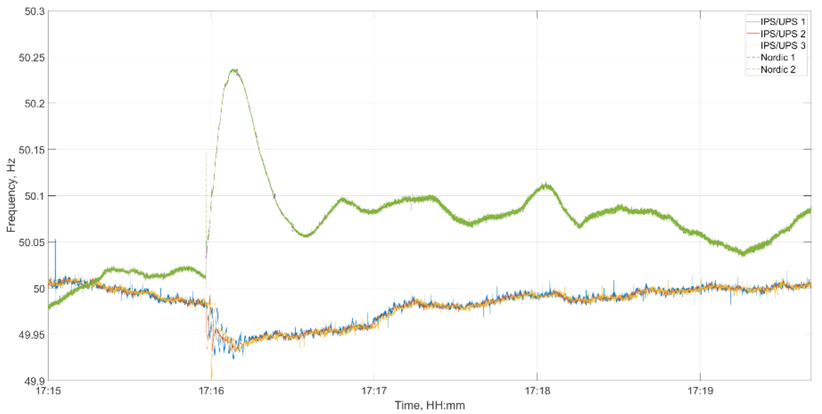

Fig. 4. NordBalt sudden outage – 700MW on Friday, 18/03/2016 at 17:16.

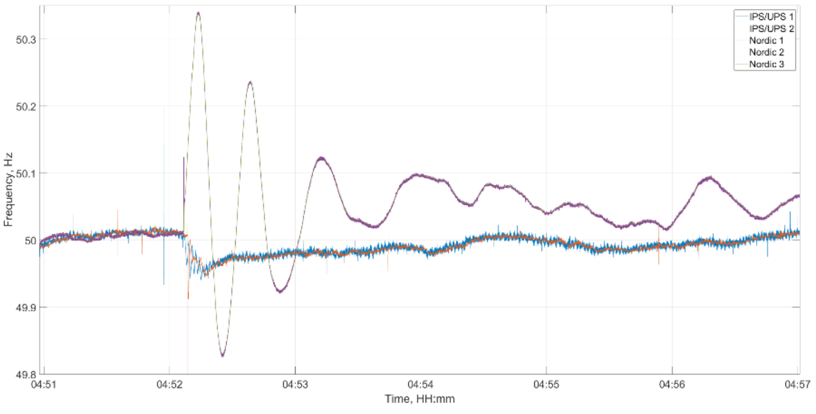

Fig. 5. NordBalt sudden outage – 700MW on Monday, 30/06/2016 at 4:52.

Table 1 presents the estimation of system mechanical inertia and inertia time constant based on eqs. 2 and 3, with derived information from frequency transients.

Table 1

Estimation of Power System Mechanical Inertia and Inertia Time Constant

Outage	NORDIC					IPS/UPS				
	$T_{,EXTR}$	$\Delta f_{a\text{-}dyn,extr}$	*ROCOF*	M_{SYS}	H_{SYS}	$T_{,EXTR}$	$\Delta f_{a\text{-}dyn,extr}$	*ROCOF*	M_{sys}	H_{sys}
24/02/2016 10:30	9	0.24	0.026	26250	9.94	1.4	0.035	0.025	28000	3.25
18/03/2016 17:16	10	0.23	0.023	30434	11.52	1	0.04	0.04	17500	2.03
30/06/2016 4:52	7	0.33	0.047	14848	5.62	1.3	0.05	0.038	18200	2.11

Due to incomplete information about power system states in the outage moment (production/consumption), inertia time constants have been estimated based on the assumption that Nordic power system has the total apparent power of 66 GW and IPS/UPS system – 215 GW. It can be seen that Nordic system inertia values fit the power system behaviour during the day, where inertia is higher during peak hours and lower at night. More precise initial information about the system is needed to estimate values more precisely. However, IPS/UPS system values seem unrealistic due to a reason that the system is approximately 3 times bigger than Nordic PS and outage of 700MW does not create significant disturbances for precise estimation.

5. CONCLUSIONS AND FURTHER RESEARCH

Application of synchrophasor measurements provides additional benefits to power system operators to quickly pinpoint the location of a problem and better assist in formulating any corrective actions or mitigation measures. It is envisaged to promote future development of synchrophasor analysis and visualisation tools with new functionalities for improving situational awareness of power systems, e.g., with dynamic line rating and grid inertia level estimations in real time.

Inertia can be foreseen to have a sort of "pervasive", but also "tricky" role in the future power system; due to a decrease in physical inertia, machine or device inertial behaviour will have direct and indirect effects on phenomena related to different forms of stability.

New functionalities of visualisation tools to estimate a grid inertia level in real time should take into account external information about the power system state (production/consumption) to decrease inaccuracy in estimation and provide power system operators with new functionality and observability.

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FĀŽU VEKTORU MĒRĪŠANAS IEKĀRTU IZMANTOŠANA ENERGOSISTĒMU INFORMĒTĪBAS UZLABOŠANAI

A. Obuševs, A. Mutule

K o p s a v i l k u m s

Raksts veltīts fāžu vektoru mērīšanas iekārtu pielietošanai, kas salīdzinājumā ar esošām SCADA sistēmām sniedz papildus priekšrocības, lai sekmētu Ziemeļvalstu, Baltijas un Eiropas elektroenerģijas sistēmu veiksmīgu transformāciju, nodrošinot darbības ar liela skaita atjaunīgo enerģijas avotiem, uzlabojot izpratni par energosistēmu uzvedību reālā laikā. Rakstā aprakstītas jaunas vizualizācijas rīku funkcionalitātes, nodrošinot energosistēmu inerces līmeņa novērtēšanu reālā laikā, pateicoties novērojumu rezultātiem starp Ziemeļvalstu un Baltijas elektroenerģijas sistēmām.

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