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**WIDE AREA MONITORING AND
CONTROL FOR TRANSMISSION
CAPABILITY ENHANCEMENT**

**Working Group
C4.601**

August 2007



WIDE AREA MONITORING AND CONTROL FOR TRANSMISSION CAPABILITY ENHANCEMENT

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EXECUTIVE SUMMARY

Background on the Working Group

The CIGRE WG C4.601 on Power System Security Assessment was formed in August 2004, at the CIGRE Session 2004 and was given the charter to specifically look at the following needs in the industry:

1. The design of controls to enhance system security. This includes local device controls as well as system wide area controls and remedial action schemes.
2. Modeling of existing and new equipment required for power system analysis. (In this task it was felt that the most pertinent and timely activity was to look at the modeling and dynamic performance of wind generation systems.)
3. The design of monitoring systems for real time stability evaluation and control.
4. New analytical techniques for assessment of power system security. In addition to advances in computational methods, this includes the development of emerging approaches such as risk-based security assessment and the application of intelligent technologies.

To this end, all of the above subject matters were tackled by the Working Group. More specifically, of the more than one hundred members and contributors to the work, three adhoc groups were developed within the Working Group, each given the task to address one of the first three subject matters above. The fourth task is one that the working group as a whole has presently started on, after having finished the other three tasks. The three completed tasks have resulted in the publication of three CIGRE Technical Brochures. These are:

- CIGRE Technical Brochure on Wide Area Monitoring and Control For Transmission Capability Enhancement (this effort was lead by C. Rehtanz)
- CIGRE Technical Brochure on Modeling and Dynamic Behavior of Wind Generation as it Relates to Power System Control and Dynamic Performance (this effort was lead by P. Pourbeik)
- CIGRE Technical Brochure on Review of On-Line Dynamic Security Assessment Tools and Techniques (this effort was lead by K. Morison)

During the course of the work, in addition to the formally elected WG members a large number of others contributed significantly to these efforts. All have been properly acknowledged. The combined group of members and contributors constituted 125 experts from 25 countries. These included experts from equipment manufacturers, utility engineers, consultants and research organizations around the world. The work on the three Technical Brochures mentioned above was completed in December 2006, with final reviews and approvals before publication occurring in early 2007. Thus, the work took nearly two and a half years to complete.

All three documents constitute timely and valuable information for transmission system planer, operators, reliability organization and engineers in research and consulting firms.

As stated previously, the Working Group is currently working on its last assignments (item 4. above). It is expected that this will be reported on in the near future.

Wide Area Monitoring and Control for Transmission Capability Enhancement

The first of the three documents deals with the subject of wide-area monitoring and control. The document presents a comprehensive description of Wide Area Monitoring and Control installations and applications around the world and future expectations for this technology. This includes:

1. Screening of existing Wide Area Monitoring and Control installations, including their applications and reasons for applying this technology.
2. Listing and reviewing of monitoring applications based on Wide Area Measurements.
3. Discussion of the future role and development of this technology from the monitoring point of view.
4. A collection of requirements to go one step further into Wide Area Control applications. This includes an evaluation of the conditions for the acceptance of Wide Area Control and an assessment of the key expected benefits and hurdles.
5. A review of Wide Area Control applications, which are presented related to real cases or considered in planning studies.

The document is divided into eight chapters that effectively cover this subject matter – chapter 1 is an introduction to the subject and chapter 8 is the list of references.

Wide Area Monitoring Systems (WAMS) and Wide Area Control Systems (WACS) are essentially a concept based on data gathering and control on a large regional interconnected area through the use of time synchronized phasor measurement units (PMUs).

Chapter 1 is a brief introduction and motivation to the subject.

Chapter 2 provides a concise, yet thorough, review of present phasor measurement unit (PMU) based wide-area monitoring systems around the world. It discusses the motivation behind each application and what they are presently used for. Limitations and future expectation are also discussed.

Chapter 3 provided a detailed discussion on the general application of WAMS. Namely, for voltage stability indication, for monitoring of power corridors, for monitoring of real-time damping of inter-area modes of rotor oscillation of groups of generators and for islanding detection. Again, where real applications of these exist, they are discussed.

Chapter 4 provides a discussion on the future role of wide-area monitoring and control systems, more specifically:

- The role they are expected to play in system monitoring and control.
- The role they can play in being integrated with existing EMS and SCADA (to improve state estimation).
- The impact WAMS data can have on planning and operation philosophies. For example, in today's system environment planning and operations are based primarily on off-line deterministic studies that define the system limits together with a safety margin. With WAMS and WACS the system observability and controllability may be improved markedly allowing one to ride closer to real-time stability limits – this of course also raises challenges as to determining what is a suitable margin of safety.
- Centralized and local functionality of PMUs.

Chapter 5 is a detailed look at the requirements for WAMS and WACS systems in order to make them widely used in power systems for continuous and emergency controls. Some of the limitations and concerns with modern PMUs are discussed. General guidelines are provided as to how WACS should be developed to ensure acceptable performance and approval in power system applications.

Chapter 6 provides an in-depth overview of all WACS applications – both those already developed and more specifically those that have presently been conceived but yet to be implemented. Suggested algorithms are given more many of these potential applications.

Conclusions

From the overview of WAMS installations in chapter 2 it can be seen that there is an increasing interest in this technology all over the world. A few installations cover huge areas of power systems, but most are concentrated in a critical area or one transmission corridor only. A number of transmission system operators have just started to explore this technology and getting familiar with its use based on small installations.

Phase angle and oscillation monitoring are obvious and the most commonly used applications. Voltage stability and thermal limit applications are used in some limited number of cases. The offline analysis of data plays a significant role for improved dynamic system models based on comparisons of simulations with recorded events. The integration of PMU data into the State Estimation is widely expected.

From the wide area perspective, three application areas can be expected. First is the further spread out of slow secondary voltage control applications based on conventional technologies. Second is the WAMS for oscillations, voltage stability or thermal limitations. Third is Wide Area Protection, especially for transient stability.

For the practical implementation of Wide Area Monitoring and Control Systems (WAMC) there are some aspects which have to be considered carefully. The whole system depends on the availability of global positioning satellite (GPS) signals. Until alternative satellite systems are installed, this could be a source of system disturbance. The design of WAMC has to consider the case of unavailability of the GPS signal, which means that in any case a local backup for control and protection actions is needed.

In conclusion, the expectations for Wide Area Monitoring and Control Systems are high and a growing community of researchers and utility experts are working on practical applications and installations of this technology around the globe. However, it will be still a long way from the first WAMS applications for different kinds of instabilities to system wide control schemes based on WAMC or even protection schemes. But the promises of this technology are shared by numerous experts. An increasing number of transmission system operators are running application studies to evaluate the benefits of this technology or even execute implementation projects.

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CHAPTER 7 CONCLUDING REMARKS AND OUTLOOK

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LIST OF ACRONYMS AND TERMINOLOGY

APG	Austrian Power Grid
ASM-S	Angle Shift Measurement System
ATC	Available Transmission Capability
CT	Current Transducer
DFR	Digital Fault Recorder
EGAT	Electricity Generating Authority of Thailand
EIPP	Eastern Interconnection Phasor Project
ELKRAFT	Danish ISO
EMS	Energy Management System
ETRANS	Swiss ISO
FACTS	Flexible AC Transmission Systems
FERC	Federal Energy Regulatory Commission
GPS	Global Positioning System
GW	Giga Watts
HEP	Hrvatska Elektroprivreda
HVDC	High-voltage direct current
ISO	Independent System Operator
NEMMCO	National Electricity Market Management Company (Australian)
NERC	North American Electric Reliability Council
NPCC	Northeast Power Coordinating Council
NTC	Net Transfer Capability
OLTC	On-Load Tap Changer
OSA	Online Stability Assessment
OSM	Oscillatory Stability Monitor
PDC	Phasor Data Concentrator
PLL	Phase Lock Loop
PMU	Phasor Measurement Unit
POD	Power Oscillation Damper
PSS	Power System Stabilizer
RAS	Remedial Action Schemes
RTDMS	Real-time Dynamic Monitoring System
RTO	Regional Transmission System Operator
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SE	State Estimation
SGCC	State Grid Corporation of China
SPS	Special Protection System
STATCOM	Static Compensator (IGBT or IGCT voltage source converter based design)
SVC	Static Var Compensator (thyristor based design)
TERNA	Italian ISO
TTC	Total Transmission Capability
UCTE	Union for the Coordination of Transmission of Electricity
VIP	Voltage Instability Predictor
VT	Voltage Transducer
WAMC	Wide Area Monitoring and Control System
WAMS	Wide Area Monitoring System
WECC	Western Electricity Coordinating Council

CHAPTER 1

INTRODUCTION

Utility grids require sufficient and reliable transmission capacity. After the recent blackouts in North America and Europe the urgency of action to relief bottlenecks in transmission grids is once again in focus, to keep and support vital energy markets and high system reliability. The process of constructing new lines implies large investments and long permit procedures, therefore a basic requirement is to better utilize the existing transmission system. Particularly, the power grid needs to be operated closer to its technical limit and high system reliability must be maintained. This requires higher flexibility for operation and control. Additional and more precise information is needed together with a higher degree of automated control.

The vision is to take a step from today's steady state view of SCADA systems to a system wide dynamic view in the sense of wide area monitoring. Wide area monitoring means, for example, time synchronized measurements of voltage and current phasors. Such systems are installed within a growing number of networks and initial experiences are available. Algorithms on top of these measurements have to support the operators in running the system closer to its limits. Most functions of these systems are separate from those of the existing SCADA systems. The implementation of such systems in addition to SCADA systems with the focus on the supervision of network interconnections would offer much more accurate network information across country borders. This information can be provided easily to all interconnected network operators. This higher transparency of especially corridors and interconnections is a first step towards an optimal utilization of available transfer capabilities in the transmission system. By means of measurement and recording of the frequency or phase-angle oscillations the current stability condition of the power system can also be evaluated and monitored.

The second step is to actively influence the system to use available transmission reserves. On the primary component side, beside generators, FACTS-devices are providing the flexibility to adapt the power system in volatile and emergency operating conditions. In order to use their capabilities in a most beneficial way it is necessary to have automated control schemes for normal and emergency situations. These control schemes have to take system aspects into account, which means the usage of dynamic wide area information. An example is the detection and elimination of unpredicted and unwanted loop flows. Automatic control schemes have to be reliable against changing system conditions to avoid any kind of misbehavior. Emergency situations need to be handled and stabilized. All automatic interactions have to be well defined and transparent for the operator to avoid unpredictable interactions. Beside these new technologies the more traditional ways of discontinuous mechanical control should be considered as well, like generator/load tripping, shunt capacitors or reactor bank switching, etc.

This report discusses Wide Area Monitoring and Control Systems (WAMC). The focus for Wide Area Monitoring Systems (WAMS) lies on the time synchronized phasor measurements as a new technology. For Wide Area Control all kinds of wide area information is considered. In both cases the target is to concentrate on the increase of transmission capability. Emergency or System Protection Schemes is excluded, since the recently published report of Task Force 38.02.19 covers this topic in depth [1]. This report uses the acronyms WAMS for 'Wide Area Monitoring System' and WAMC for 'Wide Area Monitoring and Control System'.

The scope of this report is to present a comprehensive assessment of the application of Wide Area Monitoring Systems and Control Scheme applications to date. The focus is on the use of WAMS and WAMC to increase the transmission capability and system reliability. The relief of congestions in interconnections and transmission corridors is a topic in focus. Both advanced monitoring as support for network operators and automated control of fast network controllers will be discussed.

The following selection of tasks outlines the scope of this report:

- A review of existing installations of Wide Area Monitoring Systems
- Proposals/Discussion on new algorithms and methods based on dynamic wide area information
- Impact of wide area monitoring information on network security and operation philosophies
- Usage of wide area information for wide area control schemes and related methods
- Impact of wide area monitoring information on power system stability conditions
- Impact of wide area monitoring and control on total, net and available transmission capability
- Acceptance analysis of automated control schemes

CHAPTER 2

INSTALLATIONS OF PMU BASED WIDE AREA MONITORING SYSTEMS

In this section, installations of PMU based wide area monitoring systems are described. The users present reasons, targets and expectations for the installation of these systems.

2.1 WAMS at ETRANS Switzerland

2.1.1 Project Purpose

The Swiss power system is located in the middle of the well-meshed UCTE interconnected system. Due to permanent substantial power imports to Italy, Switzerland has to handle high power transits in the north-south direction. For system security reasons, enhanced control of the corridor loading is required. Based on the nature of direct voltage phase angle measurement, phasor measurements are suitable for calculating the voltage phase angle difference between substations located at the corridor ends of the Swiss power system. The angle difference reflects the overall system loading in the main power flow direction. The advantage of this approach is that it includes the total flow together with the current system topology. Each change either in flow or topology is reflected by corresponding changes in the voltage phase angle difference. By monitoring only this one quantity, signals for the system loading can be extracted and delivered to the system operators, offering therefore an exact picture of the system corridor loading including the corridor configuration [2]-[5].

First the project started in a pilot phase. During this time the applicability and reliability of the measurement equipment including data processing tools have been observed. Due to the first convincing results, the system is currently in the stage of being integrated with the existing SCADA architecture. Therefore a kind of filtering and pre-processing of the raw values together with the initialisation of alarms is on the way to be realized. The main objectives of the filtering procedure is to decouple the high time resolution of 100 ms step size to the 10-20 s step size used in SCADA systems as well as a reduction of the amount of information piped to the control room.

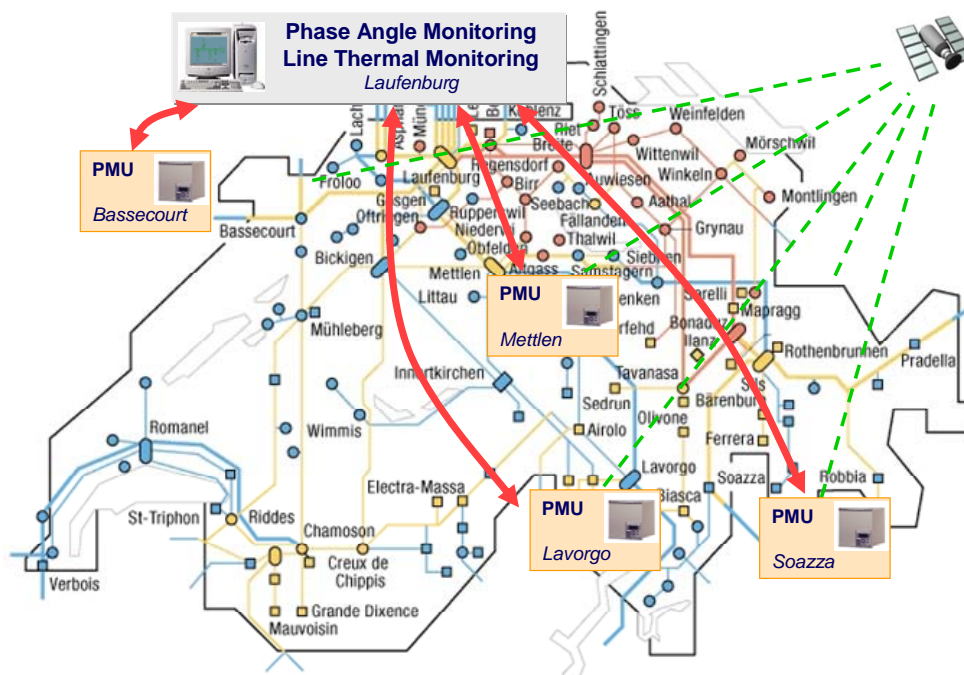


Figure 2.1.1. WAMS Installation in Switzerland

Applications within Switzerland

In addition to the corridor monitoring application, several additional applications are to be implemented for the needs of the Swiss transmission system such as:

- Line thermal monitoring by measuring the active power losses along one line and subsequently extracting the medium temperature of the line by evaluation of the line resistance changes due to thermal balance (current & solar heating / ambient cooling) [4]
- Event capture and export – automatic export functionality activated by trigger conditions as e.g. high frequency gradient. The saved files are to be used for the calibration of the Swiss dynamic model.

Application within the UCTE Interconnected System

Currently a few transmission system operators (TSOs) of the central European interconnected system (UCTE) have planned to share PMU measurements in order to realize a common use of the advantages of “wide area” applications. Different approaches for data exchange will be tested. However, the benefits of such a system can only be realized by the use of central data concentrators. Ongoing interconnection projects are envisaged between ETRANS and ELES, APG and TERNA.

The following applications are envisaged:

- Producing a general system loading overview by calculating corresponding voltage phase angle differences.
- Setting up an early warning system against inter-area oscillations by online monitoring of system damping.
- Creating alarms after forced unit outages by continuous monitoring of the system frequency gradient.
- Creating alarms for the case of part system islanding detection due to voltage phase angle difference rotation.

2.1.2 WAM – Interfaces

One major aim of the WAM project within ETRANS is the accurate interfacing of this new technology with the existing power system operation and monitoring system. Figure 2.1.2 shows the signal flow from the substation feeder VTs and CTs up to the existing SCADA system as well as the data export channel for the use of the system planning department.

The data flow is managed in such a way that timely high resolution measurements are pre-processed and filtered in order to generate, for the steady state SCADA system, alarms based on the analysis of the system dynamic behavior.

By the use of the already existing European data link channels these alarms could be distributed to the whole TSO community.

2.1.3 System Experience

The applicability of the online wide area stability monitoring approach was demonstrated during the resynchronisation process between the first and second UCTE zones on 2004 October 10th [2]. At that time PMU measurements from Switzerland and Greece were used to monitor the dynamic system stability online during the whole resynchronisation sequence.

The real benefit of Wide Area Monitoring arises when data is collected and subsequent computation performed over a large geographic region.

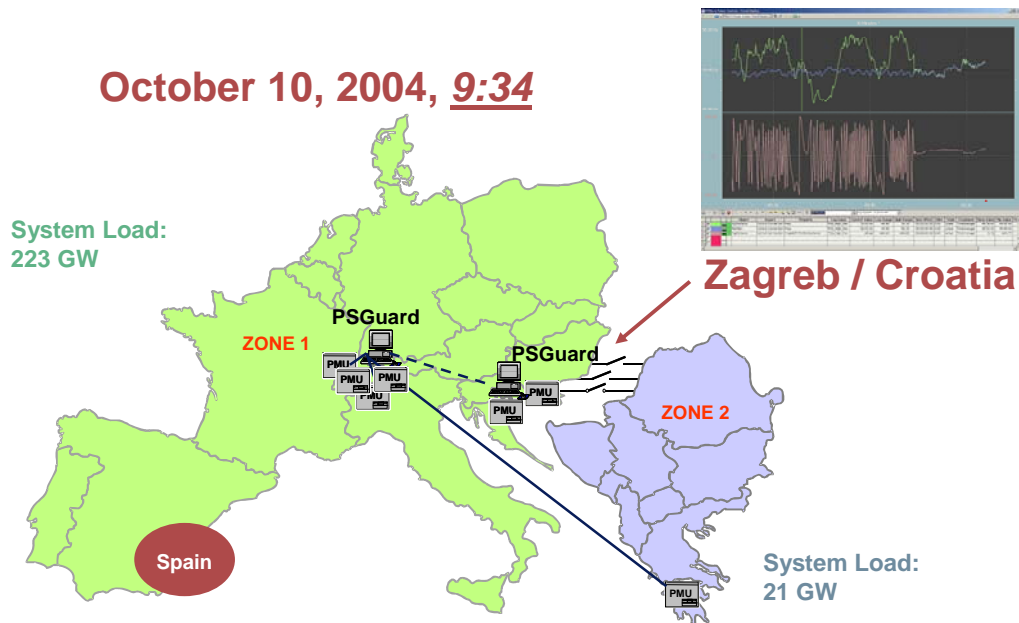


Figure 2.1.2. UCTE Re-unification of Zone 1 and 2

The measurements from far locations of the system (Greece - Switzerland) separated by more than 1000 km are currently used for continuous system stability monitoring. The measurements already extracted reflect the changes of system damping during the day, week and month as well as steady state frequency based deviations. The following observations can be summarised:

- Lower system damping in low-load condition e.g. during night hours
- Lower system damping during higher system frequency deviations from the set point (e.g. +/- 100 mHz)

Presently, on online modal analysis and corresponding online parameter identification are performed in order to obtain, based on these parameters, the most suitable alarm signals.

Within UCTE there are currently several ongoing projects with the aim of bilaterally exchange of PMU information in order to get a larger observability of the highly meshed central European interconnected system. The main intention is to "see" more than what the SCADA system delivers. Subsequent measurement processing delivers in this way additional information to the dispatch rooms, which serves in this first stage only as a decision tool.

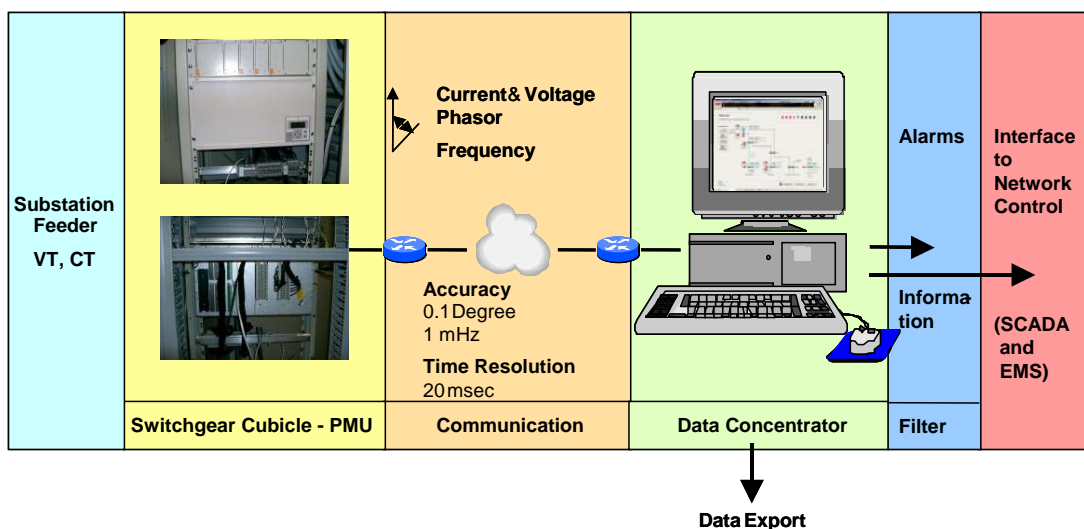


Figure 2.1.3. WAMS data flow

2.2 WAMS at HEP Croatia

HEP TRANSMISSION D.O.O. is a subsidiary company of the Croatian utility Hrvatska Elektroprivreda D.D. (HEP) that operates the country’s 400/220/110kV grid. As part of a comprehensive rebuilding and construction program, it decided to install the Wide Area Monitoring System for the online monitoring of a transmission corridor between two important nodes in its 400kV network. In addition to voltage stability, the average temperature of the line is being monitored. This allows to optimize the availability of the system as well as to safely increase the transmission capacity during peak demand.

The voltage stability monitoring provides the operator with sufficient information to evaluate the present active power margin with respect to voltage stability of a transmission line or corridor. The operator can act to correct the shortage of reactive power with generation rescheduling, reactive load compensation, tap changer blocking in the load area or incremental or complete load shedding in extreme cases. Line thermal monitoring allows full use of the transmission capacity dependent on actual ambient temperature and wind. It thus overcomes the constraints often imposed due to stability concerns originating from uncertainties about the system state.

The following benefits are expected from the installed WAMS system:

- increases the efficiency of power system operation
- maintains security at the desired level whilst optimizing power flow
- lowers the risks of power system instabilities and blackouts
- provides valuable information for efficient disturbance analysis and system expansion/reinforcement planning
- offers scalability for implementation or extension

In conclusion, the newly built line is of utmost importance in the interconnection between the UTCE network and the Balkan region. Online condition monitoring of the line gives valuable information and provides the means to optimize availability and to safely increase the power flow of the transmission corridor during peak demand.

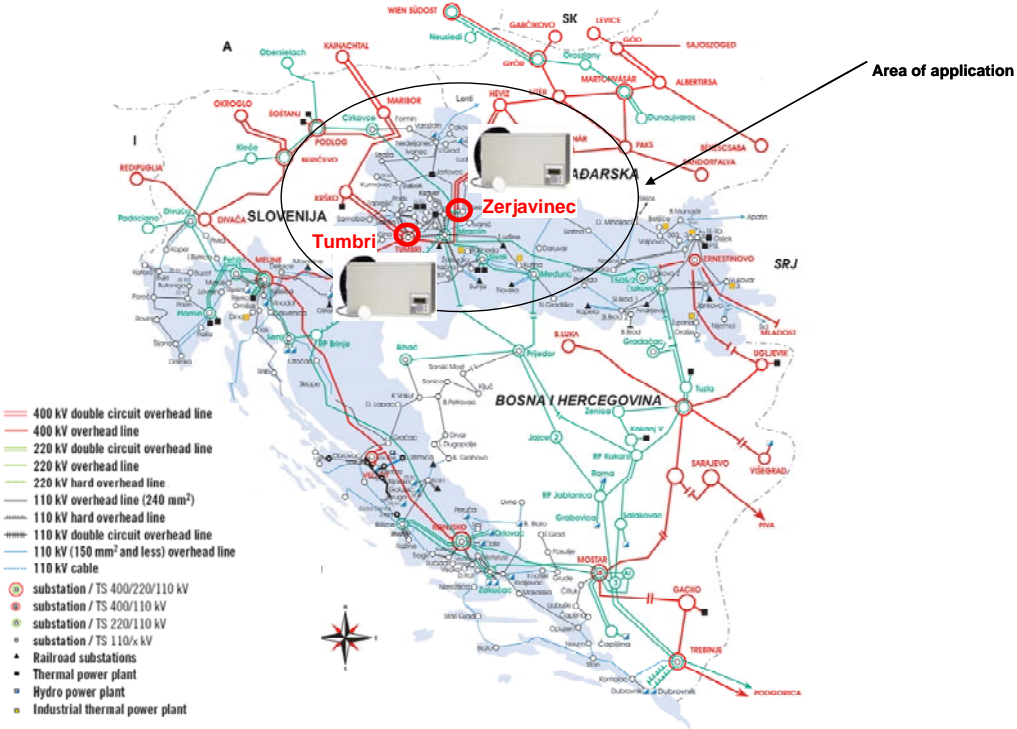


Figure 2.2.1. Network of HEP Croatia with installation of 2 PMU in a corridor

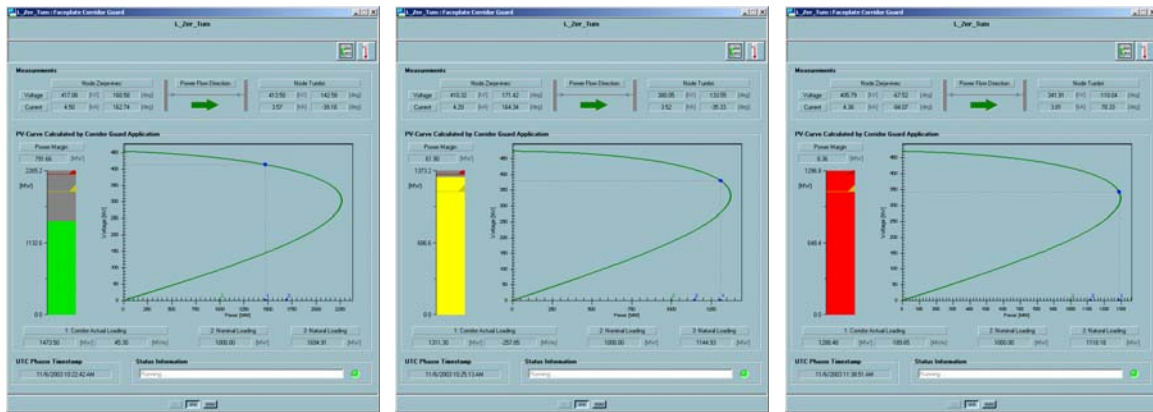


Figure 2.2.2. Graphical User Interface for Voltage Stability

2.3 WAMS at Hydro Quebec

2.3.1 Development of Wide-Area Monitoring at Hydro-Québec

As a major North American power utility, Hydro-Québec is operating and maintaining an extended and modern power system composed of large hydroelectric generation complexes mostly located in the north, hundreds of kilometres away from the loads concentrated in the southern part of the territory. Such a power network is prone to all kinds of electrical phenomena affecting its voltage, frequency and angular stability.

By the end of the sixties, Churchill Falls and Manic-Outardes power plants were already feeding a large portion of the loads through a thousand kilometres long 735 kV transmission corridor. Ten years later, this 735 kV main grid was extended with two additional corridors put in place for transmitting the new Bay-James complex generated power. The Y shaped backbone of Hydro-Quebec main transmission grid was then in place. In the eighties, a Multi-Terminal DC transmission link was built to complement the AC transmission facilities coming from Bay James and to feed local or foreign customers through Nicolet and Sandy Pond substations. At last, the whole transmission system reliability and robustness were significantly improved in the nineties with massive addition of series compensation. The present configuration of the main 735kV grid is shown in Figure 2.3.1.

Hydro-Québec's know-how in Wide-Area Monitoring was developed in parallel with the evolution of the transmission system. As a first initiative in 1976, a team of research engineers from Hydro-Québec Research Institute (IREQ) took up the challenge of measuring the angular shift between the Arnaud and Boucherville substations on the Churchill-Manic-Montreal transmission corridor. The steady state angle shift was obtained from a highly accurate counting of the zero-crossings of the sinusoidal voltage waveforms synchronized by means of Loran C-based clocks and STT satellites [6]. With a synchronizing error smaller than 46 μ s, an accuracy of $\leq 1^\circ$ was achieved on such steady state $\Delta\theta$ measurements. In 1981, the same research team was successfully performing dynamic measurements of absolute voltage angles with three measuring units at a rate of 30 Hz using GOES satellites synchronizing signals [7]. While the phasor amplitudes were not specifically measured in these first experiments, they were later derived from the peak-to-peak values of the voltage waveforms.

Additional experimental and development work went on during the following years and led in 1988 to the commissioning of an integrated Angle Shift Measurement System (ASMS), better known at Hydro-Québec by its French acronym SMDA (Système de Mesure du Décalage Angulaire). This system was implemented in four 735-kV substations each equipped with IREQ made measurement units synchronized by IRIG B time code signals and achieving a 20 μ s accuracy. Phasor amplitudes and angles were transferred in real time to the Hydro-Québec control center once every cycle of the 60

Hz. In 1991, four PMUs were added for a total of eight monitored 735 kV substations. Since then, the number of measuring sites has not changed but improvements to the functions and materials brought the system to its most recent 2004 version based on Macrodyne PMUs synchronized by GPS.

Table 2.3.1 summarizes the evolution of the ASMS concept at Hydro-Québec. It is now a mature and highly reliable system with 99 % availability over the years.

2.3.2 ASM system and its applications

As shown in Figure 2.3.1, the ASM system is supervising eight 735 kV substations, which represent about 25 % of the main grid busses. These specific locations were selected in order to monitor large generator voltage phasors (located at the remote ends of the 3 main transmission corridors: LG2 for James-Bay West, LG4 for James-Bay East and Churchill-Falls for the North-East corridor), middle corridor substations (Chibougamau and Micoua), main load busses (Nicolet substation and Boucherville substation for Montréal area) and the HQ-NYPA interconnecting bus (Châteauguay substation).

As mentioned earlier, these terminals are modern PMUs customized by Macrodyne [8] to include an algorithmic feature specific to Hydro-Québec and a 60 Hz phasor calculation rate (instead of 30 Hz). The new algorithmic feature, which migrated from the previous generation of IREQ-made PMUs, is the computation of voltage harmonic distortion present on the monitored lines (up to four lines per PMU). These variables are required by the Hydro-Québec preventive control schemes against the contingencies induced by geomagnetic storms. With this latest version of ASMS, the SCADA is responsible for collecting in real time, the wide-area phasors and harmonic data at a 60-Hz sampling rate. Processing is then performed online for time reconciliation and transmission/GPS error correction before transferring the results to one of the six applications listed below. A main SCADA is located next to the TransÉnergie control center downtown Montreal and directly linked to the EMS. A duplicate one is redundantly operating in the backup control center located in another Hydro-Québec building.

Table 2.3.1. Evolution of Angle Shift Measurement System at Hydro-Québec

Year (Version)	Type of Synchro. (Accuracy)	Number of PMUs	Sampling rate (Hz)	Data concentrator: Features - improvements
1976 (1.0)	Loran C (46 µs)	2	1	Custom database
1981 (3.0)	GOES (46 µs)	3	30	Capacity of 4000 seconds of recording
1988 (4.0)	IRIG B (20 µs)	4	60	1) Central unit on a HP-1000 computer. 2) Visualization on Sun computer using X-Windows on a multi-user OS 3) Computation of voltage asymmetry 4) New 'Raima' database with a capacity of 10000 seconds for angular records and 3000 minutes for voltage asymmetry records
1991 (4.0)	IRIG B (20 µs)	8	60	Addition of 4 PMUs
1995 (4.0)	IRIG B (20 µs)	8	60	Computation of harmonic content up to the 10 th
1998 (4.1)	IRIG B (20 µs)	8	60	Capacity of continuous recording up to 6 months
2004 (5.0)	GPS (< 1µs)	8	60	IREQ measuring units replaced by Macrodyne PMUs. Database changed from 'Raima' to 'Oracle'

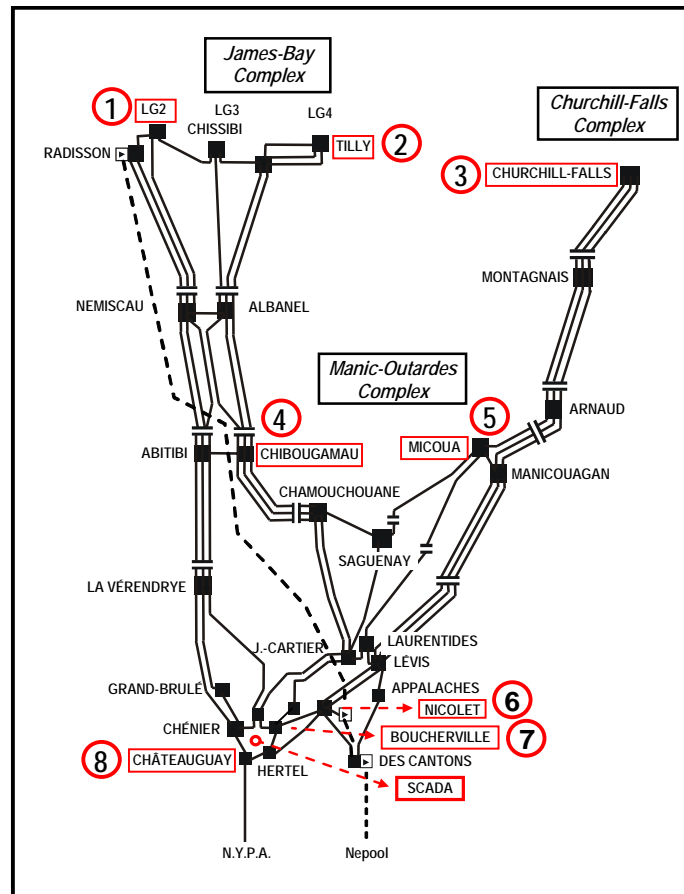


Figure 2.3.1. Hydro-Québec ASM System configuration

Applications presently in use:

1. *Post-mortem analysis of major events:*

The ASM system is very useful for Asset Management personnel involved in grid behavior analysis. Voltage phasors frequency, absolute and relative angles, harmonic contents are being correlated with the other recording tools (DFRs, event recorders, lightning activity recorders, etc.) to understand and document the most significant events occurring in the system. Transmission planning engineers are also making use of ASM records to assess the grid capacity and their operating strategies. Remote access to the Oracle database is using ODBC/Excel tools.

2. *Validation and fine-tuning of simulation models used by power system stability programs:*

This is achieved by comparing stability simulations with real recordings, given the same grid configuration. Therefore, in addition to the PMU recorded data, network state at the triggering time as well as the sequence of events are required. Both are obtained from the control center through the state estimator (LASER).

3. *Frequency regulation statistics:*

The power system frequency waveforms available on the TransÉnergie website are obtained in real time from the ASM system. These statistics are required to verify that Hydro-Québec complies with NERC frequency stability criteria.

4. *Real-time detection of geomagnetic storms:*

Since the main transmission corridors are extending from north to south over thousands of kilometres, they are prone to geomagnetic induced currents during solar storms. Depending on their intensity, these currents may bring shunt power transformers and reactors into their nonlinear characteristics and interfere with the 60 Hz voltage phasors. A trigger built from the wide-area harmonic data is

automatically generated by the ASM system and sent to the grid operators who then take preventive actions according to pre-established procedures.

5. Backup signal for load-frequency control:

From the wide-area bus frequency and angle shifts, the ASM system is computing the accumulated time error between the system voltage waveforms and the universal coordinated time. This provides a backup signal to EMS Load Frequency Control application.

6. Optional link to the state estimator:

Three angle shifts from the ASM system are sent to the state estimator data concentrator where they could help to improve the state estimate. It is planned to make the remaining five angle-shifts available to the state estimator. However, the added value of eight wide-area data should not be overstated, given that the Hydro-Québec state estimator relies already on 8000 measurements.

2.3.3 A typical ASMS recording

As an illustration of the graphical capabilities of the SCADA, a set of curves is presented in Figure 2.3.2. It was recorded by PMU #2 located at Tilly during a geomagnetic storm of high intensity K9. Bus voltage and even harmonics distortion were plotted over a period of 75 minutes. For this event, Tilly recordings were, in terms of harmonic content, the most severe in the whole ASM system.

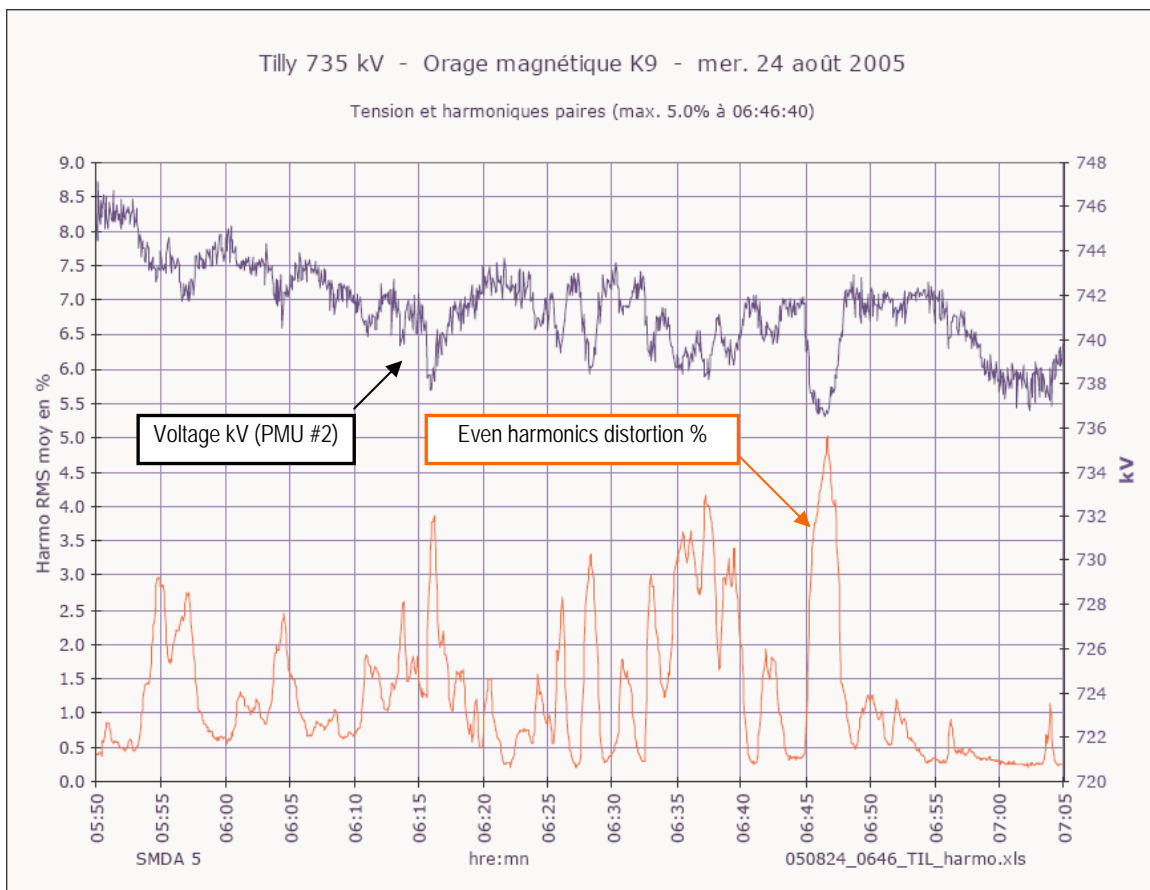


Figure 2.3.2. An example of ASMS recording: Voltage and harmonic distortion during intense geomagnetic storm (Source: TransÉnergie, Georges Blais)

2.4 The WECC WAMS in Western North America

This section is based on material taken from [9]. Wide area monitoring for a large power system involves the following general functions:

- Disturbance monitoring: characterized by large signals, short event records, moderate bandwidth, and straightforward processing. The highest frequency of interest is usually in the range of 2 Hz to perhaps 5 Hz. Operational priority tends to be very high.
- Interaction monitoring: characterized by small signals, long records, higher bandwidth, and fairly complex processing (such as correlation analysis). The highest frequency of interest ranges up to 20–25 Hz for rms quantities but may be substantially higher for direct monitoring of phase voltages and currents. Operational priority is variable with the application and usually lower than for disturbance monitoring.
- System condition monitoring: characterized by large signals, very long records, very low bandwidth. Usually performed with data from SCADA or other EMS facilities. The highest frequency of interest is usually in the range of 0.1 Hz to perhaps 2 Hz. Core processing functions are simple, but associated functions such as state estimation and dynamic or voltage security analysis can be very complex. Operational priority tends to be very high.

Interactions monitoring is the most technically demanding of these functions, and the one most likely to provide early warnings of emerging trouble. Experience from the western interconnections demonstrates that all of these monitoring functions are effectively and efficiently supported through coordinated recording of high quality synchronous data at key locations across the grid. The resulting wide area measurement system (WAMS) is a "network of networks" with about 1500 "primary" signals that are continuously recorded in their raw form. These primary signals are the basis for several thousand derived signals that are viewed in real time, or during offline analysis of power system performance. Data sources are of many kinds, and they may be located anywhere in the power system. This is also true for those who need the data, or those who need various kinds of information extracted from the data.

Figure 2.4.1 is provided as a guide to WECC geography, and to key interactions that govern wide area dynamics there. The primary "backbone" for the WECC WAMS consists of phasor networks as represented in Figure 2.4.2. PMUs stream precisely synchronized data to PDC units, and the PDCs stream integrated PMU data to StreamReader units and sometimes to other PDCs. The StreamReaders provide display, continuous archiving, and add-on functionalities such as spectral analysis or event detection. Remote dial-in access to PDC and StreamReader units is available when security considerations permit.

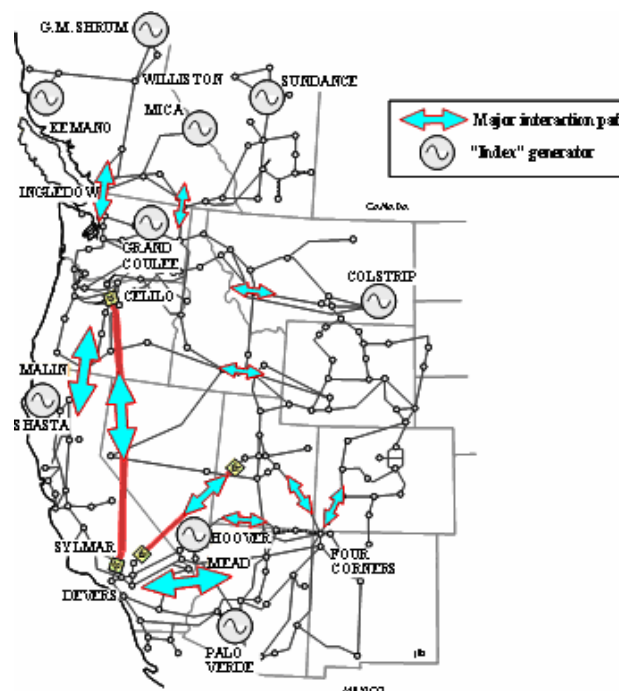


Figure 2.4.1. Key location and interactions in the western interconnection

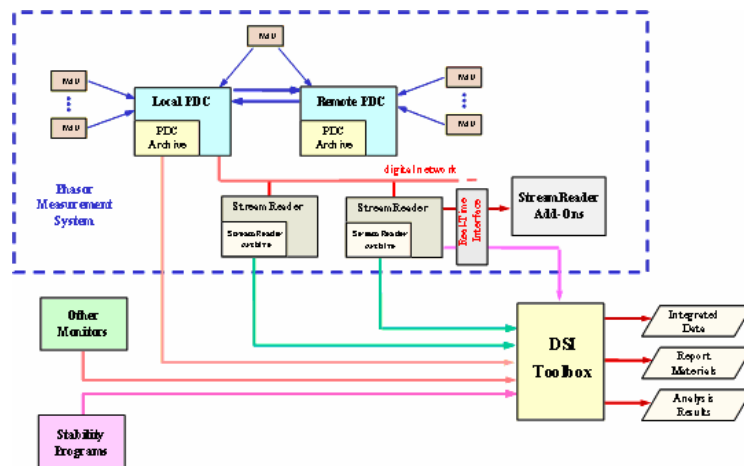


Figure 2.4.2. Flow of multi-source data within an integrated WAMS network

Each PDC has the potential of providing real-time data for power system behavior across a broad region of the power system. Some PDCs share signals to extend this coverage, and higher level networks are evolving that will consist entirely of PDCs. At present, however, most of the directly integrated phasor networks are isolated from one another and the data they collect are selectively integrated offline.

The WECC WAMS of 2004 is well along in the transition from Synchronized Phasor Measurement (**SPM**) networks to a much more general Synchronized System Measurement (**SSM**) network that accommodates signals of all kinds. Recent progress items in this area include:

- A growing WECC network of PDC units that share data in real time
- Deployment of local PMU/StreamReader packages tailored to generation facilities
- Deployment of high speed GPS synchronized monitors that continuously record point on wave data, or signals from HVDC and other FACTS-like controllers.
- Vendor options for export of controller signals into a general SSM network.

Signals collected on the WAMS backbone are continuously recorded at a rate of 20, 30, or 240 samples per second (**sps**); about half of the signals are phasor measurements. When needed, data from local monitors are integrated with data collected on the PDC network to form more detailed records of system behavior in areas of special interest. Some of the local monitors are “snapshot” disturbance monitors that use a local signal to initiate brief recordings. Digital fault recorders and some other point on wave recorders are in this category.

At present there are no fully automated Information Manager Units (**IMUs**) for WECC monitor data. Instead, the core IMU functions of data management, analysis, and report generation are produced as a staff activity. The established WECC toolset for this, the *Dynamic System Identification (DSI) Toolbox*, is the latest generation of software that has supported BPA and WECC performance validation work since 1975. It is coded in Matlab® and its core elements are distributed as freeware from WAMS websites such as ftp://ftp.bpa.gov/pub/WAMS_Information/. General reports concerning direct measurement and analysis of WECC system performance are usually distributed through internet web sites, or by WECC staff. Websites are routinely used for offline exchange of data, working documents, and software associated with WAMS operation.

The WECC WAMS is engineered to be both a distributed measurement system and a general infrastructure for dynamic information that conventional SCADA technologies cannot resolve. Specific applications are listed as follows:

- Real time observation of system performance
- Early detection of system problems

- Real time determination of transmission capacities
- Analysis of system behavior, especially major disturbances
- Special tests and measurements, for purposes such as
 - special investigations of system dynamic performance
 - validation & refinement of planning models
 - commissioning or re-certification of major control systems
 - calibration & refinement of measurement facilities
- Refinement of planning, operation, and control processes essential to best use of transmission assets

2.4.1 Performance Monitoring and Situational Awareness

One of the most obvious applications of WAMS is the detection of system performance. The importance and usefulness of this information is explained. Some grid managers, chiefly independent system operators (ISOs) and electrical utilities engaged in long distance transmission, are developing substantial measurement facilities. The critical path challenge is to extract essential information from the data, and to distribute the pertinent information where and when it is needed. Otherwise system control centers will be progressively inundated by potentially valuable data that they are not yet able to fully utilize.

These issues were brought into sharp and specific focus by the massive breakup experienced by the western interconnection on August 10, 1996. The mechanism of failure (though perhaps not the cause) was a transient oscillation, under conditions of high power transfer on long paths that had been progressively weakened through a series of seemingly routine transmission line outages.

Buried within the measurements at hand lay the information that system behavior was abnormal, and that the system itself was vulnerable. Later analysis of monitor records, as in Figure 2.4.3 and Figure 2.4.4, provides many indications of potential oscillation problems. Verbal accounts also suggest that less direct indications of a weakened system were observed by system operators for some hours, but that there had been no means for interpreting them. The final minutes before breakup represented a situation that had not been anticipated, and for which no operational procedures had been developed.

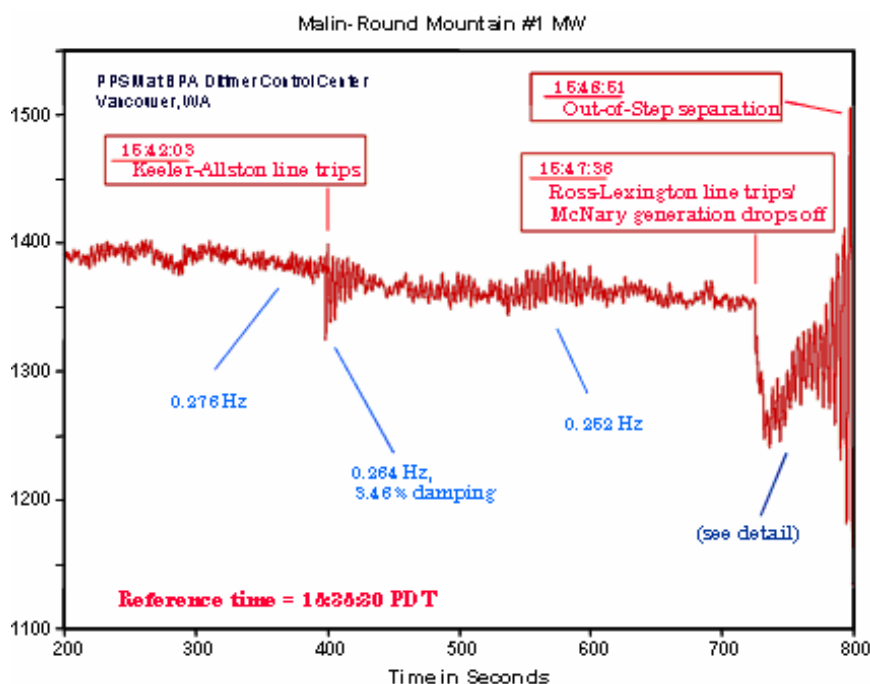


Figure 2.4.3. Oscillation buildup for the WSCC breakup of August 10, 1996

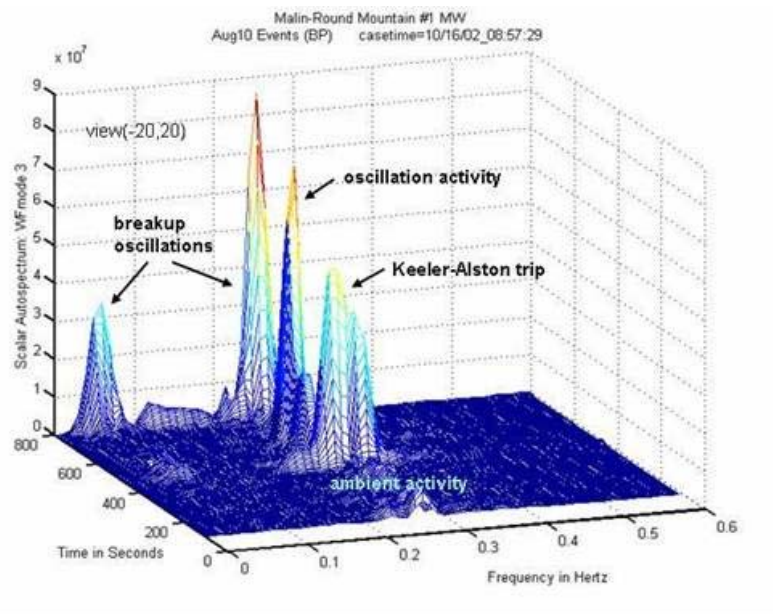


Figure 2.4.4. Oscillation spectra for the WSCC breakup of August 10, 1996

This event was a warning that utility restructuring, through several mechanisms, was making it impossible to predict system vulnerabilities as accurately or as promptly due to increasingly volatile market demands. It is likely that standard planning models could not have predicted the August 10 breakup, even if the conditions leading up to it had been known in full detail [10][11].

The U.S.-Canada Blackout on August 14, 2003, was immediately notable for its extent, complexity, and impact. Among many other actions, the event triggered a massive effort to secure and integrate regional operating records. Much of this was done at the NERC level, through the U.S.-Canada Power System Outage Task Force [12][13]. Additional background information concerning the event was gathered together by a group of utilities that, collectively, had been developing a WAMS for the eastern interconnection [14]. Like the WECC WAMS in the western interconnection, "WAMS East" had a primary backbone of synchronized PMUs that continuously stream data to PDCs at central locations for integration, recording, and further distribution.

WAMS data collected on August 14 provide a rich cross section of interarea dynamics for the eastern interconnection. Much of this information is imbedded in small ambient interactions, and is readily apparent to spectral analysis. Figure 2.4.5, for bus frequency fluctuations at the American Electric Power (AEP) Kanawha River substation, is typical of data that were collected as far away as Entergy's Waterford substation near New Orleans, LA. Frequency of the spectral peaks shows a general downward trend, plus sharp discontinuities that are associated with system events. This behavior suggests that the "swing frequencies" associated with interarea modes were declining through increasing stress and network failures on the power system. Though oscillation problems were not a significant factor in the August 14 Blackout, oscillation signatures such as those in Figure 2.4.5 provide readily available information that can be factored into "situational awareness" for real time operation of the overall grid. The August 14 Blackout provided considerable stimulus to the pre-existing Eastern Interconnection Phasor Project (EIPP, see section 2.5) [15]. Progress in this effort can be tracked by examining the WAMS website <http://phasors.pnl.gov/>.

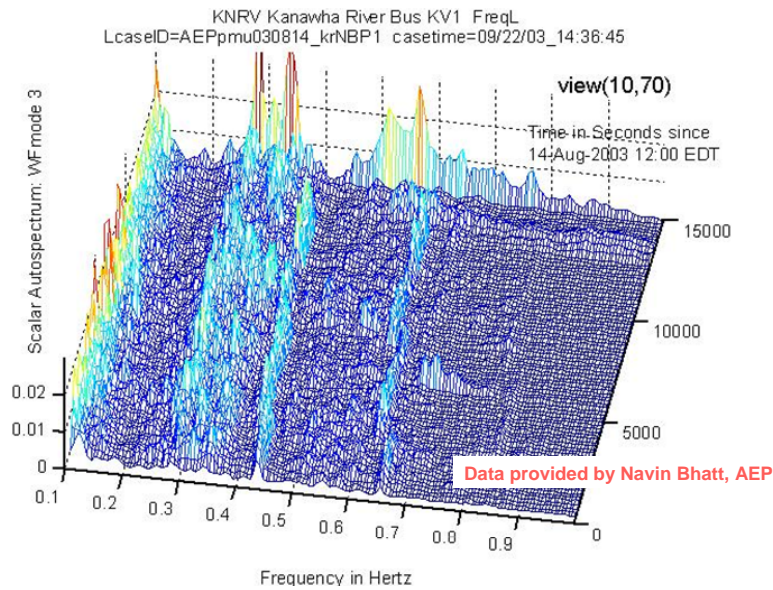


Figure 2.4.5. Spectral History for US-Canada Blackout of August 14, 2003: AEP Kanawha River bus frequency, 12:00-16:10 EDT

2.5 Eastern Interconnection Phasor Project (EIPP)

The Eastern Interconnection Phasor Project (EIPP) was started in 2002 by Department of Energy (DOE) and Consortium for Electric Reliability Technology Solutions (CERTS). DOE has served as a catalyst for collaboration among utilities, ISOs/RTOs, NERC transmission companies, researchers and vendors to demonstrate phasor technology to the Eastern Interconnection (EI) participants.

The EIPP gained momentum as a result of the August 14, 2003 blackout. EIPP targets many of the recommendations of the blackout investigations. Specifically, the project addresses several requirements in the NERC V0 Standard for Planning and many NERC blackout recommendations.

The mission statement of the EIPP, "to create a robust widely available and secure synchronized data measurement infrastructure over the eastern interconnection with associated analysis monitoring tools for better planning and operation, and improved reliability", is being supported by the industry and government officials at the highest level. The project participants are drawn from a broad array of stakeholders including utilities, operating/reliability organizations, academia, research institutions and government laboratories, manufacturers, IEEE, other standards bodies and more.

To achieve its objectives, the EIPP Work Group has been organized in six Task Teams, lead by an industry member and supported by a DOE-funded CERTS team member, to address different aspects of the project:

Equipment Placement Task Team – The responsibilities of the Equipment Placement Task Team include planning, coordinating and managing the placement of phasor measurement devices across the EI and identifying possible observability gaps across the system.

Real-Time Applications Task Team – The scope of the Real-Time Applications Task Team is to define, prototype and deploy monitoring tools for dispatchers, reliability coordinators and others responsible for maintaining grid reliability, to effectively monitor and assess the real-time operations of the power grid.

Offline Applications Task Team – The scope of the Offline Applications Task Team is to define, prototype and deploy tools for planners, analysts and others, to assess system performance, model validation and to enhance decision making related to bulk grid reliability.

Business Management Task Team – The responsibilities of the Business Management Team include coordinating and resolving matters related to agreements between the involved parties (e.g. non-disclosure agreements).

Data Management Task Team – The responsibilities of the Data Management Task Team include architecting and managing the phasor data storage and retrieval system.

Performance Requirements Task Team – The responsibilities of the Performance Requirements Task Team include evaluating performance of phasor measurement devices and components, define satisfactory performance guidelines and protocols, and acting as liaison to the standards efforts in the phasor technology area.

The Task Team leads along with NERC, CERTS and DOE representation form a Leadership Committee to facilitate communication and coordination between the activities of the different Teams. There is also an Executive Steering Group comprising of senior executives from different utilities and organizations to provide leadership and guidance as well as establish liaison with the external organizations.

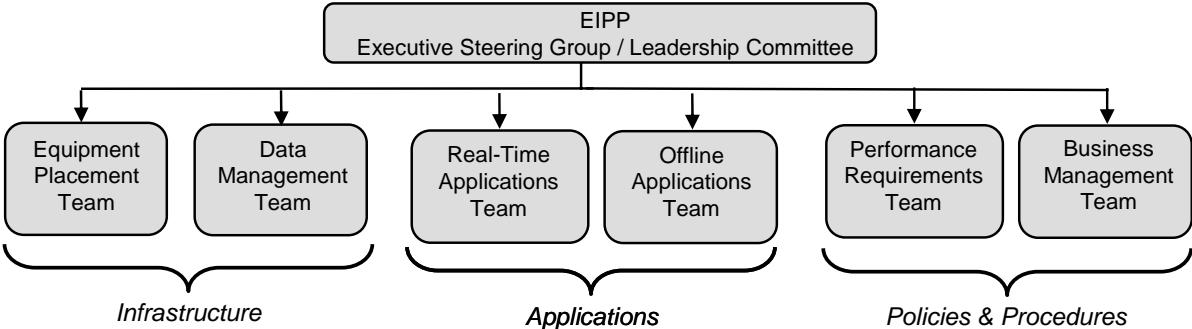


Figure 2.5.1. The EIPP Organizational Structure and Responsibilities

DOE’s facilitation of the Eastern Interconnection Phasor Project (EIPP) and initiative to fund the initial research and demonstration activities has been invaluable. This is evident both in terms of the growing involvement and contribution by industry participants as well as the project’s major accomplishments to date. The EIPP Work Group consists of over 220 interested stakeholders working together to advance the state of the art in power system monitoring and to share information deemed valuable in enhancing the reliability of the bulk grid. Industry has also stepped up to fund investments in deployment of phasor measurement devices, network infrastructure, and data collection, and vendors are stepping up their investments to bring new phasor based hardware to the market.

Under the auspices of the EIPP, the initial demonstration of a starter phasor network connecting approximately 25 existing Phasor Measurement Units within the Eastern Interconnection from multiple utilities and providing real-time wide area visibility is complete and fully operational. The additional 22 firm commitments for new installations before March 2006 demonstrates industry’s continued commitment in moving this initial demonstration forward and supporting the project. Additionally, at least 12 vendors now supply instruments with phasor measurement capabilities. DOE will continue to promote collaboration and efforts to prove the concept. Utilities, manufacturer and vendor communities shall continue to expand the underlying infrastructure into a commercial production quality system and take ownership of the maintenance and support.

2.5.1 EIPP Accomplishments

The EIPP project has made several accomplishments over a very short time span. Some of the major achievements of the project are summarized below.

Establish Starter Network – As mentioned earlier, the initial EI phasor network connecting approximately 25 PMUs dispersed across various EI utilities is in place and is fully operational. This starter phasor network uses point-to-point VPN links for real-time data transfer between utilities with existing PMU installations (i.e., Ameren, AEP, NYISO and Entergy) and Tennessee Valley Authority (TVA) which currently serves as the central host site for synchronizing this phasor data. In support of this EIPP endeavor, TVA has made substantial investment in developing a central data store, called the "Super Phasor Data Concentrator" (or "Super PDC"). The phasor measurements sent to TVA are integrated and aligned across utilities by the Super PDC to provide a precise Interconnection-wide snapshot, as well as simultaneously archived into TVA's DataWare data repository for long-term storage. Comparisons of high sub-second snapshots enable real-time monitoring and tracking of grid dynamics and stress. TVA's real-time data output stream and central archive support industry standard protocols such as BPA PDCStream for real-time streaming data and Ole for Process Control (OPC) and XML for historical data.

Provide Real-Time Wide Area Visibility – The August 14 blackout pointed to a need for operating tools that provide wide area views of the grid state and also time-synchronized history following an event. The DOE funded Real-Time Dynamics Monitoring System (RTDMS) is currently the prototype tool in place for providing this type of wide area viewing across the Eastern Interconnection phasor data in real-time. To allow convenient access to the data in real-time and at multiple locations, RTDMS uses secure web connections to retrieve data from TVA's Super PDC, cleanse the data and distribute this data to its many remote visualization terminals. These multiple RTDMS visualization applications use various geographic and graphic displays to provide operators and reliability coordinators both near real-time and time series information on:

Interconnection and local frequencies at key monitoring points across the EI - Changes in frequency are mapped to precise generation-load imbalances within the Interconnection. The local frequency measurements can be used to assess system coherency and its dynamic stress under normal operating conditions, as well as estimate the point of deceleration/acceleration during a disturbance. Phase angle differences across different utilities with respect to alarming thresholds as defined by offline analysis and operator experience allow assessing the static stress across the system and its proximity to instability. Wide area view of system voltage angle and magnitude profiles permit to identify the sources and sinks of power, and the high and low voltage regions within the grid. Also, this allows for monitoring and tracking the MW and MVAR values across key transmission lines and flowgates with respect to predefined thresholds.

This system offers flexibility in terms of it being designed as an open and scalable platform with the ability of other vendor applications to access data using its available Web Service. The RTDMS application had been deployed to the 7 operations centers and 11 reliability coordinators within the Eastern Interconnection. Some of the other early visualization tools provided by vendors like Powerworld and OSISoft are also installed at a few of the EI utilities.

Improved State Estimation – The EIPP Real-Time Task Team is providing coordination and support to a demonstration project currently under way by energy management system (EMS) vendors in collaboration with utilities to utilize phasor measurements in the state estimation process. Phasor measurement devices directly measure the system state with high precision and are therefore believed to improve state estimation. There are many alternatives available for using phasor measurements in the state estimation: some are non-invasive to the conventional state estimation process but rather use the output of these traditional state estimators in conjunction with the phasor measurements, while others use the phasor measurements along with SCADA data as direct inputs in a hybrid state estimation process. Preliminary research has shown that as little as 10% coverage by strategically placed PMUs dramatically improves the accuracy and processing speed of state estimation. Such improved accuracies in state estimation process will be reflected in economic operations (e.g. LMP computations), contingency analysis, and security margin estimates which utilize the state estimation results as inputs in their computations. The results from the state estimation activity are expected to be made available further down the road. This exercise will reveal some of the underlying challenges in

fulfilling this activity such as unobservability, data rate incompatibility, etc.

Establish Performance Guidelines – The Performance Requirements Task Team is currently investigating several key areas of interest to EIPP stakeholders with the plan to document findings in a series of “requirements documents”. The requirements documents are intended to be used by utility engineers or suppliers who wish to gather information that will help them participate in the project. The team has prepared a document on the raw phasor data utilization which covers various relevant topics such as data accuracy, minimum performance requirements phasor network components, characterization of synchronized measurement devices and instrumentation channels, etc. In addition, the team is also pursuing requirements documents for PMU testing/interoperability/calibration, PMU/PDC installation/commissioning, state estimation using synchrophasors, phase angle reference for PMU measurements, phase inconsistency in PMU measurement’s, naming conventions, etc. The National Institute of Standards and Technology (NIST) recently created a SynchroMetrology Laboratory to support this EIPP activity and other industries that make use of synchrophasors. As phasor technology and associated applications become commercial, many of these performance guidelines may eventually be incorporated into industry standards.

Project Advocacy – Perhaps the greatest contribution of the EIPP project is the overwhelming industry involvement and support that it has received in its various activities, and its success in accelerating the adoption of these new, more accurate, time-synchronized phasor measurements by the EI utilities. A key focus of the Real-Time Applications Task Team activities has been to involve the Reliability Coordinators and other system operators, to introduce them to this new technology and applications, and especially get their feedback in the definition and development of these early monitoring tools. To encourage increased stakeholder involvement in the EIPP project, the team has also prepared and distributed a generic Business Plan which interested parties may use to obtain buy-in from their management to participate in the project.

Resolve Data Confidentiality Issues – One of the major obstacles in the sharing of this high resolution phasor data has been protecting the confidentiality of this data. In the short-term, to expedite the sharing process, the Business Management Team put in place an "Interim Data Confidentiality Agreement" that was signed by each of the initial EIPP data contributors and protected the data confidentiality and its misuse. Working with NERC, the NERC "*Confidentiality Agreement for Electric System Security Data*" has now been modified to include time-synchronized phasor measurement data. All signatories of this new NERC non-disclosure agreement now have access to this real-time data.

DOE leadership and funding has been critical in galvanizing the industry behind demonstration of the phasor technology. Now the focus shifts from validating the technology to research on how to utilize and apply phasor data to improve grid reliability, security, efficiency as part of meeting DOE’s vision for the grid of the future.

2.6 WAMS at TERN A in Italy

Following the blackout that occurred in Italy on the 28th September 2003, the Italian System Operator (formerly GRTN, now TERN A) has undertaken a plan of action aimed to improve the operational security, through the enhancement of monitoring facilities. One major item of this plan is the design and the realization of a wide area synchronized network [16]. The architecture for this system is depicted in Figure 2.6.1, and is aimed to provide the control room operators with advanced monitoring tools, automatic corrective controls (both phenomenon and event-based), and linked with the ESAS protection system [17]. The WAMS project at TERN A has been developing over a time span of over two years and involves the installation of about 30 PMUs, a dedicated data network and monitoring applications for data processing and intelligent display at the National Control Center (in Rome).

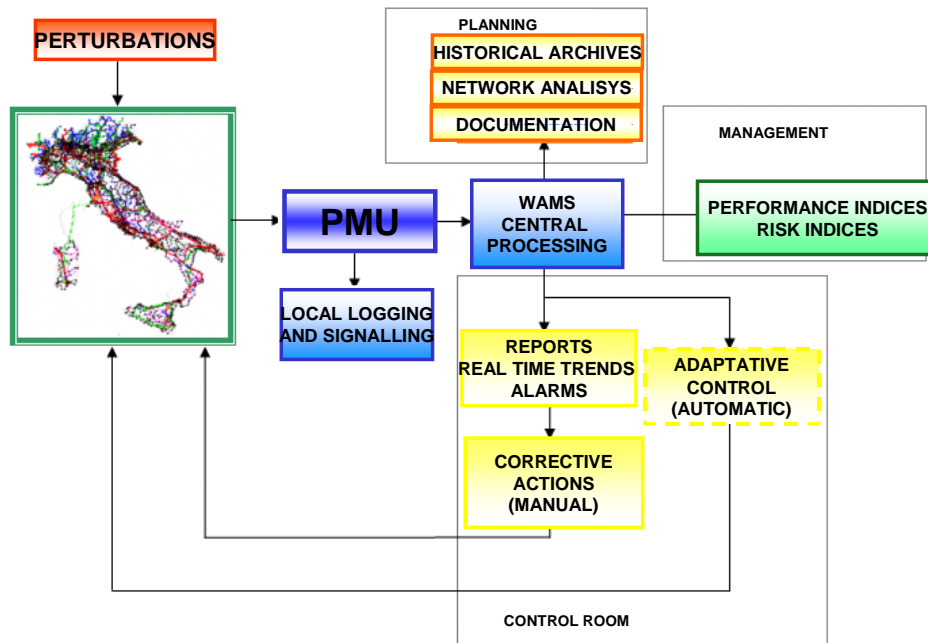


Figure 2.6.1. Architecture of the WAMS application at Terna (Italy)

The sites that will host the PMUs have been selected according to combined heuristic-analytical criteria, in order to maximise the operating value of the measurements. Each criterion concerned local and system aspects regarding separately event identification, oscillation detection, angle, voltage and frequency stability monitoring. The operators' experience pointed out a number of heuristic criteria (e.g. proximity to great generating unit, bottlenecks, borders, etc.) that were also taken into account. Figure 2.6.2 shows the deployment of the first 21 PMU to be installed into the Italian HV grid.

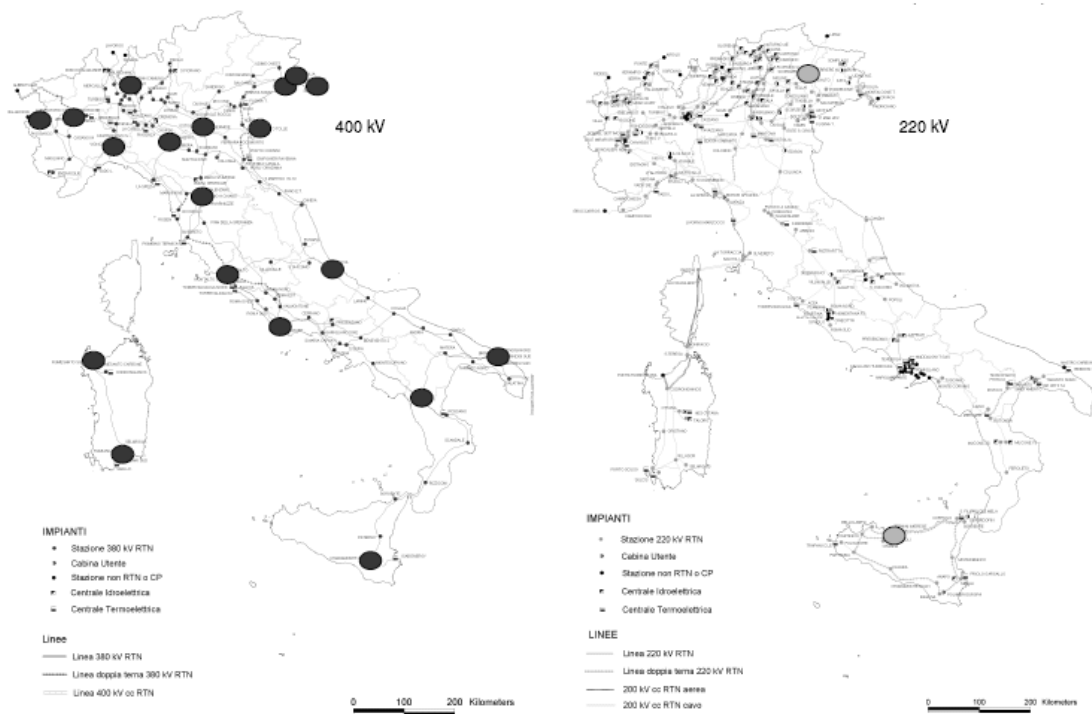


Figure 2.6.2. Deployment of the first 21 PMU devices in Italian HV grid (left: 400 kV layout, right: 220 kV layout)

Critical nodes will also be equipped with local recording and back-up functionality. Thus, in case of communication failure, the recording of significant transients is assured. Recording is triggered by

events (such as protection intervention), by specific algorithms for disturbance detection, or by external activation. A potential future application is the connection of the wide area system with the analogous systems of the neighboring countries, for comprehensive control of the interconnected power network and in-depth monitoring of the power import towards the Italian system.

The PMUs produce an output measurement set at a rate of 50 times per second (one every 20 ms). The PMU sampling window lies in between 20 and 50 ms, the delay time due to processing is less than 10 ms. The measurement errors are within 0.1° for phase and within 0.01% for frequency. The data provided by the PMUs (measurements, time stamp, and the other status information) are formatted according to the IEEE 1344 standard and continuously transmitted to a central server by means of a high-reliability, high-performance redundant communication system such as those provided by dedicated numerical circuits.

The acquired data are stored in a real-time database, hosted in the RAM of the server made redundant by hot back-up. The monitoring application programs read the PMU data and write the results in a dedicated area of the database. The database is also accessed by the alarm management applications. The memory keeps the data of the last 30 minutes, aligned and chronologically sorted by means of the time stamps. Older data are moved to a short term circular buffer containing 24 hours sampling at 20 ms, then to a long term archive hosting 30 days data sampled at a rate of one sample every 100 ms. Data is permanently saved on operator request or automatic disturbance detection trigger.

The planned monitoring functions for operator support concern voltage, angle and frequency stability. As far as voltage is concerned, displays and algorithms are made available to track closely the voltage profile and stability margins, and to give early warning of possible voltage collapse. As for angles, displaying the voltage angular difference between important line terminals or between generation and load areas is among the simplest and most effective indicators of system stress. It may also provide aid in reconnection manoeuvres. Another major application expected from the wide area synchronized system consists of the modal analysis for real time and offline identification of oscillatory behaviors. Knowledge of damping allows determining the degree of stability of the operating condition; identification of unstable modes and participation factors [18]. Recent analyses conducted on the output of the first PMU in operation confirm the importance of oscillation monitoring also for the Italian system. Frequency is going to be monitored to detect power imbalances and perform offline disturbance analysis. Response and effectiveness of the frequency regulation and adequacy of the rotating reserve will also be tested.

The WAMS project is in its initial stage with the aim to evaluate how effectively it can improve power system security. Further developments will be driven by the response, acceptance and needs expressed by the operators. One of the major issues to be analyzed will be the options for integration between WAMS and SCADA/EMS (e.g. improving of state estimation).

2.7 West Japan 60Hz System Monitoring

The West Japan 60Hz System has longitudinal interconnections between six major power companies. It is well-known that some low frequency power oscillation around 0.3 to 0.5 Hz are present. In order to monitor the wide area power system dynamics, a research project has been conducted where PMUs were installed in some universities. The most interesting feature in this project is that the PMUs measure the voltage phasor of the domestic power outlet (100V in Japan). At present 8 PMUs have been installed; Nagoya Institute of Technology, Fukui University, Osaka University, The University of Tokushima, Hiroshima University, Kyushu Institute of Technology, Kumamoto University and Miyazaki University (see Figure 2.7.1). (Two PMUs in Hachinohe Institute of Technology and Yokohama National University are installed in the 50 Hz System.)



Figure 2.7.1. Installations of PMUs in West Japan

Figure 2.7.2 shows an example to extract the lowest power swing modes by applying wavelet transformation. Power swing between Miyazaki and Nagoya (both ends) are clearly observed.

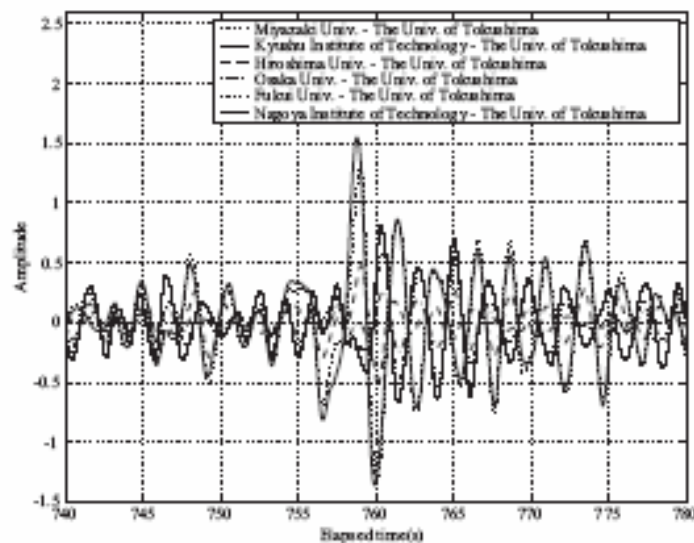


Figure 2.7.2. Lowest power swing modes

2.8 University PMU Network in Sweden

PMUs have been installed at three Swedish universities and monitor the Swedish power system from the 400 V level. The main purpose is monitoring of dynamic power system events to demonstrate the potentials of the phasor measurement technology in general and to evaluate the quality of low voltage measurements. The system has also been the basis for data management tools that have been developed for ABB by Lund University.

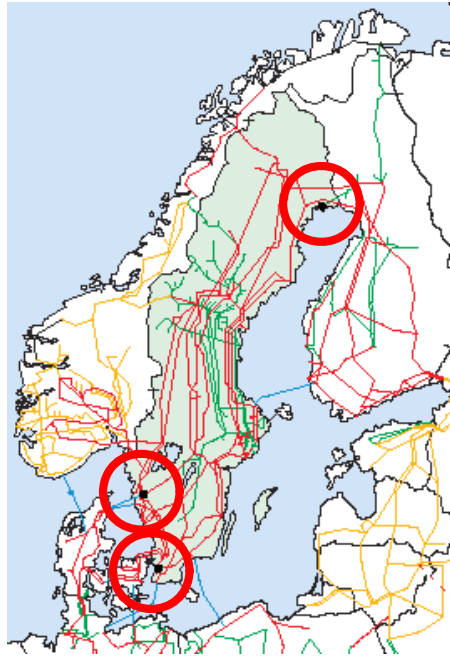


Figure 2.8.1. The Nordel transmission system and PMU locations at the technical universities at Luleå (top), Göteborg (middle) and Lund (bottom). The line across the sea in the center is the FennoSkan HVDC link.

ABB Automation Technologies AB, PTSX/TP has kindly donated an RES521 PMU to Lund University and made two others available for the university PMU network. The units have been connected at the 400 V level at the technical universities in Luleå, Göteborg and Lund (see Figure 2.8.1) and deliver streaming phasor data according to the IEEE synchrophasor standard 1344-1995. As the aim is to monitor the transmission system, no current measurements are relevant at the 400 V level and only voltage and frequency are measured. These data are continuously sent to a data concentrator in Lund via the internet, which uses the national university network as a backbone.

A dedicated PC runs the data concentrator, which aligns the data and produces a consistent system-wide data set that is continuously written to disk. A number of triggers have also been implemented, which issue an e-mail and store five minutes of data with a descriptive file name. The trigger conditions are:

- Frequency < 49.85 Hz
- Frequency > 50.15 Hz
- |Angle difference change| > 0.05 °/s

For online monitoring, a web-based interface has been developed, see Figure 2.8.2. It shows time history of voltages, angle and frequency differences of the last five minutes. It also shows frequency difference spectrum and its time history. The angle differences are closely coupled to the power flows resulting from the market situation. For this reason it has been found convenient to include a map with area exchange information from the market operator NordPool.

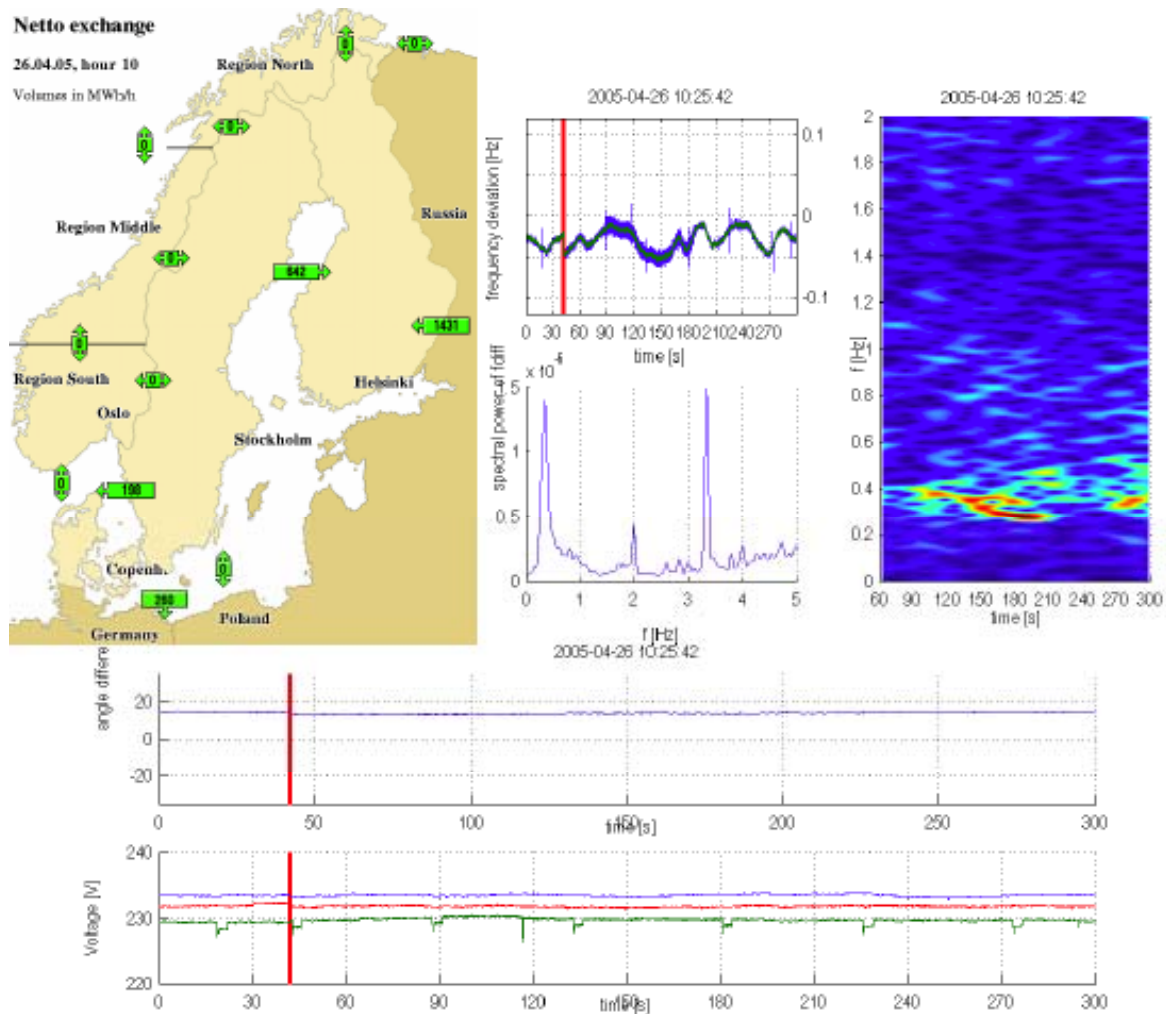


Figure 2.8.2. Web page for online monitoring showing area exchanges from NordPool (top left), frequency difference and its spectrum (top right) and angle difference and voltage (bottom). The zeros in the NordPool map shown here are mainly due to missing updates of the transfer values

A Matlab® calculator with graphical user interface has been developed [19]. By applying various mathematical operators on the primary data, quantities such as power or angle difference may easily be computed. The calculator can be used for offline analysis of data files, but also for online analysis of the streaming data. The functionality is chosen so that power system analysts can get acquainted with phasor data and experiment with visualizing arbitrary quantities. The data concentrator, the web-interface and the calculator together form a rather simple system for exploratory and flexible phasor data analysis.

Monitoring of the transmission system using PMUs connected at 400 V assumes that dynamic events in the transmission system are well reproduced in voltages at lower voltage levels. To investigate this, simultaneous recordings at transmission and low voltage levels have been carried out. The results in [20] show that the waveforms at high and low voltage levels indeed agree very well with each other during transmission events. Many types of events can thus be detected and identified using low voltage level data and two examples are given here.

At one occasion, the frequency exceeded the upper trigger level. Subsequent analysis of the data showed a steady state frequency error of about +0.08 Hz. With a frequency control reserve requirement of at least 6000 MW/Hz in the Nordel system, this translates to a loss of load or export out of the Nordel system of at least 480 MW. Simultaneous reduction in all phase angle differences indicated that the system was relieved and that the lost load or export was in the far south of the system. Later the event was described at Urgent Market Messages at NordPool as tripping of the

Kontek HVDC link exporting 550 MW from East Denmark (Nordel) to Germany (UCTE). Clearly, this is well in line with the PMU data.

In the Kontek case, the frequency increased at all PMU locations, but they may also change in different directions as shown in Figure 2.8.3. The graph shows oscillations, where frequency in Luleå initially increases while it decreases in Göteborg and Lund. The underlying event is tripping of the FennoSkan HVDC link, which connects Sweden and Finland within the synchronous Nordel system. As the link is tripped its power transfer is taken up by the 400 kV AC lines between Finland and Sweden, which is reflected in the phase angle differences between Luleå and the other sites. This step change in loading excites one of the less damped inter-area modes between Finland and western parts of the system. Transmission system dynamics is thus clearly visible also at the lowest voltage level.

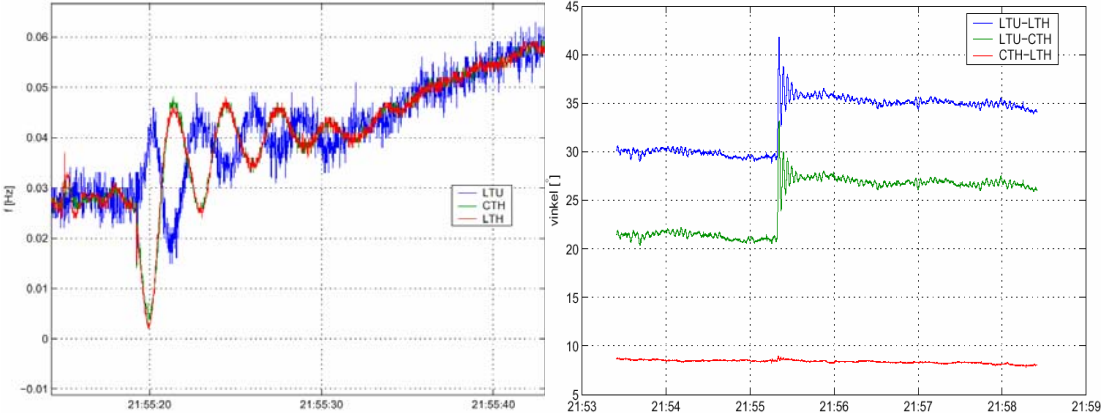


Figure 2.8.3. Trip of Fennoskan HVDC link transferring 500 MW from southwestern Finland to eastern Sweden. Frequency deviation in Hz and angle differences in degrees

The experience with the PMU network has shown good agreement with transmission level measurements. While steady state frequency changes indicate the size of the disturbance, phase angle data make it possible to locate events geographically. If fault clearing time is different at different voltage levels this adds information about where the fault occurred in terms of voltage level. Phase angle separation has proven to be a good indicator of stress on the system. In comparison with the alternatives, MW, MVA and current measurements, the phase angle is much easier to access and it is not sensitive to topology changes. Future plans for the system include extension to better cover the Nordel system.

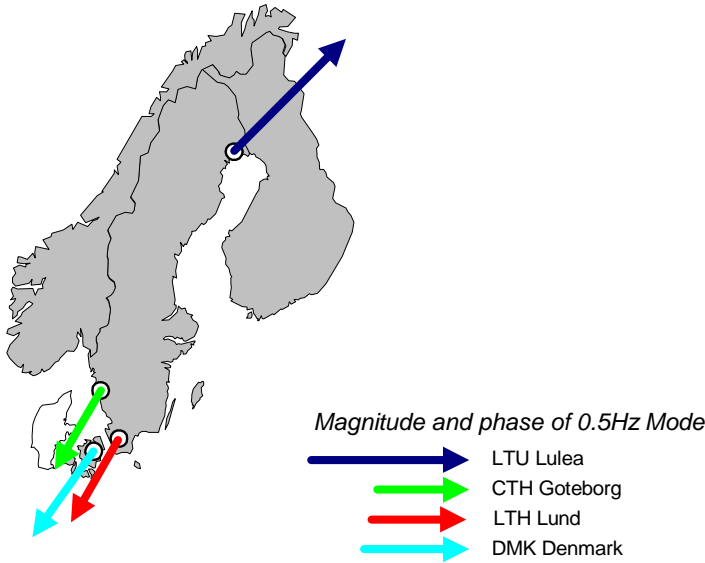


Figure 2.8.4. Mode amplitude and phase at PMU locations in Scandinavia

Data from the Swedish and Eastern Danish PMU networks was valuable for analyzing a significant dynamics issue in Scandinavia. Recurring incidences of poor damping of a 0.5Hz oscillation were observed in Finland, and synchronized measurements from Sweden and Denmark were analyzed to determine the amplitude and mode phase while the resonant condition was sustained. The observability of the mode in frequency measurements are indicated in Figure 2.8.4, showing that the condition is a wide-area phenomenon, with coherent generation in South Sweden and Denmark swinging against the North. An investigation and proposed explanation of the behavior is published in [21].

2.9 PMU Network in Eastern Denmark (Elkraft System¹)

Elkraft System is the independent system operator (ISO) in Eastern Denmark. The transmission grid in Eastern Denmark encompasses overhead lines and cables at the two highest voltage levels, i.e. 132 kV and 400 kV, and the interconnections with South Sweden and Germany. The link to Germany is a 400-kV DC interconnection with a transmission capacity of 600 MW. The interconnection with Sweden consists of AC interconnections with a total capacity of some 1900 MW. The link with Sweden also serves as an interconnection with the Nordic grid. The maximum load in Eastern Denmark is about 2870 MW and the total installed capacity is 4360 MW.

During the last fifteen years the amount of wind production has increased from negligible to cover 15 % of the total electric energy consumption. The amount of wind power has taken a significant step upwards when a 150 MW off shore wind farm at Rødsand near Nysted south of Zealand was put into service in autumn 2003. This wind farm together with most of the existing wind turbines is placed in the sparsely populated areas, where the transmission system is significantly weak. Beside the increased amount of wind power, there have been installed a number of combined heat and power units in the system. This new production displaces production from conventional power plants. Consequently the ISO has to handle a changing pattern of electric energy production. Furthermore, the deregulation of the electric energy market makes the power flow less predictable.

As the increase in utilization of wind energy and combined heat and power is expected to continue, it will become more important to gather precise information about voltages and power flows in the transmission system.

Two PMU units have been installed in the 400 kV system and two on 132 kV level in Eastern Denmark. The PMU units are developed and built in collaboration between Elkraft System and Center for Electric Technology (CET) in the Technical University of Denmark. Since the PMU's are built at CET all information about the measurement method are known in every detail.

The main purpose with the PMU project is to do research work. In the future PMU data is expected to become a helpful tool in daily control room routines and system protection.

The research work covers the following subjects:

- *PMU measurement method*
Dependent on the used measurement method in the PMU's, they have different responses during transient states in frequency, phase or amplitude. Since the PMU's are built at CET, it is possible to do experiments with different measurement methods.
- *Model verification*
After major events in the transmission system, measured dynamic responses are compared to calculated responses in order to verify the used dynamic models in the dynamic calculation tools. The phase information in the PMU data gives an improved verification of the mathematical models.
- *Stability assessment*
PMU data can improve online stability assessment of angular and voltage stability.

¹ On 1 January 2005 the Danish state took over the ownership of Elkraft System, Elkraft Transmission (Eastern Denmark) and Eltra (Western Denmark). Together with Gastra (gas transmission), the companies merged into Energinet.dk in fall 2005. Arne Hejde Nielsen is with Center for Electric Technology, Technical University of Denmark.

- *System protection schemes*
A PhD project regarding System Protection Schemes utilizing PMU advantages is going on at Elkraft System and CET.
- *Oscillation modes*
Power oscillations in the transmission grid can be investigated by analyzing the frequency or phase information in the PMU data.

2.10 Corridor Monitoring at Austrian Power Grid (APG)

Austrian Power Grid AG (APG) is a subsidiary of VERBUND, the largest producer and distributor of electrical energy in Austria's deregulated market. Headquartered in Vienna, the TSO plans, operates and maintains the super-regional high voltage and extra-high voltage grids with ties to all neighboring countries. APG ensures the safe, economical and environmentally friendly transport of some 33,110 GWh to its customers per annum. Most of this electric power is produced by the VERBUND subsidiaries AHP and ATP with around 22,700 and 5,500 GWh being generated in 88 hydroelectric and 17 thermal power plants, respectively. APG operates some 46 substations and switching stations, which are connected via 110 kV, 220 kV and 380 kV lines totaling 6.500 km in system length.

A production surplus of 1900 MW in North-Eastern Austria and a 1400 MW deficit in the South of the country bring about heavy power transfers via the three 220 kV north-south line connections with a total capacity of 1200 MW. Increasing congestion restricts electricity flows and reduces security of supply. The addition in 2006 of 1000 MW wind generation in the northeast and shutdown of coal-fired stations in the south will further aggravate the situation. Alleviation through required line upgrades to 380 kV and completion of the high-performance 380 kV line ring is imminent. Meanwhile, bottleneck management with emergency measures at power and distribution stations helps to scantily maintain network operation at exploding costs. These lead to rises in network cost and electricity prices, while the supply certainty drops. Network operators require support with maximizing transmission as well as detecting and counteracting evolving disturbance and overload situations. Figure 2.10.1 shows the transmission situation of APG.

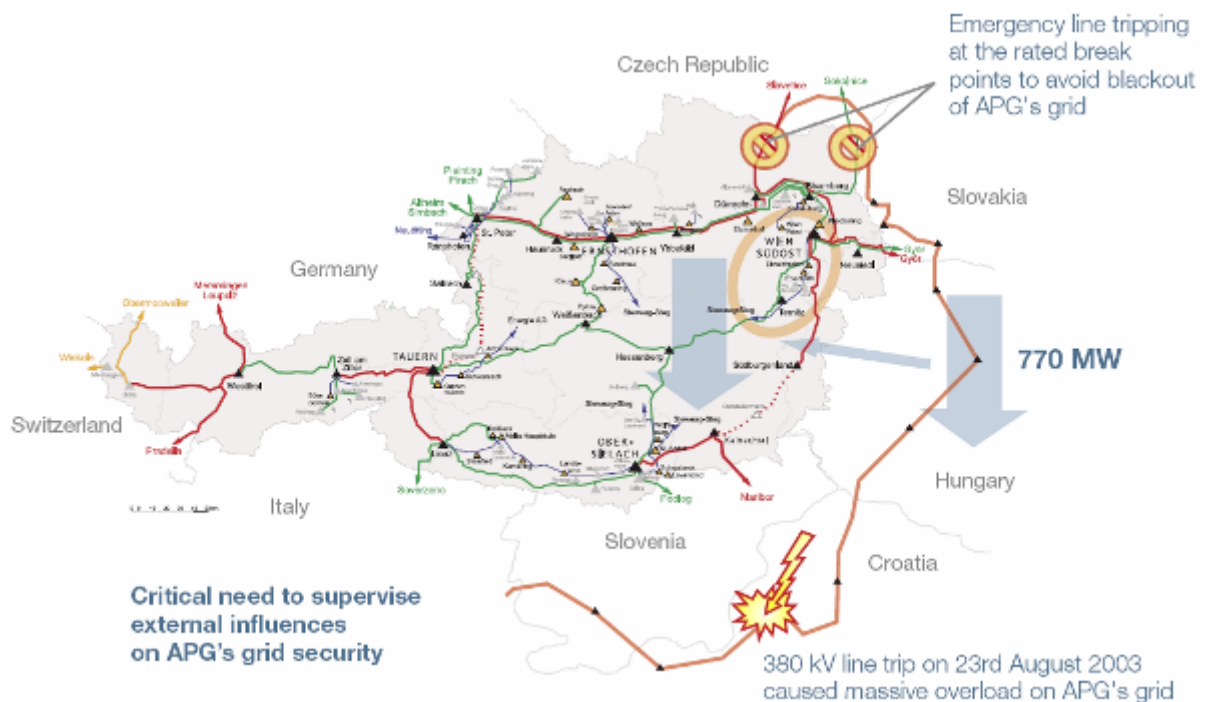


Figure 2.10.1. APG transmission network

After thorough evaluation, APG decided to realize a first phasor measurement installation and monitor the heavily loaded corridor between Vienna and Ternitz with online applications. The information especially on the load flow and average temperature progression on the double lines will aid the operational staff in fully utilizing the transmission capacity and maintaining integrity at the same time.

The Austrian Power Grid introduced the Wide Area Monitoring System (WAMS) to support its operators with:

- Detecting and counteracting evolving contingencies and overload situations
- Improved operation of the vital Vienna-SE-Ternitz 220 kV double line with applications like phase angle difference and line thermal monitoring
- Gaining experience and data to optimize the north-south power flow through the use of three phase-shifting transformers being installed in 2006

The Phase Angle Monitoring application facilitates the monitoring of network stresses caused by heavily loaded lines. It provides power system operators with real-time information to evaluate the present voltage phase angle difference between two locations – a crucial issue e.g. for the successful reclosing of transmission lines. Upon detection of an extraordinary status, the system alerts the operator by giving an early warning or, in critical cases, an emergency alarm. Actions that the operator may take to improve grid stability range from generation rescheduling to load shedding in extreme cases.

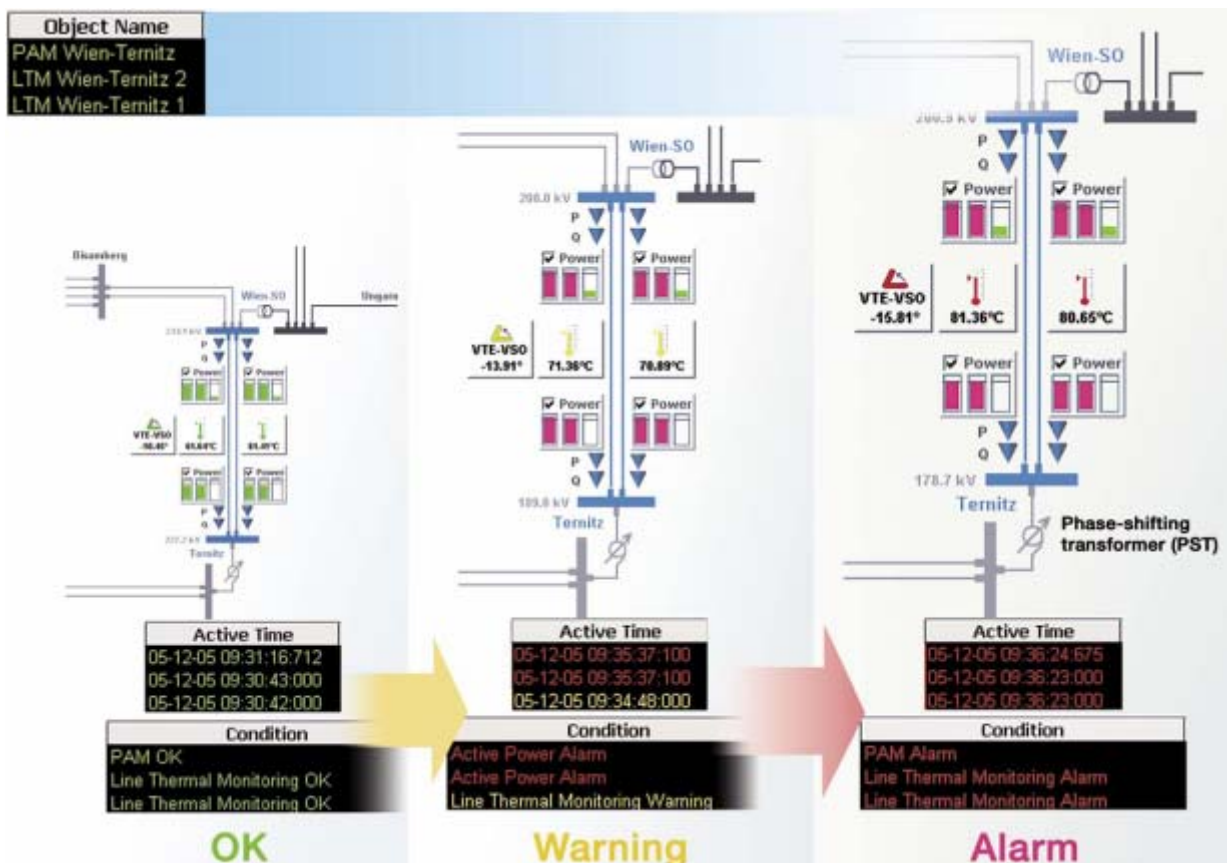


Figure 2.10.2. Visualization of system status for three different situations in a corridor of the APG network

The results of the Line Thermal Monitoring application provide better accuracy in determining the mean line temperature and changes in temperature. It computes actual impedance and shunt admittance of a line and extracts the line resistance. Based on the known properties of the conductor material, i.e. reference temperature and dependency coefficient, the actual average temperature is determined. Since the WAMS serves as an early warning system in case of potential overloads, the operators gain information to initiate corrective actions and thus avoid tripping of heavily loaded lines.

In a next step, further PMUs shall be placed in the Ternitz, Ernsthofen and Tauern substations with the aim of optimizing the use of three phase shifting transformers being installed in 2006. Their effectiveness shall be verified and their operation in a group coordinated with the aim to safely make full use of the available transmission capacity. This opens the option for a Wide Area Control of the phase shifters in the future.

The Wide Area Monitoring at APG is the third such system installed within the network of UCTE (Union for the Coordination of Transmission of Electricity) in Europe. It is of the same kind as in Switzerland and Croatia.

2.11 WAMS at EGAT Thailand

The Electricity Generating Authority of Thailand (EGAT) was founded in 1969. With an installed capacity of some 25,800 MW presently, EGAT accounts for around 60% of the countries total load. It also develops, owns and operates the national transmission network covering the entire country and operating at voltage levels of 115, 230 and 500 kV. The grid is linked to Laos via 115 and 230 kV lines and to Malaysia via 132kV lines as well as a new 300 kV HVDC lines for energy exchange. These transfers via a link with limited capacity bring about heavy power flows between the southern and the central region. In case of critical system conditions, the networks may encounter stability problems.

In weak power systems with remote generation, power oscillations caused by interactions between generators responding differently to changing system conditions and insufficient damping often limit the transmitted power and jeopardize system stability. The WAMS is installed in order to safely increase power flow through the congested and disturbance-sensitive corridor.

In a first phase, GPS-synchronized PMUs installed in substations in Bang Saphan and Surat Thani will transmit their data to the System Monitoring Center located in the Head office at Nonthaburi. Here engineers are provided with online information enabling them to monitor the power transfer and voltage phase angles. The frequency of oscillations is identified and determined, as well as its damping. This information enables the power system operators to swiftly take well-informed decisions and counteract potential instabilities. Operators can thus avoid potential cascade tripping and system islanding. The algorithm for oscillation monitoring is fed with selected voltage and current phasors. By processing these input phasors, it detects the various swing (power oscillation) modes. The algorithm quickly identifies the frequency and the damping of swing modes. It deploys adaptive Kalman filtering techniques.

The expectations on the WAMS are:

- Operator support for optimizing power flow and maintaining grid integrity
- Dynamic grid condition monitoring with early warning to prevent the spreading of disturbances
- Improved transmission network operation with applications like power oscillation monitoring
- High quality data for grid modeling and enhancement of control measures

The WAMS helps to optimize transmission as well as to detect and counteract power system instabilities. Furthermore, the information is used to perform offline studies and grid modeling, which enables one to improve stabilizing and control measures to avoid major disturbances in the future.



Figure 2.11.1. Network situation of EGAT Thailand with WAMS installation in a transmission corridor

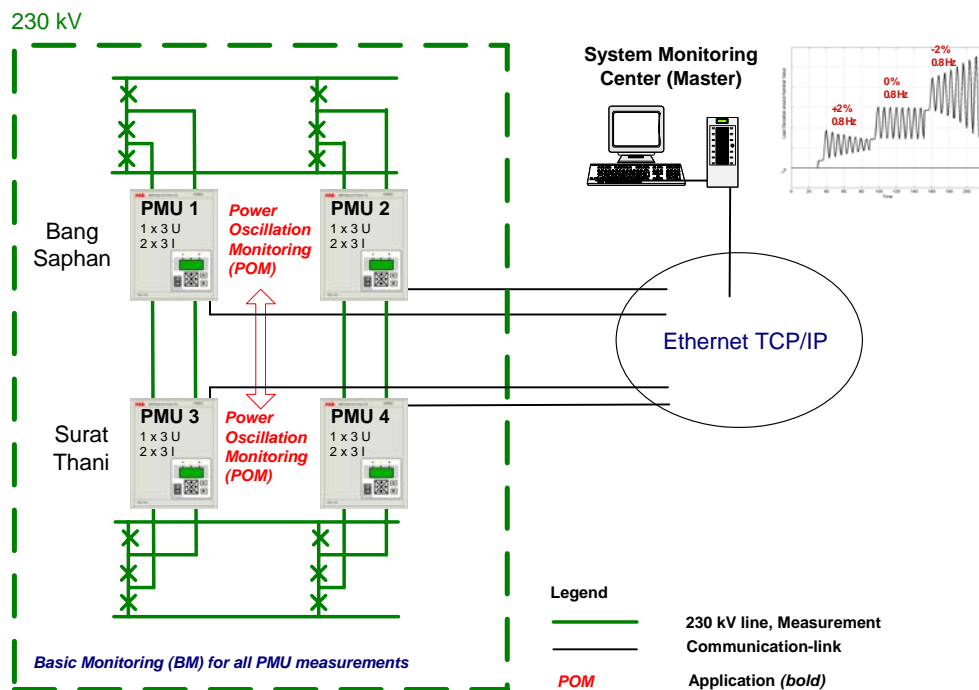


Figure 2.11.2. Visualization of system status for three different situations in a corridor of the APG network

2.12 WAMS in China

2.12.1 Review of Synchrophasor Technology in China

China owns one of the largest power networks in the world. At the end of 2004, the total power system is organized into six regional power grids (Northeastern, Northwestern, Northern, Central-China,

Eastern and Southern) and several separated provincial power grids (e.g., Xinjiang, Tibet). The Northeastern, Northern and Central-China power grids are connected via HVAC links and form a large synchronous AC power system. The Eastern and Southern power grids are respectively connected with the Central-China power grid via HVDC links. With the steady increase of economy, the power industry of China is growing rapidly. A nation-wide power grid is under development and installation. However, how to securely and efficiently operate such a complex system poses a challenging problem. To meet the new challenges and at the same time to utilize the most up-to-date information and communication technologies in the power industry, numerous efforts have been made to develop PMU/WAMS applications in China.

In 1996, a research group at Tsinghua University invented and tested the first prototype PMU. Later in 1997, a demonstrating PMU system was constructed in Heilongjiang provincial power grid, which contained 5 interconnected PMUs. At the same time, China Electric Power Research Institute (CEPRI) developed its PMU-like equipment, ADX3000, by adding a GPS clock and phasor algorithm into their traditional digital fault recorders (DFR). Some other universities and institutes have also contributed to this area, for instance, Shandong University, North China Electric University, Xi'an Jiao Tong University. From 1997 to 2001, totally about thirty devices having the function of synchrophasor measurement were installed in China's power grids. However, these early synchrophasor applications have common weaknesses: low communication rate (typically 9.6 kbps), non-real-time applications, poor-performances measurement devices, weak central stations and most of all, without a common standard.

In order to regulate the development of PMU/WAMS in China, the State Grid Corporation of China (SGCC) initiated a working group to develop a common specification. Then in 2002, "The Technologic Specification of Power System Real-time Dynamic Monitoring System (trial version)" was worked out. The Specification standardizes the general architecture of WAMS, the basic functions of its components, the communication interface and other related issues. According to the Specification, the purpose of developing WAMS in China is "in the short term to monitor and analyze and in the long term to control the dynamics of power systems". The birth of this Specification started a new era of WAMS applications in China.

2.12.2 WAMS Projects (2002 to July 2005)

Since the Specification was issued at the end of 2002, WAMS applications in China have developed very rapidly. From 2002 to July 2005, 10 new WAMS projects have been completed or partly completed. About 88 new PMUs have been put into service and another 45 PMUs are under development. Table 2.12.1 briefly illustrates these WAMS projects.

Table 2.12.1. List of WAMS projects completed and under development (from 2002 to July 2005)

No.	Project Name: WAMS of	Num. of PMUs (In use / developing)	Trans. rate (Hz) ^{*1}	Status
1	Jiangsu provincial power grid	16/4	50	The first stage was completed in April 2003.
2	Northern- & Central-China interconnected power grid	10/0	50	The first stage was completed at the end of 2003.
3	Northern power grid	9/7	100	The first stage was put into operation in December 2003.
4	Northeastern power grid	13/2	50	The first-stage system was put into operation in December 2003.

5	Guangdong provincial power grid	7/6	50	The initial system was put into operation in October 2004.
6	Southern power grid	6/1	50	Under development
7	Yunnan provincial power grid	5/0	50	Under development
8	Guizhou provincial power grid	0/4	50	Under development.
9	Henan provincial power grid	~21/0	1	The initial system was put into operation in 2003.
10	Eastern power grid	1/16	N/A	Under development.
11	Northwestern power grid	0/2	N/A	Under development.
12	Other power grid or separate PMUs	0/3	N/A	Under development.

*1: Trans. rate is the transmitting rate of phasor package, i.e., the times of transmitting phasor packages from each PMU to the central station.

2.12.3 Application functions

The application functions of these developed or developing WAMS are grouped into two categories, i.e., basic functions and advanced functions.

The Basic functions include:

- (1) Integrated phasor data platform, to gather and synchronize phasors from PMUs, to organize the phasors in the real-time and historical databases, and to offer standard data/GUI interface to other functions/operators.
- (2) Wide-area dynamic monitoring and analysis. This function provides basic tools for the operator to investigate the observed power system and to form a global and dynamic view of it. These tools are organized into four groups, i.e., the “graph-analytic” group to offer graphical and mouse-click access to system dynamics; the 'table-statistical' group to present summarized and digitized information of the observed system in the form of Excel sheets, tables and statistic reports; the 'guard and warning' group to alert the operators if the pre-defined operation limits are violated; and the 'miscellaneous' group to provides other analyzing tools, for instance, data sorting and comparison, COI (center of inertia) calculating, and so on.
- (3) Synchronized disturbance record and re-play. This function triggers globally synchronous recording of system transients and can then reconstruct the dynamic process with the recorded data.

The advanced functions include:

- (1) Generator operation status monitoring. It employs the dynamically measured phasor data and some pre-knowledge of generators to produce the P-Q-plot, in which the current operation point and the allowable operation area of each generator is calculated and plotted. Thus the operator can supervise the distances of the current operation away from the 'dangerous' limits and take effective actions if necessary to keep each generator in safe condition.
- (2) Online low-frequency oscillation detection and analysis. This function tracks the dynamics of some 'sensitive' signals online to detect the occurrence of power oscillations. An improved Prony algorithm is used to obtain detailed information of the detected oscillation, including its frequencies, damping coefficients and most related generators or buses.
- (3) Hybrid state estimation: This function combines the dynamically measured synchrophasors with the traditional measurements from SCADA to improve the speed and accuracy of state estimation.
- (4) Online pre-decision-making of emergency control scheme. In this function, faster-than-real-time simulation and online stability assessment are fulfilled to update the emergency control strategy in every several (e.g., 5) minutes.
- (5) Power angle stability prediction and alarming: In WAMS, a global and dynamic view of power angles is available, which presents helpful means to understand the system status. In this function,

advanced algorithms are developed to use angle data to evaluate and predict rotor angle stability of the observed system.

(6) Online perturbation identification. By employing the real-time information gathered by WAMS, this function achieves real-time detection, identification and location of various disturbances or faults. If PMUs have not been sufficiently deployed and precise identification and location is not realizable, a list of probable disturbances and a rough area will be given for system operators to take further steps.

(7) Dynamic voltage stability monitoring. WAMS provides a whole and moving picture of system voltages. This is very valuable for close supervision of voltage transients. In this function, both long-time and short-time swells and drops of bus voltages can be detected. Moreover, voltage dynamics are associated with power flow variation to implement some static and dynamic voltage stability indices to give indication of how far the system is away from voltage instability.

(8) Model/parameter identification. Wide-area and dynamic measurements are employed to identify the models and parameters of generators, transmission lines, loads and other devices. Considering the fact that multiple quantities related to one device are measured synchronously and the identification process is running online, the acquired model and parameters can be more accurate and consistent with the varying operation conditions. In the WAMS project of Northeastern power grid, the result of this function was compared with that obtained by local model/parameter identification equipments.

(9) Simulation validation. In China, power system operation, dispatch and control are primarily based on digital simulation analyses. However, its consistency with practical system has not been reliably confirmed. So, simulation validation becomes one of the primary tasks in WAMS development. Large disturbances are artificially applied to the real power system to acquire controllable dynamics, which are then compared with digital simulation to check the credibility of the latter. For instance, in March 2004 and 2005, three-phase-to-ground short-circuit “faults” were made in 500 kV buses in the Northeastern power grid and the dynamics were captured with WAMS. Comparisons show that the simulation results do not match the measured responses well if the original models and parameters are not modified.

2.13 WAMS in Australia

Australia’s largest interconnected power system encompasses the states of Queensland, New South Wales, Victoria, South Australia and Tasmania, with voltage levels ranging from 500kV down to 110kV. This interconnected system represents a power system that stretches for 5000 km with a maximum demand of about 32 GW. NEMMCO is both the Independent System Operator and the Market Systems Operator and is responsible for the secure operation of this power system according to the National Electricity Rules. The National Electricity Rules state that the power system is to be operated in a manner such that, following the worst single credible contingency, the halving time of all electromechanical oscillation modes must be shorter than 10 seconds. However, to allow for uncertainties the power system is operated to achieve a halving time of 5 seconds or less.

The long, thin nature of this system, which hugs the coast of eastern and southern Australia, has long presented unique problems in terms of oscillatory stability, both in design and operation. Some interconnectors can be constrained because of oscillatory stability concerns. These limits have been applied as discretionary constraints, which are determined largely by offline oscillatory stability models for the outage of the worst credible contingency. The models are benchmarked and calibrated against measured damping during staged system tests, which usually only occur during the commissioning of major interconnectors. Calibration offsets are applied to the models to account for discrepancies between the modeled and measured damping.

Given these conditions, there is potential for an interconnector to be over-constrained so that full utilization of the interconnector capability is not achieved. Only recently has the technology become available that would allow the continuous real time monitoring of the system damping modes. With this new technology it is possible to monitor system damping and ensure that the system is operated within its technical envelope. NEMMCO employs both short term and long term model-estimators to achieve this.

2.13.1 Psymetrix Power Dynamics Monitor

NEMMCO, together with PowerLink, the transmission network service provider in Queensland, have installed a Psymetrix Power Dynamics Management (PDM) system with a number of measurement nodes at various locations around the power system. The PDM nodes independently measure power flow variations in critical transmission lines and corridors, which, strictly speaking, are not wide area in nature. However, the measurements are used to determine wide area phenomena, the damping of the system oscillatory modes.

The Psymetrix PDM employs advanced signal processing techniques to continually assess system damping by monitoring the oscillations in steady state power transfers. The measurement nodes are strategically placed to provide the best possible visibility of the system electromechanical modes of interest.

As a short-term modal estimator, the Psymetrix PDM analyses a sliding three minute window of 100 ms sampled power flow data every five seconds. It is designed to alert the operator when a prescribed stability margin is violated. Frequency bands are defined in the PDM where different inter-area modes are expected. Analysis is performed to extract the damping time constants from the modes detected in each band at each measurement node. Alerting and alarming functions are provided to indicate when the measured modes violate predefined thresholds for damping and amplitude for a sustained period, which are in turn fed into the EMS to alert the operator of poorly damped conditions.

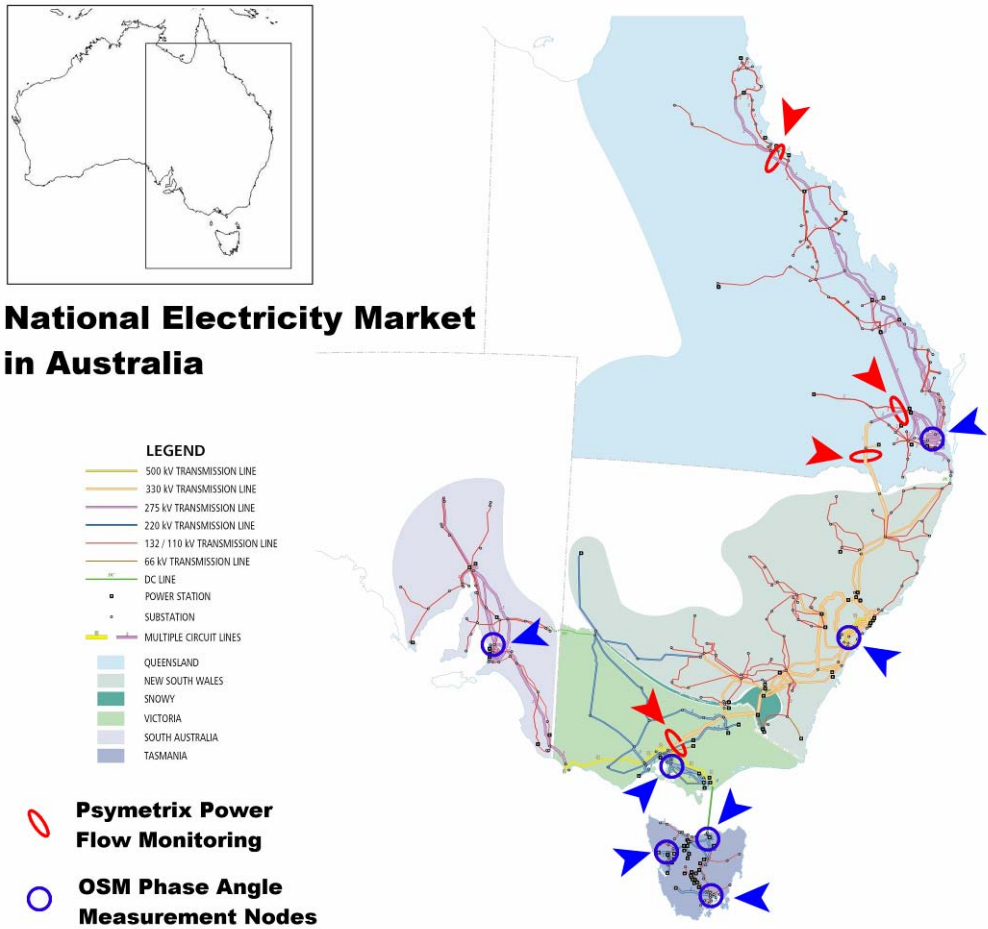


Figure 2.13.1. Transmission System Operated by NEMMCO showing Wide Area Measurement Points

When poorly damped conditions are detected the operator applies market constraints to the

interconnector of concern in order to maintain the damping at the required level. Furthermore, additional constraints are applied to interconnectors when the Psymetrix PDM is unavailable.

Operational experience has been good with the system detecting several instances of lightly damped oscillatory behavior. Most of these instances have been traced to faults in control systems and false alarms are rare. Whilst Psymetrix has proven to be good in detecting poorly damped system conditions, for comparison of measurements of well-damped oscillatory modes with analytical results, a different tool is used.

2.13.2 Oscillatory Stability Monitor

During major system augmentations of the Australian power system, tests are usually carried out to measure the modal parameters of the power system [24]. These tests are important for the calibration of models for oscillatory stability assessment. In recent times, a 0.4 s insertion of a 300 MW braking resistor in the northern part of the system has been used to produce a substantial disturbance to the system. Time-domain fitting methods were applied to the subsequent ring-down of interconnector power oscillations in an attempt to identify the parameters of the three closely spaced system oscillation modes, with typical frequencies of 0.29, 0.45 and 0.57 Hz. However, the large relative magnitude of oscillations that are continually produced by the random changes of other system loads resulted in insufficient signal-to-noise ratio for the modal parameters to be accurately identified from the ring-down tests.

The Oscillatory Stability Monitor (OSM) uses techniques based on wide area voltage phase angle measurements and utilizes the oscillations that are stimulated by the random load changes. This system provides accurate modal-parameter estimates even when the modal damping is quite good. Furthermore it has the advantage that it is a continuous non-invasive monitor with system modal estimates available in near real time. There is no longer a need to stage system perturbation tests to estimate the parameters of the system.

Phase angle information is extracted from GPS time stamped voltage measurements recorded at 10 samples per second at a number of locations on mainland Australia and on the island of Tasmania [22]. There are currently four nodes on the mainland and three in Tasmania. The algorithms for the mainland are slightly different to the ones used for Tasmania as they take advantage of the fact that there is an additional measurement node available on the mainland.

The OSM applies statistical signal processing techniques to the measurements of ambient variations in the differences between voltage angles measured at well spaced points in the system [23]. These voltage angle differences comprise the system response to random load changes. Three hours of sampled data is analyzed every five minutes in order to estimate accurately the modal parameters of the system. The close spacing of the frequencies of the three mainland system modes can make large contributions to estimation errors. For the identification of the three mainland system modes, a technique has been developed to combine different voltage-angle differences to remove the contribution from a chosen mode. This approach enhances the accuracy with which the parameters of the remaining modes are identified. By analyzing different combinations of voltage-angle differences, the parameters of all three mainland system modes are accurately identified.

Because of its long sample window, the OSM cannot provide early warning of poorly damped system conditions. However, the OSM has proved itself to be useful for calibrating small signal system models, for identifying stabilizer performance from the analysis of staged three-hour on-off testing and for the assessment of trends in system mode damping in the operational environment.

2.14 Offline oscillation monitoring in the Hungarian System

In the Hungarian system, WAMS is used for observing inter area oscillation and to help decrease these oscillations through better utilization of power system stabilizers (PSS).

The Hungarian system (see Figure 2.14.1) has a peak load of around 6300 MW. The country has a size of 500 km x 200 km. The voltage levels 750 kV, 400 kV and 220 kV are used on transmission level. There are 7 neighboring countries and 10 international transmission lines. The transit energy is large compared to the Hungarian load.

The Wide Area Monitoring is an offline system based on 'Powerlog' devices and 4 pieces are in operation and 2 more are in installation. Similar offline devices are used in other areas of the UCTE. Therefore the Hungarian case can serve as an example for experience and expectations in this area. These devices are installed on a transmission line, practically at the end of the line in a substation. They can record the 3 phase voltages, 3 phase currents and calculate the active, reactive and apparent power from the measured data and of course record the calculated variables also. The device can record in triggered and continuous way, and it can make continuous Fourier analysis. The purpose here is to observe and find the frequencies of the inter-area oscillations and observe the different feature of these inter-area oscillations (see Figure 2.14.2.). This is an offline work from the point of view of the recording device, so the recorded data download is via dial-up phone connection because the download-speed is not important. The installation point of these devices can be close to the generation, close to the loads and in the energy transfer area.

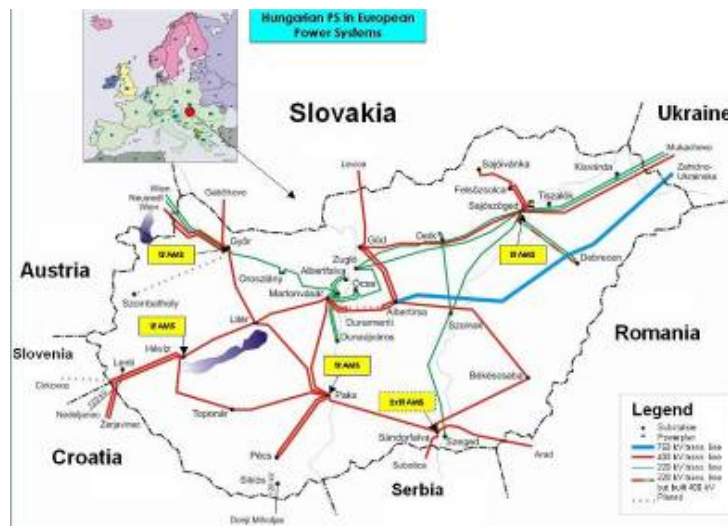


Figure 2.14.1. The Hungarian power system as part of the European UCTE system

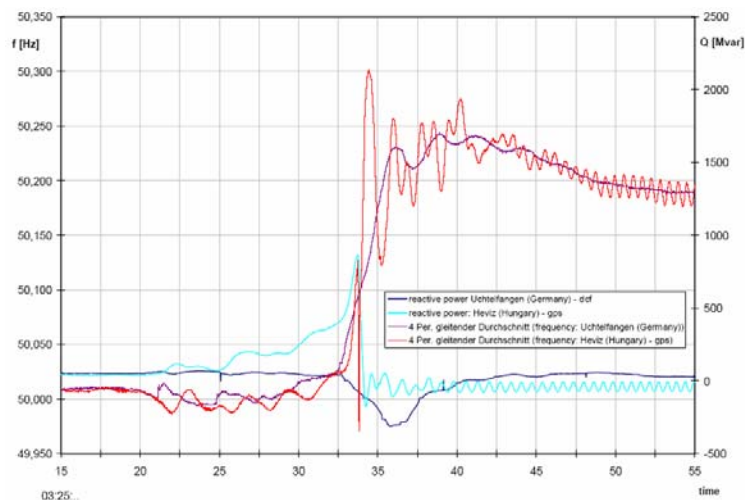


Figure 2.14.2. The measured signals (with WAMS devices) during the Italian black-out

The setting of the setting/trigger parameter is organized within the UCTE (to be more precise by the

RWE) therefore these devices are installed in the whole UCTE system (in some countries this is not 'Powerlog' but other devices with similar functionality). RWE is performing the main evaluation of these records after a significant system disturbance. At present the focus of the study is inter-area oscillations (0.15-0.28 Hz).

PMUs are presently not used for system-protection, but used for local automation to control the international load flow (e.g. in Sandorfalva, see Figure 2.14.1.) and some logical-protections, which were implemented in the SCADA system. Methods to damp the detected oscillations are mentioned in section 3.

2.15 Summary

In the following table the application areas of the WAMS installations described in the previous sections are summarized. Most of the applications are under development or are planned to be implemented in the systems. This table shows the short-term expectations for WAMS. Three areas can be identified as most widely considered applications:

- Phase angle difference monitoring,
- Oscillation/damping detection,
- Disturbance recording for offline analysis and model adaptation.

The phase angle difference gives additional information for the loading of a corridor. It shows that in a number of cases the information from the state estimation is not sufficient.

The oscillation and damping detection is the most obvious application, because it uses the synchronism and the high time resolution, and therefore the dynamic capabilities of WAMS. This application requires more sophisticated analysis algorithms (see chapter 3).

The disturbance recording and adaptation of dynamic models is a side-effect of WAMS installations. This information could be gathered from time stamped offline disturbance recorders as well. To get experience with WAMS installations this application opens up the opportunity to get familiar with this new kind of system before using it for more sophisticated online applications or even control.

Table 2.15.1. Overview of planned and existing applications in WAMS installations

Applications	ETRANS (Switzerland)	HEP (Croatia)	Hydro Quebec (Canada)	WSCC (USA)	EIPP (USA)	TERNA (Italy)	West Japan (Japan)	University Proj. (Sweden)	Elkraft (Denmark)	APG (Austria)	EGAT (Thailand)	Various Projects (China)	NEMMCO (Australia)	Hungary
Phase angle difference/ angle stability	X	X	X	X	X	P		X	X	X	X	X		
Steady state line/corridor loading	X	X		X		P			X	X		X		
Voltage stability		X		X		P						P		
Line thermal loading	X					P				X				
Frequency, power plant outage detection	P			X	X	P		X		X	X	P		
Islanding detection	P					P						P		
Oscillation/ damping identification	X		P	X		X	X		X		X	X	X	
Damping Control			P	P										
Power Flow Control										P				
State Estimation			P		P							P		
Offline disturbance analysis	X		X	X	X	P			X	X	X	X	X	X
Offline dynamic model adaptation	X		X	X		P					X	P	X	X
Commercial Operation	X	X	X	X	X	X				X	X	X	X	X
University/ Research Installation							X	X	X					

* P = in planning stage, X = in operation

CHAPTER 3

DESCRIPTION OF APPLICATIONS FOR WIDE AREA MONITORING

PMUs are presently well known [25]. Their practical value is given by applications based on their measurements. This section contains the known applications for wide area monitoring. The listed algorithms are processing the basic data into higher value information to be used by the network operator or automatic control applications. The selection of published algorithms based on PMU information shows the broad range of opportunities for this technology. Most of these algorithms are evaluated theoretically. Some of them have been tested in practice.

3.1 Introductory Note: Approaches to PMU-Placement

Due to technical and economic constraints, wide area measurement installations cannot be easily extended to all network buses. In fact the requirements to support synchronized phasor data stream and processing are especially demanding: besides an efficient telecommunication infrastructure, complex information management systems are needed. The best locations for PMU placement have then to be carefully defined in the planning stage in order to maximize the added value for operation.

The buses selected for PMU installation are closely dependent on the desired *monitoring applications*. This section presents general guidelines that may apply for the choice of device location, according to the monitoring specifications. A broad classification can be established, discriminating between 'state estimation' and 'event/phenomenon identification' purposes. The number of required devices changes significantly in the two cases. Heuristic approaches to placement can also be identified. The various aspects are briefly described below.

State estimation by phasor monitoring is a major application of wide area measurement systems, not only to support conventional state estimators based on RMS quantities but also to achieve full PMU-based, linear state estimation [26][27]. The strategies to minimize the number of PMUs under complete observability requirements aim at properly alternating directly observed and 'calculated' buses (the latter being obtained by Ohm's law exploiting the PMU line current measurements) [28]-[31]. To get a thorough picture of the system state, though, the rate of buses needing direct measurements proves to be in between 20 and 25%, which may still be too high for a preliminary WAMS project [29]. Further, the configuration for complete observability is structure-dependent: the loss of a branch may prevent some quantities from being monitored. Maintaining the specified requirement under any N-1 condition would imply a quite higher number of PMUs in the measurement system [32]. It may also be possible to account for forced PMU locations, e.g. due to already present devices or conditioned availability of communication infrastructure [33]. In order to relax in a 'controlled' way the requirement of full observability, methods have been proposed taking into account the 'depth of unobservability', i.e. the number of unobserved neighboring buses surrounded by monitored buses [33]. Such an approach may be useful in case of PMUs installed in batches.

A less demanding alternative to complete observability may simply consist of placing a reduced number of devices to monitor selected (small) parts of the system, e.g. critical cut-sets. Specific *events* may thus be promptly detected [34], possibly for use within emergency control schemes. For a better support of control center operators, however, it may be more effective to place PMUs in order to highlight system *phenomena*, e.g. oscillations and voltage collapse.

Based on topological considerations, it is possible to select the nodes presenting *higher sensitivity to generic perturbations* throughout the system [35]. Though, it seems more effective to identify the nodes that are selectively affected by individual phenomena. According to this approach, nodes are chosen for each dynamic property of interest.

The 'selective' approach, for instance, suggests to identify the groups of machines presenting coherent behavior [36][37] or the nodes presenting higher sensitivity to inter-area electromechanical modes [38]. By placing a PMU in each area/node thus determined, *inter-area oscillations* can effectively be monitored.

In order to highlight *local oscillations* and/or *transient stability*, measurement devices should be placed close to the relevant power plants. The selection may be driven by considering large-sized plants with high equivalent electrical distance from the network (that is the short circuit reactance at the generator terminal nodes). Further, PMUs close to power plants are suitable to test the control performances of the plant.

Frequency transients can be observed by placing a PMU in each one of the areas that might result from system splitting, according to the most likely modes of separation. Network zones that may experience separation under severe disturbances generally consist of highly meshed areas connected to other meshed areas by heavily loaded tie-lines. Automatic sectionalizing schemes also create electrical islands, and thus call for specific monitoring. Identification of critical tie-lines may be carried out by sensitivity analyses: for example, the lines presenting higher flow sensitivity to a generation variation of an exporting area are likely to represent the sought tie-lines.

As far as *voltage* monitoring is concerned, the most critical load areas are to be monitored. Based on operational experience and extensive simulation of critical scenarios, the nodes presenting lower loadability margin should be chosen. Another approach may focus on the "pilot nodes" of area voltage regulation. These are nodes with high short circuit power and whose voltage drives, and is representative of, the voltage of a whole area. Useful information can be derived from sensitivity based indices, and possibly applied to pilot nodes. Indices can be expressed in terms of the slope of the nose curve relating voltage to reactive power absorption, or in terms of the reactive response of the generators to reactive injection variations at pilot nodes. Higher indices denote higher criticality. For a deeper evaluation, generators' capability limits should also be considered: in this case, nonlinear simulation is required. PMUs can also be placed at the generation nodes allowing for quick detection of potential voltage collapse due to all generation reaching reactive limits.

Besides the criteria relying on some analytical basis, other methods can be introduced based on '*heuristic*' considerations. This kind of approach provides effective complement to the previous techniques, as it directly represents the operators' needs. All sites of specific interest to the System Operator (e.g. cross-border flow monitoring, plant performances testing) can herein be included, as well as all significant nodes of the network: terminal nodes of large power lines, critical interfaces, main generation plants and load areas, nodes equipped with SVCs and other FACTS, HVDC terminals, and network sections controlled by special protection systems (SPSs) [39]. In particular, both generation and consumption areas have to be monitored as the voltage angle difference between them is a good indicator of the system stress. The terminal nodes of (internal) corridors should also be monitored: besides the stress indication in normal operation, knowledge of angular displacement can help to perform successful reconnection after separation has occurred.

Following examination of the above requirements, the final PMU configuration plan results from inclusion of all the identified locations.

3.2 Voltage Stability

3.2.1 Voltage Stability Limit of one Line

The loadability of high voltage transmission lines is limited by its thermal rating as well as angle, voltage or transient/dynamic stability. For the actual operation point, local indicators can be calculated to determine the stability limit. The physically most reasonable approach for the calculation of steady state limits is the calculation of the maximum loadability point on the base of the actual measurements

at both ends of the line. This leads to a more accurate value in comparison to offline-determined values with high uncertainties.

An example calculation model is shown in Figure 3.2.1. The actual measurement v_1 and the power factor of s will be assumed to be constant. Under this assumption, the maximum load s_{\max} can be determined by solving the load flow equation.

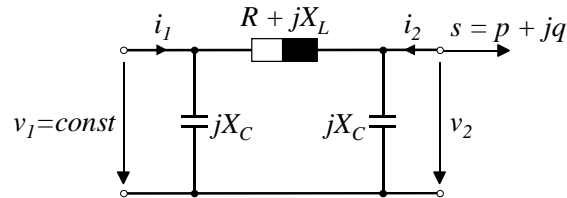


Figure 3.2.1. Model for determination of maximum loadability

The line parameters R , X_L , X_C are determined from the voltage and current phasors v_1 , v_2 , i_1 , i_2 whereas the resistance R has the largest variability. The changes of inductance and capacitance are small during operation. As an example, the change of the line resistance ΔR of 10 % leads to a loadability change of $\Delta s_{\max} = 6.5$ % for a typical 400 kV line. In the conventional offline worst-case analysis the lower limit has to be considered. With the online approach the loadability can be increased up to the calculated value, dependent on actual ambient conditions.

3.2.2 Voltage Instability Prediction (VIP)

The drawback of an undervoltage load shedding scheme is that the voltage threshold must be set in advance, and thus the relay cannot adapt to changing operating conditions in the power system. It is well known that voltage can be fairly close to nominal even though the system is close to its maximum loadability, especially if a large degree of discrete shunt reactive compensation is used. Therefore, voltage level alone may not be a reliable indicator of proximity to the maximum loadability.

Therefore other approaches based on the estimation of a Thevenin equivalent of the network at a single bus have been considered. The current through a single line feeding that bus is used to estimate an equivalent Thevenin impedance of a potentially complex network and the generation at the remote end. Many variations on this theme have been presented [40]. The drawback of these methods is that a single set of (local) measurements do not contain enough information to directly compute the parameters of the Thevenin equivalent, however these can in principle be estimated using a least-squares method once two or more sets of measurements are available. A necessary condition for accurate estimation of these parameters is that sufficient change in the measurements has occurred due to load change. During this time the feeding network and generation is assumed to remain constant. Therefore the estimation is noise-sensitive and introduces a time-delay comparable to that of standard SCADA systems (several minutes).

Voltage instability is closely related to the notion of maximum loadability of a transmission network. From circuit theory, maximal power transfer occurs when $|Z_{app}| = |Z_{net}|$, where the two impedances are given in Figure 3.2.2, showing a load bus and the rest of the system treated as a network equivalent.

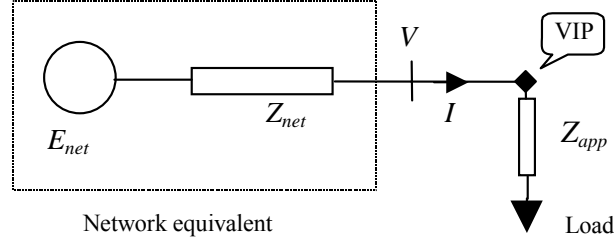


Figure 3.2.2. Local bus and system network equivalent.

It is noted that no assumption has been made about the characteristic of the load. The apparent impedance Z_{app} is merely the ratio between the voltage (V) and current (I) phasors measured at the bus. When the loading is normal, the condition $|Z_{app}| \gg |Z_{net}|$ holds; while at the inception of voltage instability, the difference between the two impedances approaches zero. Tracking proximity to voltage instability, therefore, becomes tracking the distance between $|Z_{app}|$ and $|Z_{net}|$. This is the essence of the VIP.

One challenge to the VIP is that Z_{net} is not a fixed quantity because it represents the rest of the system lumped together – a conglomeration of many different electrical entities, any of which can change status at a given time. More likely during problems of voltage instability, $|Z_{net}|$ grows (transmission becoming weaker) and $|Z_{app}|$ diminishes (load becoming heavier).

The tracking of the Thevenin equivalent is based on the following equation

$$\bar{E}_{net} = \bar{V} + \bar{Z}_{net}\bar{I} \quad (3.2.1)$$

Denote $\bar{E}_{net} = E_r + jE_i$, $\bar{V} = V_r + jV_i$ and $\bar{I} = I_r + jI_i$. The equation is rewritten as:

$$\begin{bmatrix} 1 & 0 & -I_r & I_i \\ 0 & 1 & -I_i & -I_r \end{bmatrix} \begin{bmatrix} E_r \\ E_i \\ R_t \\ X_t \end{bmatrix} = \begin{bmatrix} V_r \\ V_i \end{bmatrix} \quad (3.2.2)$$

where the subscripts r and i indicate the real and imaginary part of the phasors. Note that \mathbf{V} and \mathbf{I} are directly available from the measurements at the local bus. The unknown are R_{net}, X_{net}, E_r and E_i . There are two equations, and four unknowns, so clearly, measurements taken at two or more different times are required to solve for the unknowns. In the real environment, measurements are not precise and the Thevenin parameters drift due to the system's changing conditions. To suppress oscillations and get sufficiently different measurement values at different points in time, a larger data window of at least several minutes needs to be used. The estimation therefore attempts to minimize the error in a least-square sense. Further descriptions, simulation studies and field measurements are presented in [41],[42] and [43]. Recent developments of this approach, e.g. [44], include measurements at remote buses to assist in the estimation of the Thevenin equivalent. However, it still shows similar time delays as those observed with the standard VIP-type approaches.

3.2.3 Dynamic Voltage Stability Assessment

After a contingency occurs, the system is in a dynamic phase, which is in the case of long-term voltage instability determined by control actions for instance from on-load tap changers (OLTC), overload capacity of generators and load recovery [45][46]. This characteristic leads to a retarded behavior, which may lead to a collapse. The idea is to predict just after an event if a collapse might occur in the sequence following the event.

After a contingency, a sliding data window of PMU measurements is used to determine the actual system and especially load characteristics. A dynamic model is fed with this information. The equilibrium of this model is determined without a time domain simulation. If there is an equilibrium,

the system is predicted to be stable, otherwise the system will collapse. Figure 3.2.3 shows the principle of this approach. Phase 1 is the normal operation where N-1 calculations can be performed. Phase 2 is stable under the assumption that phase 1 was N-1 stable. After the second contingency it is not obvious at the beginning if the system is stable or not. From the conventional viewpoint of the operator, the voltage is coming back and the system seems to be stabilized during phase 3 of the simulation. But the underlying dynamics lead the system finally into a collapse. The information from the prediction algorithm can also be used for the determination of stabilizing actions.

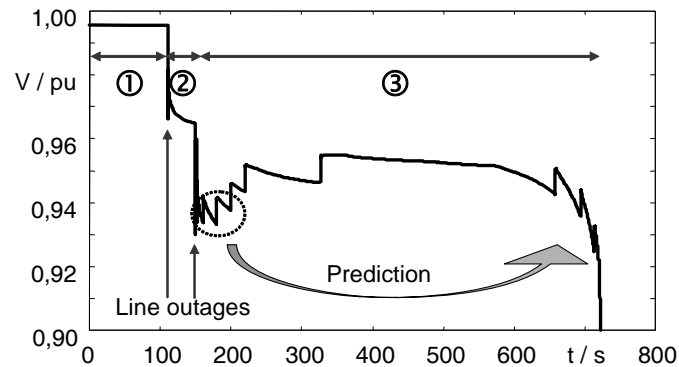


Figure 3.2.3. Simulated voltage collapse of the typical power system

The algorithm works basically as follows. Within a sliding time window measurements of the state variables can be taken for different time steps. With these measurements and the algebraic-differential equations modeling the power system an over-determined set of equations can be formulated. From this set of equations the unknown model parameters like the ones of a load model can be determined. After that the equilibrium point of this equation system is calculated. If the equilibrium exists, the power system will be stable. A detailed description of the algorithm can be found in [47].

3.2.4 Real-Time Indicator of Local Voltage Instability

From the theoretical point of view the voltage stability limit is basically recognizable when considering the classic equivalent system given by a generator, connected through a line impedance, to the load impedance. The equality of the two equivalent impedances determines the voltage stability limit. This is described in the previous section 3.2.2, including the comment on the estimation problem lasting minutes, when it successfully converges.

The critical aspects of a methodology based on this equality, when considering simply the availability at a given bus of local real-time measurements, are:

- Computing uncertainty of the grid parameter, depending on the used identification method,
- Computing time which often does not allow enough speed for real-time applications,
- The significant performance differences of the real system with respect to the simple electrical model of the considered equivalent circuit, when approaching the voltage instability condition,
- The exclusion of EHV transit nodes from this analysis, because they typically do not serve local load.

The proposed analysis [48] overcomes the above-mentioned criticisms, by defining a real-time indicator able to effectively support the practical applications through taking advantage of the high speed voltage phasor measurement, acquired through a local PMU. More precisely, in proximity of the voltage instability, the generators over-excitation limits and OLTCs operate: this dynamic phase, relatively fast, also corresponds to the contemporarily and opposite variation of the load and the Thevenin's equivalent impedances. The proposed criterion is able to distinguish these critical variations from those happening during the normal operating conditions and therefore to send a timely alarm, at the beginning of the real degradation process. Evidence is also given to the effectiveness of the proposed methodology for a transit bus.

Inside the admissible fields for $|\overline{E}_{net}|, X_{net}$ it is possible to demonstrate the interdependence of their estimation from the load variation trend. This information can be used to adaptively control the identification procedure. Moving to the real-time identification and assuming 20 ms sampling interval, the result becomes very noisy and not reliable, as previously stated. Moreover the achievable accuracy of the estimated values is not clear. To achieve an effective and robust real time identification an additional adaptation inside the procedure is required, able to overcome the uncertainty coming from the high frequency sampling, always maintaining the real-time objective.

The X_{net} is computed as the mean value on a set of n values obtained on the base of the last n sampling data. In principle n is a variable parameter depending on the load variation trend and measurements noise. Using growing sampling intervals, the procedure manages increasing intervals so as to better recognize the variations in progress. The identification updating is therefore every 20 ms while the identified value is usually based on the sampled data of the last 200 ms. Details on these results are shown in [48].

3.2.5 Corridor Monitoring

In real power systems the main limitations are typically caused by transmission corridors between generation and load areas or for trading purposes between regions. If these transmission corridors extend a certain length, voltage stability is the limiting factor, which needs to be carefully supervised to utilize the corridor to a maximum extent. The main principle of the corridor voltage stability monitoring is to use the measurements from both ends of a transmission corridor, reduce them to lump currents and voltages, and to compute a reduced equivalent model of the transmission corridor. The detailed algorithm is published in [49][50].

The main idea of the approach proposed here is to use the measurements from both ends of the transmission corridor enabling splitting of the estimation part into two stages. Firstly, the parameters of a T-equivalent of the transmission corridor can be determined through a direct calculation and therefore without any time-delay observed in VIP-type approaches of section 3.3.2. Secondly the Thevenin equivalent of the feeding generators is computed. Once the parameters of the T- and Thevenin equivalents are known, stability analysis can be carried out analytically and various stability indicators calculated using well-known and straightforward methods [51]. The main advantage over the present state of the art is that parameters of the equivalent network can be computed from a single set of phasor measurement, and thus do not have the time delay of the VIP-type approaches.

The calculation of the Thevenin equivalent is carried out in two stages in order to benefit from the fact that we have measurements at both ends of the transmission corridor. First we calculate the parameters of a T-equivalent of the actual transmission corridor, including any load or generation that may be present in the transmission corridor as shown in Figure 3.2.4.

For the measured phasors $\overline{v}_1, \overline{i}_1$ and $\overline{v}_2, \overline{i}_2$, the impedances $\overline{Z}_T, \overline{Z}_{sh}$ and \overline{Z}_L are given by:

$$\begin{aligned}\overline{Z}_T &= 2 \frac{\overline{v}_1 - \overline{v}_2}{\overline{i}_1 - \overline{i}_2} \\ \overline{Z}_{sh} &= \frac{\overline{v}_2 \overline{i}_1 - \overline{v}_1 \overline{i}_2}{\overline{i}_1^2 - \overline{i}_2^2} \\ \overline{Z}_L &= \frac{\overline{v}_2}{-\overline{i}_2}\end{aligned}\tag{3.2.3}$$

The voltage \overline{E}_g and impedance of the equivalent voltage source \overline{Z}_g cannot be calculated in the same straightforward manner. One of them is assumed known to avoid the time-delay of the estimation procedure. If the generators have voltage controllers and can be assumed not to have capability limits, \overline{E}_g can be assumed to be constant and \overline{Z}_g can be calculated as:

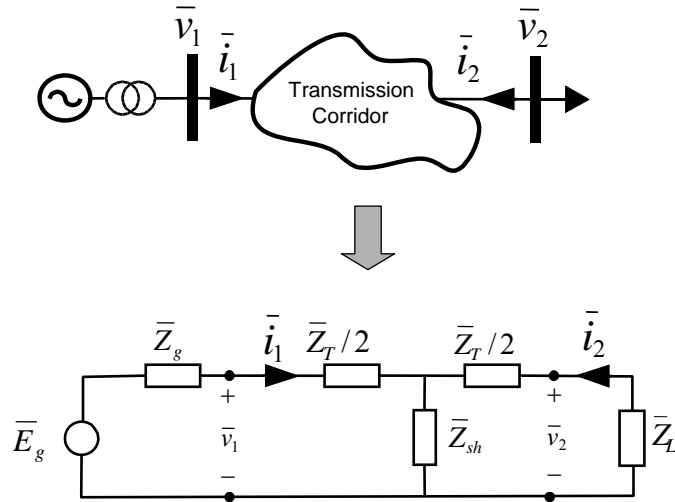


Figure 3.2.4. T- and Thevenin-equivalents of a transmission corridor fed by a generation area

$$\bar{Z}_g = \frac{E_g - \bar{v}_1}{\bar{i}_1} \quad (3.2.4)$$

However, in most practical cases \bar{Z}_g is known. Therefore, one can calculate the equivalent voltage of the generator as:

$$E_g = \bar{v}_1 + \bar{Z}_g \bar{i}_1 \quad (3.2.5)$$

Then, the second Thevenin equivalent for combined generation and transmission corridor is given by (3.2.6), see Figure 3.2.5. Based on the second Thevenin equivalent, stability analysis can be performed analytically in a straightforward way as described in the example below.

$$\bar{Z}_{th} = \frac{\bar{Z}_T}{2} + \frac{1}{\frac{1}{\bar{Z}_{sh}} + \frac{1}{\frac{\bar{Z}_T}{2} + \bar{Z}_g}} \quad (3.2.6)$$

$$\bar{E}_{th} = \bar{v}_2 \frac{\bar{Z}_{th} + \bar{Z}_L}{\bar{Z}_L}$$

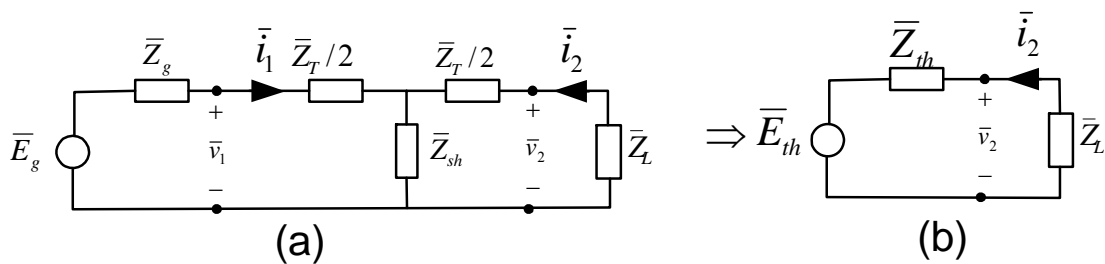


Figure 3.2.5. T- and Thevenin equivalents of transmission corridor and generation (a), and the reduction to the second Thevenin equivalent for combined generation and transmission corridor (b)

Based on the second Thevenin equivalent in Figure 3.2.5, stability analysis can be performed analytically in a straightforward way as follows. The complex power delivered to the load impedance \bar{Z}_L by the Thevenin equivalent can be written:

$$\bar{S}_L = \bar{Z}_L \left| \frac{\bar{E}_{th}}{\bar{Z}_{th} + \bar{Z}_L} \right|^2 \quad (3.2.7)$$

Assuming that the load will evolve with constant power factor, we can set $\bar{Z}_L = k\bar{Z}_{L0}$, where k is a scale factor modeling load change and \bar{Z}_{L0} the present value of load impedance as calculated according to equation 3.2.3. To find the point of maximum transfer we need to compute the maximum of

$$p_L = \Re\left[\bar{S}_L\right] = \Re\left[k\bar{Z}_{L0} \left| \frac{\bar{E}_{th}}{\bar{Z}_{th} + k\bar{Z}_{L0}} \right|^2\right] \quad (3.2.8)$$

with respect to change in the load scale factor k . Differentiating 3.2.8 and solving for the first and second order conditions we find that the critical load scale factor, where no further increase in p_L is possible, is given by:

$$k_{crit} = \left| \frac{\bar{Z}_{th}}{\bar{Z}_{L0}} \right| \quad (3.2.9)$$

giving the maximum possible active power delivered as:

$$p_{Lmax} = \Re\left[\bar{Z}_{th} \left| \frac{\bar{E}_{th}}{2\bar{Z}_{th}} \right|^2\right] \quad (3.2.10)$$

The operating point where $k = k_{crit}$ is usually referred to as the point of maximum loading. Under the assumption that the load has constant power characteristics, that is, tries to restore its drawn power to some preset value, the point of maximum loading also becomes the stability boundary, where the power system is unstable if $k < k_{crit}$. The voltage \bar{v}_2 at the virtual load bus is given by:

$$\bar{v}_2 = \bar{E}_{th} \frac{k\bar{Z}_{L0}}{\bar{Z}_{th} + k\bar{Z}_{L0}} \quad (3.2.11)$$

Based on 3.2.8 - 3.2.10, various stability margins can be defined as follows. The stability margin in terms of load impedance is defined as

$$MARGIN_Z = 100(1 - k_{crit}) \quad (\text{in percent}) \quad (3.2.12)$$

For example, if the value calculated by 3.2.12 is 20%, the power system would be unstable for a load impedance decrease larger than 20%. The stability margin in terms of active power transfer is defined as

$$MARGIN_P = \begin{cases} 100\left(\frac{p_{Lmax}}{p_L} - 1\right) & \bar{Z}_L > \bar{Z}_{th} \\ 0 & \bar{Z}_L < \bar{Z}_{th} \end{cases} \quad (\text{in percent}) \quad (3.2.13)$$

For example, if the value calculated by 3.2.13 is 20 %, the power system would be unstable for an active power load increase larger than 20 %.

3.2.6 Voltage Stability Assessment for General Topologies

The method described in this section is applicable to general network topologies. On the other hand it requires more detailed input data and more measurement points to be applicable for online use. We assume that a wide-area measurement system is available to provide a complete snapshot of the complete system state and topology with regular intervals.

Using the snapshot from a WAMS based state-estimation, a load increase is simulated on a number of selected buses until the point of maximum loadability is reached. In mathematical terms the general formulation is

$$\begin{aligned} &\text{maximize} && f(p, x) \\ &\text{subject to} && g(p, x) = 0 \\ &&& h(p, x) \leq 0 \end{aligned} \quad (3.2.14)$$

The function to maximize $f(p,x)$ can be arbitrarily chosen based on the criteria to be optimized but is here typically chosen as a fictitious active power transfer to a set of load bus known to be critical for voltage stability or the transfer to predefined critical area or through a corridor. The optimization variable p can be scalar or vector valued and is the parameter that is varied to simulate a load increase.

The function $g(p,x)$ represents the constraints given by the network equations as well as the steady state response of the FACTS control systems and other controllers. The function $h(p,x)$ contains various operational constraints such as voltage limits and actuator limits of the FACTS devices. The vector x contains the (static) state variables of the network equations, and are implicitly determined by the equality constraints.

Although these methods have originally been intended for offline studies, they are applicable also for online application if the system to be studied is modeled with moderate level of detail which is usually the case in a wide-area measurement system. Often it is enough to model the highest one or two voltage levels. For online application, a response time of tens of seconds is acceptable since here only the static aspects of voltage stability are considered.

A power margin with respect to voltage stability can be estimated if the optimization criteria $f(p,x)$ is customized to reflect the transfer to the region for which the power margin is to be computed. From the solution of 3.2.14, the maximum allowable transfer to the region can be computed and a power margin taken as the difference between the maximum transfer and the transfer at the current operating point.

Before the solution, an admittance matrix is constructed based on the snapshot from the wide-area measurement system. This admittance matrix is required to evaluate the function $g(p,x,u)$. If desired, N-1 contingency screening can be done by repeated solution of the optimization problem.

By a slight modification of 3.2.14 we can extend the method so that it also generates the optimal setpoints for FACTS devices and generator voltage regulators such that the loadability of the system is maximized. The solution yields the optimal FACTS setpoints as well as the maximum loadability provided these setpoints are applied. If contingency screening is applied using the method, also FACTS setpoints that maximize the loadability can be pre-computed for a list of credible disturbances. Case studies and simulation results using the introduced methodology can be found in [49][50].

3.2.7 Voltage degradation monitoring

Identification of voltage degradation conditions, particularly in case of medium term dynamics instability, can be based on the analysis of the voltage magnitude first and second time derivatives. The criterion mainly applies to load buses equipped with OLTC. Due to the nature of the regulation characteristic, it is possible to demonstrate that the voltage magnitude at the high voltage side of the transformer has, with a negligible delay (due to the slowness of the phenomenon), the same behavior as the transformer voltage ratio m . If the system, due to a large perturbation, shifts to an “unstable” characteristic, then the state variable m experiences a monotonic decrease, characterized by the presence of an inflection point. It is therefore possible to promptly assess inception of instability by detecting an inflection point in the voltage magnitude of the transformer HV terminal. This requires monitoring the voltage magnitude first and second time derivatives of the HV bus, hence the name \dot{V} - \ddot{V} for the algorithm herein described. A similar concept applies to generation buses, where the generator terminal voltage has the same behavior as the excitation flux, the latter being subject to limitation by overexcitation limiter.

The “pure” \dot{V} - \ddot{V} criterion needs refinements in order to be actually used.

First, selectivity of the instability criterion calls for proper filtering, in order to cancel the effects of noise and dynamic phenomena such as slow electromechanical oscillations, not affecting voltage stability. Both first and second order derivatives are computed on low-pass filtered signals.

Second, step perturbations – such as load insertions and line switching – are responsible for initiating a possibly unstable mid-term dynamic transient. The latter is the condition to be detected by the Vdot-Vdotdot algorithm. On the other hand, step variations of voltage have to be properly identified and discarded by the differentiation modules in order to avoid erroneous interpretations. This task can be accomplished either by an external function running the Vdot-Vdotdot algorithm after detection of an event, or internally, making the Vdot-Vdotdot skip analysis when too large variations between consecutive time steps are encountered.

Third, in order to make detection more reliable, the algorithm declares instability if the following conditions are simultaneously satisfied:

1. (filtered) voltage derivatives (first and second order) keep below negative thresholds for a sufficient time interval
2. absolute voltage becomes lower than a threshold

It can be observed that the algorithm works well in presence of classical OLTC mid-term transients initiated by discrete perturbations. On the other hand, it is difficult to extend the scope of the algorithm to slower phenomena such as voltage drift associated to a load ramp. In any case the threshold values result from system studies and experience.

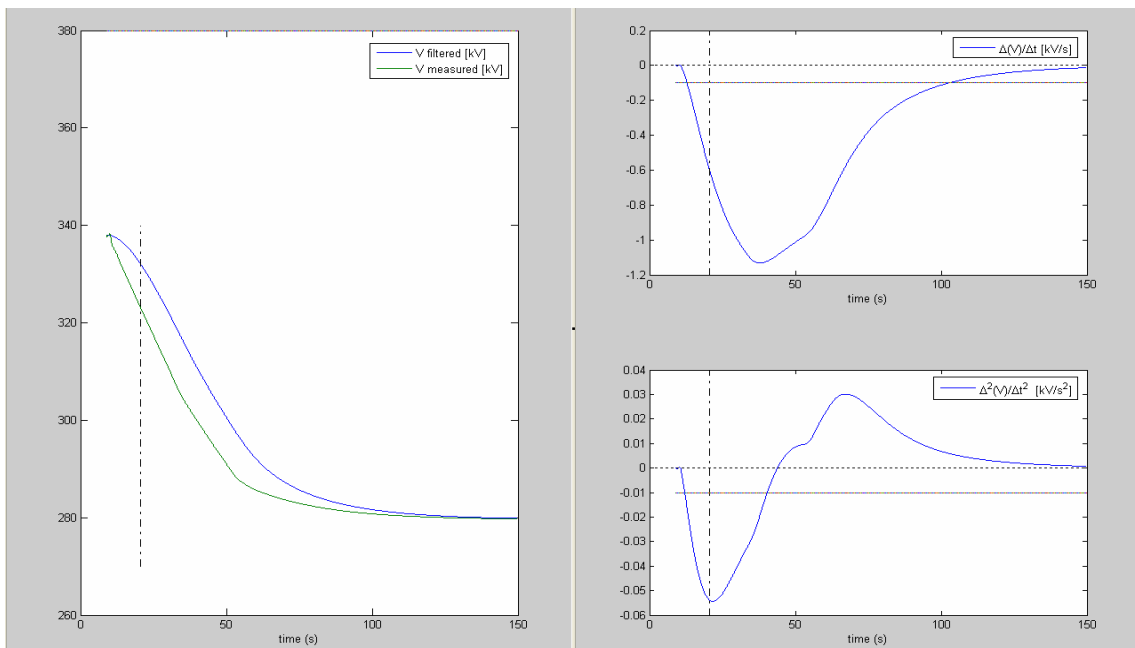


Figure 3.2.6. Response of the Vdot-Vdotdot algorithm for a line switching event. The vertical line reports instability identification

3.3 Thermal Monitoring

The determination of average line temperature based on phasor information is quite simple. Starting with the model in Figure 3.2.1 the line parameters can be determined from the phasor measurements of voltage and current at both ends of the line.

If the actual value of R is determined, the actual line temperature can be calculated according to the following formula (1).

$$\frac{R_1}{R_2} = \frac{T_1 + T_0}{T_2 + T_0} \quad (3.3.1)$$

R_1 is the determined value of R . R_2 and T_2 are a pair of given values, which are given from the original design of the line. T_0 in equation (3.3.1) is a material constant for the line wires. (e.g. $T_0 = 228 \text{ }^\circ\text{C}$ for aluminum). With the given values, the temperature T_1 can be calculated. This temperature is the

average temperature of the entire line between the two measurement points. This temperature includes the actual situation of ambient conditions like wind speed, sun and line current. Consequently, this data offers much more information than the line current as a loadability limit only. But this kind of information cannot identify hot spots and therefore sometimes cannot replace local temperature measurements.

3.4 Global and Inter-Area Oscillations

It is well known that power systems oscillate at low frequencies. Of particular concern are electromechanical oscillations involving generator rotors interacting through the power system. The potential for these oscillations to become poorly damped or unstable is a significant concern for power system operations. The level of damping of oscillatory modes in the system is usually dependent on active control through Power System Stabilizers (PSS) at generators, and can change significantly, depending on the generator dispatch and load characteristics.

Measurement-based observation of damping often reveals periods during which oscillations become poorly damped. Poor damping indicates that the system may not be secure, and it is not certain that the dynamic response to subsequent events will be stable. Such conditions may not be accurately represented in a dynamic model of the system. It is therefore valuable to use measurement-based damping observation to resolve threats to stability before they contribute to a major disturbance.

Techniques for identifying the oscillation frequency and damping have been in commercial use over the last ten years. The earliest application was in the UK, to monitor damping of an inter-area mode between Scotland and England that had produced very large unstable power oscillations during the 1980s. An operational system was first deployed in 1995 to ensure that an appropriate stability margin was maintained while the transfer level in the corridor was increased [52]. Oscillatory stability monitoring has been used for a number of applications, including:

- *System security monitoring*: Real-time monitoring of oscillation damping in the control centre alerts the system operator if a pre-defined stability margin is crossed. Appropriate action can then be taken, and the effect on the system is quickly shown. This approach is used, for example, in the UK and Australia.
- *Transfer limit management*: Where power transfer is constrained by oscillatory stability, real-time monitoring enables the system operator to relax the constraint when damping is shown to be good, and employ a more conservative constraint when damping is poor. In the UK, this approach was used to release 300MW of capacity in the Anglo-Scottish interconnection. In Australia, increases in available transmission capacity are conditional on good damping being observed when the market causes the newly released capacity to be used. The additional capacity is made firm only after oscillatory stability has been proven in practice as well as in simulation.
- *Damping controller tuning*: Continuous damping observation during stabilizer commissioning or tuning shows the immediate effect of stabilizer changes on damping of the dominant modes. It verifies that the stabilizer is indeed improving the damping as predicted, and that there is no significant destabilizing effect on other modes. Longer-term results prove the robustness of the damping control over a very wide range of operating conditions. This approach was used in Manitoba Hydro [53].
- *System testing*: Since continuous dynamics monitoring based on ambient noise perturbations, it is non-invasive, and can often replace traditional line switching or braking resistor tests of dynamic performance. It involves less risk, and less expense as the system needs not be forced into the condition required for testing, against the market.
- *Model validation*: The dynamic model can be validated against observed system dynamics. Observed mode frequency, damping, observability and relative phase can be checked against eigenvalue analyses for a wide range of operating conditions [54].
- *System synchronization*: When a major change to system topology occurs, such as synchronizing two regions, there is no prior experience of dynamic performance of the new topology. Continuous

damping monitoring gives immediate feedback on dynamic performance of the new system configuration. Thus, unexpected dynamic behavior can be identified quickly. Damping monitoring was important, for example, in synchronizing the UCTE system in 2004 or the Queensland power system to the main Australian network.

3.4.1 Identification of Oscillation Modes

Initiated by the normal small changes in the system load and disturbances such as generator or line trips, oscillations are characteristics of a power system. However, a small load increase in a line flow, for instance a couple of MWs, may make the difference between stable oscillations, which are acceptable, and unstable oscillations, which have the potential to cause a system collapse. It is another matter of fact that increasing long-distance power transfers cause the inter-area modes to become lightly damped or even unstable. However, so far there is no warning to the transmission operator indicating if a new operating condition causes an unstable oscillation.

The objective is to get an algorithm for a real-time monitoring of oscillations from online measured signals; in other words, to estimate the parameters characterizing the electromechanical oscillations such as frequency and damping, and to present this information to the operator in a user-friendly environment of the operator station. This kind of information can hardly be obtained only by watching the measured signals displayed in the time-domain. The online collected measured data from the WAMS are subject to a further evaluation with the objective to estimate dominant frequency and damping of the electromechanical oscillatory modes during normal operation of the power system.

A considerable amount of work has been done in the field of modal analysis and assessment of oscillations in power systems. Prony analysis was proposed to determine online the equivalent models and modal content from measured data. A state-space based (multi-input multi-output) identification approach to modal analysis based on pulse-type inputs and reduced order models was presented. A Fourier-based algorithm extended for analyses of multiple oscillatory modes closed in their frequency was proposed. Other authors considered a non-adaptive approach using Wiener-Hopf linear prediction to estimate the modal frequency and damping and they evaluated their approach successfully on ambient data. Nearly real-time estimation of oscillatory modes using a modified least squares (Yule-Walker) method to solve the underlying model identification problem has also been proposed. A real-time estimation of the parameters of power system oscillations was also proposed based on a method called Linear Predictive Coding Algorithm.

The need for fast response can be seen as the requirement which distinguishes the approach sought here from many others. The power system is assumed to be driven by small disturbances around a nominal operating point. The method considered here is one based on a parametric model. Evaluation of the estimated model parameters enables quantitative detection of oscillations and other properties of the system, such as actual system stability. The basic scheme of such an algorithm [55] is outlined in Figure 3.4.1. An alternative algorithm can be found in [91]. The power system is assumed to be driven by white noise disturbances $\varepsilon(k)$ around a nominal operating point. The system is modeled by a linear autoregressive model with adjustable time-varying coefficients (3.4.1). The system outputs $y(k)$ are the measurements provided by PMUs.

$$\hat{y}(k|k-1) = \sum_{i=1}^n a_i(k)y(k-i) + \varepsilon(k) \quad (3.4.1)$$

or rewritten as

$$y(k) = \sum_{i=1}^n a_i(k)y(k-i) \quad (3.4.2)$$

with the prediction error ε given by

$$\varepsilon(k) = \hat{y}(k|k-1) - y(k) \quad (3.4.3)$$

$$J = \min_{a_i} \sum \varepsilon^T \varepsilon = \min_{a_i} \sum (y(k|k-1) - y(k))^2 \quad (3.4.4)$$

$$z^n - a_1(k)z^{n-1} \dots - a_{n-1}(k)z - a_n(k) = 0 \quad (3.4.5)$$

$$\omega_i = 2\pi \cdot f_i \quad \text{and} \quad \xi_i = \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \omega_i^2}} \quad (3.4.6)$$

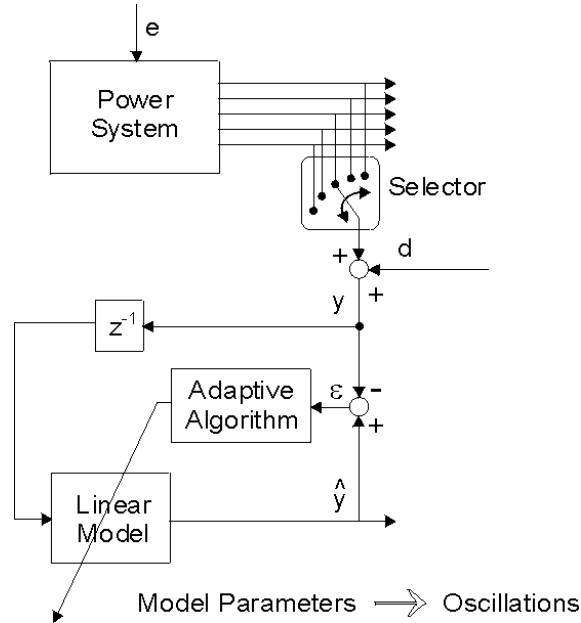


Figure 3.4.1. Basic scheme for the proposed detection of power system oscillations

The measured signal $y(k)$ may contain some measurement noise $d(k)$. A recursive algorithm called the adaptive Kalman Filter recursively optimizes the criterion (3.4.4) and yields the optimal parameters a_i of the AR-model (3.4.1) generating the same sequence of predicted data $\hat{y}(k)$ as the measured ones $y(k)$. The goal is to obtain through eigenvalue analysis of the equivalent model (3.4.2) the parameters of oscillations characterized by their frequency f_i and damping ξ_i . They can be obtained repeatedly once per given period with the so called refresh time T_r from the AR-model for the set of its n parameters $a_i(k)$ solving the polynomial (3.4.5) for a frozen time k according to (3.4.6) and converting the results into the continuous-time domain (utilizing some suitable conversion such as the Tustin's approximation) where $z_i = \alpha_i + i\omega_i$ is the solution of (3.4.5). The refresh time defines how often the dominant oscillations are calculated from the estimated model parameters and displayed to the operator. This is a trade-off between the computational power of the computer on which the application is running, taking also into account how rapidly the power system varies with time. To show the performance of the algorithm it has been applied to real measurement data from existing WAMS installations. Figure 3.4.2 shows an example that included a stepwise change of the system structure during the measurement period.

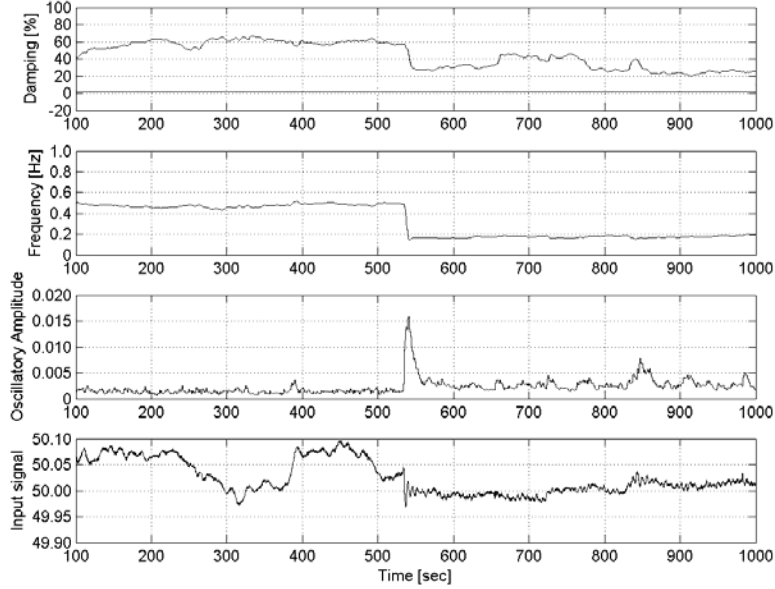


Figure 3.4.2. Oscillation detection algorithm applied to real PMU measurement data

The system has a well damped oscillatory mode at about 0.5Hz. After the change in the system structure at 530 s the dominant frequency is going down to 0.2Hz and the damping is reduced. The situation is still not critical. The provision of this information to the operator during the switching in the system made them feel much more comfortable, because of the better observability.

3.4.2 Oscillatory Stability Monitor in Australia

The Oscillatory Stability Monitor (OSM) deployed in Australia, uses a novel technique to identify and assess oscillatory modes in the power system. GPS time stamped voltage angle measurements at a number of locations are derived from the three phase voltage measurements sampled at a rate of 10 kHz, by means of the Averaged DQ method [22]. Analysis is performed on data that is sampled at 10 Hz for three-hour periods, and are updated every five minutes.

It has been found that, in the frequency range of the system modes, the load changes (over a sufficiently long period of time) have the spectrum of the integral-of-white-noise [23]. It can then be shown that the autocorrelation of a sufficiently long sample of the time differential of any measured signal (e.g. an interconnector power flow, a voltage-angle difference between two locations) will then comprise the sum of damped, oscillatory contributions with parameters that are those of the oscillation modes of the system. The parameters of the modes are then estimated by fitting them to the autocorrelation sequence.

In the mainland Australian system, the three system oscillation modes have frequencies that are closely spaced and significant overlaps occur in their contributions to any one measured signal. This feature adds significantly to the errors in the estimated modal parameters when obtained from the analysis of any one signal. The four mainland synchronized voltage angle measurements provide three independent time-differentiated voltage-angle differences. If two of these signals are $x_k(t)$ and $x_m(t)$ then it can be shown that α and τ can be found so that the contribution from a selected mode can be removed (for $t \geq \tau$) from the autocorrelation of

$$s(t) = x_k(t) + \alpha \cdot x_m(t - \tau) \quad (3.4.7)$$

The consequence is that the parameters of the remaining mode(s) are identified with a significantly greater accuracy than those obtained from the analysis of any one signal. The values of α and τ are updated every five minutes to achieve the desired cancellation.

A fortunate feature of the mainland Australian system and the chosen monitoring points is that two voltage-angle-difference signals are dominated by the contributions from the two of the three system modes with the lowest frequencies. The first step in the OSM modal-identification process is to use different combinations of α and τ to produce autocorrelations that comprise a contribution from firstly one of these two modes and then the other. Fitting a contribution from only one mode greatly improves the accuracy of the estimated modal parameters. Another pair of voltage-angle-differences is used to remove the contribution from the second-lowest-frequency mode and to estimate the parameters of the third mode from an autocorrelation that comprises contributions from only the lowest-frequency mode and the third mode. Because the contributions from these two modes are relatively well separated (and the parameters of the lowest-frequency mode have already been accurately estimated) the parameters of the third mode can also be estimated with reasonable accuracy.

One of the basic assumptions of this technique is that the power system is stationary for the duration of the sample window. Whilst it is hard to imagine that the system remain stationary for all sample windows, there are always periods where the system is sufficiently stationary to yield satisfactory results using this technique. By reducing the sampling window, the algorithm can better track changes in damping but at the expense of losing accuracy.

Test vectors have been generated from analytical models and used to benchmark the OSM modal estimation technique. Both stationary and non-stationary test vectors have been generated, the results of which have been promising. The results have been useful in defining the capabilities of the OSM particularly in its ability to track non-stationary modal parameters.

Figure 3.4.3 shows some results obtained from the damping measurement method during three-hour on/off testing of a new SVC power oscillation damper (POD). The damping constant of one inter-area mode (with a frequency of about 0.32 Hz) measured with a three-hour analysis window, is plotted against time as the old POD is firstly switched off and then the new POD is switched on and off at three-hour intervals.

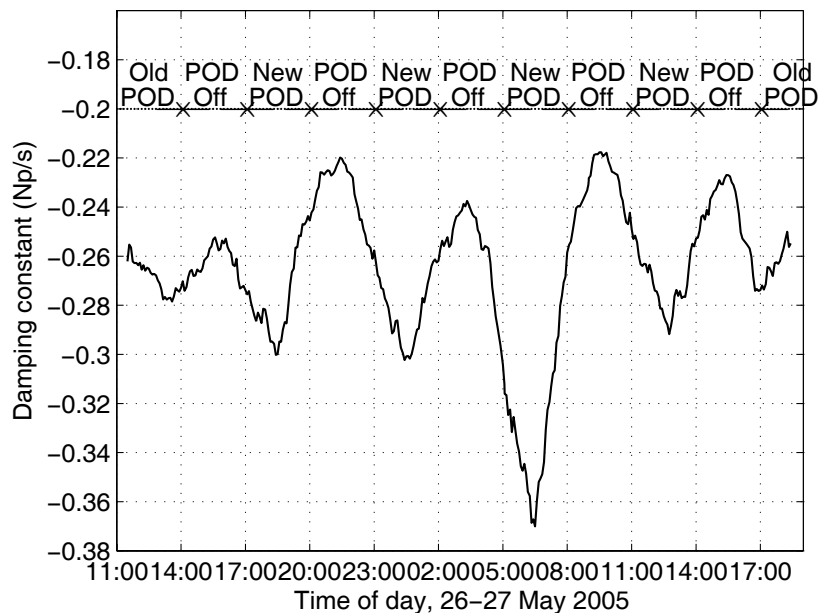


Figure 3.4.3. Measured damping of a 0.32 Hz inter-area oscillation mode in the Australian system during SVC power oscillation damper (POD) on/off testing

The results of Figure 3.4.3 show triangular variations of the measured damping caused by the combination of the three-hour on/off times and three-hour analysis window. The measured damping within each three-hour window is indicated by the peaks. This testing confirmed the significant contribution that the POD makes to the damping of the mode. The results show that, over the 30-hour

period of the testing, other factors (e.g. generation and load levels) also affect the damping of this mode. Measurements like those of Figure 3.4.3 have provided the opportunity to calibrate small-signal models of the Australian system.

3.4.3 Oscillatory Stability Assessment in Italy

The Italian power system is affected by oscillatory phenomena, mainly after contingencies, due to its longitudinal structure. Furthermore the central and southern regions are characterized by a weak level of interconnection, or weak grid sections, which could cause bottlenecks for power transfer, and cause oscillatory behavior. Great attention is paid to oscillation monitoring and assessment in the Italian WAMS application [18]. During the last year, while the WAMS system has been installed, much research was carried out to choose the most effective techniques to be applied both in online and offline assessment of system oscillations. The result of this research addressed a number of analyzing techniques that will be implemented in the Italian wide area platform.

3.4.3.1 Power Oscillation Detector

The power oscillation detector algorithm is based on a Phase Lock Loop (PLL)-like technique. It is computationally simple as it basically applies only trigonometric relationships. It has been developed to estimate the actual damping of a specific harmonic component of the system response. The estimation technique is based on the assumption that, if the frequency is known exactly, every sinusoidal wave can be treated as a phasor. Thus, having a reference frame rotating at the same angular speed of the input harmonic, it is possible to decompose that wave into its components along the reference axis. For example, let's say the input signal is a wave with frequency f_u :

$$u(t) = A \cos(2\pi f_u t + \phi) \quad (3.4.8)$$

The real axis of the rotating reference can be expressed as:

$$RE(t) = \cos(2\pi f_u t) \quad (3.4.9)$$

By a simple multiplication we can calculate the input component along the real axis:

$$A \cos(2\pi f_u t + \phi) \cos(2\pi f_u t) = A [\cos \phi + \cos(2\pi f_u t + \phi)] / 2 \quad (3.4.10)$$

The sinusoidal wave at twice the input frequency can be simply filtered out. The remaining part is exactly the real part of the input wave according to power oscillation detector inner frame. As the frequency of the harmonic component has to be known, the power oscillation detector can be seen as an ideal band-pass filter that allows only harmonic components equal to its inner frequency to pass. If there is some difference between the frequencies the power oscillation detector is able to adjust its internal angular speed to match the harmonic content of the input signal. Once real and imaginary parts of the input phasor are estimated it is simple to calculate the relative damping. Figure 3.4.4 shows the signal collected by the first PMU operating in the Italian grid in a 400 kV substation: picture (a) represents the data collected by the PMU device filtered with a high-pass filter (cut off 0.05 Hz), picture (b) shows the detail of the 0.21 Hz inter-area oscillation. The following pictures show frequency and damping estimated by the power oscillation detector. The inception of undamped oscillations produces a negative peak in the estimated damping. The power oscillation detector will therefore be used to give alarms both offline and online, by association of proper thresholds to the estimated oscillation parameters.

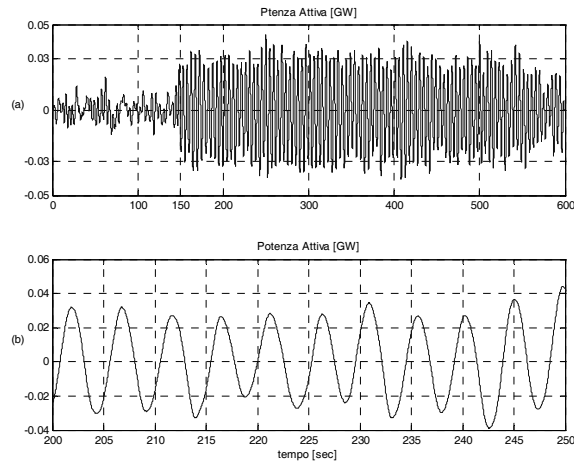


Figure 3.4.4. Oscillation recorded in Italian power system: filtered signal (a); detail of oscillation (b)

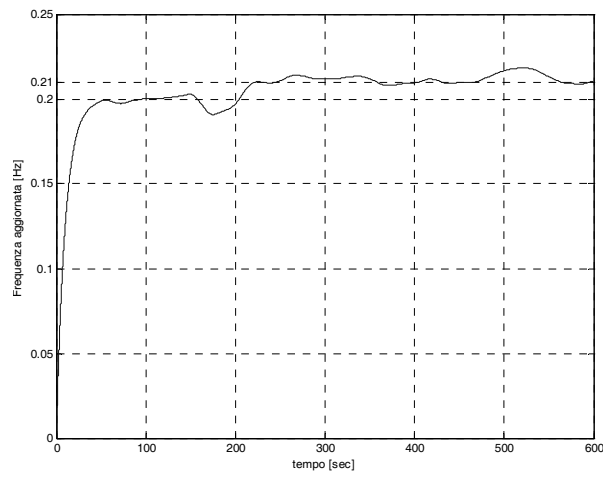


Figure 3.4.5. Estimated frequency of input oscillation (POD internal derivative of amplitudes)

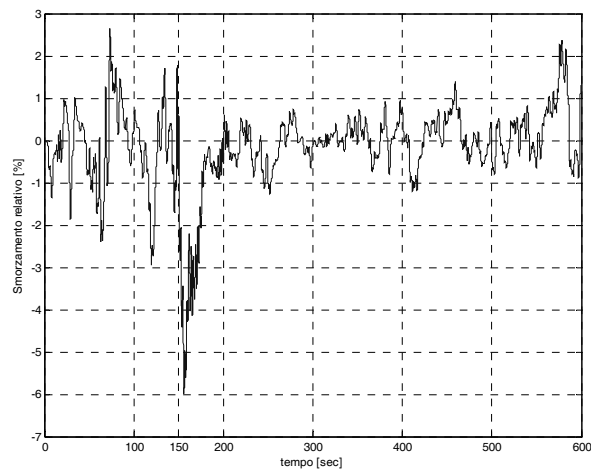


Figure 3.4.6. Estimated damping of input oscillation (POD internal derivative of amplitudes)

3.4.3.2 Identification of ARMA Models

The power oscillation detector algorithm, although very effective in some cases, has its own limits, such as its able to detect only harmonic content in a small range around its operating frequency. Thus, to perform a complete oscillation assessment, when both frequency and damping are unknown, model identification techniques were investigated.

Estimation results are strongly affected by the model structure, thus the primary concern is the choice of the most suitable structure, referred to as model family, and of its order. The performed studies aimed to identify both family and order of models to be used for oscillations assessment within the WAMS platform. A few system observations recorded by the first PMU operating in the Italian power system, at Redipuglia 400 kV interconnection substation with Slovenia, and by PMUs in Switzerland have been analyzed.

The proper model family has been chosen by means of correlation properties of the available data. Two correlation functions have been calculated: Correlation Function and Partial Auto-Correlation Function. These functions, calculated with recorded data, addressed the use of an ARMA model.

The optimum model order n was estimated according to the Final Prediction Error (FPE) and by Cross-Validation tests. The FPE index addresses the best model order making a trade-off between prediction error (decreasing with model order) and model complexity (increasing with order). Cross-Validation checks the ability of the estimated model to predict a sequence of observations different from the one used to estimate parameters. A simple indicator of prediction goodness is the fitting index given by:

$$\left(1 - \frac{\|y - \hat{y}\|^2}{\|y\|^2}\right) 100 [\%] \quad (3.4.11)$$

where y is the observed output value and \hat{y} is the predicted one.

The combined results of FPE and Cross-validation tests indicated that an ARMA(3,3) was the best representation of data for the most of recorded sequences (see Figure 3.4.7). This result agrees with the spectral properties of the collected signal, which showed substantially one dominating frequency in the range 0.2 to 1 Hz.

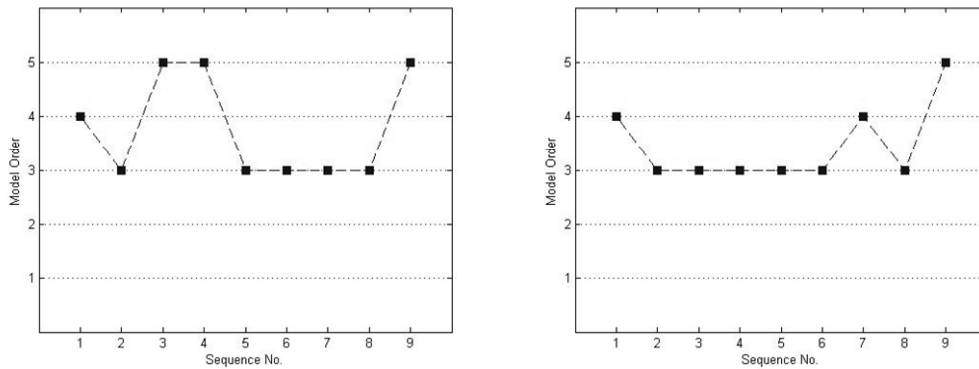


Figure 3.4.7. Optimum model order according to FPE (left) and Cross-validation (right) tests

The estimation of model parameters will be made by means of an Extended Kalman Filter (EKF) technique. This approach proved to be the most robust with respect to the estimation of ARMA(3,3) parameters based on the recorded data available. EKF allows the recursive minimization of the squared prediction error (3.4.12) although the problem to be solved is time-varying and non linear.

$$J = \sum_{k=1}^t (y(k) - \hat{y}(k))^2 \quad (3.4.12)$$

Identification of ARMA models with the EKF technique will be applied to perform an online modal analysis, with the aim of a continuous assessment of system damping.

3.4.3.3 Prony Analysis

Prony analysis of recorded data is already implemented as the first monitoring facility in the Italian WAMS system. The experience of system operators has suggested a number of nodes among which often one can observe inter-area oscillations. Simply by recording the actual phase shift between two of these nodes it is possible to give a first estimation of frequency and damping of the oscillatory mode the busses are involved in.

The adopted model was validated by estimating frequency and damping of oscillatory modes reported in collected data. A preliminary Fourier analysis has been performed, in order to detect the dominant mode and make a first estimation of oscillations frequency. Spectral analysis of recorded data showed in all signals a dominant oscillatory mode at a frequency in the range 0.2 to 0.25 Hz. This inter-area mode is referred to as the first UCTE global mode [56].

Among the collected data (real and reactive power flows, magnitude and angle of phase voltage, line currents), real power flows have been selected for identification procedures, as they showed the highest participation factor. This agrees with the past modal analysis performed on Italian HV grid model. Raw data have been pre-processed in order to remove the dc component of the signal and low frequency modes (e.g. load/frequency control). Identification procedures have been validated comparing estimated frequencies and damping with Fourier analysis (see Table 3.4.1).

Table 3.4.1. Estimated results.

Sequences (active power)	\hat{f} [Hz]	\hat{f} (FFT) [Hz]	$\hat{\zeta}$ [%]
May-01-2005	0.208	≈ 0.21	3.81
May-20-2005	0.235	≈ 0.24	10.1

3.4.3.4 Wavelet Analysis

The Wavelet Transform (WT) proved to be an effective tool both to analyze collected data and to build very intuitive man-machine interfaces. Wavelet analysis was tested on both online collected data (first operated PMU in Italy) and offline simulated scenarios.

The WT is basically a generalization of Fourier analysis, it simply breaks up a signal into shifted and scaled versions of the original (or mother) wavelet. WT can be very useful in handling signals with sharp changes that might be better analyzed with an irregular wavelet than with a smooth sinusoid. The WT allows representation of cases when (and to what extent) the input signal is similar to a given “daughter wavelet” function. If the wavelet function is approximated by its fundamental frequency component, then a time-frequency analysis is obtained. The wavelet transform can therefore tell whether and when a sinusoidal component is present in the signal.

Furthermore a wavelet is a waveform of effectively limited duration that has an average value of zero. This avoids, during online transformations, the use of a window function, which often introduces distortion in the signal spectrum. Thus, it appears more suitable for use as an online spectral analysis tool than Short-Time Fourier Transforms. These interesting properties are complemented by the fact that wavelet analysis is particularly suitable for effective graphic presentation. As an example, Figure 3.4.8 shows how an inter-area oscillation could be represented by means of wavelet analysis and three-dimensional visualization. The wavelet module of the Italian WAMS will perform the time-frequency analysis, by means of wavelet transform, of signals received from PMU devices and make a graphical representation of wavelet coefficients (color maps) telling the operator, in a quite immediate way, how the frequency content of the system response changes with time.

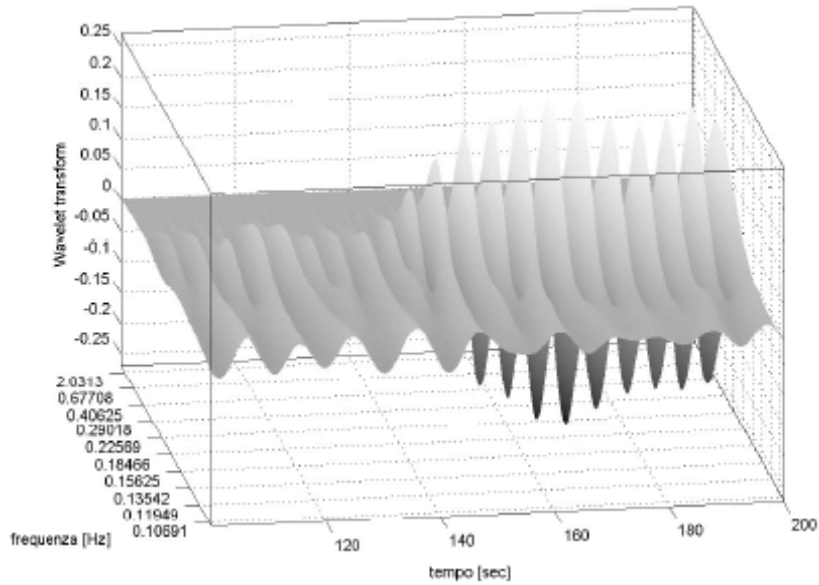


Figure 3.4.8. Wavelet analysis of recorded inter-area oscillation: three dimensional representation

3.5 State Estimation

This section is strongly related to section 4.5 the integration with SCADA/EMS. This section deals with a new formulation of SE, i.e. algorithmic side, whereas section 4.5 deals with the technical infrastructure issues, such as data engineering and conceptual issues related to the graphic user interface (GUI) etc.

A continuous monitoring of the most important quantities (such as line flows, bus voltages etc.) in an electric power system is crucial for secure operation of the power system. To determine these quantities, it is sufficient to have information about the topology of the power system and states x . The states are bus voltages, both their magnitude and phase angle. Traditionally, phase angles could not be measured due to the inability to handle the synchronization of measurement devices. Therefore a procedure called State Estimation (SE) has been employed in order to extract them from other measurements z , such as voltage magnitudes; line active and reactive power flows. However, various types of errors r , which are assumed to have an additive nature, bias measurements. Thus the goal of SE is minimization of these errors with the help of redundant measurements:

$$\min r'Wr \quad (3.5.1)$$

The situation is even more complicated since relationships between states and measurements are usually nonlinear:

$$z = h(x) + r \quad (3.5.2)$$

Difficulties of SE come from several sources. The network parameters are changing over time with ambient conditions (e.g. temperature, radiation), aging of devices etc. The topology of the network needs to be updated automatically or manually dependent on the switching status of the devices (line in or out e.g. for service or after a fault). New network elements need to be inserted into the SE system after their installation.

A common situation is that RTUs (Remote Telemetry Units), used for measurement throughout the transmission network, have various origins (vendors and age), accuracy and most importantly – sampling frequency. Therefore measurements processed by SE have been taken in various times and thus tries to “align” them to create a snapshot of the system state.

3.5.1 WAMS to detect State Estimation Reliability

There are techniques in the area of SE, which may indicate a topology error or bad measurements. However, an additional indication of the quality of SE would provide a further back-up layer. Synchronized phasor measurements would serve this purpose very well. Particular applications can range from a simple comparison of values provided by SE and measured by more than two PMUs, to employment of various statistical mathematical methods (e.g. variance computations etc.) in processing phasor measurements from many PMUs covering entire areas. The final logical comparison shall be executed on the SCADA/EMS level, but up to that point, implementation may also vary from independent WAMS to an integration of PMUs in the SCADA signal chain.

If the difference is above a certain threshold, ε , an indicator flag is set and a warning signal (light or noise) or error message will be issued to the operator in the control center. The signal or message can be integrated into the SCADA system and screen. The indicator flag can be set by all kinds of comparison operations between voltage magnitudes, angles or phasors and current magnitudes, angles or phasors between PMUs and SE results. In the case a faulty SE is identified an analysis process has to be started identifying the cause for the error according to the sources described above (topology, transient, network data, faulty measurement, SE software problem).

3.5.2 State Estimation with Synchronized Phasor Measurements

Another option for improving SE is to directly integrate synchronized phasor measurements into SE. That would require changes both on the hardware and software side. From the hardware point of view, PMUs can be integrated within the SCADA system as any other measurement device (i.e. RTU). Software changes imply modification of the SE algorithm itself and its implementation. In the literature there are proposals to use Phasor Measurement Units (PMU) as data sources for state estimation [57][60]. If only PMUs are used, the angles of voltage and currents are directly measured. The measurement model in this case is linear, yielding replacement of nonlinear constraint (3.5.2) by equation (3.5.3):

$$z = H \cdot x + r \quad (3.5.3)$$

It is most probable that the measurement set would be mixed, i.e. consisting of synchronized phasor measurements and RMS measurements coming from RTUs. Therefore instead of applying (3.5.3), equations (3.5.1) and (3.5.2) should be modified. Reference [57] elaborates on this topic further.

3.5.3 Multi-Area State Estimation

Large interconnected power systems, such as the UCTE in Europe or the Eastern and Western Interconnections in North America, have been formed by interconnecting originally independent systems. However, a supervision structure has remained intact, i.e. parts of an interconnected system are usually monitored and controlled by different entities (Transmission or Independent System Operators). This applies also on state estimation. From the viewpoint of state estimation this results in occasional difficulties, for example with bad data detection, on interfaces between systems, where network observability is suddenly reduced. To overcome this problem, several proposals have appeared in the literature, e.g. [58] and [59]. The main idea is to introduce a coordination framework where synchronized phasor measurements from different areas play a central role. Attractive features of this approach are that it requires only sparsely located PMUs and a minimal data exchange among areas.

However, there are several more reasons, besides distributed network control responsibility, favoring multi-area state estimation. Even in a case of a single entity supervising a large power system, fragmentation of state estimation offers advantages, such as possible reduction of computational burden, better robustness etc.

3.6 Event detection

Within control room monitoring and control activity, an interesting function may consist of fast detection, identification and localization of system events. Knowledge of the events occurring in the system (short circuits, step variations of active and/or reactive injection, line switching) helps to understand the causes of system transients, thus providing a clearer picture of the overall situation. Currently, the available information regarding events is essentially limited to breaker status signals, transmitted with the usual SCADA delays. Under the hypothesis of complete system observability, accurate event detection has been shown to be achievable, as reported in [34]. The underlying analytical concepts rely on Fast Decoupled Load Flow, DC Load Flow and Network Sensitivity techniques. Starting from accurate synchronized measures sampled at a high sampling rate (e.g. one phasor per cycle), both the nature and location of the events can be determined by compared analysis of bus voltage magnitude and phase variations between successive sampling steps: the sign of the variations, along with their concordance within all buses and with the support of thresholds, allows to discriminate among the possible events; the largest variations are associated to the event location. Further information may be derive from line current measurements.

An event detection algorithm based on the above considerations has been tested with simulated data of a detailed Italian system model (400/220 kV). Results are very accurate, when all bus voltage magnitudes and phases are monitored (Figure 3.6.1); performances are less accurate under partial observability conditions. In particular, sensitivity and selectivity decrease as the event location is farther and farther from the monitored buses. However, even in this case the application might be useful to the operators, to better realize the occurrence of high impact events close to strategic (therefore monitored) nodes. A further validation step should consist of feeding the algorithm with field measurements, to check if the real PMU output (affected by noise, delays, and inaccuracies) can effectively be used by the detection algorithm.

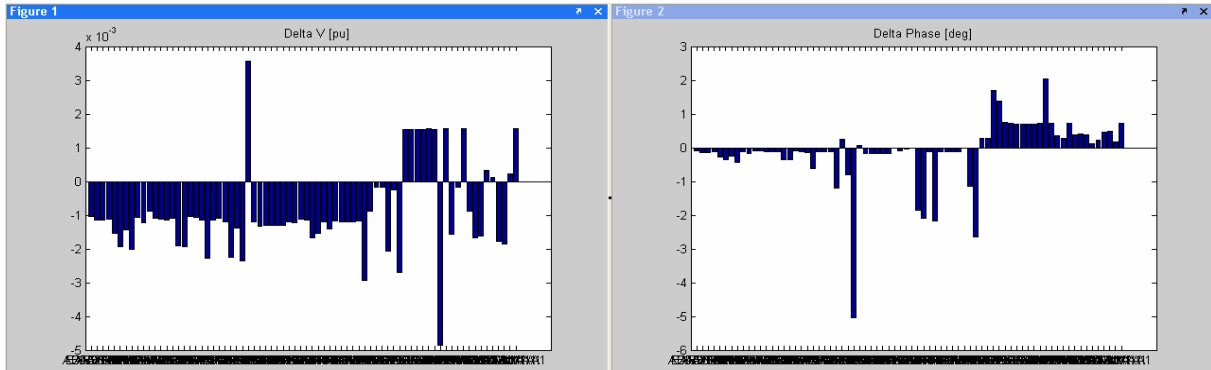


Figure 3.6.1. “Step variations” of bus voltage magnitude and phase angle caused by line opening

3.7 Islanding detection

Frequency is a good phenomenological indicator of system integrity. In a connected electrical island, steady state frequency is identical at all buses. In case of severe disturbances, the power system may split into islands, because of cascaded line tripping or special protection scheme intervention. The new configuration is characterized by (at least slightly) different values of the steady state frequency in the resulting islands. System connection is a topological property: it is determined exactly by the information on the network structure and the switching device status, within Energy Management System (EMS) applications. A faster identification of system separation, however, might help the operator to follow promptly the evolution of events. The application can be based on the analysis of phase angle trends. Because different islands present different frequencies, the relevant bus voltage

absolute phase angles experience increasing displacement. This condition is persistent, i.e. the displacement goes on increasing indefinitely, at a pace dependent on the frequency gap between the areas: therefore its detection appears quite practical after a suitable observation time. Of course, the longer the observation time, the more robust the detection. On the other hand, in order to obtain a fast detection, the observation time should be as short as possible. In this case a risk may arise, to confuse the initial dynamics of system splitting with the sharp increase in phase angle deviation which may occur in case of loss of synchronism. To avoid false alarms, discriminating islanding from loss of step, two distinct criteria may be adopted. They are suitable respectively for “severe” and “mild” frequency gaps between islanded areas. Both of them are based on the following concepts applied to the current time t :

- absolute phase angle deviation of bus i with respect to its value Δt_w seconds before:

$$\delta_i^{\Delta t_w}(t) = \delta_i(t) - \delta_i(t - \Delta t_w)$$
- phase angle displacement between two generic buses i, j , occurred in the last Δt_w seconds:

$$\theta_{ij}^{\Delta t_w}(t) = \delta_i^{\Delta t_w}(t) - \delta_j^{\Delta t_w}(t).$$

At each time t , absolute phase deviations $\delta_i^{\Delta t_w}$ ($\forall i \in \{\text{monitored nodes}\}$) are computed (Figure 3.7.1 (a)) and sorted in increasing order (Figure 3.7.1 (b)); then, phase angle displacements $\theta_{ij}^{\Delta t_w}$ are computed between consecutive buses as resulting from the previous sorting (Figure 3.7.1 (b)). It follows that $\theta_{ij}^{\Delta t_w} \geq 0$. The largest such $\theta_{ij}^{\Delta t_w}$ is the *maximum gap*: if it is larger than 180° , separation or loss of step may have occurred.

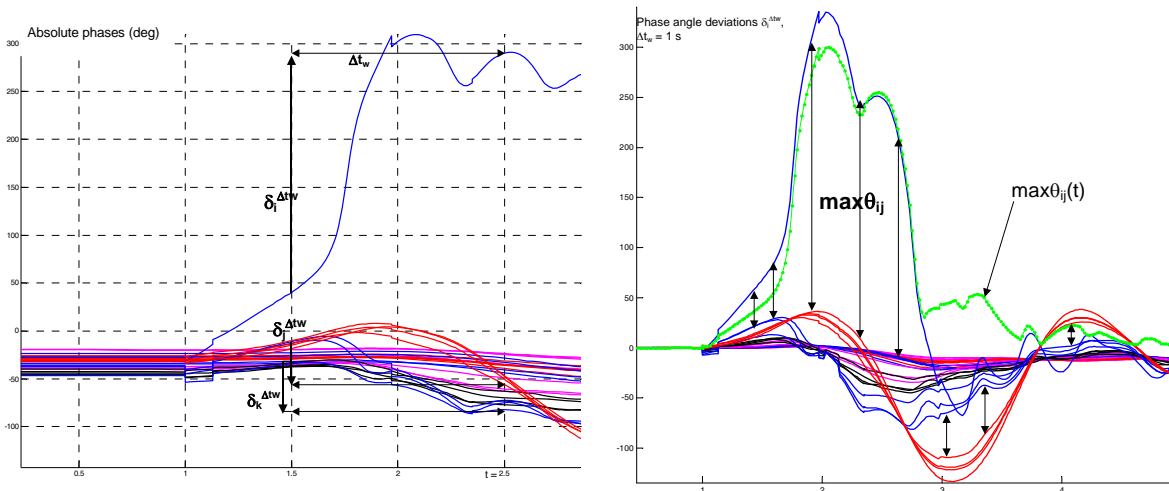


Figure 3.7.1. (a) - Construction of phase deviations $\delta_i^{\Delta t_w}$ from the plot of phase angle curves (case of loss of synchronism); (b) - Construction of maximum gap curve $\theta_{ij}^{\Delta t_w}$ from the plot of phase deviations $\delta_i^{\Delta t_w}$

Loss of synchronism is declared by the “severe” criterion, if the maximum gap experiences an “impulse” which develops and vanishes in a very short time interval, because of spontaneous recovery of synchronism or protection intervention (tripping of unstable machines): hence, a suitable value for the time window is $\Delta t_w = 1$ s. Conversely, separation is declared by the “severe” criterion, if a large angle gap $\theta_{ij}^{\Delta t_w}$ is observed with the same observation window ($\Delta t_w = 1$ s), and it does not cancel out within a suitable time interval (application of a time delay, e.g. 1.5-2 s). Moreover, splitting is declared by the “mild” criterion if the maximum gap is large with respect to large time windows (e.g. $\Delta t_w = 8-25$ s), whereas the gap has not exceeded the threshold with the small window values (e.g. 0.5-1 s). This case allows the detection of islanding between areas exchanging nearly no power in the pre-contingency situation.

The above solution provides detection as fast as possible, as allowed by system conditions. In case of severe disturbances with cascaded tripping, the last stage before complete separation may consist of

two subsystems electrically connected by weak ties, mutually slipping for some seconds (“asynchronous systems”). In order to correctly identify such situations, the above criterion can be improved with a logic declaring the loss of synchronism when the separation conditions are accompanied by large excursions of the electrical quantities.

The algorithm, also described in [16], is going to be implemented in the Italian WAMS platform.

CHAPTER 4

FUTURE ROLE OF WIDE AREA MONITORING SYSTEMS

In this chapter the vision of the working group members and related experts shows the direction in which this technology will go in the future.

4.1 Expected Future Application Areas of WAMS

From the discussions and contributions within this working group there are a few major trends which can be summarized:

1) The basic angle measurement is seen as valuable additional information for the operation of the power system. This is due to the fact that State Estimation calculations are not always accurate. The additional information from the PMU gives operational people a higher confidence in the system status. Based on this basic information, voltage stability information is seen as valuable for specific network situations. As future development of this a full integration of PMU information into SCADA/EMS systems is expected. This includes especially a hybrid state estimator based on conventional and PMU information. This kind of information is not using the time resolution and dynamics of PMU, but the angle information only. The results of the algorithms are alarm messages for the operators.

2) To use the dynamic capabilities of PMU, especially oscillations detection algorithms, are seen as important for the future. In a number of large scale power systems unexpected un-damped situations might occur, which could be detected in an early phase or even before their occurrence with a WAMS. The result is an alarm message for the operator.

3) Another topic which is mostly not considered in research about WAMS systems is the evaluation of offline information for planning purposes. Especially dynamic measurement sequences can be used for a better dynamic modeling of power systems. In a number of countries a better static and dynamic model would increase the accuracy of all kinds of planning calculations, but as well give better parameters for state estimation, control and protection. Both network planning and operational planning are seen to benefit from measurement recordings.

4) For Wide Area Monitoring and Control (WAMC) applications (see chapter 6), the most anticipated next step is the wide area damping control or wide area power system stabilizer. Further control applications for power flow control are as well expected. A centralized wide area control is putting high expectations especially on the communication architecture of WAMS. Therefore in most cases the experience and trust on WAMS will be gained first with the implementation of offline or online monitoring functions.

5) There are high expectations to use WAMS as a base for a system wide protection scheme in the future. Wide Area Protection (WAP) applications (see chapter 6) can be used for general grid protection solutions. They are able to operate in wide areas whereas special protection systems (SPS) are too specifically linked with defined events in a given part of the network. The use of PMU allows the timely recognition of risky phenomena, their nature, origin and propagation. It is an extremely difficult but fundamental task to develop effective emergency control systems to be used in any grid.

Even if the online system identification is more accurate than today, the implementation of an automatically acting scheme for emergency situations is seen as an extremely difficult task when it is to be deployed as an online adaptable system instead of a fixed rule based one. WAMS as SPS will only be considered in practice if it does not contain too much intelligence and if the rules for the actions are very transparent and are as simple as possible. Scientifically this is an interesting area, but the practical application is expected to happen after the first four topics have been implemented successfully.

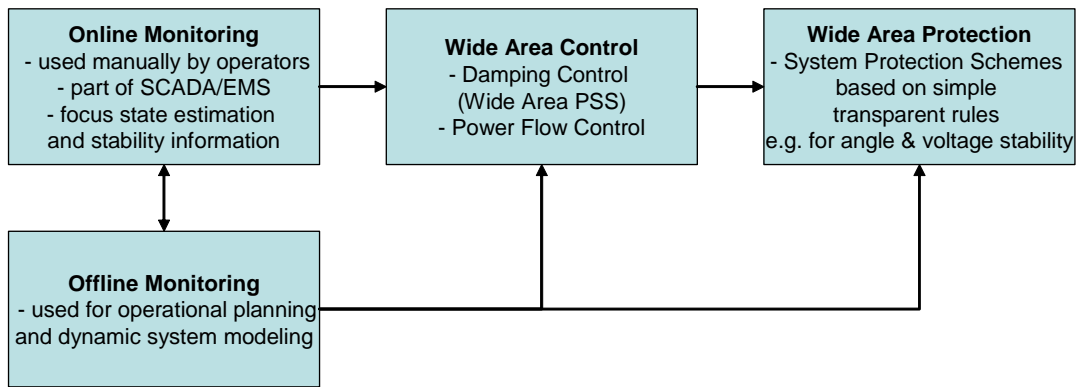


Figure 3.7.1. Expected applications for WAMS

4.2 WAMS as Intelligent Alarm Processor and Enhanced Decision Tool

If a WAMS is used for online system monitoring it is obvious that the gained information should lead to alarm messages in the case of the infringement of a threshold value for a certain stability value. This could be applicable for all kinds of stability, like phase angles, frequency, thermal limitations or voltage stability. In [61] it is stated: Simple algorithms should be developed for alarms based on conditions such as islanding, undamped, or negatively damped system oscillation, or unacceptably large power angles across selected segments of a power system.

The usability of this information is crucial for the operator. The information should be integrated into the SCADA/EMS operation scheme, like for example into the alarm message window. In case of an alarm message it must be very transparent as to which part of the network or which event has caused the alarm situation. Because of the speed of the WAMS systems the operator is more and more the bottleneck for taking quick actions. Therefore transparent and complete information are crucial for a successful implementation of WAMS as an alarm processor tool.

4.3 Impact of Monitoring Information on Operation Philosophy

Today's operation of a power system is mainly based on deterministic offline planning studies. All limits of the power system are determined by planning studies and set in a conservative way to lower the risk of system instabilities. In normal operation this limits the use of the existing networks for instance for market activities. In emergency situations it may be possible that based on the limits that are too conservative, operational actions are over-reacting. On the other hand if the planning limitations do not fit to the actual situation, operations might not be aware of the criticality of an emergency situation. Both are dangerous and unsatisfactory.

If we assume that more detailed information about the actual system status is available, the operator can more precisely operate the system based on the actual situation. The alarm information is expected to pre-warn of the imminence of critical situations. Indicators about the system situation will help to avoid over- or under-reactions of the operators. The impact of the WAMS algorithms used mainly as intelligent an alarm system will be a shift closer to real-time operational limits.

The monitoring functionality as such can hardly allow increasing the transmission capability. But it helps to give a clear warning message if a stability boundary is coming close. (See also section 5.3)

It should be noted that WAMS and WAMC systems may thus allow one to "walk closer to the edge" of system limits due to increased observability and controllability. The need and determination of what may constitute a suitable stability margin must still be considered, but is beyond the scope of this document.

4.4 Integration of Monitoring Information in Operational Planning

Operational planning requires both accurate steady state and dynamic system models. Generation and load models have a strong influence on oscillatory behavior, voltage stability and transient stability. The line parameters also play a role; presently these are usually taken from construction information, consequently they may be different under practical conditions.

WAMS-information can be used to generate or verify accurate system models. The usage of a WAMS system as disturbance recorder provides dynamic information and allows improving system models. The idea would be to link dynamic measurement recordings with disturbance and outage information and statistical surveys.

Up to now there are not many recommendations on how to include these data into the operational planning process in a structured way. However, it can be foreseen that this area will get more and more important in the future, because it is a first step to utilize WAMS-information in a secure offline way.

In section 2 it could be seen that WAMS is widely used for offline analysis of network situations and models. Proper models are a key for system operation. The WAMS can provide information to have proper models in place for all kinds of operational planning. Via the offline evaluation of the data the information gets into updated models for planning but as well into the SCADA/EMS system. The integration of these worlds is expected for the future. Offline planning based on dynamic information, steady state online operation (SCADA/EMS) and dynamic operation (WAMS) will be an integrated world in the future.

4.5 Integration of WAMS into SCADA/EMS systems

A total replacement of all RTUs in a transmission network does not seem to be realistic expectation. Neither is a completely independent system covering the entire transmission system, solely relying on phasor measurements and operated in parallel to existing SCADA/EMS system. Rather a complementary approach can be adopted.

One way of integration is the usage of PMU measurements in the State Estimation to improve its accuracy. A certain advantage of PMU is lost. If PMU information are going into the SCADA system including the time stamp, all Wide Area System applications could run within the SCADA system. This would mean to have the Wide Area System functionality fully integrated. A more practicable approach is to have the Wide Area System separate and show the results on an integrated human-machine interface (HMI) to the operator. The fully synchronized system can stay separate from the SCADA system, which makes it much easier to expand the SCADA system in a modularized way. Future generations of SCADA/EMS will perhaps integrate this functionality further. As far as it concerns the wide area control (WAC) and wide area protection (WAP), which are critically linked with the real-time protection and control problems, their integration into the SCADA/EMS system could determine many technical problems and relevant application delay with respect to a separate solution simply including data exchange for monitoring needs.

Indeed, existing installations of WAMS are operated mainly as independent systems and cover only minor parts of transmission systems. There are basically two types of concepts in this context:

- PMUs sparsely spread throughout the transmission system: This is the main approach of North American utilities, e.g. BPA, TVA and ETRANS in Europe.
- PMUs only fully observing a small dedicated portion of the transmission system: In this approach WAMS installation focuses mainly on a crucial transmission corridor consisting either of a single line (HEP, ETRANS) or several lines (EGAT).

4.6 Central Functions vs. Local Functions in PMU

In principle the PMU technology would allow the implementation of some algorithms within the PMU. Additionally some functionality could be placed on the substation level. The VIP algorithms from section 3.2.2 were foreseen to be placed in a PMU, but they were finally tested on a central computer or within a SCADA/EMS environment. Other installations like section 2.3 required special adaptations to the PMU algorithms but in most of the installations standard PMUs are used and all specific WAMS algorithms are placed in the central computer after collecting the data.

The possibility to implement applications within PMUs for Wide Area Monitoring, protection and control could be taken into account during the system design phase. The local data processing could contribute to a time gain as well as a simplification of the centralized computing in a specific area. From the product perspective of solutions this is maybe more difficult than having standard PMUs and specific applications only on a central computer.

CHAPTER 5

REQUIREMENTS FOR COORDINATED AND EMERGENCY CONTROL

This section collects the requirements for coordinated and emergency control. These requirements should allow increasing the transmission capacity, and avoiding misbehavior of fast network controllers like for instance PSS or FACTS-devices. The requirements shall consider as well the user acceptance and practical implementation questions like the communication systems.

5.1 Today's Coordination of Network Controllers

The coordination of controllers in today's power systems is implemented in the form of a hierarchical concept, where avoiding conflicting of controls is achieved by temporal and spatial separation. This can be summarized as three layers having the following properties:

- *Primary layer:* Quick local controllers with very short time constants (e.g. AVR on generators, SVCs etc.).
- *Secondary layer:* Controllers with medium time constants, in geographical sense covering regions. The task of a secondary controller is to coordinate primary controllers by determining set values for primary controllers in its respective control area (e.g. automatic generation control).
- *Tertiary layer:* Controller with long time constants, responsible for the performance of the entire power system, usually in geographical sense corresponding to a country. The task of a tertiary controller is to coordinate secondary controllers by determining their set values (e.g. typically in present day systems this is operator action).

Note that a description, equivalent to the above, can be found in a number of textbooks, e.g. [62].

The network controllers are usually coordinated only during their design phase. This means, that no adaptation is made during operation. The controllers cannot adapt themselves to actual situations; all possible situations need to be considered during the design phase. To guarantee a stable operation with this conservative design, the system cannot be used up to its boundaries.

The exceptions are given by two (automatically) coordinated control systems:

- The power-frequency control, where the active power production by some control generators are regulated in real time to maintain the system frequency and the exchanged powers with the surrounding countries, at the rated values.
- The transmission network voltage control system (Secondary and Tertiary voltage Regulations) where the reactive powers by the main generators are controlled in real time to maintain the pilot node voltages at the optimized values.

For frequency related controls, the wide area coordination is naturally given by the frequency itself. Therefore the load frequency control is by nature a wide area control and can be coordinated very well. If locally triggered load shedding is assumed as a part of the load frequency control the coordination gets lost, if at two places loads are shed based on the same criteria. This means that potentially too much load is shed. To avoid this, an additional coordination with wide area communication is needed to improve the performance.

For EHV voltage controls, the wide area coordination is naturally required among the pilot node voltages in the system and among the control generators of each area around a pilot node. Therefore the transmission network voltage control is, by its design, a wide area control strongly based on reactive powers coordination, including switching components and FACTS.

All the phenomena in relation with transmission capabilities need to consider an explicit system view,

like for instance voltage stability over a specific corridor or wherever it happens. Today the system view is available in some way in the control center through the SCADA/EMS system. Therefore all kinds of control, from compensation switching to FACTS set values, are coordinated from this place mainly manually. The time frames for this control are related to the time frames of information in the SCADA system. This means that all coordination is done in minutes or if manually executed in several minutes time frame and this is the approach even during major system disturbances.

The consequence of today's control is that set values are predefined for longer time frames and are changed only on manual request. The set values must be prepared for all expected system changes and may therefore not be optimal for the present system condition. This means, that capabilities of faster acting devices are not used and the system is running permanently sub-optimal in the best hypothesis. The transmission capability is not utilized as it could be. Emergency situations are handled manually.

Wide Area Monitoring and Control possesses specific features with respect to today's hierarchical control concept, explicitly:

- *Time/speed aspects*: Synchronized and frequent sampling of WAMC is close to the primary controllers.
- *Area/location aspects*: In terms of geographical coverage, WAMC acts either on the secondary or tertiary layer (or even beyond that in case of interconnected power systems monitoring, e.g. inter-area oscillations).

5.2 Acceptance Criteria for Wide Area Control Schemes

The behavior of Wide Area Control Schemes must be deterministic, transparent and easy to understand for the operator. Under all conditions such schemes need to stabilize the system and never weaken it.

If a system is rule based the control rules must be valid under all conditions otherwise the control should follow conservative conventional schemes. If a certain kind of controller is used within the wide area control scheme it needs to be coordinated with all other controllers, but for practical reasons in case of a system extension a re-design of all existing controllers need to be avoided.

In general it is necessary to have a wide area control system which does not contain 'hidden intelligence', which may lead to the system behaving in an unpredictable way. The operators need always to know what a wide area control system is doing or will do. This is a key criterion for practical acceptance.

A detailed requirement specification for network controllers with the example of FACTS can be found in [63]. The basic requirements are:

- New controller design does not require a redesign of already installed network controllers
- Several network controllers work together with the same control approach without significant dynamic interaction with each other
- Robustness according to requirements of power system operation (change of operational points and system conditions during time periods of hours, days and years)
- Modular controller design for system control and ancillary services; scalable for different control ranges
- No misbehavior in contingency situations

In practical terms this means that an appropriate system model needs to be available to design controllers for special purposes and for their tuning. The WAMS-information as described earlier can deliver such information for better dynamic modeling. On the other hand to get a robust system the controller should be based on measured system performance, which means the precise and dynamic measurements of the WAMS are a precondition to implement control schemes.

It needs to be stated that not in all cases of wide area control, a WAMS system based on PMU is required. For example, for power flow control a fast flow measurement of different parallel lines would be sufficient – time synchronization would not be necessary. In this case the data-transfer rate and communication requirements would be the same as for a PMU based WAMS system.

A wide area control scheme always needs a conventional local control scheme as a backup in case the wide area system or communication fails. Conservative local control settings are required and need to be considered during the design of such a system. Methodologies to consider these requirements are discussed in theory, e.g. in [64].

As a main requirement we always have to keep in mind that WAMC should do what an operator would do, if he or she would have sufficient time to analyze the situation and take the action. All actions need to be simple and fully transparent.

5.3 Increase of Transmission Capability versus System Security

WAMC promises to increase the transmission capability and system security. In the USA the NPCC (Northeast Power Coordination Council) for instance does not allow wide area actions for ATC or TTC improvements. Wide area applications are only allowed for Remedial Action or Special Protection Schemes (RAS/SPS). The EU instead allows considering all kinds of automated actions in the NTC calculations.

But despite of the regulations the basic technical question is: Does an increase in the transmission capability reduce the system security? If we calculate a TTC value based on imprecise measurements, we have to incorporate a comparably large security margin. If our TTC value is more accurate, we can define a smaller margin and know more exactly where the system is operated in relation to the stability boundary. Related to online systems like the WAMS this is only applicable if the TTC value is calculated as well online. This is not the case in most of today's power systems.

There has to be a clear distinction between normal (usually continuous or stepwise) control actions and RAS or SPS, which apply only in critical conditions. To operate closer to stability boundaries and misuse the RAS/SPS to stabilize the system if something goes wrong is definitively seen as a wrong approach.

Therefore the WAMC applications should always be a well defined continuous or stepwise kind of control for normal operation. But additionally it has to consider carefully how to react in contingency cases and it has to be integrated as well into RAS/SPS action schemes to avoid any kind of misbehavior.

Table 5.3.1. gives an overview of the applications and benefits of WAMS and WAMC related to steady state, continuous and emergency monitoring and control. In steady state operation the benefits of WAMS is limited because conventional approaches are typically adequate. In some specific cases the accuracy can be increased by a WAMS, leading to a higher security.

For continuous phenomena like oscillations and damping, only WAMS is able to significantly provide new kinds of information and enables early warning information. Therefore the system security is improved. Together with additional control schemes including damping, the transmission capability can be increased. For contingencies the value of WAMS and WAMC comes primarily from actions beyond N-1, especially for multi- or cascading contingencies when all predefined values from OSA are not available anymore. But the design requirements listed in the previous section have to be considered carefully.

Table 5.3.1. Impact and benefits of WAMS and WAMC in various operational conditions

	Steady state operation	Continuous change of operation	Contingencies
Monitoring (WAMS)	WAMS improves accuracy of Online Stability Assessment (OSA) based on N-1 (maybe N-2)	WAMS supervision of system dynamics like oscillations / damping	Accurate monitoring after contingencies, even after more than one contingency when information from OSA is not available.
Actions / Control (WAMC)	WAMS improved OSA updates RAS/SPS actions. WAMC is prepared to trigger actions fast and accurate	Continuous power flow control, reactive power control or wide area damping. Coordination and adaptation of local network controllers	Fast and accurate triggering of RAS/SPS actions. To a certain extend reasonable actions can be initiated based on simple rules even after more than one contingency.

5.4 Requirements on Communication and GPS for Wide Area Control

The communication system is the backbone of a WAMS. It is presently the limitation in terms of costs, reliability and speed. Especially for control applications it is very critical to have a deterministic behavior and reliable operation [65]. In principle all kinds of communication channels can be used for WAMS, but for wide area control a high-speed communication is required. The critical issue is not so much the bandwidth, but the time-delay of the communication. If a non-deterministic protocol like TCP/IP is used, the maximum expected time delay is relevant for the controller design. This is especially an issue for wide area damping controllers like wide area PSS as well as for the Secondary Voltage Control. Details can be found for example in [66]-[70]. Table 5.4.1 contains some estimates for the required communication time for various control applications. A communication time below 200 ms can be achieved with TCP/IP system with a high probability. A communication time below 20 ms is almost impossible even with dedicated communication channels. A high technical effort has to be taken.

Present day expert opinion suggests that dedicated communication channels are required to interconnect PMUs. Shared network solutions are not accepted presently. This requirement is even stronger for WAMC than for WAMS. For WAMC redundant communication channels are always required. Another consideration is that for redundancy and security purposes it is recommended that a WAMS system is running fully independently from RTU and other conventional monitoring systems. Only then the additional value can be fully used to increase the system security. On the other hand, if all applications like protection, control, state estimation, etc. would be based only on the same time-synchronized data, an integration and coordination of applications could be much simpler in the future.

In addition, there is the concern about the GPS system. GPS is a military system which could be switched off any time because of military decisions. More frequent are losses of the GPS-antenna signal because of bad weather conditions. A WAMC or WAMS system must be designed in a way that it provides information for a specified time period without receiving a GPS signal. When the European Galileo satellite system is in place there will be the requirement to equip PMU with two antennas for both systems to get redundancy. A direct synchronization between substations without using satellite signals would be beneficial, but there is no recommended solution available today.

The placement of the antenna is a critical issue as well. In present day practice, a separate antenna is used for each PMU. The antennas are not placed carefully enough in all cases to avoid electromagnetic incompatibilities with other substation equipment. One well placed antenna providing a signal to all PMUs is preferred. It is seen as a trend that the time-synchronizing signal will be used by more Intelligent Electronic Devices (IED) within the substation than just by PMUs. This means that in the future many more time synchronized information can be gained and used for applications.

Table 5.4.1. Estimates of cycle and communication time requirements for WAMS and WAMC applications

Application	Data collection window for algorithm or cycle time for control	One way communication time from PMU to central controller or vice versa
Voltage Stability	20 ms - 300 s	uncritical
Thermal Monitoring	20 ms	uncritical
Oscillation / Damping Monitoring	20 ms / <5 s	uncritical
Wide-Area PSS with wide area closed loop	50 ms	< 20 ms
Wide-Area PSS with wide area update of controller parameters	> 10 s	> 1 s
Power Flow Coordination	0.5 s - 1 s	< 200 ms
Transient Stability	< 100 ms	< 40ms
RAS / SPS	0.5 s - 1 s	< 200ms

5.5 Consistent Measurements with PMU

A major challenge to integrate processing for a large WAMS is to assure that measurements from the various data sources are consistent. Dissimilar filtering among analog instruments is a notorious cause of inconsistent signals, and some signals may require special compensation. Digital technologies, and phasor measurements in particular, offer the possibility to avoid this burden. Many details remain unresolved, however, and cross validation of multi-source data remains a necessary precaution in the analysis of major system events.

Phasor instruments and phasor networks represent new technologies that are still being adapted to a wide range of situations. Once installed, a PMU will very likely undergo one or more upgrades. Some of these upgrades may significantly change the dynamic response of the instrument and/or the degree to which its outputs are consistent with outputs from other units.

Anomalies, once detected, are usually corrected within days to weeks. Important records may be acquired before that time, however, and it is not unusual for the correction of one PMU anomaly to reveal or produce yet another one. This leads to a data archive in which some signals must be repaired or compensated in different ways for different recording times. Sometimes the need and the information to do this are not revealed until well after the data is recorded. A comprehensive log of PMU configuration and firmware is essential, and so is a corresponding library of data repair tools.

5.5.1 Challenges of Consistent Measurements

5.5.1.1 Inconsistencies Produced by Filter Differences

This section is based on material taken from [9]. PMUs and other transducers produce rms signals through some kind of averaging process involving or equivalent to a filter. The extent to which

transducer filtering can "color" the view of power system transients is illustrated in Figure 5.5.1.

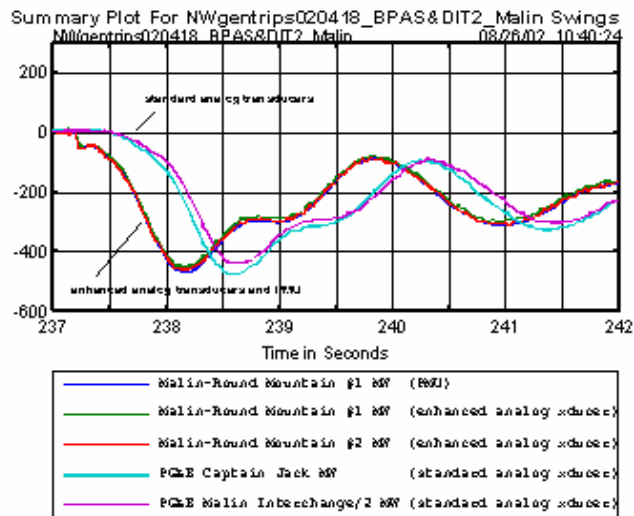


Figure 5.5.1. WECC Malin area signals for NW Generation Trip Event of April 18, 2002 (initial offsets removed)

All signals are from the WECC Malin area, near the Oregon-California border, and were recorded at BPA's Dittmer Control Center. Despite their obvious differences, all of the signals were obtained for essentially identical inputs to the various transducers. Except for fixed offsets (not shown) plus higher levels of measurement noise, the enhanced analog transducers on the Malin circuits produce signals that are closely consistent with each other and with the corresponding PMU signal. However, the signals produced by the standard transducers are somewhat different and both are seriously inconsistent with the other signals. They have lost their sharper features, and they have been delayed by roughly 400 milliseconds. These are the effects of low pass filtering, within the transducers themselves and possibly within the analog communication channels from Malin to Dittmer.

Considering the filtering properties, the signals from the narrow bandwidth analog transducers are valid and useful. Figure 5.5.2, produced by spectral analysis under quiescent conditions, shows that all of the analog transducer signals contain the same basic information about dynamic activity. As briefly indicated in a later example, correlation analysis permits the filtering differences to be determined, modeled, and compensated when the need arises. PMUs are not free of inconsistent filtering. A later section shows laboratory test results for this, and that the response of four specific PMUs would differ by ± 15 degrees for a 1.4 Hz local mode oscillation. There are many measurement applications in which such discrepancies would introduce unacceptable errors.

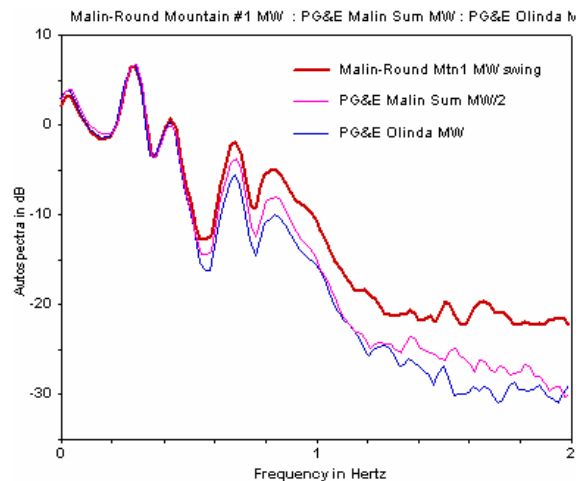


Figure 5.5.2. Ambient noise autospectra for Malin area transducers

5.5.1.2 Timing Inconsistencies Produced as Pure Time Delays

Erroneous time delays among PMU signals have been encountered from the following sources:

- time stamps that do not match the time at which the PMU output was produced
- PMU frequency signals that are not time aligned with the phasor outputs
- PMU outputs that were not produced at a standard time (the timestamps may be correct)

Important event data that are acquired before these problems must be either repaired or discarded. Examples of PMU timing errors are shown in Figure 5.5.3 and 5.5.4 for fault tests performed at BCH. PMU MPLV is located at BPA's Maple Valley substation, near Seattle WA, and the remaining PMUs are located within the BCH system. PMU ING1 and ING2, at Ingledow substation, share the same inputs but are of different types. Earlier fault tests showed that the BCH signals were out of time with the BPA signal, and that no two of the BCH signals were timed consistently. This lack of timing consistency was partly because ING1 had just received a partial software update. Additional updates produced the much better timing shown in Figure 5.5.3, though signals produced with older software were still out of time by about one second. An error of this sort is easily corrected by editing the time stamp for the entire PMU record, but one must know which PMU data to correct and by how much.

Figure 5.5.4 shows a case in which the PMU frequency signal is not time aligned with the phasor outputs. Correcting the data for this error is somewhat laborious, and estimating the size of the correction can be more so. This situation is fairly common, and a good countermeasure is to replace some or all instrument frequencies by estimated frequencies derived from bus angles.

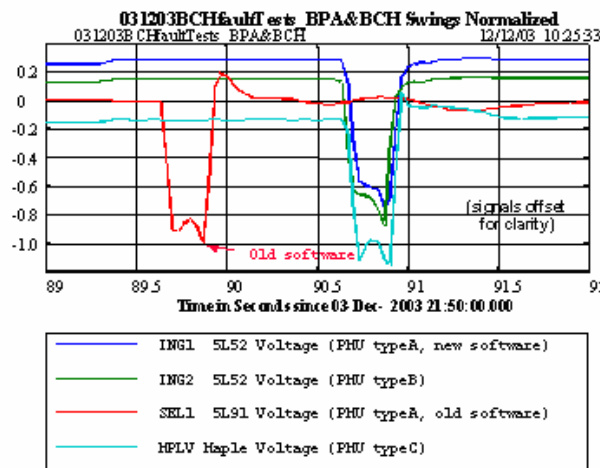


Figure 5.5.3. Relative timing of VMag signals. BCH fault test on December 3, 2003

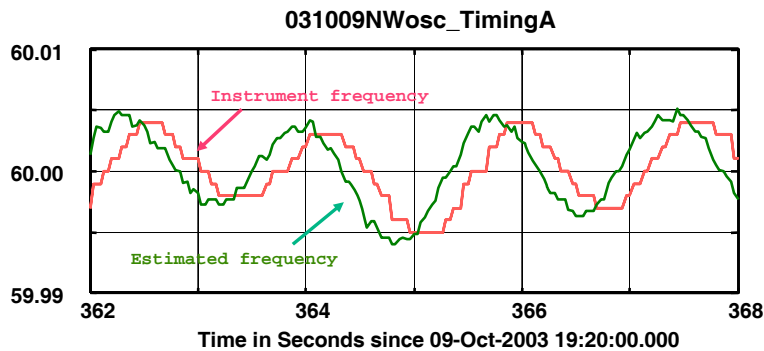


Figure 5.5.4. Timing anomaly in FreqL signal from ING1 PMU. NW oscillation on October 9, 2003

PMU outputs that were not produced at a standard time can produce major errors in bus angle. An example of this is mentioned in [75] but not shown. Resampling will repair such data, provided that the timestamps are correct.

5.5.1.3 Evaluation of PMU Performance

A PMU is both a network element and an RMS transducer. Evaluation of PMU performance is a complex matter that draws upon laboratory tests, model simulations, and comparative measurements under field operating conditions.

Full evaluation of PMU performance must consider both its network performance, and its performance as an RMS transducer for steady state and dynamic information on the power system. All of these are major issues, and attention here is focused upon dynamic performance only. Though the discussion is phrased in terms of PMUs, much of it applies to transducers and RMS calculations of other kinds.

RMS transducers provide average measures of point on wave input signals that represent local voltages and/or currents in the power system. The inputs can be thought of as sets of modulated carriers, containing dynamic information that is impressed through a combination of amplitude modulation and frequency modulation. The carrier frequencies are usually but not always harmonically related to the system operating frequency. Transducer inputs occasionally contain additive components for which the frequencies are essentially arbitrary, and which probably have no direct association with generator activity [76].

Beyond the problems mentioned here, there might be other lingering issues in phasor technology. These are for example protection against aliasing, anomalous modulation of frequency and angle outputs when some PMU types are submitted to amplitude modulation, and lack of an established standard for PMU tracking of small signal dynamics.

5.5.2 **Issues Associated with PMUs**

5.5.2.1 PMU Standard

The functional operation of PMUs is defined in the international standard IEEE Std C37.118-2005, 'IEEE Standard for Synchrophasors for Power System' [77].

The purpose of this section is to provide a rapid survey of the standard requirements for the purpose of determining its limits. In any WAMS or WAMC scheme using PMUs, a user will have to determine his/her requirements and verify that a PMU abiding to the standard will meet his/her specifications. That could be the case in many applications but it could turn out also that the standard does not go far enough when applied to some advanced schemes. When a PMU does not abide to the IEEE standard, it is left to the user to verify if its specifications satisfy his/her needs and requirements or not.

5.5.2.2 Communication with other PMUs and Concentrators

The standard defines four types of message frames: data, configuration, header and command. The first data message conveys information in a fixed and recurrent fashion from a PMU to a concentrator. The configuration and the header are sent upon request from a concentrator. The last command message goes from a concentrator to a PMU.

Among the data type defined in the standard, we find phasors (voltage or current), frequency, rate-of-change of frequency, analog quantities and Boolean variables (breaker status for example).

5.5.2.3 Synchrophasor Definition

The former synchrophasor standard (IEEE Std 1344-1995) did not have a synchrophasor definition per se but introduced the convention for a synchrophasor representation for a sinewave at rated frequency

of 60 (or 50) Hz. The convention is represented in Figure 5.5.5: for a signal $v(t)=\sqrt{2} V \cos (\omega_0 t+\varphi)$, the corresponding phasor is $V e^{j\varphi}$ and the angle φ is chosen as zero if the sample corresponding to the start of the second (1 PPS signal) falls on the waveform maximum.

$$v(t)=\sqrt{2} V \cos (\omega_0 t+\varphi)$$

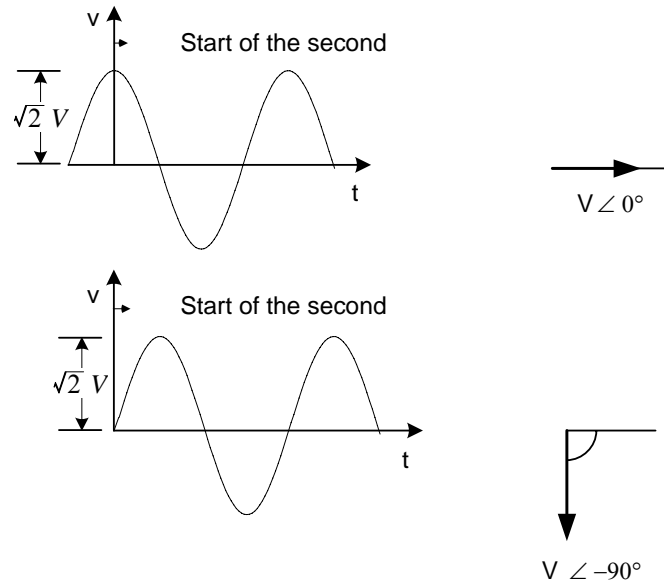


Figure 5.5.5. Convention for phasor representation

In the new standard, definitions for both a phasor and synchrophasor are introduced and correspond basically to the previous convention. The ambiguity of the phasor representation outside rated frequency is completely removed: a phasor phase angle will change at a uniform rate (in rad/s) proportional to the frequency deviation and equal to $2\pi(f-f_0)$ where f is the signal frequency and f_0 the rated frequency. As an example, a signal $v_1(t)=\sqrt{2} V \cos (2\pi 61 t)$ will rotate at a rate of 122π rads/s and will have the same phase angle as the signal $v_2(t)=\sqrt{2} V \cos (2\pi 60 t)$ at the start of the 1 PPS clock signal.

5.5.2.4 Synchrophasor accuracy

The accuracy in a phasor calculation is now defined by way of the Total Vector Error (TVE) concept. The total vector error is an error criterion where the measured phasor is compared to an ideal phasor response as expressed in the next equation.

$$TVE = \sqrt{\frac{(X_r(n) - X_r)^2 + (X_i(n) - X_i)^2}{(X_r + X_i)^2}} \quad (5.5.1)$$

In this equation, $X_r(n)$ and $X_i(n)$ are the synchrophasor real and imaginary parts measured at the n th sample and X_r and X_i are the coordinate of the synchrophasor with an ideal response. It should be borne in mind that the TVE does not apply specifically to the error in magnitude or phase angle but combines the two errors in a single value.

The TVE should not exceed 1% under conditions defined by two accuracy classes: level 0 and level 1. Level 0 requires the TVE to be within 1% for the frequency interval of ± 0.5 Hz whereas for level 1 the frequency interval is extended to ± 5 Hz. At off-nominal frequency, the ideal and measured phasors will be rotating phasors so that in order to comply with the 1% requirement, the measured phasor will have to be compensated for the filtering system group delay. Compensating for the filtering system group delay in turn imposes the instant the time tagging should be chosen for a given phasor. The principle for the time-tagging of a synchrophasor is imposed by the nature of the TVE. Preference is given therefore in the latest standard to tracking and accuracy rather than causality.

5.5.2.5 Synchrophasors in steady and transient states

The standard defines a synchrophasor in steady state as the condition when neither the magnitude, nor its frequency (which could be outside rated) nor its phase angle is changing. In order to comply with this requirement outside rated frequency, PMUs have to be compensated for their filtering system group delay. As a consequence of the TVE definition and when the filtering system group delay is compensated properly, two PMUs belonging to two different technologies should provide equal phasors (within 1% as imposed by the TVE error) corresponding to two identical waveforms in steady state. The new standard is more concise and complete therefore regarding the measurement accuracy of a phasor corresponding to a waveform in steady state.

In transient state, that is defined as the condition where a change is taking place either in a waveform magnitude, phase angle or frequency, the standard does not impose any specific requirement. Two PMUs abiding to the standard are not expected to have the same responses in the transient state. The condition for having the same responses in the transient state for two PMUs is that they must have identical hardware or have exactly the same phasor measurement algorithms.

5.5.2.6 Synchrophasors filtering system

The standard does not impose any type of filtering system. Clauses are introduced, however, that define the maximum level of harmonics or out of band interfering signals before the allowed TVE of 1% could get exceeded (see Table 3 in [77]).

5.5.2.7 Synchrophasors filtering system response time

The IEEE standard specifies the conditions for measuring a PMU response time. It does not provide, however, any limiting values for this delay. Unless two PMUs are identical, a user should not expect the PMUs to have the same response time.

5.5.2.8 Frequency and rate-of-change of frequency

Frequency and rate-of-change of frequency are two measurements which are essential in WAMS and WAMC schemes. Frequency and rate-of-change of frequency are not phasors but rather scalar quantities. The synchrophasor standard requires the measurement of the frequency and the rate-of-change of the frequency but falls short to provide specifications for these measurements. Particularly and contrary to the synchrophasor, the following issues are not covered in the standard:

- Accuracy of the frequency measurement
- Frequency range on which the accuracy is applicable
- Level of filtering and time delay associated with the frequency measurement
- Principle for the time-tagging of the frequency measurement

The same considerations are applicable to the rate-of-change of frequency measurement. In view of this, only two identical PMUs will provide similar measurement of the frequency and its rate-of-change at different locations on a network under transient conditions.

5.5.2.9 Analog quantities

There is provision to send analog quantities but they are not defined. It is therefore left to the PMU vendor to define the accuracy, filtering level, principle for time-tagging etc. of any analog quantity.

5.5.2.10 Reliability issues

There are few clauses pertaining to reliability issues in the IEEE standard. Practically there are only two clauses allowing detecting an abnormal condition:

- A bit in the data frame provides indication if the PMU is synchronized or not.
- All message frames incorporate cyclic redundancy check to verify that there are no communication errors in the message.

Issues like the loss of the synchronizing source, requirement for a time flywheel, breakdown of the communication channel, errors or failure in the PMU data acquisition etc. are not covered in the standard. It should be borne in mind that in certain critical applications like real time control or remedial action schemes, the level of reliability offered by the two mentioned clauses will not be enough to guarantee proper operation under adverse conditions. It is therefore left to the user to enhance his/her PMUs scheme to achieve the desired level of reliability. Redundant (and even triple) PMUs with different paths for the communication channels, and verification that the information received is identical, are one of the conventional means at the disposal of system engineers to achieve their goal.

CHAPTER 6

DESCRIPTION OF APPLICATIONS FOR WIDE AREA CONTROL

This section describes algorithms for wide area control. Most of the algorithms are available only in theory today. Selection targets on the most promising methods are provided together with the technical requirements for their implementation.

6.1 Increase of Transmission Capability with Coordinated Power Flow Control

6.1.1 Optimal Network Control with Price Signals

The coordination of the power flow control devices of the grid improves the efficiency of the overall control action. Usually, the power flow control, minimizes (or maximizes) a quantity, called the objective function. Traditionally, this quantity represents the total losses of the grid so that the control is considered efficient if the grid security objectives are met with minimal transmission losses. In a power market context, energy is exchanged between zones and, as a consequence, it is natural to run the grid in order to maximize the transmission capacity and to allow thus market-based power exchanges. The objective function should thus be enriched to integrate this aspect.

Moreover, it has been shown (see e.g. [78]) that maximizing the overall transmission capacity (the approach is called market volume maximization) is not optimal from an economical point of view. Indeed, the energy price could be quite different from one zone to another. The absolute value of the transmission capacity has thus less significance as an objective function of the network control in a context in which this capacity is auctioned. The objective function should in this case also take into account the market price signal in order to maximize the transmission capacity in the most valuable directions (market value maximization).

If it is technically possible to increase the transmission capacity through two flowgates at the same time, it is preferable to promote the most valued flowgate, i.e., in the general case, to maximize the benefit function of the market defined as

$$B(t) = \sum_b p_b t_b \quad (6.1.1)$$

where p_b is the price and t_b the quantity of the transaction b through a given flowgate.

The price signal in (6.1.1) depends on the nature of the control which is implemented and generally should provide financial weights for the flowgates. A typically used measure for this is the difference in energy prices at the ends of the considered flowgate (see [79] and [80] for congestion management).

Including price signals in the coordinated power-flow control is a way to make this control compliant with the market mechanism that is run in parallel. However, it should be noted that by doing so the overall efficiency is improved but the control could be suboptimal for local interests (forcing the local physical flow to individual reference values, ensuring internal security margins etc.). Such a control should thus be complemented by financial mechanisms to entice private owners of power-flow control devices to run them on the references given by the overall coordinated control.

6.1.2 Coordinated Power Flow Control

Shifting power flows between areas of a power system means to deviate from the natural power flow. The target for doing this is to increase the power flow over a line or corridor with free capacity or to decrease the flow in an overloaded part of the system. The benefit is measured as the increase of the

total market value as defined in the paragraph above, which considers the N-1 criteria. The drawback is normally increased losses in the system and the fact that the N-1 security margins request to reduce the working domain.

Traditionally the set values of power flow control devices, usually phase shifting transformers (PST), are predetermined to be optimal for all expected contingencies. This means that the maximum transfer for the expected most critical contingency is increased when using power flow control devices. If one uses bilateral capacity measurement as ATC/TTC (see [81]), the benefit is the difference $TTC_2 - TTC_1$ in Figure 6.1.1. The system is prepared to face this contingency, but it is running almost all the time in a non-optimal way according to losses or other criteria.

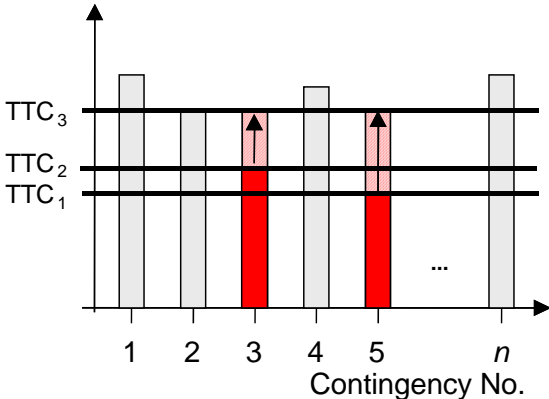


Figure 6.1.1. Total Transfer Capability without (TTC_1) and with (TTC_2) traditionally controlled power flow controller and fast power flow controller (FACTS) (TTC_3)

In comparison to this traditional approach, a fast controllable dynamic power flow control device (DFC = Dynamic Flow Controller = FACTS based power flow controller) opens up opportunities to change the set values within or even below the time range of a second to adapt to the just occurring contingencies. The benefit can be twofold:

1. The power system operates optimally (e.g. loss optimal) most of the time. Only in emergency situations the DFC changes to a pre-determined set value according to the contingency.
2. Two contingencies, which would require contradictory control actions, can be handled with one device. In Figure 6.1.1, contingencies 3 and 5 would require contradictory actions to increase the TTC value. The DFC adapts its action to the respective contingency just after its occurrence. In Figure 6.1.1, this gives the additional benefit $TTC_3 - TTC_2$.

In both cases an automatic control scheme needs to be implemented. The time scales of changing the set values depend on which kind of stability boundary is limiting the transfer capability. In case of voltage stability, a fast action within seconds needs to be applied requiring the speed capabilities of the DFC. In case of thermal limitations a certain overload during a couple of minutes can be accepted, but the speed of the action increases the flexibility to react on changing situations.

There are two principle options to automate the control scheme:

1. The information on the most severe contingencies, for instance line outages, must be transmitted to the controller. The controller has a set of pre-defined post-contingency set-values, which are used according to the specific contingency. The calculation of these pre-defined values must be done frequently to be as accurate as possible to the actual situation.
2. As an alternative, not the contingency itself, e.g. the outage of a line, is measured, but the effect on the parts of the system leading to the limitation. In this case, the flows on the parts or lines, which tend to be overloaded after the contingencies, need to be measured and transferred to the controller. The controller automatically controls the flow of the most critical line to its defined maximum.

In both cases the control scheme is based on rules, which guarantee well defined and unambiguous actions of the DFC. The second control scheme has the advantage of a higher accuracy and robustness, because the effect of the contingency is directly measured and no pre-calculated set-values are required except the maximum flows over the lines.

The required speed for the communication depends on the desired control speed. The fastest and most accurate control system would be a wide area control system based on time-synchronized phasor measurements. With such a system, specific algorithms to identify actual limitations of corridors or lines can be applied as input variables for the DFC controller.

Both DFC and PST are devices which can control the power-flow and thus contribute to the network regulation. However, they operate with different time constants and this can be exploited to improve the efficiency in non emergency situations. More precisely, if \bar{f} denotes the vector of maximum physical power flows across the flowgates which are considered for the security analysis and M^{N-1} the N-1 vector of security margin usually reserved on those flowgates, the following two-level control strategy can be imagined:

- a) first, one can compute in a coordinated manner for both PST and DFC setpoints such that the overall objective function (defined via price signals as in the paragraph above) is minimized under N constraints and considering the physical flows limited to $\bar{f} - M$ where $0 \leq M \leq M^{N-1}$.
- b) next, in case of an N-1 contingency, the potential constraints are eliminated by a corrective action exclusively implemented with DFCs. Indeed, those devices are sufficiently rapid to solve this emergency problem in reasonable time delays for operation.

This means that the fraction $\tilde{M} = M^{N-1} - M$ of the regular N-1 margin is used in normal operation for trading and this obviously leads to an improvement of the overall benefit. This is possible only if this quantity can be recovered in the N-1 situation exclusively using the DFCs. In other words, \tilde{M} should be sufficiently small such that the DFCs could create a counter flow on the selected flowgates at least equal to \tilde{M} . This is the dual of the Minimal Reserved Tap Range Problem introduced in [78] and it could be formulated as follows:

Maximal Security Margin Reduction (MSMR): Given a set of rapid dynamic power flow controllers (DFC) with setpoint ranges defined by vectors α_{\min} , α_{\max} , find \tilde{M} the overall maximal amount of counter-flow on a given set of flowgates which can be ensured with the DSC control.

If a linear model (sensitivities) is used to express grid constraints (see, e.g., [79]), the MSMR problem can be written as

$$(\tilde{M}, \tilde{\alpha}) = \arg \max_{\substack{H_{DSC} \Delta \alpha \leq -M \\ \alpha_{\min} \leq \alpha \leq \alpha_{\max} \\ M \geq 0}} \|M\| \quad (6.1.2)$$

where H_{DSC} is the DSC sensitivity matrix (Power Transfer Distribution Factors-PTDF) computed in N-1 situation and $\Delta \alpha$ is the variation of the setpoint of the DSC from the position around which the linear model has been computed. The result of (6.1.2) is optimal for the overall set of flowgates in the sense that the sum of \tilde{M}_i on each flowgate i is maximized (if norm 1 is used). This can obviously be changed in order to privilege some flowgates if necessary by introducing weights in the norm used in (6.1.2). More details about power flow control can be found in [78] and [83].

6.2 Wide-Area Control of Dynamic Shunt Compensators at Hydro-Québec

The development of Hydro-Québec's 735-kV network has been characterized by a sustained effort to minimize the number of transmission lines by using less costly solutions to meet stability performance standards. Almost all conceivable means have been used to improve power system stability starting with basic measures and evolving towards more elaborate techniques:

1) Basic stability improvement measures: Reduction of fault-clearing time, systematic use of fast-acting bus-fed static excitation systems on generators, addition of power system stabilizers.

2) Implementation of dynamic-shunt compensation: Fast-acting voltage control along the network immediately after a disturbance prevents a severe voltage drop from generation to load centers that is highly detrimental to system stability.

Phase 1: Dynamic shunt compensation in 735-kV substations was first implemented with nine synchronous condensers. These SCs have a nominal rating of 250 MVA each, are equipped with high-ceiling-voltage static excitation systems (from 6.4 p.u. on the first units to 15.3 p.u. on the latest ones) and lead-lag circuits in their voltage regulator to accelerate their response and enhances their capability to support voltage.

Phase 2: Static Var Compensators (SVCs) were considered preferable to synchronous condensers for James Bay transmission network due to their faster response. Consisting essentially of shunt capacitors and reactors controlled by thyristor switches, the injection of reactive power in response to voltage drops is almost instantaneous, limited only by the voltage regulator response time which can be almost negligible. Eleven 300-Mvar units were installed.

3) Addition of series compensation: Hydro-Québec adopted series compensation as the preferred technology to further optimize the design of its transmission system. Series compensation is a theoretically better method than dynamic-shunt-compensation to improve stability on long transmission systems. It solves the power system stability issue in the most straightforward way by reducing the series impedance of the transmission network, a basic advantage that allows operating generators with a reduced rotor phase angle. This in turn enhances the capacity of generators to develop synchronizing and damping electrical torques required to maintain stability. A total of 11,000 Mvars of series capacitors were installed along 32 line sections, providing a variable degree of compensation (from 17% to 44%) depending on the location of the line sections.

These major investments were followed in the last ten years by R&D work to further improve the power system stability limits. More specifically, interesting innovations were made in the field of regulation and protection systems. In this context, a new concept of PSS was developed and implemented on a digital platform in partnership with ABB. The so-called Multi-Band PSS has been recently standardized as PSS4B in the revised IEEE Std 421.5. This PSS4B uses a sophisticated algorithm to synthesize the rotor speed from a measurement of the generator terminal voltages and currents, and also provides a three-band transfer function, each band being independently adjustable to optimize damping for each of the oscillatory modes likely to be found on the system, which are:

- High band (0.8 Hz to 4.0 Hz) corresponding to oscillations between a specific generator and the other generators in the same plant (inter-machine oscillations) or between generators that are interconnected through a relatively strong low-impedance network, for instance within a same generation area.
- Intermediate band (0.1 Hz to 1.0 Hz) corresponding to oscillations between generators that are interconnected through a long high-impedance network, typically between large remote generation areas like Churchill Falls and James Bay (inter-area oscillations);
- Low band: At a low frequency around 0.04 Hz, corresponding to a global in-phase oscillation of all generators as found in Hydro-Québec system which is asynchronously connected and therefore isolated from its neighbors.



Figure 6.2.1. Dynamic shunt compensation units in Hydro-Quebec main grid: (2) Synchronous Condensers and (1) Static VAR Compensators.

The multi-band PSS principle is presented with the simplified functional diagram of Figure 6.2.2. A Bode locus corresponding to a typical setting illustrates the flexibility of such a concept.

With this simplified setting, each band consists of a band-pass filter that is defined by a center frequency (F_L , F_I or F_H) and a gain (K_L , K_I or K_H). The resulting transfer function (the global curve in Figure 6.2.2) provides an excellent performance in terms of generators transient and dynamic stability with a suitable phase lead (almost constant from 0.02 to 7 Hz) and a frequency dependent increasing gain [84][85].

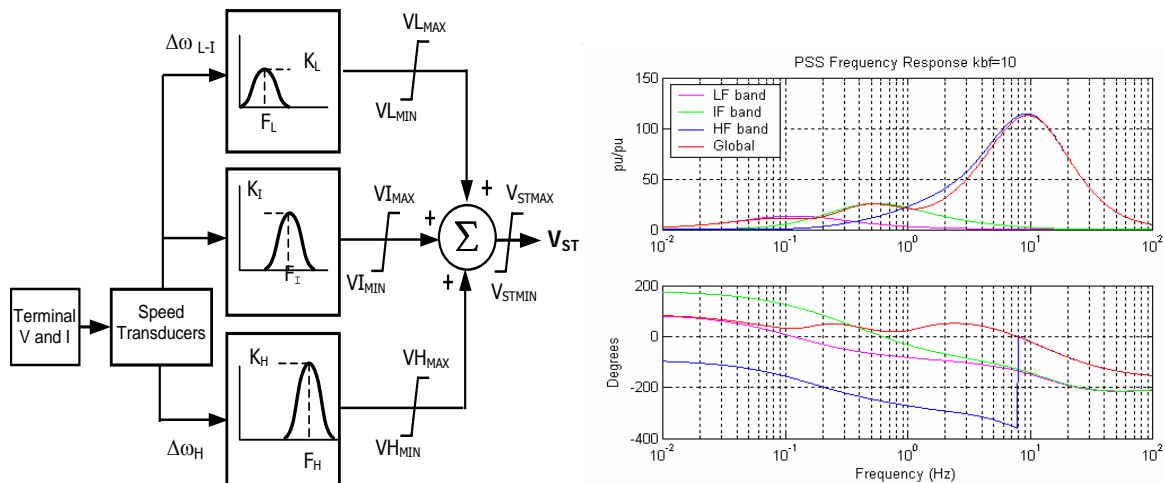


Figure 6.2.2. Simplified functional diagram of the MB-PSS (left) and frequency response of a typical setting (right)

More recently, the possibility of applying this multi-band concept to dynamic shunt compensators was considered in order to further improve system stability. The key idea was to add new control loops to the present SCs and SVCs regulators and take advantage of the huge potential of these equipments. Two specific applications were identified, the first one to improve long term voltage stability and the second one to provide supplementary damping of the main 0.6 Hz inter-area mode found on the Hydro-Québec transmission system. Furthermore, these new functions will be implemented in two distinct steps, one using locally available voltage and current signals (in the substation) and the others taking advantage of extended wide-area measurements for additional performance.

In this context, the local scheme is more simple and easier to implement and will be used to increase the power system transmission capacity while the wide-area level, being more complex and relying on telecommunication systems, will be dedicated to system robustness improvement until its reliability is fully established. These applications are presented in the next two paragraphs.

6.2.1 Long Term Voltage Stability

Voltage stability is an issue in the southern part of Hydro-Québec's power system where there are large concentrated loads namely the cities of Montréal and Québec. Providing sufficient voltage support is becoming a main concern because the number of transmission lines can hardly be increased due to economic and environmental constraints while the power demand is rising year after year. Severe contingencies involving loss of key circuits in the southern portion of the corridors may therefore induce severe voltage drops at the load and require large amount of shunt reactive power to avoid voltage instability.

Supplying additional static (capacitor banks) or dynamic (SCs or SVCs) reactive power in the substations located near the load would be an immediate but costly solution. On the other hand, system studies have shown that, with their present regulation loops, shunt compensators located in the transmission corridors cannot significantly contribute to the voltage support during these severe contingencies though they still have available "dynamic VARs" to supply. In order to benefit from these VARs sources, it was decided to use a supplementary input to the compensator voltage regulator suitable for detecting the voltage drop at the load. To do so, the local scheme would estimate the next downstream substation voltage phasor while the wide-area application would extend this concept with a load voltage phasor measurement transmitted through telecommunication links.

6.2.2 Supplementary Damping of Inter-Area Oscillations

As shown on Figure 6.2.1, the three largest hydroelectric complexes in Hydro-Québec system (James Bay, Churchill Falls and Manic Outardes) are located far north. Electrically speaking, each of these main complexes is equivalent to a coherent rotating mass and is prone to inter-area oscillations. Two

such oscillation modes are in fact found on the system, a dominant one at 0.6 Hz involving western (James Bay) and eastern areas (Churchill Falls together with Manic Outardes) and a less significant one at 0.9 Hz between the two eastern areas (Churchill-Falls versus Manic-Outardes).

Use of PSSs on generators is a classical and well-proven means to improve system dynamic performance. Hydro-Québec plants larger than 100 MW are all equipped with such PSSs. Their performances have been continuously improved over the years either by the evolution of the platforms themselves (analog versus digital devices), the input signals (ΔP_e , ΔP_{acc} , $\Delta \omega$), the transfer function flexibility (multi-band versus standard single band principle) and the tuning methods to coordinate and optimize the settings on voltage regulators and PSSs [86].

More recently, Hydro-Québec simulation studies have clearly demonstrated the inherent efficiency of MB-PSS to damp inter-area oscillations in general and more specifically on its own transmission system [85]. For example, a targeted application to the two largest plants namely LG2 (5000 MW) and Churchill-Falls (5500MW) showed a significant improvement of the dominant 0.6 Hz mode damping. However, the efficiency of generator terminal voltage modulation at the far end of transmission corridors is limited by the voltage regulation action of the SCs and SVCs of these same transmission corridors. Coordination of these generator and compensator control loops was therefore found to be a major avenue to further improve the angular stability of the whole system.

6.2.3 Implementation of the new shunt compensators control loops

As mentioned above, the two target applications will be set up in a hybrid scheme made of local and wide-area control loops. The implementation will be done in two phases in order to progressively demonstrate the feasibility of these new principles and to take advantage of the local loops impacts in a shorter term. The proposed infrastructure is illustrated on Figure 6.2.3.

Local signals are extracted from the DLO relays connected to the corridor transmission lines. Each of these is responsible for detecting the status of its line and for estimating with the PTs and CTs measurements and the line model the local and remote bus voltage phasor V_L , V_R when the line is found in a closed state. Doing so, the local differential variables are obtained averaging the values computed by the DLOs:

$$\Delta V_{\text{Corridor}} = |V_L| - |V_R| \quad (6.2.1)$$

$$\Delta \theta_{\text{Corridor}} = \angle V_L - \angle V_R$$

For a given substation, wide-area signals are extracted from the local bus phasor V_L , the load voltage V_{Load} in the Montreal area and two major plants involved in the dominant 0.6 Hz inter-area mode V_{LG2} and V_{CF} . In this case, the wide-area differential variables are obtained with the following expressions:

$$\Delta V_{\text{System}} = |V_L| - |V_{\text{Load}}| \quad (6.2.1)$$

$$\Delta \theta_{\text{System}} = \angle V_{\text{LG2}} - \angle V_{\text{CF}}$$

Each of these four control variables corresponds to a supplementary loop in the new multi-functional MB-PSS as shown on Figure 6.2.4. To the original bands 2 (Low), 3 (Intermediate) and 4 (High) are added band 5 dedicated to the voltage loops and band 1 for very low frequency phenomena. This particular band is used for those compensators located near the load in order to reduce the power system "very slow" frequency deviations and consequently the burden for the AGC plants. Due to the differential structure of the bands, band 5 can handle both $\Delta V_{\text{Corridor}}$ and ΔV_{System} .

With the wide-area scheme in operation, the ΔV_{System} and $\Delta \theta_{\text{System}}$ are normally the active loops with the highest performances but they need to be backed up by the local ones characterized by a very high degree of availability. The relative performances of the two types of loops are presented in the next section.

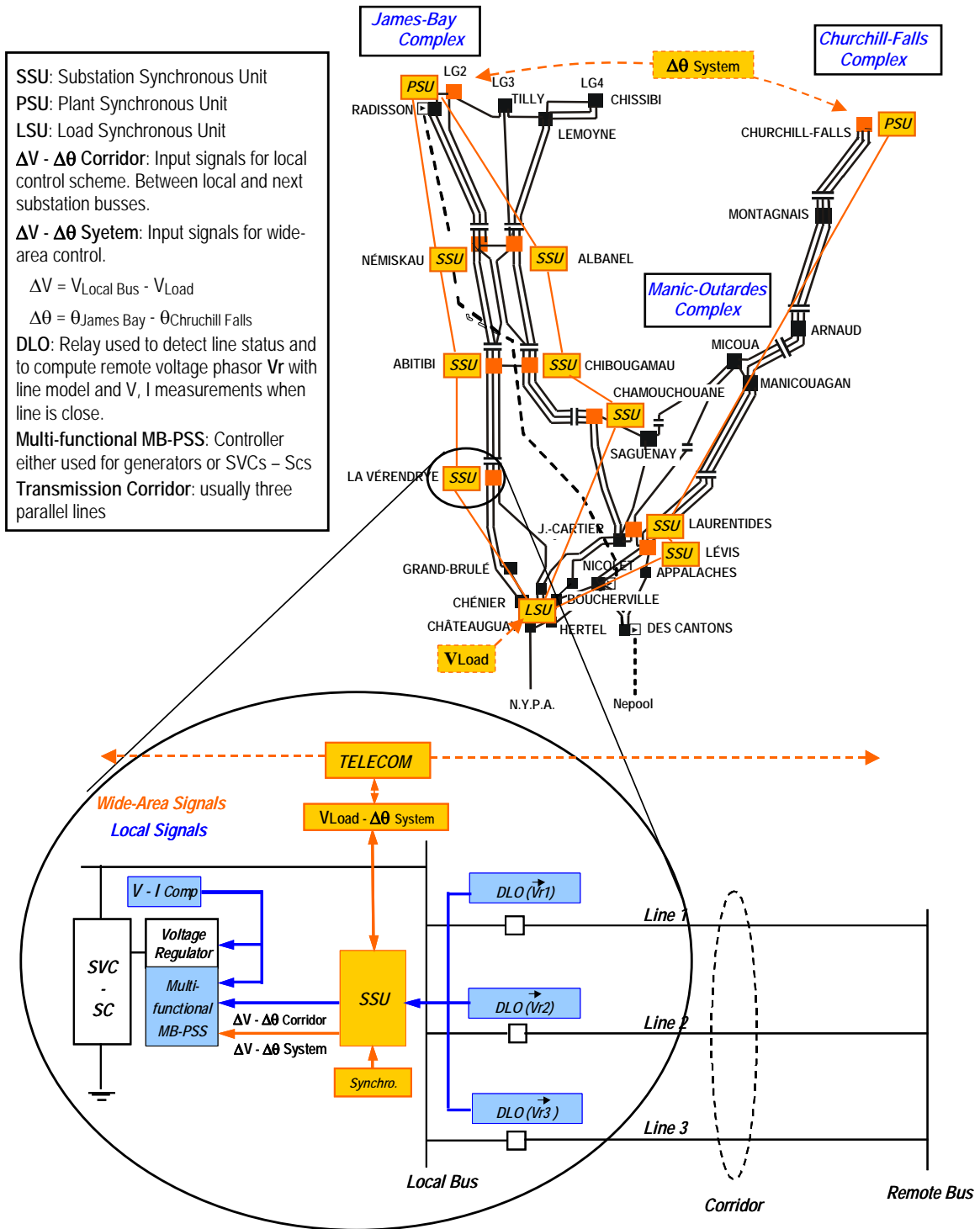


Figure 6.2.3. Local and wide-area control loops: implementation schemes

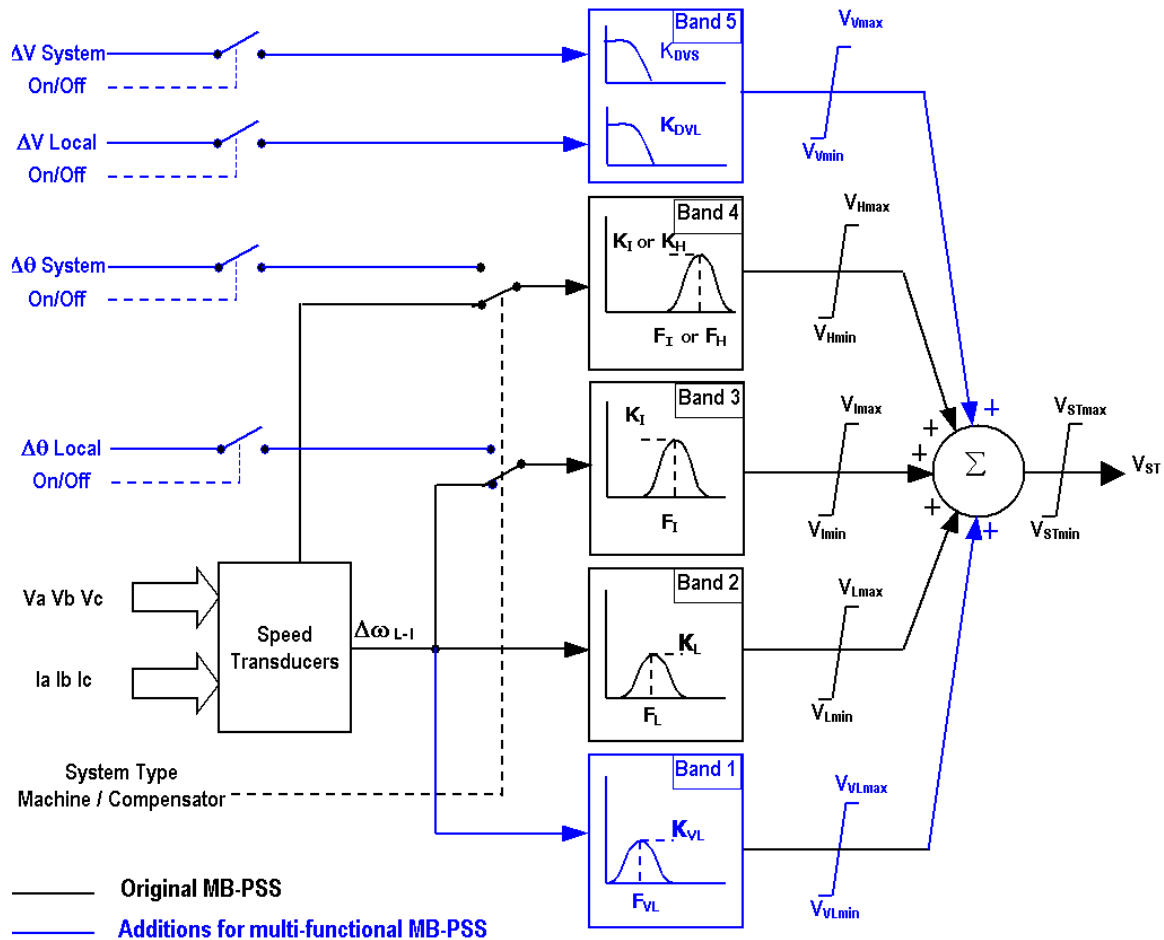


Figure 6.2.4. The multi-functional MB-PSS is using five bands instead of the original three

6.2.4 Performances of the new control schemes

To estimate the gains in terms of power system transmission capacity and reliability, stability studies were conducted on Hydro-Québec transmission system.

Load voltage support application:

To illustrate the gains in load voltage support, four long-term severe voltage stability scenarios were simulated and analyzed from the peak grid 2004 [89]. A total of 15 shunt compensating equipment in 8 substations were involved for both local and wide-area control strategies. The stability model included all transformers with on-load-tap-changers as well as the shunt reactors equipped with the so-called MAIS voltage-controlled switching system [87]. When a bus voltage is abnormally low (< 0.97 p.u.) for a certain period of time, the fully local MAIS device automatically disconnects a shunt reactor. At the limit, all shunt reactors in the load area will be switched off just before a complete collapse. Therefore, one simple way to measure the effectiveness of the new control loops is to count the number of reactors disconnected as a result of such severe contingencies. Another approach is to use the software tool ELISA [88] to determine the power transfer limit gains with respect to long-term stability. The results from these two approaches are shown in Table 6.2.1.

For contingency 4, both local and wide-area control prevent disconnection of any reactors, compared to the base case where 3 reactors were required for the long-term stability of the system. In other cases, wide-area control out-passes local control by 1 or 2 reactors. Giving that each reactor represents 330 MVAR, the total reactive reserve against voltage collapse provided by each of the control

schemes is impressive, whatever the contingency: 990 MVAR in the wide-area case and from 330 to 990 MVAR in the local case.

Again in Table 6.2.1, the transfer limit in one of the system main transmission path provides a complementary picture of the three studied situations: while the worst-case limit for contingency #1 is only 100-MW without control, it jumps to 1125 and 1950-MW with local and wide-area control respectively. For this specific transmission path, the average gain for this set of contingencies is over 700 MW with the local scheme and over 1800 MW with the wide-area control. The largest gap between the base case and the new control schemes is for contingency 3 with respectively 1675 MW and 3100 MW for local and wide-area schemes.

Table 6.2.1. Performance of local and wide-area control schemes versus the base case in terms of available VARs and additional MW transfer limit

Contingency #	Shunt Reactors switched off by MAIS (1 inductor = 330 MVars)		
	Base Control Scheme	Local Control Scheme	Wide-Area Control Scheme
1	4	2	1
2	4	3	1
3	4	2	1
4	3	0	0
Contingency #	Transfer limit gain in MW on one main transmission path		
	Base Control Scheme	Local Control Scheme	Wide-Area Control Scheme
1	100	1125	1950
2	900	1050	1725
3	500	2175	3600
4	2000	2200	3600

Inter-area oscillation application:

The performances of the new local and wide-area $\Delta\theta$ control loops were also studied on TransÉnergie grid model used in the operations planning for the 2004 winter peak [89]. The supplementary $\Delta\theta$ control loops were implemented in 6 substations. Two main transmission paths have been assessed under two assumptions: all additional power is transferred on path #2 or simultaneous transfer occurs on both paths #1 and #2. No Special Protection Systems such as MAIS or RPTC (generation and remote load shedding) is included in the model. Table 6.2.2 presents the increase in power transfer limits on path #2 under the first assumption given seven critical contingencies and assuming a summer load model ($N_p=1.0$, constant current) or a winter load model ($N_p=1.3$). In each case, the contingency is simulated for 15 s and the transfer limit is determined with ELISA by an iterative process for which the load flow is increased by 25 MW steps until loss of synchronism is reached. Here are the main observations derived from Table 6.2.2:

- The system is limited by the inter-area mode damping for contingency #6. In that case, the wide-area and local control significantly increases the power transfer limit, whatever the load model.
- For contingencies 1, 2, 3 and 4 which at the limit, result in a first swing instability, the local control gains are less significant in comparison with wide-area control that provides an increase of the stability margin as much as 425 MW for contingency 3. This is due to the inherent capacity of wide-area schemes to "observe" the system transient and dynamic phenomena.

Table 6.2.2. Performance of local and wide-area control schemes versus base case in terms of additional MW transfer limit for two different load models (Voltage exponent for active power $N_p = 1.0$ or 1.3)

Contingency #	Transfer limit gain in MW for 7 contingencies: Load model $N_p = 1.0$	
	Local Control Scheme	Wide-Area Control Scheme
1	175	300
2	150	425
3	0	425
4	50	425
5	150	175
6	100	150
7	75	100
Contingency #	Transfer limit gain in MW for 7 contingencies: Load model $N_p = 1.3$	
	Local Control Scheme	Wide-Area Control Scheme
1	75	325
2	25	425
3	0	375
4	25	350
5	150	175
6	200	250
7	100	125

6.3 Damping Solutions in the Hungarian System

Oscillations have to be clearly distinguished into oscillations after an outage, oscillations which take place by themselves (spontaneous), extinguish by themselves (0.15-0.28 Hz) and the local unit oscillation (about 1 Hz).

To damp these oscillations the following methods could be chosen:

- The damping of the local unit oscillation is already solved (PSS tuned on ~ 1 Hz).
- The damping of the ~ 0.2 Hz inter-area oscillations (which takes place by itself – see Figure 6.3.1) is according to our experience impossible with the present applied PSS structure, if we do not allow huge reactive power oscillations. In other words, the frequency oscillation is damped but the reactive power oscillation is increased. Therefore a new PSS structure is developed [82]. This PSS creates acceptable reactive power oscillations and decreases the frequency of oscillation effectively but it is not installed yet. The results are only from simulations.
- Another solution is to reduce the time interval of actions of turbine governors. It can be reached by appropriately choosing of the deadband of units (see Figure 6.3.2.). Consequently, each unit has a deadband, but the resultant deadband, of the power plant investigated, may be near to zero.

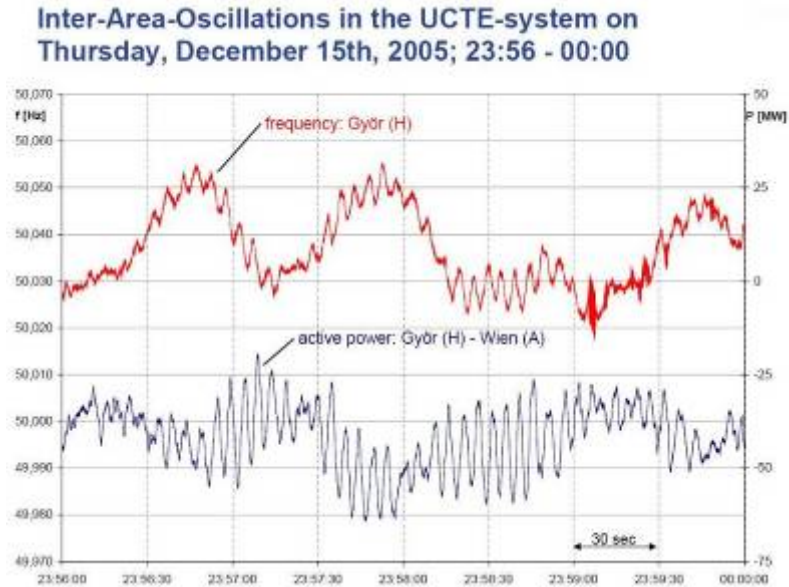


Figure 6.3.1. Inter-Area Oscillation, which takes place by itself, measured in Hungary by WAMS device

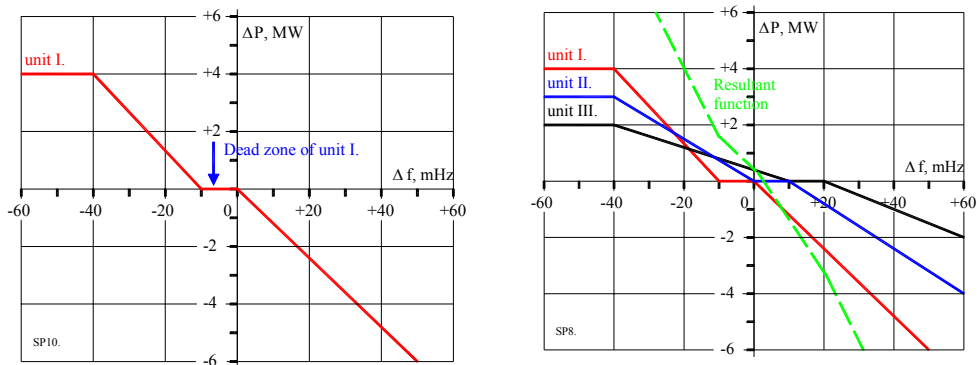


Figure 6.3.2. Static load-frequency characteristic of turbine governor of units in a power plant

6.4 BPA's Wide-Area stability and voltage Control System (WACS) Project

Figure 6.4.1 shows a block diagram of the power system stability control environment. Power system stability encompasses electromechanical (rotor angle) stability among groups of synchronous generators, and voltage stability involving load response to disturbances [94]. RMS-type sensors are generally used—electromechanical oscillations and slow voltage variations amplitude-modulate the 50 or 60 Hz power frequency waveforms.

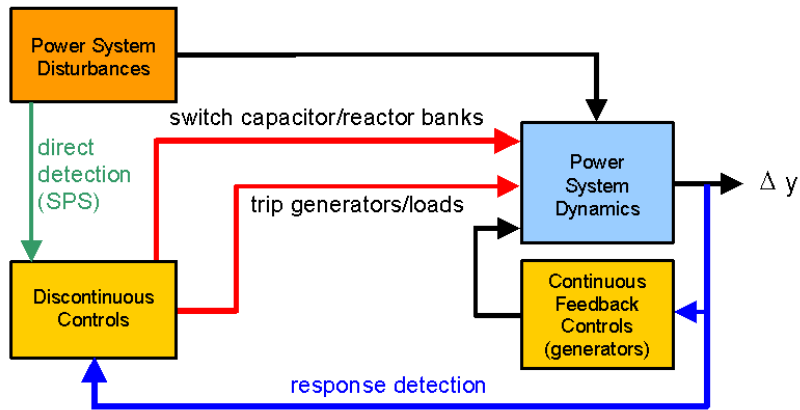


Figure 6.4.1. Local and wide-area, continuous and discontinuous power system stability controls

Most stability controls are continuous feedback controls at power plants: automatic voltage regulators and power system stabilizers for generator excitation control, and prime mover control (speed governor). Controls are largely the single-input single-output type, designed via classical feedback control methods. Additional local continuous stability controls are at transmission-level, such as power electronic devices (static VAR compensators, etc.). There are also local discontinuous controls for reactive power compensation (capacitor/reactor banks) switching and load shedding.

Installed wide-area stability controls are mainly emergency feedforward discontinuous controls termed special protection systems (SPS) or remedial actions schemes (RAS). An SPS is usually based on *direct detection* of pre-defined outages, with high-speed binary (transfer trip) signals to control centers for logic decisions, and then to power plants and substations for generator or load tripping and capacitor/reactor bank switching. Compared to continuous control, discontinuous control tends to be safer - action is only taken when necessary. Discontinuous control has similarities with biological systems where stimuli must be above an activation threshold.

Disadvantages of SPSs include control for only pre-defined events, complexity, and a relatively high cost.

In contrast with SPSs, wide-area *feedback* controls employ strategically placed sensors to react to the power system *response* to arbitrary disturbances. Bonneville Power Administration (BPA) has developed and demonstrated a Wide-Area Stability and Voltage Control System termed WACS [95]-[97]. WACS provides a flexible platform for rapid implementation of sending-end generator tripping and reactive power compensation switching for transient stability and voltage support of a large power system. Features include synchronized positive sequence phasor measurements, digital fiber optic communications from substations, a National Instruments real-time control computer programmed in the G language (LabVIEW RT), and output communications for hydro generator tripping and 500-kV capacitor/reactor bank switching. The WACS software runs two algorithms in parallel. The first application of WACS is for Pacific 500-kV intertie stabilization.

WACS provides single discontinuous stabilizing actions or true feedback control. As true feedback control, the need for discontinuous action is determined and commanded, the power system response is observed, and further discontinuous action such as generator tripping or capacitor bank switching is taken when necessary. The WACS platform may also be used for wide-area modulation control of generators and transmission-level power electronic devices, and for control center operator alarms and monitoring.

WACS uses twelve voltage magnitude measurements from seven 500-kV stations, and fifteen generator reactive power measurements from five power plant switching stations. A voltage magnitude based algorithm (Vmag) first provides swing transient stability control, and relieves stress

to improve transient damping. For growing oscillations it will operate at some point for stabilization. A weighted average voltage is computed with highest weight for measurements close to the Oregon–California border. A nonlinear accumulator (integrator) computes volt-seconds below a threshold setting. Accumulation is blocked for voltage recovery. Control action results when the volt-second accumulation reaches a setpoint.

A voltage magnitude and generator reactive power based algorithm ($V_{mag}Q$) combines weighted average voltage magnitude measurements and weighted average generator reactive power measurements using fuzzy logic. A crisp output value above a threshold enters an accumulator. When the accumulator setpoint is reached, the capacitor/reactor bank switching or generator tripping is commanded. Capacitor/reactor bank switching occurs first and together with generator tripping only in more severe situations where capacitor/reactor bank switching is not available or not sufficient.

WACS exploits advances in digital/optical communications and computation. Specific advantages include:

- Control for outages and conditions not covered by feedforward controls (SPS).
- Potentially simplifies operations for changing system conditions - presently operators are required to reduce power transfers when unstudied conditions are encountered.
- Improved observability and controllability compared to local control. Discontinuous control reduces exposure to adverse interactions.
- Flexible, high reliability 'open system' platform for rapid, low-cost control and monitoring additions, including wide-area continuous control.
- Provides an increase in both reliability and power transfer capability.
- Caters to uncertainty in simulation results used to determine operating rules and limits.
- Future potential with cost reductions and further IT advances. Potential for application in meshed grid as well as intertie corridors. Control inputs and outputs may be extended over a larger geographical area such as the entire western North American power system.

The addition of wide-area feedback control to frequently used wide-area feedforward control is an effective additional layer of defense against blackouts [98], as well as facilitator of electrical commerce.

6.5 Wide-area Damping Control System

In modern large-scale power systems, inter-area low-frequency oscillations have become a serious bottleneck in elevating transfer capabilities. Existing damping controllers, like traditional generators' PSSs, cannot always be effective in easing the problem. This is due to a lack of global observability, mutual coordination and placement flexibility. Fortunately, the recently developed wide-area measurement system (WAMS) technology offers a great potential for ameliorating the situation. WAMS can accurately measure and quickly transfer synchrophasors in the range of the whole power system, thus making it possible to construct global damping control systems.

In designing a WAMS-based damping control system, several key issues should be well addressed. That includes: (i) configuring an appropriate framework to coordinate the functions of local and wide-area control loops; (ii) properly placing observers (PMUs) and controllers; (iii) implementing control laws with constraints of information structure, optimization, adaptability, robustness and etc; (iv) dealing with the time delays introduced by wide-area transition of data.

For issue (i), a two-loop control system will be appropriate, wherein the inner loop executes real-time damping control by using multi-input from WAMS, while the external loop adjusts the parameters of the inner loop in a near-real-time way so as to accommodate the variation of operation conditions. However, in many cases, the external loop is difficult to be realized because of incomplete information about the whole system or an excessively high calculation burden. Thus an adaptive self-learning loop should be embedded into the real-time control loop so as to adapt the control parameters to the varying

operation points.

For issue (ii), a practical and efficient method based on the concept of comprehensive observability and controllability has been developed for properly sitting the observers (PMUs) and controllers. The comprehensive observability index denotes the strength of a dominant mode exhibited in a response (or a node). Thus, those signals (or nodes) having large values of observability should be selected as the feedback signals (or location of PMUs). Similarly, the wide-area control actions should be performed by control inputs that are of large controllability indices.

Issue (iii) is the key to successful implementation of wide-area damping control. For the two-loop control system mentioned above, adaptive tuning of controller parameters is fulfilled within the external adjustment loop. It firstly gathers data from WAMS (/EMS), and then performs a linear (or hybrid) state estimation to obtain the most recent operation status of the system. If the variation of operation condition is beyond the pre-defined range, it initiates a new round of “coordinated & optimized control design” upon the “online faster-than-real-time simulation platform”. The control-design procedure includes obtaining a low-order system model (with disturbance injection approaches, e.g., PRBS, and model identification algorithms, e.g., Prony and N4SID) and tuning controllers’ parameters simultaneously (e.g., with the theory and algorithm of optimal output-feedback control with constraints of information structure and robustness). If the near-real-time adjustment loop is unrealizable, an embedded self-tuning loop is appreciated. For instance, the direct neural dynamic programming (DNDP) would be recommended for this purpose. The DNDP-based control is a model-independent online learning control paradigm that handles nonlinearities, uncertainties and delays very well.

For issue (iv), either a robust control is realized, which can tolerate communication delays; or the delays are forwardly compensated to make originally designed control work as well as expected. However, since the communication delays are generally of random characteristics, a combination of these two methods may be the best way to handle this issue.

At present, some initial research work (numerical and/or RTDS simulation study) on this topic is ongoing, for instance, wide-area supplementary modulation control of multiple HVDC links in Southern Power Grids, wide-area excitation/governor control in the Northeastern-Northern interconnected power grids, etc. The purpose of these studies is to evaluate the feasibility and effectiveness of wide-area damping control. At this point, a taste of the difficulties in its implementation and propose possible solutions and related work can be found in [91] and [92].

6.6 TEPCO’s System Separation against Small-disturbance Angle Instability

In TEPCO’s (Tokyo Electric Power Company, Japan) power system there are three major generation centers located in eastern, southeastern and northern areas and connected to the 500 kV bulk transmission grid. About 10 GW of power flows on the 500 kV power grid from east to west during summer peak days. Western generation centers with major loads are connected to some 275kV radially operated transmission networks. Since very severe but rare contingencies may cause small-signal instability between western generation centers and others, a Special Protection Scheme was installed in 1989 to separate the western networks from the major grid in cases that rotor angle instability is detected.

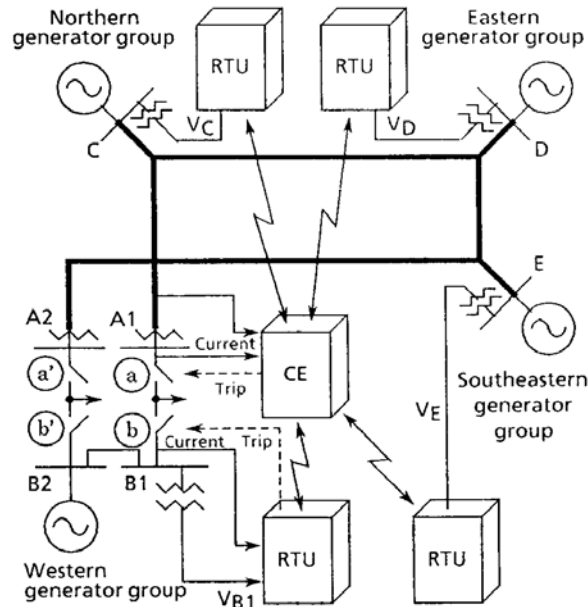


Figure 6.6.1. TEPCO's System Separation System

The SPS is composed of two identical relaying systems for the purpose of separating two 275kV power systems. Each system has Central Equipment (CE) installed in 500kV substation near the western generation centers, three Remote Terminal Units (RTUs) installed in three substations located near the north-eastern, south-eastern and northern generation centers, and one RTU installed in the 275kV substation near the western generation centers. The CE and RTUs are connected in a star topology through microwave synchronized communication channels owned by TEPCO. This is a fully redundant system.

The RTUs simultaneously sample busbar voltages at 600Hz, which are transmitted to the CE. The CE calculates in real time the phase differences between the W-NE, W-SE and W-N systems. When two out of three phase difference values predicted at 200ms in the future exceed the pre-determined threshold value, the CE detects the loss of synchronism of western generation centers from the main grid. Based on the tripping signal from CE, the western system separation from the main grid is then initiated.

This scheme uses a high-speed synchronized data communication network applied to current differential relay instead of PMU based technology. However, from the application point of view it is a wide area application which could be implemented on a PMU base instead.

6.7 Wide-Area Voltage Regulation and Protection

A very promising EHV Wide Area Voltage Protection (WAP) solution to face voltage stability and system security problems is proposed. It does not necessarily require the use of PMUs but its unique ability resides in its effective co-ordination with a modern Wide Area voltage Regulation (WAR) system.

Considering that in transmission network voltage control we have to distinguish between:

- The continuous or discrete-time control actions devoted to sustain the network voltages at the values around the normal operating conditions, facing load changes and contingencies. These are called “Regulating Controls” aimed to stabilize and maintain in operation the overall system feeding all the loads with continuity;
- The extreme step control actions that are continuously ready to act but rarely operate on the real system. This control is only active during extreme conditions when the risk to loose the system or part of the system is high. These are called “Protecting Controls” aimed to confine the incoming

problem and to minimize the part of the system to be lost and/or the part of load to be shed.

In a future perspective, the objectives to increase the power system security, reliability, operation quality and management economy become increasingly important. In this aspect the System Wide Area Regulating controls (WAR) and the System Wide Area Protection solutions (WAP) represent the most concrete and feasible ways to achieve the required objectives. WAR and WAP have to operate together, in a coordinated way, according to the different roles they play, reciprocally taking into account their co-existence and operating states, including limitations, failures, saturation, out-of-service, etc. They can help each other in recognizing the phenomena in progress and in taking decisions for their specific control actions.

Obviously, the operation of a protection system is influenced by the presence of a regulating system working over the same grid area. In fact, the control decisions of the protection system should be strongly related and coordinated with those of the regulating system, taking also into account its operating conditions. This coordination is, in general, not simple to define and strongly dependent on the characteristics, functionality and performances of the two WAP and WAR schemes. In principle they should be designed together in order to assure a correct separation of their roles, a correct synchronization of their interventions and above all, it is important to have an effective optimization of the achievable contribution of each of them as well as their reciprocal support. This dynamic coordination and functional synergy between the regulating and protection wide area schemes is, in general, a complex problem that differs from one case to another. Nevertheless a particular situation does exist where a strong simplification and a wide harmony between the two real-time schemes is easily achievable: that is the case of a wide area voltage stability protection combined with a transmission network voltage control. The latter is based on a hierarchical real-time control structure realizing the Secondary and Tertiary Voltage Regulations (SVR and TVR respectively).

6.7.1 Basic SVR and TVR concepts

The basic concepts of SVR and TVR [68]-[70] mainly related to WAP are:

- The generating units' reactive power is the main resource already available in the field, low-cost and simple to control for network voltage support;
- The control structure, based on the grid subdivision into control areas, automatically and, as much as possible, independently regulates each area pilot node voltage with dynamics of tens of seconds;
- The SVR reactive power level $q_j(t)$ of the j -area, represents the control instantaneous effort underway at the j -area and therefore the real-time reactive power load for the j -area control units.
- The pilot node voltage of a grid area is therefore regulated by SVR, while increasing the load, to the desired value unless all the area control units reach their over-excitation limits. Under TVR the approaching of this extreme operating condition determines the achievement of the area voltage instability limit [71]. Before reaching this limit, SVR also operates the turning on/off of reactor banks and shunt capacitor, the up/down of the OLTCs and FACTS set-points, up to the area OLTCs block.

According to this and because the voltage degradation does usually take some minutes from the initial instability to the irreversible collapse, it appears reasonable, simple and effective to compute directly inside SVR a real-time, online indicator of the j -area proximity to voltage instability, mainly based on the actual value of the area reactive power level $q_j(t)$ [71]-[73].

The TVR idea comes from the need to increase the system's operating security and efficiency through centralized coordination of the decentralized SVR structure. The pilot nodes voltage set points must be adequately coordinated and updated in real-time. This is done on the base of either the real grid conditions or the global control system structure and its real-time measurements. Useless and conflicting inter-area control efforts can be avoided.

If the j -area level $q_j(t)$ reaches the maximum value $+1$, all the j -area control units begin to operate at their over-excitation limits. Usually, under TVR, the SVR operates the units at their over-excitation limits only in extreme conditions. In fact, the operation of the limits is strongly linked with the

transformer tap-changers reverse action that anticipates the voltage collapse mechanism triggering. SVR achieves the objective by also controlling in advance all the other possible reactive power resources (capacitors banks, reactors, synchronous or static compensators, etc.) installed in the j-area, in such a way to reduce the $q_j(t)$ operating value and therefore the control effort of the area units. In parallel TVR prevents the updated voltage plan from being unacceptable for the incoming heavy operating conditions. When all these control actions concerning the j-area voltage are accomplished and area control units do not allow additional excitation over-loading, then the difference “ $1-q_j(t)$ ” does clearly represent the distance of the j-area from its voltage stability limit.

6.7.2 Basics on real-time voltage stability indices

With SVR and TVR, the already proposed [71] proximity indicator $VSI_j(t)$ to voltage instability is:

$$VSI_j(t) = q_j(t) + \rho \frac{\partial q_j(t)}{\partial t} \Delta t \quad (6.7.1)$$

Where: ρ is a suitable weight coefficient for introducing a derivative term with a useful lead effect; $-1 \leq \rho \leq +1$; Δt is the sampling time interval.

Without the TVR the voltage stability index $VSI_j(t)$ does not really represent the j-area distance from the voltage stability limit, but only the distance of the SVR from its operative limits. $VSI_j(t)$ is a real-time updated variable which refers to few seconds before the current j-area operating state, therefore it can be more effectively used for real-time automatic regulating and protective controls, in the operation of the TVR. More precisely when $VSI_j(t)$ exceeds a first threshold value corresponding to the j-area consistent voltage control effort and small voltage control margin, the proposed control logic will order the automatic switching of capacitors banks, reactors and the set-points update of SVCs of the j-area according with a proper priority. A checking, online, of the switching fatigue of those reactive power equipment will restrict automatically the number of time they are switched according to design prescriptions and network voltage criteria. The switching speed will also be related to the value of the $VSI_j(t)$ derivative term and its dynamics.

After working out all the j-area reactive power resources and while still maintaining a local network working condition with small reactive power control margins, the $VSI_j(t)$ could reach a second critical threshold. When this threshold is reached, the SVR automatically modifies the voltage set-points or the transformer ratio of the j-area OLTCs for obtaining a reduction of the load seen by the local transmission network.

After these “first barriers” of regulating controls, the $VSI_j(t)$ based logic could point out the overcoming of a considered very critical threshold, or the reaching and the permanence of all the j-area control units at the upper terminal voltage limit, or the inhibit of pilot-node voltage reduction under the lowest allowable value by TVR. In any of the above-mentioned extreme working conditions, the control logic will automatically block the j-area OLTCs. After this last control the SVR will have operated, in the j-area, all the possible automatic regulating controls at its disposal for supporting the j-area pilot node voltage. Besides, the SVR will have drawn the operator attention, monitoring the j-area voltage value and the stability index value and asking for possible manual extreme controls. At this advanced stage with the control system reaching its saturation condition, the j-area WAP should enter into operation coming to the aid of j-area WAR (which cannot contribute more). The criteria through which the WAP will operate from now on are described in the following section. When critical operating conditions will be left, $VSI_j(t)$ will decrease and the SVR will release the j-area OLTCs and reduce the operating reactive power resources.

6.7.3 Wide Area Voltage Instability Protection

From the above considerations, SVR will operate on its limits only when the transmission network voltages are low, once all the network reactive power resources are in operation for voltage support. In these conditions $VSI_j(t)$ becomes fully significant and reliable, because the j-area operating limits are

reached despite of the reduced pilot node voltages plan and saturated reactive power control efforts. Therefore the Wide Area Voltage Protection system (V-WAP) can be simply defined in case the SVR-TV_R (here also called V-WAR) is operating on the power system [73][74]:

- The V-WAP structure simply follows the SVR areas and the possible changes of their edges. This is the first, very important, exchange of information between V-WAR and V-WAP for their alignment in terms of areas edges.
- The j-area V-WAP, adequately informed on the SVR operating conditions will leave the task to regulate voltages and maintain stability in the j-area to the correspondent V-WAR, until the SVR correctly works (information coming from SVR auto-diagnostics).
- The V-WAP system will therefore be authorized to operate only when it will be able to take the place of the V-WAR control significantly, that is when the two following conditions are verified:
 - The j-area control system has reached its own saturation limits after operating all its available continuous controls on the generators and discontinuous controls on the other reactive power resources as well as on the OLTCs.
 - The area real-time voltage instability index confirms the high instability risk in the area.

At that time V-WAP will enter in to operation at the j-area and will command the following control actions: it confines the part of the power system which is the first cause of the voltage instability (whenever this part has been recognized); it sheds the local loads in the percentage and with the frequency required by the real-time needs. The sole objective is the removal of a serious voltage instability risk in the j-area under its control. This relevant intervention is simply decided on the base of the reduced margins of the j-area control system with respect to its saturation. Therefore, it is proposed that the area protective decision be guided by the local area control system. In this sense the proposed protective solution is not conventional and appears extremely simple because it is substantially based on the measurements and on the state of operation of the j-area V-WAR. The V-WAP protective controls have to command:

1. If locally available, the paralleling of hot running reserves for reactive power support, already alarmed at the time the V-WAR regulator were reaching its saturation. The time delay required by the reactive reserve to be thrown in the network should be coordinated with the $VSI_j(t)$ index threshold activating V-WAP. This first protective action, even if expensive, does not determine cuts on the feeding of the area users.
2. The progressive reduction of the local j-area loads, starting (if possible) from the prevailing inductive load, when they were known. Priority is also given to confining the first cause of voltage lowering whenever the j-area nodes having very low voltages and high reactive power absorption were recognizable: opening of the lines feeding those loads. After the starting of loads selection with given characteristics or connected to selected busses and always maintaining a continuous monitoring on the persistence of the under way phenomenon, V-WAP progressively sheds the other local area loads by following possible defined priorities. The speed of the shedding will also be dependant on the $VSI_j(t)$ index trend and will be reduced to zero only when this trend change slope and the local voltages assume normal values. The protective action will stop only when the SVR and TV_R have reached again their normal operating conditions, outside their saturation limits.

6.7.4 Simulation Results

To demonstrate the value and limits of the proposed wide area protection controls, simulation tests were performed on the Italian Transmission system, particularly on the North Region strongly involved in the 2003 blackout. Detailed models are adopted for the generators and their speed and AVR controls. These models also include the dynamic limits in over and under-excitation. Moreover the on-load tap changers of the grid transformers and their controls are simulated in detail as well as the load influence on the voltage. A detailed model of SVR is used; the TV_R functionality operates till when the pilot nodes voltages are maintained higher than 0,9 p.u. The load shedding based on $VSI_j(t)$ index is commanded according to the protective criteria defined above, by using adequate filtering for the computation of $VSI_j(t)$. The performed tests refer to the same percentage of load increase in all the system to significantly check the differences between the four selected cases:

Figure 6.7.1: PVR only - voltage transients of the main EHV busses at peak load, without V-WAP;

Figure 6.7.2: SVR-TVR, OLTC block via $VSI_j(t)$. Pilot nodes transients at peak load, no load shedding;

Figure 6.7.3: PVR only - EHV busses voltage transients at peak load, with V thresholds load shedding;

Figure 6.7.4: SVR-TVR, OLTC block and Load Shedding $VSI_j(t)$ based - pilot nodes voltage transients.

Without SVR and V-WAP, the voltages collapse at 620s (Figure 6.7.1). At the second load step the generators reach their over-excitation limits and the subsequent transients are characterized by the alternating interventions of the generators limits and the OLTCs. With SVR and OLTC blocking based on $VSI_j(t)$, the collapse is avoided (Figure 6.7.2), with voltages around 0.9 p.u. at 600s and without load shedding. Figure 6.7.3 shows the very simple classic protection based on the voltage thresholds criteria: the voltages go below 0.85pu, voltage collapse is avoided. The transients in Figure 6.7.4 show the overcoming of voltage decrease and instability problems, even when the load increase lasts up to 820s, with voltages controlled around 0,96 p.u. With distance protections, even in front of possible separations, the voltage profile is maintained very high showing a good stability result when operating the V-WAP $VSI_j(t)$ [73][74]. This performance is also confirmed at low load operating conditions or in case of load variation localized in a given part/area of the system. The ability of the proposed WAP is clearly evidenced by the fact that the stability improvement is remarkable in a situation similar to that related to the 2003 blackout in Italy [73].

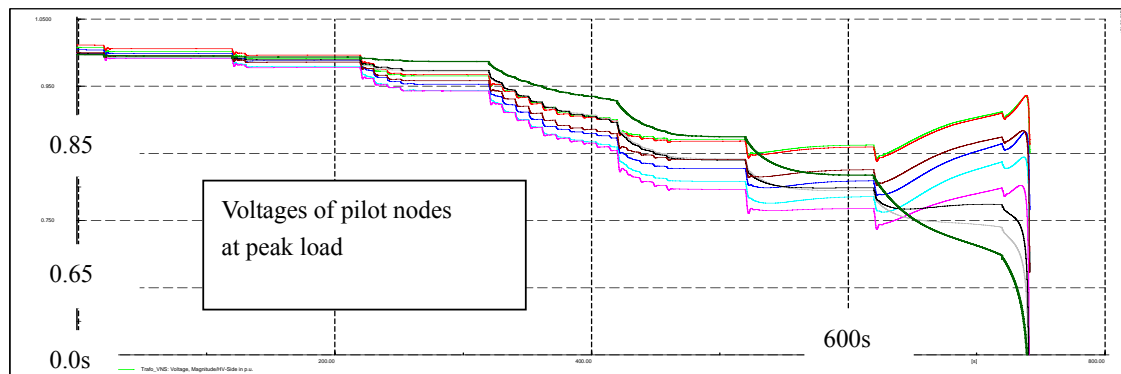


Figure 6.7.1. Load increase, primary voltage regulation only, voltage collapse

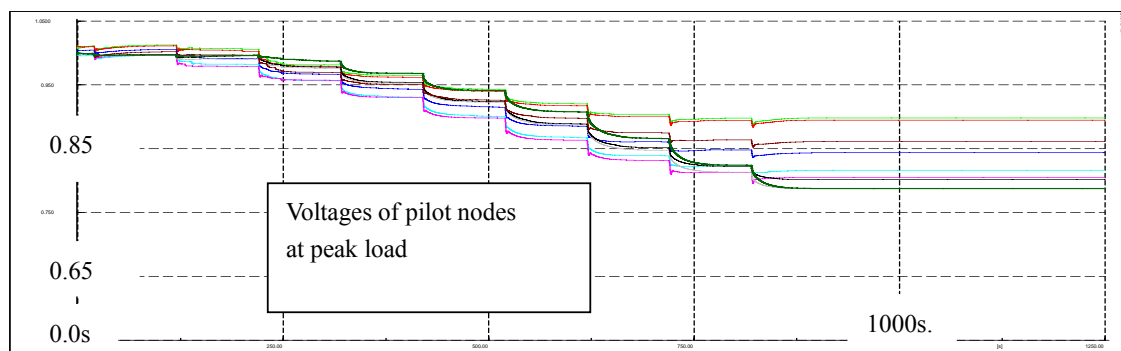


Figure 6.7.2. Load increase, SVR –TVR – OLTCs lock based on $VSI_j(t)$

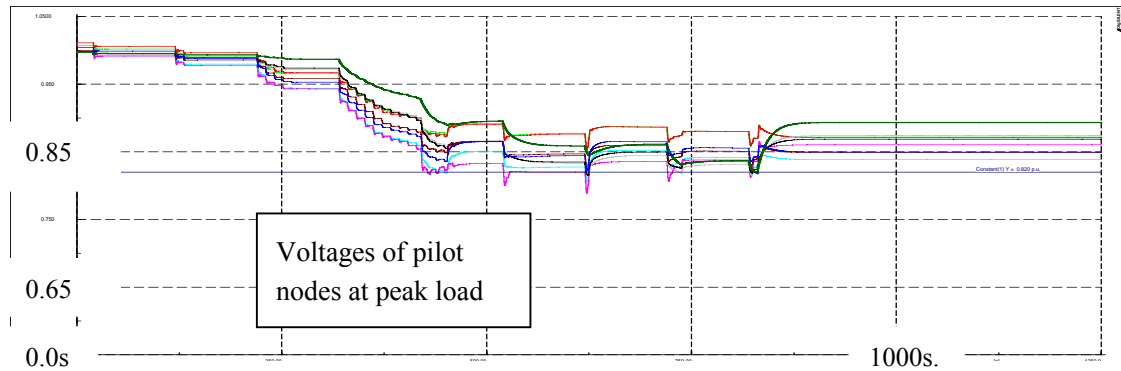


Figure 6.7.3. Load increase, PVR; Load Shedding based on voltage thresholds

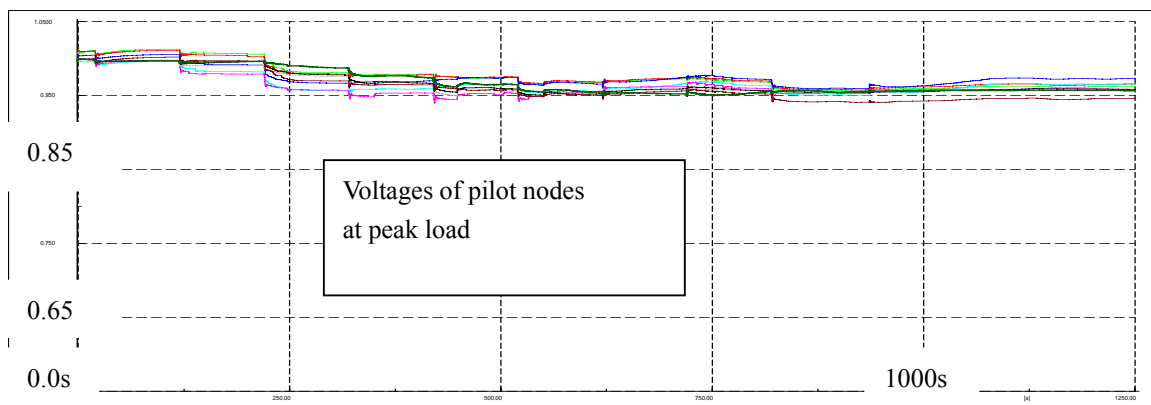


Figure 6.7.4. Load increase, SVR –TVR ; OLTCs lock and Load Shedding based on $VSI_i(t)$

6.7.5 Conclusions

A V-WAP protecting solution, very simple and very effective in eliminating the risk of voltage instability in a given network area under SVR and TVR control, is presented. The main simplifications come from the fact that the network area where WAP is required to operate is already dynamically defined by the operating SVR which, as known, is of decentralized type over an region of the power system. It is shown that, in the presence of TVR, the real-time index VSI proposed for the voltage stability not only helps SVR in the control action but, above high risk thresholds, it also becomes the reference for the V-WAP intervention. This is the second, very important simplification. The third simplification comes from the fact that, in the presence of TVR and SVR, the V-WAP is able to correctly and timely operate in a selective-precise way, by only considering measurements, voltage stability index, logic states, etc., coming from V-WAR and with very simple processing and computing of those data. Loosing SVR or in case of primary voltage regulation (PVR) alone, the proposed WAP protection based on the main busses (the pilot nodes if they are known) voltage thresholds can be easily used for a timely load shedding with acceptable stability improvement. With PVR alone, the solution based on the risky index fails in some cases. This index also requires heavy computing. The simulation results confirm the value of the proposed coordination between V-WAR and V-WAP. The operated controls minimize the load shedding amount due to the timely-reciprocal co-ordination and support between WAR & WAP. This is a compromise between the voltage values to be sustained, when greater than a minimum threshold, and the amount of loads to be shed to avoid the voltage collapse.

6.8 Further algorithms

Beside the control algorithms introduced above there are proposals for using PMU and WAMS for wide-area backup of conventional protection schemes, e.g. [93].

CHAPTER 7

CONCLUDING REMARKS AND OUTLOOK

From the overview of WAMS installations in chapter 2 it can be seen that there is an increasing interest in this technology all over the world. A few installations cover huge areas of power systems, but most are concentrated in a critical area or one transmission corridor only. A number of transmission system operators have just started to explore this technology and getting familiar with its use based on small installations.

Phase angle and oscillation monitoring are obvious and the most commonly used applications. Voltage stability and thermal limit applications are used in some limited number of cases. The offline analysis of data plays a significant role for improved dynamic system models based on comparisons of simulations with recorded events. The integration of PMU data into the State Estimation is widely expected.

Today, widely established and accepted wide area control applications are AGC and Secondary Voltage Control [99]. Even these conventional wide area control schemes are not applied everywhere. It is expected that PMU-based Wide Area Control Systems will be installed more and more during the next few years. However, at the moment there are only a few projects in place to establish this technology. A number of basic studies are going on to investigate this technology for practical installations. It is expected that this technology will be used for wide area damping purposes, e.g. wide area coordination of PSS or FACTS-devices. A coordinated reactive power control is considered as well. Another application could be the wide area power flow control, which means the coordinated control of Phase Shifting Transformers or FACTS-devices. The coordination of Phase Shifting Transformers is evaluated to be beneficial, but a control scheme based on WAMS with PMU is only considered in planning studies so far.

In addition to the Wide Area control applications there are high expectations on Wide Area Protection Schemes. Many utilities have Wide Area Protection Schemes in place (see [1]). These are based on different rule based technologies and implemented in the SCADA/EMS system or with hard-wired data channels. It is expected that WAMS can improve the reaction time and accuracy of actions. Dedicated PMU-based Wide Area Protection Systems are not in place yet.

From the wide area perspective, three application areas can be expected. First is the further spread out of slow secondary voltage control applications based on conventional technologies.

Second is the WAMS for oscillations, voltage stability or thermal limitations. The oscillation detection is expected to lead to an improved damping control scheme for PSS or FACTS-devices. The WAMS will detect the performance and update the control parameters accordingly. For damping purposes there will be no wide area closed loop control because of the performance of the communication channels in the near future. For voltage or thermals limitations a closed loop wide area control is considered possible. The detection of instabilities and control actions can be taken within several seconds. Therefore the actions are faster than by coordination via SCADA/EMS systems.

Third is Wide Area Protection, especially for transient stability. Since this application has to be very fast within less than a second typically, rule based sets of controls with dedicated hard wired communication channels are required. However, an online dynamic security analysis based on improved system data and models supported by PMU information is expected.

For the practical implementation of Wide Area Monitoring and Control Systems (WAMC) there are some aspects which have to be considered carefully. The whole system depends on the availability of global positioning satellite (GPS) signals. Until alternative satellite systems are installed, this could be a source of system disturbance. The design of WAMC has to consider the case of unavailability of the GPS signal, which means that in any case a local backup for control and protection actions is needed.

It has to be noticed that WAMC will only be accepted if their actions can be followed and understood easily by the operators. This means that all WAMC action must be based on simple rules or algorithms that are transparent to the operator.

Another aspect is the communication system. The communication system is expected to be redundant and dedicated for WAMC applications. It is expected that more and more high speed communication systems will be established making it easier to install wide area systems. But if dedicated communication channels have to be installed, the costs of WAMC will increase drastically.

From the product perspective of WAMS it is required that these systems are more standardized and easier to be implemented. From system protection schemes it is known, that the installation costs are several million US-dollar because of dedicated communication and extensive system studies. Therefore, a higher degree of productized solutions is expected from WAMS. This is supported by more and more industrial vendors. Furthermore, WAMS are expected to be integrated in the operator working places, which means that at least the graphical user interface for WAMS will be part of the SCADA/EMS screens. The closer integration of PMU-data into SCADA/EMS applications for example the State Estimation is expected in the near future and most SCADA/EMS vendors are working on this.

There are PMU products available from several vendors. Some of them are presently quite mature, but others are not. This mean one has to consider carefully the usage of PMUs. There are concerns that the accuracy of PMUs become degraded when the system frequency deviates drastically from the nominal frequency of 50Hz or 60Hz, which is usually the case during disturbances. A second concern is the accuracy of the used instrument transformers. Some PMU-functionalities use the protection coil of the instrument transformer and others use the measurement coil. The overall system accuracy has to be considered to be aware of the limitations of the WAMS accuracy and the accuracy of its applications. Since there is in the first installations no data redundancy in WAMS, like in conventional State Estimation, the accuracy of the installed components directly influences the overall accuracy. For more elaborated WAMC application a PMU redundancy has to be considered. In the future it is expected that time-synchronization will be implemented for other substation equipment. This means that almost all signals from a substation could be obtained synchronously, which opens up the opportunity for new applications and new developments.

One critical issue for WAMC is the fact that these technologies might lead to the system being operated closer to stability limits with a highly increased vulnerability and reduced security. The information benefits of WAMS and WAMC can either be used for higher power system security or for higher network utilization. The latter includes the risk that operating closer to network stability limits might lower the system security drastically. The balance between these two benefits has to be considered carefully when specifying and designing a WAMC system. A recommendation of how much security margins could potentially be reduced by WAMC without reducing the security is an open topic for research.

In conclusion, the expectations for Wide Area Monitoring and Control Systems are high and a growing community of researchers and utility experts are working on practical applications and installations of this technology around the globe. However, it will be still a long way from the first WAMS applications for different kinds of instabilities to system wide control schemes based on WAMC or even protection schemes. But the promises of this technology are shared by numerous experts. An increasing number of transmission system operators are running application studies to evaluate the benefits of this technology or even execute implementation projects.

CHAPTER 8

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