WIDE-AREA MONITORING AND CONTROL UTILIZING PMU MEASUREMENTS FOR A SYSTEM PROTECTION SCHEME

by

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B.A.Sc., Simon Fraser University, 2007

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Electrical & Computer Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

April 2015

Abstract

The ever increasing complexity of the electrical grid has made it difficult to predict and anticipate contingencies. This is mainly due to the advent of deregulated electricity markets, aging transmission infrastructure and the growing penetration of renewable resources. The wave of blackouts in recent years has made utilities much more aware of the need for power system wide monitoring and control. One of the fundamental requirements to achieve that goal is to have common measurement reference. A few technology enablers have emerged which have led to development of a new kind of measurement paradigm; Phasor Measurement Units, or PMUs.

PMUs bear high potential for wide-area system monitoring and control as well for conducting advanced engineering analysis. PMUs can provide time-synchronized high-resolution estimates of voltage and currents (both phase amplitude and angle) as well as frequency and rate of change of frequency. Such measurements, alternatively called synchrophasors, can provide visibility of a power system distributed over a wide geographical area and can be utilized in a multitude of applications including real-time monitoring, advanced power system protection, and advanced control schemes.

In this thesis, a new special protection scheme (SPS) is proposed based on synchronized measurements provided by PMUs. An existing remedial action scheme (RAS) protecting for contingencies impacting the tie-line interconnecting the Alcan system to B.C. Hydro, using conventional relays is studied, and a new scheme based on time-synchronized, and high-resolution voltage angle measurements from PMU's in a Wide-are monitoring system (WAMs) is proposed . In this new scheme, the angles of the buses at large power plants in both systems are examined and used to calculate various criteria based on region center of angle and the kinetic energy function to implement RAS.

The results of a number of time domain simulations demonstrate that the proposed scheme can lead to faster operation of the SPS and decreased amount of generation and load shedding in the Alcan system. The achieved speed and efficiency of the proposed scheme in comparison to the existing installed scheme further highlight the opportunity in utilizing PMU measurements in online applications for power system protection and monitoring.

Preface

Portions of the introductory text and methodology are used with permission from Rahmatian et al. (2015) of which I am an author. The data and all performed experiments used in this dissertation is an original intellectual product of the author, A. Palizban.

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List of Abbreviations

Abbreviation	Elaboration
PMU	Phasor Measurement Unit
WAMS	Wide Area Monitoring Systems
WAMC	Wide Area Monitoring & Control
BCH	British Columbia Hydro & Power Authority
BPA	Bonneville Power Administration
DSA	Dynamic Security Analysis
EMS	Energy Management System
FACTS	Flexible Alternating Current Transmission System
ISO	Independent System Operator
RTO	Regional Transmission Operator
RAS	Remedial Action Scheme
SPS	Special Protection Scheme
SCADA	Supervisory Control and Data Acquisition
PDC	Phasor Data Concentrator
RTU	Remote Terminal Unit
PT	Potential Transformer
CT	Current Transformer
COI	Centre of Inertia Angle
CASI	Centre of Inertia Angle Stability Index
KESI	Kinetic Energy Stability Index
KMO	Kemano
KMOCD	Kemano Centre of Angle Deviation
VKE	Kinetic Energy
WECC	Western Electricity Coordinating Council

Acknowledgements

I would like to thank Professor José R. Martí for his guidance and support throughout my studies at UBC and my committee members, Professor William Dunford and Professor Juri Jatskevich for their valuable time.

I owe particular thanks to Dr. Ali Moshref for his mentorship and making time out of his busy schedule to answer my technical questions. I would also like to thank fellow student, Matin Rahmatian for helping me navigate through the potholes of various software tools.

I extend my gratitude to Gordon Dobson-Mack, my manager and mentor at Powerex Corp., for offering me support throughout my studies and providing me with the essential software tools that I needed to conduct my research work.

I should take this opportunity to thank my parents for their loving support and encouragement in my many years of education and for teaching me that with hard work and dedication dreams can come true.

Finally, I would like to thank my life partner, Amir R. Tamadon for his patience in keeping me up to the mark in my research and his endless moral support.

“Sell your cleverness and buy bewilderment.”

Rumi

1 Introduction

Stability problems may not happen frequently but, when they do, their impact can be enormous. In fact, for many utilities, it can be safely stated that dynamic stability becomes the most significant risk facing the network operator during cascading events and extreme contingencies. At present, power system defense plans against these rare contingencies are based on event detection using breaker status and fault signals from relays. This is mainly because the more appealing response based approach is not yet fast enough to allow for effective remedial actions. However with the recent advances in wide-are monitoring and measurement, fast response-based stability assessment of extreme contingencies seem to have better prospects.

This new approach, which ranks the contingency stability using dynamic information measure online, is potentially more robust than event-detection schemes alone, which rely heavily on offline simulations of system conditions intentionally set to be more conservative than those prevailing at the present time. The lack of transmission system expansion means that in any case the current stability defense mechanisms will reach their limit at a time when it may appropriate to supplement them with more refined and context-sensitive wide-are response-based remedial actions or special protection schemes (RAS/SPS). The goal of this research thesis is to explore how observations taken by phasor measurement units (PMU's) on wide-area voltage magnitudes and angles can be used in dynamic performance monitoring of the grid during disturbances during real-time operations. The application of PMU measurements in improving and/or augmenting some existing Remedial Action Schemes in BC Hydro's system will be studied.

The need for wide-area situational awareness and visualization received significant attention following the 2003 North American blackout. Supported by technological advancement as well as funding mechanisms, most of the North American bulk power utilities (including generator and transmission owners), system operators/owners (ISOs/RTOs) and reliability coordinators have embraced strong programs to develop PMU infrastructures. Currently more than 1000s PMUs and PDCs (phasor data concentrators) have been installed in North America dwarfing the total number of installed devices in 2010 (approximately 150). Globally, similar initiatives are being carried out, particularly in Europe, Asia and South America (1).

Phasor data and applications are valuable for grid reliability because they give grid operators and planners unprecedented insight into what is happening on the grid at high resolution, over a wide area in time synchronized mode, and where needed, in real-time. Current SCADA systems observe grid conditions every 4 to 6 seconds, which is too slow to track dynamic events on the grid. They also do not monitor key indicators such as phase angles. SCADA data are not consistently time-synchronized and time-aligned and those data are not shared widely across the grid. Thus SCADA does not give grid operators real-time, wide area visibility into what is happening across a region or interconnection.

In contrast, synchrophasor systems allow the collection and sharing of high-speed, real-time, time-synchronized grid condition data across an entire system or interconnection. This data can be used to create wide-area visibility across the bulk power system in ways that let grid operators understand real-time conditions, see early evidence of emerging grid problems, and better diagnose, implement and evaluate remedial actions to protect system reliability. Phasor systems are being used for wide-area measurement systems (WAMS) in the Eastern and Western Interconnections of North America and in China, Quebec, Brazil, and Europe.

The lack of wide-area visibility prevented early identification of the August 14, 2003 Northeast blackout. The U.S.-Canada investigation report into the blackout hypothesized that if a phasor system had been in operation at that time, the blackout preconditions — in particular, the growing voltage problems in Ohio — could have been identified and understood earlier in the day. In the last few minutes before the cascade, there was a significant divergence in phase angle between Cleveland and Michigan.

Having wide-area situational awareness could have prevented the Western Interconnection outages in the summer of 1996. Bonneville Power Administration (BPA) had several stand-alone PMUs in the field during the August 10, 1996 outage. Post-disturbance analysis indicated that the relative phase angles across Pacific Northwest were outside safe operating limits and that reactive reserves at power plants were low. BPA's recognition of the great value provided by the wide-area measurements led them in 1997 to develop the first Phasor Data Concentrator to network PMUs and stream data to control centers in real-time, implement a phase angle alarm using PMU data, and develop operating procedures on what to do when the angles change too quickly (2).

1.1 Current Technology Status

Phasor measurement units (PMUs) can provide time-synchronized high-resolution estimates of voltage and currents (both phase amplitude and angle) as well as frequency and rate of change of frequency (3).

In spite of such rapid progress in PMU technology, the use of synchrophasors has been mostly limited to offline analysis and real-time system monitoring, largely excluding online system control. Infrastructure bottlenecks, data quality issues, data analytics limitations, production grade software tool unavailability and slow technology acceptance are few of the challenges in this context.

At BC Hydro (BCH), synchrophasor technologies have been deployed and maintained for over a decade. However, the primary use has been in state estimation at the control center, leaving ample opportunities for more proliferated use throughout the organization.

The concept of phasors and their application in power system was developed in the late 19th century. However, only recently, the practical solutions for time-synchronized phasors started to materialize. Combined with the availability of global positioning systems (GPS), acceptance of various IEEE standards to codify the time-synchronization process, and a strong need for wide-area system visibility (following the 2003 North American blackout), the power industry started to embrace this technology throughout the world.

1.1.1 PMU Components

The purpose of a synchronized phasor measurement system is to provide accurate, reliable and high-speed (1-2 samples per cycle) phasor data to power system control centers for monitoring and analyzing the grid conditions in real-time or near real-time. The phasor measurements include precise time stamps, which are synchronized to a common global positioning system (GPS) radio clock.

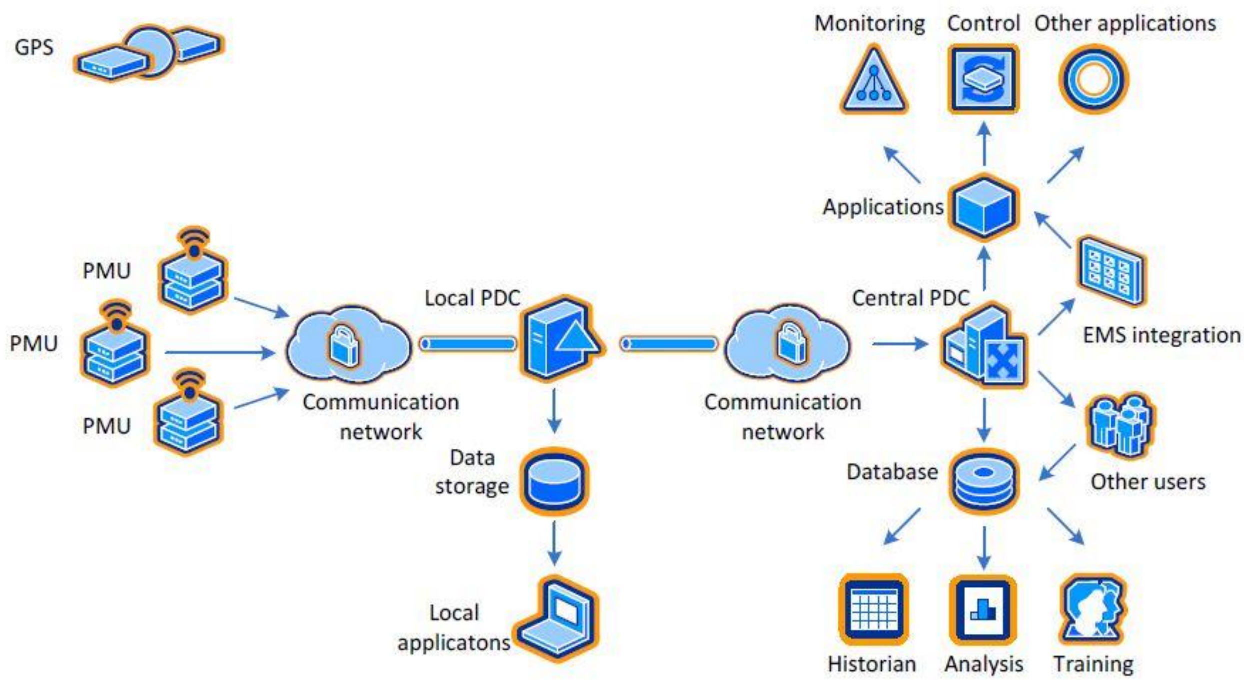

Figure 1-1: Generic Synchrophasor Architecture

Phasor Measurement Unit (PMU): According to IEEE, a phase measurement unit (PMU) is defined as "a device that produces synchronized phasor, frequency, and rate of change of frequency (ROCOF) estimates from voltage and/or current signals and a time synchronizing signal." Unlike other measurement devices such as digital fault recorders (DFR) or conventional relays, PMUs provide precision time-tagged positive sequence pahsors measured at widely separated geographical locations of the gird. In essence, a PMU is a transducer that coverts (i.e., estimates) three-phase analog signals of voltage or current into time-synchronized phasors, alternatively called 'synchrophasors'. In addition to estimating sequence voltages and currents (including magnitudes and angles), local frequency, local rate of change of frequency (ROCOF), circuit breaker and switch status and other quantities (time, location, special analog or digital signals). Most PMUs can capture 8 to 45 signals simultaneously. Many conventional relays are currently being enhanced with PMU functionalities. Also, there are efforts in coupling GPS signals with DFRs to enable PMU-type measurements. In short: three variations of PMUs are currently available off-the-shelf: (a) standalone PMUs (b) fault recorders with PMU capabilities, and (c) protection devices with PMU functionality. PMU devices are placed in a substation, in a manner similar to conventional relays (through CTs and CVT/PTs, (Figure 1-2, Figure 1-3) (1) (3). An outline of a broader PMU network is provided in Figure 1-4.

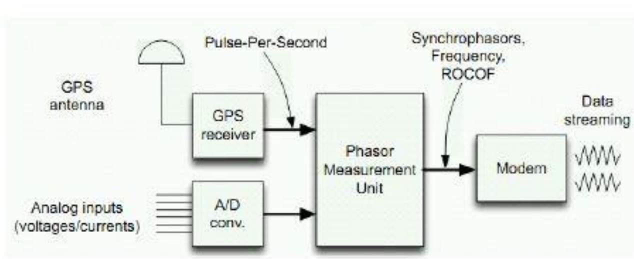

Figure 1-2: PMU Device Functional Blocks (4)

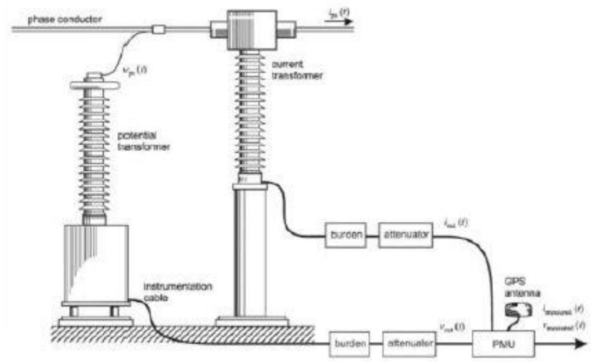

Figure 1-3: PMU Device Placement (5)

Phasor Data Concentrator (PDC): A phasor data concentrator (PDC) receives measurements from multiple PMUs, conducts data quality checks (latency, errors and time-alignment) and combines the measurements from multiple PMUs into a single packet with a single time tag. This data is streamed via wideband, high-speed Ethernet or serial links to end-applications or other PDCs (often called SuperPDC or SPDC). The end-applications can include: visualization tools, state estimators, and alarm processors. Some PDCs may also provide local/substation-level data access and monitoring/control functionalities (1).

Synchrophasor Network: The most fundamental components of a synchrophasor network are phasor measurement units (PMUs) and phasor data concentrators (PDCs). PDCs are devices with additional intelligence to receive streamed data from multiple PMUs (as well as other PDCs), conduct time-alignment, perform data-quality checks, monitor the health of the end-devices, and feed to a database platform. Depending on the needs/availability, PDCs can provide access to the streamed data at local substations. PMUs, PDCs and the end-applications (data historians, achiever, and end-applications) rely on communication networks and technologies for streaming the data reliably and securely (1) (3).

Super Phasor Data Concentrator (PDC): A super phasor data concentrator (SPDC) collects information from various phasor data concentrators to afford greater use of the total amount of phasor data collected over a wide-area (1).

Communication Network: A media to transport the data from one location to another location. Unlike conventional supervisory control and data acquisition (SCADA) system, PMU networks generally impose more stringent requirements on the communication systems. This network also needs to be flexible, high-speed, and secure. The ultimate goal of the synchronized phasor measurement system is to achieve real-time monitoring and control of the grid. Therefore, the bi-directional communication is also an essential attribute for the synchrophasor communication network.

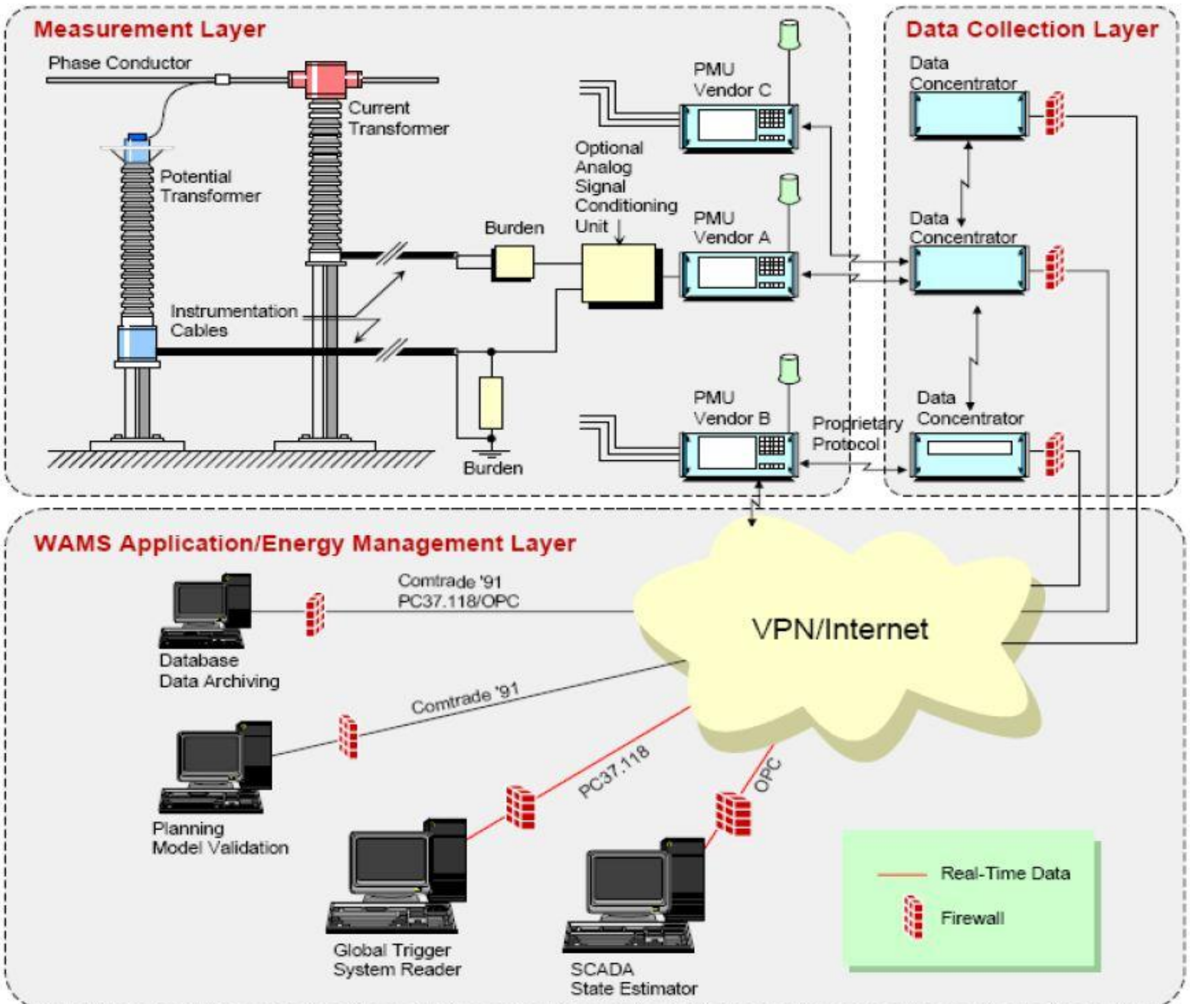

Figure 1-4: PMU Network Overview (6)

Data Archiver and Storage: A system to store the phasor data and make it conveniently available for offline applications, such as post-event analysis. Conventional tools are generally capable of providing historian, display and data-accessibility features. However, in presence of very large amount of PMU data, concepts of intelligent data mining, sorting and pattern matching algorithms are being proposed.

System Architecture: Depending on the power system topology, ownership of assets, and operational and reliability jurisdictions, the architecture of the synchrophasor network may vary. Typically, distributed PMU devices are interfaced with a PDC through serial or IP communication. Data from the PDC is either streamed to other PDCs, or directly to a control center. Various online applications (such as, visualization, alarming, event detection, and control), data processing, offline engineering analysis and SCADA/EMS integration are facilitated at this PDC level. In absence of any standardized system architecture, a conceptual architecture named NASPInet has been proposed by North American SynchroPhasor Initiative (NASPI) (1). Besides the NASPInet, many utilities deploy in-house/customized systems in order to meet their specific needs.

1.2 PMU Applications is Power Systems

Based on a comprehensive literature survey, a broad range of PMU-based applications in Power Systems has been identified. These can be generally categorized under offline or online applications:

Offline PMU-based applications:

- Post-Event Analysis
- System Baselining and Parameterization
- Dynamic Model Validation;
- System Protection & Control Planning

Online PMU-base applications include:

- Enhance State-estimation
- Situational Awareness & Visualization
- Oscillation Monitoring & Control
- Voltage Security Assessment & Control
- Transient Security Assessment & Control
- Frequency Stability Monitoring & Control
- System Protection & Real-time Control
- Transfer Capability Assessment
- Fault Location & Detection
- Intelligent Islanding & Resynchronization
- Renewables and other applications

1.2.1 Post-Event Analysis

Offline and post-disturbance analyses are very useful in understanding grid dynamics. Post-disturbance event analysis includes investigating an event by means of reconstructing its sequence, identifying associated device responses, and evaluating system performance. Using data recorded by PMU's for this type of analysis is particularly helpful during complex events where multiple factors may have contributed to a single event in a short interval.

PMU's will allow for both local and distribute wide-area measurements thereby allowing targeted investigations as well as system-wide event analysis. Some of these power systems applications are: fault analysis, post-mortem analysis, compliance monitoring, geomagnetically induced current monitoring, modal analysis, frequency response analysis, and contingency analysis.

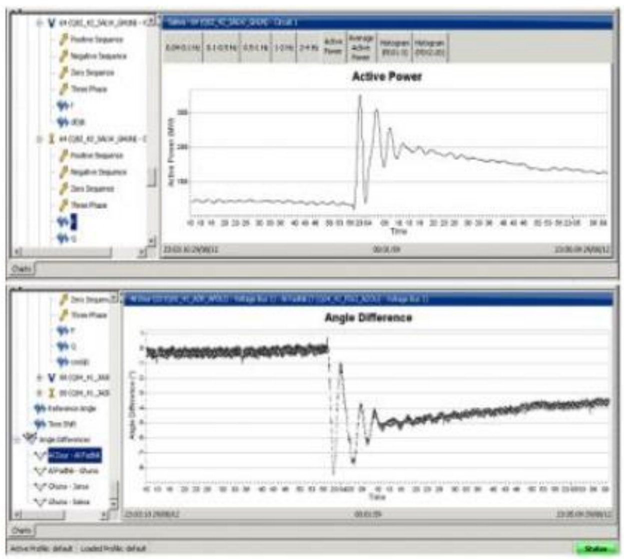

Figure 1-5: Post-Disturbance Event Analysis

PMU measurement can also assist in developing operating guidelines, systems reinforcement needs and other remedial action measures to correct problems that had led to a stability event. PMU data can assist in Operator training by providing system operators with advanced experience on how to manage the system during a physical disturbance.

1.2.2 System Baselining & Parameterization

System baselining implies analyzing bulk PMU data and identifying nominal and off-nominal (excluding large disturbances) operating conditions of a given system. Applications include line parameter identification, cable thermal ratings, trending path loading and protection setting verification. These observations can be used in various planning studies as well as in setting operational guidelines.

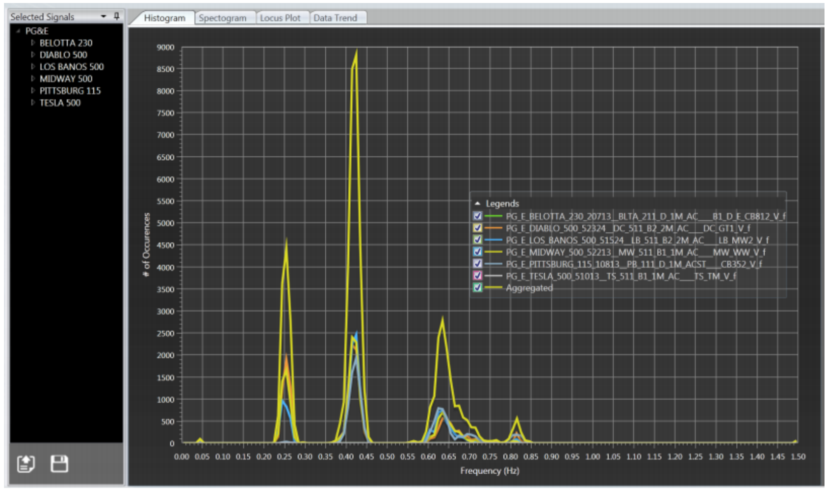

Figure 1-6: Histogram of Observed Modes of Oscillation during Dynamic Performance (7)

1.2.3 Dynamic Model Validation

Dynamic modeling and validation of power systems components are essential for optimal operation, and safety and security of the grid. Also, important decisions on new capital investments are dependent on the accurate modeling of the different components in the system. Obtaining accurate model parameters in that the model truly represents system behavior is a challenging task. This is due to the unpredictable nature of system disturbances and modeling short-comings to reflect real-time dynamic response of the system during events. In addition, the rapid increase in renewable resource penetration in the system further highlights the need for more accurate models and improved validation methods.

Failure of a model to predict or replicate the system's response to a disturbance is an indication of model weakness and inaccuracy. An example of this was observed for the WECC system separation event of August 1996. Figure 1-7 shows the discrepancies between the simulated California-Oregon Intertie power transfer and the active power flow recorded at Malin substation at the time of the event. The off-line simulated studies were not able to capture the growing oscillation phenomena while in reality the system presented an unstable response.

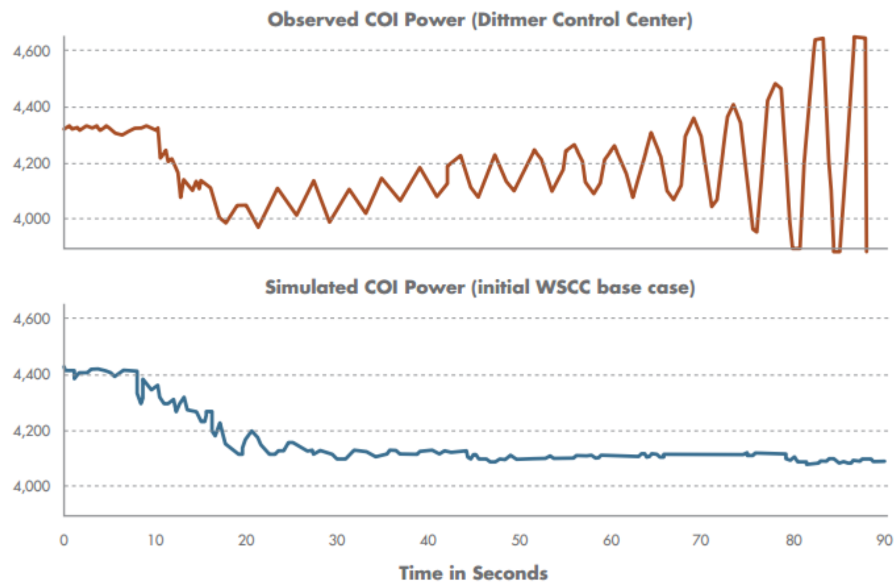

Figure 1-7: Dynamic Model Mismatches - WECC 1996 Blackout (8)

Disturbances (either controlled or coincidental) captured through synchrophasors can be utilized in calibrating the dynamic models of various power system equipment. This includes generators and associated controls (exciter, governor, and stabilizers), FACT devices (HVDC, SVC, STATCOM) and loads. PMU measurements can complement current practices of model development using manufacturer data and testing such as Power System Stabilizer (PSS) tuning. Composite load models can be developed using PMU data, as well as parameterizing and validating these models for broader acceptance and usage. This includes exploration of phenomenon such as fault-induced delayed voltage recovery (FIDVR). PMU data can also be utilized for the development and validation of renewable energy and storage device models. Unlike conventional measurement, PMU data can be consolidated over a wide area allowing further model turning and calibration that reflect system-wide characteristics.

1.2.4 System Protection & Control Planning

Development of SPS (Special Protection Schemes), SIPS (System Integrity Protection Schemes) or RAS (Remedial Action Schemes) require detailed planning with considerations for special system conditions and associated risks. System islanding, generator shedding, load shedding, planned outages and many other techniques may constitute such plans.

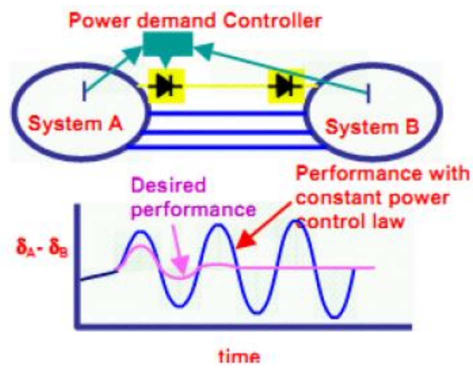

Figure 1-8: Concept of HVDC Control for Oscillation Damping (9)

Conventional protection and control systems primarily consider local measurements or dedicated signals from remote locations. In contrast, phasor measurements can provide system-wide remote signals, facilitating the development of more advanced schemes. Other applications in which PMU measurements can be utilized include: developing islanding detection and resynchronization algorithm, blackstart and restoration plans, adaptive relaying scheme design, Out-of-step protection design, and power oscillation damping.

1.2.5 Enhanced State-Estimation

The speed, accuracy and resolution of the PMU data can significantly enhance the accuracy and convergence characteristics of the existing state estimators. Currently, hybrid state estimator (which uses combined data from both conventional measurement units and the PMUs) are being tested and deployed at many control centers. PMU-only state estimators are also being researched. PMU data are of higher resolution compared to SCADA based measurements, which provide greater detail of the system states. Also, unlike conventional measurements, PMU based phase angle information can be used in advanced state estimation engines. With prudent placement of PMUs, a wider system-wide visibility or observability can be achieved, which can also be used in ensuring sufficient redundancy in measurement network and estimating the system states more accurately.

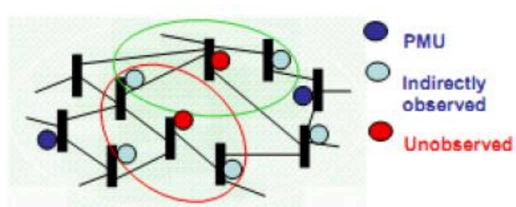

Figure 1-9: PMU Placement and Observability (9)

1.2.6 Situational Awareness & Visualization

The concept of wide-area situational awareness refers to a set of PMU-based solutions to improve the monitoring of a power system across a wide geographic area. This provides system operators with a broad and dynamic picture of the overall condition of the system. Thus a better understanding and optimized management of power system components, behavior and performance can be obtained. With these solutions in place, it is expected that the system operators can anticipate, prevent and respond to problems before disruptions arise.

The most direct way to improve the situational awareness is to display the phasor information to the operators including bus voltage magnitude, voltage angle, transmission line flow and frequency. Some applications include: operator decision support, cascading outages prevention, system inertia monitoring, angular separation and power swing monitoring, voltage stability and reactive reserve monitoring, and small signal stability monitoring.

Effective visualization has to go hand-in-hand with effective analysis for wide-area situational awareness. Figure 1-10 shows two images from a grid visualization and analysis tool that uses PMU data to show operators what is happening on the grid in real-time using various metrics and indicators.

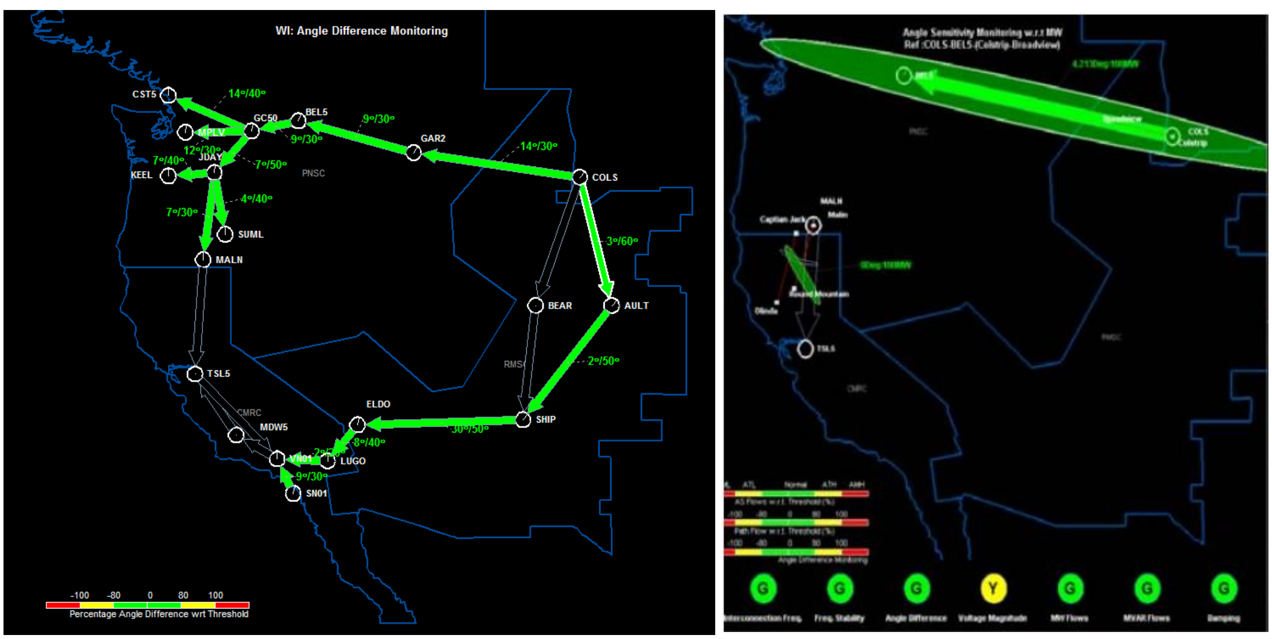

Figure 1-10: (a) Phase Angle Differences across WECC (b) Phase Angle Sensitivities across Key WECC Transmission Paths (2)

1.2.7 Oscillation Monitoring & Control

Oscillation monitoring and control schemes may contain functionalities for detecting inter-area oscillation, identifying the mode shapes through intelligent processing, and taking appropriate actions, either in the forms of alerts or alarms, or by means of direct close loop control. Such control actions may include: real power flow control, brake insertion, or FACTS/HVDC setpoint adjustments. With system-wide measurements and intelligent control of responsive devices, local and inter-area oscillations can be damped more effectively than conventional approaches.

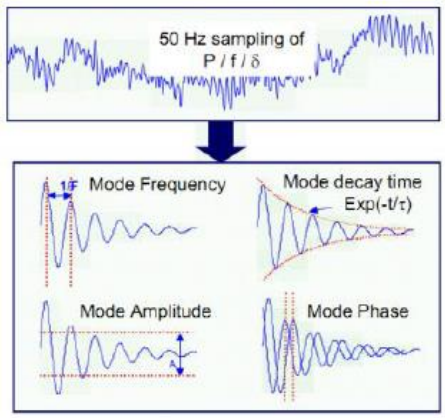

Figure 1-11: Small-Signal Oscillation

1.2.8 Voltage Security Assessment & Control

The WECC power system has dynamic stability problems, both local and inter-area oscillatory modes have been identified across the grid, which can result in catastrophic events such as the 1996 blackout. This prompts the need to monitor oscillation and voltage changes in the system. Current tools used to monitor voltages are SCADA information, which do not provide granular enough resolution to monitor dynamic bus voltage changes in the system.

Monitoring system conditions such as voltage profile, voltage sensitivities and reactive power reserves using PMU measurements allows the system operators to recognize the voltage levels in key locations in real-time. A trending application could provide an early indication of voltage instability, or vulnerability to voltage collapse. Subsequent automated or human-intervened control actions can be taken using

PMU-assisted software tools such as, online voltage security assessment (VSA) tool. These control actions may include switching in/out reactive devices or adjusting their setpoints.

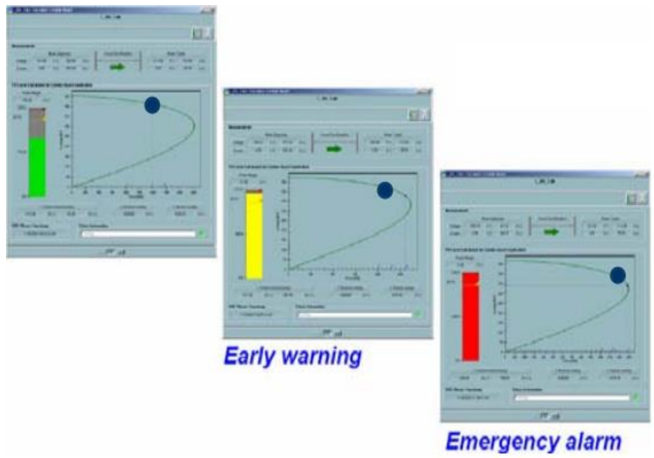

Figure 1-12: Monitoring and Control of Voltage Stability (10)

Unlike conventional control schemes, PMU-based system-wide schemes provide more effective and wide-area control over reactive resources. PMU measurements can potentially allow for identification and management of reactive reserves available through wind power plants.

1.2.9 Transient Security Assessment & Control

With the opportunity to directly measure the phase-angles at key locations, visualization tools can allow direct observation of events associated with angle-separations. This can alarm the operators of a stressed system condition. In addition, PMU-assisted software tools such as online transient security assessment (TSA) tools may provide important means for maintaining system stability. As was mentioned before, wide-area visibility and monitoring can provide more effective measures for transient stability control using PMU data.

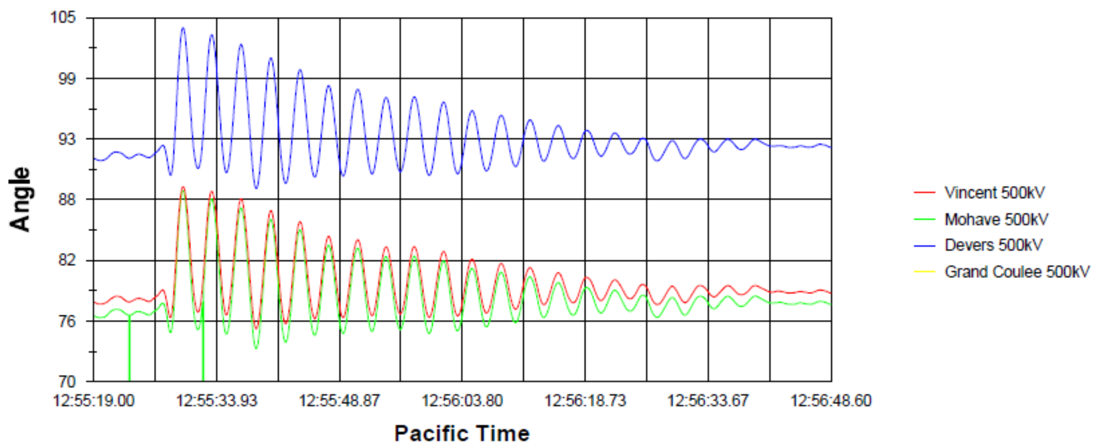

Figure 1-13: WECC System Oscillation under Stressed Conditions – August 4, 2000 (Angle Reference Grand Coulee 500kV) (10)

1.2.10 Frequency Stability Monitoring & Control

By providing a real-time system-wide frequency monitoring and trending, the operator can gain better situational awareness on the seriousness of an event. Frequency excursions also indicate the control practices, including the governor response, the capability of the AGC to replace the loss of generation and improve reserves. The trending curve can provide the system operator with a good knowledge on system frequency stability of current operating condition.

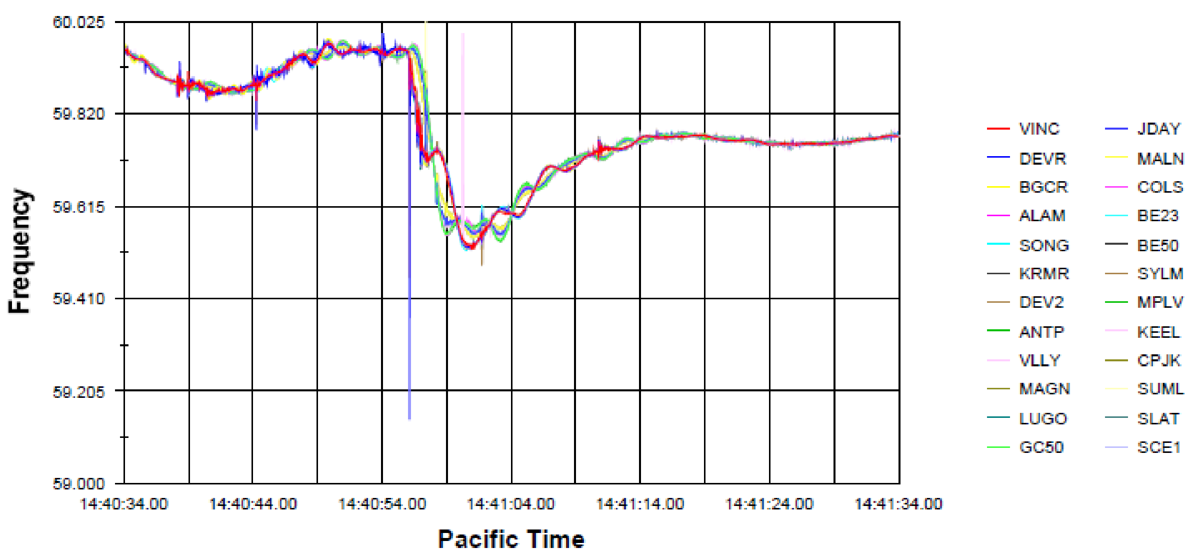

Figure 1-14: Frequency Plots from different PMUs showing Loss of Palo Verde Units 1,2 & 3 on June 14th 2004 (10)

PMUs are capable of measuring frequency and rate of change of frequency (ROCOF) directly. This provides a direct indication of the balance between generation and load in a power system. Also, for networks with large penetration of variable renewables, PMU based frequency stability analysis tool can potentially provide direct indication of the balance between load and generation, as well necessary actions for maintaining this balance.

1.2.11 System Protection and Real-time Control

In addition to the event-driven discrete-time control schemes such as, SPS or RAS, continuous feedback control systems using PMU measurements are being researched globally. This may include control of generators, HVDC/FACTS and other devices as shown below.

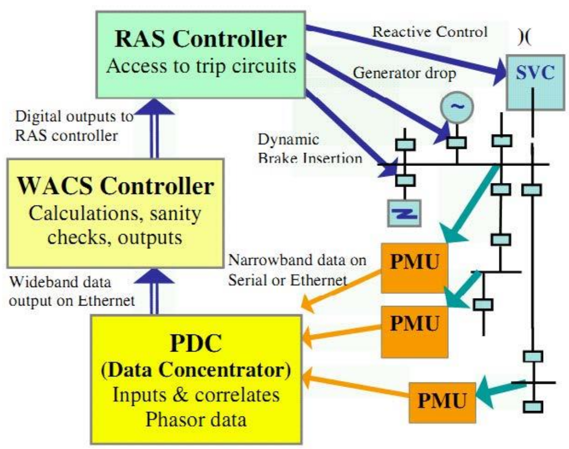

Figure 1-15: Closed Loop Control using PMUs (11)

This application will allow for advanced automation and incorporation of intelligent algorithms and improved system reliability, such as dynamic setting adjustments under stressed system conditions.

1.2.12 Transfer Capability Assessment

The current practice to real-time congestion management is to compare actual flow on a transmission path against a Nominal Transfer Capability (NTC) which is calculated in advance using an offline methodology. The NTC is determined based on the minimum of thermal limits, voltage stability or transient stability limits. Fixed seasonal summer or winter thermal ratings are typically chosen based on fixed assumptions regarding ambient temperature, wind speed and solar heating input to arrive at a conservative value for transmission line conductor ampacity based on a maximum allowable conductor temperature. The congestion management tool can use the accurate state-estimator solution of the real-time flow on a line or path to either reduce the level of unnecessary dispatch adjustments and lower system operation costs or to perform a timely dispatch adjustment for maintaining reliability. In that sense, by providing the real-time flow, PMU technology can improve the performance of the congestion management tools.

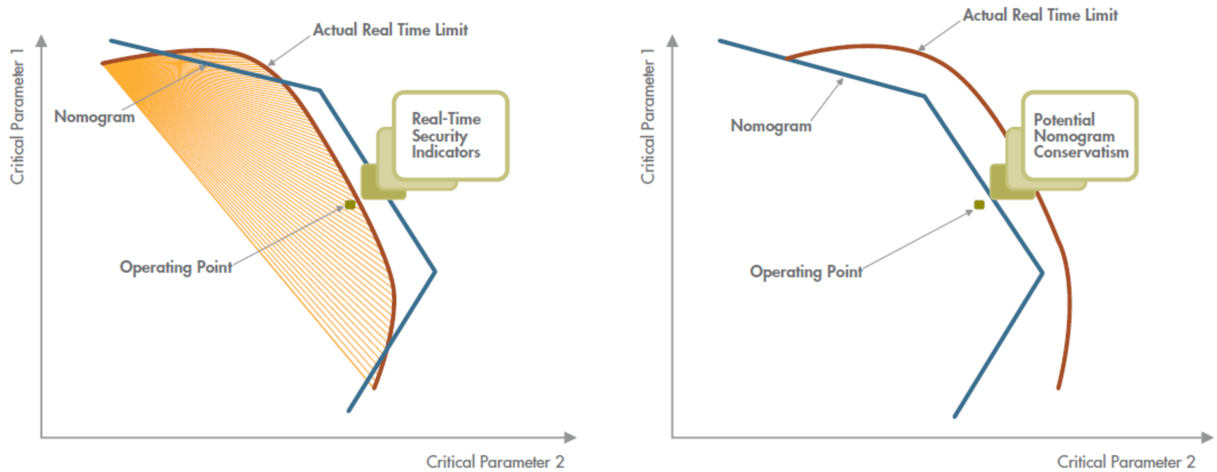

Figure 1-16: Transfer Capability Assessment using Nomograms (8)

Transmission limits, such as Path or System operating Limits (SOLs) are usually forecasted to be more conservative due to unknowns about real-time operating conditions and other uncertainties, and therefore the NTCs calculated offline may prove to be un-optimized. By utilizing real-time flow information, PMU technologies can potentially allow for better congestion management; Providing relief to inherent conservative SOL estimates will allow for more efficient power transfers across different transmission operators, yielding more efficient market operation.

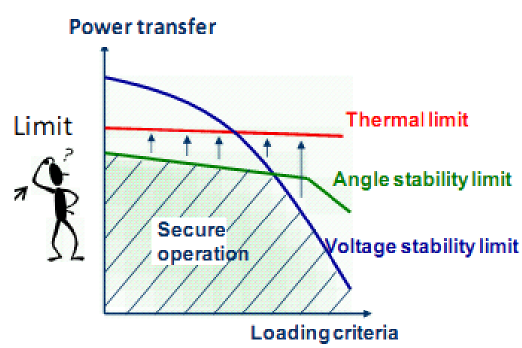

Figure 1-17: Determining Transfer Limits (8)

1.2.13 Fault Location Detection

Accurate fault location for transmission lines is of vital importance in restoring power systems, reducing outage time, improving power system reliability and cutting the maintenance costs. Over the years, two main methodologies have been developed and widely used by utilities: (a) single-end based fault location algorithms, and (b) multiple-end based fault location algorithms. PMU data can be potentially exchanged over the communications link between the two (or more) ends of the transmission line. Following a fault, fault detected by a substation equipment can be compared against these measured/received voltages and currents extracted from a memory buffer. Due to time-synchronization and availability of high-resolution data, fault detection and distance identification schemes using PMUs are expected to be more accurate compared to conventional methods. The online PMU-based fault location applications are still in the early stage for the North America utilities due to the limited coverage available through PMUs.

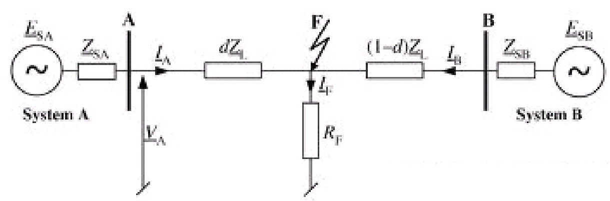

Figure 1-18: Fault Location and Distance Identification

1.2.14 Intelligent Islanding & Resynchronization

Controlled system separation (or islanding) is considered as a last resort to prevent a wide-spread blackout under severe disturbances. To avoid power outages in an uncontrolled fashion, the control center may separate the transmission system in a controlled manner to ensure that, in every island formed, sufficient loads can remain connected and are reasonably balanced by the remaining generation in the same island through the separated transmission network. The formation of islands if properly designed will also make their resynchronization easier, towards a prompt system restoration.

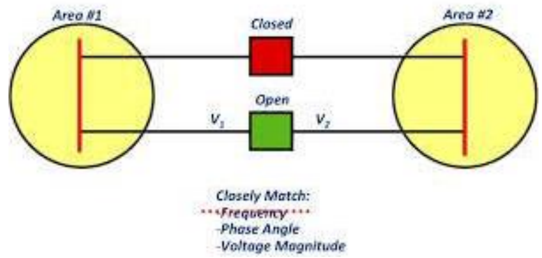

Figure 1-19: Islanding and Synchronization

Direct frequency measurements from PMUs can serve as a direct indicator of power system integrity. Bus frequencies at key locations may also serve as indicators for islanding conditions and system separation points. Frequency information from PMUs can serve as a critical tool during black-starts and in system restorations/resynchronizations.

1.2.15 Renewables and other applications

Subject to availability of (a) resource data synchronized with other PMU data, and (b) large set of historical measured data, the patterns of variable renewable generation (wind, solar and others) and their interactions with conventional generation systems can be analyzed for scoping and enhancing renewable integration studies. For instance, selection of worst-case conditions and spatial/temporal variability of renewable resources can be quantified using measured historical data, which can be included in renewable-based IPP impact studies. In addition, various renewable-based distributed resources can be conceptually better monitored, managed and controlled using PMU based data. While the operational aspects may benefit from online PMU-based applications, the design process may take advantage of the availability of PMU data during the planning phase.

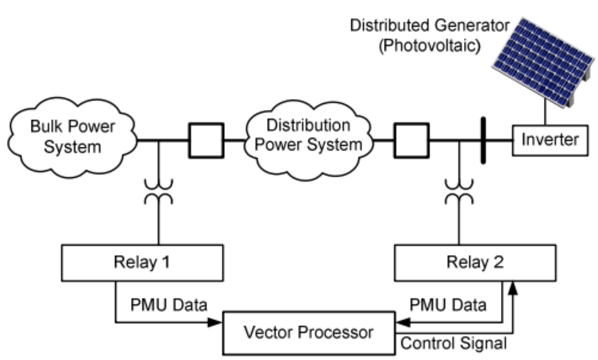

Figure 1-20: DG Integration using PMU Data

High-speed PMU-based monitoring provides operators better situational awareness and visualization of actual variable output and its effects on the bulk power system, and thus allows better grid management and responsiveness. Over time phasor data could be used for automated control of real system, including generation and load balancing, switching of reactive power compensation, demand management and energy storage, and for other intelligent protection and operations. Phasor data offers better location and time-specific datasets on technology and plant performance over time, and thus can be used to improve generation prediction, and plant performance models, as well as to improve understanding of how these resources affect the interconnected grid.

1.3 PMU's Potential Benefits & Challenges

The fundamental benefits of PMU technologies are in their wide-area time-synchronize high-resolution measurement. To provide a context, conventional SCADA based measurements can be compared with this technology, as shown in **Error! Reference source not found.**.

Table 1-1: SCADA vs. PMU Measurements

Attribute	SCADA based Measurements	PMU based Measurements
Measurement type	Analog	Digital
Measurement resolution	2-4 samples/second	30-240 samples/second
Observability & Response	Steady state/quasi steady state	Dynamic/transient
Phase angle measurement	No	Yes
Measured quantities	$\|V\|$, MW, MVAR	$\|V\|$, δ, MW, MVAR, $\|\delta_2-\delta_1\|$
Time synchronization	No (Synchronization at the EMS)	Yes (synchronization with 1~2 microsecond accuracy)
Monitoring	Local	Wide-area
Communication	Primarily Legacy	Primarily advanced

As can be seen, wide-are monitoring and control using PMU's will allow for a much higher data resolution, about 10-100 times more when compared to traditional SCADA systems. However there still remain some challenges hindering the broader industry-wide adoption of PMUs.

The primary elements of the physical infrastructure of a synchrophasor network are PMUs, PDCs, CTs, and VT/PTs. Other essential physical elements include communication devices, data storage and computing resources. PMUs are generally categorized under two classes: M Class and P Class. Key characteristics of these classes are:

Table 1-2: PMU Classes

PMU Class	Identifier	General Characteristic	Frequency Range	Voltage Magnitude	Harmonic Levels
P	Protection	Faster response, no filtering	+/- 2 Hz	80 - 120%	1% (low)
M	Measurement	Higher accuracy, anti-aliasing filter, slower response	Up to +/- 5 Hz	10 – 120%	10% (high)

Considering the different application of PMU technology, attention should be given in selecting and using the primary sensors, especially the CTs. Similar to the P and M Class PMUs, corresponding classes of CTs exhibit differing characteristics. For protection applications where higher currents are expected, protection CTs are generally appropriate, which means higher errors when used in metering applications. On the other hand, if high-accuracy is desired for applications such as state estimation and visualization, metering CTs can be used.

Depending on the complexity of the network, multiple layers of PDC may need to be accommodated in the synchrophasor network. For instance, a typical North American ISO may have distribution of PDCs throughout its footprint among its members, generator owners and transmission owners as is shown in Figure 1-21.

In addition to the selection of PMUs, PDCs and CT/PTs, placement of equipment is also a non-trivial problem. Depending on the intended application, asset ownership/jurisdiction and availability of existing facilities, such as relays, devices may need to be placed differently. In general, the following locations are of interest:

1. Large generating plants
2. Renewable generation plants
3. Critical generating facilities
4. Large load centers
5. Major transmission paths

6. HVDC lines and links
7. Dynamically controlled/FACTS devices
8. SPS/RAS control elements
9. Islanding/separation interfaces
10. Remotely monitored buses

Existing guidelines and industry practices (12) (13) can help in the process of PMU site selection.

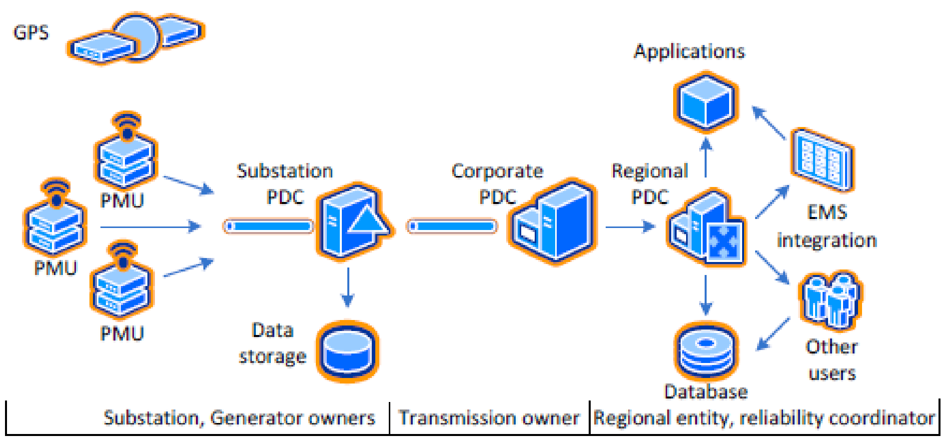

Figure 1-21: PMUs and PDC's in an ISO

In a modern energy management system (EMS), data is collected from remote terminal units (RTUs) and is processed through a supervisory control and data acquisition system (SCADA). Data is refreshed in an interval of several minutes, and its granularity limits the end-use only to state-estimation and several other steady-state analyses. In contrast, a synchrophasor-assisted EMS can potentially provide faster real-time monitoring and control capabilities. This is considered as a paradigm shift in power system operation.

Some of the challenges hindering the broader industry-wide adoption of PMUs are: Physical infrastructure issues such as hardware selection and placement, data quality & reliability, communication bandwidth and cyber security. The availability of data management and analytical software, and storage and sharing/accessing of data are also amongst the challenges facing PMUs.

2 Synchrophasor Technology at BC Hydro

2.1 About BC Hydro

BC Hydro's existing bulk transmission network consist of a 500 kV backbone which connects several large and remote generating stations in the Peace River and Columbia River areas with the major load centers being in the Lower Mainland and Vancouver Island (representing over 70% of BC Hydro's load) (Figure 2-1). Due to the long distance transmission, voltage stability problem is known to be one of the main limiting factors of BC Hydro's transmission system.

Figure 2-1: BC Hydro System Map (Source: BC Hydro)

The thirty integrated hydroelectric generating stations, two gas-fired thermal power plants, and one combustion turbine station have a total installed generating capacity of over 11,000 MW. Over 80% of BC Hydro's installed generating capacity is at hydroelectric installations in the Peace and Columbia River basins: Gordon M. Shrum, Peace Canyon, Mica, and Revelstoke power projects. BC Hydro's integrated transmission system also connects to Alberta (AESO) and Washington state (BPA), enabling BC Hydro to export/import electricity when necessary. BC Hydro connects to BPA by via two inter-ties: one double-circuit 500 kV transmission line from Ingledow substation in B.C. to Custer substation in Washington state, and one 230 kV interconnection between Nelway and Boundary. These interconnections together are known as Northern intertie by the Western Electricity Coordinating Council (WECC).

2.2 Current Synchrophasor Infrastructure

Presently, BC Hydro's phasor measurement network consists of ten substations (seven grid substation and three generating stations). A total of eleven PMUs are placed in these substations (two at GMS, one at others substations). There are two PDCs at FVO (Fraser Valley Operation, BC Hydro Control Centre), and one at Ingledow substation. PMU measurements are collected at Ingledow through serial links, and are streamed to FVO by dual redundant filter and radio links. The sampling rate of the measurements is 30 times per second (14).

BC Hydro's current wide-area measurement system on the 500 kV network is shown in Figure 2-2. The network architecture is shown in Figure 2-3. In addition to the existing (or recently upgraded) dedicated PMUs (Table 2-1), all 500 kV substations are being equipped with relays with PMU functionalities (Table 2-2).

Figure 2-2: BC Hydro's Wide Area Measurement Network (Source: BC Hydro)

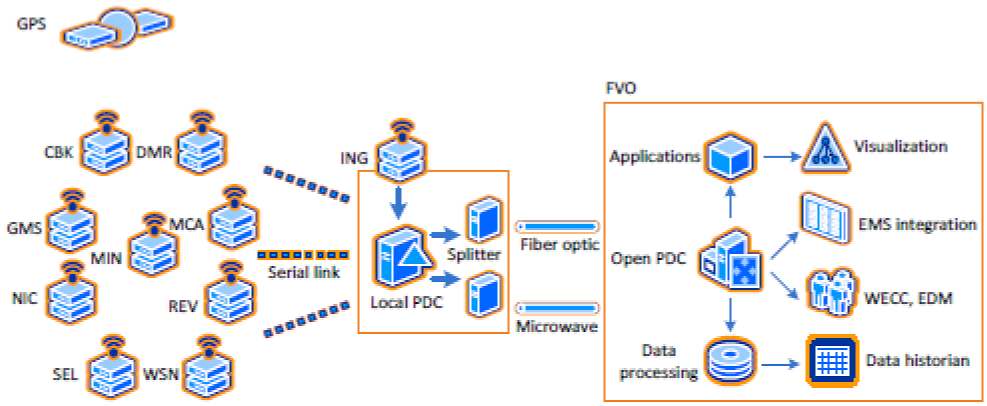

Figure 2-3: BC Hydro's PMU Network Architecture

At present, synchrophasor data in BC Hydro is utilized in:

- Sharing data with WECC, and receiving visualization for the entire western interconnect;
- Hybrid state estimation at FVO for operational purposes;
- Archiving for future use and investigative analysis.

A number of advanced applications and system upgrades are currently being explored, as part of various ongoing development programs.

Table 2-1: PMU Devices and Locations

Station Name	Station Code	Station Type	kV Level	Number of PMU's	Reporting to (ING/FVO)
Cranbrook	CBK	Transmission	500	1	Yes
Dunsmuir	DMR	Transmission	500	1	Yes
Gordon M. Shrum	GMS	Generation	n/a	2	Yes
Ingledow	ING	Transmission	500	1	Yes
Mica Creek	MCA	Generation	500	1	Yes
Minette	MIN	Transmission	287	1	Yes
Nicola	NIC1	Transmission	500	1	Yes
Revelstoke	REV	Generation	n/a	1	Yes
Selkirk	SEL	Transmission	500	1	Yes
Williston	WSN	Transmission	500	1	Yes

Table 2-2: Relay-PMUs at 500kV Substations (Current or Near-Future)

Station Name	Station Code	Station Type	kV Level
Skeena	SKA	Transmission	500
Telkwa	TKW	Transmission	500
Vaseux Lake	VAS	Transmission	500
Ashton Creek	ACK	Transmission	500
Cheekye	CKY	Transmission	500
Clayburn	CBN	Transmission	500
Glenannan	GLN	Transmission	500
Kelly Lake	KLY	Transmission	500
Kennedy	KDS	Transmission	500
Meridian	MDN	Transmission	500

Following the several blackouts in the Western Interconnect, BC Hydro joined the WECC initiative on installing a wide-area measurement system (WAMs) in 1998. By 2005, nine PMU devices were installed, and the PMU measurement system was integrated to BC Hydro's EMS state estimator. Subsequently, accurate and faster state estimation, post-disturbance event analysis and basic visualization schemes were developed.

Also in 2010, BC Hydro joined the Western Interconnection Synchrophasor Program (WISP). This provided a collaborative platform for developing a wide-area network including multiple utilities and jurisdictions. This program involves developing standards and guidelines for devices and systems associated with PMU, PDC/SuperPDC, IT infrastructure, communication network, and software solutions.

The future PMU network architecture for BC Hydro should allow for significantly larger number of devices that would support online real-time as well as off-line or post event analysis.

3 The North Coast System and Alcan

The Northern Region transmission system of B.C. Hydro is shown in Figure 3-1. Known for its long radial transmission lines serving remote loads and connecting dispersed generation facilities, it is susceptible to transient instability and is closely monitored by BC Hydro. Various special protection schemes (SPS) exist to protect against severe contingencies.

The North to South 500 kV transmission Corridor through Williston substation (WSN) moves power from the large generation facilities at G.M. Shrum and Peace Canyon to lower mainland through the Kelly Lake substation (KLY). The Northern region transmission system is characterized by a single 500kV backbone system that branches from Williston westward to Glenannan (GLN), Telkwa (TKW) and finally terminating at Skeena substation (SKA).

Rio Tinto Alcan own and operates a hydroelectric generation facility called Kemano, situated 75 kilometers southeast of Kitimat, in the northwest coast of British Columbia. Kemano generation was built primarily to provide energy for the Alcan aluminum smelter load situated in Kitimat. However with the expansion of the plant in later years, today Alcan exports the plant’s excess power to BC Hydro.

As is shown in Figure 3-2, the Kemano plant consists of 8, 120 MW generation units, totaling an installed capacity of 960MW. The plant however is operated to a maximum of 880 MW due to operating constraints. The 13.8kV Generator buses are connected to a 287kV bus through four, three-winding Step-up transformers. The Kemano 287 KV bus connects to Kitimat station, approximately 80 kilometers to the northwest through two parallel lines: 87L and 88L. The Potline smelters are connected at Kitimat and modelled as individual loads of varying sizes, totaling to about 450 MVA. From Kitimat station a short line connects the Alcan system to BC Hydro at Minette substation (MIN). Finally, a 60 kilometer 287 kV transmission line connects Minette substation of Skeena, adjoining the 500 kV backbone system.

The 2.5 kilometer 287kV transmission line connecting Kitimat station to Minnett substation is named 2L103 and is monitored by BC Hydro as the tie-line with the Alcan system (Figure 3-3). Power transfer on this tie line is usually between 250 to 450 MW from Kitimat into BC Hydro. The operating status of the Alcan sub-system and power transfer between the two systems is of significant importance to B.C. Hydro, especially in cases where BC Hydro is exporting power to Northwestern U.S. (BPA).

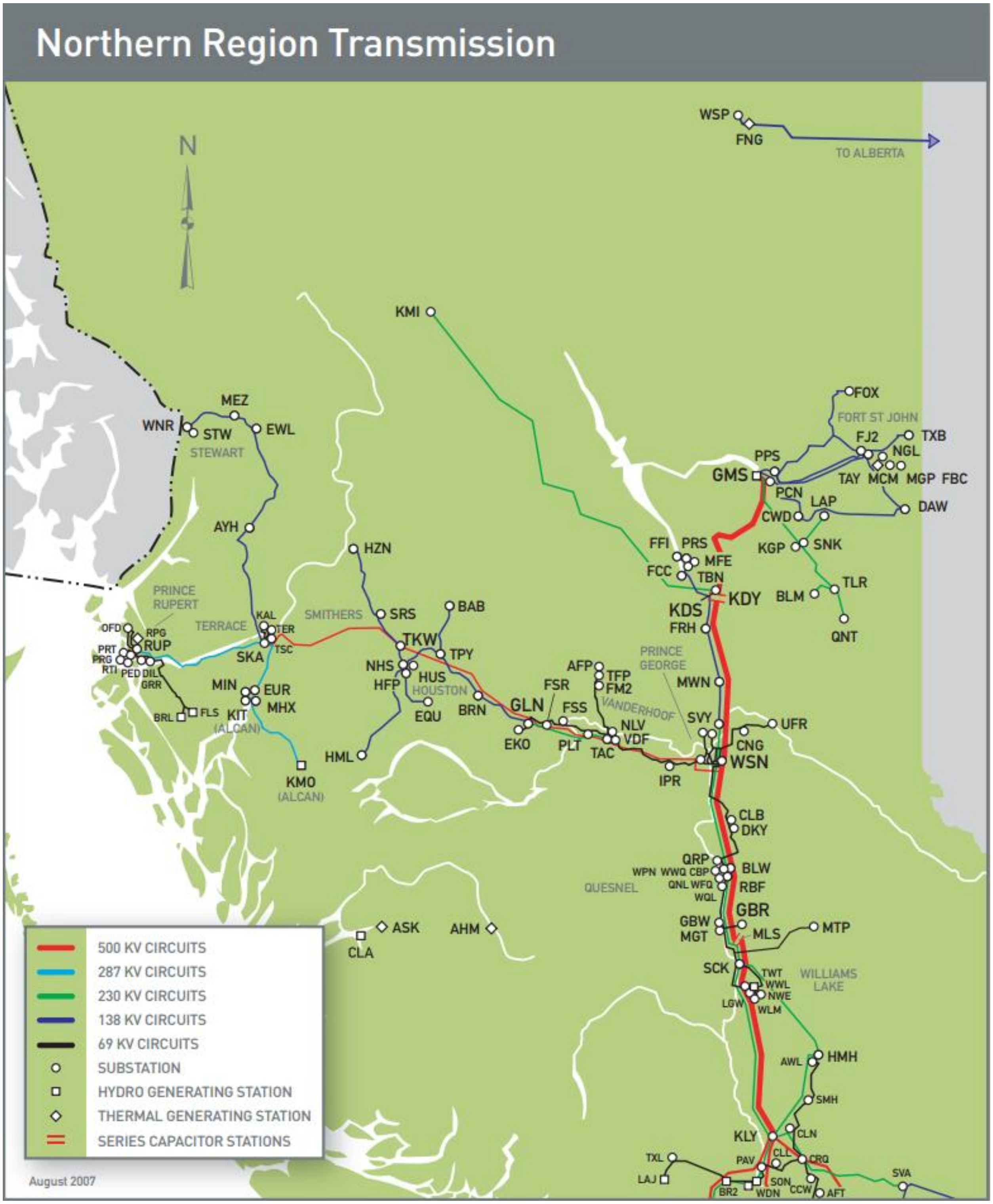

Figure 3-1: Transmission System in the Northern Region of BC Hydro (Source: BC Hydro)

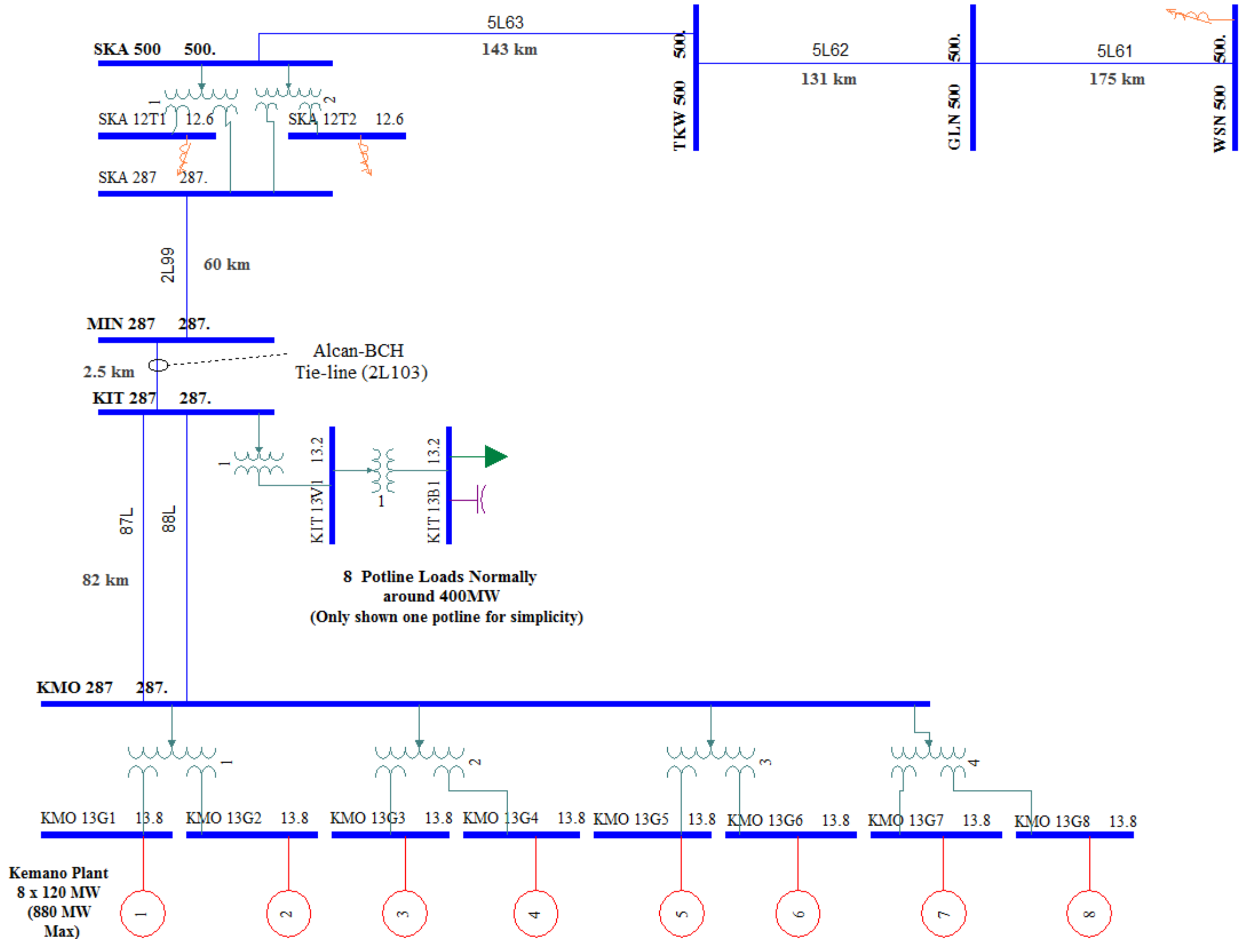

Figure 3-2: Single Line Diagram for Alcan System and Interconnection to BC Hydro

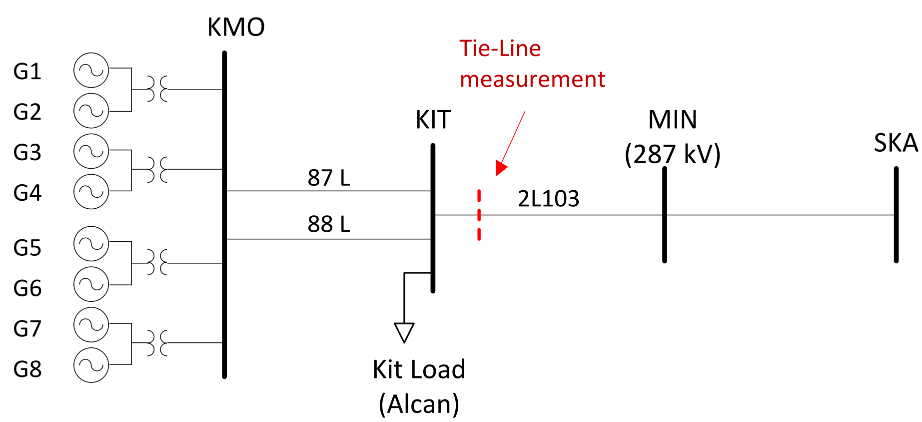

Figure 3-3: Simplified Alcan System and Interconnection to BC Hydro

3.1 Kemano Generation Shedding Scheme

As was mentioned in the previous section, generation at Kemano and tie-line flows between Alcan and B.C. Hydro is closely monitored by B.C. Hydro operators. During certain system conditions, contingencies near the Alcan tie-line will cause unacceptable dynamic performance of the system, leading to the undesired tripping of 2L103, the Kitimat to Minette 287 kV transmission line. This leads to the loss of power being transferred into BC Hydro from Alcan. To mitigate this problem, B.C. Hydro has implemented a remedial action scheme (RAS) or special protection scheme (SPS), called the Kemano Generation shedding scheme. In this scheme, with the detection of faults of interest, the existing Kemano generation shedding functions will be armed.

Severe contingencies close to the interconnection of the Alcan system can lead to transient stability issues and arming of the existing Kemano generation shedding. The Kemano generation shedding functions reside at GMS station and the scheme is designed to achieve an overall speed of less than 14 cycles for completing remedial action after fault incidence. All Kemano generation shedding signals are routed to GMS and can be programmed at GMS to key a single dual tone transfer trip from GMS to Kemano. At Kemano, this single transfer trip can be programmed by Alcan operators in Kitimat to trip any combination of the eight Kemano units.

The existing generation shedding scheme is effective in protecting for the transient stability of the two systems, however when armed and activated, this RAS will shed all generation at Kemano and the entire load connected at Kitimat substation. In the following section, a new remedial action scheme is proposed to achieve faster operation of the SPS and decreased amount of generation and load shedding in the Alcan system.

4 Methodology

In this research work the interconnection between the Rio Tinto Alcan system, and BC Hydro is under consideration for transient stability assessment. Severe contingencies close to this intertie can lead to transient instability and the shedding of generation at Kemano which leads to loss of transfers from Alcan to BC Hydro. This will cause transient instability problems in the BC Hydro network, especially when there are transfers between BC Hydro and the Northwest in the North to South direction. There is opportunity to optimize the existing remedial action scheme which will trip all generation at the Kemano plant as well as loads connected at Kitimat. In this section the methodology for utilizing PMU measurements for designing a new more optimized generation shedding scheme is discussed.

In this analysis WECC operation planning models are used for the studies. Different snapshots of the Summer 2013 base case covering four different operating conditions, for various transfers from BC to BPA are selected. The Northern intertie transfers up to 3,000 MW of power between BC Hydro and BPA. In developing the four bases cases for this study, transfers of 3,000, 2,500, 1,500, and 950 from BC Hydro to BPA were considered. Different stable and unstable contingencies in the Alcan and BC Hydro system were also included in the analysis to obtain a data-set composed of different operating conditions and credible contingencies. Dynamic behavior of the system after occurrence of each contingency is simulated in time-domain using DSATools TSAT software. In the next step, different real-time synchronized measurements or indices, such as angle, are obtained from the PMU measurements in pre and post contingency. Based on the results of the simulations, the key indices for assessing the transient stability of the system are selected and prediction of unstable scenarios is made possible.

It is envisioned that RAS controllers will in turn use signals from these new calculated indices to trigger the required corrective actions for unstable contingencies and form the basis for a new RAS recommendation. The performance of the various indices is compared and an optimal scheme based on one or more indices is proposed.

According to NASPI (North American Synchrophasor Initiative), PMUs should be installed at major power plants and also critical corridors and bottlenecks. In this study, it is assumed that all the major power plants in BC Hydro (GMS, Peace Canyon, Mica and Revelstoke), and the Kemano generation plant in the Alcan sub-system, the inter-tie between these two systems, and also the major corridors transferring power from major power plants located in Northern parts of BC Hydro are equipped with PMUs.

Consequently, the powers, angles and frequencies at these points are accessible at the control center in real-time.

In this study, it is assumed that the PMUs installed at different locations of the power system have the capability to measure the parameters and transfer them to the control center in up to 150 milliseconds. As well, a breaker operation time of three cycles is included in the simulations.

4.1 Wide-Area Severity Indices

To assess dynamic security, different types of measurements, features or indices have been investigated in the literature. Many proposed methods utilize direct measurements obtained from the power system (15) (16), while others use calculated indices or features (17) (18). The use of the energy function is also investigated widely in the literature (19) (20). However this method has not yet been applied for on-line or real-time stability assessment.

4.1.1 Dynamic Stability Assessment based on Synchronized Measurements

In this thesis, some synchronized measurements of the system from both pre-fault and post-fault states of the system are selected for analysis. Only the quantities with the feasibility of synchronized measurement through the wide-area monitoring and protection system (WAMPS) are used in the algorithm.

Various studies in the literature have used different parameters or synchronized measurements from wide-area monitoring systems for determining dynamic stability. For example in (16) PMU measurements for voltage phase angles, current flows, active power flows, reactive power flows are used to calculate the square of voltage magnitude and monitored current magnitudes multiplied by branch impedances. The synchronized measurements used (21) are active and reactive power output of the generators, active and reactive power at load buses, total active and reactive power of the system, and voltage and angle difference of buses. In (22) total active and reactive power generation of the system and the total load, voltage magnitude and angle of each load bus in pre-fault steady-state of the system are selected as the features for training an intelligent system. Also, post-fault dynamic features such as rotor angles, rotor speeds and voltage profiles are included.

In this thesis some synchronized measurements from the pre-fault state are selected such as, the total power generation of the major power plants in the two regions, BC Hydro and Alcan; the power generation of individual major power plants, the angle of the buses connecting major power plants to the systems and also the interface substations. Moreover, the power flow of the intertie connecting the two regions, i.e. line 2L103, and the power flow on the intertie connecting BC Hydro to BPA are selected as the relevant features/attributes. Among the post-fault synchronized measurements, the synchronized measured angles at the buses connecting the major power plants in both regions and the interface substations are selected in the attribute set.

4.1.2 Dynamic Stability Assessment based on Proposed Indices

Different indices and features based on the region center of inertia (COI) and transient energy function are explored extensively in literature (17) (23) (24). In this section, both angle-based and energy function methods are investigated and compared to formulate the proposed system protection scheme. An energy function is defined as the amount of critical energy which is stored in the power system before a fault is cleared. The power system should have the capability to restore to a stable state after the fault is cleared (25).

The fundamental idea in the energy function method is to group all the machines in the system into two regions. One equivalent machine will represent the group that fall under a sub system under study, and rest of the system is represented as another equivalent machine. The swing equations of an n-machine system can be given, as follows (25):

$$\frac{H_i}{\pi f}\frac{d^2\delta_i}{dt^2} + D_i\frac{d\delta_i}{dt} = P_{mi} - P_{gi}\,, i = 1, 2, \, .., n \tag{1}$$

Where,

H_i = Inertia constant of the ith machine in seconds

D_i = Damping constant of the ith machine in seconds

P_{mi} = Mechanical input of the ith machine in per unit

P_{gi} = Electrical power output of the ith machine in per unit

δ_{gi} = Rotor angle of the ith machine with respect to a synchronously rotating reference frame in radians.

The relative behavior of rotor angles is key for assessing stability of the system as angles are a state variable of the system. Here we have two options; to use either the relative rotor angle changes, or the center of inertia (COI) formulation. The region center of angle is defined as:

$$\delta_{COI} = \frac{1}{M_{total}} \sum_{i=1}^{n} M_i \delta_i \tag{2}$$

And the region center of speed is:

$$\omega_0 = \frac{1}{M_{total}} \sum_{i=1}^{n} M_i \omega_i \tag{3}$$

Where,

$$M_i = \frac{H_i}{\pi f} \tag{4}$$

And ω_i is the angular velocity of the rotor and,

$$M_{total} = \sum_{i=1}^{n} M_i \tag{5}$$

In the above formulae, δ_i is the synchronized measured angle at the substations connecting a major power plant to the region, M_i is the inertia constant of the *i*th generator in the region, and M_{total} is the total inertia constant of all generators in one region.

Next these angles are used for calculation of two indices, center angle deviation (CD) and center of angle stability index (CASI).

An index expressing the COI deviation for a region, compared to pre-fault condition, is called center deviation (CD). Centre of Angle Deviation index can be calculated for each of the two regions: BC Hydro and Alcan and is defined as follows:

$$CD = \frac{\delta_{COI}^{post-fault} - \delta_{COI}^{pre-fault}}{\delta_{COI}^{pre-fault}} \tag{6}$$

For the two regions i and j connected via an intertie, another index called center of angle stability index (CASI) has been demonstrated to be effective in determining instability (26):

$$CASI = \left| \frac{\delta_{COI,i}^{post-fault} - \delta_{COI,j}^{post-fault}}{\delta_{COI,i}^{pre-fault} + \delta_{COI,j}^{pre-fault}} \right| \times 100 \tag{7}$$

where, CASI is the proposed RAS index based on the center of angle of BC Hydro and Kemano in this study and δ_c is region center of angle defined for BC Hydro and Kemano in pre-fault and post-fault conditions.

The potential energy function for an *n-machine* power system is a function of *n* variables, and the sum of kinetic and potential energy is as follows (25):

$$V = V_{K.E.} + V_{P.E.} \tag{8}$$

$$V_{K.E.} = kinetic\ energy = \frac{1}{2} \sum_{i=1}^{n} M_i\, \widetilde{\omega}_i^2 \tag{9}$$

$$V_{P.E.} = potential\ energy = -\sum_{i=1}^{n} \int_{\theta_i^s}^{\theta_i} f_i(\theta) d\theta_i \tag{10}$$

Where,

$$\theta_i = \delta_i - \delta_0 \tag{11}$$

$$\widetilde{\omega}_i = \omega_i - \omega_0 \tag{12}$$

And,

$$f_i(\theta) = M_i \frac{d\widetilde{\omega}_i}{dt} \tag{13}$$

Another stability index based on the kinetic energy of the two regions can be defined as KESI, kinetic energy stability index, as follows:

$$KESI = \left| \frac{V_{ke,i}^{post-fault} - V_{ke,j}^{post-fault}}{V_{ke,i}^{pre-fault} + V_{ke,j}^{pre-fault}} \right| \tag{14}$$

Where V_{ke} is the kinetic energy function calculated for BC Hydro and Alcan both in pre-fault and post-fault conditions.

Next, a number of time domain simulations including credible contingency and different operation scenarios were performed to determine the optimum threshold for the proposed indices.

5 Simulation Results

A number of time domain simulations including four different levels of power transfers between BC Hydro and BPA were performed, as was described in the previous section. The obtained synchronized measurements from the simulation results are used to calculate the indices as were discussed in section 4. These calculated indices are shown in Figure 5-1 to Figure 5-6. In these figures, the capability of the different indices to distinguish between the stable and unstable cases is shown in the time domain. The blue lines show the stable cases while the red lines show the unstable cases. According to these figures, KMOCD, CASI, and Kinetic Energy difference attributes can discriminate between stable and unstable cases better than the other indices. Therefore, these features are used for designing the new remedial action scheme for generation shedding at Kemano.

As was mentioned in previous sections, the different curves shown in the result figures refer to different contingencies in the Alcan and BC Hydro regions, over four different base cases constructed from WECC cases with varying power transfer on the Northern inter-tie. All the selected contingencies are reasonable and have the probability of occurrence. Most of the contingencies leading to transient instability occur in the Alcan power system.

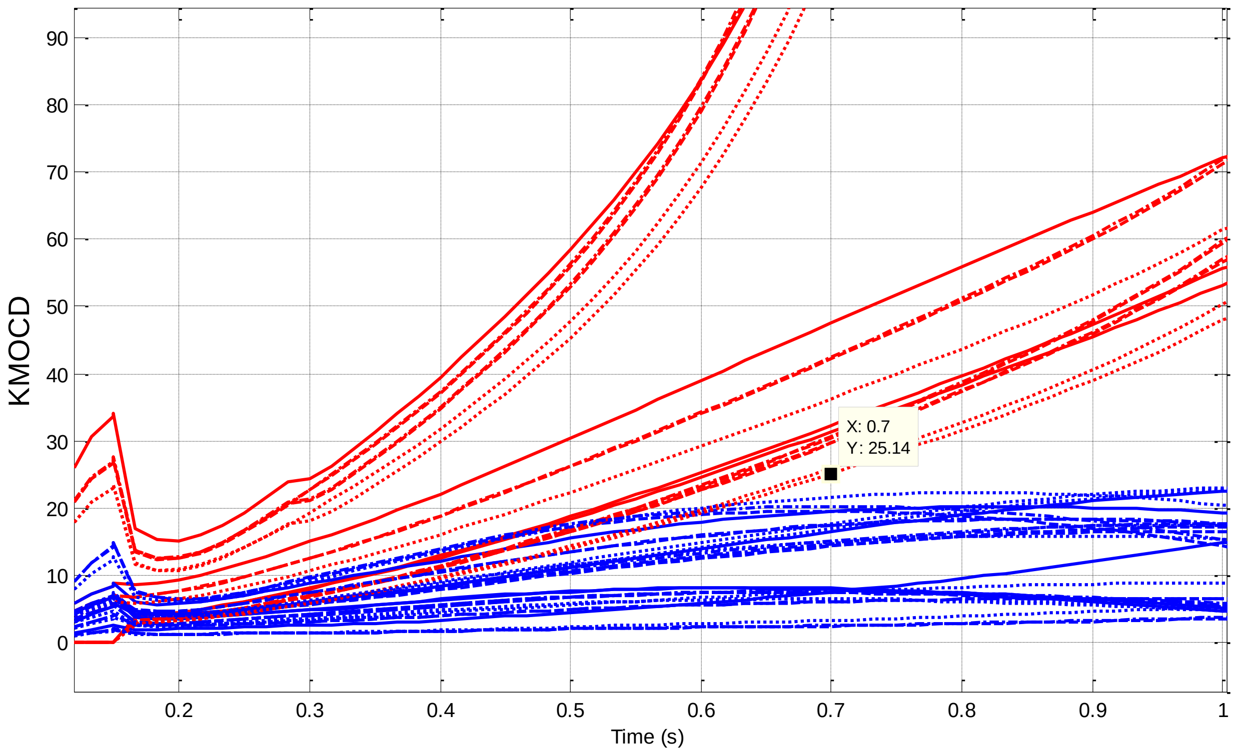

Figure 5-1: KMO Region Centre of Angle Deviation

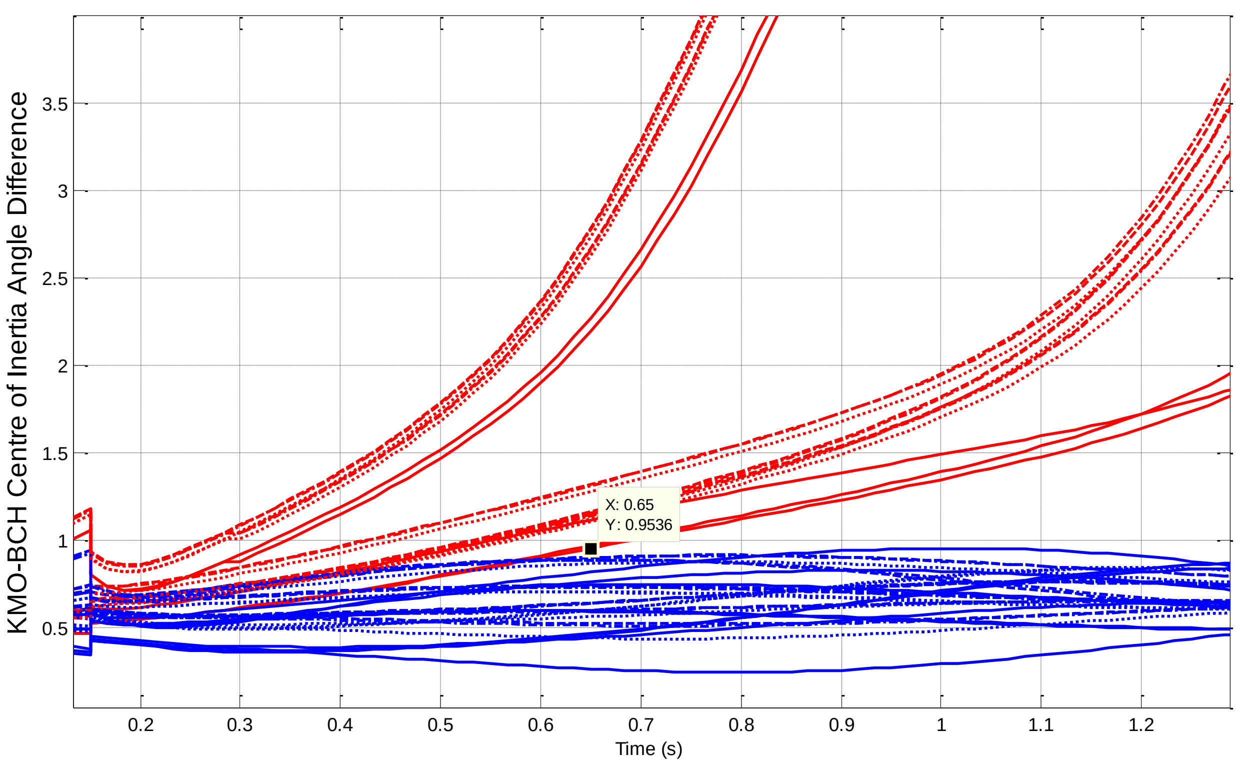

Figure 5-2: BCH-KMO Center Angle Difference

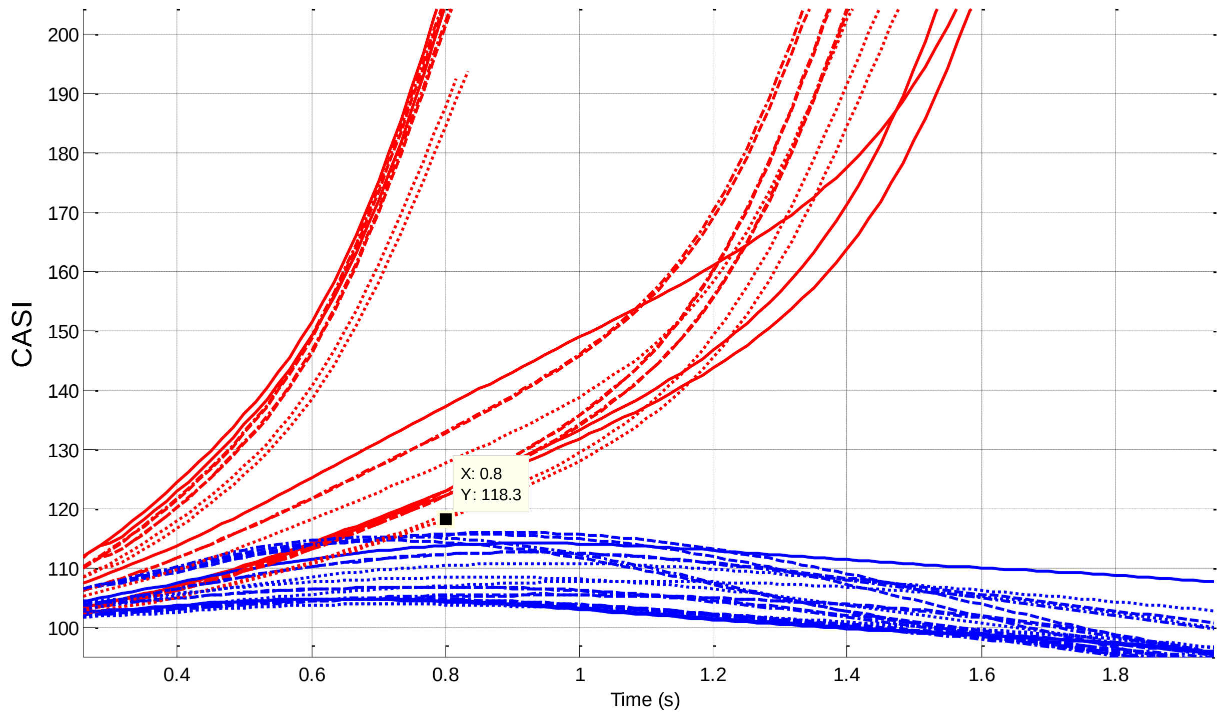

Figure 5-3: CASI

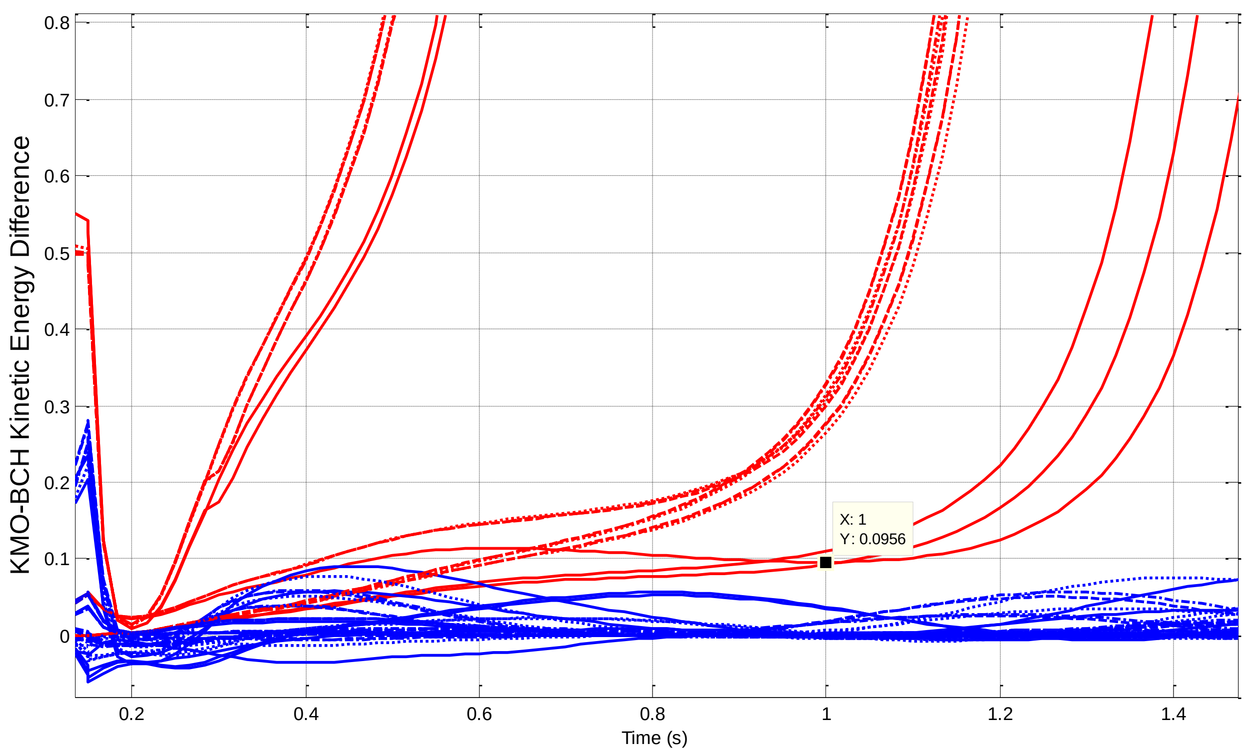

Figure 5-4: Kinetic Energy Difference

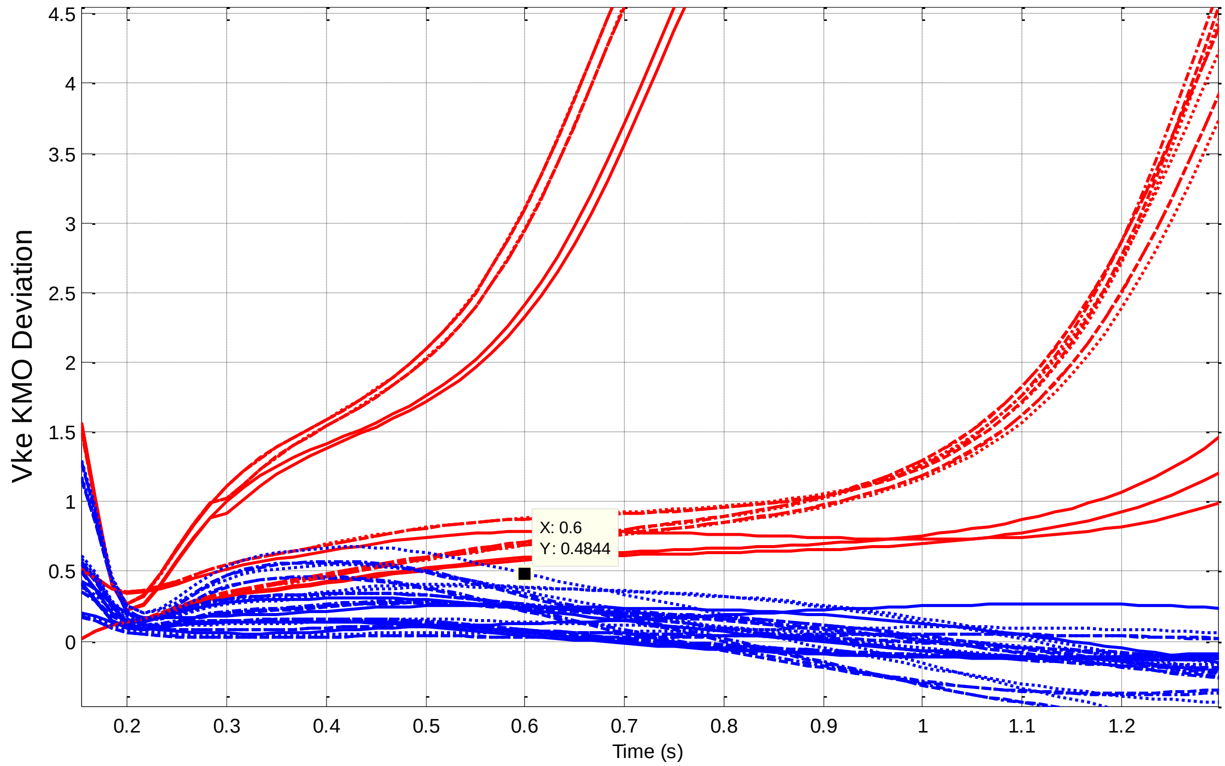

Figure 5-5: Kemano Kinetic Energy Deviation

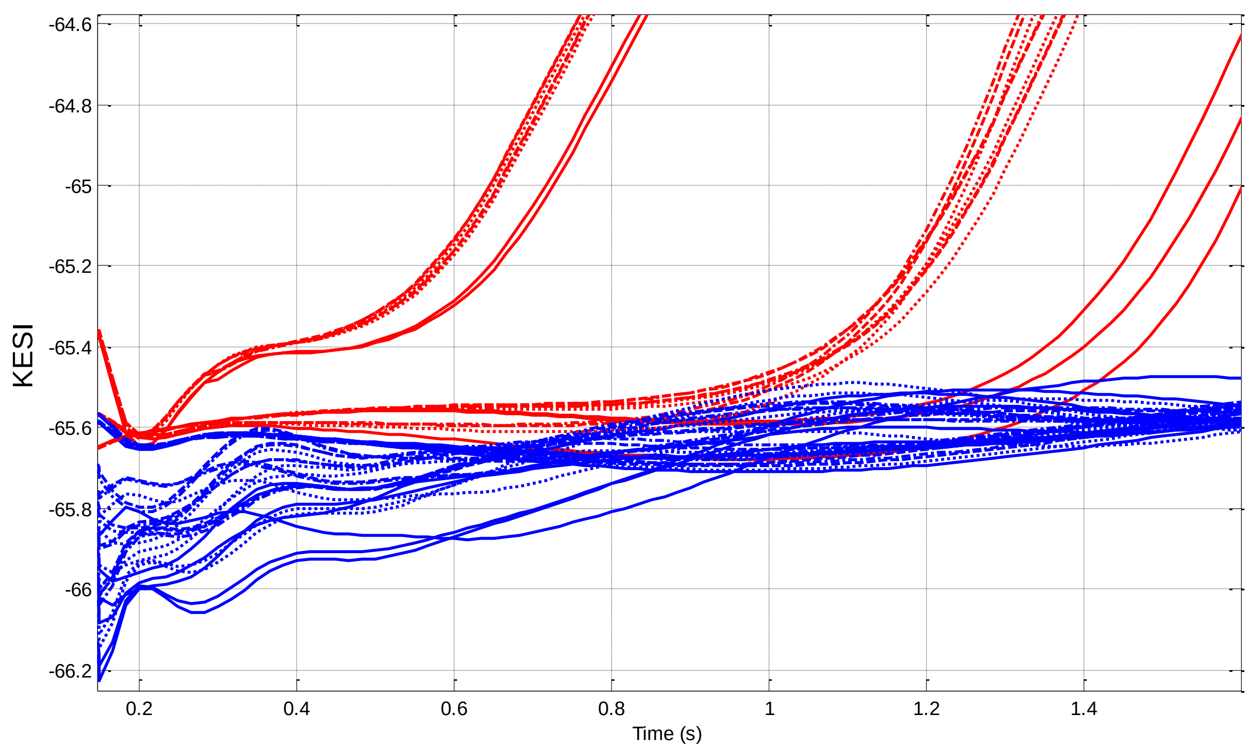

Figure 5-6: KESI

In all the contingency simulations, the fault occurs at the time instant of 100 ms and lasts for 3 cycles, i.e., 50 ms. Therefore, the fault is cleared at the time instant of 150 ms. Data acquisition and timing are an important part of wide-are monitoring systems. PMUs have an essential role in synchrophasor measurements and are divided into two classes as was discussed in section 1.3, i.e., M class and P class. The M class PMUs are developed for monitoring purposes and provide accurate measurements with more latency while, the P class PMUs are used for protection applications which are quicker in measuring, with less accuracy when compared to the M class PMUs (27). In this study it is assumed that the measurements are obtained from P class PMUs, and as was discussed in section 4, a data transfer latency of 150 ms and breaker operation time of 3 cycles is included in the analysis.

Now, considering the indices of choice, i.e. KMO Center Angle Deviation (KMOCD), CASI, and Kinetic Energy difference, a threshold should be established for a proposed RAS scheme based on each index. Referring to graphs of Figure 5-1, Figure 5-3, and Figure 5-4 , we can select the following thresholds: KMOCD_TH = 25, CASI_TH = 118, and BCH-KMO V_{ke} Diff_TH =0.1. Using these thresholds, three different remedial action scheme were modelled utilizing each set of measurements. An example of such a RAS model is depicted in Figure 5-7 for KMO Centre Deviation (KMOCD).

As can be seen from the graphs for each index, the measurement values undergo large fluctuations during the fault. In order to not have RAS activate on these fluctuations, a time function was modelled to only trigger RAS action with a sustained measured value over the threshold for 0.05 ms or more. This functional block is depicted in Figure 5-7 for KMOCD-based remedial action scheme. Based on this design the protection scheme will look for any 0.05 ms window in time in which the value of the index remains above the chosen threshold in order to activate the remedial action scheme.

Table 5-1 below compares the performance of the proposed remedial action scheme based on the above thresholds for each index. Note that the activation time of the existing RAS is based on the timing that was described in section 3.1 for Kemano generation shedding, and includes estimates for response times for conventional relays.

Table 5-1: Performance of Various Indices used for Kemano RAS

		Base Case 1 = 3,000 MW N-S		Base Case 2 = 2,500 MW N-S		Base Case 3 = 1,500 MW N-S		Base Case 4 = 950 MW N-S	
RAS Index	Activation Time (s)	Gen Shed (MW)	Load Shed (MW)	Gen Shed (MW)	Load Shed (MW)	Gen Shed (MW)	Load Shed (MW)	Gen Shed (MW)	Load Shed (MW)
Existing RAS	0.63- 1.23	880	395	809	375	704	355	457	315
KMOCD	0.32 - 0.71	330	138	304	131	264	124	172	110
CASI	0.41 – 0.84	440	146	404	139	352	132	229	117
KMO-BCH Kinetic Energy Diff	0.32 - 1.21	660	240	607	228	528	217	343	193

As the results of Table 5-1 indicate, the Remedial action scheme based on angle measurements, i.e. KMOCD and CASI are generally faster acting when compared to the energy function-based RAS scheme. Consequently, the generation and loads in Alcan are shed sooner preventing the power system from insecurity. The existing RAS is faster acting compared to the Kinetic energy-based schemes. However, the main advantage of the proposed schemes is the decreased amount of generation and load shedding that is required to stabilize the system following the occurrence of faults. Comparing the two angle-based schemes, it is apparent the a RAS based on Kemano Centre Angle deviation is faster acting and yields less load and generation shedding. However the CASI index normalizes the angle difference of the two regions based on initial conditions, and as can be seen from Figure 5-3, this index discriminates much better between stable and unstable contingencies. Therefore of the new indices investigated, the CASI index is chosen as the preferred scheme.

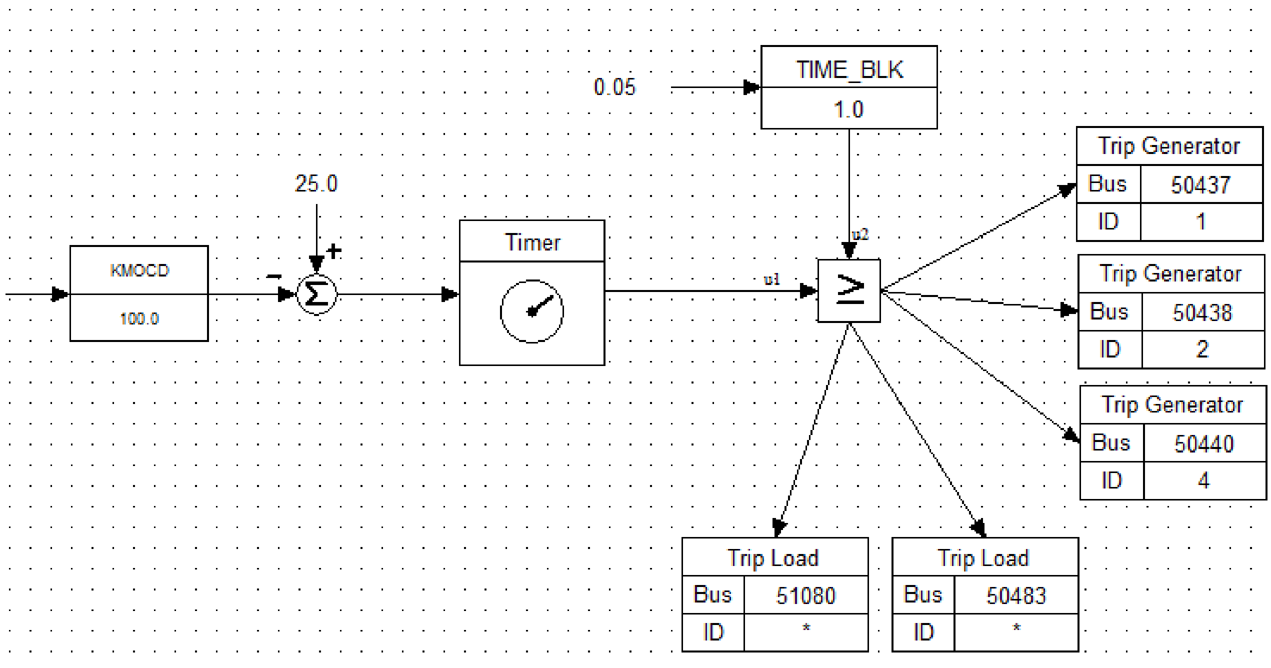

Figure 5-7: RAS Model using KMOCD Index

As the results of RAS simulations show, PMU measurements help achieve faster and more efficient protection scheme. Both the angle-based and energy function based schemes can act faster in comparison to the existing RAS, however it was shown that the angle-based scheme is more efficient and also capable of more reliably detecting the unstable scenarios. The results showed that the angle based indices performed better in more accurately distinguishing between stable and unstable scenarios with less likelihood of miss-classification. Both the angle-based and kinetic energy-based protection schemes yield to reduction in generation and load shedding when compared to the existing RAS. Therefore, we have shown that the proposed protection scheme based on direct angle measurements of the system can significantly improve the performance of the protections system.

Improving the reliability of the proposed protection schemes in correctly classifying between stable and unstable scenarios is a problem that should be further investigated. As it has been described in detail thus far, remedial action schemes should only be activated upon the detection of the unstable scenarios or contingencies. The results of the studies conducted showed that miss-classification of scenarios did occur for 2 - 5% of the entire set of scenarios that were simulated, depending on the index that was used. However this list is by no means exhaustive; the number of possible scenarios that can be studied for a given system is unlimited and needs to include all credible system topologies, contingences, and operating conditions, etc. Therefore a comprehensive set of scenarios is required to be studied in order to ensure that every possible scenario meets the designed thresholds for implementing RAS.

Not utilizing a more sophisticated predictive method, it can be assumed that all unstable scenarios will fall within the designed thresholds, and unless more accurate predictive methods are implemented the RAS schemes are designed more conservatively to ensure that the power system can withstand the possible occurrence of unclassified unstable scenarios.

6 Conclusions and Recommendations

The ever increasing complexity of the electrical grid has made it difficult to predict and anticipate contingencies. This is mainly due to the advent of deregulated electricity markets, aging transmission infrastructure and the growing penetration of renewable resources. The wave of blackouts in the recent years has made utilities all over the world much more aware of the need for power system wide monitoring and control. One of the fundamental requirements to achieve that goal is to have common measurement reference. A few technology enablers have emerged which have led to development of a new kind of measurement paradigm; Phasor Measurement Units, or PMUs.

PMUs show high potential for wide-area system monitoring and control as well for conducting advanced engineering analysis. PMU's time-synchronized high-resolution measurements can provide visibility of a power system distributed over a wide geographical area and can be utilized in a multitude of applications including real-time monitoring, advanced power system protection, and advanced control schemes.

In this thesis, a new special protection scheme (SPS) was proposed based on synchronized measurements provided by PMUs. An existing remedial action scheme (RAS) protecting for contingencies impacting the tie-line interconnecting the Alcan system to B.C. Hydro, using conventional relays is studied, and a new scheme based on time-synchronized, and high-resolution voltage angle measurements from PMU's in a Wide-are monitoring system (WAMs) is proposed . In this new scheme, the angles of the buses at large power plants in both systems are examined to implement the RAS. These angles are used to calculate various criteria based on region center of angle and the kinetic energy function.

The results of a number of time domain simulations demonstrate that the proposed angle-based scheme can lead to faster operation of the SPS and decreased amount of generation and load shedding in the Alcan system. The achieved speed and efficiency of the proposed scheme in comparison to the existing installed scheme further highlight the opportunity in utilizing PMU measurements in online applications for power system protection and monitoring.

A protection system designed using PMU measurements can greatly improve the performance of the protection system. In the lightly meshed or radial power systems, deciding where PMUs should be placed is relatively simple and will depend on the type and complexity of the scheme and the role of

PMU measurements. However, the requirements for implementing a fast and accurate system-wide protection scheme are more difficult for highly meshed networks. A large number of PMUs need to be installed to realize a system-wide protection scheme. These PMUs need a communications infrastructure to support the large amount real-time data transfer. This wide area monitoring and control system will also requires a control system capable of processing data from hundreds of PMUs to initiate protection orders based on detection (or prediction) of system instability.

In this thesis it was assumed that the PMUs installed at different locations of the three power systems have the capability to measure the parameters and transfer them to the control center in up to 150 ms and control actions could be performed based on processed data short after. Longer measurement times can lead to better discrimination between stable and unstable cases, however this latency may deteriorate the effectiveness of possible follow up SPS schemes that are to be implemented and hence defeat the purpose of the study. Therefore, a trade-off is needed between accuracy and the effectiveness of corrective steps following fault detection.

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