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Preferential Subject 1

Leveraging PMU data for better Protection, Automation and Control Systems

Special Report

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Summary

The CIGRE Study Committee B5 – Protection and Automation - covers within its scope principles, design, application and management of power system protection, substation control, automation, monitoring and recording; this including associated internal and external communications, substation metering systems and interfacing for remote control and monitoring. This colloquium will also approach the theme of Synchronized Phasor Measurement Systems (SPMS).

This paper is the Special Report for Preferential Subject No. 1, Leveraging PMU data for better Protection, Automation and Control Systems, and it will address the main contributions of the submitted papers.

Keywords

PMU, WAMPACS, Adaptative Protection Scheme, Fault Disturbance Location, Control Strategy, Real-time Emergency Control Scheme.

1. Introduction

The Preferential Subject No.1 of the CIGRE SC B5 2019 Session in Tromso (NO) is entitled “Leveraging PMU data for better Protection, Automation and Control Systems”, associated to the following subitems:

- ➢ Use of PMU data to improve system models and to monitor analogue inputs
- ➢ Adaptative protection concepts utilizing PMU data
- ➢ Wide area schemes, novel backup protection, power swing protection, and synchronizing schemes base on PMU data
- ➢ Improvements in PACS commissioning and post-event analysis using PMU data

A total of 28 papers by authors from 11 different countries, have been received for this Preferential Subject. These papers are divided into 8 groups, with some that address more than one subject:

1. PMU Fault Disturbance Type Identification and Location - **4 Papers**: 102 (CN), 117 (US), 121 (RU), 127 (IN);
2. Wide Area Protection and Control System - **6 Papers**: 104 (CA),108 (US), 110 (SI),112 (CL),113 (CL),116 (UK);
3. New Research and Techniques with PMU Applications - **2 Papers:** 101 (CN), 111 (CN);
4. PMU Calibration and Real Time Simulation **- 4 Papers**: 105 (CN), 106 (BR),107 (BR), 109 (CN);
5. Wide Area Control and Situational Awareness - **6 Papers**: 114 (IN), 115 (IN), 119 (RU), 120 (RU), 122 (RU), 128 (ES);
6. Adaptative Protection Schemes **- 2 Papers**: 123 (RU), 126 (HR);
7. Parameter Identification, Monitoring and Model Validation - **3 Papers**: 118 (RU), 124 (RU), 125 (BR);
8. PMU Optimal Placement **- 1 Paper**: 103 (CN).

2. Group Overview and Questions for the Technical Session

This session contains an overview of the 28 papers separated in 8 subjects and 12 questions proposed for discussion during the PS1 Discussion Session.

2.1 PMU Fault Disturbance Type Identification and Location

Given the possible applications for automated identification of power system events using PMU data, the works below apply PMU quantities and specific algorithms for fault location determination. The topic is very relevant and is attracting attention of both transmission and distribution segments throughout the world.

Paper 102 from China discusses the implementation of transient recording fault indicators and also address the main difficulties for fault detection (accuracy of rate of change). A single-phase grounding fault in a small resistance grounding 10 kV system was simulated and tested in China. Finally, the paper proposes a fault type location scheme for distribution transmission lines and the required technology challenges to be overcome.

Paper 117 from USA elaborates the use of PMU data to locate faults in the power system and mitigate cascading outages. It provides a method for monitoring how the system behaves after complex switching actions caused by cascading events as single-phase faults with small resistance grounding system. A total of 2500 tests were performed, where 80% of these tests were employed for training the proposed classifier model whereas, the remaining 20% were used for testing. The paper also presents a system-wide fault location method for transmission lines using electromechanical waves propagation theory, and proposes actions to intentionally island the system, which can minimize load shedding and maintain stable the voltage profile in each island.

Paper 121 from Russia presents the technical requirements adopted by the Russian System Operator - SO UPS, and details the use of PMU measurements to detect electromechanical oscillation. It also proposes the use of PMU data for post-event analysis in the SO UPS system.

Paper 127 from India describes a new methodology based on “model-free fault location” applying PMU data for transmission lines to improve the accuracy of fault location. The simulations were performed with the PSCAD/EMTDC software platform in one transmission line with the following characteristics: 220 kV, 50 Hz and 120 km. 480 tests in total were performed and the errors for parameter estimation and fault location were presented.

When applying this method, the fault location results were not influenced by the fault resistance, fault type and SIR characteristics of the transmission line.

2.1.1 Questions

Question 1.1: What are the main challenges in relation to fault type location? What are the benefits when employing PMU data to identify disturbances**?**

Question 1.2: What are the processes involved in terms of mitigating and analyzing the impact of disturbances using PMU data?

2.2 Wide Area Protection and Control System

In this session, WAMPAC issues will be discussed. With the improvement of telecommunication infrastructure, special protection schemes using PMU data are being applied for several purposes such as controlling certain islanding conditions and avoiding blackouts, in current protection schemes, and in controlling the damping of electromechanical oscillations.

Paper 104 from Canada presents one Remedial Action Schemes (RAS) operated in conjunction with the status of the Transient Stability Status Prediction (TSSP) to develop a simple method to identify coherent clusters of generators using PMU data. It also discusses one application of a "real-time emergency control scheme" for controlled islanding to prevent blackout during transient condition operation. The simulations were performed in the TSAT software platform for the IEEE 39 bus test system.

Paper 108 from USA describes the concepts and the performance class of two PMU equipment in accordance with the IEEE C37.118.1 Standard. Situational awareness, line differential protection, power swing monitoring and recording using PMU were also presented. Moreover, the paper also presents the system integrity protection schemes (SIPS) based on the use of PMU data, the integration of PMU in the IEC61850 standard for monitoring and control and, finally, the testing of synchrophasors based on protection system.

Paper 110 presents the WAMPAC system (Slovenia Technology System), already in operation in ETESA (Panamanian Transmission System Operator) since November, 2013. The project commenced with 20 PMU installed in the 230 kV transmission system. The paper also presents a number of recorded events in the ETESA system and focus on the events recorded on March, 17th of 2017 and on July, 1st of 2017, which had a huge influence on the entire Central America region. The upgrade from WAMS to WAMPAC in the last year of implementation has significantly improved the dynamic stability of the Panamanian electrical system.

Paper 112 from Chile presents an overview of the Chilean Interconnected Power System and the challenges faced during WAMS deployment. Real-time data from electromechanical oscillations were used to improve Chilean electrical transmission analysis. Several PMU are currently being implemented on generator terminals of the main participants of the primary frequency control to verify the performance of the generators and their contribution to the oscillations.

Paper 113 from Chile approaches an overview of Chile's grid code. The WAMS system was initially designed to audit phenomena analysis inside a selected area of the power system. The project was expanded to 1 Master PDC and 8 PMU placed in 7 selected substations. After 2014, the system was expanded to 1 Master PDC, 5 local PDC and 44 PMU, which spans over 3100 km. Finally, the paper presents the current/recent evolution of the Chilean WAMS as well as its architecture solution adopted in the project.

Paper 116 from United Kingdom presents the architecture and deployment of PMU equipment in the Indian Electric Transmission System and also the use-case and operational experience. Analysis of events, wide area monitoring, electromechanical oscillation, islanding detection and other applications are discussed in the paper.

2.2.1 Questions

Question 1.3: What recommendations and experiences can be provided regarding the implementation of RAS and SPS in the field of WAMPAC systems?

Question 1.4: When considering real-time emergency control scheme for controlled islanding, which are the most suitable applications to minimize or avoid the risk of blackouts?

2.3 New Research and Techniques with PMU Applications

With large scale deployment of PMU measurement systems, new algorithms and new techniques are beginning to be explored, with a wide variety of possibilities. This has influenced new engineers, research and development institutes and companies in general to create new solutions using PMU data applied to the real time scenario, in order to get better observability, controllability and reliability of the power system.

Paper 101 from China focuses on the disturbance detection, fault location and control strategy as well as on the estimation of the energy during the disturbance based on concepts of entropy (a chemistry concept). The paper demonstrates the association of energy entropy and free energy (Gibbs Mathematical Formulation). The energy entropy estimation for the synchronous generator based on the Shannon Entropy formulation was approached and the tests were carried out in the IEEE New England 39 Bus System.

Paper 111 from China presents the difficulties for implementing real-time applications using angle differences obtained from PMU measurements, mainly due to the time synchronization error in the measurement of power transfer, PMU algorithm errors and others. The paper also proposes a new method using a cluster algorithm to classify the phase angle difference data in order to screen out the right PMU phase angle difference values, combined with DC power flow (electrical validation). The paper analyses the hyperplane cluster method to cluster phase angle difference data. Finally, the paper compared the results with those from the k-means algorithm.

2.3.1 Question

Question 1.5: How can these new methods and techniques be improved to contribute to the actual Special Protection Schemes?

2.4 PMU Calibration and Real Time Simulation

With the evolution of digital signal processing technology, associated with new complex and robust applications, many of them being applied already in real time, in this session of the report, the work related to the tests of approval, validation and acceptance are presented.

Paper 105 from China proposes one optimization algorithm for PMU phase calibration where it can be possible to verify the frequency error during the tests and minimize this error. The procedure of repeated playback was presented in order to improve the sampling rate per unit period of the signal source. Finally, in order to calibrate correctly the phase error of the PMU tester, the paper proposes an FFT-based phase calibration method.

Paper 106 from Brazil presents the Control Center Phasor Measurement System CC-PMS project already in operation in the Brazilian Interconnected Power System (BIPS).
The paper also shows the results (a total of 600 tests) when applying RTDS system to verify PMU performance in accordance with IEEE Standard requirements.

Paper 107 from Brazil presents the initiatives of CEPEL (Brazilian Electric Energy Research Center) in relation to PMU testing and Application in the BIPS (Brazilian Interconnected Power System), including the new applications developed and implemented in the SAGE PDC, such as: stress monitoring, assistance on closing transmission loops, assistance on reconnecting islands and system oscillation monitoring. A new "Golden PMU" was presented with the purpose to test the PMU equipments during field tests (routine tests) in order to validate the results accordingly to IEEE C37.118 technical requirements.

Paper 109 from USA approaches the IEEE standard evolution and also harmonization between IEC and IEEE, that commenced in the year of 2013, with the joint working group activities completed in September 2018. Discussion about PMU class usage (P and/or M) about the most important applications such as short-circuit, fault location, low frequency detection, wide area backup protection and others are also addressed.

2.4.1 Questions

Question 1.6: What are the procedures adopted for testing, validation and homologation of PMU equipment in accordance with IEEE C37.118 Standard and how have countries dealt with PMU validation testing procedures?

Question 1.7: How are end-to-end type tests being conducted considering the entire chain of a WAMPAC system in order to ensure the required reliability? Are there any proposals or experiences that could be presented?

2.5 Wide Area Control and Situational Awareness

With the evolution and penetration of the PMU technology in the control centers around the world, the strategies of large-scale control application and the situational awareness of the operators in the control center room has propitiated a new era in relation to the control strategies.

Paper 114 from India approaches the FACTS devices implemented within the India power system over the last years. Currently, TCSC controllers use local input signals either obtained from power flow calculation or from the current measurement in the line on which they are installed. Under URTDSM (Unified Real-Time Dynamic State Measurement) project, PMU are going to be installed at all generating stations (Voltage Level ≥ 220kV). The simulation was performed using the PSSE software platform and the PMU data were used as external signals to be input in the FACTS systems in order to optimize the controllers and, with this, obtain better results as well as dumped oscillations.

Paper 115 from India presents data from the Indian Power System (installed power capacity around 350 GW).

In the sequence, the paper presents the DIR (Disturbance Indicator) application to capture disturbance events using rate of change of frequency and PMU voltage quantities, to identify the location of a sudden load or a generation loss.

Paper 119 from Russia depictures a PMU project implementation in Russia that was carried out during the development and implementation of a system for monitoring the operation of system regulators (SMSR). The main purpose of SMSR is the continuous determination of low-frequency synchronous oscillations in the normal and also emergency modes of the power system. A proposed method and condition of creating a control system on the SMSR platform is considered in the paper.

Paper 120 from Russia presents the possibility of using PMU data to implement automatic control for "liquidation" of asynchronous mode (Alarm). Using this method, it becomes possible to predict in real-time, islanding condition and also unstable power swing oscillation.

Paper 122 from Russia initially describes the Russian PMU Project Implementation, examining the effective method for IED functional analysis during electromagnetic and electromechanical transient processes, showing the performance results of the digital filters for estimation of instantaneous frequency during these conditions.

Paper 128 from Spain describes the submarine HVDC link in the Mediterranean Sea that connects the Mallorca Island with the Spanish mainland, the HVDC Control System and the Stability Function Strategy. The solution implemented is based on synchrophasor technology, IEC61850 communication for commands, PDC and PLC for processing the data and calculating the remedial actions, sending the results in fast GOOSE messages to the IED, including an operator HMI to visualize the system condition. The paper also approaches the factory and site acceptance tests, and finally, the benefits and improvements are presented.

2.5.1 Questions

Question 1.8: What are the main challenges when implementing a large-scale WAMPAC system, considering the latency of the telecommunication infrastructure?

Question 1.9: What are the proposals for validation tests of large-scale control applications, using PMU data, performed during the FAT (Factory Acceptance Test) and during the SAT (Site Acceptance Test)?

2.6 Adaptative Protection and Equipment Condition Monitoring

With the possibility of having PMU data in real time, it becomes possible to monitor the conditions of the equipment more efficiently. With high data acquisition rates, which can reach a rate up to 200 frames/s, or greater in the future, representing data reception intervals in the PDC of less than 5 ms, several applications, in the perspective of adaptive protection, become possible, improving the applications already present and in operation.

Paper 123 from Russia describes a new approach to development of one adaptive PACS system for networks with renewables, which identifies changes in operation modes of both generation and/or load using PMU data to initiate a new setpoint calculation in real-time.
The paper also approaches the process for determining external static equivalents. The IEEE 14-node test scheme was simulated and the results were analyzed.

Paper 126 from Croatia focused on an algorithm that anticipates optimal PMU placement and then uses adaptive power swing protection based on traditional IED supported by synchronized measurements quantities.
The proposed system was tested on a specific transmission system area in Croatia that is considered a mix of HPP, Wind Farms and radial transmission lines over the islands.

2.6.1 Question

Question 1.10: What are the main challenges and current difficulties in implementing an adaptive protection scheme based on PMU measurements?

2.7 Parameter Identification, Equipment Monitoring and Model Validation

With the acquisition of PMU data in real time, it is possible to carry out the monitoring of the equipment operation conditions, such as transformer load-curve, check, overload, etc. Considering PMU installed on both terminals of a transmission line, it is possible to estimate, with good precision, the line parameters, positive and zero sequence component, and thereby maximize the power transfer through the transmission line (corridor). Regarding the model validation strategy, it is possible to optimize the adjustments of the voltage and speed controllers as well as the PSS, refining the adjustments in the equipment, improving the operation, but also the operating conditions.

Paper 118 from Russia presents a new method based on the use of an adaptative model of a synchronous machine where parameters were determined through PMU data. Condition monitoring of the generation is undertaken by analyzing the operation during operation. Dynamic characteristics (behavior) of synchronous machine using PMU data were also compared (using model validation). One implemented algorithm determined the equivalent inertia and reactance via PMU data.

Paper 124 from Russia describes the new approaches to determine the external equivalent of the power system and the transfer function parameter identification using PMU data, such as stochastic gradient descending method and genetic algorithm (GA) that allows to determine the optimum parameters of adjustment of the controllers.

Paper 125 from Brazil commences by describing the Itaipu Hydroelectric Power Plant (HPP) system, one of the largest HPP in the world. Further to this, the paper presents a proposal to deploy real time PMU monitoring of safe operating regions of Itaipu HPP 60 Hz sector. Finally, the paper describes the system simulation, including double and triple contingences in the high voltage transmission system side.

2.7.1 Question

Question 1.11: What were the achieved gains and benefits with model validation (transmission line parameter, voltage and frequency controller adjustment parameter, including PSS, and others), when deploying PMU data?

2.8 PMU Optimal Placement

The optimum allocation of PMU in an electrical system has as main objective to increase its observability. Some studies have shown that when system parameters are known accurately, it is necessary to install PMU between 1/4 and 1/3 in relation to the number of busbars in the network to ensure full observability.

The best algorithms applied to the optimal allocation solution need to verify all the possible solutions for a given system model, and heuristic methods are applied to balance the computation time for the optimal and feasible solution. Therefore, it is a very important task in a project to optimize the PMU allocation already in its initial project implementation plan, especially considering its scalability in the future.

Paper 103 from China describes the methods involving heuristic algorithms such as "annealing", "minimum spanning tree", "tabu search algorithm", "genetic algorithm" and the problems with convergence speed. The paper proposes a new linear integer programming method (0-1) using a deterministic algorithm, to solve the multi-objective PMU placement problem. The new algorithm was tested by using IEEE 14 and IEEE 39 systems.

2.8.1 Question

Question 1.12: What other optimization techniques or criteria being considered for the placement of PMU equipment in electrical power systems?

3. Conclusions

The challenges, current applications and future trends involving the use of synchrophasor information under the Preferential Subject No.1 "Leveraging PMU data for better Protection, Automation and Control Systems" were addressed in the 28 papers presented from 11 different countries. The contributions were associated with the use of PMU data to improve system models, concepts related to adaptive protection, wide area control and protection schemes, power swing protection, synchronization schemes and improvements in relation to the analysis and identification of events. The technical analysis of the papers was accomplished by dividing them into 8 groups, in order to facilitate the reference according to the nearest themes. This colloquium brings together important applications and the state-of-the-art of various synchrophasor implementations from several countries. Real-time applications become more and more feasible, and qualitative and quantitative gains can already be quantified.

In general, there is a strong tendency to implement end-to-end tests in WAMPAC systems, to verify the performance of the entire infrastructure chain such as: communication channel, latency, PMU equipment performance during steady state and also dynamic operation, and the overall system solution performance implemented in the PDC. The diversity of applications involving PMU represents a new paradigm in the way of operating the electric power systems mainly in real time, being necessary the knowledge of the dynamic and transient phenomena by the operators. In this sense, there is an intrinsic need for professional training and improvement in order to successfully face these new technological advances that are already a reality and in the operation in several electric systems around the world.

With the evolution of time synchronization systems, communication infrastructure, performance of digital signal processing techniques - including improvements in the filtering and digital windowing processes, development of new algorithms in the scope of WAMPACS, now PMU is widely used in interconnected power systems, corroborating the general sense that this new technology shall be increasingly present in power system applications. The topics discussed in this Colloquium under the PS1, will surely contribute to a better understanding of the challenges of implementation as well as practical results considering different projects around the world.