Processing of PMU Data Acquisition for Operational Power System Analysis

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Abstract: Wide Area Monitoring System (WAMS) using Phasor Measurement Unit (PMU) have been widely implemented in power systems. Due to its voltage and current measurements accuracy and precision, PMU can be adopted into power system defense plan as well as WAMS. However, there are considerations of the PMU data acquisition to be able to deliver performing analysis of the electrical power system, i.e.: the synchronization of data acquisition time, reporting rate effect, data sample acquisition, and data acquisition range. This paper addresses problems in PMU data collection and method to solve them prior to carrying out analysis to achieve reliable results. Further, the proposed method has been exercised and implemented in actual power systems accordingly the data collection issues in PMU for WAMS analysis have been solved. In contrast to other studies, this research offers insight into data collections and its solutions before they are examined.

Keywords: Wide Area Monitoring System, Data Acquisition, Phasor Measurement Unit, Power System Analysis

1. Introduction

The electrical power system interconnection is one of the most complex man-made systems in operation. It tied large number of power plants in generation, connected numerous subsystems in transmission and delivery huge load to multiple points in distribution. Balance between generation and load shall be maintained in transmission allowing the operation parameters within the service level agreement. Every possible contingency and planned operation scenario, both normal and emergency circumstances shall be calculated and considered carefully and precisely. Defense schemes to anticipate the critical operation and occurrence of system disturbances shall be planned and exercised well with all means necessary from the desk jobs study to the real time system monitoring.

Statistics have evidenced that various blackout events or widespread disturbances occurred event in well designated systems and affected millions of people all over the earth. The latest incident also occurred in Indonesia power system, particularly the Java Madura Bali (JMB) interconnection systems on August 4th, 2019. This incident was recorded as one of the global severe impact blackouts in the power system.

A blackout in a power system or a widespread disruption is usually a consequence of unclear isolation of an incident in power system. Blackout can be introduced by a single disturbance in one of the backbone interconnection transmission lines or occurs when a large generating unit or large load suddenly interrupted. Particularly in Indonesia, blackouts are partly started from transmission faults followed by instability of the entire electrical power system in the connected network.

Previously, conventional duplication and main-back up transmission protection schemes have been implemented to anticipate any possibilities of fault in power system as instantaneous reactive measures followed by defense schemes i.e. automatic load shedding, frequency curtailment up to the final stage of islanding of subsystems have been set in operation contingency, to ensure the stability of power system and balance both generating and loading after the fault interruption whenever necessary. These conventional defense schemes in JMB have been now improved into Adaptive Defense Scheme (ADS) that allowed the composition of

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generating units, network configuration and load variations are accounted to the dynamic of defense scenarios to enable more flexible system reconfiguration post disturbance events. Both conventional and adaptive defense schemes utilize SCADA as main support system which

This research will be devoted especially to the PMU (Phasor Measurement Unit) data acquisition which is able to provide the required data more quickly than conventional Supervisory Control and Data Acquisition (SCADA) / Energy Management System (EMS) and more widely monitoring range compared to conventional protection systems.

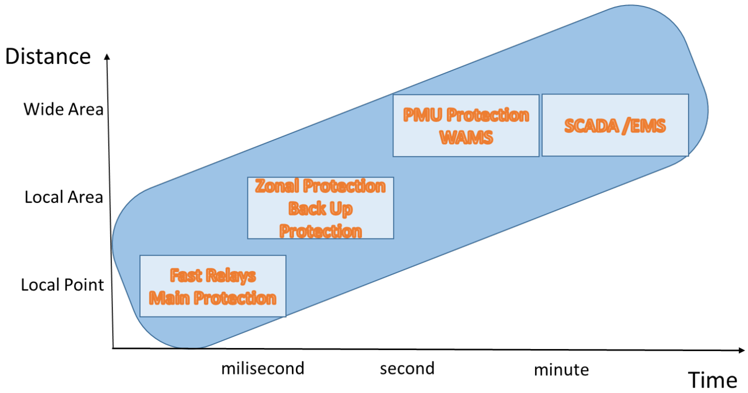


Fig. 1. Power System Protection and Operating Time

Wide Area Monitoring System (WAMS) for power system is implemented in many electric utilities. The development and improvement of large power interconnections management on the basis of new computer and information technologies is focused on using electrical regimes parameters synchronized measurement [1]. Phasor Measurement Unit (PMU) can be utilized to collect data for the implementation of WMAS and power system defense schemes [2-4]. The PMU is utilized for accurate voltage or current measurement. According to [5], the accuracy of PMU measurement can approach 120 samples/second, allowing the PMU to be used for a variety of system stability assessments, including small signal stability or interarea oscillation, remedial action schemes, and adaptive defensive schemes. Furthermore, measurement data from two or more PMUs is required prior to conducting a system stability study utilizing WAMS or a Special Protection Scheme (SPS). [6]

Research has indicated that investment in communication networks and PMU measurements is the most competitive cost and most feasible to achieve budget optimization added to PMU observations can be carried out well technically [7]. Placement of PMUs in an power system can be optimized that all buses can be observed including cost minimization, telecommunications infrastructure using the BICA and Dijktra algorithms [8]. Optimization of PMU placement shall observe 2 criteria in phasor measurements, namely measurable and calculated [14]. Various communication channel methods, clocking, PMU classes, etc. have been simulated to investigate their latency [9].

Research has addressed various concerns on acquiring data from a PMU for power system study. This study suggested factors that should be considered while acquiring data from several PMUs, i.e. data acquisition time synchronization, reporting rate effect, data sample acquisition, and data acquisition range. This paper novelty is on data collecting consideration, challenges and remedies prior to proceeding further into analysis process to obtain an accurate outcome.

2. Data Acquisition Factors That Affecting the Analysis of Multiple PMU Data

A. Time Synchronization

PMU must be able to be synchronized to UTC (Coordinated Universal Time) time with accuracy that meets the requirements of IEEE Std C37.118.1 [10-11]. The utilization of the GPS (Global Positioning System) antenna for PMU has an impact on data synchronization. Fig. 2

illustrates how several PMUs are time-synchronized with the use of GPS satellite. Nevertheless, many PMUs are not always in synchronous mode due to their GPS antenna capability restrictions. Monitoring PMU data will not function effectively in case of issues with GPS time synchronization and the telecommunications system [12]. The tagging time for measurement between PMUs varies as a result as well as the analysis precision.

There is variation in the quality of the GPS antenna that PMU uses to gather data. Some antennas are quite exact at identifying satellites, whereas others are not precise enough. The PMU measurement time tag will become void if the GPS antenna is of poor quality. While it is possible to perform the measurement time tag, there are variations of several milliseconds. As illustration: The GPS antenna at site B receives 7-8 satellites for time synchronization, but the antenna at location A only detects 3–4 satellites. In this case, GPS antenna place B shall be more precise than of location A.

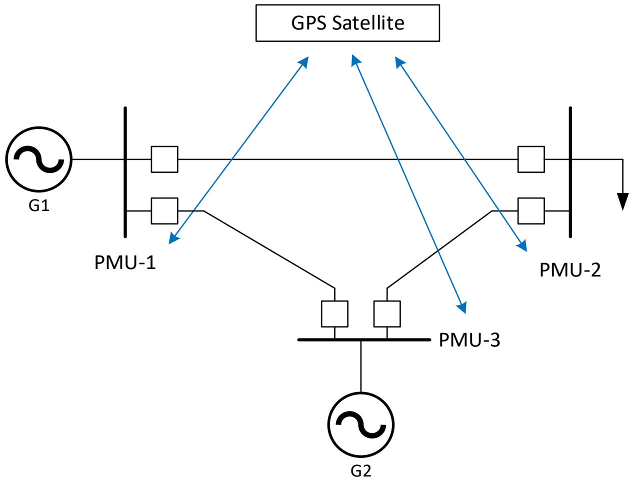


Fig. 2. GPS Satellite for Time Synchronization

Things that induce the quality of the GPS antenna in acquiring satellites are location, weather conditions, satellite acquisition method, and type of antenna. An antenna placed outdoors will be more effective in detecting satellites than those placed indoors. Rainy, overcast, and bright weather have impacts on how well the antenna detects satellites. Furthermore, the GPS antenna's quality will undoubtedly be enhanced by the already sophisticated satellite collection technique. Numerous investigations into GPS signal gathering techniques have been carried out in [13–14]. Various GPS antenna types must also be taken into account as their specifications vary. If these circumstances are not satisfied, PMU time may be out of synchronization and the analysis of these data will result in a less accurate outcome.

B. Reporting Rate

Another thing that must be noticed in data acquisition is the setting of reporting rate in PMU. PMUs must provide reporting rates of 10, 25, and 50 frames per second for 50 Hz fundamental frequency [10-11]. Table 1 shows options of reporting rate setting for 50 and 60 Hz fundamental frequency, which can be adjusted according to requirement.

As previously stated, two or more PMUs are required for analysis. An analysis error could occur if each PMU has a distinct reporting rate. A signal reporting at a rate of 50 frames per second indicates that 50 data frames are reported every second, and each frame takes 20 milliseconds to process. There is possibility that the data cannot be compared if there are differences in the reporting rates amongst various PMUs.

Table 1. Required PMU Reporting Rate
Source: IEEE Std C37.118.1-2011

System Frequency	Reporting rate (Fs – frame per second)
50 Hz	10
	25
	50
60 Hz	10
	12
	15
	20
	30
	60

C. Sampling Data Acquisition Technique

It's not necessary to run the continuous analysis procedure in the absence of triggers. For instance, it is known that network switching, major load shifts, reclosing, and prior short circuit disruptions can all contribute to these incidences when analyzing minor signal stability. After the occurrence of any event, it is resolved that the analysis process may proceed. To commence the monitoring of the PMU readings, the triggers and their settings must be defined by the system operator in the interconnected power system.

For example, tiny signal stability analysis necessitates full measurement data from the pre-, during, and post-event periods. There's a chance that measurement data is lacking if the analysis is done directly with real-time data. Fig. 3 describes the measurement data illustration. First In First Out (FIFO) data from PMUs is fed into a data array of size n for analysis. When an event occurs (a major shift in load, a fault, etc.) for the pre-event issue, the data to be analyzed is the data that was stored in the data array at the corresponding precise moment. Data collected prior to the occurrence of such event is then not preserved.

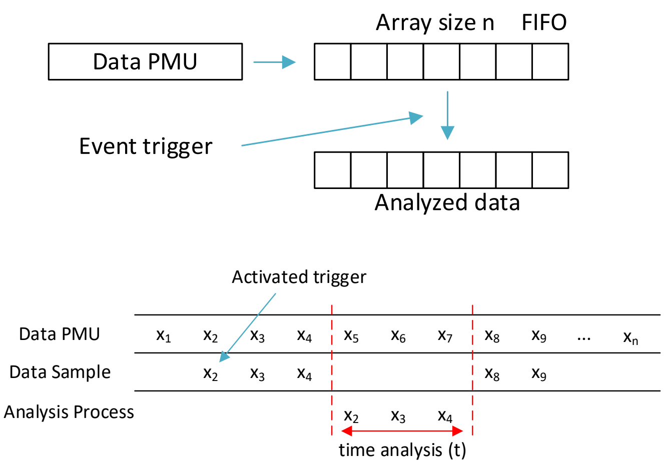


Fig. 3. Real-time Data Collecting Technique

D. Range of Data Acquisition for Analysis

The previous section mentions that small signal stability issues may be promoted by fault, switching, change of load, or reclosing. A variety of samples are required for the detection and analysis of low-frequency oscillation in the power system since it impacts the analysis time range. The analysis time range increases with the number of data samples required for analysis due to application memory consumption.

Analyzing such as small signal stability is used to determine the impact of the system fault to maintain the stability of the system. The tolerance for system stability is approximately range up to 30 seconds, as shown in Fig. 4. Then, in order to have more time to carry out necessary action within that 30-second time window, the analysis results must be able to be communicated in less than 30 seconds. A set of 750 sample data are required if the reporting rate is set to 50 frames per second and the analysis time frame is estimated to be 15 seconds.

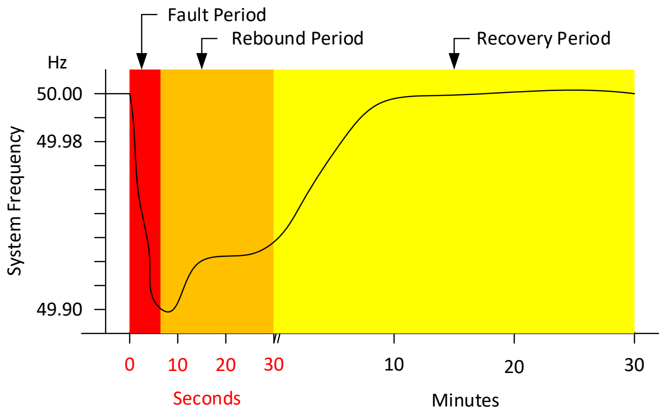


Fig. 4. Sequential Action and Impact on System Frequency Control

3. Data Acquisition Solution & Result

When analyzing the sampling data acquisition, two considerations must be taken into account i.e. time synchronization and sampling data acquisition technique. These issues can be solve by validating data and overlapping data acquisition technique. Described in Fig. 5, this method is used to solve the above problems, namely time synchronization, reporting rate setting, sampling data acquisition techniques and data acquisitions range for analysis. Validation data process is done to solve problems with time synchronization and reporting rate. The concept is that the incoming data from some PMUs will be validated where the time tag data received will be checked. If not valid then there is a follow-up to check the setting time synchro and reporting rate of the PMU. The concept is to perform a temporary data storage that will represent a pre-event to get an entire event with enough data range for fault, rebound and recovery periods to make the analysis more accurate.

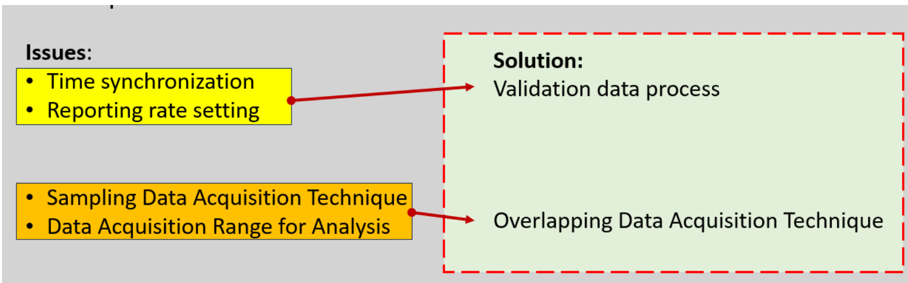


Fig. 5. Solution of Data Acquisition Problem

A. Validation data process

In essence, analysis might take place in a centralized server following data collection. Instead, distinct GPS antennas are used by PMUs that are installed in multiple substations at different remote locations. Thus, a checkpoint is required to synchronize time across several PMUs prior to the data being transmitted to the analysis database in the centralized server. A data validation procedure is depicted in Fig. 6 prior to data analysis. The information of date and time of the data are those to be verified. An error data notification appears when the information of time or date of data differs one from another. Afterwards, an event's power system study could be performed. This concept is implemented in the power system analysis dashboard, as seen in Fig. 7.

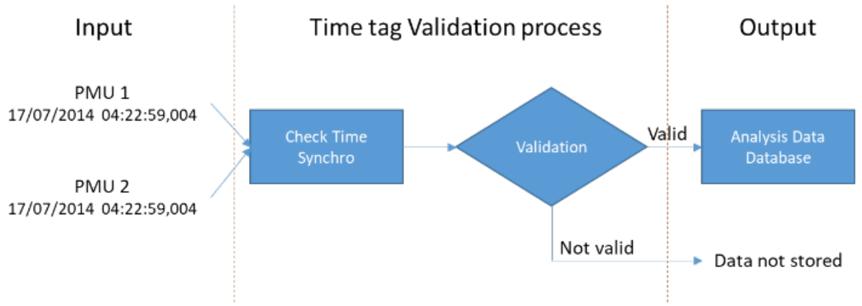


Fig. 6. Data Validation Process

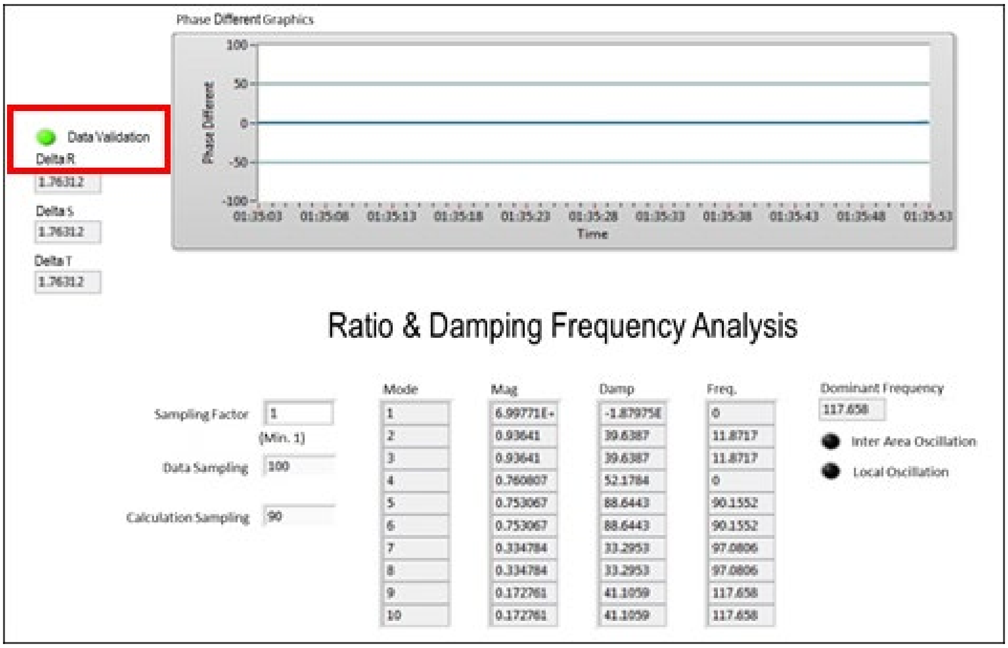


Fig. 7. Data Validation Dashboard Implementation

B. Sampling data acquisition technique

The analysis in the previous section requires all data measurement data from the pre-, during, and post-event periods. However, due to the application's memory utilization, the analysis time range will add up with the number of data samples required for analysis. This method of acquiring data will be the solution to overcome this issue. Overlapping data samples are employed in the sample data collection approach, where additional data is added to the sample data that is saved to account for pre-event conditions prior to the trigger event being triggered.

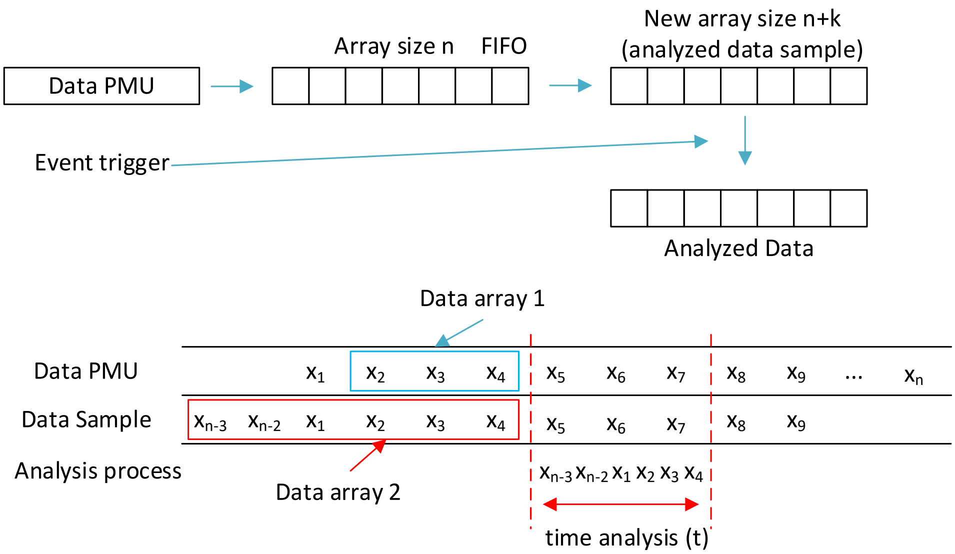


Fig. 8 Overlapping Acquisition Data Technique

Fig. 8 shows overlapping acquisition data technique. PMU measurement data is stored in the first data array (event database) with n-size according to FIFO data flow. In this technique, n+k, where k is the variable overlap data required for the pre-event, is used to generate a new array (analytical database). When there is a trigger in the occurrence of an event, the pre-event data is still attached for analysis in addition to this new array. The procedure for data analysis is shown in Fig. 9. As an illustration, the size of the analytical database is six and the event database is three. Pre-event, event, and post-event data are used for analysis when an event occurs in x2 as in Fig. 8. This overlapping technique refers to flow data which is gathered on-site and examined to determine whether any event triggers exist (analytical database).

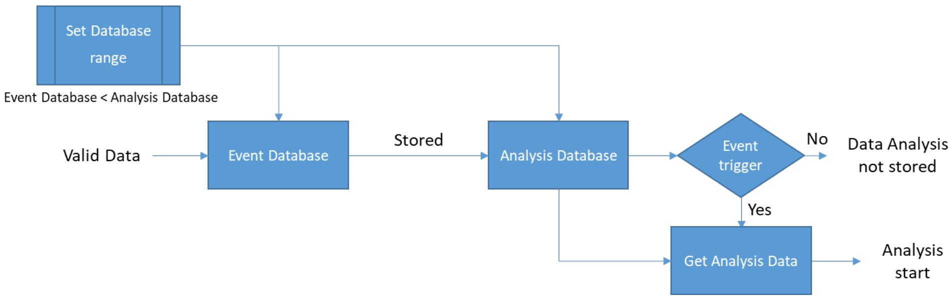


Fig. 9 Data Analysis Process

Fig. 10 shows the application of the overlapping acquisition data technique in an unstable power system following a fault state as the validation procedure consecutive. The analysis process requires 5 second time frame data from the pre-event to the post-event i.e. a total of 252 data. This data consists of 52 pre-event data (1s) and 200 event and post-event data (4s). A power system that is unstable has been identified in the implementation outcome.

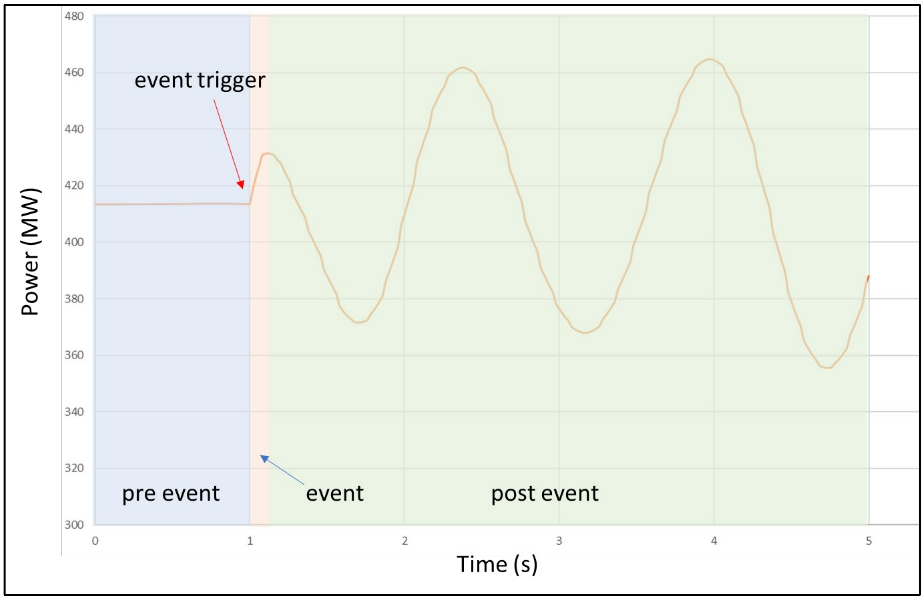


Fig. 10 Unstable Power System Event

C. Power System Simulation

The Kundur's four-machine two-area test system [15] model was employed to obtain the data of electrical parameters i.e. current, voltage, and frequency in each bus in the network. The simulation will automatically generate data of the system covering either stable or unstable condition after the huge disturbance. Electrical parameters on each bus will be sampled with different reporting rates i.e. 25 samples/second and 50 samples/second.

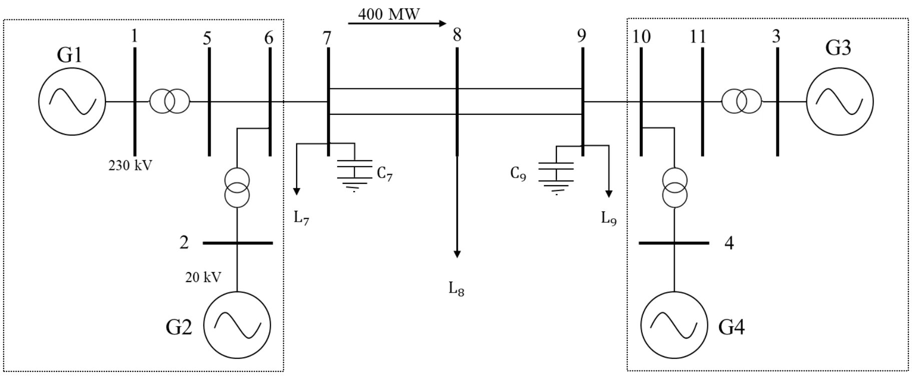
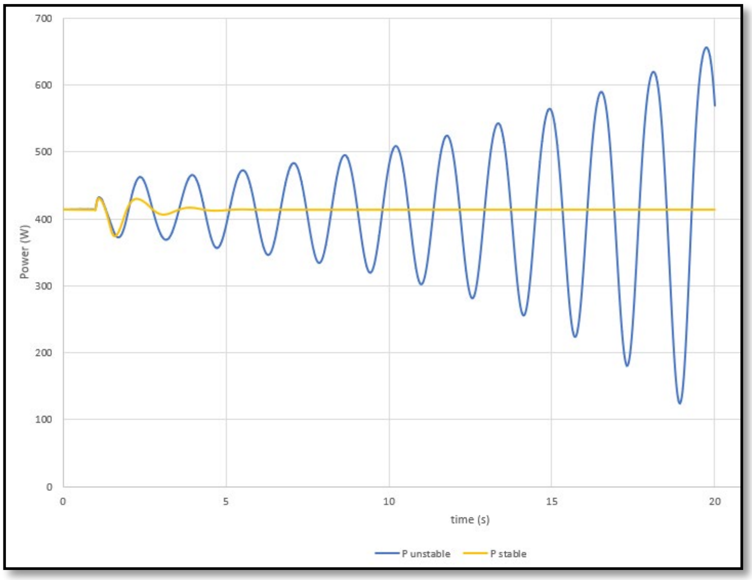
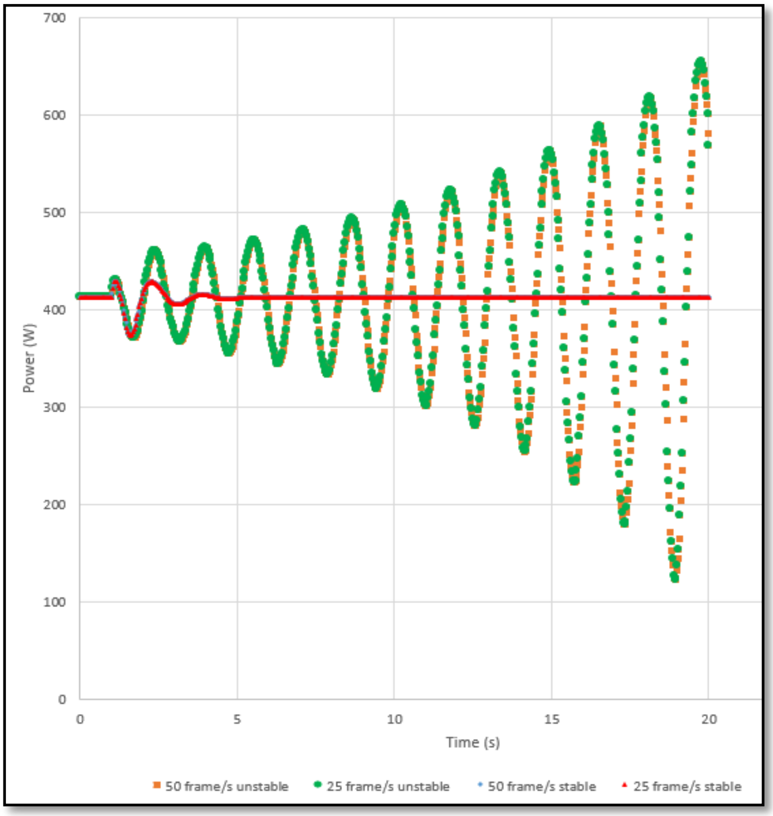


Fig. 11 Kundur's Four Machine Two Area Test System [14]

The test will be conducted under two different conditions: the stable power system condition following a three-phase fault on the tie line and the unstable power system condition with a small signal instability/low frequency oscillation following other event. Although the data frame time tag differs, there are data gaps even though the supplied data truly coincides. As a result, each PMU's reporting rate settings need to be checked. Fig. 12(a) shows power data of two waveforms. The waveform of steady oscillation is marked by the yellow line. The waveform oscillates as can be seen, but rapidly damped and stabilized. On the other hands, the blue waveform indicates the unstable oscillation waveform that is undamped.



(a)



(b)

Fig. 12 Stable and Inter-area Signal with 50 frame/s and 25 frame/s
(a) Smooth Line Signal (b) Scatter Signal

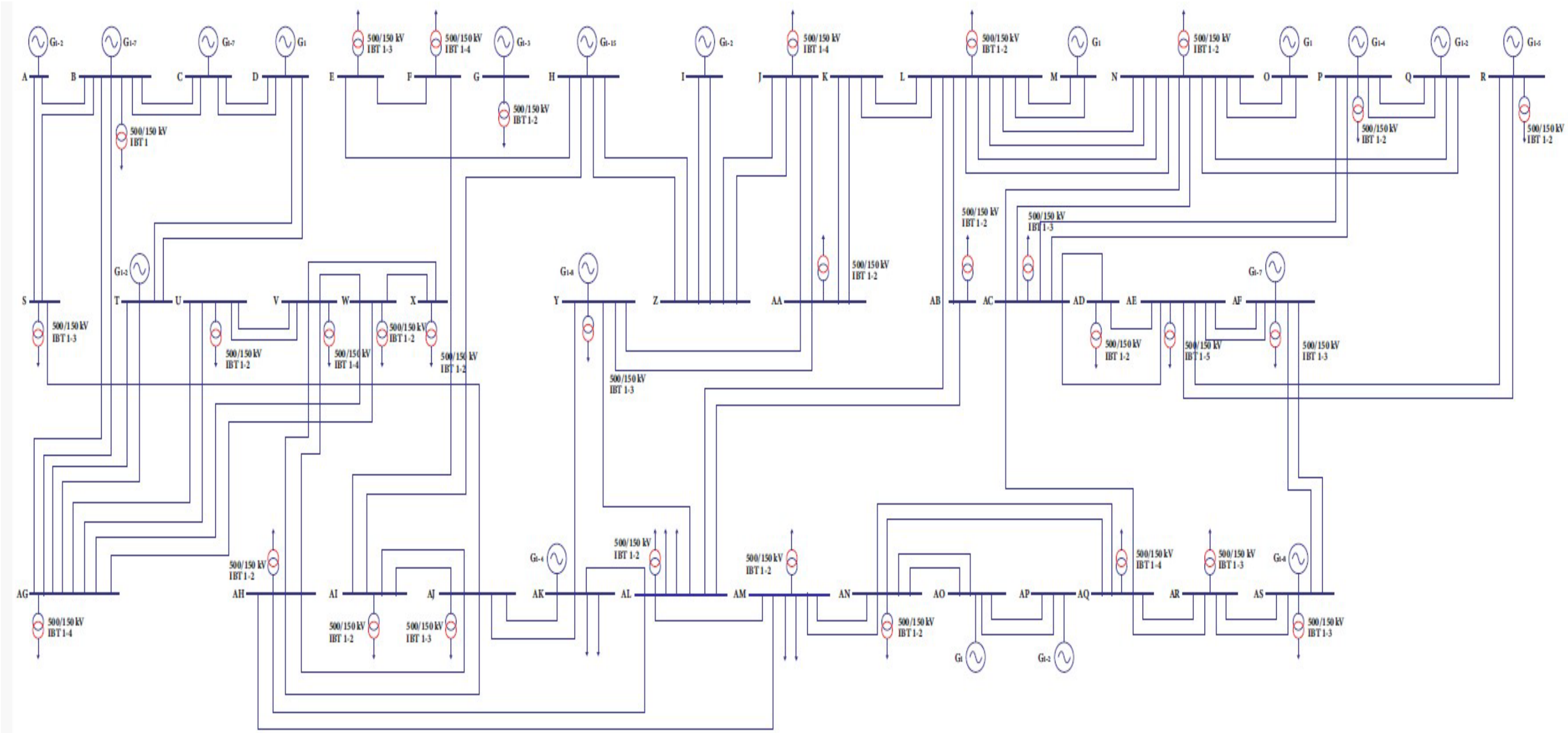


Fig. 13 500 kV Power Siystem Interconnection

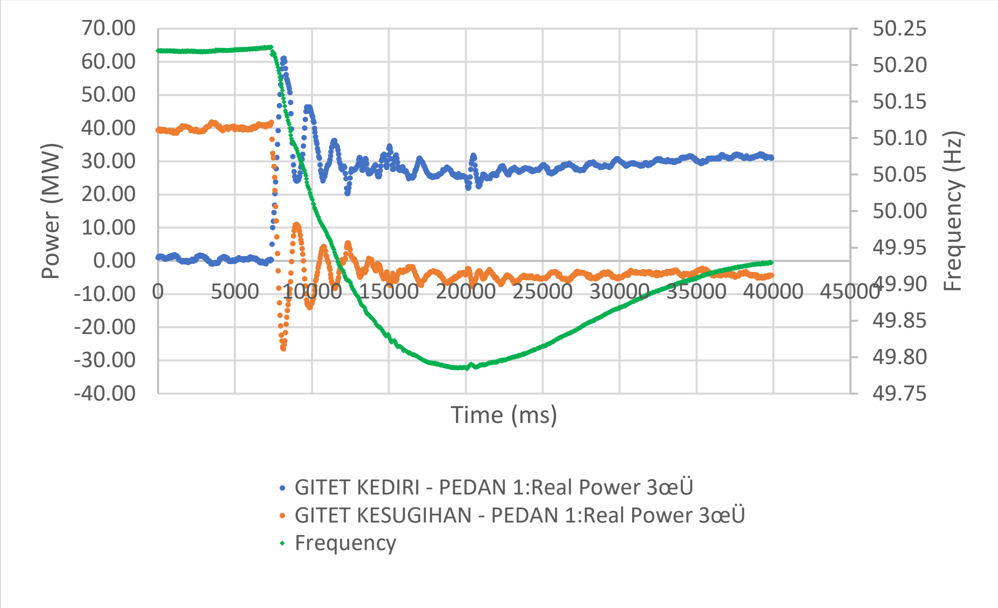


Fig. 13 Power Flow Change and Frequency during Load Rejection Test

D. Real Power System Measurement

The actual measurement of PMUs was set in the 500 kV Indonesia interconnection system. This real power interconnection system consists of 500 kV buses of which 45 buses are extra high voltage (EHV) substation in the whole power system interconnection. The first event occurred during a load rejection test at one of the generators in bus I, which produced 880 MW out of the total load of 30,000 MW (or around 3% of the load). The frequency (green line) of the power system dropped from 50.227 Hz to 49.875 Hz during the test. The measurement also detected the damped oscillation during this event as shown in Fig. 14. PMU measurement was reported at a rate of 25 frames per second.

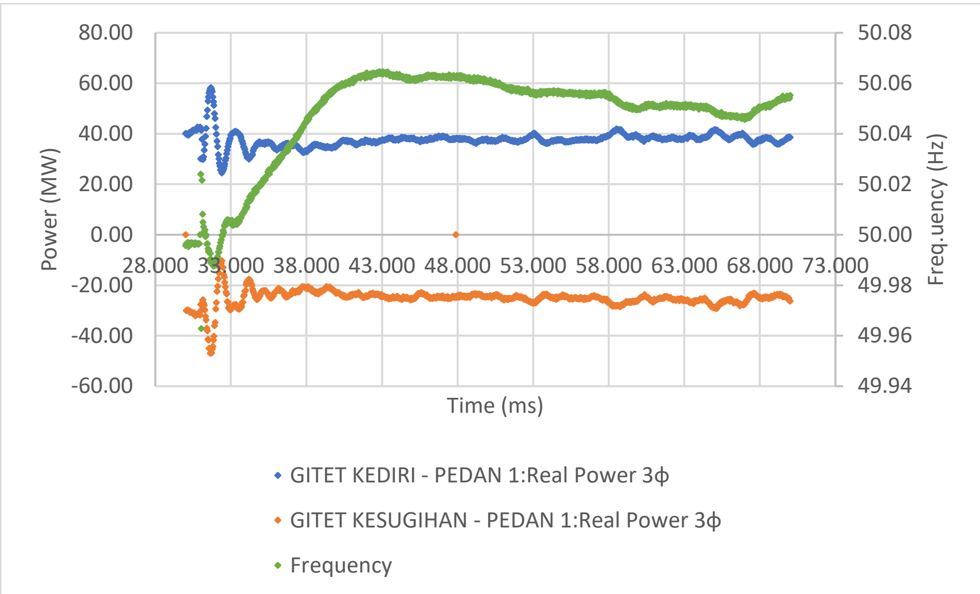


Fig. 15 Power Flow and Frequency during Phase to Ground Fault

Fig. 14 and Fig. 15 also show us the data acquisition of the PMU can be analysed for further real time power system analysis in wide area monitoring system.

As presented in Fig. 16, the power flow between the line and substation in the power system interconnection altered during the load rejection test at bus I i.e. at the transmission line between bus AR and bus AQ (blue line) and transmission line between bus AN to bus AQ (brown line). It can be seen also the damped power oscillation before the power system condition stabilized.

The second incident, of which power flow measurement presented in Fig. 15, occurred at 500 kV extra high voltage (EHV) overhead line (OHL) connecting bus AI to AJ during a phase to ground fault. The transmission main protection cleared the fault in 50 ms and then reclosed after 900 ms. The power system's frequency (green line) and power flow at the transmission line between bus AR and bus AQ (blue line) and transmission line between bus AN to bus AQ (brown line) were not changing all that much.

4. Summary

Multiple PMUs are used in utilities to construct Wide Area Monitoring Systems. The processing of data from several PMUs becomes crucial in order to solve power system issues. Prior to analysis, there are, nevertheless, certain data collecting concerns that must be taken into account. Time synchronization, reporting rate, data sampling methodology, and analysis sampling range are among the concerns. In order to enhance power system analysis outcomes in WAMS, the real power system interconnection has effectively applied the solution to this data acquisition problem.

In conclusion, this study has provided valuable insights into data acquisition issues. It is crucial to recognize its drawbacks, too, as they include the power system analysis approach, real-time data processing, and noise reduction for actual field data. These limitations imply that there is still a lot to learn about this area. In order to have a more thorough grasp of the power system analysis utilizing WAMS, it is advised that future research projects dig further into the noise reduction, real-time data processing, and the power system analysis technique elements. We can provide the foundation for a richer and more complex corpus of knowledge in real-time power system analysis by tackling these topics.

5. References

[1] Zolin D.S, Ryzhkova E. N. 2021. "Wide Area Monitoring System (WAMS) Application in Smart Grids". 3rd *International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE)*, Rusia

[2] Nanda P., Panigrahi C.K., Dasgupta A. 2017. "PMU Implementation for a Wide Area Measurement of a Power System". Device for Integrated Circuit (DevIC), India.

[3] Golshani M., Taylor G.A., Pisica I., Ashton P. 2013. "Implementation of Wide Area Monitoring System and Laboratory -based Deployment of PMUs". *International Universities Power Engineering Conference (UPEC)*, Ireland.

[4] Wang Y.J., Liu C.W., Liu Y.H. 2005. "A PMU based Special Protection Scheme: A Case Study of Taiwan Power System". *International Journal of Electrical Power and Energy Systems.*

[5] Dusabimana E., Guk Yoon S. 2020. "A survey on the Micro-Phasor Measurement Unit in Distribution Networks" *MDPI Journals, Electronics* 2020, 9(2), 305, http://doi.org/10.3390/electronics9020305.

[6] Ghosh D., Kumar C., Ghose T., Mohanta D.K. 2014. "Performance Simulation of Phasor Measurement Unit for Wide Area Monitoring System" International Conference on Control, Instrumentation, Energy & Communication, India.

[7] Phadke, A.G., Thorp, J.S. 2008. "Synchronized Phasor Measurements and Their Applications", Springer.

[8] Mohammadi, M.B., Hooshmand, R.A., Fesharaki, F.H. 2016. “A New Approach for Optimal Placement of PMUs and Their Required Communication Infrastructure in Order to Minimize the Cost of the WAMS”, *IEEE Transactions on Smart Grid* Volume 7 84-93.
[9] Hussain A., Ahmed A., Magsi H., Soomro J.B., Bukhari S.S.H., Ro J.S. 2021. ”Adaptive Data Length Method for GPS Signal Acquisition in Weak to Strong Fading Conditions”. MDPI Electronics 2021, 10, 1735.
[10] IEEE C37.118.1 Std. 2011. “*IEEE Standard for Synchrophasor Data Transfer for Power System*”.
[11] IEEE C37.118.2 Std. 2011. “*IEEE Standard for Synchrophasor Data Transfer for Power System*”.
[12] Dakhlan D. F, Dityagraha R. D., Popov M. 2015. “Experience of Design and Implementation Intranet based Telecommunication for Phasor Measurement” *IEEE International Conference on Smart Energy Grid Engineering (SEGE)*, Canada.
[13] Bose S. 2018. “GPS Satellite Signal Acquisition and Tracking” ECEN 5254 Remote Sensing Signals and Systems University of Colorado, USA.
[14] Blair, S.M., Syed,M.H., Roscoe, A.J., Burt, G.M., Braun, J.P. 2019. “Measurement and Analysis of PMU Reporting Latency for Smart Grid Protection and Control Applications”, *IEEE Access* Volume 7 48689 – 48698.
[15] Kundur, P 1994. ‘Power System Stability and Control”, McGraw-Hill Inc., New York, USA.
[16] Dakhlan D. F, Dityagraha R. D., Hariyanto N, Soedjarno B.A. 2023. “Consideration of PMU Wide Area Monitoring Data Acquisition for Operational Analysis” *IEEE International Conference on Electrical Engineering and Informatics (ICEEI)*, Indonesia.

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