Memorias de SICEL 2023 | UNIVERSIDAD NACIONAL DE COLOMBIA

Identificación de Diferencia Angular en Sistema de Distribución con Energía Fotovoltaica

Identification of Angular Difference in Distribution System with Photovoltaic Energy

Andrés Felipe Duque Montenegro[1], Alvaro Zambrano[2], Javier Rosero Garcia[3]

[1,2,3] Electrical Machine and Drives, EM&D, Department of Electrical and Electronical Engineering, Faculty of Engineering, Universidad Nacional de Colombia, Bogotá, Colombia
[1] **Orcid:** 0000-0001-8451-1833, **Email:** afduquem@unal.edu.co
[2] **Orcid:** 0000-0002-1038-201X, **Email:** jaroserog@unal.edu.co
[3] **Orcid:** 0000-0003-2690-4772, **Email:** aazambranop@unal.edu.co

Recibido: 22/06/2023. Aceptado: 22/08/2023. Versión final: 24/09/2023

Resumen

El comportamiento angular del sistema eléctrico tiene un interés de estudio por la diferencia de fase entre los ángulos de las tensiones en dos nodos, si estos están interconectados en la red eléctrica permite establecer un indicador de la estabilidad del sistema. En este artículo se presenta la implementación de una aplicación de red WAMS para el estudio de la diferencia angular en el sistema eléctrico del Campus Universitario, esto mediante la aplicación de un algoritmo de categorización que permitió agrupar eventos relacionados con la diferencia angular entre dos puntos de la red relacionados con un sistema de generación solar, esta aplicación permitió encontrar que el ángulo de fase de la tensión entre los dos nodos donde se ubican las PMUs tiene oscilaciones asociadas a la generación fotovoltaica, caracterizando la región de operación del sistema relacionada con su diferencia angular en un nodo del sistema..

Palabras clave: unidades de medición fasorial; diferencia angular; energía solar; clasificación de aprendizaje de maquina; sistema de distribución de potencia

Abstract

The angular behavior of the electrical system has an interest of study by the phase difference between the angles of the voltages at two nodes, if these are interconnected in the electrical network allows to establish an indicator of the stability of the system. This article presents the implementation of a WAMS network application for the study of the angular difference in the electrical system of the University Campus, this by means of the application of a categorization algorithm that allowed grouping events related to the angular difference between two points of the network related to a solar generation system, this application allowed finding that the phase angle of the voltage

Como citar: A. F., Duque Montenegro, A. Zambrano and J. R. Garcia, “Identification of Angular Difference in Distribution System with Photovoltaic Energy,” in *XI Simposio Internacional de Calidad de la Energía Eléctrica*, Valledupar: Universidad Nacional de Colombia, Nov. 2023. doi: https://doi.org/10.15446/sicel.v11.109321

between the two nodes where the PMUs are located has oscillations associated to the photovoltaic generation, characterizing the region of operation of the system related to its angular difference in a node of the system.

Keywords: phasor unit measurement; difference angular; solar energy; machine learning classification; distribution power system

1. Introduction

The phasor measurement units allow to obtain the magnitude and angle at a specific point of the electrical system, the obtained phasors of voltage and current are measured with a high resolution to be synchronized by means of a GPS with other phasor measurement units. These devices facilitate new studies in the electrical system, being widely used to monitor power systems [1]. PMUs were developed in order to be able to evaluate the electrical system in a synchronized way and have high-speed responses to any event in the system, with the advent of these devices an entire architecture has been developed for monitoring, protection and control of the system [2]; An example of this is the development of wide area monitoring systems (WAMS) that encompass the deployment of several PMUs that send the measured information to one or more phasor data concentrators, in order to integrate them and subsequently analyze them to respond to system events. These technologies are born as a need in power system monitoring, due to the development of Synchrophasor concepts and applications [3] in the 80s and fault events occurred in the United States, Italy, Greece and Nordic countries around 2003.

The first prototype of modern PMU technologies in the world was born at Virginia Tech in the early 1980s, with the United States being one of the countries that has pushed these technologies the most [4]. In the western part of the US, research and prototype testing efforts were boosted by the California Independent System Operator (CAISO) in 2002 [5], thanks to this initiative they have had about 420 PMUs installed in the Northeast, 400 PMUs in the Midwest, 150 PMUs in the South, 120 PMUs in Texas, 500 PMUs in WECC and at least 300 PMUs in Mexico [6]. In China between 1995 to 2002, about 30-40 PMUs were installed at major WAMS data concentrator stations these were established in eastern China, southern China and northwest China. At present China has PMUs in all 500 kV substations, some major 220 kV and 100 MW substations. In total, more than 3000 PMUs have been installed being a reference in the implementation of these technologies [7]. In Europe, PMUs are distributed in seven regions of the continent improving the control with synchronized phasors, this infrastructure allows real-time detection of phase angle differences of a region with the rest of the country, enabling monitoring in the operations center [4]. Transmission lines in the region are interconnected with different countries in the continent, these are disconnected from the interconnected system once the angular difference between two nodes exceeds the established limits, thus clearing any failure that could cause the other systems to collapse.

In Latin America there are also different experiences in PMU, since the end of 2000, the Brazilian ISO ONS has launched two projects related to WAMS that aim to implement a large-scale synchronized phasor measurement system (SPMS), both for off-line and real-time applications [8]. The former a phasor recording system to record system dynamics during long duration disturbances, and the latter an application of phasor measurement data for real-time system control decision making. Another example in the region is the implementation carried out by CENACE (the national electricity operator of Peru) in which 22 PMUs allow monitoring areas of high operational relevance obtaining a better observability of the system [9]. In Colombia, XM's National Backup System in the event of large-scale events (SIRENA) project was presented, which seeks to implement a new generation System Integrity Protection Scheme (ESPIS) in the long term [10]. This arises due to the collapse of the system in 2007 in order to control and protect the system by allowing the deployment of 12 phasor measurement units to analyze the behavior of the network, making it possible to find phase lags at different geographical points of the system in the phasor angle and prevent the occurrence of large magnitude events in the National Interconnected System.

The experiences of deployed PMU systems have shown that synchronized measurement technology is necessary to accurately analyze and control the performance of the power grid of different countries in real time and off-line PMU technology has been beneficial for synchronized data analysis and early warning systems, improving system models for optimal monitoring and control of the power grid. In addition to the implementations in different countries, universities have joined efforts in the creation of small and large scale pilots of these devices, in [11] a virtual WAMS is presented at laboratory scale applicable to test future applications. In this case for the development of tests a physical network at laboratory scale was used, which has 4 buses: 1 load, 1 generation and 2 maneuver buses monitoring the voltage and current phasors of each of the buses with a data transmission rate of between 10 and 60 packets per second. Information on the components and requirements of WAMS is presented in [12], along with an implementation of a pilot system in the Brunel University laboratory based on hardware in the loop for the incorporation of an adaptive observer to estimate phasor quantities. One of the most important elements of the phasor measurement units is the ability to estimate the angular difference between buses of the same system, with their respective GPS synchronization. In order to join efforts in the research of these devices, a pilot system is implemented with 2 PMUs connected to the servers of the LAB+I smart grid laboratory and synchronized to monitor the angular difference between two nodes of the electrical distribution network of the National University of Colombia. The first PMU is connected to a 11400 V node on the high voltage side of the transformer and the second PMU is connected to a 127 V node on the low voltage side of the transformer.

2. Materials and Methods

The phasor measurement units (PMU) are devices made up of different blocks that are responsible for pre-processing the voltage and current phasors through an anti-alliasing filter that is responsible for rejecting the frequencies that are not of interest, once the main signal is filtered it passes through an A/D converter that samples the signal with a high resolution. With the digital signal, the phasor measurement unit processes the digital signal information to extract the phasors and synchronize the information through a GPS receiver. This information is sent through the IEEE C37.118 protocol generating a data stream with a storage or display system. These devices calculate the phasors of the nodes where they are located, with the great advantage of performing the measurements in a synchronized manner among all PMU units [14]. Likewise, these devices have the capacity to calculate up to 60 phasors per second, increasing the observability of the monitored systems.
The collected data are sent to a phasor data concentrator that allows the arrival of different phasor measurement units, according to the IEEE C37.244-2013 representation [15], the main and most important function of the PDC is to aggregate and forward data from multiple PMUs according to the GPS receiver timestamps. Based on these guidelines, IEEE introduced in 2019 the PDC standard IEEE Std C37.247-2019 [16], which specifies the requirements for PDC. With the development of technology in this area, PDC also has the ability to process and store data and configure more functions according to different requirements. The implementation of distributed phasor measurement units in an electrical system, together with sending the information to phasor data concentrators to develop end-use applications in the system generates the concept of wide area measurement systems WAMS.

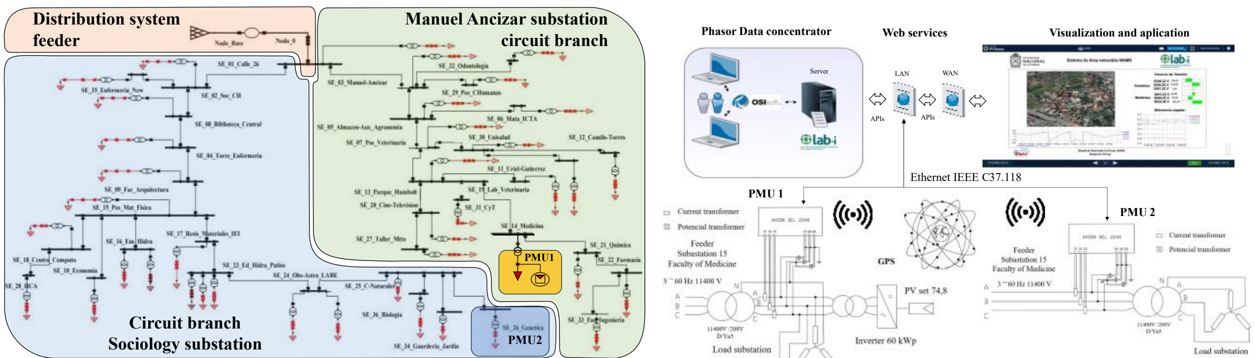
$$\hat{V}_{Bus1}(t) = \hat{V}_m \cos\left(\omega t + \hat{\emptyset}_1\right) \quad (1)$$

$$\hat{V}_{Bus2}(t) = \hat{V}_m \cos\left(\omega t + \hat{\emptyset}_2\right) \quad (2)$$

$$\widehat{\Delta\emptyset}_{Bus}(t) = \hat{\emptyset}_1 - \hat{\emptyset}_2 \quad (3)$$

They are defined as software applications that process the phasor information stored in the PDC for a specific purpose (real-time monitoring, power system control, safety and protection, parameter characterization and fault location). The following are the applications that can be used with the implemented phasor measurement system. Normally, power systems are monitored through SCADA systems, which have information update rates ranging from a few seconds to even periods of minutes, providing information that is not synchronized between the different monitored nodes, in [20] a comparison between SCADA systems is made. This represents a great disadvantage when analyzing events of very rapid occurrence, since, under this monitoring scheme, it is not possible to accurately identify the behavior of this type of incident [21]. Likewise, it is difficult to make control decisions about the system when faced with this type of event, since the variables of the electrical system are not precisely known.
The smart grid laboratory LAB+I is a platform for the integration of different measurements both from the university campus and external entities [27]. This currently has an infrastructure deployed throughout the campus for the measurement of electrical variables of the system has a set of servers that store, monitor, and visualize the measurements, which allows consulting historical data and observing them in real time for analysis.
This infrastructure is used for the implementation of a monitoring system with phasor measurement units in the electrical system of the Universidad Nacional de Colombia. The internal network of the National University is composed of a local distribution system (SDL) of voltage levels 1 and 2, and has 2 branches that interconnect to the main node at the substation on 26th Street which is fed from the national interconnected system SIN at 11. 4 kV, defining the commercial border between the Campus and the distribution system. Figure 1 shows the implementation of the pilot WAMS in the distribution system of the university campus, the Figure 1a shows the topology of the distribution system, which has a primary distribution circuit in radial topology of 11.4 kV, a secondary distribution system of 208 V and a photovoltaic generation system in the medical school. Figure 1b shows the architecture of the implemented application, the data from the two phasor measurement units are sent to a data concentrator hosted in OSISOFT via Ethernet connection and IEEE C37 protocol. 118, once the information is received in the concentrator it is

stored and the phasor data is processed to find the angular difference between the two measured nodes, the medicine node must be adjusted with the transformer phase shift referring the low voltage side to the high voltage side, in order to synchronize the measurements with the voltage angle seen by the PMU installed in Genetic bus. Being an oscillatory system, the angles can move forward or backward depending on the point where they are, this causes the medicine angle adjustment value to vary depending on the point where the system is located. With the adjusted angles we proceed to subtract the angles of the two nodes, verifying that being a distribution system and not having a considerable distance, the subtraction of the angles oscillates in 0.



a. National University distribution system. Adapted from []

b. Architecture WAM application

Figure 1. Implementation of a test WAMS in university campus

The first PMU is located at the medical school substation, this building has a 60 kW peak power photovoltaic system, this is interconnected to the grid at a 208 V connection point on the low voltage side of the transformer upstream of the photovoltaic system and the building load. This PMU is located on the second branch of the campus electrical system and is one of the last circuits on this branch.

The second PMU is located in the genetics building which is located in the last substation of the first branch of the campus electrical system, the connection point of this PMU is 11400 V on the high voltage side of the transformer measuring the total load of the substation. The transformers of the system have a delta connection in their high voltage winding and a star connection in their medium voltage winding, the connection of the windings of these transformers generate an offset between the phase angles of the high voltage and low voltage side of 150°, this connection is called DY5.

In order to evaluate the behavior of the system, a time series simulation of the system presented in Figure 1 is carried out, in order to see the approximate angular difference that would be obtained between the nodes to be studied. Figure 2 shows the results of one day of simulation, where the phase angle is -0.5549 ° having in principle a constant angular difference due to the distance of the nodes and a dynamic difference due to the variation of the load in each of the nodes. The generation of solar energy at the medicine node also causes the angular difference between the nodes to increase, being more significant between 10 and 16 o'clock when there is a greater generation potential.

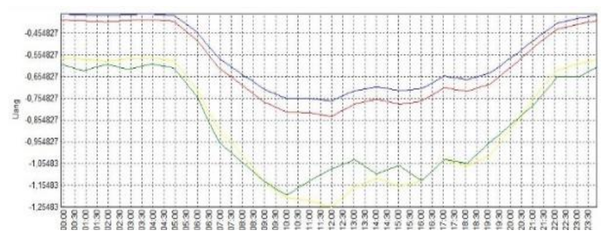


Figure 2. Neplan simulation of the Campus distribution system

Finally the angular difference calculation algorithm consists of subtracting the phase of the voltage angle of each of the nodes in the three phases of the system, however, being an oscillatory system cycles must be defined to not generate errors in the calculation, for this the following algorithm is proposed, which allows correcting when the phase angle has completed 180 °, in addition to making the phase adjustment due to the DY5 transformer that lags 150 ° measurements. This algorithm makes the comparison between the two signals by means of a conditional that evaluates which signal is the largest, depending on this it takes the signal of the medicine node and subtracts it with the signal of the synchronized genetics node, if the signal of the medicine node is advanced it subtracts 360° of a complete turn, if it is the opposite case it only makes the correction for the phase difference of the transformer. Once the angular difference is calculated, we proceed to label the events of interest, these will be found in the region of operation of the two systems between -0.5° and 0.5° according to the simulations developed, the main variation is given by changes in the injection of photovoltaic power and changes in power demand.

```
for i = 1:lo
if(PMU1(i,8)>=PMU1(i,9))
DifA(i,1)=(PMU1(i,8)-PMU1(i,9))+150-360;
else
DifA(i,1)=(PMU1(i,8)-PMU1(i,9))+150;
end
end
```

The changes outside the operating region are classified as unusual angular difference events and labeled as events generated by communication interruptions and events associated with the medical and genetic substation.

3. Results

Once the architecture is implemented, system operation tests are performed to observe its region of operation and typical data, first, exploratory analysis is developed to characterize the individual behavior of each of the systems with the data extracted by the phasor measurement units, we have that for the genetics node the voltage ranges from 6392.4 to 6680 V per phase having a difference of around 287.6 V, in this same node the current ranges from 0.8 A to 3.65 A having a difference of 2.85 A. In this first phasor measurement unit we can observe some limit values per phase in Table 1, having a maximum demanded power of 24.1 kW and a minimum power of 5.26 kW per phase, with a difference in frequency of 0.257 Hz with values ranging from 59.86 Hz and 60.117 Hz.

Variable	Maximum	Mínimum	Mean	Median	Standard deviation
Frequency	60.1152	59.7865	60.0005	60.0023	0.0226
Voltage A	6606.6	6460.9	6542	6543.9	0.972
Voltage B	6653.4	6507.6	6592.2	6592.4	0.984
Voltage C	6623.2	6462.3	6561.1	6561.2	0.988
Current A	2.0368	0.7789	1.1436	1.1463	0.1230
Current B	1.8461	0.8174	1.0997	1.1051	0.1089
Current C	2.1616	1.1405	1.4614	1.4615	0.0990

Table 1. Values per phase of the magnitudes of the genetic PMU

For the medicine node the voltage goes from 123.4 to 129.7 V having a difference of about 6.3 V, in this same node the current goes from 0.17 A to 102.5 A having a difference of 102.33 A. In this first phasor measurement unit we can observe some limit values per phase in Table 2, having a maximum demanded power of 12.68 kW and a minimum power of 21.08 W per phase, with a difference in frequency of 0.24 Hz with values ranging from 59.87 Hz and 60.117 Hz. The voltage variability at the medicine bus in per unit is 5.25% higher than that of the genetics bus at 2.52%. This is mainly due to the solar photovoltaic generation at the medicine bus.

Within the analyzed data, the angular difference and the frequency are correlated; when the frequency oscillates between 60.1 and 59.85 Hz, it is evident how the angular difference between the nodes also varies, reaching values of up to 6° of difference between the two nodes, which are associated to the stability of the frequency. The relationship between the photovoltaic generation power and the angular difference between the nodes has variations between -2.5° and 1.5° due to the abrupt change in generation, showing how these changes can destabilize the angle of the medicine substation node with respect to the genetics substation node.

Feature	Maximum	Mínimum	Mean	Median	Standard deviation
Frequency	60.1152	59.7865	60.0005	60.0023	0.0226
Voltage A	129.6167	123.426	125.145	124.145	0.972
Voltage B	129.7304	125.036	127.485	126.325	0.984
Voltage C	129.0514	124.402	127.245	125.145	0.988
Current A	68.6726	4.8172	35.2145	40.568	19.7259
Current B	75.6855	0.1742	40.2564	60.458	10.6452
Current C	102.5454	3.5973	60.4523	70.458	8.6583

Table 2. Values per phase of the magnitudes of the medicine PMU

The data is filtered to eliminate large angular differences caused by loss of communication of any of the phasor measurement units, once the atypical data is filtered, a visualization of the data dispersion in three dimensions is performed, in order to observe the space of characteristics, from the filtered data, the solar generation events are labeled with a yellow color and the non-generation events with a blue color, in order to observe the behavior of the system when there is solar photovoltaic generation. Figure 3 shows the node voltages and the angular difference, the blue points are events where there is no photovoltaic generation and the yellow points when there is generation, it is evident that most of the generation events tend to have a smaller angular difference when there is no power injection of the photovoltaic system, except for a group of events that have a greater angular difference due to voltage drops in the genetics substation.

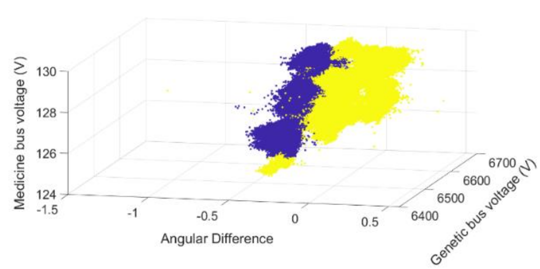


Figure 3. Grouping of angular difference events with respect to the generation and voltages of the two nodes

Figure 4 shows the correlation between the nodes of genetics and medicine, it is observed that there is a correlation directly proportional and as there is photovoltaic generation this tension decreases in the two nodes.

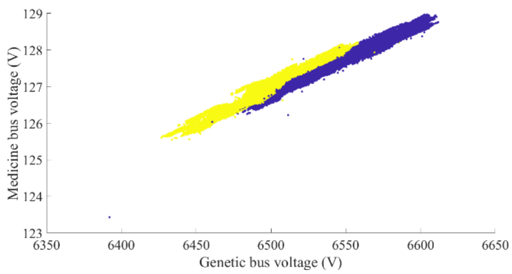


Figure 4. Correlation between the measured node stresses

The behavior of the angular difference, the genetic current and the photovoltaic generation differential are studied. These characteristics can be segmented into three groups, the first when the angular difference is positive and will depend on a level of photovoltaic generation, the second when the angular difference is negative in which the levels of low or zero generation are concentrated and the load at the genetics node is low and finally the third group when the angular difference is negative and the current at the genetics node is high.

Figure 5 shows the correlation between the change in angular difference and the photovoltaic generation at the medicine bus, obtaining an angular difference that increases as there is more available solar generation. As the generation increases, the phase angle of the medicine bus leads the phase angle of the genetics bus, making the difference turn positive. When there is no generation, this difference is below 0°, reaching up to -0.7°.

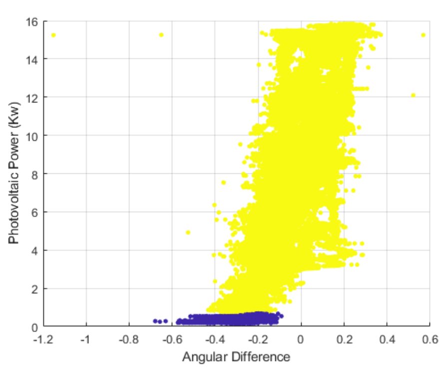


Figure 5. Correlation between solar generation and angular difference

Figure 6 shows the correlation between the genetics current, the photovoltaic generation current and the angular difference, it is observed that the angular difference will depend mainly on the generation current of the photovoltaic system, reaching an angular difference of about 0.5° between the observed nodes, when there is no photovoltaic solar generation, an angular difference of -0.5° is evident, showing the oscillation between -0.5° and 0.5° of the system due to the photovoltaic solar generation.

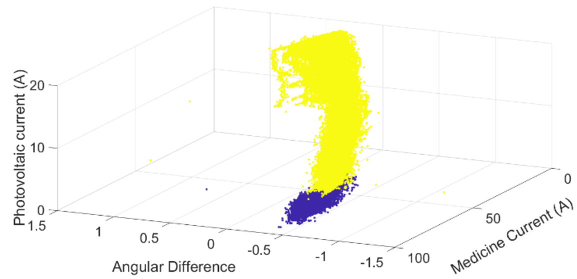


Figure 6. Variation of the angular difference with respect to the medical current and the current of the photovoltaic system

Figure 7 shows the behavior of the angular difference of the three phases, in order to observe the regions of operation of the system. It is observed that the angular difference of the three phases has their region of operation by the oscillation of the photovoltaic system between quartiles 3 and 1 for each phase, with a median of -0.15° for phase A, -0.49° for phase B and finally -0.13°, atypical values may occur due to communication failures or system events that modify the angular difference, these are identified in the space of carcateristicas, evidencing that some depend on the drop of the system tension, abrupt changes in frequency and abrupt changes in solar photovoltaic generation.

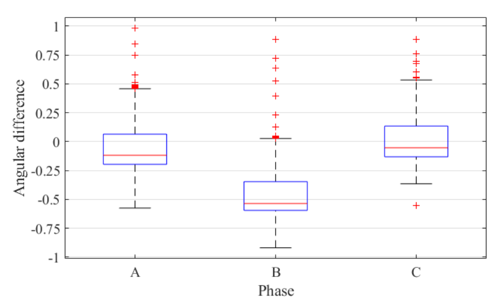


Figure 7. Boxplot of angular difference in the three phases

After analyzing the data of each fasorial measurement unit under normal conditions, anomalous data of the angular difference is classified and 5 private classes arise, the first when the angular difference takes very high values due to the loss of communication of the PMU located in the medical substation, the second when the same increase of the angular difference occurs but this time due to loss of communication of the PMU located in the medical substation, the third class when an increase of angular difference occurs due to a voltage drop in the medicine node, the fourth when the increase of the

angular difference is related to the voltage drops in the genetic node and finally when the increase of the angular difference is associated with the frequency variation.
Angular difference events are classified by evaluating each of the events of this variable that are outside the normal operating range of the evaluated system, data are obtained for two months with a sample time of 0.016 seconds resulting in a database of 5'184.000 samples and 32 characteristics, each sample is labeled finding 18 communication loss events, being 7 of the medicine node and 11 of the genetics node. These events allow us to rule out that the angular difference is due to system instability, thus avoiding any drive associated with protection systems. In terms of tension anomalies, 21 events were found in which it exceeds the limits allowed by the regulation, 6 associated to the medical substation and 15 to the genetic substation. Figure 9 shows an angular difference event caused by abnormalities of the voltage of the medicine node, in this has a voltage drop to about 90 volts, increasing in turn the angular difference of the buses.

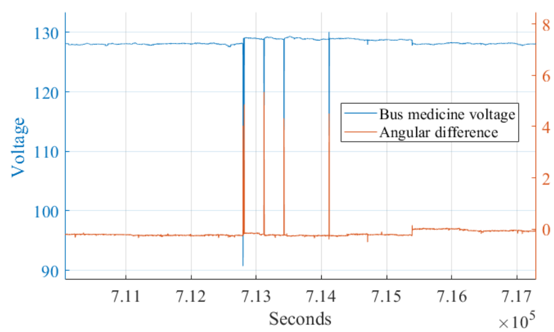


Figure 9. Angular difference event due to voltage drop in the medicine bus

From the analyzed and classified events can be generated classification rules for angular difference events outside the operating range, constantly monitoring the lag of the two buses studied. The application of classification rules allows to differentiate the events by instability and communication of high angular difference between the two nodes, having inputs to give a diagnosis of why the event occurred in the system, at the same time it can be observed that the photovoltaic solar generation is directly correlated with the variation of the angular difference, this being also an indicator of the stability of the photovoltaic solar generation by which it can be monitored.

4. Conclusions

The implementation at laboratory level of phasor measurement systems allowed observing the behavior of two nodes in the branches of the distribution system studied, the genetics node has a more stable behavior because its electrical behavior depends only on the demand and being an educational building, its energy consumption is stable over a longer period of time, The medicine node has a much more variable behavior due to the uncertainty of the incident solar radiation, this injection makes the photovoltaic system to set its phase angle in the voltage modifying the phase angle of the genetics node, observing an oscillation between the two extreme nodes of -0. 5° to 0.5° which evidences some of the effects of solar PV injection on the phase of the system voltage angle.

The application of the phasor measurement units allows studying the electrical behavior of the node in which it is located, obtaining high precision data with a higher resolution than traditional measurement systems. In addition to allowing the individual study of the node, information from other phasor measurement units that are interconnected to the network can be intertwined, relating the voltage phasors between the two nodes measured, this allows to observe of the typical values in which the system operates from the angular difference between the phase angles of the voltages in the three phases of the system and in turn show from the characteristics of the phasors that anomalous events can occur by variations of the observed phasors.

5. Recommendations

For future studies, it's imperative to delve deeper into the benefits observed at the laboratory level with phasor measurement systems. We strongly recommend expanding the scope by integrating these systems on a broader scale to encapsulate more nodes in the distribution network. By doing so, researchers can gain an intricate understanding of the entire network's behavior and the interconnected dynamics. Prioritizing the installation of PMUs, given their evident superiority in accuracy and resolution over conventional measurement methods, is also paramount. Harnessing the high-resolution data they provide will pave the way for advanced analytics and predictive modeling. Such models can be instrumental in preemptively identifying and addressing potential system anomalies or disruptions stemming from observed phasor variations. This trajectory of research will not only advance our understanding but also bolster the reliability and efficiency of power distribution networks.

Acknowledgements

This research was supported Electrical Machines Drives research Group (EMD) from Universidad Nacional de Colombia and project Think Green on the island of San Andres, BPIN 2016000100002 EEDAS ESP.

References

[1] H. H. Alhelou, A. Y. Abdelaziz, and P. Siano, Wide Area Power Systems Stability, Protection, and Security. 2021.

[2] A. G. Phadke and T. Bi, "Phasor measurement units, WAMS, and their applications in protection and control of power systems," J. Mod. Power Syst. Clean Energy, vol. 6, no. 4, pp. 619–629, 2018, doi: 10.1007/s40565-018-0423-3.

[3] R. Arghandeh et al., "Synchrophasor Monitoring for Distribution Systems: Technical Foundations and Applications," North Am. SynchroPhasor Initiat., no. January, pp. 1–62, 2018, doi: 10.13140/RG.2.2.35267.04649.

[4] A. G. Phadke and T. Bi, "Phasor measurement units, WAMS, and their applications in protection and control of power systems," J. Mod. Power Syst. Clean Energy, vol. 6, no. 4, pp. 619–629, 2018, doi: 10.1007/s40565-018-0423-3.

[5] J. F. Hauer, N. B. Bhatt, K. Shah, and S. Kolluri, "Performance of 'WAMS East' in providing dynamic information for the North East Blackout of August 14, 2003," 2004 IEEE Power Eng. Soc. Gen. Meet., vol. 2, pp. 1685–1690, 2004, doi: 10.1109/pes.2004.1373161.

[6] J. Y. Cai, Z. Huang, J. Hauer, and K. Martin, "Current status and experience of WAMS implementation in North America," Proc. IEEE Power Eng. Soc. Transm. Distrib. Conf., vol. 2005, pp. 1–7, 2005, doi: 10.1109/TDC.2005.1546889.

[7] Q. Yang, T. Bi, and J. Wu, "WAMS implementation in China and the challenges for bulk power system protection," 2007 IEEE Power Eng. Soc. Gen. Meet. PES, pp. 0–5, 2007, doi: 10.1109/PES.2007.385835.

[8] X. Fan, F. Xiong, and L. Jiang, "PMU-WAMS research and application in Brazil," Glob. Energy Interconnect., vol. 2, no. 1, pp. 85–93, 2019, doi: 10.1016/j.gloei.2019.06.011.

[9] G. Rivera and A. D. La Torre, "Estrategias para la Implementación de un Sistema de Monitoreo de Área Extendida WAMS en el Sistema Nacional Interconectado del Ecuador," Rev. Técnica "Energía," vol. 9, no. 1, pp. 34–43, 2013, doi: 10.37116/revistaenergia.v9.n1.2013.134.

[10] R. León, J. E. Gomez, J. W. Gonzalez, G. J. Lopez, and M. Osorio, "Sistema de Respaldo Nacional ante Eventos de Gran Magnitud – SIRENA," Investig. y Desarro., vol. 1, p. 8, 2007, [Online]. Available: http://www.xm.com.co/BoletinXM/PublishingImages/Boletin256/PaperXMSirena_PremioAsocodisCNO.pdf.

[11] A. Nechifor, P. Regulski, D. Cai, and V. Terzija, "Development of a flexible laboratory testing platform for assessing steady-state and transient performance of WAMS," 2011 IEEE Int. Work. Appl. Meas. Power Syst. AMPS 2011 - Proc., pp. 62–67, 2011, doi: 10.1109/AMPS.2011.6090442.

[12] T. D. Duong, S. D'Arco, and J. O. Tande, "Architecture and laboratory implementation of a testing platform for Wide Area Monitoring Systems," IECON Proc. (Industrial Electron. Conf., vol. 2019-Octob, pp. 6419–6424, 2019, doi: 10.1109/IECON.2019.8927319.

[13] C. Lopez de Alba, "Implementación de un sistema de monitoreo de área amplia a escala de laboratorio para sistemas eléctricos de potencia Implementation of a Wide Area Monitoring System on a laboratory scale for Power Systems," Ing. Investig. y Tecnol., no. número 2, pp. 195–207, 2019.

[14] A. V. Rodionov, D. N. Popov, A. S. Sosnin, A. V. Mokeev, and A. I. Popov, "Extending Functionality and Application Scope of Synchronised Phasor Measurement Technology," 2018 Int. Youth Sci. Tech. Conf. Relay Prot. Autom. RPA 2018, pp. 1–15, 2018, doi: 10.1109/RPA.2018.8537229.

[15] "Phasor Measurement Unit using GPRS Wireless Connectivity."

[16] A. G. Phadke and J. S. Thorp, Synchronized Phasor Measurements and Their Applications (Power Electronics and Power Systems). 2008.

[17] A. Popelka, D. Jurik, P. Marvan, and V. Povolny, "Advanced applications of WAMS," IET Conf. Publ., vol. 2013, no. 615 CP, pp. 10–13, 2013, doi: 10.1049/cp.2013.1082.

[18] "Prototype Phasor Measurement System for a Generator Synchronic."

[19] G. C. Patil and A. G. Thosar, "Application of synchrophasor measurements using PMU for modern power systems monitoring and control," 6th Int. Conf. Comput. Power, Energy, Inf. Commun. ICCPEIC 2017, vol. 2018-January, pp. 754–760, 2018, doi: 10.1109/ICCPEIC.2017.8290464.

[20] X. Xie, Y. Xin, J. Xiao, J. Wu, and Y. Han, "WAMS applications in chinese power system," IEEE Power Energy Mag., vol. 4, no. 1, pp. 54–63, 2006, doi: 10.1109/MPAE.2006.1578532.

[21] L. Ramesh, S. P. Chowdhury, and S. Chowdhury, "Wide area monitoring protection and control - A comprehensive application review," IET Conf. Publ., vol. 2010, no. 558 CP, 2010, doi: 10.1049/cp.2010.0325.

[22] D. L. Alvarez, J. A. Rosero, F. Faria da Silva, C. L. Bak, and E. E. Mombello, "Dynamic line rating — Technologies and challenges of PMU on overhead lines: A survey," 2016 51st Int. Univ. Power Eng. Conf., pp. 1–6, 2016, doi: 10.1109/UPEC.2016.8114069.

[23] A. Mutule, E. Grebesh, I. Oleinikova, and A. Obushevs, "Methodology for transmission line capacity assessement based on PMU data," 19th Power Syst. Comput. Conf. PSCC 2016, no. 79, pp. 4–8, 2016, doi: 10.1109/PSCC.2016.7540986.

[24] X. Wang, “Estimating dynamic load parameters from ambient PMU measurements,” IEEE Power Energy Soc. Gen. Meet., vol. 2018-January, no. 1, pp. 1–5, 2018, doi: 10.1109/PESGM.2017.8273913.

[25] S. D. Chowdhury and N. Senroy, “PMU data based online parameter estimation of synchronous generator,” 2016 IEEE 6th Int. Conf. Power Syst. ICPS 2016, 2016, doi: 10.1109/ICPES.2016.7584050.

[26] S. M. . Téllez Gutiérrez, J. Rosero García, y O. G. Duarte Velasco, «laboratorio nacional de redes inteligentes (lab+i) como herramienta educativa para la formación de ingenieros», EIEI ACOFI, ago. 2014.

[27] A. F. Duque, J. Rosero García, and E. Perez, “Demand-Side Management Through Load Control and Local Generation in a Medical Education Facility: a Case Study,” Int. Rev. Electr. Eng., vol. 17, no. 2, pp. 131–140, 2022, doi: 10.15866/iree.v17i2.20969.