American Journal of Electrical and Computer Engineering
2023; 7(1): 1-9
http://www.sciencepublishinggroup.com/j/ajece
doi: 10.11648/j.ajece.20230701.11
ISSN: 2640-0480 (Print); ISSN: 2640-0502 (Online)

Current Unbalance Monitoring In Four-Wire System Based on Fuzzy Logic

Achmad Marzuki*, Bangbang Hermanto, Wawan Heryawan, Abu Bakar

Department of Electrical Engineering, State Polytechnic of Pontianak, Pontianak, Indonesia

Email address:

mzkachmad@yahoo.com (Achmad Marzuki), ir.bangbangh@gmail.com (Bangbang Hermanto), wawan.heryawan@gmail.com (Wawan Heryawan), a_bukatek@yahoo.co.id (Abu Bakar)

*Corresponding author

To cite this article:

Achmad Marzuki, Bangbang Hermanto, Wawan Heryawan, Abu Bakar. Current Unbalance Monitoring In Four-Wire System Based on Fuzzy Logic. *American Journal of Electrical and Computer Engineering*. Vol. 7, No. 1, 2023, pp. 1-9. doi: 10.11648/j.ajece.20230701.11

Received: January 20, 2023; **Accepted**: March 13, 2023; **Published**: March 15, 2023

Abstract: The daily consumption profile of electric power is different for each electrical customer, which is random and unpredictable, especially in residential, commercial, and educational areas, which are dominated by single-phase electrical loads. The abundance of this one phase load can enhance the current unbalance of the three-phase four-wire system, and will cause several other power quality problems e.g., Increasing Neutral current, displacement of neutral point, Increasing heating in one phase and losses in distribution network. However, the PIUR (Phase current unbalance rate) value as one of indicators of power quality must not exceed the threshold recommended by the NEMA standard, which is a maximum of 30%. For this reason, this paper proposes a current unbalance monitoring based on Fuzzy Logic to produce an unbalance quality (excellent, good, moderate, bad, and poor) that can be monitored by electric customers globally. The unbalance quality is very useful for electric customers to rearrange their single-phase load installation so that the power quality indicator value is expected to be within the allowable range. In addition, this prototype (proposed system) is also able to provide great convenience for electric customers to monitor the changes of profile uses of loads, and at the same time can detect the emergence of disturbances early that may occur in each phase.

Keywords: Current Unbalance, Phase Current Unbalance Rate, Power Indicator Quality, Fuzzy Logic, Unbalance Quality

1. Introduction

The use of electrical energy in residential, educational, and commercial areas always increases in accordance with the growth in the number of electrical loads that must be served. Installation of electrical loads carried out by consumers often ignores the current balance in each of its phases. In a Three-phase System, a system is said to be unbalanced if either the currents or voltages or both of any phase in a three-phase system are not the same in magnitude or phase difference or both (the system is also said to be asymmetrical or imbalanced) [2]. Current unbalance in a Three-phase, four-wire distribution system is a well-known quality issue that can be caused by an asymmetric of loads, and this can contribute to an increase in current in the neutral conductor (neutral current) [2, 3]. The excessive neutral current will also cause several other power quality problems in the system [3, 4]. Unbalance load also has a major influence on increasing power losses in the distribution network [4-6].

An imbalance of electric currents in a three-phase electrical system will also cause a voltage imbalance that must be detected as soon as possible so as not to cause several unwanted conditions, namely: shifting of the neutral point, excessive heating in one phase, increased losses (load losses) [6], and the disruption of the work of the LV transformer on the supply side. This unbalance condition will cause several conditions, namely: reducing lifetime, disrupting load operations, reducing torque and overheating on induction motor loads, torque (speed) on induction motor loads can become vibrating [6, 7], low power factor, flicker, and can even cause fatal damage to electrical loads. Thus, the condition of the voltage and current unbalance will affect the quality of the distribution of electrical power. Therefore, the electrical customer must be able to monitor the current unbalance condition so that it does not exceed the threshold that has been determined by the NEMA MG-1 standard. To monitor current unbalance can be done by estimating and diagnosing the CUF (Current Unbalance Factor) parameters with the CPS (circular phase shift) algorithm, and estimating the three-phase parameters are estimated by a circular cross-correlation (CCC) algorithm for unbalance diagnosis [8].

In another study, it was stated that the educational and residential sectors are dominated by single-phase electrical loads that vary with dynamic characteristics [9], which are non-linear, have a resistive-inductive and capacitive in character. Of course, in practice, it is impossible to achieve a perfect balance of single-phase consumers in a three-phase system [10]. Therefore, researchers continue to make efforts so that the load imbalance can be reduced in such a way as to improve the quality of electrical power distribution so that the power indicator values such as VUF, IUF, PVUR, PIUR, VR, and voltage drop do not exceed the threshold according to the standards that have been set by IEC, IEEE, and NEMA.

To reduce the effect of unbalance, this quality problem must be managed and mitigated by both the utilities and the customer (consumer). And it can be done in two ways: technical and economically (tariff base method). A Technical method is a technical solution, it is to arrange or distribute the loads in such a way that the system becomes more balanced. Meanwhile, the tariff base method, the customers will be forced to do this duty by applying the unbalanced base tariff and penalty [11]. Other researchers limit unbalance current on the distribution network side (network distribution) with the insertion of capacitors based on the iterated local search (ILS) method [12]. This method can identify how many capacitors are required, which BUS (trunk line) they should be connected to, and the power of each capacitor.

Researchers have made many efforts to overcome the imbalance problem. In Reference [13], the unbalance current of a three-phase load is monitored by using an Arduino Uno microcontroller by displaying the imbalance value on an LCD. If the imbalance value exceeds the threshold value of 25%, the system will sound a buzzer as an alarm to the customer. In reference [14], a model is proposed to move customers and PVs between the three phases in the best way possible using static transfer switches (STSs) to reduce the amount of energy lost due to current imbalance.

A new wiring method and three-phase load adjustment policy were proposed to balance the three-phase load distribution network with an abundant single-phase load. When the load of the trunk was unbalanced, the controller will switch the connected single-phase loads from one phase to another to balance it using the minimum count of loads adjustment and the most balanced adjustment algorithm [15]. Other researchers use the current flowing in the neutral conductor as a threshold. If it exceeds a certain value, the controller will carry out a balancing process, namely by moving the current biggest load toward a phase that has the smallest load current [16]. Reference [17] conducted research on the detection and assessment scheme of voltage and current unbalance on the generator side. Other practical efforts are carried out by monitoring energy usage data on measuring instruments located in distribution transformers for 24 hours. This data is used to predict the current unbalance, and with the help of LabView Software, a balancing process is carried out [18]. Another practical approach is to use the characteristics of the low voltage distribution grid in the three-phase four-wire system as input to the intelligent phase change controller and phase communication switch to reduce load imbalance and improve power system performance [19]. Another smart approach is to use the new commutation switch and an improved quantum genetic algorithm (IQGA). The commutation switch uses zero-crossing commutation technology, which can eliminate "inrush current" at the moment of load switching. And in this commutation, it uses a two-phase THYRISTOR parallel contactor structure to avoid the heating problem [20]. Another commutation method is using the SHO (Spotted Hyena Optimizer) Algorithm that has the advantages of fewer operations, faster search speed, and saving operation time and re-source space. This method controls the commutation switch better, makes the optimal commutation strategy for unbalanced three-phase current, and effectively reduces the three-phase current unbalance to less than 15% [21]. Related researchers have proposed The Particle Swarm Optimization (PSO) algorithm-based controller is used for generating the control signal of an electric spring. The simulations carried out show that the electric spring is effective in reducing neutral current under unbalanced loads [22].

The power quality indicator related to voltage imbalance is PVUR (Phase voltage unbalance rate), while the one related to unbalance current is PIUR (Phase current unbalance rate). PVUR or another equivalent indicator should not exceed 2-3% in the LV distribution network, according to standards such as EN50160 and ANSI C84.1. The Phase Current Unbalance Rate (PIUR) [23, 24] is defined as in (1):

$$PIUR = \frac{Maximum(Current\ Deviation)}{Avarage\ Phase\ Current}.100\ (\%) \tag{1}$$

It was found that Japan is the only country that has a standard for phase balancing in three-phase installations. This standard JEAC8001-2011 of having phase unbalance up to 30% is expected to be satisfied in three-phase installations [24]. Unfortunately, there is no standard for current unbalance. But by attention to the NEMA MG-1 standard: The maximum limit of Current unbalance due to 3% of voltage unbalance can be advised as 30% [11, 25].

Power quality indicators should be monitored and evaluated to avoid unwanted economic losses. In reference [26], this monitoring activity begins by taking current and voltage signals from the load, identifying the unbalance phase, calculating the three-phase unbalance degree, and ending with the calculation of line loss.

Previous research [1–25] found that the current unbalance value in a four-wire system distribution can only be understood by users with engineering knowledge. Meanwhile, efforts to reduce the value of unbalanced current are carried out with complicated algorithms and do not involve electrical customers who generally do not have good electrical engineering skills. Therefore, it is necessary to involve electrical customers to improve power quality, especially in an effort to reduce the value of unbalanced current in each area with an easier access and uncomplicated methods. The use of Fuzzy Logic Controller in helping consumers in several fields has been carried out by many researchers. For example, in the field of management minimum consumption energy offers valuable insights in an attempt to adjust consumer behavior optimally [27, 28]. With the development of telecommunications technology, the use of Android-based smartphones has also been extended to three-phase voltage and current monitoring activities with low cost and greater effectiveness [29].

In this paper, a fuzzy logic scheme is proposed to produce a quality value for the unbalance of electric current or load with the consideration that fuzzy logic is commonly applied to issues relating to elements of uncertainty and imprecision [30, 31], as well as daily consumption profiles of electric power that are different for each customer, which is random and unpredictable. Unbalance quality in this proposed system can be accessed by electronic consumers globally via the Telegram application, while the prototype (proposed system) uses a low-cost microcontroller (esp8266) and a multifunction sensor (PZEM004) which can be placed on an electrical panel, easily and practically. Besides unbalanced quality, electrical customers can monitor power usage and energy consumption from time to time.

2. Method

Current Unbalance Monitoring in Three-phase Four-wire System will focus on testing sensor performance and data connectivity, hardware design, fuzzy inference system (FIS), programming procedure, and testing.

2.1. Current Sensor Performance Evaluation

The current sensor is an important component in the proposed design, which functions to measure the electric current parameters in each phase. This test was carried out using 3 PZEM004 sensors connected to an ESP8266 Microcontroller, Three Fluke 17B type of Digital Multi meters, and a laptop as shown in Figure 1.

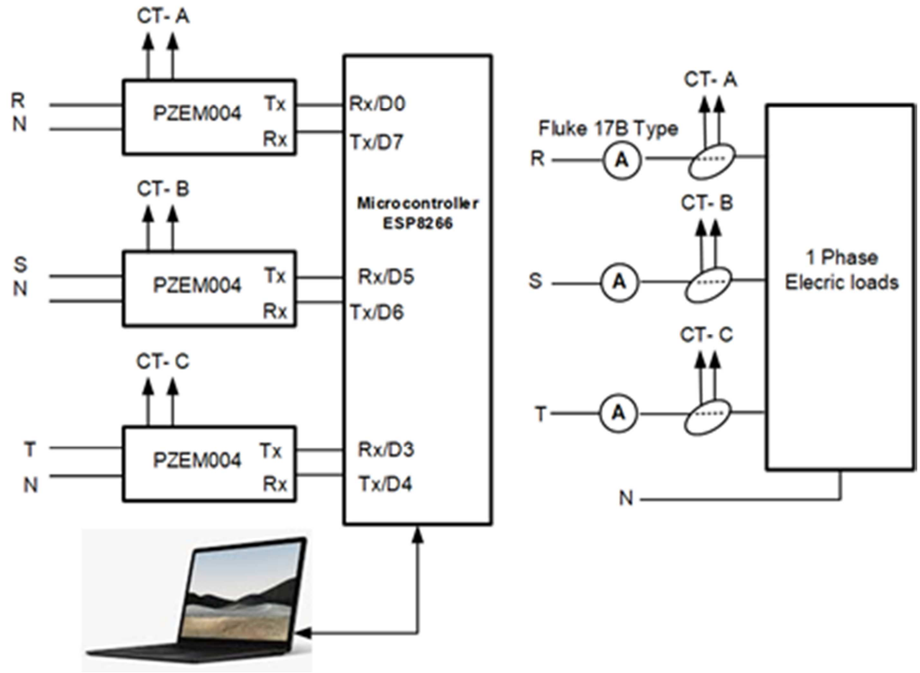


Figure 1. *Current sensor performance test.*

Figure 2. *Testing the connectivity of data transmission.*

2.2. Checking for Connectivity

This connectivity test is carried out to find out if the data sent by the esp8266 microcontroller to a smartphone and vice versa runs well. In this connectivity test, a DHT22 sensor is used to measure ambient temperature and humidity, which is sent to a smartphone (customer) via the Telegram application (multi-platform messaging service), as shown in Figure 2. Besides being accessible via telegram, data stream should be monitored directly through the cloud server.

2.3. Hardware Development

The proposed hardware design has several elements, namely: a three phase MCB (Mini circuit breaker), three Multifunction Sensor PZEM004 which has a maximum current detection capability of 100A, a Microcontroller ESP8266, a DC relay (5V), a three phase magnetic contactor, and 1 phase electrical loads (linear and non-linear), and a DHT22 sensor to measure the temperature around the electrical panel. The schematic diagram of hardware design is shown in figure 3.

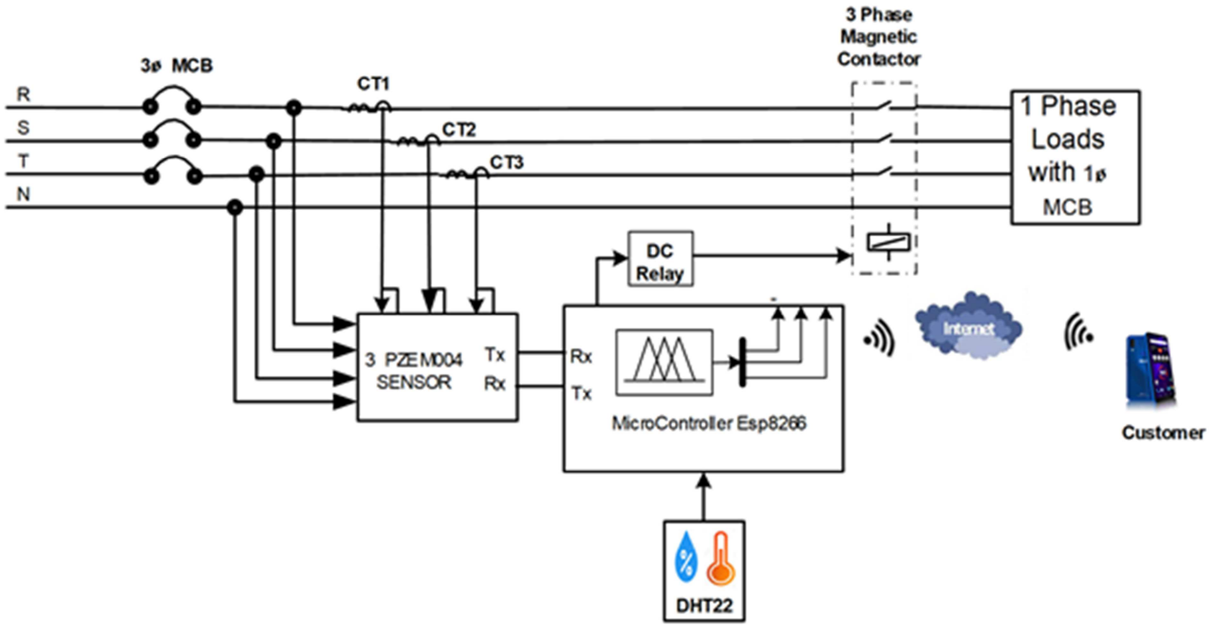


Figure 3. *Schematic Diagram of proposed system.*

The PZEM04 sensor is connected to the Three-phase+N voltage terminal and to the CT (current transformer) terminal, which is analog signal. Then it is converted into a digital signal, which is then sent serially via the TX/RX terminal to the ESP8266 microcontroller. Three-phase currents (I_R, I_S, I_T) will be processed by FLC (fuzzy logic controller) to produce unbalance output and unbalance quality. The electric customers can use the Telegram App on their smartphones to directly access Unbalance quality as the main parameters, and the other three phase secondary parameters, such as voltage (V), power factor (pf), power (P), and energy (E). Meanwhile, the DHT22 sensor can be used to determine the temperature around the electrical panel. The connection and disconnection of electrical loads is carried out by a three-phase magnetic contactor through a DC relay, which is connected to one of the output ports of microcontroller.

2.4. Fuzzy Inference System (FIS)

FIS is a method of mapping the input fuzzy to the output fuzzy using a set of fuzzy rules. In this proposed system, the MAMDANI FIS method is used with fuzzy input in the form of 3 phase currents I_R, I_S, and I_T (mA) flowing in electrical loads, while the fuzzy output is a current Unbalance value (%). The membership function (MF) for input and output variables uses a trapezoidal shape, as shown in Figure 4. The establishment of fuzzy rule of the FIS method consists of collection of Fuzzy IF-THEN rules with 27 rules as shown in table 1.

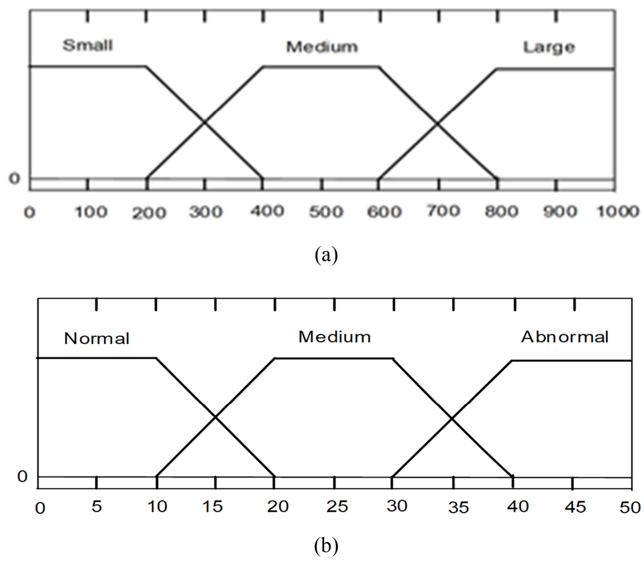


Figure 4. *(a) MF of Three-Phase Current (I_R, I_S, and I_T). (b) MF of Unbalance Output.*

Table 1. *Fuzzy Rule of Current Unbalance System.*

No.	If I_R	And I_S	And I_T	Then Output Is
1	Small	Small	Small	Normal
2	Small	Small	Medium	Enough
3	Small	Small	Large	Abnormal
4	Small	Medium	Small	Enough
5	Small	Medium	Medium	Enough
6	Small	Medium	Large	Abnormal

No.	If I_R	And I_S	And I_T	Then Output Is
7	Small	Large	Small	Abnormal
8	Small	Large	Medium	Abnormal
9	Small	Large	Large	Abnormal
10	Medium	Small	Small	Enough
11	Medium	Small	Medium	Enough
12	Medium	Small	Large	Abnormal
13	Medium	Medium	Small	Enough
14	Medium	Medium	Medium	Normal
15	Medium	Medium	Large	Enough
16	Medium	Large	Small	Abnormal
17	Medium	Large	Medium	Enough
18	Medium	Large	Large	Enough
19	Large	Small	Small	Abnormal
20	Large	IS Small	Medium	Abnormal
21	Large	Small	Large	Abnormal
22	Large	Medium	Small	Abnormal
23	Large	Medium	Medium	Enough
24	Large	Medium	Large	Enough
25	Large	Large	Small	Abnormal
26	Large	Large	Medium	Enough
27	Large	Large	Large	Normal

2.5. Programming Procedure

After going through the test, all components are complete and have been well integrated, then a comprehensive programme (sketch) is written using the ARDUINO IDE 1.8.19 software version. The programming algorithm is structured according to the following steps:

Initialization which includes: Wi-Fi connection to the access point (SSID and password), Determine the Telegram token that has been obtained from the Telegram Bot, Determine the MF of 3 phase current (I_R, I_S, I_T) and Unbalance Output, and Building the fuzzy rules.

Reading the three-phase current Input (I_R, I_S, I_T) and other parameters from the PZMEM004 and DHT22 sensor outputs, such as voltage, power factor, power, energy, and temperature.

Calculating FIS output and quality unbalance: if it exceeds the threshold, it will be sent automatically to the customer.

Read the Incoming messages sent by the different customers via the smartphone, and the results are sent back to the customer via the Telegram application.

Steps 2, 3, and 4 will loop during the dc power is still supplied.

2.6. Performance Analysis

This performance analysis is intended to determine the performance of all components after being integrated as a whole (sensors, relays, microcontrollers, and magnetic contactors). So that the prototype hardware can be used in actual conditions without a decrease in performance for a long time. Then, move on to the analysis of the results based on the FIS simulations output of the imbalance.

3. Result and Discussion

3.1. Simulation Result

After FUZZIFICATION and fuzzy rule formation, the implementation is carried out by using MATLAB software to determine the unbalance output for changes in I_R, I_S, and I_T flows. Figure 5 is the result of experiment 1 on the Rule Viewer. Column 1 describes changes to I_R flows, Column 2 changes to I_S flows, and Column 3 changes to I_T flows. Column 4 describes the state of unbalanced output. In Figure 5, if the currents I_R, I_S, and I_T are 200, 300, and 500 mA, respectively, the Unbalance output is 25%.

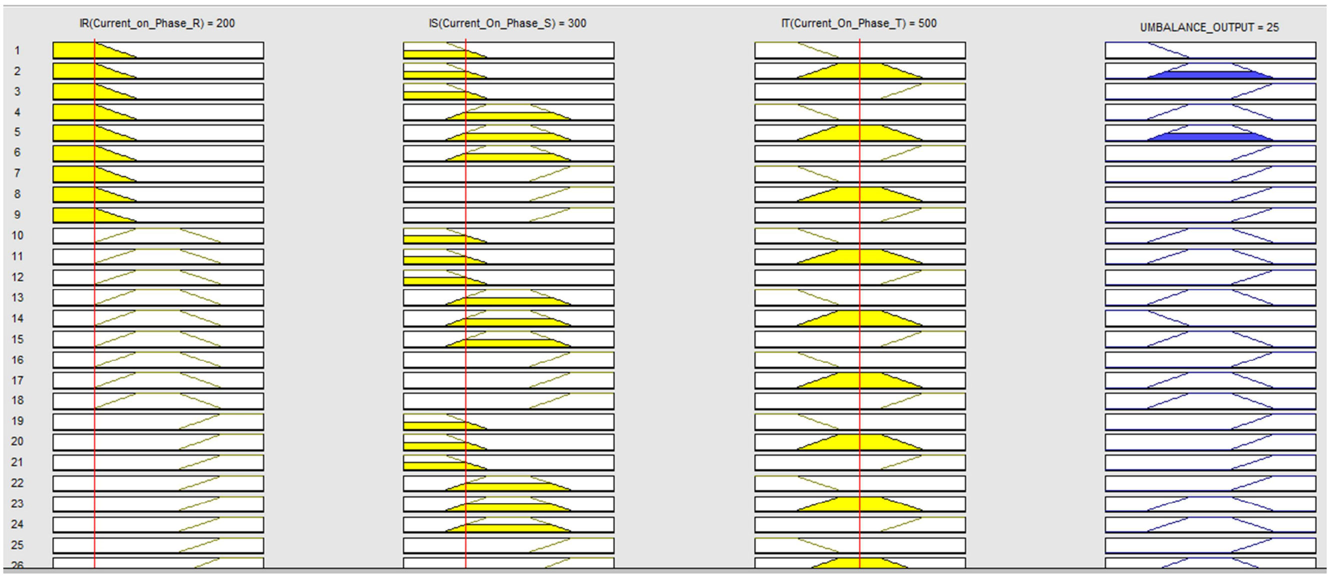


Figure 5. *Experiment 1 with I_R, I_S, and I_T (200,300,500 mA).*

Figure 6 is the result of experiment 2 on the Rule Viewer. If the I_R, I_S, and I_T currents are 450,300,500 mA respectively then the Unbalance Output is 18.7%.

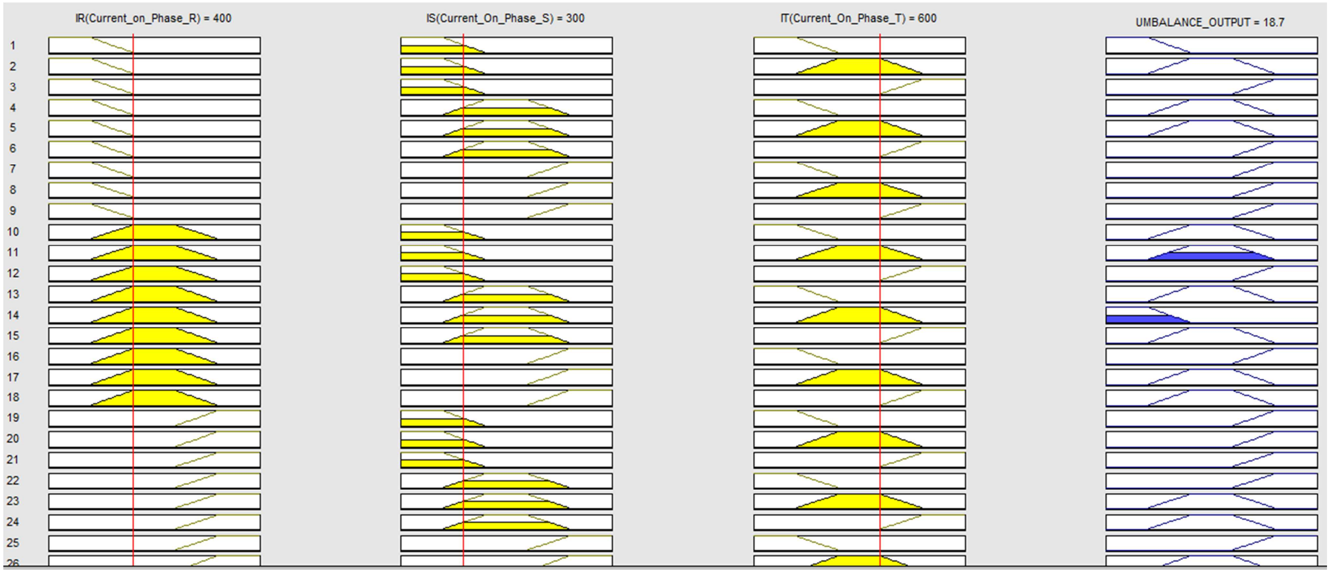


Figure 6. *Experiment 2 with I_R, I_S, and I_T (450,300,600 mA).*

The relationship between the input of I_R, I_S, and I_T and unbalance output value in 3-dimensional form through the Surface Viewer is shown in Figure 7. The X-axis represents the value of the current variable in R phase (I_R), the Y axis represents the value of the current variable in S phase (I_S), and the Z axis represents the value of the Unbalance Output (%). In the surface viewer image, the current value in phase T (I_T) is made constant at 500 mA.

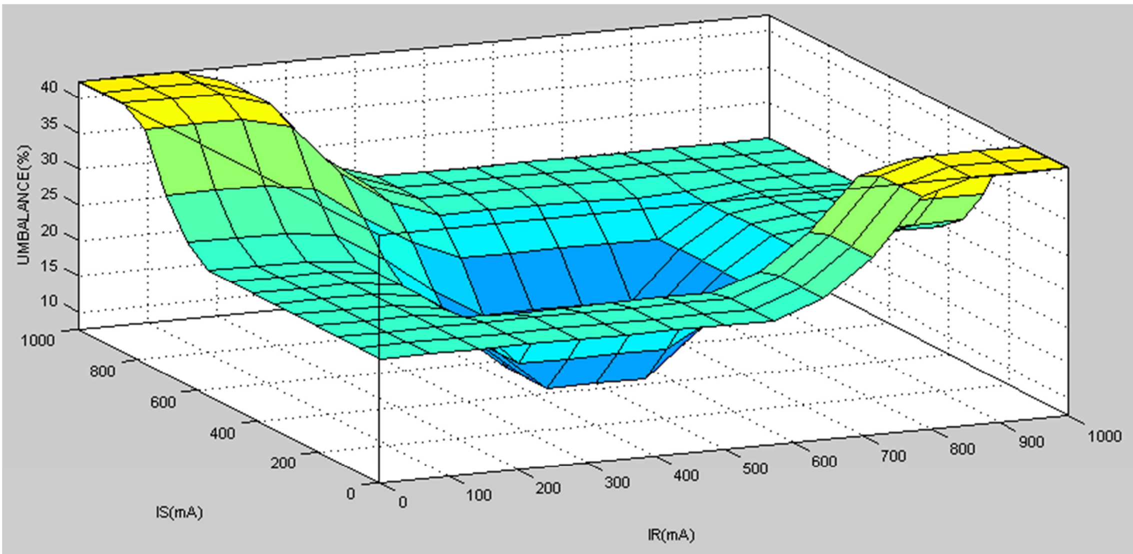


Figure 7. *MATLAB Surface Viewer with I_R, I_S, and Unbalance output.*

3.2. Rule Weight

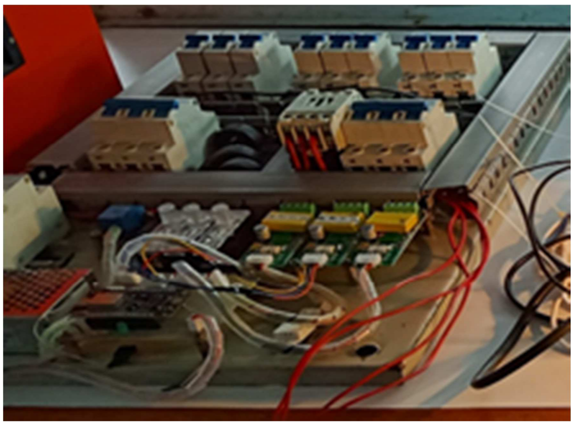
Table 2. *The Rule Weight of Unbalance Current.*

No.	Quality of Unbalance	Rule Weight
1.	Excellent	0 - <= 19
2.	Good	>19 - <= 23
2.	Moderate	>23 - <= 27
3	Bad	>27 - <= 30
4.	Poor	> 30

The unbalance output value (%) is obtained after the fuzzy inference and defuzzification process, the next step is the weighting process with the rules weight as shown in table 2. This weighting is intended so that the output value becomes five Unbalance quality values namely Excellent, Good, Moderate, Bad, and Poor, which is easily understood by electrical customers.

3.3. Experiment

The monitoring of current unbalance (developed system) has been placed on a Three phase, 380/220V, 50 HZ electrical panel (figure 8 a). In the fuzzification process of three phase currents input, only three MF in trapezoidal form (small, medium, and large) are selected with a maximum current of 1000 mA, as shown in Figure 4 a. The next step is the formation of MF of the imbalance output, with the maximum value of the imbalance being 50% in the form of a trapezoid, namely normal, enough, and abnormal, as shown in Figure 4 b. The rule base used is the "fuzzy IF-THEN rule" with 27 rules (Table 1) have the input operator AND, while the FIS uses the MAMDANI method. To obtain the value of output crisp in the defuzzification process, the COA (Centre of Area) method is used. The experiment was carried out by providing some electrical loads in each phase to produce changes in electric current, while the load used was a combination of linear and non-linear loads (figure 8 b), namely: LED lamp, incandescent lamp, electric soldering, water pump motor, LCD projector, and humidifier. By changing the load in each phase, the Unbalance quality and other parameters sent to the smartphone's consumer are shown in table 3.



(a)

(b)

Figure 8. *Developed system (a) Prototype of controller, (b) 1 phase loads.*

Based on the trials that have been carried out on the prototype system, several different Unbalance qualities are produced, as shown in table 3. The Three-phase current changes are carried out by varying the loading, resulting in different Unbalance output and unbalance quality values. The output and quality value of the imbalance are very dependent on the "fuzzy rule" that has been made previously based on the PIUR threshold value, practical experience, and the magnitude of changes in the maximum load current that may occur. The unbalance quality produced by this prototype is highly dependent on changes in the electrical loads in each phase. For example, if current I_R=0 mA, I_S=880.5 mA, and I_T=742.5 mA, the resulting unbalance output is 41.65 which exceeds the NEMA MG-1 standard limit (30%). Based on table 3, this value is in the Unbalance quality is Poor category.

Table 3. *The Unbalance Quality of Three-phase system with the load changes.*

No.	I_R (mA)	I_S (mA)	I_T (mA)	Unbalance Output	Unbalance Quality
1.	0	0	0	7.8	Excellent
2.	114.8	0	0	7.78	Excellent
3.	78.0	118.5	432	25	Moderate
4.	76.5	457.5	432	25	Moderate
5.	337.5	459.0	432	15.53	Excellent
6.	468.0	117.0	432	25	Moderate
7.	466.5	118.5	787.5	40	Poor
8.	765.0	118.5	787.5	41.6	Poor
9.	765.0	118.5	388.5	241.2	Moderate
10.	420.0	118.5	209.5	25.0	Moderate
11.	409.5	460.5	715.5	19.94	Good
12.	826.5	459.0	715.5	25	Enough
13.	721.5	459.0	714.0	20.2	Good
14.	721.5	462.0	742.5	21.43	Good
15.	721.5	879.0	745.5	16.99	Excellent
16.	0	880.5	742.5	41.65	Poor
17	826.5	350.0	715.5	28.27	Bad

Parameters accessed by electric customers via telegram application on different smartphones are Unbalance quality as the main parameter, and three phase electrical parameter (I, V, P, P f, and E) as a secondary parameter, as shown in figure 9. These parameters can help electrical consumers in making the right decisions, especially those related to the Rearrange of load installation in each phase in order to achieve current balance. Another additional parameter is the temperature (T), which can be used to determine the condition around the electrical panel related to early detection of fires. Although this system can be accessed globally, it is equipped with security access that can prevent illegal access, so that only registered users can access legally.

Figure 9. *Data display in Telegram.*

Another feature of this prototype, electric customers can monitor the characteristics of three-phase currents (I_R, I_S, I_T) via an external cloud server www.thingkSpeak.com (IoT analytics platform service) as shown in figure 10. The live 3 phase current streams can provide information on changes of profile usage of loads over a certain period of time. Thus, an electric customer can detect as early as possible the emergence of disturbances that may occur in each phase.

(a) (b) (c)

Figure 10. *Three-phase current stream at certain period of time (a)* I_R*, (b)* I_S*, (c)* I_T*.*

4. Conclusion

The objective of this research is to develop a prototype (proposed system) for current unbalance monitoring based on fuzzy logic that can be accessed by electrical consumers globally. The result shows that the quality of the unbalance (Excellent, Good, Moderate, Bad, Poor) with these low-cost microcontroller and multifunction sensor can provide an overview of the state or condition of a three-phase four-wire electrical system, especially in commercial, residential, and educational areas that are dominated by single-phase loads. With the unbalance quality information that can be accessed globally, electrical consumers can quickly re-arrange the installation of electrical loads in each phase, by switching the connected single-phase loads from one phase to another to achieve load balance. This proposed system can not only provide unbalance quality, but it can also provide other parameters for each phase, namely voltage (V), current (I), power (P), power factor (P f), energy consumption, electric panel temperature, and also profile usage of loads. The Unbalance quality information combined with other electrical parameters can be used as a reference or guideline for maintenance, repair, disconnection, and connection of loads, or other necessary emergency actions. We think this prototype is a great way for people who use electricity to keep an eye on things, especially when it comes to keeping the Power Quality of electricity in an area.

Acknowledgements

The authors would like to acknowledge Research unit of State Polytechnic of Pontianak for the financial support.

References

[1] A. S. Vijay, Suryanarayana Doolla, Mukul C. Chandorkar, “Unbalance mitigation strategies in microgrids”, The Institution of Engineering and Technology, Volume 13, Issue 9, pp. 1687-1710, July 2020, DOI: 10.1049/iet-pel.2019.1080.

[2] Nandita Dey, A. K. Chakraborty, Ph. D, “Neutral Current and Neutral Voltage in a Three Phase Four Wire Distribution System of a Technical Institution” International Journal of Computer Applications (0975 – 8887), Volume 72–No. 3, May 2013, doi: 10.5120/12471-8864.

[3] P. Asha, Ancy Sara Varghese, “Mitigation of Neutral Current in a Three Phase System using Electric Springs”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering”, Vol. 4, Issue 9, pp. 7424-7431, September 2015, DOI: 10.15662/IJAREEIE.2015.0409004.

[4] Yunxia Dong, Yuefeng Shi, “Analysis of Losses in Cables and Transformers with Unbalanced Load and Current Harmonics”, Journal of Electrical and Electronic Engineering, Vol. 9, No. 3, 2021, pp. 78-86, June 4, 2021, DOI: 10.11648/j.jeee.20210903.13.

[5] Ibrahim I. Al-Naimi, Jasim A. Ghaeb, Mohammed J. Baniyounis, Mustafa Al-Khawaldeh, “Fast detection technique for voltage unbalance in three-phase power system”, International Journal of Power Electronics and Drive Systems (IJPEDS), Vol. 12, No. 4, pp. 2230-2242, December2021, DOI: http://doi.org/10.11591/ ijpeds.v12.i4.pp2230-2242.

[6] Benren Pan, Yan Zhang, Xiaozhi Gui, Yong Wan, “Analysis and Research of Three-phase Unbalance in Distribution Transformers”, IOP Conf. Series: Earth and Environmental Science, Volume 252, Issue 3, 2019, doi: 10.1088/1755-1315/252/3/032196.

[7] Osahenvemwen, O. A, Okhumeode, M. E, Emakpor. S, “The Effects of Unbalanced Load in Power Distribution Sub -Station Network”, American Journal of Sciences and Engineering Research, Volume 3, Issue 5, September 2020, [Online]. Available: https://www.researchgate.net/publication/34418851.

[8] Zoubir Hamici, Wejdan Abu Elhaija, “Novel Current Unbalance Estimation and Diagnosis Algorithms for Condition Monitoring WITH Wireless Sensor Network and Internet of Things Gateway”, IEEE Transactions on Industrial Informatics, Volume: 15, Issue: 11, pp. 6080-6090, November 2019, DOI: 10.1109/TII.2019.2935743.

[9] Joel Ogunyemi And Najeem O. Adelakun, “Investigation of Voltage Unbalance in a Distribution Network: A Case Study of Federal Polytechnic Ilaro”, Journal of Energy Technology and Environment Vol. 3 (1), pp. 16-22, March 2021, https://doi.org/10.37933/nipes.e/3.1.2020.2.

[10] Gabriel Nicolae Popa, Angela Iagar and Corina Maria Dinis, “Considerations on Current and Voltage Unbalance of Nonlinear Loads in Residential and Educational Sectors”, Energies 2021, 14, 102, 27 December 2020, DOI: 10.3390/en14010102.

[11] Hossein Arghavani, Mitra Peyravi, “Unbalanced current-based tariff”, 24th International Conference & Exhibition on Electricity Distribution (CIRED), Glasgow, 12-15 June 2017, pp. 883–887, DOI: 10.1049/oap-cired.2017.0129.

[12] Tatianna A. P. Beneteli, Luciano P. Cota, Thiago A. M. Euzébio,” Limiting current and voltage unbalances in distribution systems: A Metaheuristic-based decision support system”, International Journal of Electrical Power & Energy Systems, Volume 135, February 2022, doi: 10.1016/j.ijepes.2021.107538.

[13] Bambang Suprianto, Lucky Aggazi Subagyo, “Control System of Current Flow 3-Phase Unbalanced Based on Arduino Uno”, International Journal of Engineering and Applied Sciences (IJEAS), Volume-4, Issue-9, September 2017, [Online]. Available: https://www.ijeas.org/download_data/IJEAS0409028.pdf.

[14] Adel Heidari-Akhijahani, Amir Safdarian, Matti Lehtonen, “Unbalance mitigation by optimal placement of static transfer switches in low voltage distribution feeders”, IET Generation, Transmission & Distribution, Vol. 14, Issue. 20, pp. 4612-4621, 20th July 2020, DOI: 10.1049/iet-gtd.2019.1467.

[15] Yanwei Zheng, Lisheng Zou, Jian He, Yongyi Su, Zhiquan Feng, “Fast Unbalanced Three-phase Adjustment based on Single-phase Load Switching”, TELKOMNIKA, Vol. 11, No. 8, pp. 4327~4334, August 2013, DOI: http://dx.doi.org/10.11591/telkomnika.v11i8.3031.

[16] Cok Gede Indra Partha, “Design and Balancing Load Current in 3-Phase System Using Microcontroller ATMEGA 2560”, International Journal of Engineering and Emerging Technology, Vol. 2, No. 1, pp. 76-83, January-June 2017, DOI: https://doi.org/10.24843/IJEET.2017.v02.i01.

[17] Ragab Abd Allah Mahmoud, “Detection and assessment scheme of voltage and current unbalance for three phase synchronous generators using dual numerical techniques based on correlation and deviation percentage concepts, The Journal of Engineering published by John Wiley & Sons Ltd, Vol. 2021, Issue 9, pp. 477–495, September 2021, DOI: 10.1049/tje2.12051.

[18] R. Sureshkumar, and P. Maithili, “Three Phase Load Balancing and Energy Loss Reduction in Distribution Network Using LabView”, International Journal of Pure and Applied Mathematics, Volume 116 No. 11, pp. 181-189, 2017, DOI: 10.12732/ijpam.v116i11.19.

[19] Yongxia Li, Yulei Gong, “Design of Three Phase Load Unbalance Automatic Regulating System for Low Voltage Power Distribution Grids”, International Conference on Smart Materials, Intelligent Manufacturing and Automation (SMIMA 2018), https://doi.org/10.1051/matecconf/201817302040.

[20] Xue Liu, Jun Jia, Jian Wang, “Research of Three-Phase Unbalanced Treatment in Low-Voltage Distribution Network Based on New Commutation Switch”, World Journal of Engineering and Technology, 7, pp. 10-17, 2019, https://doi.org/10.4236/wjet.2019.74B002.

[21] Yi Zhang, XianBo Sun, Li Zhu, ShengXin Yang, and YueFei Sun, “Research on Three-Phase Unbalanced Commutation Strategy Based on the Spotted Hyena Optimizer Algorithm”, Complexity, Volume 2022, 10 pages, July 2022, doi: 10.1155/2022/2092421.

[22] Chien-Kuo Chang, Shih-Tang Cheng and Bharath-Kumar Boyanapalli, “Three-Phase Unbalance Improvement for Distribution Systems Based on the Particle Swarm Current Injection Algorithm”, Energies 2022, 15, 3460, https://doi.org/10.3390/en15093460.

[23] Catalin Iosif Ciontea and Floring Lov, “A Study of Load Imbalance Influence on Power Quality Assessment for Distribution Networks”, Electricity 2021, 2, pp. 77-90, 1 March 2021, DOI: 10.3390/ electricity2010005.

[24] Mahir Mahdee, “Investigation of Three-Phase Balancing Techniques A Comparative Study of Different Solutions with Respect to Telecom Industry Needs”, M. S. Thesis, Dept. Elektro, UPPSALA Universitet, Sweden, 2020, [Online] Available: https://www.diva-portal.org/smash/get/diva2:1476266/ FULLTEXT01.df.

[25] NEMA Standards Publication MG 1-2009, Revision 1-2010, [Online]. Available: https://pdfcoffee.com/ qdownload/nema-mg1-2-pdf-free.html

[26] WEI Meifang, LONG Min, LI Junyi, PANG Wenlong, WU Xixiu, “Research on the Monitoring System Design for the Line Loss of the Distribution Line Based on Dynamic Three-phase Unbalance degree”, The 5th International Workshop on Wireless Technology Innovations in Smart Grid (WTISG), Halifax Canada, 2019, doi: 10.1016/j.procs.2019.08.120.

[27] Dimitrios Kontogiannis, Dimitrios Bargiotas and Aspassia Daskalopulu, “Fuzzy Control System for Smart Energy Management in Residential Buildings Based on Environmental Data”, Energies 2021, Volume14, Issue 3, 752, DOI: 10.3390/en14030752.

[28] Rabaza L. Busisiwe, Sumbwanyambe Mbuyu, and Netshikweta N. Reginald, “A Fuzzy Logic based Residential Electrical Energy Optimisation System based on Time of Use Tariffs”, International Energy Journal, Volume 21, Issue 3, pp. 415-426, September 2021, [Online]. Available: http://www.rericjournal.ait.ac.th/index.php/reric/article/ view/2582/pdf.

[29] Mohannad Jabbar Mnati, Alex Van den Bossche, and Raad Farhood Chisab, “A Smart Voltage and Current Monitoring System for Three Phase Inverters Using an Android Smartphone Application”, Sensors 2017, 17, 872; doi: 10.3390/s17040872.

[30] Chavan Mayur D, Swami P. S, Thosar A. G. Dr. Prof., and Gharase Rajendra B, “Fault Detection of Induction Motor Using Fuzzy Logic”, International Journal of Engineering Research & Technology (IJERT), Vol. 2, Issue 12, pp. 2672-2679, December 2013, DOI: 10.17577/IJERTV2IS121048.

[31] Dr. Rajeev GajananSapre, ” On Fuzzy Logic to handle Vague and Imprecise Data”, International Journal of Software & Hardware Research in Engineering, Volume 3, Issue 9, September 2015, pp. 75-80, [Online] Available: https://ijournals.in/wp-content/uploads/2017/07/14.3920-Sapre.compressed.pdf.