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Voltage Unbalance Issues with uneven Distribution of Single-Phase PV System on LV Distribution Network

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Abstract*—As the LV distribution feeder continues to experience increasing and uneven integration of single-phase rooftop PV systems with variations in per-phase load, the distribution feeder will face increased system losses, excessive heat in customers' equipment resulting in accelerated ageing or component failure, and transformer failure due to high voltage unbalance. In this paper, a radial LV distribution is modeled in MATLAB/Simulink environment to investigate the effect of uneven distribution of a single-phase PV array on voltage imbalance. The investigation covered three different scenarios (PV array distribution pattern). IEEE Standard 45-2002 definition of voltage unbalance was used to evaluate the percentage voltage unbalance of the feeder. According to the simulation results, the percentage voltage unbalance for scenarios 1, 2, and 3 is 9.87%, 7.68%, and 5.93%, respectively, and are higher than the 3% voltage unbalance limit specified in IEEE Standard 45-2002. These voltage unbalance levels are harmful the system loads, motors and transformers. Therefore, proper regulation of the single-phase PV arrays is required so as to control the voltage unbalance level in LV distribution feeder.

***Indexed Terms*— Distribution Network. Power Quality, Single-Phase PV System, Voltage Unbalance**

I. INTRODUCTION

The urge to reduce greenhouse gases in response to the abrupt rise in global temperature has resulted in a huge push for renewable energy technologies such as photovoltaic (PV) and wind turbine technology [1]. The increased integration of single and three phase PV systems into the electricity system has resulted to changes in the low voltage (LV) distribution feeder as a result of government policies and strategies aimed at facilitating rooftop PV system installation. One such technique is the Feed-in Tariff (FIT) programme. The FIT plan enables distribution network consumers to participate in electricity generation by encouraging large-scale integration of rooftop PV systems ranging from 1 to 10kW [2][3]. The integration of single-phase photovoltaic (PV) systems into LV distribution networks has become increasingly prevalent as a sustainable energy solution. However, this integration poses challenges related to voltage imbalance due to the uneven distribution of single-phase PV systems across the network. The unequal and unregulated (high) integration of single-phase rooftop PV systems on the LV distribution feeder, along with the relative volatility of per-phase loading which is unlike three-phase systems that inherently balance loads across phases can lead to voltage imbalances when concentrated in specific areas of the LV network. Voltage unbalance is expected to increase due to the variation of the per-phase loading of the LV distribution feeder, spatial distribution of PV system, variability of PV output due to intermittency, network topology and configuration, and operational conditions of the LV distribution system. Voltage unbalance is becoming an interesting topic to customers because sensitive equipment and nonlinear loads are sensitive to power quality problems [4] [5]. According to [6][7], three-phase motors can be damaged or fail prematurely because they are designed to handle certain levels of voltage imbalance. It can also cause damage to power system transformers, increase system losses, cause excessive heat in customers equipment leading to accelerated aging or component failure. These issues not only affect the efficiency of power delivery but also impact the stability and resilience of LV distribution networks. Due to the impact of voltage unbalance on the power system, organizations like IEEE, NEMA, and IEC have developed power quality standards that will maintain high power quality [8][9][10]. They have also defined the maximum voltage unbalance limits.

Numerous studies [11][12][13][14] have investigated voltage unbalance in power system networks These studies often employ simulation tools, field measurements, and analytical methods to assess voltage variations and imbalance levels across network phases. This paper aims to contribute valuable insights on the integration of single-phase PV systems in a radial LV distribution networks.

II. VOLTAGE UNBALANCE ESTIMATION

Voltage imbalance is defined as the highest departure of the three-phase voltage from the mean voltage divided by the average voltage value of the three-phase line voltage. IEEE Standard 45-2002 states that the unbalance voltage in a three-phase system must not exceed 3% of the average voltage in each phase [8]; whereas ANSI Standard C84.1-1995 states that the current unbalance must not exceed 5% of the average in each phase of the three-phase power system [9]. There are various techniques for estimating three-phase voltage unbalance (or current unbalance) in power distribution networks [15][16][17][18][19]. When all of the parameters of a three-phase system are equal, it is considered symmetric. It is also considered balanced when the magnitude and phase are equal and 120° apart. When the magnitude of voltage (or current) is unequal, a three phase system is considered imbalanced. The symmetrical component technique can be used to estimate voltage unbalance (or current), and it allows detailed per-phase analysis of unbalanced loads and fault circumstances.

The symmetrical component approach is used to study and estimate voltage (or current) unbalance in three-phase systems using three-phase unsymmetrical or unbalance phasors, which can then be resolved using a three-set component set of balanced phasors with a specific symmetry [20]. Assuming a three-phase is represented by a, b, and c, the positive phase sequence components are a, b, and c, while the negative sequence components are a, c, and b. The zero, positive, and negative sequences are denoted by subscripts 0, 1, and 2, respectively.

Regarding the voltage in the line, voltages such as $V_{AB,}$ V_{BC}, V_{CA} fluctuate in a positive and negative sequence, as shown in Equations 1 and 2, while the zero component does not exit...

$$V_1 = \frac{1}{3}\left(V_a + \alpha V_b + \alpha^2 V_C\right) \tag{1}$$

$$V_2 = \frac{1}{3}\left(V_a + \alpha^2 V_b + \alpha V_C\right) \tag{2}$$

When we assume that the negative sequence component in Equation 2 is zero (V2 = 0), we only have the positive sequence component depicted in Equation 1. When the positive sequence component is zero (V1=0), only the negative sequence component remains, indicating an unbalanced three-phase system (V1 ≠ 0 and V2 ≠ 0).

The line voltages now become;

$$V_{ab} = V_1 + V_2 \tag{3}$$

$$V_{bc} = \alpha^2 V_1 + \alpha V_2 \tag{4}$$

$$V_{ca} = \alpha V_1 + \alpha^2 V_2 \tag{5}$$

where α is (1 < -120)

To access the unbalance voltage of the power system network, the conjugate coefficient of the line unbalance voltage in Equation 6 is used to determine the unbalance.

$$K_u = \frac{V_2}{V_1} = \frac{V_{ab} + \alpha^2 V_{bc} + \alpha V_{ca}}{V_{ab} + \alpha V_{bc} + \alpha^2 V_{ca}} = \frac{V_2}{V_1} e^{j\varphi_u} \tag{6}$$

The coefficient of unbalance can be estimated without considering the angle between the positive and negative sequence components. Therefore, the coefficient of the line voltage unbalance can be defined as;

$$K_u = \frac{V_2}{V_1} = \frac{V_{ab} + \alpha^2 V_{bc} + \alpha V_{ca}}{V_{ab} + \alpha V_{bc} + \alpha^2 V_{ca}} \tag{7}$$

The coefficient (K_u) can be estimated using Equation 6 and 7. the line voltage in equation 3 - 5 can be presented as;

$$V_{ab} = V_1(1 + k_u) \tag{8}$$

$$V_{bc} = \alpha^2 V_1(1 + \alpha^2 k_u) \tag{9}$$

$$V_{ca} = \alpha V_1(1 + \alpha k_u) \tag{10}$$

According to [20], Rachwaiski invented an approximation method based on the approximation of the positive sequence voltage component. In the method, he hypothesized that the positive sequence component at minor unbalance could be approximated by the average voltage values in the power network, as shown in equation 11. Equation 12 illustrates how auxiliary variables were introduced to simplify the procedure.

$$U_1 = \frac{1}{3}\left(V_{ab} + V_{bc} + V_{ca}\right) \tag{11}$$

$$h_1 = \frac{V_{ab}}{U_1};\ h_2 = \frac{V_{bc}}{U_1};\ h_3 = \frac{V_{ca}}{U_1}; \tag{12}$$

The coefficient of the unbalance voltage is now determined by

$$K_u = \frac{(h_3 - h_2)(h_3 + h_2)}{2\sqrt{3} sin\varphi_u} \qquad 13$$

Where the angle φ_u is;

$$ctg\varphi_u = \frac{\sqrt{3}}{3}\left[2\frac{h_1 - h_2}{h_3 - h_2} - 1\right] \qquad 14$$

III. METHODOLOGY

A. System Description

The LV distribution feeder used for the investigation is a 400 V, 1.2 km system with a 200kVA transformer as shown in figure 1. The feeder has a resistance and reactance of 1.652 Ω and 1.2 Ω respectively. The load distribution on the LV distribution feeder is shown in Table 1. A single phase 10kW PV array was used for the analysis. The PV array is distributed unevenly on the distribution feeder. The uneven distribution pattern of the PV array and loading percentage (penetration level) are shown in Table 2. The capacity of the PV array distributed to different phase is regarded as scenarios. The LV distribution feeder, PV array and load distribution are simulated in MATLAB/Simulink work environment as shown in figure 3.2. Figure 3.3 shows the 10kW single phase PV system modeled and used for the analysis in MATLA/Simulink work environment.

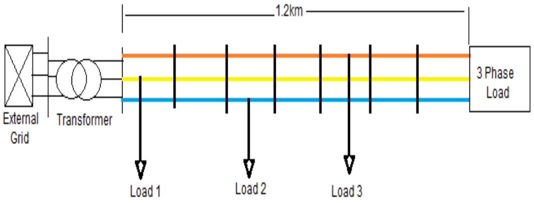

Fig 3.1: Radial LV distribution feeder used for the Analysis

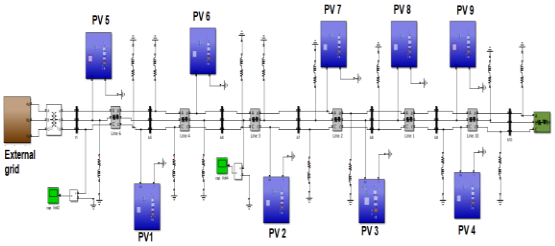

Fig 3.2: LV Distribution network with uneven distribution of single-phase PV system

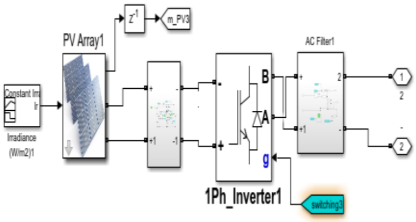

Fig 3.3: Single Phase inverter-based PV system arrangement in Simulink

Table 3.1: Load distribution on the feeder

Feeder Phases	Rating (VA)
Phase A	32.1kW
Phase B	52.5
Phase C	72.5

Table 2: Single Phase PV Distribution pattern on the feeder

Cases	Red Phase(A)	Yellow Phase (B)	Blue Phase (C)
Scenario 1	60kW (186.9%)	36kW (68.6%)	12kW (16.5%)
Scenario 2	24KW (74.7%)	48kW (91.4%)	36kW (49.6%)
Scenario 3	24kW (74.7%)	24kW (45.7%)	60kW (82.7%)

B. Method of Investigation

The IEEE Standard 45-2002 voltage unbalance method is used to evaluate and analyse the effects of unequal single-phase PV system integration on the LV distribution network. The standard defines voltage unbalance as the ratio of the maximum voltage deviations to the magnitude of the mean line voltage as shown in equation 15 and equation 16.

$$\text{Voltage unbalance} = \frac{Maxi\ mum\ voltage\ deviation\ from\ the\ avearge\ line\ voltage}{Avreage\ line\ voltage\ magnitude} \qquad 15$$

$$\text{Voltage unbalance} = \frac{(V_a - V_{Avg})(V_b - V_{avg})(V_c - V_{Avg})}{V_{Avg}} \qquad 16$$

where V_a, V_b, and V_c are the line voltages while V_{Avg} is the average voltage.

IV. RESULTS AND DISCUSSION

IV. A Impact of uneven distribution of single-phase Loads

To calculate voltage unbalance without integrating the PV arrays into the LV distribution network, it is essential to first consider the distribution of single-phase loads across the three phase distribution network. Table 3.1 provides a representation of how these loads are unevenly distributed among the phases. This distribution pattern directly impacts the voltage balance within the network. Figure 4.1 illustrates the voltage waveform and unbalance characteristics without the presence of the PV system on the LV distribution network. This waveform showcases the voltage variations across the three phases, highlighting any existing unbalance issues. Additionally, Figure 4.2 presents the magnitude of the absolute values of the voltages in each phase. Analyzing these magnitudes helps assess the degree of imbalance present in the system and provides insights into potential corrective measures. The calculated percentage unbalance in the LV distribution network, in the absence of PV integration, is determined to be 0.447%. This value falls within the acceptable range defined by the IEEE standard, indicating that the network's voltage unbalance, due to uneven distribution of single-phase loads, is within permissible limits. This analysis underscores the importance of evaluating voltage unbalance metrics both with and without PV system integration. It allows for a comprehensive understanding of how different factors, such as load distribution and renewable energy integration, influence network performance and compliance with industry standards.

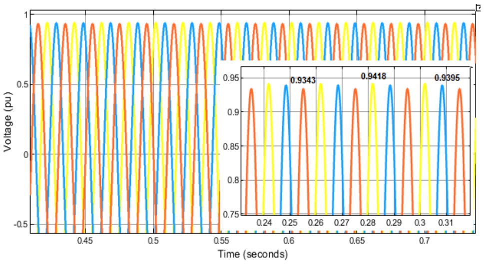

Fig 4.1 Unbalanced Nature of the distribution network

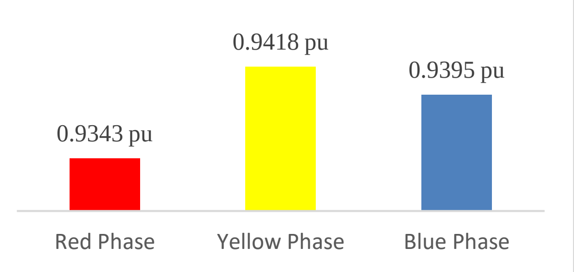

Fig 4.2: Absolute values of the line voltages

IV.B Uneven Distribution of Single- Phase Grid-ted PV System (Scenario 1)

In Figure 4.3, we observe the distorted imbalance voltage waveform, which signifies a scenario where the integration of PV systems has introduced significant unbalance into the LV distribution network. This imbalance is further illustrated in Figure 4.4, which displays the absolute values of the voltages across the various phases in scenario 1. In this specific scenario, Phase A exhibits the largest penetration of PV generation, measured at 186.1%. This indicates that a substantial portion of the PV system's output is connected to Phase A of the network. Conversely, Phases B and C have lower penetration levels, with percentages of 68.6% and 16.5%, respectively. This unequal distribution of PV generation among the phases contributes significantly to the observed voltage unbalance. Figure 4.5 provides a graphical representation of the absolute values of voltage magnitude as a function of PV penetration level. This plot illustrates how the penetration level of PV generation influences the magnitude of voltages across the phases, highlighting the impact of phase penetration on voltage balance within the network. The analysis of this scenario reveals that the influence of phase penetration levels from PV systems has resulted in a percentage voltage unbalance of 9.87%. This value significantly exceeds the IEEE voltage unbalance standard limit, indicating a substantial deviation from balanced voltage conditions in the LV distribution network. The high percentage of voltage unbalance in scenario 1 underscores the importance of carefully managing PV integration and phase allocation within the network. Strategies such as phase balancing techniques, optimal placement of PV systems across phases, and advanced control algorithms can help mitigate voltage unbalance issues and improve network performance. This scenario serves as a critical example of how the integration of renewable energy sources, such as PV systems, can impact voltage balance in distribution networks. It emphasizes the need for comprehensive analysis, planning, and mitigation strategies to ensure the reliable and efficient operation of LV distribution systems amidst increasing renewable energy integration

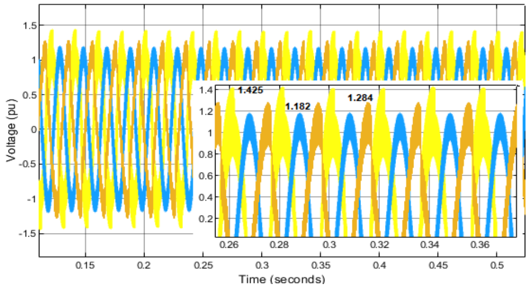

Fig 4.4: Voltage Unbalance of scenario 1

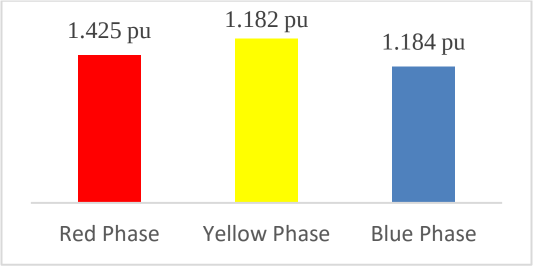

Fig 4.5: Absolute values of line voltages Magnitude of Scenario 1

IV.C Uneven Distribution of Single- Phase Grid-ted PV System (Scenario 2)

In Scenario 2, the percentage voltage unbalance is calculated to be 7.68%, primarily attributed to the specific penetration pattern of the single-phase PV array within the LV distribution network. Figure 4.6 provides a visual representation of the distorted voltage waveform, highlighting the phase differences caused by the PV integration. Analyzing Scenario 2 further reveals that Phase B is more heavily loaded compared to Phases A and C, with penetration levels of 91.4%, 74.7%, and 49.6%, respectively. This unequal distribution of loads among the phases leads to absolute phase voltages of 1.121pu, 1.287pu, and 1.235pu for Phases A, B, and C, as depicted in Figure 4.7. The percentage voltage imbalance in this scenario exceeds the IEEE standard limit of 3%, indicating a substantial deviation from balanced voltage conditions within the network. This imbalance is exacerbated by the specific penetration pattern of the PV array, emphasizing the importance of considering load distribution and phase allocation in PV integration strategies. Addressing voltage imbalance issues in Scenario 2 requires implementing corrective measures such as load balancing techniques, phase allocation adjustments, and voltage control strategies. These measures aim to optimize the distribution of loads and PV generation across phases, thereby improving voltage balance and network performance. The analysis of Scenario 2 underscores the intricate relationship between PV penetration patterns, load distribution, and voltage imbalance in LV distribution networks. It highlights the need for careful planning, monitoring, and control to ensure the reliable and efficient operation of networks with integrated renewable energy sources, while also meeting regulatory standards and compliance requirements

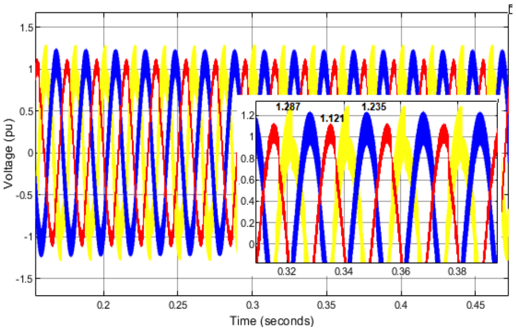

Fig 4.6: Voltage Unbalance magnitude of scenario 2

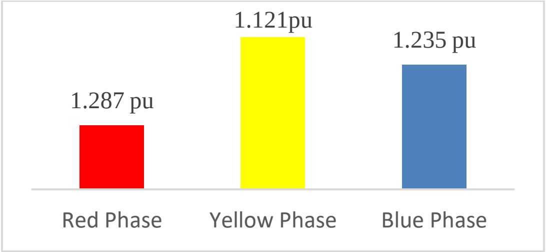

Fig 4.7: Absolute values of line voltages of Scenario 2

IV. D IV.B Uneven Distribution of Single- Phase Grid-ted PV System (Scenario 3)

In Scenario 3, Figure 4.7 presents the imbalanced and distorted waveforms caused by the specific phase penetration pattern of the PV system within the LV distribution network. This pattern results in a deviation from balanced voltage conditions, leading to the observed voltage waveform distortions. Analyzing Scenario 3 reveals a penetration level of 74.7%, 45.7%, and 82.7% for Phases A, B, and C, respectively. This uneven distribution of PV generation among the phases contributes to variations in voltage magnitudes across the network. Figure 4.8 illustrates the absolute voltage magnitudes for Phases A, B, and C, measured at 1.236 pu, 1.143 pu, and 1.121 pu, respectively. These differences in phase magnitudes reflect the impact of the PV system's phase penetration level on voltage balance within the network. The percentage voltage unbalance calculated for Scenario 3 is 5.93%, which exceeds the IEEE's percentage voltage unbalance standard limit. This deviation from the standard limit highlights the significance of the phase penetration pattern in influencing voltage imbalance and underscores the need for effective mitigation strategies. Addressing voltage unbalance issues in Scenario 3 necessitates implementing corrective actions such as optimizing phase allocation, adjusting load distribution, and implementing voltage control measures. These actions aim to reduce voltage deviations, improve balance across phases, and enhance overall network stability and performance.

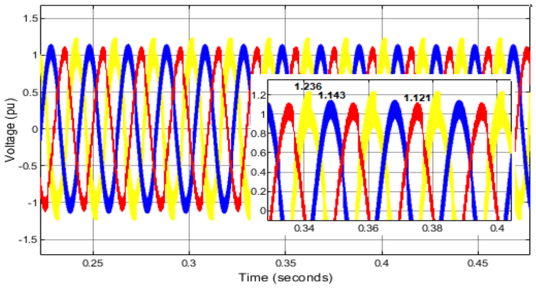

Fig 4.8: Voltage Unbalance magnitude of scenario 3

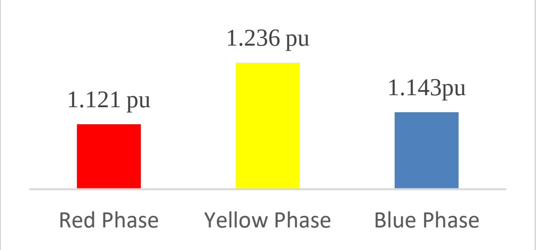

Fig 4.9: Absolute values of line voltages of Scenario 3

V. HELPFUL HINTS

The research of voltage unbalance in a radial LV distribution networks with single-phase photovoltaic (PV) systems leads to significant conclusions regarding the challenges, possible solutions, and future directions in this domain. Our investigation describes and analyse the potential impact of uneven and controlled penetration of single phase PV array. The results reveal that the investigated scenarios gave percentage voltage unbalance of over 3% which is above the IEEE Standard 45-2002 limit and will possibly lead to high losses, transformer failure, etc. Addressing voltage imbalance issues in LV networks with single-phase PV systems requires a multidisciplinary approach, involving technical innovations, policy interventions, and collaborative efforts to build resilient and sustainable energy infrastructure. By implementing proactive measures and advancing research frontiers, the vision of a balanced and efficient LV distribution network with renewable energy integration can be realized

REFERENCES

[1] Ebhota, W. S., and J. Tien-Chien J. Fossil fuels environmental challenges and the role of solar photovoltaic technology advances in fast tracking hybrid renewable energy system. International Journal of Precision Engineering and Manufacturing-Green Technology Vol. 7 pp. 97-117, 2020.

[2] K. Say, J. Michele, D. Roger, and T. W. Raymond,. The coming disruption: The movement towards the customer renewable energy transition." Energy Policy 123 PP.737-748, 2018.

[3] V. Tyagi. Developing business model based on product service system approach for successful implementation of rooftop solar PV systems in India. PhD dissertation, College of Management and Economic Studies, UPES, Dehradun, 2023.

[4] Y. Z. Gerdroodbari, Z. Yasin, R. Reza, and S. Farhad. Improving voltage regulation and unbalance in distribution networks using peer-to-peer data sharing between single-phase PV inverters. IEEE Transactions on Power Delivery 37, no. 4 pp. 2629-2639, 2021.

[5] E. Hossain, R. T. Mehmet, P. Sanjeevikuma, A. Selim, and K. Imtiaj. Analysis and mitigation of power quality issues in distributed generation systems using custom power devices. IEEE Access 6, pp. 16816-16833. 2021

[6] H. M. Bollen, R. Paulo, Y. G. Irene, and A. D. Carlos. Trends, challenges and opportunities in power quality research. European Transactions on Electrical Power 20, No. 1 pp. 3-18. 2010.

[7] A. Aderibigbe, O. Ayodeji, A. Raphael, and S. Isaac. The performance of a 3-Phase Induction Machine under Unbalance Voltage Regime." Journal of Engineering Science & Technology Review 10, No. 5 2017.

[8] E. Muljadi, S. Rich, and A. L. Thomas A. Induction machine phase balancing by unsymmetrical thyristor voltage control. Annual Meeting Industry Applications Society, IEEE, pp. 1330-1338. 1984.

[9] H. R. Stewart, D. Stewart, F. Stone, F. Rocchio, J. Cospolich, D. Bishop, C. Darnell, and M. Islam. Panel discussion of IEEE-45-2002. IEEE recommended practice for electrical installation on shipboard. In IEEE Industry Applications Society 50th Annual Petroleum and Chemical Industry Conference, Record of Conference Papers., pp. 351-353. IEEE, 2003.

[10] ANSI, ANSI. Electric Power Systems and Equipment Voltage Ratings (60 Hertz). Electric Power Systems and Equipment—Voltage Ratings (60 Hertz) 2011.

[11] U. Jayatunga, P. Sarath, C. Phil, and A. P. Agalgaonkar. A review of recent investigations on voltage unbalance management: Further contributions to improvement of IEC/TR 61000-3-13: 2008. IEEE 16th International Conference on Harmonics and Quality of Power (ICHQP), pp. 268-272. 2014.

[12] E. W. Sinuraya, M. Soemantri, and I. R. Rafif. Evaluation and Mitigation of Voltage and Current Unbalance at MSTP Undip Jepara. In Journal of Physics: Conference Series, vol. 2406, No. 1, p. 012013. IOP Publishing, 2022.

[13] D. Flumian, L. Philippe, and S. Emmanuel Calculation of the Voltage Unbalance Factor for High-Speed Railway Substations with V-Connection Scheme. Electronics 11, No. 4 pp. 595. 2022

[14] J. Ogunyemi, and O. A. Najeem O. Investigation of voltage unbalance in a distribution network: A case study of federal polytechnic Ilaro. Journal of Energy Technology and Environment 3, No. 1 pp. 16-22. 2021

[15] I. Naumov, P. Sergey, I. Dmitri, T. Alexander, and B. Andre. Analysis of unbalanced load low-voltage electrical networks operating modes. In E3S Web of Conferences, Vol. 295, p. 02005. EDP Sciences, 2021.

[16] N. C. Woolley, and J. V. Milanović. Estimating the voltage unbalance factor using distribution system state estimation. IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe), pp. 1-7. 2010.

[17] F. J. Alcántara, and S. Patricio A new technique for unbalance current and voltage estimation with neural networks. IEEE Transactions on Power Systems 20, No. 2 pp. 852-858. 2005.

[18] N. C. Woolley. and J. V. Milanovic. Statistical estimation of the source and level of voltage unbalance in distribution networks. IEEE Transactions on Power Delivery 27, No. 3 pp. 1450-1460. 2012

[19] Z. Liu, and J. V. Milanović. Probabilistic estimation of voltage unbalance in MV distribution networks with unbalanced load. IEEE Transactions on Power Delivery 30, No. 2 pp. 693-703. 2014.

[20] O. Zbigniew, W. Andrzej Methods of Unbalance estimation in Electric Power Network. Electric Power Quality and Utilization Journal. Vol. 12, No 2, pp. 71-76. 2006.