ANALYSIS OF VOLTAGE UNBALANCE REGULATION

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ABSTRACT

This paper presents an analysis of the present voltage unbalance regulation in the deregulated power industry in the Philippines. The regulation of voltage unbalance was examined in the light of various standards pertaining to voltage unbalance. The response of three-phase electrical equipment to voltage unbalance is evaluated as per limits of Philippine Distribution Code (PDC). The voltage unbalance limits for transmission and distribution were investigated if it were practical using a numerical simulation of an electric power system. Recommendations and conclusions were drawn as per the analytical outline for voltage unbalance regulation.

Keywords: voltage unbalance, regulation, voltage unbalance limits, Philippine Distribution Code, Philippine Grid Code, performance compliance

I. INTRODUCTION

The restructuring of electric power industry in the Philippines as per Republic Act No. 9136 continues the regulation of power delivery entities, transmission and distribution. Significant regulation compliance for these industry players is power quality (PQ) for PQ affects consumers of electricity. The Philippine Grid Code (PGC) [1] and Philippine Distribution Code (PDC) [2] present these PQ performance conformances though in general approach. An important PQ index is the voltage unbalance measurement for both transmission and distribution systems. The PGC and PDC define voltage unbalance in different formulas and different limits. Voltage unbalance can be due to the transmission and distribution line asymmetries and connected unbalanced loads. Line configurations produce unequal mutual coupling that result in unbalance in potential difference between lines. Obviously, loads that are unbalanced affect the terminal voltage to which they are connected. In distribution systems, single-phase and three-phase loads are utilized so therefore it is expected that the voltage unbalance is at a higher level than in transmission system. Therefore, voltage unbalance can propagate from electric utility's and consumers' power systems.

The voltage unbalance concern has generated issues in the electric power industry because of its implication on three-phase equipment. Voltage unbalance impact the operation of three-phase equipment that are mostly used in industrial and commercial power systems. Induction motors connected in three-phase supply heats up because of the presence negative sequence components that are opposing the positive sequence components as the motor is running. If voltage unbalance has a magnitude that overheats the motor, the motor needs to be derated to alleviate heating. In [3], the authors have analyzed the effect of voltage unbalance supply input on the performance of AC-DC rectifiers of industrial type.

Given these issues arising from voltage unbalance, this paper imparts an analytical examination of the present voltage unbalance regulation in the restructured power industry. As stated previously, the existing codes provide different equations for solving voltage unbalance and corresponding limits for transmission and distribution systems. There is a need to further analyze the utilization of these different equations and limits stated for voltage unbalance compliance. With PDC [2], the unbalance definition can create confusion whether to utilized line to line or phase to neutral voltages in computing voltage unbalance. Moreover, the evaluation of voltage unbalance at various transmission and distribution connection points for user system is presented.

This paper is organized as follows: Section II presents the various industry definitions of voltage unbalance citing standards and analyzes the voltage unbalance regulation definitions; Section III shows a numerical example for further analysis of voltage unbalance regulation; Section IV details recommendations for voltage unbalance regulation; Section V discloses the conclusions of the study.

II. VOLTAGE UNBALANCE STANDARD DEFINITIONS AND REGULATORY COMPLIANCE

A. Voltage Unbalance Definitions

There are presently four voltage unbalance definitions [3-4], these are stated and analyzed below in the light of PGC and PDC requirements.

1. National Equipment Manufacturer's Association (NEMA) definition

$$\%\mathrm{LVUR}=\frac{\text{maximum}\left|V_{AB}-\frac{V_{AB}+V_{BC}+V_{CA}}{3},V_{BC}-\frac{V_{AB}+V_{BC}+V_{CA}}{3},V_{CA}-\frac{V_{AB}+V_{BC}+V_{CA}}{3}\right|}{\frac{V_{AB}+V_{BC}+V_{CA}}{3}}\text{x }100 \qquad (1)$$

This is simply,

$$\%\mathrm{LVUR}=\frac{\text{maximum voltage deviation from average line voltage}}{\text{average line voltage}}\text{x }100 \qquad (2)$$

This voltage unbalance definition is known as the line voltage unbalance rate (LVUR). Notice that the voltages are line to line values and phase angles are ignored. NEMA requires induction motor derating when voltage unbalance is as much as 1% [5].

2. Institute of Electrical and Electronics Engineers (IEEE) 112-1991 definition

$$\%\mathrm{PVUR1}=\frac{\text{maximum}\left|V_{an}-\frac{V_{an}+V_{bn}+V_{cn}}{3},V_{bn}-\frac{V_{an}+V_{bn}+V_{cn}}{3},V_{cn}-\frac{V_{an}+V_{bn}+V_{cn}}{3}\right|}{\frac{V_{an}+V_{bn}+V_{cn}}{3}}\text{x }100 \qquad (3)$$

This is simply,

$$\%\mathrm{PVUR1}=\frac{\text{maximum voltage deviation from average phase voltage}}{\text{average phase voltage}}\text{x}100 \qquad (4)$$

This definition of voltage unbalance is stated in IEEE 112-1991, this is also known as the phase voltage unbalance rate (PVUR1). Notice that the voltages are phase to neutral values and again the phase angles are ignored.

3. Institute of Electrical and Electronics Engineers (IEEE) 936-1987 definition

$$\%PVUR2 = \frac{\text{maximum}(V_{an}, V_{bn}, V_{cn}) - \text{minimum}(V_{an}, V_{bn}, V_{cn})}{\frac{V_{an} + V_{bn} + V_{cn}}{3}} \text{ x } 100 \quad (5)$$

This is simply,

$$\%PVUR2 = \frac{\text{difference between maximum and minimum phase voltage}}{\text{average phase voltage}} \text{ x } 100 \quad (6)$$

IEEE dictionary, 936-1987, gives a different definition of voltage unbalance for phase voltage unbalance rate. In this formula, the phase voltages are utilized and phase angles are likewise neglected.

4. Negative Sequence Unbalance Factor definition

$$\%NSUF = \frac{V_2}{V_1} \text{ x } 100 \quad (7)$$

Where V_1 and V_2 are positive and negative sequence components of three-phase line voltages where,

$$V_1 = \frac{V_{ab} + a.V_{bc} + a^2.\ V_{ca}}{3}, \quad (8)$$

and

$$V_2 = \frac{V_{ab} + a^2.V_{bc} + a.\ V_{ca}}{3} \quad (9)$$

where, $a = 1\angle 120^\circ$ (10)

The negative sequence unbalance factor (NSUF) is regarded as the true definition of voltage unbalance [3-4].

B. Voltage Unbalance Regulatory Compliance

The PGC voltage unbalance definition [1] is based on the true definition given in equation (7). This definition is of clarity as it uses line to line voltages with their corresponding phase angles. The maximum NSUF at the connection point of any user shall not exceed one (1) percent during normal conditions [1]. Modern PQ analyzers employ the same definition for measuring unbalance.

The PDC [2] defines voltage unbalance as the maximum deviation from the average of the three-phase voltages divided by the average of the three-phase voltages, expressed in percent, which is not to exceed 2.5% excluding the unbalance passed on from the Grid during normal conditions at the connection point of any system user. This definition can be either equation (1) or equation (3) since it does not clearly state whether line voltages or phase voltages are to be utilize for computation. Also, these definitions neglect phase angles. Unbalance in voltage occurs when there is difference in voltage magnitudes and/or phase angles differ from 120 degrees displacement which is balanced condition [4]. Present day PQ analyzers do not use equations (1) or (3) for calculating measured voltage unbalance. When in actual measurements, the PDC definition will surely deviate from PQ analyzer's voltage unbalance results.

The voltage unbalance in the distribution system can be up to 5% as defined in the PDC. Example for Luzon grid, the connection point of the user (distribution system utilities or industrial plants) is at the 69kV level which is not a transmission voltage since 69kV interconnections are in radial connection. So, the 1% voltage unbalance limit is applied from 115kV up to 500kV levels. In this case, the voltage unbalance requirement at the 69kV level is therefore 2.5%. But the PDC states that the 2.5% voltage unbalance compliance is for distribution system connection point at the user system (residential, commercial and industrial users) excluding the unbalance created by the 69kV level connection point. This means that if voltage unbalances at transmission and distribution connection points are at the maximum acceptable voltage unbalance, the expected magnitude of voltage unbalance is 5% at the distribution connection point of any user. This 5% voltage unbalance which is analyzed as allowed by the PDC can create problems for three-phase devices, especially induction motors, connected to the distribution system. A voltage unbalance of 3.5% can increase motor losses by approximately 20% [5] and when the unbalance reaches 5%, the thermal quality in the motor begins to rise so fast that protection from damage becomes impractical [6]. In three-phase industrial grade rectifiers, the output power decreases and harmonic distortion increases as the voltage unbalance increase in magnitude [3].

The difference in definition in voltage unbalance regulation, when equation (1) is used for PDC and equation (7) is utilized for PGC, will not impact measurements for small unbalance, say 5%, but will have significant effect when measuring 20% unbalance [4].

Further, the limits at the connection points need clarifications. If the voltage unbalance at the transmission connection point at the 69kV level is measured at 2.5%, then the anticipated voltage unbalance at the 230kV side of the 230/69kV power transformer will not be likely less than 1%. This technical observation will be further investigated using an example system discussed in the next section.

III. NUMERICAL EXAMPLE

In this section, a numerical example is shown for voltage unbalance compliance. The test system shown in figure 1 is a typical configuration. The line configuration for 230kV line is taken from [7] using conductor coded Drake using a line length of 25 kms. For 69kV lines, the subtransmission triangular line configuration of D_{ij} = 3 feet, is taken from [8] utilizing conductor type with code Linnet utilizing a line height of 30 feet and line length of 15kms. The 13.8kV lines utilized 4/0 ACSR 6/1 conductor and the line configuration given in page 93 of reference [9] with line length equal to 3 kms. The loads per phase are started at 1200kW and power factor is 0.98 which is held constant. To introduce unbalance, the load at phase A is increase by increments of 100kW while the load at phase C is decreased by decrement of 50kW. In all simulation cases, the load at phase B is held constant. A three-phase load flow program was used to calculate voltages at each node.

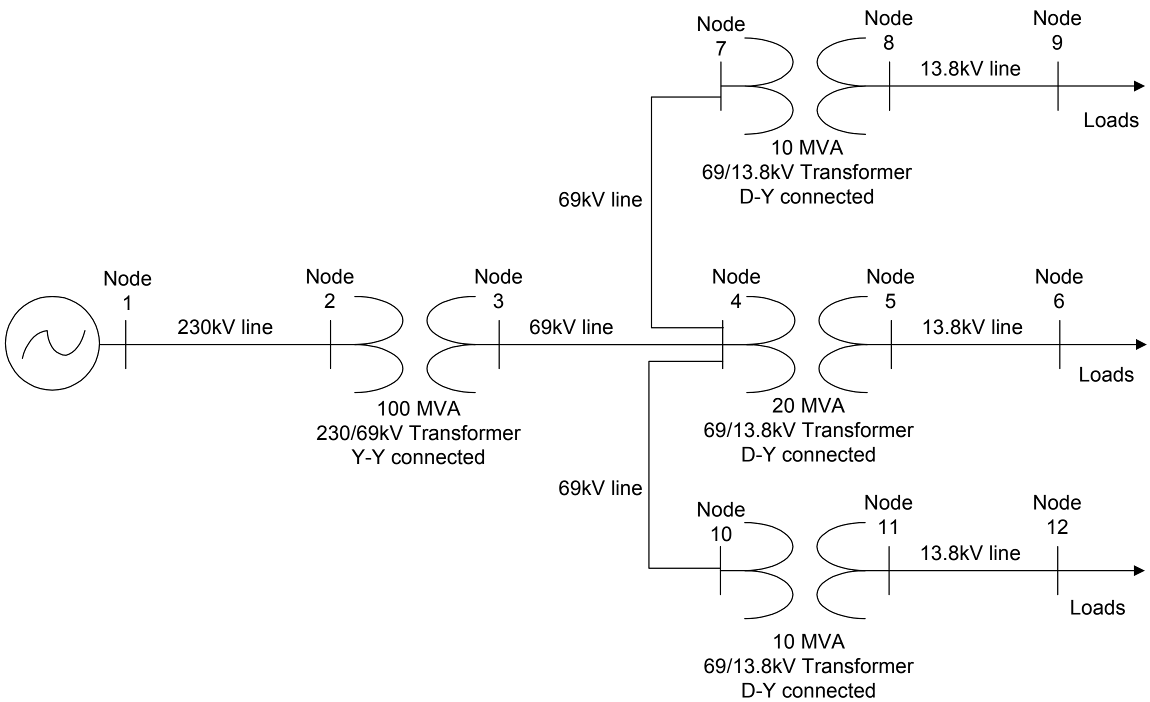

Figure 1. System for numerical example.

From the results of the load flow analysis, we calculate the voltage unbalance at each node using equations (1), (3) and (7) to analyze differences in the usage of different definitions.

Given in tables 1-4 are results of two cases. Case 1 is balanced loads while for case 2 is unbalanced loads; phase A load = 3200 kW, phase B load = 1200 kW, phase C load = 200 kW, all at 0.98 power factor.

Table 1. Voltage Unbalance in nodes 1-3.

Cases	Voltage Unbalance in Percent								
	Node 1			Node 2			Node 3		
	NSUF	LVUR	PVUR1	NSUF	LVUR	PVUR1	NSUF	LVUR	PVUR1
1	0.0	0.0	0.0	0.012	0.012	0.015	0.006	0.005	0.002
2	0.0	0.0	0.0	0.228	0.227	0.229	1.14	1.095	1.103

Table 2. Voltage Unbalance in nodes 4-6.

Cases	Voltage Unbalance in Percent								
	Node 4			Node 5			Node 6		
	NSUF	LVUR	PVUR1	NSUF	LVUR	PVUR1	NSUF	LVUR	PVUR1
1	0.151	0.147	0.209	0.156	0.154	0.148	0.226	0.246	0.281
2	2.425	2.407	2.569	5.511	5.463	4.064	8.351	8.504	14.017

Table 3. Voltage Unbalance in nodes 7-9.

Cases	Voltage Unbalance in Percent								
	Node 7			Node 8			Node 9		
	NSUF	LVUR	PVUR1	NSUF	LVUR	PVUR1	NSUF	LVUR	PVUR1
1	0.201	0.195	0.264	0.210	0.207	0.200	0.418	0.393	0.551
2	2.888	2.856	3.073	6.016	6.013	4.568	8.995	9.129	14.781

Table 4. Voltage Unbalance in nodes 10-12.

Cases	Voltage Unbalance in Percent								
	Node 10			Node 11			Node 12		
	NSUF	LVUR	PVUR1	NSUF	LVUR	PVUR1	NSUF	LVUR	PVUR1
1	0.201	0.195	0.264	0.210	0.207	0.200	0.418	0.393	0.551
2	2.888	2.856	3.073	6.016	6.013	4.568	8.995	9.129	14.781

The following are observations from the results:

- In case 1, the voltage unbalance are all within limits of PGC and PDC. Notice that the voltage unbalance at node 3 is the voltage unbalance “passed” by the Grid.
- In case 2, the PDC limit is violated at nodes 5-6, nodes 8-9 and nodes 11-12. Even the PDC limit is violated, the PGC limit is not violated at node 2 and node 3 unbalance does not exceed PDC limit. This shows that the voltage unbalance needs to be severe at the downstream components before it can affect the upstream voltage unbalance measurements.

- The voltage unbalance computed for nodes 7-9 and nodes 10-12 are the same since both interconnections are similar in characteristics.
- There is a good agreement between values of computed NSUF and LVUR but values of PVUR1 seem to deviate from NSUF and LVUR values both for cases 1 and 2 as show in the tables and figures 2 and 3.

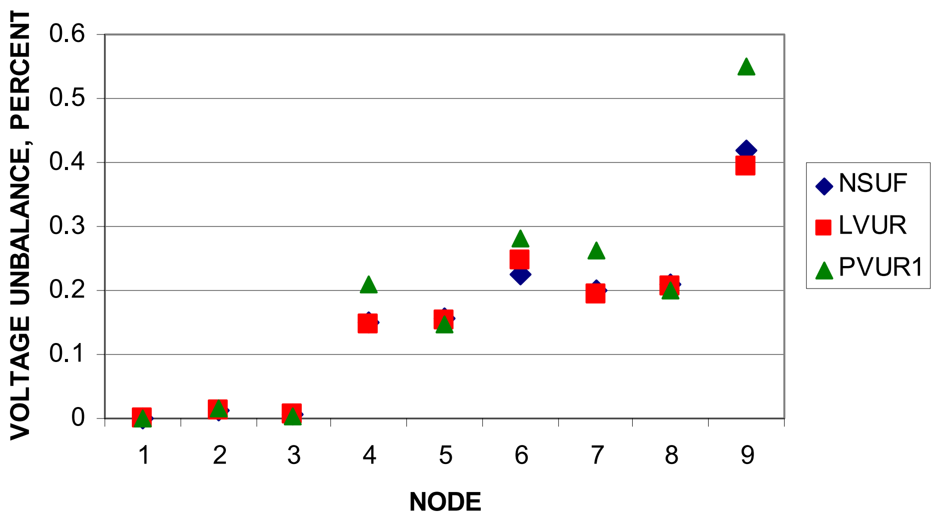

Figure 2. Voltage unbalance at various nodes from Case 1.

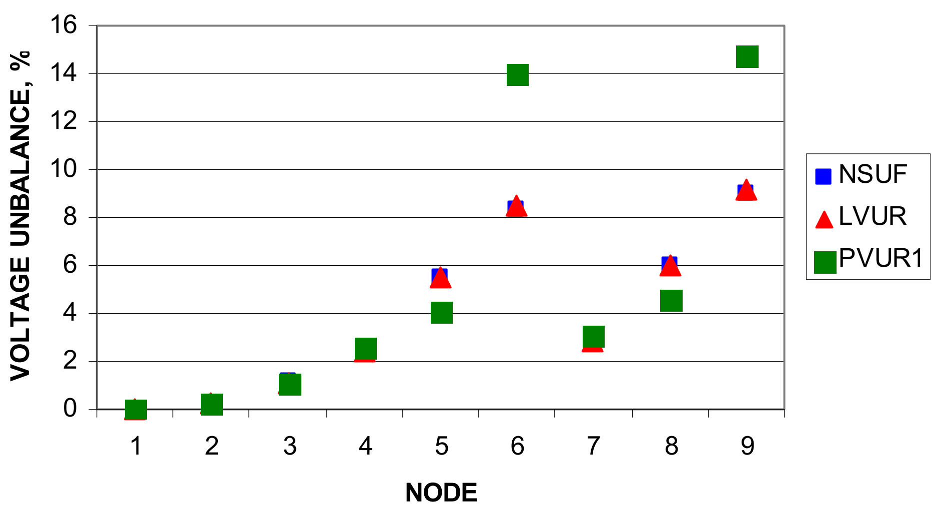

Figure 3. Voltage unbalance at various nodes from Case 2.

IV. RECOMMENDATIONS FOR VOLTAGE UNBALANCE REGULATION

The following are recommendations as drawn from above discussions:

1. The present PDC allowable voltage unbalance of 5% must be reviewed since it can affect three-phase equipment performance.
2. The regulator must provide clarification on what equation must be utilize for PDC voltage unbalance compliance, LVUR or PVUR1. This paper recommends LVUR since it has a good agreement with NSUF as shown in the numerical example.

V. CONCLUSIONS

This paper examined the present voltage unbalance regulation in the Philippine electric power industry. Different standard definitions of voltage unbalance were cited to help analysis of the present regulation. The implications of voltage unbalance on three-phase equipment were discussed in the light of the present limits in the PDC. Example simulations were conducted to investigate the correspondence of various voltage unbalance definitions and regulatory limits. Recommendations for harmonizing voltage unbalance limits and electrical equipment and further clarification of PDC voltage unbalance equation were cited.

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