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Electrical system load re-phasing: a case of a university building in the Philippines

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ABSTRACT

In the pursuit of attaining energy efficiency, administrators must delve deeply into the electrical system of a facility, especially if it is an old structure. As years go by, renovations and the addition of new equipment may lead to an imbalance in the electrical system. These imbalances may lead to inefficiencies, contributing to damage to equipment. This study aimed to investigate the electrical system of a university building by determining whether the percent current and voltage unbalance values in the system meet the standards. For non-conforming electrical branches, re-phasing schemes were proposed. Data revealed that the majority of the panelboards in the building have voltage imbalances that are within the allowable limit, while there is a considerable number of panelboards with above-the-minimum current unbalance value. The original configurations of some panelboards were retained to avoid further increase in the percentage of current imbalance associated with re-phasing. Merging certain panelboards, however, resulted in a reduction of current imbalances within the acceptable limit. If the re-phasing and merging of loads are to be implemented, a cost-benefit analysis and a study on the improvements in energy efficiency may be considered for further research.

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1. INTRODUCTION

Fifty-five percent of the global electricity comes from the building sectors [1]. It is expected to rise, especially in developing countries, as the global floor area is increasing exponentially. Additionally, consumers are buying more air conditioners and other appliances [2]. To compensate for the high demand, building administrators employ some form of passive or active energy efficiency measure [3]. Active energy efficiency includes savings obtained through measuring, monitoring, and controlling a building's energy usage [4]. Meanwhile, buildings with passive energy efficiency measures consider building envelopes [5]. Aside from the typical energy efficiency measures, there could be potential by looking at the distribution of electrical loads in the building. Issues in the electrical system arise when the load distribution becomes uneven [6]. Usually, it is a result of the changes in the electrical requirements in the building as years go by. One of the reasons is that the building may be used differently than originally intended [7]. Loads in a public building are single-phase in nature and connected in a three-phase system. This action is preferred since a three-phase power supply can provide three times more power than a single-phase power supply while requiring only one additional wire [8]. If there are multiple loads, they should be equally distributed among the phases, i.e., each line should carry the same amount of load. Electrical parameters like voltages, currents, etc., in all three phases should be identical. Otherwise, the circuit is classified as unbalanced [9]. Voltage imbalances and current imbalances both impact motors [10]-[12]. The two are related in such a way that voltage unbalance can create a value of current unbalance 6 to 10 times the voltage unbalance's magnitude [13]. The increase is approximately twice the square of the percentage of voltage unbalance [14]. Significant findings must be corrected as power losses increase with increasing degrees of unbalance in the system [15].

To mitigate these effects, it is necessary to check whether the percent voltage and the current unbalance still meet the prescribed standards. The former is expressed in percentages, where the maximum deviation from the average of the three-phase voltages is divided by the average of the three-phase voltage, expressed in percent [16]. In other words, it is the deviation of individual phase voltage magnitudes from the nominal values. Computation of current unbalance also follows the same process. Usually, the most common reason for unbalanced operation in distribution systems is the single-phase loading. In general, these unbalances can be corrected by load balancing [17]-[19], also known as, phase balancing [20], [21]. It is a technique that can be done by phase swapping or phase re-sequencing and load re-phasing.

A university building in the Philippines experiences a similar case of load imbalance. The said infrastructure is about 50 years old and has been subjected to several renovations. There were also upgrades in the electrical equipment throughout the years, such as the addition of air-conditioning units and the installation of sophisticated laboratory equipment. In this context, the old building needs to be assessed whether its electrical system is still in accordance with standards in terms of acceptable current and voltage imbalances.

The main goal of the study is to provide a basis for the administrators of the university for the upkeep of the said building as part of its advocacy for energy efficiency. Through a walk-in survey, the researchers aimed to conduct measurements of voltage and current in the main line and branch circuits. After the survey, the current and voltage imbalances in each panel were computed and compared with existing standards. Based on the findings, the researcher provided a re-phasing scheme to reduce the said imbalances.

2. METHOD

The researchers assessed the status of the engineering building in a university in the Philippines with respect to its electrical loading by survey and audit. The said building has two adjoining structures: the old engineering building (EB) and the Aguinaldo Hall (AH). The old engineering building has 14 panelboards while the Aguinaldo Hall has only 1 panelboard containing 5 branch circuit breakers.

Initially, a letter addressed to the administrator was written to ask permission to conduct a room survey. A copy of the blueprints of the engineering building was also requested to determine the location of the panelboards. Some rooms were excluded from the survey, such as the audio-visual room and rooms that belonged to other units of the university. The reason is due to renovations being made during the time of the survey.

Voltage and current measurements in each panelboard were conducted using a three-phase power clamp meter (PEAKMETER Professional MS2203). These measurements were then used as inputs in the computation of the current/voltage unbalance. The researchers measured the current and voltage in each of the three phases then the average current/voltage was calculated using (1). After this, the absolute difference between each phase current/voltage was calculated using (2). The largest among the absolute differences is identified is the maximum deviation. The percent current or voltage unbalance can be calculated by dividing the maximum deviation by the average current/voltage as shown in (3).

$$Average\ Current\ or\ Voltage = \frac{L_1+L_2+L_3}{3} \tag{1}$$

Where L_1, L_2 and L_3 = line currents or voltages.

$$Deviation = \ Line\frac{Current}{Voltage} - Average\ \ Currentor\ Voltage \tag{2}$$

$$Current\ or\ Voltage\ Unbalance = \frac{Maximum\ Deviation\ from\ Average\ Current\ or\ Voltage}{Average\ Current\ or\ Voltage} x100 \tag{3}$$

Results were then evaluated to determine whether they conform with standards. According to IEEE Standard 45-2002, the maximum limit for voltage unbalance is 3% of the average voltage in each phase. Meanwhile, the American national standard for electric power systems manual also recommends that the value of current unbalance should be limited to 2.5-3% during normal operating conditions [22]. On the other hand, according to ANSI Standard C84.1-1995, the maximum for current unbalance is 5% from the average current in each phase [23]. Panelboards which exceeded the standard values were proposed with re-phasing schemes to reduce the imbalances to acceptable limits.

3. RESULTS AND DISCUSSION

3.1. Current and voltage measurements in the rooms

The researchers surveyed each panelboard found in the building and tabulated their measurements. The electrical loads in the building consist of lights, convenience outlets, and ACUs. As seen in Table 1, the panelboard in room EB 214 of the old engineering building recorded the highest current reading. The said panelboard caters power to laboratory rooms for physics and chemistry classes. This room contains sets of laboratory equipment, large ratings of ACUs and several electric fans. Meanwhile, the highest recorded current reading in Aguinaldo Hall is found at CB 4, which powers several rooms equipped with ACUs. On the other hand, voltage readings range from 213.60 V to 242.40 V.

Table 1. Current and voltage readings in the panelboards

Panelboard	Line 1		Line 2		Line 3	
	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)
EB 107	20.90	227.50	40.70	233.10	45.30	227.00
EB 110	10.00	221.00	12.50	227.00	19.80	220.20
EB 113	12.90	229.40	9.90	228.90	20.30	229.50
Library	18.20	221.60	22.90	225.60	9.10	221.00
EB 201	2.40	235.00	8.60	227.30	8.70	229.10
EB 204	11.80	226.10	16.10	233.00	8.50	227.40
EB 205	10.70	235.00	4.80	227.30	6.60	229.10
EB 207	45.40	227.20	20.60	233.70	27.30	225.50
EB 214	**55.10**	221.00	**50.90**	228.80	**56.20**	220.70
EB 215	4.10	220.70	9.80	228.00	23.00	221.50
EB 217	20.60	217.50	20.20	231.60	4.10	221.90
Stentorian Office	57.20	213.60	25.60	225.50	50.80	224.60
AH CB 1	8.80	230.80	8.70	238.90	4.10	231.50
AH CB 2	30.00	233.80	17.80	241.60	26.10	232.00
AH CB 3	14.90	231.20	2.70	240.00	14.80	233.10
AH CB 4	**47.10**	232.80	**41.60**	240.40	**28.10**	232.50
AH CB 5	7.50	234.60	0.80	242.40	7.80	234.30

3.2. Percent voltage and current unbalance in each panelboard

As seen in Table 2, most of the panelboards in the building are below the maximum limit of voltage imbalance except for the panelboards found in EB 217 and the Stentorian Office. Inspection of the lines revealed that these panelboards have one or two electrical lines providing power to more equipment than the other lines. The unequal and random distribution of single-phase loads is one of the reasons for this problem [24]. Interviews with past building administrators showed that the rooms connected to the said panelboards had been installed with additional equipment. The Stentorian Office, for instance, used to be only a part of an adjacent room. It was recently converted to an office which required an air-conditioning unit and other appliances.

Table 2. Percent voltage unbalance in each panelboard

Panelboard	Average voltage	L1 deviation	L2 deviation	L3 deviation	Maximum deviation	Voltage unbalance	Remarks
EB 107	229.20	1.70	3.90	2.20	3.90	1.70%	Below
EB 110	222.73	1.73	4.27	2.53	4.27	1.92%	Below
EB 113	229.27	0.13	0.37	0.23	0.37	0.16%	Below
Library	222.73	1.13	2.87	1.73	2.87	1.29%	Below
EB 201	230.47	4.53	3.17	1.37	4.53	1.97%	Below
EB 204	228.83	2.73	4.17	1.43	4.17	1.82%	Below
EB 205	230.47	4.53	3.17	1.37	4.53	1.97%	Below
EB 207	228.80	1.60	4.90	3.30	4.90	2.14%	Below
EB 214	223.50	2.50	5.30	2.80	5.30	2.37%	Below
EB 215	223.40	2.70	4.60	1.90	4.60	2.06%	Below
EB 217	223.67	6.17	7.93	1.77	7.93	**3.55%**	**Exceeded**
Stentorian Office	221.23	7.63	4.27	3.37	7.63	**3.45%**	**Exceeded**
AH CB 1	233.73	2.93	5.17	2.23	5.17	2.21%	Below
AH CB 2	235.80	2.00	5.80	3.80	5.80	2.46%	Below
AH CB 3	234.77	3.57	5.23	1.67	5.23	2.23%	Below
AH CB 4	235.23	2.43	5.17	2.73	5.17	2.20%	Below
AH CB 5	237.10	2.50	5.30	2.80	5.30	2.24%	Below

Table 3 indicates that the current imbalance in most of the panelboards exceeded 5%, with values as high as 86% on some panelboards. As mentioned, the electrical loads in the building are single-phase equipment and are the reason for the unbalance. As public buildings, their main loads include lighting, ventilation, and office appliances [25]. Looking at the deviations in the line in each panelboard, it could be noticed that there are one or two saturated lines and another line that is underutilized. Inspection reveals that the problem is caused by random connections due to the installation of air-conditioning units in each room.

Table 3. Percent current unbalance in each panelboard

Panelboard	Average current	L1 deviation	L2 deviation	L3 deviation	Maximum deviation	Current unbalance	Remarks
EB 107	35.63	14.73	5.07	9.67	14.73	41.35%	**Exceeded**
EB 110	14.10	4.10	1.60	5.70	5.70	40.43%	**Exceeded**
EB 113	14.37	1.47	4.47	5.93	5.93	41.30%	**Exceeded**
Library	16.73	1.47	6.17	7.63	7.63	45.62%	**Exceeded**
EB 201	6.57	4.17	2.03	2.13	4.17	63.45%	**Exceeded**
EB 204	12.13	0.33	3.97	3.63	3.97	32.69%	**Exceeded**
EB 205	7.37	3.33	2.57	0.77	3.33	45.25%	**Exceeded**
EB 207	31.10	14.30	10.50	3.80	14.30	45.98%	**Exceeded**
EB 214	54.07	1.03	3.17	2.13	3.17	5.86%	**Exceeded**
EB 215	12.30	8.20	2.50	10.70	10.70	86.99%	**Exceeded**
EB 217	14.97	5.63	5.23	10.87	10.87	72.61%	**Exceeded**
Stentorian Ofc	44.53	12.67	18.93	6.27	18.93	42.51%	**Exceeded**
AH CB1	7.20	1.60	1.50	3.10	3.10	43.06%	**Exceeded**
AH CB 2	24.63	5.37	6.83	1.47	6.83	27.74%	**Exceeded**
AH CB 3	10.80	4.10	8.10	4.00	8.10	75.00%	**Exceeded**
AH CB 4	38.93	8.17	2.67	10.83	10.83	27.83%	**Exceeded**
AH CB 5	5.37	2.13	4.57	2.43	4.57	85.09%	**Exceeded**

3.3. Re-phasing scheme for the panelboards with non-conformities

Inspection of the loads connected to panelboards EB 113, EB 201, EB 204, EB 214, AH CB1 to AH CB5 reveals that re-phasing is not viable. Re-phasing the loads will lead to further increase in percent current unbalance. The only solution for this issue is to combine the loads of the said panelboards. With this, only the panelboards in the Stentorian Office, Library, EB 110, EB 215, EB 217, EB 205, EB 207, and EB 107 were prepared with a re-phasing scheme by the researchers. The succeeding tables (Table 4 to 11) show the original arrangements of circuit breakers and the proposed re-phasing scheme for the above-mentioned panelboards. The highlighted circuit breakers (CB) in the tables are the loads that were moved to other phases.

The proposed action entails a reduction in the percent current unbalance on the panelboards, as shown in Table 12. Although there is a drop in the percentage of the current unbalance values on the panelboards, 5 of them still exceed 5%. To further reduce the imbalance, the electrical loads of the said panelboards were combined as follows: i) EB 107 and EB 110, ii) EB 205 and EB 207, and iii) Stentorian Office, EB 215, and EB 217. The proposed arrangement of loads can be seen in Table 13 which resulted in acceptable values of percent current unbalance as summarized in Table 14. This means that, for the electrical system of an old building to be in a balanced state, some re-wiring is necessary.

Table 4. Arrangement of loads in the Stentorian Office

L12	L23	L31
Original configuration		
CB1=10.80	CB5=1.00	CB3=26.60
CB2=5.90	**CB6=0.60**	**CB4=10.30**
CB7=0.40	CB11=0.80	**CB9=1.40**
CB8=5.4 0	CB12=2.40	**CB10=8.60**
Total=22.50	Total=4.80	Total=46.90
Proposed re-phasing		
CB1=10.80	**CB4=10.30**	CB3=26.60 A
CB2=5.90	**CB10=8.60**	**CB7=0.40 A**
CB8=5.40	CB12=2.40	-
CB9=1.40	CB5=1.00	-
CB6=0.60	CB11=0.80	-
Total=24.10	Total=23.10	Total=27.00

Table 5. Arrangement of loads in the engineering library

L12	L23	L31
Original configuration		
CB1=8.70	CB5=8.20	**CB3=0.30**
CB2=9.20	**CB6=SPARE**	**CB4=SPARE**
CB7=SPARE	CB11=SPARE	CB9=SPARE
CB8=SPARE	CB12=SPARE	CB10=SPARE
Total=17.90	Total=8.20	Total=43.00
Proposed re-phasing		
CB1=8.70	CB5=8.20	**CB2=9.20**
CB4=SPARE	**CB3=0.30**	**CB6=SPARE**
CB7=SPARE	CB11=SPARE	CB9=SPARE
CB8=SPARE	CB12=SPARE	CB10=SPARE
Total=8.70	Total=8.50	Total=9.20

Table 6. Arrangement of loads in EB 110

L12	L23	L31
Original configuration		
CB1=SPARE	CB5=10.20	CB3=9.20
CB2=1.30	**CB6=9.70**	CB4=2.90
CB7=SPARE	CB11=SPARE	**CB9=1.20**
CB8=SPARE	CB12=SPARE	CB10=SPARE
Total=1.30	Total=19.90	Total=13.30
Proposed re-phasing		
CB9=1.20	CB5=10.20	CB3=9.20
CB6=9.70	**CB2=1.30**	**CB1=SPARE**
CB7=SPARE	CB11=SPARE	CB4=2.90
CB8=SPARE	CB12=SPARE	CB10=SPARE
Total=10.90	Total=11.50	Total=12.10

Table 7. Arrangement of loads in EB 215

L12	L23	L31
Original configuration		
CB1=SPARE	**CB5=SPARE**	CB3=SPARE
CB2=7.00	**CB6=SPARE**	CB4=7.50 A
CB7=2.70	CB11=SPARE	CB9=SPARE
CB8=SPARE	CB12=SPARE	**CB10=1.30**
Total=9.70	Total=0.00	Total=8.80
Proposed re-phasing		
CB1=SPARE	**CB7=2.70**	CB3=SPARE
CB2=7.00	**CB10=1.30**	CB4=7.50 A
CB5=SPARE	CB11=SPARE	CB9=SPARE
CB8=SPARE	CB12=SPARE	**CB6=SPARE**
Total=7.00	Total=4.00	Total=7.50

Table 8. Arrangement of Loads in EB 217

L12	L23	L31
Original configuration		
CB1=9.40 A	**CB5=SPARE**	CB3=SPARE
CB2=9.00 A	**CB6=SPARE**	**CB4=1.10**
CB7=SPARE	CB11=SPARE	CB9=7.90
CB8=SPARE	CB12=SPARE	CB10=1.90
Total=18.40	Total=0.00	Total=10.90
Proposed re-phasing		
CB1=9.40	**CB2=9.00**	CB3=SPARE
CB5=SPARE	**CB4=1.10**	**CB6=SPARE**
CB7=SPARE	CB11=SPARE	CB9=7.90
CB8=SPARE	CB12=SPARE	CB10=1.90
Total=9.40	Total=10.10	Total=9.80

Table 9. Arrangement of loads in EB 205

L12	L23	L31
Original configuration		
CB1=SPARE	**CB5=SPARE**	CB3=SPARE
CB2=5.60 A	CB6=SPARE	CB4=3.80 A
CB7=SPARE	CB11=SPARE	**CB9=2.50 A**
CB8=SPARE	CB12=SPARE	CB10=SPARE
Total=5.60 A	Total=0.00 A	Total=6.30 A
Proposed re-phasing		
CB1=SPARE	**CB9=2.50 A**	CB3=SPARE
CB2=5.6 A	CB6=SPARE	CB4=3.80 A
CB7=SPARE	CB11=SPARE	**CB5=SPARE**
CB8=SPARE	CB12=SPARE	CB10=SPARE
Total=5.60 A	Total=2.50 A	Total=3.80 A

Table 10. Arrangement of loads in EB 207

L12	L23	L31
Original configuration		
CB1=10.60	CB5=0.10	CB3=10.50
CB2=10.20	CB6=0.10	CB4=10.70
CB7=3.20	**CB11=SPARE**	**CB9=2.00**
CB8=0.80	**CB12=SPARE**	**CB10=1.20**
CB13=0.90	**CB17=SPARE**	CB15=SPARE
CB14=3.60	**CB18=SPARE**	CB16=1.0
Total=29.30	Total=0.20	Total=25.40
Proposed re-phasing		
CB1=10.60	CB5=0.10	CB3=10.50
CB11=SPARE	CB6=0.10	CB4=10.70
CB7=3.20	**CB2=10.20**	**CB18=SPARE**
CB8=0.80	**CB14=3.60**	CB16=1.00
CB13=0.90	**CB10=1.20**	CB15=SPARE
CB12=SPARE	**CB9=2.0**	**CB17=SPARE**
Total=15.50	Total=17.20	Total=22.20

Table 11. Arrangement of loads in EB 107 laboratory room

L12	L23	L31
	Original configuration	
CB1=9.50	**CB5=9.60**	CB3=SPARE
CB2=0.40	CB6=21.60	CB4=10.00
CB7=SPARE	CB11=SPARE	CB9=2.60
CB8=3.90	CB12=SPARE	**CB10=SPARE**
Total=13.80	Total=31.20	Total=12.60
	Proposed re-phasing	
CB1=9.50	**CB10=SPARE**	CB3=SPARE
CB2=0.40	CB6=21.60	CB4=10.00
CB7=SPARE	CB11=SPARE	CB9=2.60
CB5=9.60	CB12=SPARE	**CB8=3.90**
Total=19.50	Total=21.60	Total=16.50

Table 12. Percent current unbalance before and after re-phasing

Panelboard	Current unbalance (before)	Current unbalance (after)
Stentorian Office	42.51	**9.10**
Library	45.62	4.54
EB 107	41.35	**21.30**
EB 110	88.70	**5.22**
EB 205	45.24	**36.00**
EB 215	80.79	**35.14**
EB 217	80.79	3.75

Table 13. Combined loads of panelboards

L12	L23	L31
	EB 107 and EB 110	
CB1(107)=9.50	CB5(107)=9.60	CB6(107)=21.60
CB5(110)=10.20	CB4(107)=10.00	CB2(107)=0.40
CB3(110)=9.20	CB6(110)=9.70	CB8(107)=3.90
CB2(110)=1.30	CB9(110) =1.20	CB9(107)=2.60
		CB3(110)=1.90
Total=30.20	Total=30.50	Total=31.40
	EB 205 and EB 207	
CB1(207)=10.60	CB5(207)=0.10	CB13(207)=10.50
CB2(205)=3.80	CB6 and CB9(207) =0.10+1.20	CB14(207)=10.70
CB7(207)=3.20	CB2(207)=10.20	CB15(207)=1.00
CB4(207)=0.80	CB14(207)=3.60	CB16=SPARE
CB13(207)=0.90	CB2(205)=5.60	CB17=SPARE
CB9(205)=2.50	CB12(207)=2.00	CB18=SPARE
Total=21.80	Total=22.80	Total=22.20
	Stentorian Office, EB 215, and EB 217	
CB1(217)=9.40	CB1(S)=10.80	CB3(S)=26.60
CB2(217)=9.00	CB4(S)=10.30	CB4(215)=7.50
CB10(S)=8.60	CB9(217)=7.90	CB7(215)=2.70
CB2(215)=7.00	CB2(S)=5.90	CB10(215)=1.30
CB8(S)=5.40	CB7(S)=0.40	CB10(217)=1.90
CB4(217)=1.10	CB5(S)=1.00	CB11(S)=0.80
	CB6(S)=0.60	
	CB12(S)=2.40	
	CB9(S)=1.40	
Total=40.50	Total=40.70	Total=40.80

Table 14. Percent current unbalance of combined panelboards

Merged panelboard	Current unbalance (after combination)
EB 107 and EB 110	2.28%
EB 205 and EB 207	2.40%
Stentorian Office, EB215, and EB217	0.41%

4. CONCLUSION

The majority of the panelboards in the building have a percent voltage unbalance that is within the allowable limit except for two panelboards. A thorough investigation suggests that the problem comes from the actual wiring design of one of the lines. Meanwhile, there is a considerable number of panelboards with above-the-minimum percent current unbalance value. The original load configuration of some of these panelboards was retained since re-phasing them will lead to a further increase in the percent current imbalance. For the other panelboards, the proposed re-phasing schemes entailed a reduction in the percent current unbalance. However, there are panelboards that are still above the standard value even after the re-phasing. Hence, to successfully reduce the current and voltage imbalances of all panelboards, it may be beneficial to couple the re-phasing schemes with other techniques, such as combining the loads of nearby panelboards. When the loads were combined, the current imbalance was reduced to acceptable values. If the re-phasing and merging of loads are to be implemented, a cost-benefit analysis and a study on the improvements in energy efficiency may be considered for further research.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state that there is no conflict of interest in the conduct of the study.

DATA AVAILABILITY

The data supporting this study's findings are available on request from the corresponding author, ED.

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