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Substation Load Management for Electric Power Distribution's Sustainability

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Abstract. In Nigeria, perhaps due to lack of conscious and planned preventive maintenance culture coupled with inadequate measuring equipment, power system equipment such as transformers are not adequately monitored for preventive maintenance. As a result, most are left to work until a breakdown occurs. Poor loading and uneven distributions are also common phenomena in many of these distribution transformers. Hence, there is a frequent power outage and supply interruption. This paper reports daytime monitoring of voltage, current and apparent power from three transformer substations at Federal Polytechnic Ilaro, Nigeria, to ascertain loading and transformer conditions. The study involved data acquisition of the parameters of interest (voltage, current and apparent power) using Lutron DW 6095 power harmonic analyzer for 2-4 hours with 5 min logging interval. The data analysis was carried out using the computer system. The range of loading conditions encountered was: Substation 1: 75.00−80.60 kVA which was 15−16.14 % of transformer rating; Substation 2: 73.70−90.30 kVA representing 14.74−18.08 % of the transformer rating; Substation 3: 19.04−19.28 kVA representing 3.81−3.85% of the rated transformer capacity. Load factors of 0.97, 0.87, and 0.99 were obtained for the three substations respectively indicating that energy usage was relatively constant during the period under consideration. An ANOVA test at a 5% significant level on each transformer phase current reading yielded *F*-values of 4475.38, 859.92 and 239117.68 respectively for the substation transformers indicating a huge level of imbalance in the transformer loading. Load balancing is recommended for a sustainable electric power distribution in the locality.

Key words: distribution transformer, load management, phase imbalance, transformer substation, sustainable power distribution, transformer load factor

Introduction

The use of monitoring methods to improve electricity distribution reliability and reduce maintenance costs is essential. When employed regularly and in a systematic manner, it can identify potential areas for preventive measures. One of such areas of electric power distribution needing monitoring is the transformer substation. Monitoring involves acquiring significant parameters of interest from the equipment or device involved to carry out analysis and diagnosis of its condition for maintenance, failure management and controlling system. A transformer substation consists of a power transformer, feeder pillar, switching, measurement and protection and control devices to ensure safe and efficient operations (Johnson, 2015; Murty, 2017). Electric power distribution transformers need adequate monitoring to avoid unplanned breakdowns and avoidable forced power outages (Boknam et al., 2007; Mbuli et al., 2020).

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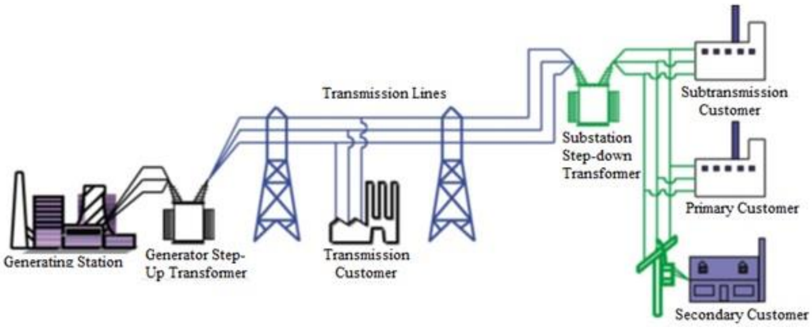

Figure 1. Basic structure of the electric system (Khan et al., 2018)

The basic structure of the electric system where the transformer substation is depicted as the link between the power distribution and the customers is shown in Figure 1. As shown in the figure, power transformers are critical to electric power distribution in the distribution network. These transformers thus need proper monitoring and management for the sustainability of power distribution (Siderakis, Pylarinos, & Thalassinakis, 2014). Typical substation monitoring configuration is depicted in Figure 2 where power quality meters are used to monitor both the transmission lines and the substations. Many problems bedevil the distribution substation transformers. Such common problems of substation transformer include poor and uneven load distribution and these have undesirable effects including neutral current flow, reduced transformer life and increased losses (Bao & Ke, 2019; Davis, Broadwater, & Hambrick, 2007). Such problems often result in power quality problems due to phase voltage variations and negative sequence voltages (Pezeshki, Wolfs, & Ledwich, 2014; Tianrui & Sen, 2012).

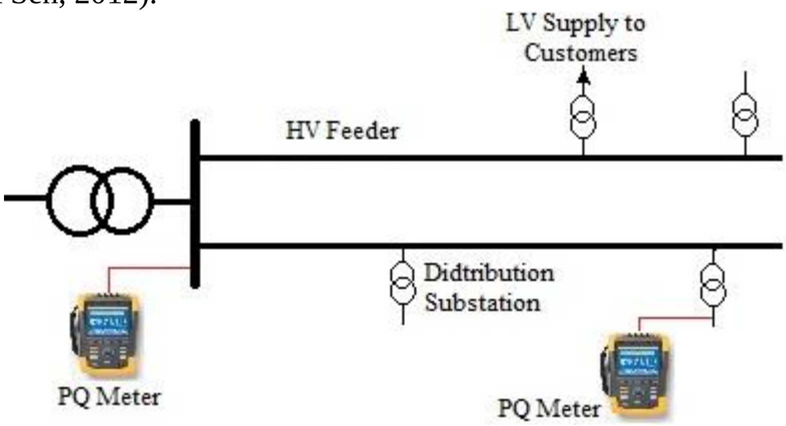

Figure 2. Typical substation monitoring configuration
Source: Author, based on Paracha (2011).

Distribution Substations (Datsios & Mikropoulos, 2017; Rad & Moravej, 2017) consists of a supply line, power transformer, outgoing feeders, switching device, and protection device to ensure efficient operation. In Nigeria, 11/0.38kV Substations are common sight on the streets and perform the function of distributing power supply to a number of customers in a given neighborhood. The low voltage (LV) Substation is the final stage of the electric power distribution system as the circuits leave the Substation at 380 V and are delivered by three-phase, 4-wire system. Distribution involves the primary and secondary transformation of high voltage to the standard medium and LV by the appropriate transforming equipment. These consist of high voltage (11 and 33 kV) networks from primary and sub-primary Substations. Substations need monitoring and assessments for operational efficiency. An automated system for monitoring Distribution Substations, to enable power transformer loading supervising in an optimized way, has been presented in the literature (Boknam et al., 2007; Jardini et al., 2004; Tianrui & Sen, 2012; Zhengdao, Xiyuan, & Qiqi, 2015). Some of these have been employed for daily load forecasting and distribution monitoring (Chao et al., 2003).

A multi-stage distribution substation expansion planning (Kaewmamuanga et al., 2019) requires adequate empirical data and real-time system monitoring such as presented by Oyetunji (2013) to implement. Such data can also lead to knowledge of the customers' consumption patterns which can be utilized for load forecasting such as presented in (Chicco et al., 2004). Power transformers' health indices (Gorgan et al., 2010; Sahoo et al., 2018) that reveal the condition of a power transformer can also be assessed. Load losses have also been determined using such data (Bozkurt et al., 2015; Castro et al., 2004; Pande & Ghodekar, 2012). Such monitoring and assessment will pave the way to a viable distribution substation expansion planning.

In Nigeria, most often perhaps due to lack of adequate measuring equipment, many devices such as transformers are not adequately monitored for preventive maintenance. As a result, most are left to work until a breakdown occurs. Poor loading and uneven distributions are also common phenomena in many of these distributions transformers. Hence, there is a frequent power outage and supply interruption. A heightened electrical power distribution reliability assessment and monitoring can help the Nigerian power distribution system. Comprehensive data for LV power distribution substations are not readily available in Nigeria or scanty at best. Thus this paper presents real-time monitoring and assessment of selected 11/0.380 kV, LV power distribution substations for obtaining much-needed empirical data for decision making on the power distribution network. This will also help to prevent an avoidable breakdown of critical substation equipment such as transformers and feeder pillars by serving as preliminary data to set up reliability and maintenance management for the substations.

Methodology

Description of the Substations

The study was set out to monitor three LV transformer substations in the Federal Polytechnic, Ilaro campus. Voltage, current and apparent power data were monitored. The substations feeders were on 11/0.38 kV LV supply. The three locations used for the study were the 500 kVA Female Hostel Substation (Substation 1), 500 kVA SLT Substation (Substation 2) and the 500kVA Polaris Bank Substation (Substation 3).

The three substations monitored are characterized by various loads typical of an academic community. Specifically, they are briefly described as follows: Substation 1 supplies power to part of staff quarters, departmental offices, a Microfinance bank, Water factory, the institution's primary and secondary schools and the guest house. Substation 2 covers Work and Services departmental offices, departmental buildings of School of Management Studies, ICT Center, and Ceremonies Pavilion Ground. The third substation connects electric power to a few lecture halls, a multipurpose hall, Staff Club, offices for Academic and Physical Planning Unit and the Directorate for Students Affairs.

Materials and Methods

Lutron DW 6095 power harmonic analyzer was employed to log data from the feeder pillar for 2-4 hours (depending on supply availability) using 5 minutes logging interval at each Substation. Lutron DW 6095 power harmonic analyzer is a multi-function power analyzer device that measures precisely direct current, alternating current, AC-voltage, DC-voltage the intensity of DC or AC, phase rotation and idle, apparent and effective power. An SD Card (Secure Digital Card) which is an ultra-small flash memory card designed to provide high-capacity memory in a small size of 2GB was used for the work to store the data been recorded by the power analyzer. The data was logged onto the flashcard and subsequently downloaded onto a computer system. The data acquisition set-up involved fitting the current probe signal plugs and current probe power plug to the appropriate terminals and connecting the voltage and neutral input cable to appropriate terminals at the feeder pillar of the substation as shown in Figure 3. At the initial measuring equipment setup, a clamp-on meter was simultaneously used to measure the load current per phase. Thus, the power harmonic analyzer was set to acquire the data of interest and save these onto the flashcard. Daytime measurement was taken as the selected Substations were situated within an academic environment where most electric power consumption takes place during the day.

Figure 3. On-site data-acquisition equipment set-up

Transformer Load Factor Determination and Voltage Spread

The line voltage monitored was analysed for each substation to identify the voltage level and dip structure. The load factor (LF) is determined as the ratio of the average load during a designated period to the peak load encountered in that period (Gustafson & Baylor, 1989).

$$LF = \frac{Average\ Load}{Peak\ Load} \quad (1)$$

The LF was determined for each transformer using eqn. (1) based on the data acquired from each substation.

Statistical Test of Significance for Transformer Current Loading

The voltage data acquired were presented graphically using descriptive statistics. The line voltages were composite bar charts. Graphical representations of the phase voltages were obtained using radar charts for each substation transformer loading. The current per phase readings of the three transformers were subjected to a one-way analysis of variance (ANOVA) test using a 5 % significant level to investigate whether the current readings were significantly different or the phases were evenly loaded. The ANOVA test was carried out taking the following steps:

Step 1: State the null and alternative hypotheses.

Since the data are observed to be normally distributed, the test is carried out to determine whether there is statistical evidence that the means of current readings are significantly different or not.

The null hypothesis, H0, and alternative hypothesis, H1, for the one-way ANOVA test are as follows:

H_0: $\mu_1 = \mu_2 = \mu_3$; i.e. the means are not significantly different.

H_1: At least the means for two sets of current readings have different means.

Step 2: Calculate F-statistic and p-value for the one-way ANOVA test.

The F-statistic is calculated based on the F-test that compares the variance in each set of current readings mean from the overall current variance. If the variance within groups is smaller than the variance between groups, a high F-value will return for the F-test.

Results and Discussion

The data acquired from the three substation transformers are presented in Tables 1-3 respectively. The hours for which the substations were monitored differ because of lack of power supply at various substations. The times of measurement for individual substations are as indicated in Tables 1-3. The tables of results show an observable huge imbalance on the substation transformer. Table 1 results show that line 1 (V12) and line 3 (V31) voltages are consistently higher than line 2 (V23) with about 4-5V and 1-2V differences respectively. The phase voltages follow the same pattern though with smaller values. The magnitude of the phase voltage distribution for the three substations is shown in Figure 4. It can be seen that the phase voltages have huge disparities in value and these are more pronounced with substation 3. However, lines voltages are observed to be totally different. Line 2 is consistently conspicuously higher than others with line 3 having the lowest values. Consequently, lines 2 and 3 apparent power values have the highest and lowest respectively. The line voltage distributions for the three substations are shown in Figure 5. Similar patterns in values of the line voltages for Substation 1 are repeated for Substations 2 and 3 as shown in Tables 2 and 3.

Table 1. Data acquired from Substation 1

Time	V_{12}(V)	V_{23}(V)	V_{31}(V)	V1 (V)	V2 (V)	V3 (V)	A1 (A)	A2 (A)	A3 (A)	S1 (kVA)	S2 (kVA)	S3 (kVA)
09:48:26	389.5	384.0	384.8	224.0	223.1	221.6	126.6	154.8	54.8	28.3	34.5	12.1
09:53:26	390.2	385.3	386.4	224.2	224.0	222.6	131.8	163.4	54.3	29.5	36.6	12.1
09:58:26	390.1	384.9	385.3	224.0	223.9	221.9	125.8	161.3	57.1	28.1	36.1	12.6
10:03:26	390.3	384.7	386.3	224.6	223.3	221.8	128.4	165.0	53.3	28.8	36.8	11.8
10:08:26	391.3	386.0	386.5	225.2	224.2	222.7	127.5	165.4	53.3	28.7	37.1	11.8
10:13:26	389.2	385.2	386.3	224.0	223.8	222.7	138.5	151.7	52.7	31.0	33.9	11.7
10:18:26	388.8	384.5	385.8	223.9	223.4	222.3	135.3	165.9	52.9	30.2	37.0	11.7
10:23:26	389.4	383.3	385.7	224.3	223.1	222.0	134.1	173.0	52.5	30.0	38.6	11.6
10:28:26	389.2	384.2	385.4	224.0	223.4	221.8	134.7	165.8	52.8	30.1	37.0	11.7
10:33:26	389.3	383.9	385.0	223.7	223.0	221.6	132.3	160.0	52.7	29.5	35.6	11.6
10:38:26	389.5	383.6	385.3	224.1	222.8	221.6	132.1	164.9	55.0	29.6	36.7	12.2
10:43:26	389.7	385.0	385.9	224.1	223.5	222.0	132.0	160.0	55.7	29.5	35.7	12.3
10:48:26	388.6	384.4	385.6	223.6	223.3	222.3	136.0	170.3	55.3	30.4	38.0	12.2
10:53:26	388.4	383.0	384.4	223.5	222.6	221.4	136.0	171.0	55.5	30.3	38.0	12.2
10:58:26	388.1	383.2	384.3	223.2	222.5	221.5	134.7	169.1	54.7	30.0	37.6	12.1
11:03:26	390.8	385.6	385.9	224.4	223.2	222.3	133.8	169.9	54.9	30.0	37.9	12.2
11:08:26	389.4	385.0	387.0	224.3	223.7	222.9	138.3	167.9	47.8	31.0	37.5	10.6
11:13:26	389.7	384.8	386.9	224.4	223.3	222.6	135.3	170.5	47.5	30.3	38.0	10.5
11:18:26	390.4	385.2	386.2	224.6	223.3	222.4	136.5	162.6	48.6	30.6	36.3	10.8
11:23:26	389.1	384.7	387.3	224.4	223.7	222.9	140.1	163.1	47.6	31.4	36.4	10.6
11:28:26	388.4	383.9	385.8	223.7	222.9	222.2	139.7	163.3	47.9	31.2	36.4	10.6
11:33:26	388.6	383.7	386.0	223.7	222.8	222.0	139.9	163.7	48.2	31.2	36.4	10.7
11:38:26	389.5	384.7	387.4	224.7	224.1	222.9	135.7	157.5	48.1	30.4	35.2	10.7
11:43:26	390.8	386.0	386.4	224.1	223.8	222.8	137.3	156.5	48.4	30.7	35.0	10.7
11:48:26	390.0	384.3	385.4	224.0	223.0	222.2	140.8	162.1	48.2	31.5	36.1	10.7

Table 2. Data acquired from Substation 2

Time	V_{12} (V)	V_{23} (V)	V_{31} (V)	V1(V)	V2 (V)	V3 (V)	A1 (A)	A2 (A)	A3 (A)	S1 (kVA)	S2 (kVA)	S3 (kVA)
08:39:41	393.2	386.1	388.1	226.7	224.8	223.0	116.4	154.2	64.6	26.3	34.6	14.4
08:44:41	391.9	386.1	388.1	226.0	224.4	223.2	120.7	154.8	67.7	27.2	34.7	15.1
08:49:41	392.1	387.1	387.5	225.4	225.0	222.9	117.9	148.0	65.1	26.5	33.3	14.5
08:54:41	392.7	386.4	387.4	225.7	224.7	222.7	120.5	151.7	65.7	27.1	34.1	14.6
08:59:41	391.8	386.2	388.5	226.4	224.3	223.5	119.8	156.0	65.0	27.1	35.0	14.5
09:03:41	391.8	386.5	386.5	225.4	224.7	222.5	114.6	164.9	64.7	25.8	37.0	14.4
09:08:41	392.3	386.1	388.2	225.5	224.1	223.4	118.7	163.1	65.5	26.7	36.5	14.6
09:13:41	392.1	385.2	387.4	225.9	224.0	222.4	116.8	164.3	65.0	26.3	36.8	14.4
09:18:41	391.2	386.4	387.3	225.1	224.3	223.2	125.4	167.4	65.6	28.2	37.5	14.6
09:23:41	392.1	384.6	387.2	225.4	223.6	222.5	124.4	173.8	66.2	28.0	38.8	14.7
09:28:41	391.3	386.7	386.6	225.1	224.9	222.4	123.9	166.3	65.5	27.8	37.4	14.5
09:33:41	391.1	386.0	386.5	224.9	224.8	222.4	123.7	166.9	66.3	27.8	37.5	14.7
09:38:41	391.5	385.0	387.0	225.4	223.3	223.0	124.9	215.3	63.9	28.1	48.0	14.2
09:43:41	391.3	386.7	387.1	225.4	224.9	222.5	125.2	162.8	63.3	28.2	36.6	14.0
09:48:41	391.6	384.8	388.4	225.0	223.8	223.4	124.4	169.2	63.5	27.9	37.8	14.1
09:53:41	393.4	386.3	388.3	225.6	224.9	222.6	125.3	161.9	63.5	28.2	36.4	14.1
09:58:41	391.9	386.8	387.6	226.2	224.7	223.8	128.4	161.2	63.7	29.0	36.2	14.2
10:03:41	394.3	387.4	389.0	225.7	225.4	223.2	125.7	150.1	65.8	28.3	33.8	14.7
10:08:41	392.6	388.7	388.2	226.0	225.8	223.6	126.5	150.5	63.9	28.5	33.9	14.3
10:13:41	392.6	386.5	388.1	225.8	224.5	223.8	126.7	152.0	63.8	28.6	34.1	14.2
10:18:41	393.3	387.3	387.9	225.3	225.3	222.7	137.5	154.4	61.5	30.9	34.7	13.6
10:23:41	393.4	387.9	388.1	225.7	225.6	222.9	126.8	156.6	61.6	28.6	35.3	13.7
10:28:41	392.2	387.0	387.9	226.0	225.0	223.2	125.5	164.7	64.7	28.3	37.0	14.4
10:33:41	393.4	387.5	388.1	225.6	225.4	223.0	130.5	169.8	61.7	29.4	38.2	13.7
10:38:41	393.4	387.5	387.6	225.5	225.4	222.6	104.2	162.9	61.2	23.5	36.7	13.6

Table 3. Data acquired from Substation 3

Time	V_{12} (V)	V_{23} (V)	V_{31} (V)	V1 (V)	V2 (V)	V3 (V)	A1 (A)	A2 (A)	A3 (A)	S1 (kVA)	S2 (kVA)	S3 (kVA)
08:17:23	403	395.4	401.1	235.3	228.6	229	16.99	38.32	27.98	3.99	8.76	6.40
08:22:23	403.9	394.8	402.2	234.7	228.4	229.2	16.94	38.29	27.96	3.97	8.74	6.40
08:27:23	403.0	395.1	402.1	235.0	229	229.5	16.96	38.48	27.88	3.98	8.81	6.39
08:32:23	401.6	395.7	401.7	234.3	229.5	228.8	16.88	38.76	27.59	3.95	8.89	6.31
08:37:23	401.4	400.0	403.7	234.8	229.2	228.6	16.99	38.6	27.73	3.98	8.84	6.33
08:42:23	401.3	394.4	405.4	235.5	228.5	229.4	17.08	38.38	27.56	4.02	8.76	6.31
08:47:23	403.1	395.8	403.2	234.5	229.1	229.4	16.98	38.51	27.81	3.97	8.82	6.37
08:52:23	401.2	398.6	402.2	234.3	229.5	228.8	16.94	38.49	27.74	3.96	8.83	6.34
08:57:23	400.2	396.8	403.2	234.8	229.1	228.6	17.04	38.43	27.70	4.00	8.80	6.33
09:02:23	402.2	394.8	403.9	235.0	228.4	228.8	17.06	38.35	27.80	4.00	8.76	6.36
09:07:23	401.1	397.7	401.6	234.5	228.5	229.3	17.07	38.41	27.83	4.00	8.77	6.38
09:12:23	400.9	396.9	404.6	235.4	228.9	229.6	17.20	38.45	27.75	4.04	8.80	6.37
09:17:23	402.0	394.5	402.0	234.5	229.3	229.6	16.91	38.43	27.90	3.96	8.81	6.40
09:22:23	401.3	398.6	401.1	234.4	229.4	228.9	16.91	38.64	27.78	3.96	8.86	6.35
09:27:23	402.5	398.1	404.3	235.4	228.8	228.6	16.96	38.29	27.60	3.99	8.76	6.30
09:32:23	401.1	396.2	400.1	234.7	228.8	229.5	16.91	38.38	27.89	3.97	8.78	6.39
09:37:23	402.3	399.2	403.0	235.2	228.8	228.5	17.08	38.46	27.73	4.01	8.79	6.33
09:42:23	404.2	395.2	400.7	235.1	228.5	228.5	17.04	38.7	27.68	4.00	8.84	6.32
09:47:23	401.6	391.9	403.9	234.3	228.4	229.2	16.93	38.65	27.71	3.96	8.82	6.34
09:52:23	401.0	395.2	402.3	234.6	229.1	229.4	16.96	38.64	27.78	3.97	8.85	6.37
09:57:23	401.0	396.2	404.2	235.0	229.2	228.9	16.97	38.69	27.69	3.98	8.87	6.33

10:02:23	401.2	395.7	403.5	235.1	228.8	228.6	17.00	38.55	27.65	3.99	8.82	6.32
10:07:23	400.9	394.9	404.3	234.6	229.0	228.7	16.95	38.49	27.75	3.97	8.81	6.34
10:12:23	400.4	397.6	400.7	234.4	228.8	229.4	16.92	38.62	27.76	3.96	8.83	6.36
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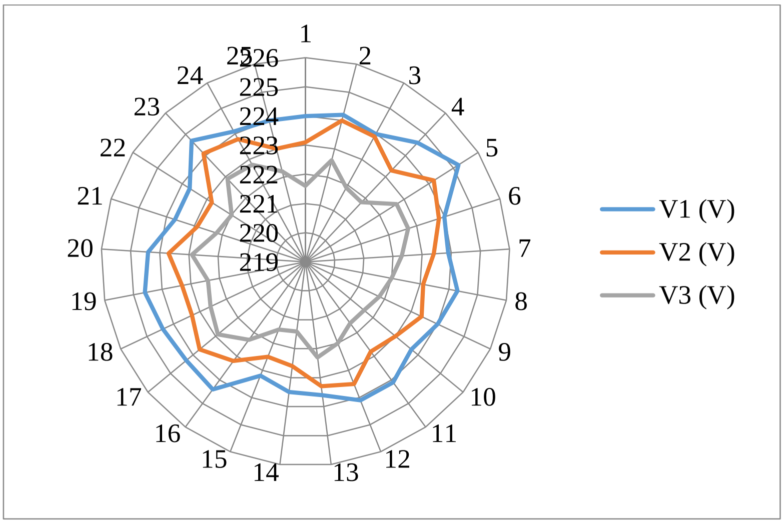
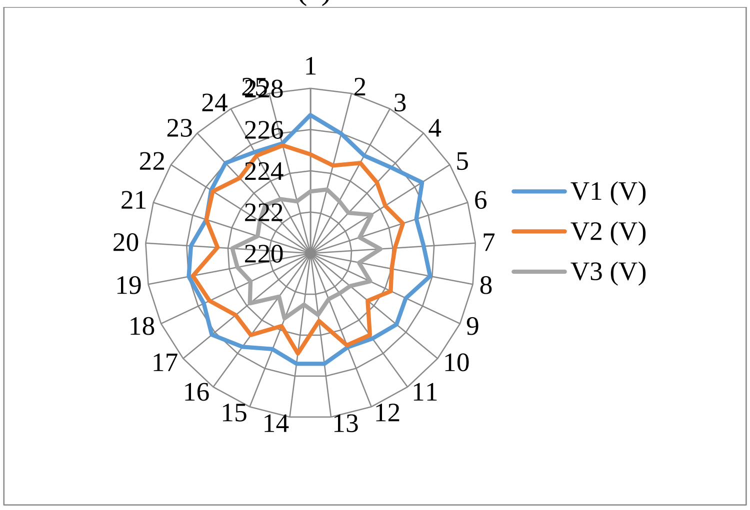
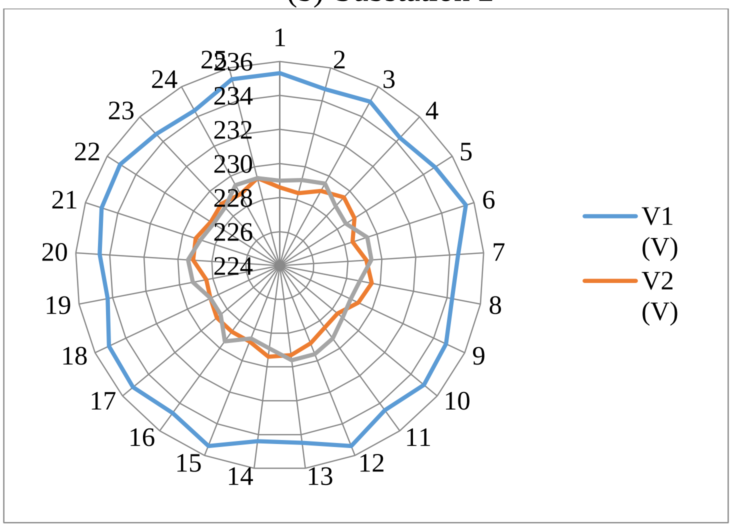


(a) Substation 1

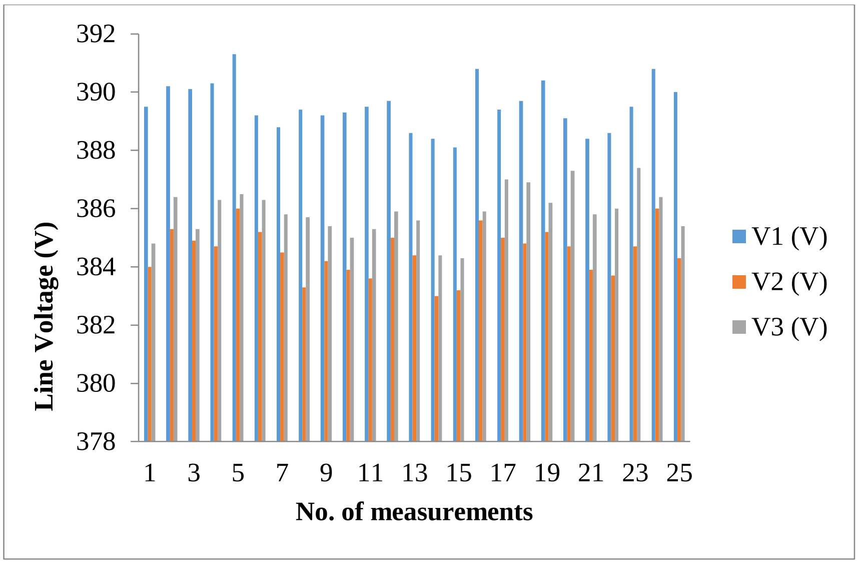


(b) Substation 2

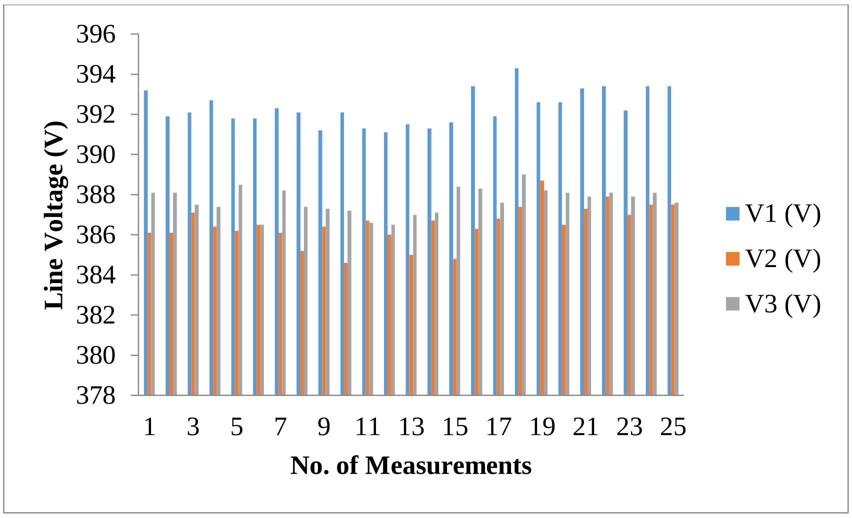


(c) Substation 3

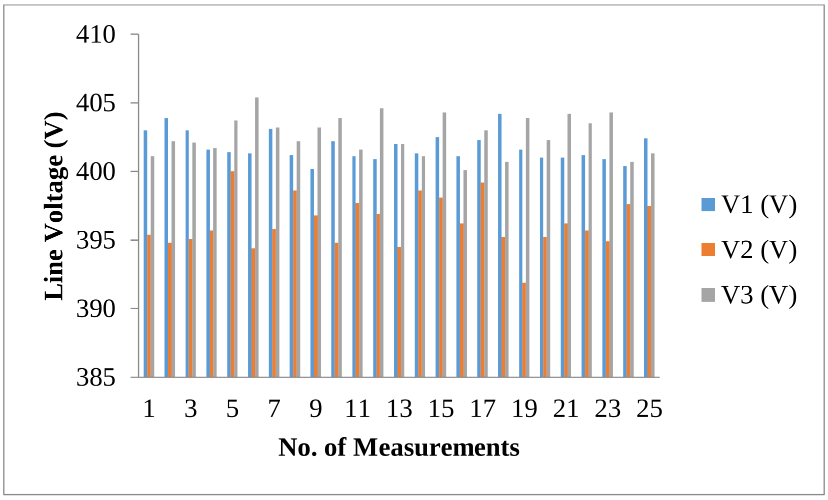
Figure 4. Phase voltage distribution for the substations



(a) Substation 1



(b) Substation 2



(c) Substation 3

Figure 5. Live voltage distribution for the substations

The measurement parameters, LF calculated and the range of apparent power measurement are summarised in Table 4. The three-phase loading for the three substations is presented in Figures 6, 7 and 8. The ANOVA test results are as presented in Tables 5. The results yielded *F*-Value of 4475.38, 859.92 and 239117.68 for the three substation transformers respectively and show that the substation transformers phases were severely unbalanced in all substations under study. These can also be observed from Figures 6-8.

Table 4. Substation transformers parameters

Transformer Parameters						
Substation	**Rated Apparent Power (kVA)**	**Average Load (kVA)**	**Peak Load (kVA)**	**Minimun Load (kVA)**	**% Load**	**LF**
1	500	78.18	80.60	75.00	16.12	0.97
2	500	78.48	90.30	73.7	18.06	0.87
3	500	19.15	19.28	19.04	3.86	0.99

Table 5. Summary of ANOVA test results on substation transformer phase loading

Substation 1					
Source	**SS**	**df**	**MS**	F Statistics	P-Value
Between-treatments	168432.28	2	84216.14	4475.38	0.00001
Within-treatments	1354.87	72	18.82		
Total	169787.15	74			
Substation 2					
Between-treatments	121939.55	2	60969.77	859.92	0.00001
Within-treatments	5104.932	72	70.90		
Total	127044.48	74			
Substation 3					
Between-treatments	5789.3185	2	2894.66	239117.68	0.00001
Within-treatments	0.9058	72	0.0126		
Total	5790.22	74			

As observed from Table 4, the maximum load demand for the Substations are 80.6, 90.3 and 19.28 kVA for Substations 1, 2 and 3 respectively whereas each transformer was rated 500 kVA. Thus, it is seen that the three substation transformers were under light loading. The percentage loading were 16.12, 18.06 and 3.86 % respectively. This means that the transformers were grossly underutilised but since the loading of each transformer was within 80 % of its rated power, it can be concluded that the transformers were in stable conditions. However, the transformer load factors were high (0.97, 0.87, and 0.99; see Table 4) and indicate that energy usage was relatively constant and that there was less period of idleness of the substations during the period under consideration.

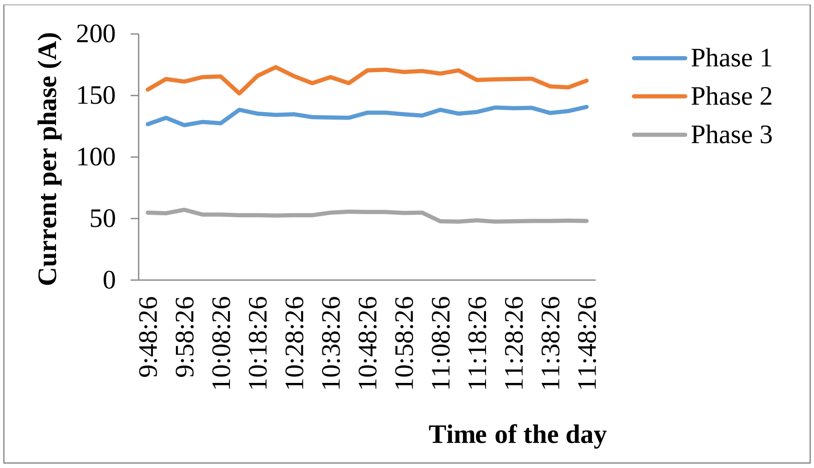


Figure 6. Loading per phase for Substation 1

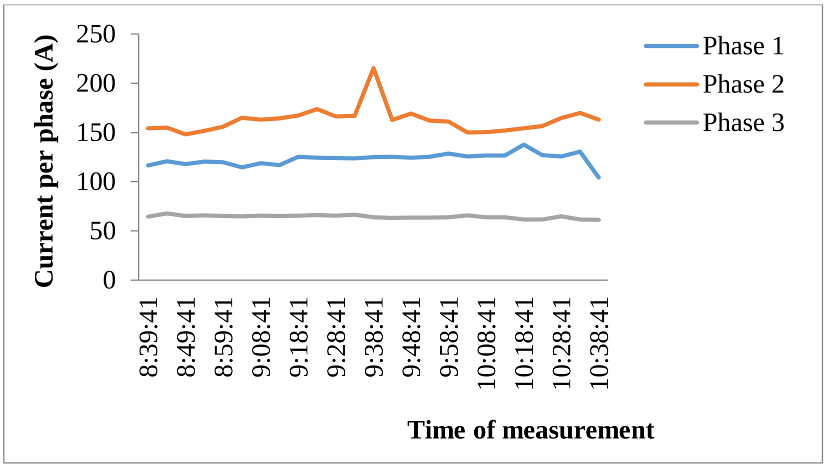


Figure 7. Loading per phase for Substation 2

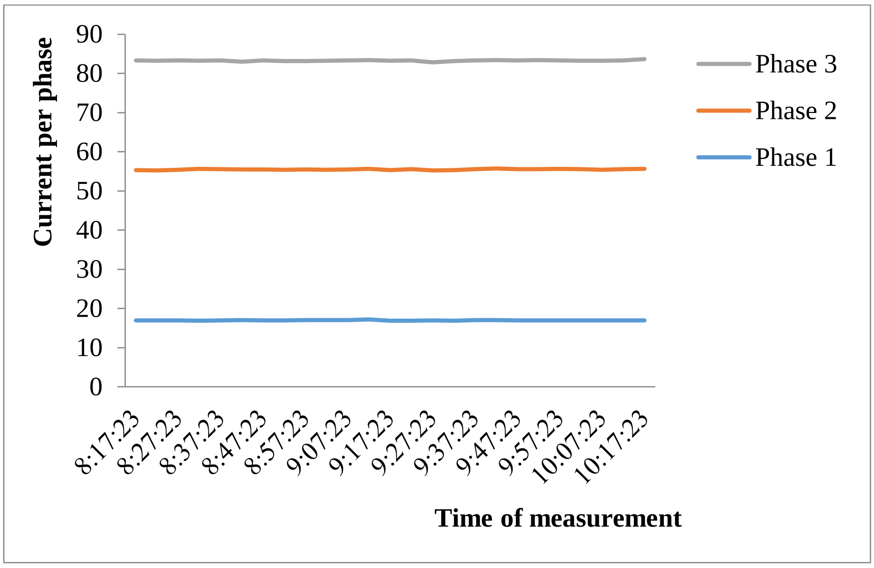


Figure 8. Loading per phase for Substation 3

Conclusion

Three LV transformer substations were monitored in this study for the transformer health, energy utilisation and load management. The study findings revealed that though electric power was not regular and the transformers were seemingly in stable electrical condition, the phase loading was severely unbalanced and the transformers were highly underutilised. It is suggested that the phase loading of the transformers should be checked for proper load balancing. This will ensure the longevity and sustainability of the insulation resistance of the windings of the transformer. The data obtained in this study are useful for substation transformer load management. This study is recommended for other substations in the power distribution network to achieve optimum power delivery and efficient use of electrical power-delivering equipment. When the study is replicated in many locations and substations, valuable information regarding the power distribution network can be obtained on the health and status of various substation transformers and by extension the distribution network. For a sustainable electric power distribution in the locality, a dutiful load balancing is recommended for the substation transformers.

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