Analysis of Voltage Drop in a Low Voltage Electrical System for Statistical Control Process

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Abstract: This paper presents a unique method for the assessment of voltage drop issues in low voltage electrical systems using MATLAB's powerful Simulink toolbox. The approach is based on two fundamental tools of statistical process control, namely Control Charts and Process Capability Analysis (PCA). Normality tests and Partial Autocorrelation for samples generated by simulation two major modes used by low voltage electrical systems is conducted. The results of the Xbar-S control charts are interpreted along with an assessment of the quality improvement foundation are conducted using Process Capability Analysis. The test systems simulated in this research are Single Phase electrical systems and their Three Phase counterparts (in a low voltage environment). The major objective of this research is to assess the state of statistical process control in such an environment which could then lead to better industry standards for continuous improvement.

Keywords: Xbar-S Control Charts, Statistical Process Control, Low Voltage Systems, Simulink Toolbox

1. Introduction

One of the main indicators for measuring the efficiency of an electrical installation in low-voltage distribution system is the voltage drop. According to Gonen (1967), the fall of voltage in an electrical system corresponds to the difference between the voltage of the supply side and the voltage load and depends on the length of the feeder, the section of the driver and the current flowing from the source to the load. For a single-phase or three-phase system, voltage can be obtained using the equations (1) and (2), respectively.

$$VD_{1\phi} = I_{1\phi}(KR_R \cos\theta + K_X Xsen\theta)L \quad (1)$$

$$VD_{3\phi} = I_{3\phi}(R\cos\theta + Xsen\theta)L \quad (2)$$

In equation (1), $VD_{1\phi}$ is the voltage drop for a single phase (Volt) system, $I_{i\phi}$ is the current flowing in a single phase power supply (in Ampere), K_R and K_X are correction factors which depend on the degree of use of the current flowing through the neutral, R is the resistance of the conductor (in Ω/Km), X is the reactance of the driver (Ω/Km), θ is the angle of the impedance of the driver (in degrees) and L is the length of the conductor (in Km). According to Gonnen (1986), for systems with neutral landed, $K_R = K_X = 2$. In equation (2), $VD_{3\phi}$ is the voltage drop to a three-phase system (in Volt), $I_{3\phi}$ is the current flowing through a three-phase power supply (in Ampere), R is the resistance of the conductor (in Ω/Km), X is the reactance of the conductor (in Ω/Km), θ is the angle of the impedance of the

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driver (in degrees) and L is the length of the conductor (in Km). According to industry standards specified by SEC (203), voltage should not exceed 3% of the nominal voltage of the power supply, provided that the total voltage drop in the most unfavorable point of the system does not exceed 5% of the rated voltage. Given this condition, low voltage electrical systems are designed so that the voltage drop does not exceed 3% of the nominal voltage, making it necessary to monitor and control the voltage drop within the range of variability in such a way to ensure the quality of supply to the facilities.

In the first part of the paper, we describe the main features of the Xbar-S Control Charts (considering that during this research, the records were ordered into 24 sub-groups) and process capability indices. The following sections describe testing systems that were used for data acquisition and sampling, then we present the main results of data processing using the free R statistical software. Finally we present the main conclusions of the research.

2. Literature Review

2.1 Control Charts $\overline{X} - S$

According to Hitoshi (2002) and Montgomery (2005), control charts were introduced in 1924 by W.A. Shewhart of Bell Telephone Laboratories in order to monitor the variability of the process, thereby attributing the variations detected during posting of comments to random causes or assignable causes. For the control variables sorted into subgroups, it is advisable to work with control charts type Xbar-R or Xbar-S. Xbar-S control charts are very useful when the size of the subgroup is greater than 12, since it allows us to better reflect the behavior of the variability of the process. Equations (3) and (4), are used to calculate the parameters of Xbar and S letters, respectively.

$$UCL = \overline{\overline{X}} + \frac{3\overline{S}}{c_4\sqrt{n}} = \overline{\overline{X}} + A_3\overline{S},$$

$$CL = \overline{\overline{X}} \quad , \quad LCL = \overline{\overline{X}} - \frac{3\overline{S}}{c_4\sqrt{n}} = \overline{\overline{X}} - A_3\overline{S} \qquad (3)$$

$$UCL = \overline{S} + \frac{3\overline{S}}{c_4}\sqrt{1-c_4^{\,2}} = B_4 + \overline{S} \; CL = \overline{S} \quad ,$$

$$LCL = \overline{S} - \frac{3\overline{S}}{c_4}\sqrt{1-c_4^{\,2}} = B_3\overline{S} \qquad (4)$$

In the equations (3) and (4), UCL, CL and LCL are the upper, central and lower control limits respectively, c4 is a constant that depends on the size of the subgroup, n is the number of subgroups, X bar is the average of averages of subgroups, S bar is the average of the standard deviations of the sub-groups and constants A_3, B_3 and B_4 are factors of construction of control Xbar charts - S. Figure 1, shows a typical control Xbar - S chart.

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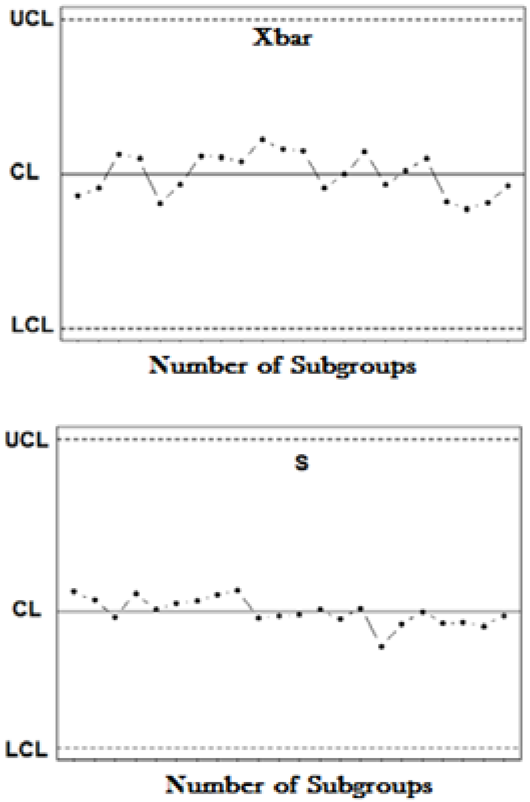

Fig.1 : Bar Charts of Control XBar – S

2.2 Analysis of Capability of Processes

Process capability analysis, is a statistical tool that allows us to study the variability of the "process variable" with respect to the requirements of the specifications of the product considering the limits of the specifications, the nominal value (or Target) and the distribution of the sample. Figure 2 shows a typical process capability analysis graph where LSL corresponds to the lower limit of the specifications, μ is the mean value of the process, T is the nominal value or Target and USL is the upper limit of the specifications.

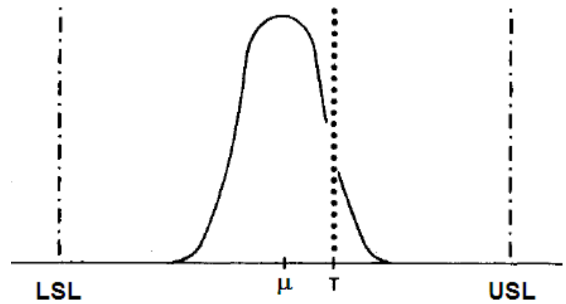

Fig.2 : Typical Graph for Process Capability Analysis

To study the performance of a process, some indexes introduced by Kane (1986) are used. These include index of potential process capability Cp, real of the Cpk process capacity index and the index centering of the K process.

2.3 Cp Index

The potential Cp process capability index compares the variation in the specifications of the process with the actual variation observed. It is obtained by dividing the width of the specifications between the amplitude of the natural variation of the process as shown in equation 5.

$$C_p = \frac{USL - LSL}{6\sigma} \quad (5)$$

where σ is the standard deviation of the process.

Table 1 describes the categories of the quality of the process, depending on the value of the Cp index, according to Gutieprez (2009).

Table 1.
Interpretation of the potential Cp Process Capability Index

Index	Category	Interpretation
Cp ≥ 2	World Class	It is Six Sigma Quality
Cp > 1.33	Class 1	Appropriate – The inspection may be reduced
1 < Cp < 1.33	Class 2	Partially Adequate – Sufficient Inspection by sampling
0.67 < Cp < 1	Class 3	Not suitable for work - Cp must be increased to at least to 1. The process requires serious changes.
Cp ≤ 0.67	Class 4	Very bad - the process requires very serious modifications

2.4 Cpk Index

The Cpk index is considered a corrected version of the Cp index, since it takes into account the centering process. Cpk will always be less than or equal to Cp. When the value of Cpk is very less than Cp, the process average is remote from the center of the specifications, on the other hand, when Cpk value is very close to Cp the mean of the process is very close to the center of the specifications. Equation 6 shows the calculation of the index Cpk.

$$C_{pk} = Minimum\left(\frac{\mu - LSL}{3\sigma}, \frac{USL - \mu}{3\sigma}\right) \qquad (6)$$

where μ and σ are the mean and standard deviation of the process, respectively.

In table 2, the actual capacity of the process, depending on the value of the Cpk index is described by Taguchi (1985).

Table 2
Interpretation of Cpk Index

Index	Interpretation
Cpk > 1.25	Satisfactory Capacity (for existing processes)
Cpk > 1.45	Satisfactory Capacity (for new processes)
Cpk < 1	The process fails at least one of the specifications
Cpk ≤ 0	The mean of the process is outside specifications

2.5 Index K (index centering process)

It is an indicator that measures the centeredness of the distribution of a process with respect to the specifications of a given quality characteristic. The centering process index is obtained by equation (7):

$$K = \frac{2(\mu - T)}{(USL - LSL)}.100\% \qquad (7)$$

If K is positive, then the mean of the process (μ) is more than the nominal value (T), if K is negative the average process (μ) is less than the nominal value (T). Acceptable value of K is

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considered to be less than 20%.

2.6 Cpm Index (Taguchi Index)

Cpm index (Taguchi Index) is similar to the Cpk, but considers simultaneous centering and the variability of the process. It is calculated by using equation (8).

$$C_{pm} = \frac{USL - LSL}{6\tau} = \frac{USL - LSL}{6\sqrt{\sigma^2 + (\mu - T)^2}} \qquad (8)$$

If Cpm < 1, the process does not meet specifications either due to problems of centralization or due to excess variability. If Cpm > 1 the process complies with the specifications and the average is within the third part of the central band of the specifications. If Cpm > 1.33, process meets the specifications and the average is within the fifth central band of the specifications.

2.7 Tests of Normality and Partial Autocorrelation

According to Montgomery (2005), to apply the theory of control charts and process capability analysis it is necessary to carry out the tests of normality and partial autocorrelation of samples. The first test aims to validate the acceptance of the hypothesis of normality to the dataset in study, while the second test is intended to test whether there is a dependency between observations of samples. In this research, we use the free statistical software R developed by the R Development team (2008), specifically, the Shapiro-Wilk (1965) normality Test tools, the package "plugin e-pack" for the partial autocorrelation test and the "plugin qcc" package for the capability analysis and control charts. Once the data is processed in the R software, normality and partial autocorrelation test acceptance criteria are as follows:

- Accept the hypothesis of normality when the p-value is greater than 5%, that is, when p-value > 0.05, according to Montgomery (2005).
- Accept if the independence of observations of partial autocorrelation (partial ACF, represented by vertical bars in the graph that delivers the R software) is within the range of 5% confidence bands.

3. Testing Single Phase System

Single-phase test system was simulated on the powerful MATLAB Simulink circuit simulator and is structured in the following way: VF (voltage of 220V RMS, 50 Hz AC power supply), RC and XC (burden of proof inductive resistive type), R and X (power N ° 14 AWG conductor) and extent (recorder brand HIOKI-3286-20 model). Figure 3 shows the complete circuit design.

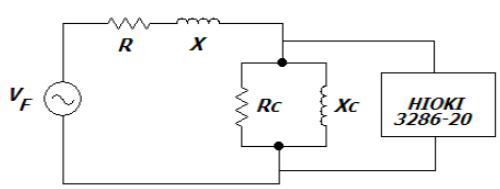

Fig. 3: Single Phase Circuit for Measuring and Recording

Observations were simulated for 5 days (according to average load data), Monday to Friday, with an hour sampling times. In table A.1 of annex a. "data test systems", show records of single phase system voltage for the days Monday through Friday. Table 3 shows the results of the p-value for each day of registration, applying the Test of normality of Shapiro - Wilk voltage samples using the R software.

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Table 3

Results of the Shapiro-Wilk Normality Test for Single-Phase Sample

	Mon	**Tue**	**Wed**	**Thu**	**Fri**	**X-Bar**
p-value	0.2034	0.1040	0.1978	0.5721	0.7255	0.2254

Figure 4 shows the graphical results of the behavior of the factor of partial autocorrelation (partial ACF) for single-phase voltage sample. Looking at the results from table 3 and Figure 4, it can be concluded that the hypothesis of normality is accepted and single-phase voltage sample observations are independent, therefore we can build control charts of X-bar-S.

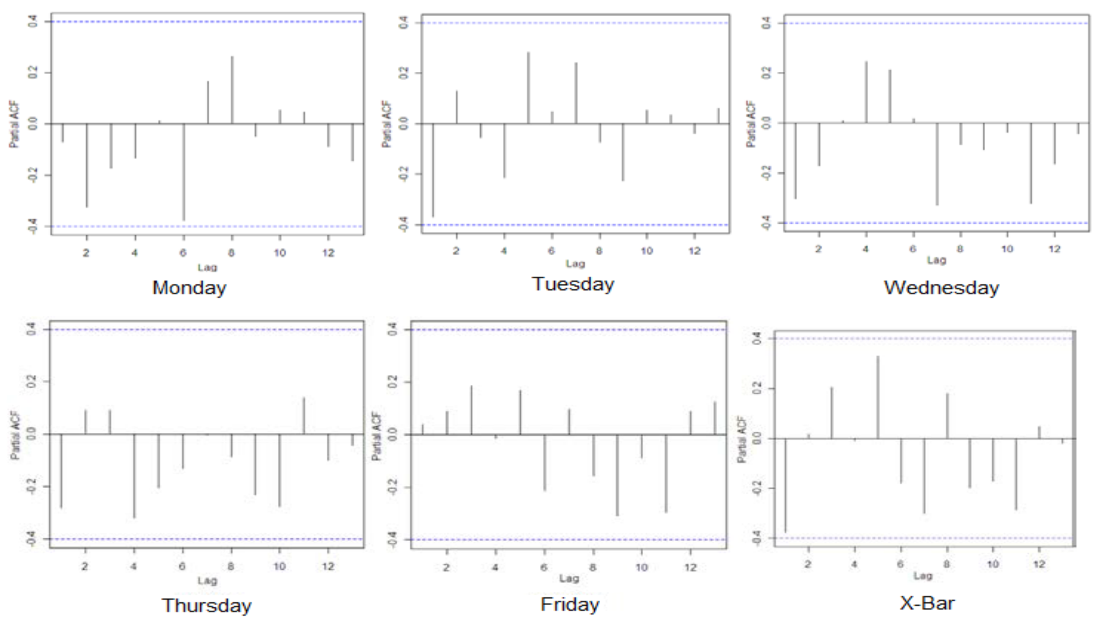

Fig. 4: Graph of Partial Autocorrelation Factor (ACF) for Single Phase

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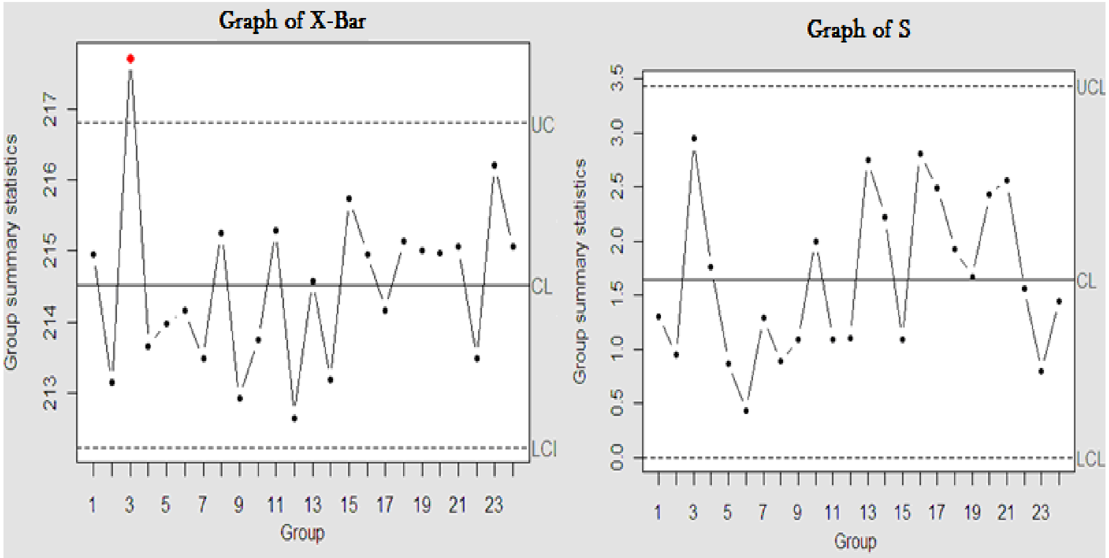

Fig. 5: Graph of Control XBar-S for Single Phase Sample

Figure 5 shows graphs of control X bar-S for single-phase sample, with 24 subgroups for 5 days of consecutive measurement. Figure 6, shows the behavior of the process against the limits of specifications of voltage, which for this case, correspond to LSL = 213, 4 (V) and USL = 220 (V), as designated by the industry standard 4/2003 according to SEC (2003). For processes with bilateral specification limits, it is common to assume a nominal value or Target average, for specification limits, accordingly, the Target for the single-phase test system value would be 216,7 (V).

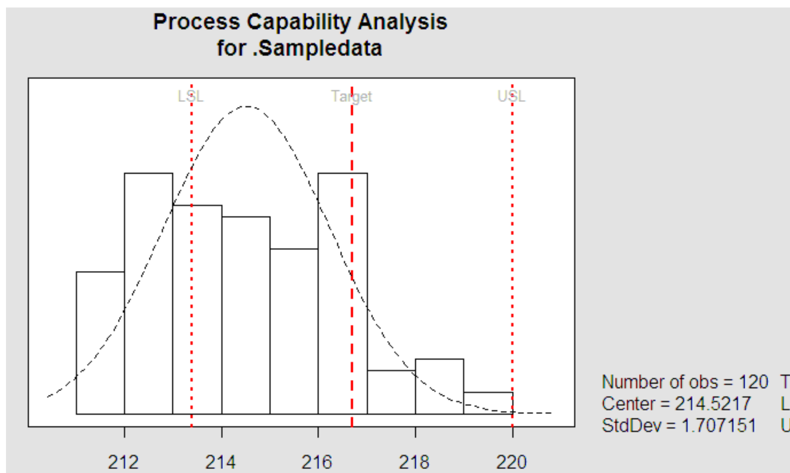

Fig. 6: Analysis of Process Capability for Single-Phase Sample

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Table 4
Summary of the interpretation of the results of the single-phase test system

Index	Interpretation
p-value	As noted in table 3, the p-value for each day of sampling is greater than 0.05, therefore the hypothesis of normality is accepted.
Partial ACF	In accordance with Figure 5, Partial ACF for each day of sampling factor lies within the confidence interval, therefore, observations are independent.
Graph of XBar	Looking at Figure 6, we observe that no. 3 exceeds the upper control limit, therefore, process variable voltage is out of statistical control.
Graph of S	Looking at Figure 6, we can see that all observations are within the bounds of control, therefore, the variability of the process is under statistical control.
Cp = 0.644	Very bad capability, the process requires serious changes.
Cpk = 0.219	The process fails, at least one of the specifications.
K = 66.01%	Serious problems of negative centralization.
Cpm = 0.218	The process does not meet specifications by problems of centralization.

4. Testing an Industrial Three Phase System

The burden of industrial test used for sampling, corresponds to a simulation of a metallurgical plant of medium mining activities. The sampling system is described in Figure 7.

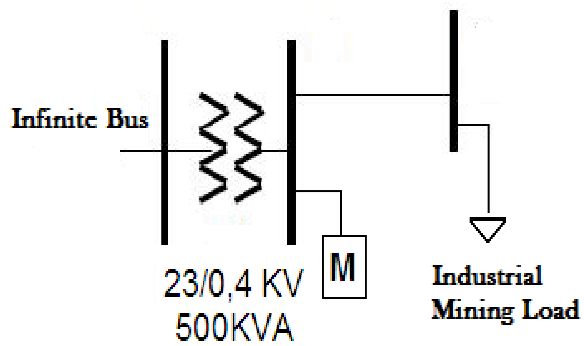

Fig. 7: Unilineal Diagram for Measuring and Recording of a Three Phase Test System

Observations were simulated for 7 days, Monday through Sunday, with times of sampling of one hour for each of the three phases at the side of the low-voltage transformer (400 Volt). The Xbar-S is made up of 24 subgroups that represent 24 / 7 samples that represent the 7 days of registration.

Table A.2 of Annex A, "data test systems", contains records of the three-phase system for three-phase voltage. Table 5, shows the results of the p-value for each day of registration and for each phase. We then apply the Test of normality of Shapiro - Wilk using R software.

Looking at the results in Table 5 and Figure 8, it can be concluded that the hypothesis of normality is accepted and that the observations of three-phase voltage for each phase sample are independent, therefore we can build control charts Xbar-S for each phase. In Table 5, we see that all values of p-value are greater than 5%, indicating that the hypothesis of normality for three-phase samples is accepted. From Figure 8, it can be concluded that the observations are not correlated; therefore, the

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samples are independent. Figures 9 and 10 show us that all observations are within the bounds of control, therefore the process is in statistical control for the average of the voltages and the variability of the samples.

Table 5

Results of the Shapiro-Wilk Normality Test for Three-Phase Sample

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**	**X-Bar**
p-value phase R	0.2682	0.1159	0.5268	0.3875	0.3579	0.8536	0.06631	0.5960
p-value Phase S	0.8773	0.06454	0.2538	0.1490	0.8484	0.1333	0.8686	0.3399
p-value Phase T	0.2513	0.9487	0.1261	0.8648	0.3868	0.6998	0.6239	0.1876

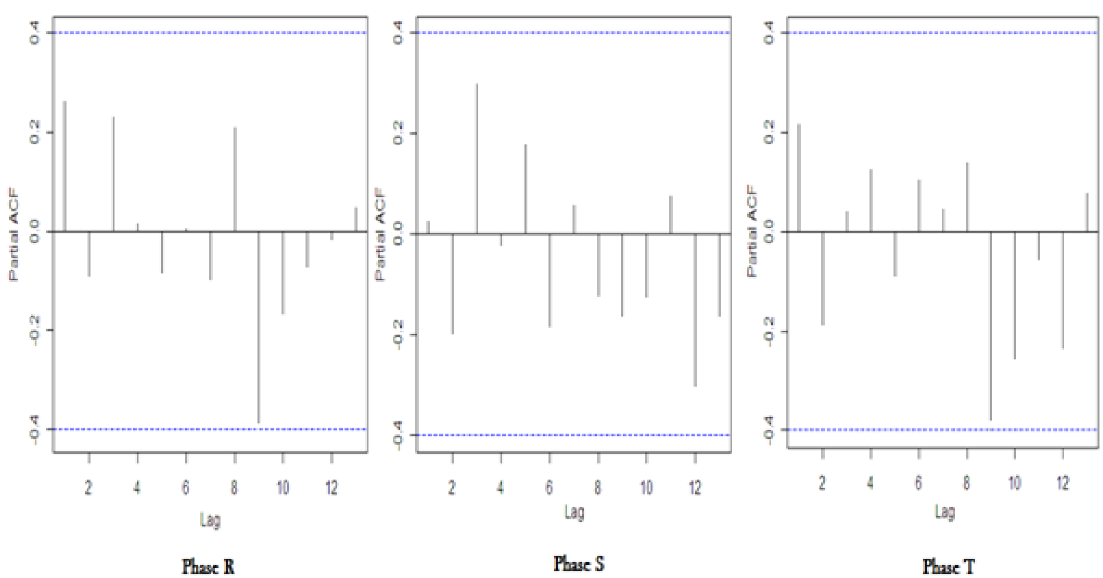

Fig. 8: Graphs of the Partial Autocorrelation Factor (partial ACF)

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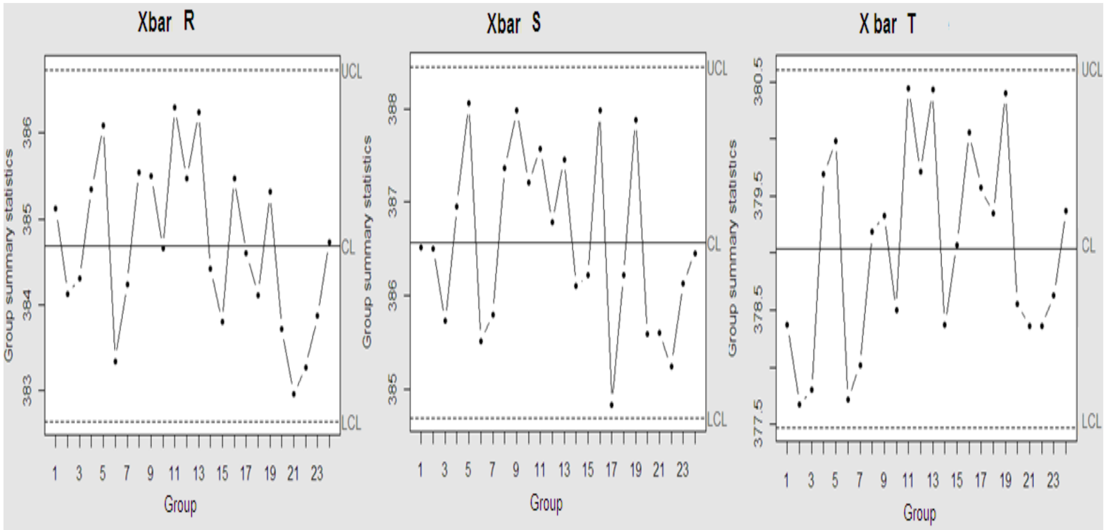

Fig. 9: Graph of XBar for R, S and T Phases

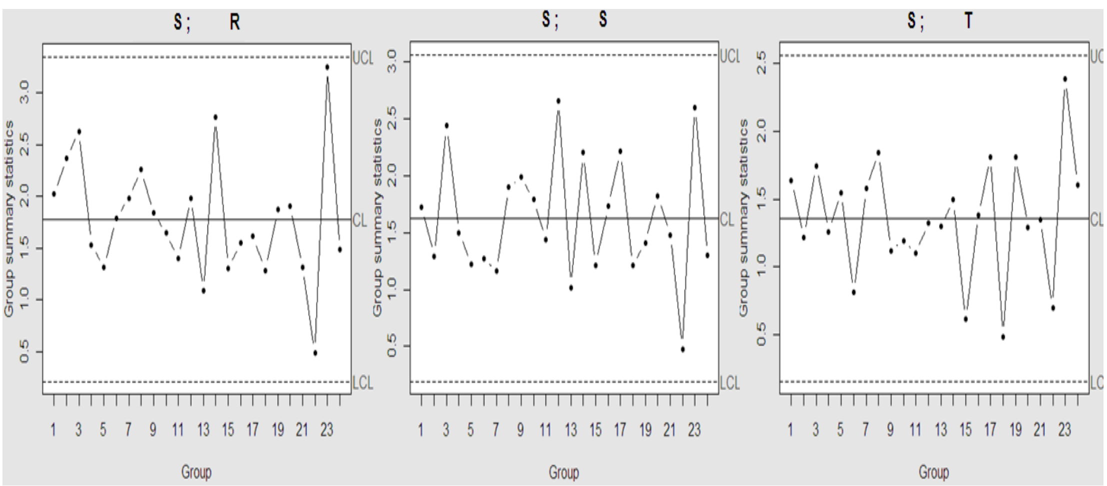

Fig. 10: Graph of S for R, S and T Phases

Figure 11 shows the behavior of the process against the limits of specifications of three-phase voltage, which for this case, correspond to LSL= 388 (V) and USL = 400 (V), as designated by the industry standard 4/2003 according to SEC (2003). For processes with bilateral specification limits, it is common to assume as a nominal value or Target the average specification limits, accordingly, the Target for the three-phase test system value would be 394 (V).

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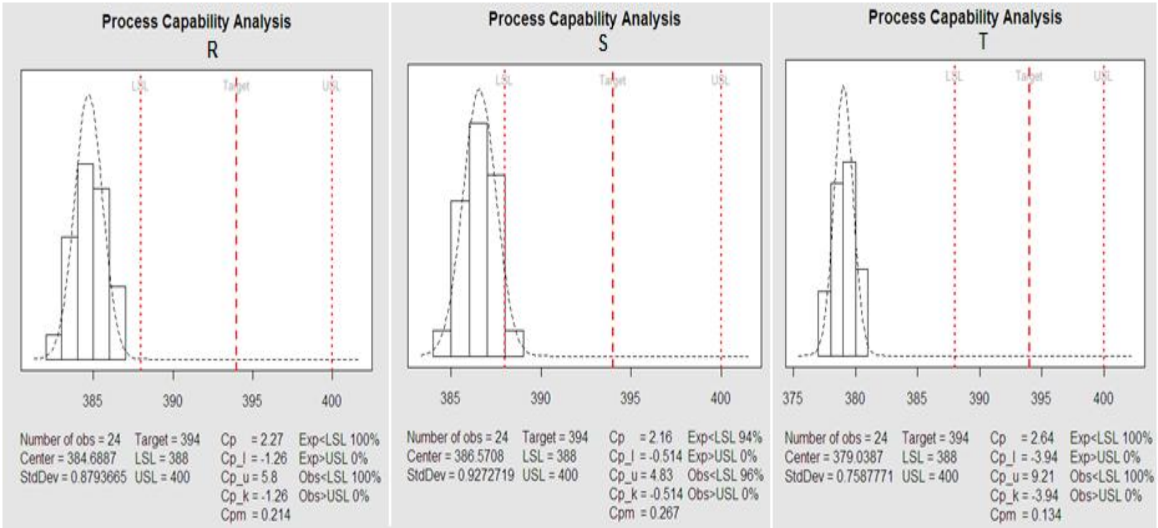

Fig. 11: Analysis of process capability for R, S and T phases

Table 6

Summary of the interpretation of the results for each phase of the three-phase test system

Index	**Phase**	**Interpretation**
Cp = 2.27	R	Very low variability is six Sigma quality.
Cpk = 1.26	R	The mean of the process is outside specifications.
K = 155.2%	R	Serious problems of negative centralization.
Cpm = 0.214	R	The process does not meet specifications by problems of centralization.
Cp = 2.16	S	Very low variability is six Sigma quality.
Cpk = 0.514	S	The mean of the process is outside specifications.
K = 123.8%	S	Serious problems of negative centralization.
Cpm = 0.267	S	The process does not meet specifications by problems of centralization.
Cp = 2.64	T	Very low variability is six Sigma quality.
Cpk = 3.94	T	The mean of the process is outside specifications.
K = 249.4%	T	Serious problems of negative centralization.
Cpm = 0.134	T	The process does not meet specifications by problems of centralization.

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5. Conclusion

Study of the single-phase voltage sample concludes that although the value of the medium voltage drop (214, 52 V) lies within the range established by the industrial standards by SEC (2003), the process is out of statistical control since an observation that exceeds the upper limit of control was found in the graph of X-bar. With regard to the three-phase samples, it can be concluded that the voltage drop process is under control, although none of the phases complies with the requirement of voltage drop being less than 3% of the nominal voltage. Considering the industrial electrical standard by SEC (2003), with respect to the voltage drop at the worst point, the R and S phases meet a voltage drop less than 5% of the nominal voltage.

In the three-phase sample problems arise in breach of the limits of voltage specifications and excessive decentralization towards the left of the samples, even though the Cp capability index is greater than 2 according to Gutieprez (2009), which means that the process has a quality Six Sigma type (this is because the variability of the variable three-phase voltage is very low).Then we performed the statistical analysis of voltage for single-phase and three-phase samples and it may be recommended to establish some kind of voltage regulation to take the middle of the process to the Target value. In this way, the process improves by increasing its category in potential capacity, reducing the costs of operation of the electrical system due to the decentralization and increasing its quality by compliance with the specifications.

The statistical analysis of the voltage drop carried out in this paper allows us to outline the guidelines and actions that allow the improvement of the process linked to the quality of the power supply. This type of approach can be applied to the study of other electrical variables such as power factor of power and other systems directly related to the quality of electricity supply.

6. References

1. Gönen T. (1986). Power System Engineering and Distribution. McGraw-Hill, 1986, ISBN 0-07-023707-7.

2. SEC (2003). Electricity Consumption in Low Voltage Installations. Superintedndent of Electricity and Fuels

3. Hitoshi K. (2002). Basic Statistical Tools for Quality Improvement. Norma Editorial, ISBN 958-04-6719-6.

4. Montgomery D. C. (2005). Statistical Quality Control. Wiley, ISBN 968-18-6234-1.

5. Kane V. E. (1986). Indices of Process Capability. Quality Research Journal, vol. 18, n.1, p.41-52, ISSN 0022-4065,

6. Taguchi G (1985). Quality Control and Assurance Tutorial- the Taguchi methods, Las Vegas, Nevada: ASA Annual Meeting, 1985.

7. Gutieprez P. H., De La Vara R. (2009). Statistical Quality Control and Six Sigma. McGraw-Hill, ISBN 978-970-10-6912-7.

8. R Development Core Team (2008). The R Project for Statistical Computing.

9. Shapiro S.S., Wilk M.B. (1965). Variance test for normality – An Analysis. Biometrics, vol. 52, p. 591-611.

APPENDIX

This appendix presents the complete data collected by simulating the test systems.

Table A.1

Data for Single Phase Test System

Hour	Monday	Tuesday	Wednesday	Thursday	Friday
12 AM	212.8	214.9	215.4	215.4	216.3
1 AM	213.3	211.6	213.4	213.2	214.2
2 AM	218.5	212.5	219.6	219.2	18.8
3 AM	216.4	211.8	212.5	213.7	213.9
4 AM	215.1	212.9	213.6	214.6	213.7
5 AM	213.8	213.8	213.9	214.8	214.4
6 AM	213.7	213.7	215.4	212.1	212.5
7 AM	215.2	216.1	214.2	216.2	214.6
8 AM	211.9	213	213.3	211.9	214.5
9 AM	216.7	211.8	212.1	214.6	213.5
10 AM	216.3	215.6	216.3	214	214.3
11 AM	214.2	211.7	213.4	211.8	212.1
12 PM	212.8	218.7	211.5	215.4	214.5
1 PM	213.7	211.3	212.4	216.8	211.7
2 PM	216.5	214.4	216.7	214.7	216.4
3 PM	211.9	212.3	215.4	216.9	218.3
4 PM	212.8	215.7	212.4	217.8	212.1
5 PM	216.7	216.7	215.4	212	214.9
6 PM	215.7	212.4	216.4	214.3	216.2
7 PM	214.8	217.4	212.7	212.5	217.5
8 PM	212.7	212.1	218.1	216.3	216.1
9 PM	211.5	213.4	212.9	213.8	215.8
10 PM	216.8	215.2	215.8	216.1	217.2
11 PM	212.7	216.3	216.1	214.8	215.4

All Values Measured in Volt RMS (Root Mean Square)

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Table A.2

Data for Three Phase Test System

Hour	Phase R	Phase S	Phase T
12 AM	396.22	397.62	389.48
1 AM	395.24	397.61	388.78
2 AM	395.41	396.84	388.91
3 AM	396.45	398.07	390.8
4 AM	397.2	399.17	391.1
5 AM	394.45	396.62	388.82
6 AM	395.35	396.91	389.12
7 AM	396.65	398.48	390.3
8 AM	396.61	399.1	390.44
9 AM	395.77	398.32	389.61
10 AM	397.41	398.68	391.55
11 AM	396.58	397.9	390.82
12 PM	397.35	398.57	391.54
1 PM	395.52	397.21	389.48
2 PM	394.91	397.32	390.18
3 PM	396.58	399.1	391.17
4 PM	395.71	395.94	390.68
5 PM	395.22	397.32	390.45
6 PM	396.42	399	391.51
7 PM	394.82	396.7	389.67
8 PM	394.07	396.71	389.47
9 PM	394.38	396.35	389.47
10 PM	394.98	397.24	389.74
11 PM	395.84	397.57	390.48

All Values Measured in Volts RMS (Root Mean Square)

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