IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

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To cite this article: A H Vizuete *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **559** 012011

Voltage Supply Assessment Using Process Capability Concepts: A Case Study

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Abstract. The following case study examines a company which experienced several difficulties caused by low-quality voltage supply. Two main points were considered in the analysis, one located next to the substation transformer and a second one inside the company. Voltage parameters such as harmonics presence, voltage flickers, average voltage, and power factor were measured in this study. As a result, 62 000 samples were collected. The data obtained from point 2 (control group) revealed the necessity of introducing voltage regulators in order to improve the energy efficiency and save in energy costs at the company. Therefore, 1 500 samples were collected at point 2 (treatment group) to verify the voltage regulators' efficiency. Comparing the control and treatment group, there was a significant improvement of 93% regarding process capability in power factor phase CN.

1. Introduction

Energy sector faces serious problems nowadays [1]. Voltage supply quality is the main concern regarding work efficiency in any industry. The maintenance processes for controlling voltage stability generate uncertainty towards electric supply-demand [2]. The intense load in transmission lines causes voltage related problems in different industries [3]. Furthermore, automated industrial processes induce the incorporation of nonlinear loads, which are important perturbation sources in electric systems [4]. These disturbances inject current harmonic that distorts the fundamental waveform. Hence, when an interaction with the system happens, it distorts the voltage and provokes problems in the equipment that comprises the system.

In Ecuador, the rising development of the industries has resulted in a more demanding market for energy suppliers. Not only in terms of the service but also, requiring better standards for the energy delivered [5]. Legal regulations are administered in Ecuador by the regime law of the electric sector. These standards establish responsibilities between the consumer and the suppliers. National and international norms limit the permitted ranges of voltage waveform distributed by the supplier and distortions made by the consumers in their production processes.

At an international level, the regulation that governs these types of systems is IEEE 5191992. This norm includes the harmonic distortions introduced by nonlinear loads in order to solve problems regarding potency quality [6]. The norm IEC 61000-4-30 is widely used for measuring processes of electricity quality [7]. Additionally, in Ecuador, the CONELEC 004/01 norm establishes a regulating format of the electricity quality distribution, which allows locating in an efficient way the quality in three stages: product, technical service and commercial service [8]. This regulation points out the energy quality evaluation as a form to improve its efficiency. Moreover, it determines corrective actions in order to suppress the perturbation content in the main network feeder.

Consequently, the following case study describes the evaluation of the voltage source at a wood-processing company located in Ecuador with almost 40 years of experience in the market. In 2000 and 2006, the industry went through an evaluation of national institutes which suggested few changes to improve the energy consumption. Some of the suggestions included motors and light bulbs replacement and the installation of new instruments to regulate the voltage consumption, especially during rush-hours.

The main objective of this study is to determine a strategy to reduce the most relevant perturbations regarding the quality of the electric supply. Utilizing as a reference, national and international norms that regulate the limits, measurement periods and compliance stages.

2. Methodology

A preliminary assessment was performed to evaluate the voltage efficiency using two points of reference:

- The first point was located at the distribution transformer which provides energy to the whole town.
- The second point was located inside the company studied at 800 meters distance from the first point.

As the main feeder delivers line voltage and phase voltage, to have a point of reference, only phase voltages were studied. Thus, voltage phases' parameters were treated separately as AN, BN and CN.

Table 1 enumerates the time taken to collect the average voltage, harmonics presence, electrical flickers, and power factor samples. Moreover, the electrical network configuration, nominal voltage, working frequency, and the equipment used to measure the data.

Table 1. Initial analysis - points' details.

	Point 1	**Point 2**
Analysis time length	62 days	14days
Configuration	3 Phases + Neutral Wye configuration	
Phase voltage	13800 V	440 V
Frequency	60 Hz	
Analysis instrument	Fluke 1750	

As a result of this preliminary analysis, three Siemens JFR Distribution Step-Voltage Regulators in delta configuration were installed in the company. A second assessment of 10 days in point 2 was performed in order to test the results of implementation of the voltage regulators. Point one measurement was analyzed to obtain baseline information regarding the energy quality delivered by the local electricity provider.

CONELEC 004/01 norm envisages voltage as a product delivered by national electric power industries. Thus, a process capability analysis was performed on the data sets collected. According to CONELEC 004/01, the product has to fulfill specific requirements regarding three main aspects: average voltage, voltage flicker and power factor. In the case of voltage flicker, the norm considers only short-term flicker perceptibility (Pst) and all data has to be collected under the International Electrotechnical Commission (IEC) norm 60868. Since process capability indices can be understood as the number of non-conforming parts per million [9], this concept accords with CONELEC 004/01 assessment parameters.

Data sets were analyzed using the statistical package Minitab. Process Capability Sixpack report was utilized to compare the intervention effects of the voltage regulators. Point 2 of the initial analysis is considered as the control group while the data collected at the secondary assessment is the treatment group.

3. Results

This section presents the data collection of three factors: power factor, voltage flickers and the average voltage at point 2. Harmonic distortion was not considered for the results since it did not alter the voltage efficiency. In the preliminary assessment, 62 000 samples were taken, whereas over 1 500 samples were taken after the installation in the second point. However, only the treatment group data is in detail described for each voltage distribution phase.

3.1. Power Factor

According [10] a process capability lesser than 0.5 means at least 13.36% of the data is out of tolerance Figure 1, Figure 2 and **Figure 3** show that process capability (cp) at the phase CN is out of tolerable limits after the implementation of the step voltage regulator. Figure 4 shows a slight improvement compared with the values collected in the preliminary assessment. Hence, AN phase and BN phase meet acceptable quality parameters.

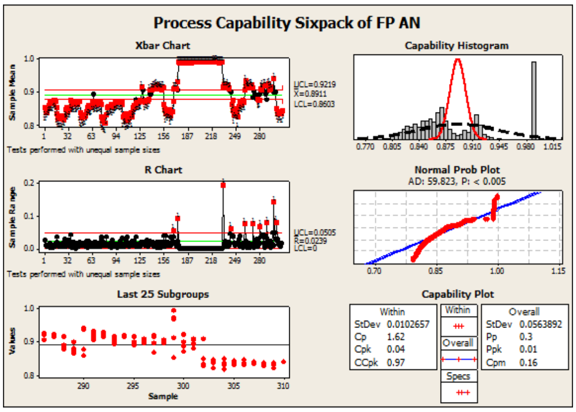

Figure 1. Average Power Factor AN.

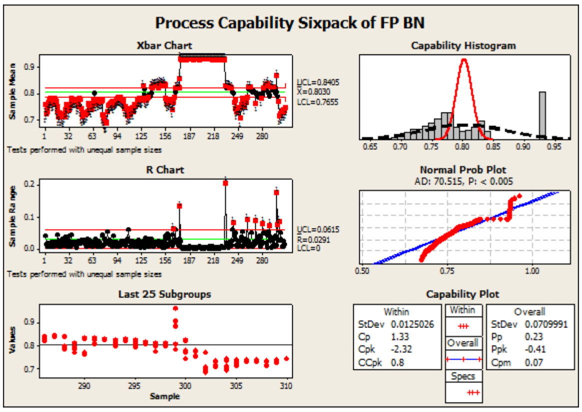

Figure 2. Average Power Factor BN.

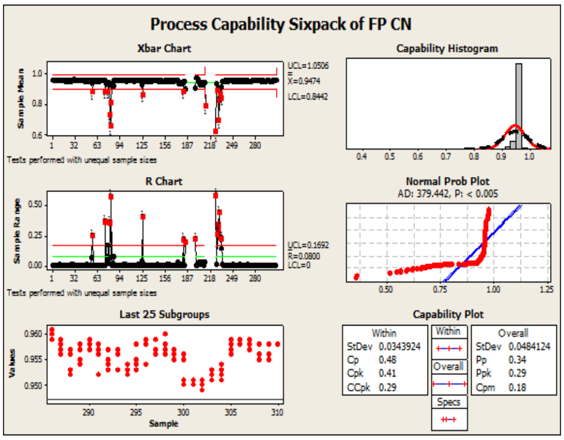

Figure 3. Average Power Factor CN.

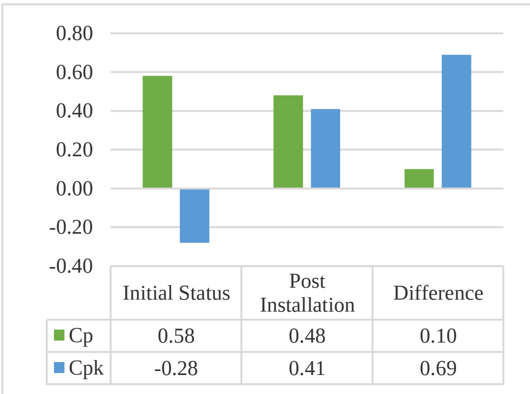

Figure 4. Cp and Cpk at point 2. CN power factor's changes analysis.

Figure **4** shows the initial state of the process and the effect of the treatment in process capability (Cp, CpK) The increment of 0.69 in Cpk translates to a considerable improvement of 93%.

3.2. Power - line flickers

Figure 5, Figure 6 and **Figure 7** summarizes short term flicker perceptibility (Pst) of AN, BN and CN. The IEC61000-4-15 flickermeter standard establishes that Pst should ideally be 1.00 with a tolerance of 5%. An Upper Control Limit of 1.35, 1.30 and 1.34 from AN. BN and CN Xbar chart respectively, demonstrates that all phases are out of limits regarding Pst.

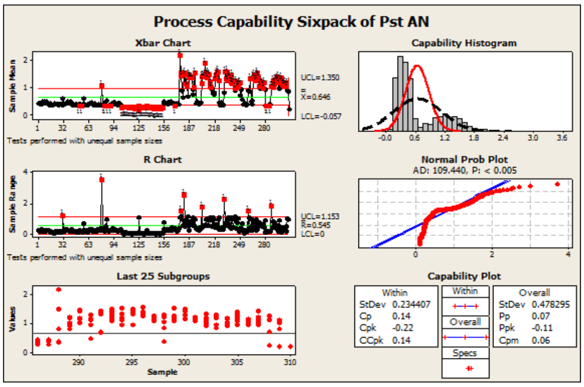

Figure 5. Pst - Phase AN.

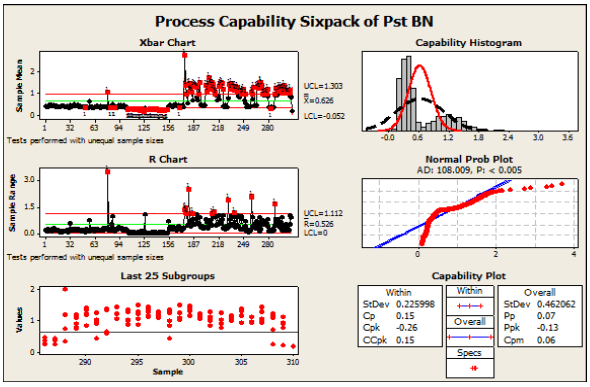

Figure 6. Pst - Phase BN.

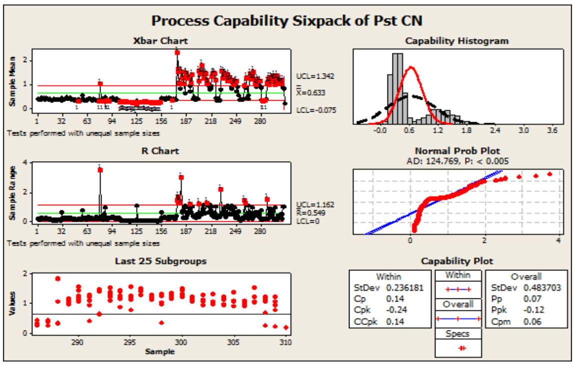

Figure 7. Pst - Phase CN.

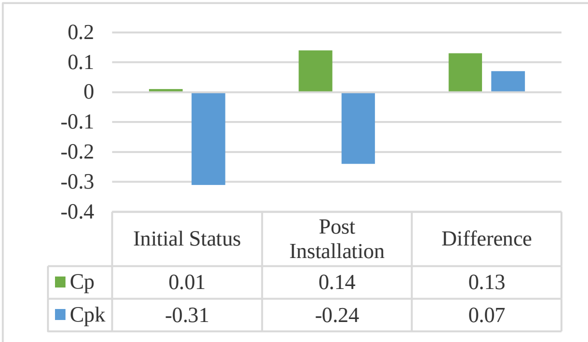

Figure 8. Cp and Cpk at point 2. CN Pst's changes analysis.

Nonetheless, **Figure 8** shows there was a slight improvement in comparison with the initial state at phase CN. This, due to the fact that external loads cause voltage flickers to the company.

3.3. Average voltage

Figure 9, Figure 10 and **Figure 11** show a satisfying cp in all cases AN, BN and CN average voltage. With a cp of 19.98, 18.72 and 20.1 at AN, BN and CN respectively, the process achieved a six-sigma performance. As reported by [11], a six-sigma process does not produce more than 4 defects per million opportunities. Since the main objective of a step voltage regulator is to stabilize nominal voltage, then the instrument is completely efficient.

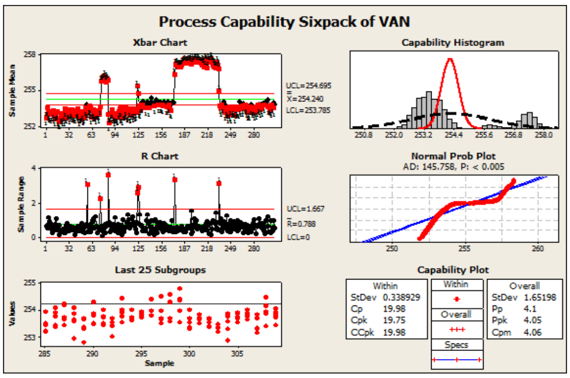

Figure 9. Average Phase Voltage AN.

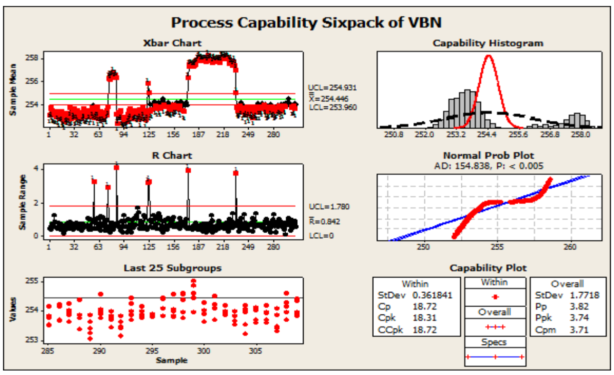

Figure 10. Average Phase Voltage BN.

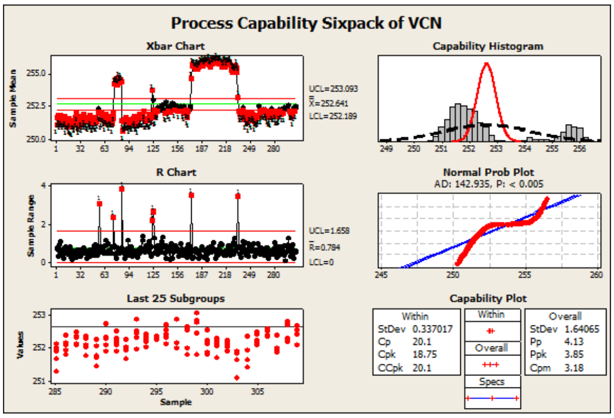

Figure 11. Average Phase Voltage CN.

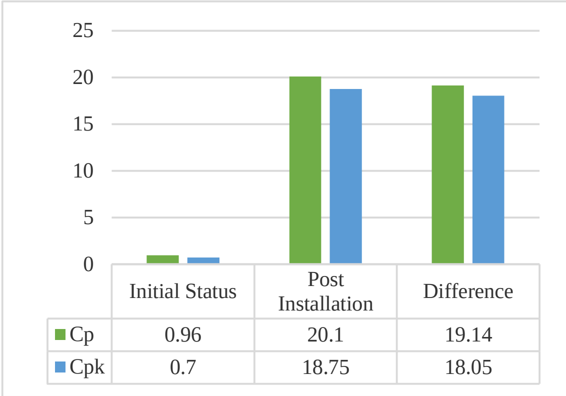

Figure 12. Cp and Cpk at point 2. CN average voltage changes analysis.

However, Figure 12 highlights the most significant improvement from all the voltage parameters studied.

3.4. Economic analysis

In 2014, the company experienced working hours loses due to multiple power outages. It resulted in a financial loss of over 190000 USD. Therefore, voltage step regulators and capacitor banks were implemented. Figure 13 shows the economic losses in 2015. As a result, the losses were reduced in nearly 93% which means 175000 USD in the year 2015 compared to the previous year where no treatment was applied.
Almost 100% of the voltage variations of the samples are within the allowed limits of ±8.0% that the regulation specifies. In relation to flicker, 24 % of the samples per phase were outside the limit that is 1, and with respect to power factor, 54% of the samples were less than the limit of 0.92. In the same way, the presence of harmonics was verified but they did not exceed the allowed limits.

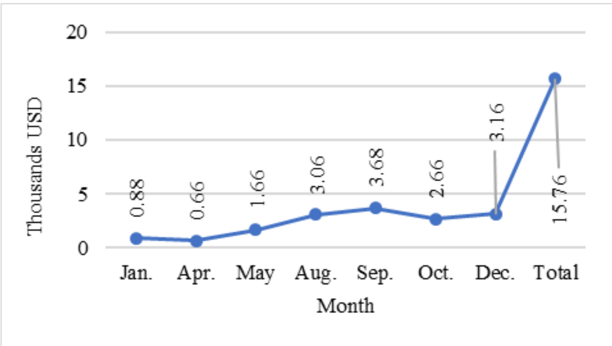

Figure 13. Losses due to power outage – year 2015.

4. Discussion

The analysis at the delivery point (Point 1, main feeder) and the output of the transformer (Point 2) showed that parameters such as: voltage, harmonics and flicker were outside the limits allowed by the national electricity regulation institute (CONELEC 004/01). After technical and statistical analysis, the installation of banks of capacitors and regulators was justified. The final effect was the correction of most of these parameters except flicker.

The infringement of regulations are mainly associated with users connected to the distribution network in the industrial range. Electric arc furnaces and high energy consumption loads introduce disturbances in the transmission network. For this reason, the energy quality provided by the local

energy supplier at the delivery point of analysis (Point 1) is affecting the electric distribution in the system.
On the other hand, current harmonics, as well as the unbalance in the 13.8 kV bus of the Local Feeder No. 5 substation, were significant. However, one of the functions of the voltage regulator is that it works as a harmonic filter. Therefore it is possible to reduce them and satisfy the requirements of the Energy Quality Regulator.
The power factor at the delivery point (Point 1) is outside the permitted values according to the regulation. Thus, a 300 kVA capacitor bank was connected in parallel to the load in order to correct this requirement. It can be verified that the voltage variation has been controlled with the installation of the single-phase voltage regulators, and it also shows that they serve as low-pass filters, decreasing the harmonic content.
It is observed that the process capability indexes Cp and Cpk increased after the installation of the voltage regulators per face and capacitor banks. This showed that the variability of the parameters of voltage, flicker and power factor were optimized as a result of the corrections made. Additionally, during the year 2015, the company did not invest in replacing broken electrical equipment due to the voltage disturbances. Certainly, it cannot be adduced that the step voltage regulator completely resulted in the financial improvement. Some electrical equipment could have had their own failures due to the length of time they had been used.

5. Conclusions

Energy efficiency is a paramount concern within small, medium and large enterprises because of the economic savings it represents for a business. Ecuadorian electricity distribution causes economic losses for corporations. For this reason, companies are in the need to find solutions inside their production processes. The study presented above captured how small interventions can contribute to great improvements in productivity and reducing costs.
The case study evaluated electricity efficiency at a wood manufacturer company located in Ecuador. A preliminary analysis of voltage efficiency was performed measuring different electrical factors at two critical points: outside the company at the distribution transformer and the second point inside the company. As a result of this analysis, voltage regulators were set up at company's premises.
In order to verify the success of this interventions, further measures were taken at point 2 and compared with the previous samples collected at the preliminary study. The results obtained revealed a great improvement in the process capability of 93% regarding power factor at one of the voltage lines and an astonishing reduction in costs. This study represents a proof that simple informed decisions based on proper analysis can lead to considerable changes in productivity and competitive advantages that benefit an organization.

6. References

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