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RESEARCH ARTICLE

The Efficiency of Voltage Stabilizer Installation in Addressing Power Quality Issues through Analysis Using an Injection Power Analyzer in the Manufacturing Industry of PT XYZ

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Abstract

In today's modern era, electrical energy has become a vital secondary need for society and serves as a key foundation for economic development. Along with the rapid advancement of complex electronic devices, various power quality disturbances have emerged, negatively impacting industrial equipment such as active line modules and motor drivers, potentially disrupting production processes. A similar issue occurred at PT XYZ that is manufacturing company operating in the industrial sector with focusing on production packaging and label material activities, prompting real-time power quality monitoring using a power analyzer installed on the Low Voltage Main Distribution Board (LVMDB) panel. This device can record and analyze power quality trends visually. Based on the data, PT XYZ took corrective actions, including the transformer tap position was adjusted to optimize the voltage supplied to the production machines and installing a voltage stabilizer, which effectively stabilized the voltage supplied to production machines. Furthermore, a harmonic analysis simulation showed a Total Harmonic Distortion of 8,35% for current and 7,92% for voltage. After applying a power filter design in ETAP, these values significantly decreased to 1.98% (current) and 2.08% (voltage). Based on these findings, it is recommended that PT XYZ proceed with the installation of a power filter to comprehensively improve power quality.

Keywords: Power Quality, electronics devices, power analyzer

1. Introduction

The demand for a reliable and high-quality power system has significantly increased in line with advancements in technology and automation within the manufacturing sector. In modern industrial environments, even minor disruptions in electrical power systems can have serious consequences for operational efficiency, workplace safety, and overall productivity [1]. One of the most critical elements in industrial electrical systems is power quality, which includes voltage stability, frequency stability, and minimal waveform distortion [2].

Poor power quality can cause various severe issues such as equipment damage, production interruptions, and significant financial losses [3]. Voltage fluctuations including sags, swells, transients, and phase imbalances can interfere with operations, particularly in sensitive equipment like inverters, programmable logic controllers, and automation systems [4]. Even short disturbances lasting just a few milliseconds can stop production or result in data corruption [5]. One of the primary causes of poor power quality is the presence of non-linear loads, which generate harmonic distortion [6].

The use of modern electronic equipment such as variable speed drives, power converters and battery charging systems produces non-sinusoidal current waveforms that introduce harmonics into the power system [7]. These harmonics can lead to overheating of transformers, malfunction of protection systems, and overall system inefficiencies [8]. According to IEEE Std 519-2014, harmonic control is critical to maintaining system performance and preventing equipment damage [9].

Another pressing issue are loads unbalance, which frequently occurs in three-phase systems due to the uneven operation of single-phase loads. Load imbalance causes high neutral currents, increased losses, and a reduction in power factor [10]. Over time, voltage imbalance can lead to insulation failures in motors and transformers, reducing the operational lifespan of critical equipment [11]. Voltage disturbances, including sags and swells, may also result from external factors such as short circuits, lightning strikes, insulation breakdowns, or abrupt load switching [12]. These events further compromise the stability of industrial power systems, particularly in medium and low voltage networks [13]. Therefore, power quality monitoring and control have become essential aspects of modern electrical power system management.

To address these issues, the use of voltage stabilizers has become a widely adopted solution. These devices function to maintain voltage levels within the desired range, even when fluctuations occur on the supply side [14]. Voltage stabilizers adjust input voltage and deliver a stable output voltage that meets the operational requirements of industrial equipment [15]. Their application has been shown to improve power factor, reduce Total Harmonic Distortion (THD), and prolong the service life of sensitive equipment [16]. Numerous studies support the effectiveness of passive, active, or hybrid power filters in mitigating harmonics and improving the stability of power systems [17]. Additionally, combining filtering solutions with voltage regulation devices, such as voltage stabilizers and automatic tap changers, has proven to optimize power delivery to sensitive loads.

This research aims to analyze the overall impact of implementing a combination of corrective strategies including tap changer adjustment, voltage stabilization, and harmonic filter design in improving the power quality within PT XYZ's electrical distribution system. Power quality analysis and measurement are important in PT XYZ's electrical system to maintain stable and reliable operation of machines and production equipment. Electrical disturbances such as harmonics, voltage fluctuations, and power interruptions can affect equipment performance and cause machine breakdowns or production problems. Therefore, power quality measurement is needed to identify electrical issues and improve the reliability and efficiency of the electrical system. The study also used ETAP as an analysis tool in this study; therefore, the focus of the evaluation is the electrical system performance rather than the software itself. [18].

Maintaining power quality improves energy efficiency, equipment lifespan, and industrial reliability. As automation increases, effective power quality management becomes more important [19]. This study is expected to serve as a reference for industries facing similar power quality problems and encourage the use of real-time monitoring and corrective systems [20].

2. Power Quality and Associated Problems

2.1 Power Quality

Power quality refers to the extent to which the voltage, current, and frequency in a power system conform to nominal standards. According to IEEE Std 1159-2019, power quality is defined as a concept relating to the adequacy of voltage, current, and frequency characteristics so that electrical equipment can operate correctly and efficiently [9]. Poor power quality can cause equipment to overheat, operate inefficiently, or even become damaged.

A measurable indicator known as the Power Quality Factor (PQF) has been proposed to comprehensively reflect various aspects of power quality, as previously described [21]. This factor is expressed as:

$$PQF = \sum_{i} w_i(1 - QA_i) \tag{1}$$

The formula represents the calculation of the Power Quality Factor (PQF) used to evaluate the overall condition of an electrical system based on several weighted power quality parameters. Each parameter is assigned a weighting factor (w_i)according to its importance, while (1-QA_i)represents the quality deviation of each parameter. The final PQF value indicates the overall power quality performance of the system.

2.2 Voltage Quality Factor

A measurable indicator, referred to as the Voltage Quality Factor (VQF), is proposed to comprehensively reflect various aspects of voltage quality QAi (i = 1, 2, 4) as previously formulated. This is expressed as :

$$VQF = \sum_{i=1,3} w_i(1 - QA_i) \tag{2}$$

In formula (2), iis an index representing each voltage quality parameter (QA_i)included in the Voltage Quality Factor (VQF) calculation. The notation i=1,3indicates that the summation starts from parameter 1 and ends at parameter 3, meaning that three voltage quality parameters are considered in the analysis.

where QA_i represents the assessment value of each voltage quality parameter, such as voltage magnitude stability and voltage unbalance, while w_i denotes the weighting factor assigned to each parameter according to its importance. The term (1-QA_i)indicates the deviation of each parameter from the ideal condition. A value of QA_i=1represents perfect voltage quality with no deviation, whereas lower values indicate poorer voltage quality performance. By aggregating these deviations, the Voltage Quality Factor provides a comprehensive measure of voltage quality performance [22]. A lower Voltage Quality Factor (VQF) value indicates better voltage quality, while a higher value signifies greater deviation and potential concern for system reliability or equipment performance [23].

2.3 Associated Problems with Power Quality

2.3.1 Total Harmonic Distortion

Total Harmonic Distortion in current and voltage significantly impacts the performance, efficiency, and reliability of electrical power systems, especially in industrial environments. High total current harmonic distortion (THD$_i$) leads to overheating of conductors, transformers, and neutral lines, causing increased energy losses and potential equipment failure. Meanwhile, total voltage harmonic distortion (THD$_v$) can damage sensitive electronic equipment, create unwanted torque in motors, and disrupt control systems. Each distortion in a single-phase network (or balanced multi-phase network) is conventionally defined as:

$$THD_V^2 = \frac{\sum_{h \neq 1} V_h^2}{V_1^2}, \qquad THD_1^2 = \frac{\sum_{h \neq 1} I_h^2}{I_1^2} \tag{3}$$

where V and I represent the root mean square (RMS) values, and 1 and h denote the fundamental and harmonic orders, respectively.

The first quality aspects, QA1 and QA2, are identified by the total harmonic distortion of voltage (THD$_v$) and current (THD$_I$) for an unbalanced three-phase system, and are defined as:

$$QA_1 = THD_v = \frac{V_{eH}}{V_{e1}}, \qquad QA_2 = THD_I = \frac{I_{eH}}{I_{e1}} \tag{4}$$

where Ve1 and Ie1 represent the equivalent fundamental phase voltage and current.

The definitions in Equations (3) and (4) satisfy the specific requirement that the total losses in the equivalent balanced three-phase system must be equal to those in the actual system under study. The underlying assumptions are the losses in lines and equipment at a given frequency are proportional to the square of the voltage or current, and the parameters of the lines and equipment are symmetrical. Currently, the maximum allowable limits for total harmonic distortion of current and voltage are defined by the IEEE Std 519-2014 standard. The standard data can be seen in the table 1.

The table shows the maximum voltage harmonic distortion limits based on the IEEE 519-2014 standard. For systems ≤1 kV, the maximum THD is 8%, while for systems above 1 kV, the THD limits become more stringent for example, only 5% for 1-69 kV, and 2.5% for 69-161 kV. The higher the voltage level, the smaller the allowable distortion tolerance in order to maintain power quality.

Table 1. Total harmonic voltage distortion, IEEE Std 519 -2014 Standard

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5[a]

The table above outlines the maximum permissible harmonic current distortion levels based on IEEE Std 519-2014. It classifies the limits according to the ratio of short-circuit current to load current (*Isc/IL*) and groups harmonic orders into specific ranges. Each row shows allowable percentages for individual odd harmonics and the Total Demand Distortion (TDD). As the short-circuit capacity increases (higher *Isc/IL*), the system can tolerate greater harmonic levels. This ensures that weaker systems maintain stricter limits to prevent excessive voltage distortion and protect power quality.

Table 2. Total harmonic current distortion, IEEE Std 519 -2014 Standard

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a,b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

– **Harmonic distortion** occurs when non-linear loads are connected to the electrical network, causing the current flowing through the lines to contain harmonics. The voltage drop caused by these harmonics across the line impedance results in distortion of the supply voltage [2]. This is illustrated in Fig. 1 [Yacamini, 1995].

– **Inter harmonics**: These appear when there are current components that are not related to the fundamental frequency. Such components can be generated by arc furnaces or cyclo-converters (devices that, although supplied at 50 Hz, allow the formation of output voltage and current at lower frequencies) [2]. This is illustrated in Fig. 2 [Yacamini, 1995].

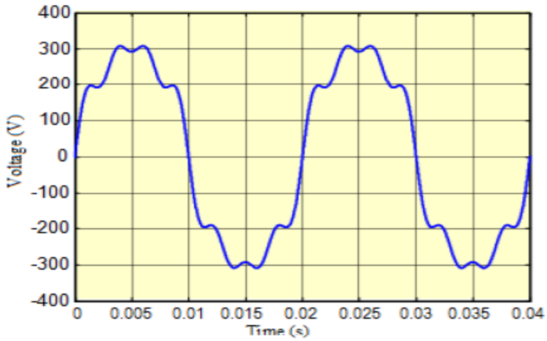

Figure 1. Harmonic distortion

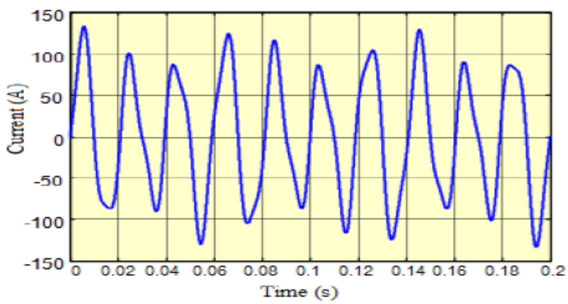

Figure 2. Inter-harmonics

2.3.2 Voltage sag

Voltage sag, also known as a voltage dip, is one of the most common and disruptive power quality disturbances in electrical systems, especially within industrial environments. It is defined as a short-duration reduction in RMS voltage, typically ranging between 10% and 90% of the nominal voltage, and lasting from 0.5 cycles to one minute, according to IEEE Std 1159-2019 [4]. Voltage sags are often caused by the sudden starting of large loads such as induction motors, short circuits, lightning strikes, or insulation failures within the distribution network. In industrial systems, even brief sags can lead to malfunctions of sensitive equipment, unintended shutdowns of programmable logic controllers, errors in data processing, and disrupted production lines.

The severity of a voltage sag is characterized by its magnitude and duration. For example, a sag to 70% of nominal voltage lasting for 10 cycles can be enough to trip electronic devices [24]. IEEE classifies voltage sags into three categories: slight (70-90%), moderate (40-70%), and deep (<40%), each with specific implications on equipment performance. Mitigating voltage sags often requires the use of power quality devices such as voltage stabilizers, uninterruptible power supplies to maintain system reliability and protect critical operations.

3. Research Methods

The research methodology used in this study is illustrated in Fig. 3.

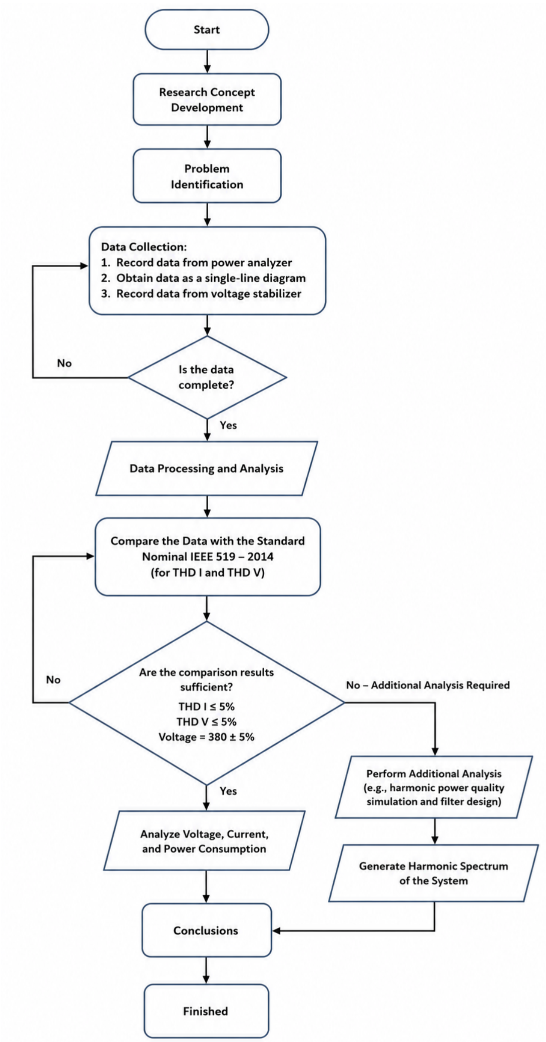

Figure 3. Research Flowchart

The process begins with the formulation and development of the research concept, followed by the identification of the problem. Once the issue is clearly defined, the next stage involves data collection, which includes recording measurements from a power analyzer and obtaining the as-built single-line diagram of the electrical system.

After data collection, the next step is to verify whether the collected data is complete. If not, the process loops back to collect the missing information. If the data is complete, the flow continues with data processing and analysis. The analyzed data is then compared against standard limits, particularly those defined in IEEE Std 519-2014, which specifies acceptable limits such as THD for current (8%), THD for voltage (5%), and voltage level around 380V ± 5%.

If the comparison and analysis results are satisfactory, the process proceeds to generating graphs of voltage, current, and power consumption. Otherwise, further evaluation is conducted, including harmonic simulation and power filter design, followed by harmonic spectrum analysis. Finally, conclusions are drawn based on the findings, and the study is completed.

3.1 Data Collection

The data collection process is carried out by installing a power analyzer device MYeBox -1500, as shown in the figure 4, The data will be recorded by the device and then connected to VG software, which allows the data to be converted into XLS format for further analysis using MATLAB and ETAP software.

Figure 4. Injection Power Analyzer

The purpose of using a Power Quality Analyzer is to measure and analyze electrical parameters in real time within an electrical distribution system. The device records important parameters such as voltage, current, power factor, frequency, and harmonic distortion to evaluate power quality performance. The measured data are used to identify electrical disturbances, improve system efficiency, prevent equipment damage, and ensure compliance with IEEE Std 519-2014. Therefore, the Power Quality Analyzer is an important tool for maintaining reliable and stable electrical system operation.

3.2 Installation of voltage stabilizer equipment

The installation diagram of the voltage stabilizer used for machine protection is shown in Fig. 5.

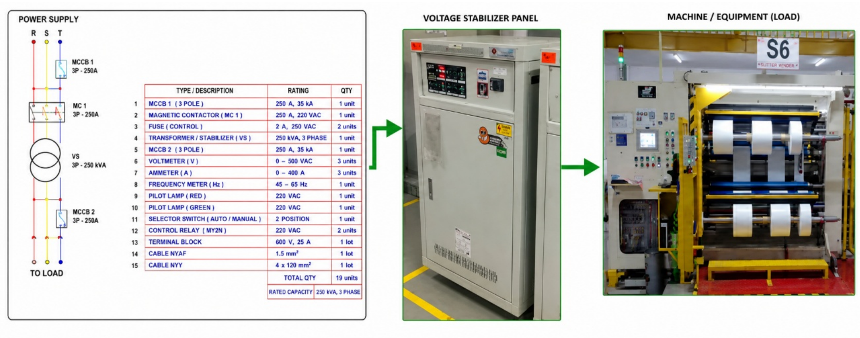

Figure 5. Installation of voltage stabilizer equipment

The voltage stabilizer is connected to the incoming line of the machine's main panel, and its output is then distributed to each production machine. The voltage stabilizer is capable of autonomously increasing the voltage when a drop occurs and decreasing the voltage when there is an overvoltage condition. The voltage fluctuation caused by abnormal conditions ranges between 1 to 20 Volts AC and is corrected within milliseconds. The stabilizer designed for connection to the main panel has a capacity of 60 kVA, with a primary voltage range of 278–415 V and a secondary voltage of 380 V. Due to its reliability, the voltage stabilizer is engineered to protect against abnormal conditions such as under-voltage and over-voltage through alarms or automatic cut-off features. Additionally, it offers protection against overcurrent, short circuits, phase failure, and unbalanced loads.

3.3 Changing the position of the Transformer Tap Changer

The transformer is equipped with a Load Tap Changer, which is one of the main components in electrical power systems and industrial applications. A load tap changer allows for voltage regulation or phase shifting by varying the transformer winding ratio under load conditions. The transformer's function is to adjust the output voltage level to meet the required operating conditions. This is achieved by altering the transformer's ratio, specifically by changing the number of turns in one of the windings accurately. The reason for adjusting the tap changer position on the transformer unit is due to the observed trend of secondary nominal voltage being significantly higher than the standard voltage requirements of the connected machines.

The nominal secondary voltage, when the tap changer is set to position 3, is 420–425 volts AC.

The nominal secondary voltage, when the tap changer is set to position 1, is 385–400 volts AC.

3.4 Power Filter Design

This study uses ETAP software version 21.0.1 to simulate the single line diagram of the production machine load path. The analysis focuses on the total harmonic distortion value of the voltage. The components in the SLD created in ETAP are generally

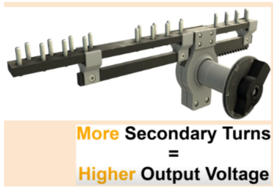

Figure 6. Tap changer position 3

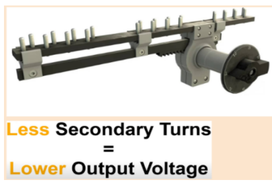

Figure 7. Tap changer position 1

similar to those in a conventional single line diagram or the actual equipment used in the machines. However, each component must be provided with specific data values or ratings to accurately represent its behavior in the simulation.

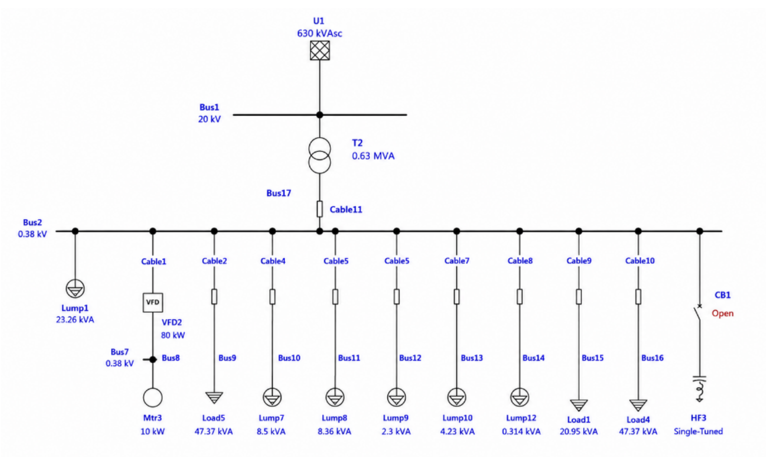

Figure 8. SLD is completely inactive

This system begins from the main source at Bus1 with a voltage of 20 kV, which is connected to transformer T2 with a capacity of 0.63 MVA. This transformer steps down the voltage to 0.38 kV, which is then distributed to Bus17. From there, power is delivered to various loads through Bus2 and Bus7 up to Bus16. Several key loads in the system include motor loads (e.g., Mtr3, 10 kW), loads using Variable Frequency Drives (VFDs), and various lumped loads (such as Lump1, Load5, Lump7, etc.) with capacities ranging from 0.314 kVA to 47.37 kVA.

4. Results and Discussion

To evaluate the electrical power quality conditions in the system, a power analyzer was installed and monitored continuously for two weeks. The measurement results obtained during the monitoring period are presented and discussed in the following sections.

4.1 Inter-phase voltage measurement results

Table 3 presents the measurement results of line-to-line voltages (V12, V23, and V31) over a 14-day period (D1 to D14). In general, the line-to-line voltages remain within a relatively stable range, between 392.2 V and 400.6 V, with minor daily fluctuations.

Table 3. Results of Inter-Phase Voltage Measurements

AVG Day-n	V12	V23	V31
AVG -D1	395.9	400.6	397.8
AVG -D2	394.6	399.1	396.4
AVG -D3	394.5	398.7	396.4
AVG -D4	394.1	398.7	396.5
AVG -D5	394.8	399.6	397.1
AVG -D6	394.0	397.8	396.9
AVG -D7	393.7	398.4	395.6
AVG -D8	394.1	398.5	396.0
AVG -D9	394.4	398.8	396.0
AVG -D10	395.0	399.6	396.5
AVG -D11	394.5	399.3	396.4
AVG -D12	394.6	398.8	397.2
AVG -D13	395.0	400.2	398.3
AVG -D14	392.2	397.1	394.0

The graph displays figure 9, the line-to-line voltage measurements (V12, V23, and V31) recorded over a 14-day period. Overall, the voltage values remain within a relatively stable range, with V23 consistently showing the highest readings, between approximately 397 V and 401 V. V31 follows a similar but slightly lower pattern, ranging from around 396 V to 399 V. V12, on the other hand, displays the lowest voltages, fluctuating between roughly 393 V and 396 V. Notable variations are observed on Day 13 and Day 14, where all three voltages experience a sharp drop, particularly V31 and V12, indicating a possible disturbance or anomaly in the system during those days. Despite these fluctuations, the voltage levels remain generally within acceptable operational limits

4.2 Voltage measurement results for each phase

Table 4 shows the average phase voltage measurements (V1, V2, and V3) over 14 days. Generally, the voltage ranges were V1: 224.4–227.9 V, V2: 230.0–233.0 V, and V3: 228.0–230.4 V. V2 consistently had the highest voltage, while V1 tended to be the lowest, especially on Day 14, where it dropped significantly to 224.4 V. This pattern

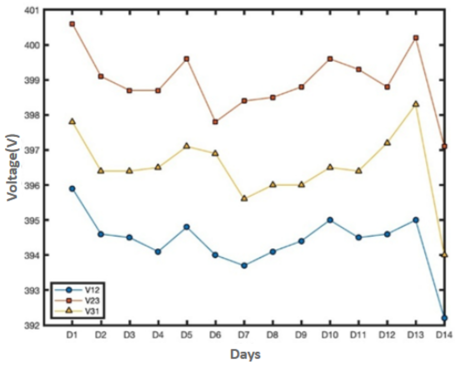

Figure 9. Inter-phase voltage consumption

indicates a voltage imbalance between phases, although still within the acceptable tolerance for a 230 V system.

Table 4. Results of measuring voltage for each phase

AVG Day-n	V1	V2	V3
AVG -D1	227.9	231.9	229.6
AVG -D2	226.7	231.5	229.0
AVG -D3	226.1	231.5	229.1
AVG -D4	227.0	231,0	228.5
AVG -D5	227.4	231.5	229.1
AVG -D6	227.1	231.1	228.8
AVG -D7	227.0	230.5	228.1
AVG -D8	227.2	230.8	228.2
AVG -D9	227.1	231.1	228.3
AVG -D10	227.5	231.4	228.7
AVG -D11	227.4	231.2	228.4
AVG -D12	227.3	231.9	229.1
AVG -D13	226.4	233.0	230.4
AVG -D14	224.4	230.7	228.0

The graph illustrates figure10, the phase voltage measurements (V1, V2, and V3) over a 14-day period. Throughout the observation, V2 consistently recorded the highest voltage, ranging around 230–233 V, while V1 had the lowest, fluctuating between 224.4 V and 228 V. A notable voltage drop in V1 occurred on Day 14, indicating a potential issue or unbalance. V3 showed moderate values between those of V1 and V2. The overall pattern highlights a persistent phase voltage imbalance, although the voltages remained within acceptable operational limits for a 230 V system.

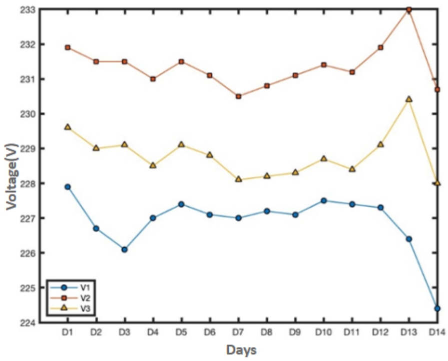

Figure 10. Voltage consumption per phase

4.3 Active power consumption measurement results

Table 5 shows the active power (P) consumption measurements for three phases (P1, P2, and P3) over 14 days. Overall, phase P3 recorded the highest power consumption compared to P1 and P2, indicating an unbalanced load distribution. Significant drops in power consumption were observed on Day 6 (D6), Day 12 (D12), and Day 13 (D13), possibly due to load reduction, power outages, or system disturbances.

Table 5. Active power consumption measurement results

AVG Day-n	P1	P2	P3
AVG -D1	25.7	23.3	45.3
AVG -D2	24.8	22.1	42.8
AVG -D3	24.9	22.2	43.5
AVG -D4	23.2	20.7	40.9
AVG -D5	19.9	17.7	33.8
AVG -D6	8.7	7.8	14.1
AVG -D7	22.6	19.4	38.5
AVG -D8	24.5	21.4	41.8
AVG -D9	24.3	21.8	41.1
AVG -D10	24.5	22.1	43.8
AVG -D11	24.9	22.4	43.6
AVG -D12	2.5	2.6	4.7
AVG -D13	2.8	2.7	4.7
AVG -D14	25.1	22.3	43.2

The graph shows figure 11, the active power consumption (in kW) for three phases P1, P2, and P3 over a 14-day period. It is evident that phase P3 consistently recorded the highest power usage, indicating an unbalanced load across the phases. Notable power drops occurred on Day 6 (D6), Day 12 (D12), and Day 13 (D13), where all three phases experienced significant decreases in consumption. These dips likely indicate load shedding, temporary shutdowns, or power disturbances during those specific days.

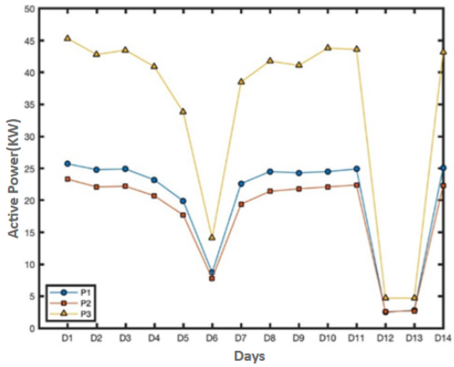

Figure 11. Active Power Consumption

4.4 Reactive power consumption measurement results

Table 6 presents the reactive power consumption measurements for three quarters (Q1, Q2, and Q3). The data shows variations in reactive power consumption across both days and quarters. Certain days, such as AVG-D6, AVG-D12, and AVG-D13, recorded higher consumption in all three quarters, suggesting heavier loads or more intensive electrical activity. In contrast, days like AVG-D7 showed relatively low power consumption.

Table 6. Reactive power consumption measurement results

AVG Day-n	Q1	Q2	Q3
AVG -D1	8.3	8.2	17.5
AVG -D2	8.4	8.0	17.8
AVG -D3	8.5	8.1	17.9
AVG -D4	8.4	7.7	17.2
AVG -D5	8.2	7.7	16.6
AVG -D6	10.8	10.8	20.0
AVG -D7	7.3	7.2	15.8
AVG -D8	8.3	8.1	18.2
AVG -D9	8.6	8.3	18.2
AVG -D10	8.5	8.1	17.2
AVG -D11	8.5	8.2	17.6
AVG -D12	11.1	11.2	20.5
AVG -D13	11.0	11.4	20.5
AVG -D14	8.0	7.9	16.3

The graph displays figure 12, reactive power consumption (in kVAR) across 14 days for three quarters Q1, Q2, and Q3. Quarter Q3 consistently recorded the highest reactive power usage, ranging mostly between 17 and 21 kVAR. In comparison, Q1 and Q2 showed much lower values, generally fluctuating between 7.5 and 11.5 kVAR. Notable peaks in all three quarters occurred on Day 6, Day 12, and Day 13, indicating higher load demands or intensified equipment activity. Conversely, a dip in consumption can be observed on Day 7, suggesting a temporary reduction in reactive power demand during that period.

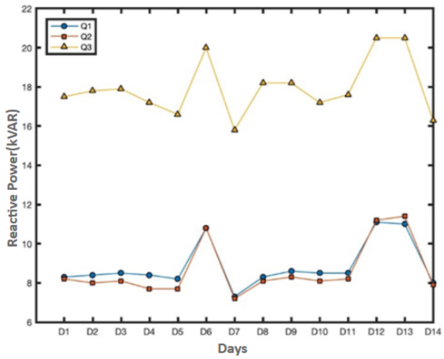

Figure 12. Reactive Power Consumption

4.5 Current consumption measurement results

Table 7 presents the current consumption measurements for the three phases (I1, I2, and I3) over a 14-day period (AVG D1 to D14). The highest current values were consistently recorded in phase I3, with most readings above 190 A, indicating that this phase carries the heaviest load. In contrast, AVG-D12 and D13 showed significantly lower current values across all three phases, possibly suggesting a substantial drop in electrical load or an abnormal.

Table 7. Current consumption measurement results

AVG Day-n	I1	I2	I3
AVG -D1	118.3	106.3	210.6
AVG -D2	116.5	102.5	203.8
AVG -D3	117.3	103.1	206.4
AVG -D4	109.1	96.2	194.7
AVG -D5	96.0	84.6	166.5
AVG -D6	69.9	65.2	119.4
AVG -D7	105.1	90.1	183.2
AVG -D8	113.8	99.2	199.8
AVG -D9	114.6	101.5	198.1
AVG -D10	114.8	102.4	206.5
AVG -D11	116.5	104.0	206.3
AVG -D12	51.1	50.5	93.3
AVG -D13	52.3	51.9	94.5
AVG -D14	117.1	102.3	201.7

The graph displays figure 13, current measurements for three lines labeled I1, I2, and I3 recorded over a 14-day period. Line I3 consistently shows the highest current values, indicating it carries a significantly heavier load compared to I1 and I2. Lines I1 and I2 remain relatively balanced with similar trends, though at lower current levels. A sharp drop in current is evident on Day 6 (D6) and Days 12 to 13 (D12–D13) across all three lines, suggesting a major load reduction, system shutdown, or power interruption. Overall, the pattern indicates that while the system is relatively stable, there is a noticeable load imbalance concentrated on line I3.

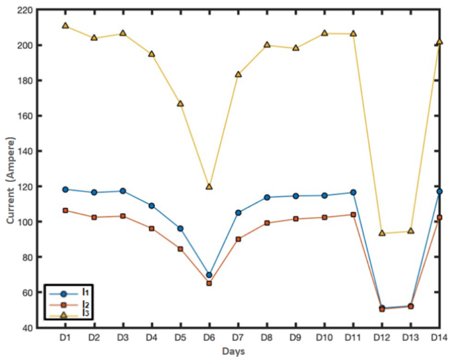

Figure 13. Current consumption

4.6 *Harmonic Simulation Power Filter Design*

4.6.1 *Simulation Scenario Based on Load Flow Analysis*

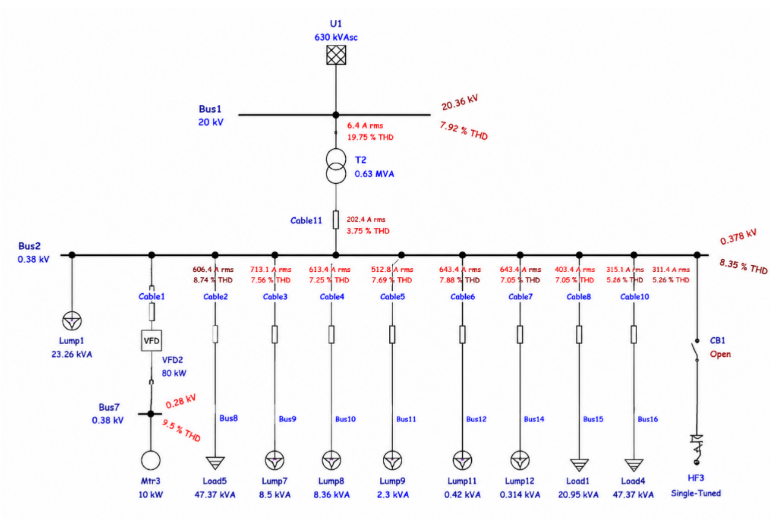

Figure 14. Scenario simulation after load flow analysis

The figure 14, above presents the results of a load flow analysis on a Single Line Diagram using ETAP. Based on the simulation, the system operates at 20.06 kV on the primary side and approximately 0.378 kV on the secondary side of transformer T2 (0.63 MVA), with a voltage drop that remains within acceptable limits. However, there is an indication of power quality disturbance in the form of Total Harmonic Distortion, particularly on the secondary side.

The highest recorded THD is 8.35% at the last several busses, which exceeds the IEEE standard limit (typically 5%). Additionally, the current flowing through some cables is considerable such as 71.3 A in Cable3 and Cable9 indicating heavy loading at those points. HF3 is currently in an open state (inactive), which explains the high THD levels in the system. If the filter is activated, the THD is expected to be reduced. Overall, the power flow in the system runs smoothly, but special attention is needed to address power quality issues caused by high harmonic levels.

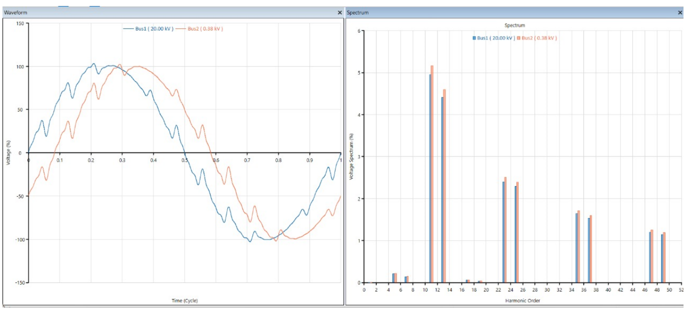

Figure 15. Harmonic simulation spectrum without power filter

The figure 15, above shows the harmonic spectrum analysis of the ETAP system without using a harmonic filter. The graph on the left display voltage waveforms at Bus1 (20 kV) and Bus2 (0.38 kV), where it is evident that Bus2's waveform is significantly more distorted than Bus1's. This indicates power quality issues on the low-voltage side due to nonlinear loads.

The spectrum graph on the right shows dominant harmonic components at the 5th, 7th, 11th, and 13th orders, with harmonic magnitudes exceeding 5% in several cases. This surpasses the IEEE 519 standard, which generally limits total voltage harmonic distortion to below 5%. This condition indicates that the system, without a harmonic filter, suffers from considerable harmonic pollution especially on the load side (Bus2) which can negatively affect electrical equipment performance and overall energy efficiency.

4.6.2 Power Filter Sizing Design

In this simulation, the filter used is a single-tuned filter specifically designed to eliminate dominant harmonics, typically at the 5th and 7th orders. The first step is to calculate the appropriate power filter values.

The single-tuned power filter design was calculated based on the system parameters, including a 115 kW load, 380 V nominal voltage, measured THDv of 8.5%, THDI of 7.92%, and dominant harmonic orders of 5 and 7. The calculation results were verified and adjusted according to the measured data and applicable power quality standards.

a) Calculating the total load current:

$$S = \frac{s}{pf}$$
$$= \frac{115000}{0.9}$$
$$= 127778\ A$$
$$I_{total} = \frac{s}{\sqrt{3}x380}$$
$$= \frac{127778}{\sqrt{3}x380}$$
$$= 194,3\ A$$

b) Calculating harmonic current

$$I_h = THD\ i\ X\ I_{total}$$
$$= \ 0.0792\ x\ 194.3$$
$$\approx \ 15.39\ A$$

assume the 5th and 7th order harmonics contribute 80% of the total,

$$I_{h(5+7)} \approx 12.31A, \qquad I_{h(5)} = I_{h(7)} \approx 6.15A$$

c) Calculating phase voltage

$$V_{ph} = \frac{V_{line}}{\sqrt{3}} = \frac{380}{\sqrt{3}} \approx 219.4V$$

d) Calculate the reactive power if the capacitor value per phase is 6.97 microfarads.

$$Q = 3\ .\ 2\pi\ .\ 50\ .\ 6.97x10^{-6}\ .\ (219.4)^2$$
$$Q = 3\ .\ 314.16\ .\ 6.97 \times 10^{-6}\ .\ 48,133.6\ \approx\ 3\ .\ 10539.6 = [31,619VAR] \approx [31.6kVAR]$$

e) Total filter capacity:
Multiplied by 2 filters (order 5 and 7) to obtain:
Qc = 2 x 31.6 kVar = 63.2 kVAR.

Based on the harmonic analysis, the 5th and 7th harmonic orders were identified as the dominant components. Therefore, a single-tuned passive harmonic filter was selected to reduce these harmonics. The calculated reactive power compensation for each filter was approximately 31.6 kVAR, resulting in a total filter capacity of 63.2 kVAR for the 5th and 7th harmonic filters.

The figure 16, shows the sizing results of a single-tuned power filter in ETAP. This filter is designed to reduce dominant harmonics, particularly the 5th harmonic, which commonly occurs due to the use of nonlinear loads such as VFDs. The resulting capacitance value, C1, is 1393 µF, equivalent to 63.21 kVAR at 0.38 kV. The inductance value, L1, is determined using a reactance of XL1 = 0.0189 Ω, giving L1 = 0.018 H. The quality factor (Q Factor) is set to 1.5, which defines the filter's frequency selectivity.

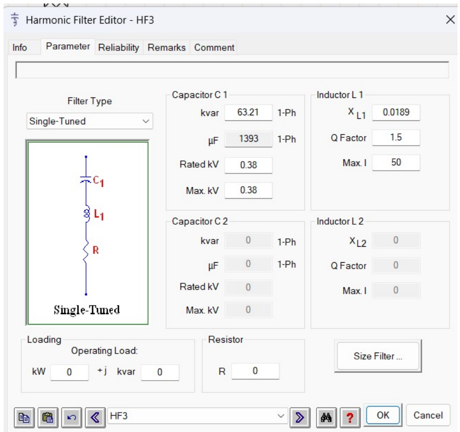

Figure 16. Sizing design power filter

4.6.3 Harmonic Simulation After Power Filter Design

The following figure 17, is a single line diagram of the subnet data distributed for the electricity needs of production machine equipment with a power filter installation design.

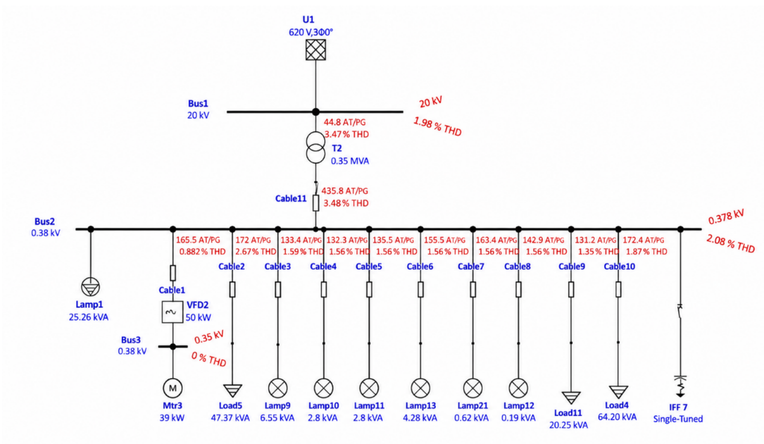

Figure 17. Scenario simulation with power filter

After the installation of a harmonic filter (HF3 – Single-Tuned Filter) in the electrical distribution system based on the ETAP single line diagram, a significant reduction in THD was observed at several critical points in the network. For example, at Bus1 (20 kV), the THD dropped from 7.92% to just 1.98%, and at Bus2 (0.38 kV), the THD decreased from 8.35% to 2.08%.

The filter effectively attenuated low-order harmonics, particularly the 5th and 7th, which are commonly dominant in systems with numerous nonlinear loads such as

VFDs and motors. This reduction was also evident in the main distribution cables, such as Cable11, which recorded a much cleaner harmonic current with only 0.347% THD. With this drop in THD, power quality improves significantly, the system becomes more stable, equipment efficiency increases, and the risks of disturbances and damage caused by harmonics are minimized.

The following figure 18, is a single line diagram spectrum graph after installing a power filter on the existing single line diagram.

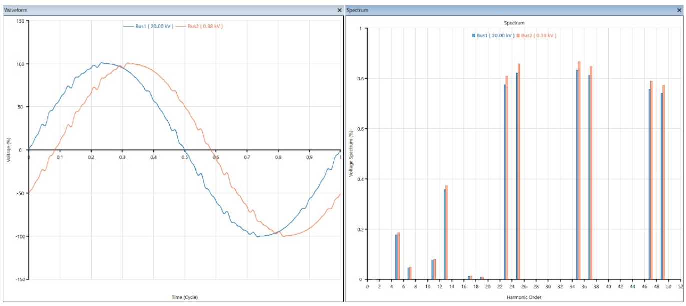

Figure 18. Harmonic simulation spectrum with power filter

After the installation of a single-tuned harmonic filter, the voltage spectrum results in ETAP show a significant reduction in harmonic levels, particularly for the dominant 5th and 7th order harmonics. Previously, as seen in the spectrum without the filter, low-order harmonics (5th, 7th, 11th, and 13th) contributed the most to the THD, reaching over 7% in the low-voltage system (Bus2 0.38 kV). This was due to the presence of nonlinear loads such as Variable Frequency Drives (VFDs) and other electronic equipment.

However, after adding the single-tuned harmonic filter consisting of a 63.21 kVAR capacitor (1393 μF), a 0.0189 Ω inductor, and a Q factor of 1.5 at 0.38 kV a dramatic reduction in harmonic components was observed. The updated spectrum shows that the amplitudes of the 5th and 7th harmonics were almost entirely eliminated, while higher-order harmonics were also reduced to below 1%. As a result, the system's THD dropped from approximately 8.35% to just 2.08% at Bus2, and around 1.98% at the medium-voltage side (Bus1 20 kV), as reflected in the analyzed single line diagram.

4.7 Voltage Analysis of the Voltage Stabilizer System

To address the trend of overvoltage or voltage drops in power quality supplied to production machines, a voltage stabilizer was installed. Voltage levels were recorded during each shift, and the recorded nominal voltages are illustrated in the graph below.

The phase-to-phase voltage graph for May 2025 indicates that the electrical distribution system generally operated under stable and controlled conditions. The three phases—AB, AC, and BC—maintained voltage ranges within a safe operational window, approximately between 378 and 387 Volts. This reflects that, despite daily fluctuations, the phase-to-phase voltages did not experience extreme deviations that could pose risks to electrical equipment.

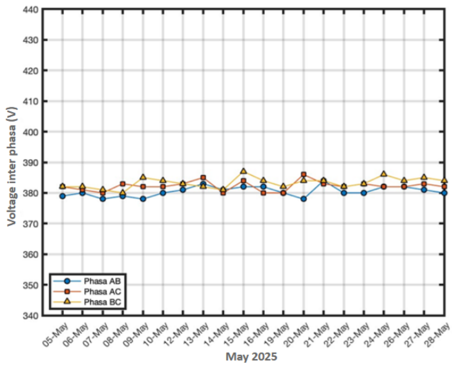

Figure 19. Inter-Phase Output Voltage of the Voltage Stabilizer

Phase BC consistently remained above 382 Volts, demonstrating good stability and likely indicating a strong power supply along that line. Phases AC and AB also showed a tendency to recover quickly after voltage dips, suggesting that the system is capable of maintaining stability in response to load changes.

Moreover, there were no signs of long-term voltage drops or concerning over-voltage/undervoltage trends, indicating that the voltage control mechanisms are functioning effectively. Overall, the phase-to-phase voltage performance during this period reflects good power quality and supports the reliability of the power system as a whole.

4.8 Efficiency of Voltage Stabilizer installation and Tap Changer Adjustment

Machine breakdowns in the industrial sector can cause significant operational and financial losses due to production downtime and reduced output. The following outlines the time-related losses due to machine breakdowns:

Case 1: Occurred on August 1, 2021, and the machine resumed normal operation after the installation of new spare parts on August 15, 2021. The total breakdown duration was 20,880 minutes.

Case 2: Occurred on December 21, 2021, and the machine became operational again after new spare parts were installed on August 6, 2022. The total breakdown duration was 23,040 minutes.

As a response to these incidents, PT XYZ took corrective action by installing a voltage stabilizer and adjusting the transformer tap changer position to level 3. As a result, there have been no further occurrences of damage to electronic equipment such as active line modules and other devices operating with non-linear loads since the implementation of these measures.

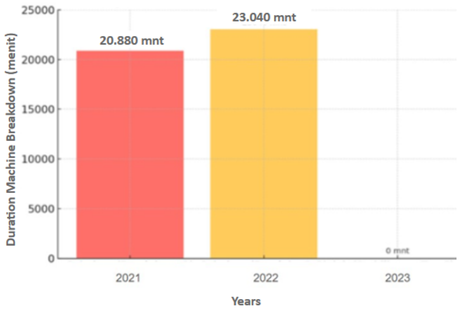

Figure 20. Comparison of engine breakdown time before and after power quality improvement

5. Conclusion

Based on the result, the following conclusions can be drawn:

1. A significant load imbalance among the phases is evident. This imbalance is also reflected in the current graph (I3) figure 20, which tends to be higher than the others, and is accompanied by a simultaneous sharp voltage drop across all phases, both phase-to-phase and phase-to-neutral.
2. A comparison of the single line diagrams before and after the installation of the HF3 harmonic filter shows a substantial improvement in Total Harmonic Distortion (THD) parameters for both voltage and current. Prior to installation, current THD at several points reached high levels, even exceeding 8.35%, while voltage THD at the transformer output side was around 7.92%. After installing the HF3 filter, both voltage and current THD values dropped significantly to below 2% at most distribution points. This demonstrates that the harmonic filter effectively reduces harmonic distortion, resulting in improved power quality, lower risks of overheating and equipment failure, and enhanced overall system efficiency.
3. Following the installation of the voltage stabilizer, the phase-to-phase voltages distributed to the production machines remained within safe limits without any dangerous surges or drops. The AB phase voltage ranged from 378-384 V, AC phase from 380-386 V, and the BC phase being the most stable ranged from 380-387 V. These voltage ranges indicate no significant deviation, reflecting good power quality.
4. In 2021 and 2022, machine breakdown times were relatively high, at 20,880 minutes and 23,040 minutes respectively. However, in 2023, breakdown time dropped dramatically to 0 minutes, indicating that the corrective measures implemented were highly successful in eliminating machine disruptions.

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