Investigation and Mitigation of Harmonic Distortion and Parallel Resonance in an Industrial Power System Using ETAP

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ABSTRACT

Harmonics, primarily generated by non-linear loads, can lead to voltage distortion, equipment overheating, and reduced system efficiency. This project analyzes harmonic distortion in the electrical distribution network of a cement plant using ETAP software. A detailed Single Line Diagram (SLD) was modeled, and harmonic load flow analysis was conducted to evaluate Total Harmonic Distortion (THD) at key bus locations. A frequency scan was performed to identify parallel resonance conditions, which were mitigated by installing series reactors with capacitor banks. Additionally, passive filters were designed to reduce dominant harmonic components and ensure compliance with IEEE 519 standards. The study demonstrates a significant improvement in power quality and highlights ETAP as an effective tool for harmonic analysis and mitigation in industrial systems.

Keywords: harmonics, total harmonic distortion, capacitor bank, resonance, ETAP

INTRODUCTION

The cement plant draws its primary power from a nearby 66 kV grid substation through a 2.8 km long, 630 sq.mm single-core underground cable, with a contracted demand of 12 MVA. Power is imported via two 66/11.5 kV, 12.5/15 MVA transformers, with a % impedance of 8.22 and a vector group of Dyn11. The star points of the transformers and the Waste Heat Recovery System (WHRS) generator are grounded through Neutral Grounding Resistors (NGR) with a current limit of 100 A. The plant operates various non-linear loads such as motors, crushers, and mills, which are common in cement production. In cement plant, operators often encounter unexplained issues related to voltage instability and overheating of electrical equipment, especially in areas with high-power-demand loads. One frequent cause of these disturbances is the interaction between the plant's non-linear loads and capacitor banks used for power factor correction. This interaction can lead to amplified voltage fluctuations, causing equipment like motors and transformers to overheat, malfunction, or even fail prematurely. Additionally, plant operators may notice that protective devices like relays and circuit breakers sometimes trip unnecessarily or fail to operate correctly, resulting in unexpected shutdowns and increased downtime. These problems typically go unnoticed until they cause significant operational disruptions.

The underlying cause of these issues is the harmonic amplification due to the interaction between the plant's electrical loads and the capacitor banks. Addressing these disturbances is critical to maintaining equipment reliability, improving system stability, and reducing operational disruptions in cement plant operations.

Harmonics Study

Harmonic analysis was conducted to evaluate power quality disturbances in the industrial electrical distribution network caused by nonlinear loads and reactive compensation devices. The study focused on identifying the magnitude and propagation of harmonic distortion as well as potential resonance conditions that may adversely affect equipment performance, system efficiency, and protection coordination. All simulations were performed using ETAP software, employing harmonic load flow and frequency scan techniques in accordance with IEEE harmonic assessment guidelines [1].

Harmonics Overview

Harmonics are voltage or current components whose frequencies are integer multiples of the fundamental supply frequency (50 Hz in India). These components are primarily generated by nonlinear loads such as variable

frequency drives, rectifiers, and power electronic converters, which draw non-sinusoidal currents even under sinusoidal voltage conditions.

The presence of harmonics can lead to transformer overheating, increased losses in rotating machines, capacitor stress, nuisance tripping of protective devices, and possible resonance amplification within the network.

To quantify waveform distortion, Total Harmonic Distortion (THD) is used as defined in IEEE Std. 519-2014 [1]. The current THD is calculated using (1), while voltage distortion is evaluated using (2). These indices were computed at multiple buses to identify critical locations where distortion exceeded recommended limits.

To quantify the harmonic content in a waveform, the IEEE 519-2014 standard defines Total Harmonic Distortion (THD) as follows:

$$THD\_I = \frac{\sqrt{(I_2^2 + I_3^2 + \dots + I_n^2)}}{I_1} \times 100\% \qquad (1)$$

Where:

I_1 = RMS value of the fundamental current

$I_2, I_3, \dots, I_n$ = RMS values of harmonic current components

$$THD\_V = \frac{\sqrt{(V_2^2 + V_3^2 + \dots + V_n^2)}}{V_1} \times 100\% \qquad (2)$$

Where:

V_1 = RMS value of the fundamental voltage

$V_2, V_3, \dots, V_n$ = RMS values of harmonic voltage components

Total Harmonic Distortion (THD) represents the degree of waveform distortion caused by harmonic components relative to the fundamental frequency. It serves as a key indicator of power quality and is widely used to assess the impact of nonlinear loads on electrical networks.

In the studied industrial system, multiple VFD-driven loads, including raw mill drives, crusher motors, and process fans, act as dominant harmonic sources.

These nonlinear devices inject harmonic currents into the distribution network, leading to voltage distortion, additional losses, and potential resonance interactions with reactive compensation equipment.

A harmonic load flow analysis was therefore carried out using ETAP to evaluate the magnitude and propagation of harmonic currents and voltages across various buses.

The calculated THD values were compared against the limits recommended by IEEE Std. 519-2014 to identify critical buses requiring mitigation.

The key objectives of the THD assessment included:

• Measurement of voltage and current THD at major PCC locations

• Identification of buses exceeding IEEE harmonic limits

• Evaluation of harmonic propagation and accumulation within the network

• Supporting the design of passive filtering and resonance mitigation strategies

Resonance Conditions in Industrial Networks

Resonance in an electrical power system occurs when the effective inductive reactance of the network equals the capacitive reactance at a specific frequency, resulting in significant amplification of harmonic voltage or current. In industrial distribution systems incorporating power factor correction capacitors, parallel resonance is particularly critical because it may cause excessive voltage magnification and overstressing of capacitor banks.

The resonance frequency is determined using (3). If this frequency coincides with dominant harmonic orders such as the 5th or 7th, severe harmonic amplification, increased equipment losses, and protection maloperation may occur. Consequently, resonance assessment is essential for ensuring reliable operation of industrial power systems with nonlinear loads and reactive compensation.

The parallel resonance frequency is expressed as:

$$fr = \frac{1}{(2\pi\sqrt{(L*C)})} \qquad (3)$$

Where:

fr = Resonant frequency (Hz)

L = Equivalent inductance (H)

C = Capacitance of the capacitor bank (F)

Parallel resonance can lead to several adverse effects, including:

• Overstressing and premature failure of capacitor banks

• Voltage magnification at harmonic frequencies

• Nuisance tripping of protective relays and circuit breakers

• Increased harmonic distortion across the network

In this study, frequency scan analysis was performed at buses containing capacitor banks to identify resonance peaks using impedance versus frequency characteristics obtained from ETAP. The analysis enabled detection of critical resonance conditions and supported the selection of appropriate mitigation measures such as detuned filtering and capacitor bank tuning.

METHODOLOGY

The harmonic study was performed in ETAP using the following structured approach:

1. Model Development: A comprehensive Single Line Diagram (SLD) of the cement plant was created in ETAP, incorporating all major buses, power transformers, motors, VFD loads, capacitor banks, and the grid connection. Accurate modeling of impedances, load profiles, and grounding was ensured.

2. Non-linear Load Identification: All significant non-linear loads such as variable frequency drives, converters, and inverters were identified and modeled with their respective harmonic current spectra based on equipment datasheets or typical harmonic profiles as per IEEE 519.

3. Harmonic Load Flow Analysis: The Harmonic Load Flow module was used to compute the voltage and current harmonics across the network. Total Harmonic Distortion (THD) values were evaluated at multiple PCCs and critical buses to identify locations with excessive distortion.

4. Frequency Scan Analysis: For buses equipped with capacitor banks, ETAP's Frequency Scan function was utilized to sweep the system impedance over a wide frequency range (0 Hz to several kHz). This helped identify parallel resonance frequencies by detecting peaks in bus impedance.

5. Standard Comparison: All observed harmonic distortion levels were compared against the allowable limits specified in IEEE 519-2014. This allowed the identification of non-compliant locations requiring corrective measures.

6. Result Interpretation and Mitigation Planning: Based on the analysis results, causes of observed power quality issues were correlated with field symptoms reported by plant personnel. Mitigation strategies, including detuned reactors and passive filters, were proposed and evaluated in ETAP.

RESULTS AND SUGGESTION

Suggestion-01:

At Load Centre-01 bus, located upstream near the transformer, harmonic analysis revealed that the current Total Harmonic Distortion (THD) exceeded acceptable limits. The measured THD at this location was 22.18%, significantly higher than the permissible limits defined by IEEE 519 for systems below 69 kV. The excessive current THD at Load Centre-01 bus is primarily attributed to the presence of multiple VFD-based drives connected to the crusher and auxiliary motor loads. The relatively low short-circuit strength at the bus ($I_{sc}/I_L = 24$) increases system harmonic sensitivity, resulting in amplified harmonic current distortion and higher thermal stress on connected cables and transformers.

Further analysis showed that the 5th harmonic was the dominant contributor to the distortion. Additionally, the harmonic current flowing through the connected cable was beyond its thermal and insulation limits, potentially leading to overheating, increased losses, and reduced cable lifespan. at Load Centre-01 bus. The impedance characteristics of the upstream network allowed the 5th harmonic current to propagate toward the transformer, increasing copper losses and causing additional voltage distortion at adjacent buses. This indicates that the harmonic problem was not localized but had the potential to affect upstream equipment reliability.

I_{SC} = 28000 A

I_L = 1185 A

So I_{SC}/I_L =24, so the current THD should be less than 8% as per IEEE 519-2014, but it is 22.18%.

Bus ID	Current THD (%)	Voltage THD (%)	IEEE 519 Status	Technical Observation
Load Centre-01	**22.18**	**2.96**	**Severe violation**	Dominant 5th harmonic source; filter installation required
Load Centre-04	1.61	0.685	Within limit	Normal harmonic level
Load Centre-03	1.04	0.575	Within limit	Electrically stable bus
P.H, Kiln & Cooler Bus	5.95	0.486	Near limit	Moderate VFD harmonic contribution
Cement Mill HT Bus	3.92	0.458	Within limit	Acceptable distortion
Load Centre-05	0.982	0.239	Within limit	Very low distortion
Load Centre-06	1.15	0.248	Within limit	Stiff bus with minimal harmonic propagation

Raw Mill HT Bus	8.07	1.78	Critical	High nonlinear loading; resonance risk
Load Centre-02	1.73	1.32	Within limit	Slight voltage distortion but acceptable

Table 1: THD level observed at different buses

The results indicate that harmonic distortion is highly localized, with Load Centre-01 acting as the primary harmonic injection point within the distribution network. Although voltage THD at Load Centre-01 bus remains within IEEE-519 limits, the current THD is significantly high due to dominant nonlinear load current injection. The relatively low voltage distortion indicates a stiff upstream system; however, excessive harmonic current may still lead to overheating, equipment stress, and potential resonance risk, thereby necessitating harmonic mitigation.

Mitigation Strategy:

A single-tuned passive filter tuned to the 5th harmonic (250 Hz) was selected due to the clear dominance of the 5th harmonic component and its cost-effective implementation compared to active filtering solutions. The filter provides a low-impedance path for harmonic currents while simultaneously improving reactive power compensation at the bus. Passive filtering was preferred over active filtering due to lower installation cost, reduced maintenance requirements, and predictable harmonic spectrum in cement plant drives.
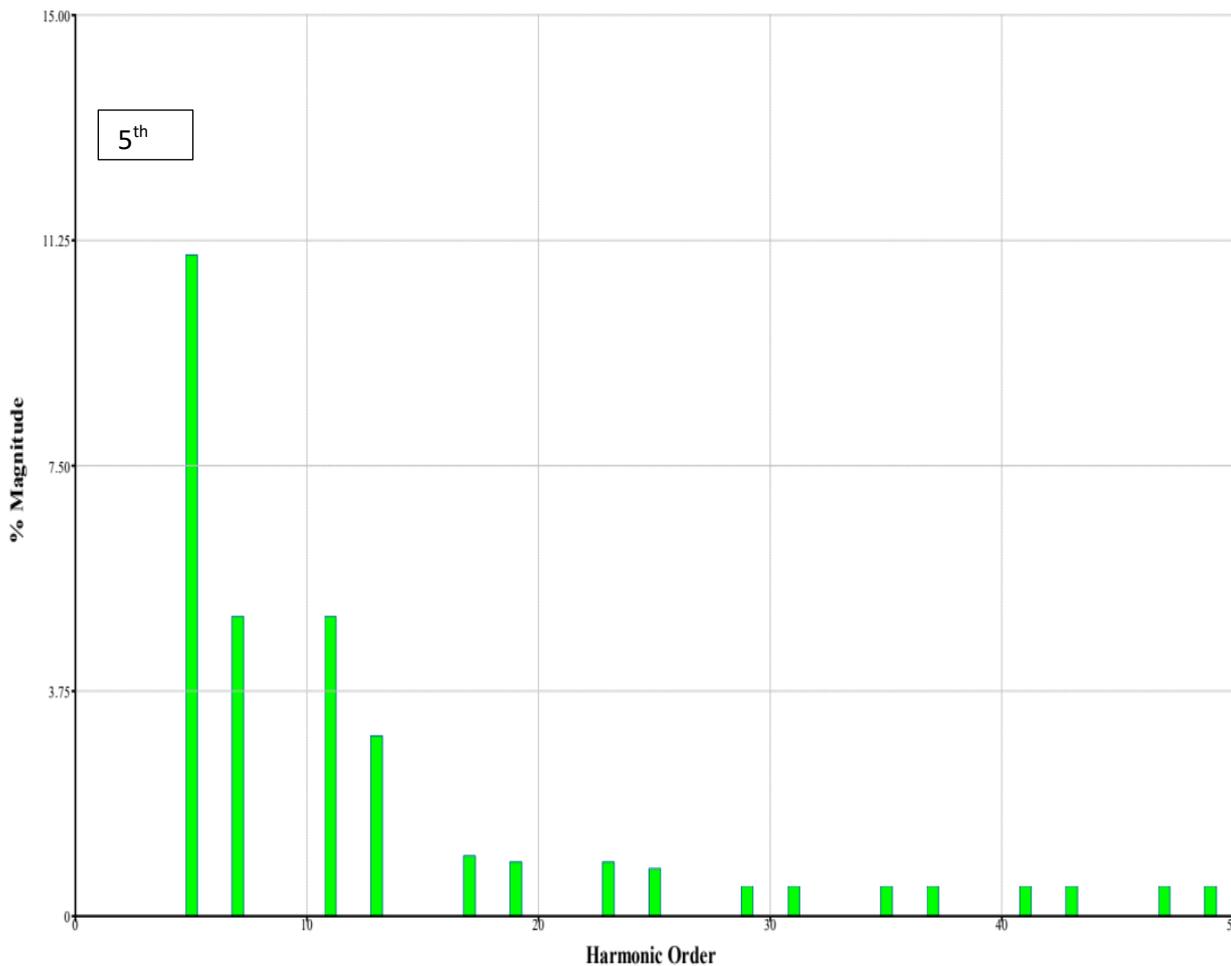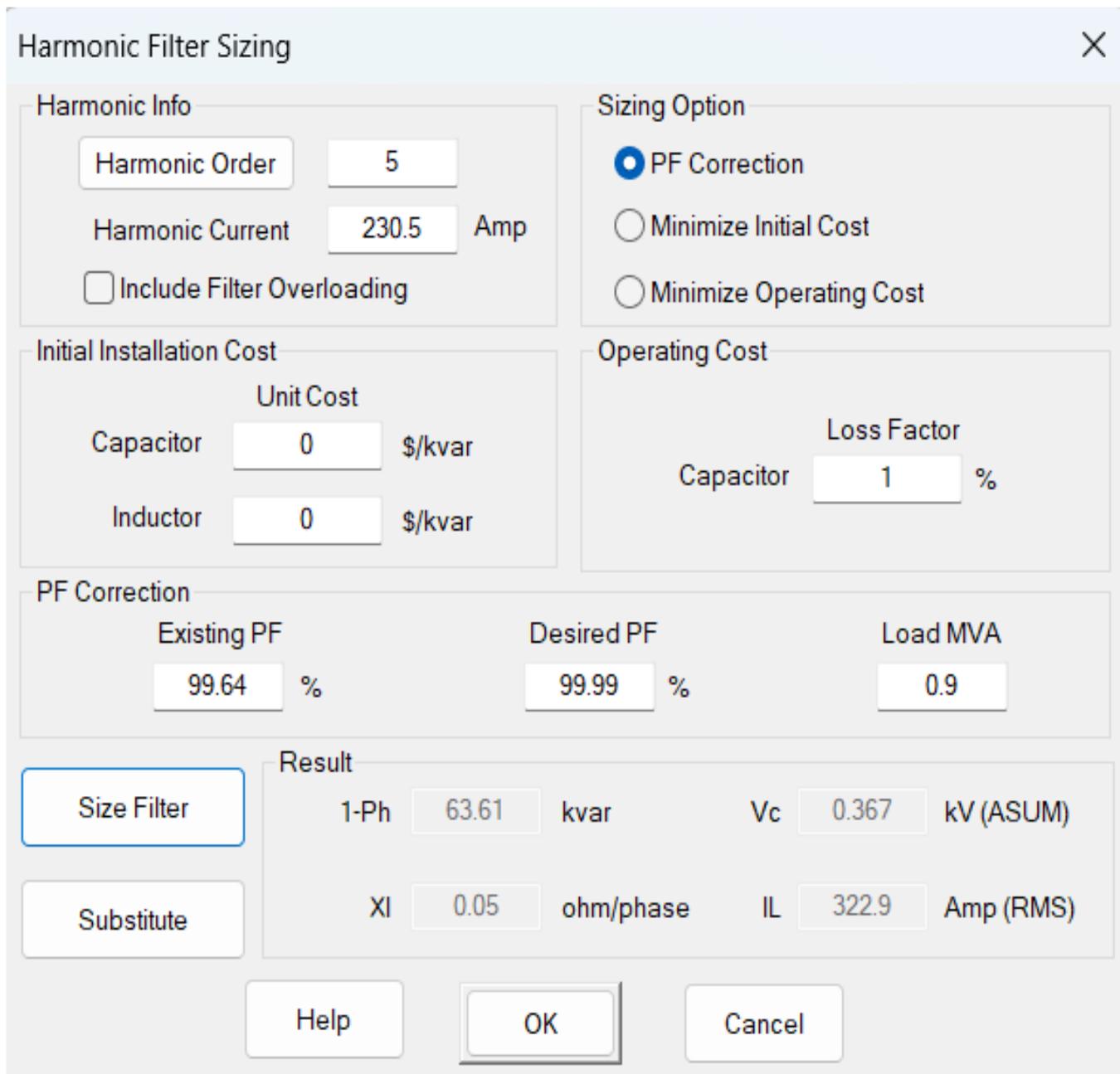

Figure 1: Harmonics spectrum

Harmonic Filter Sizing   ✕

Harmonic Info

| Harmonic Order | 5 |
| Harmonic Current | 230.5 | Amp |

☐ Include Filter Overloading

Sizing Option

◉ PF Correction
○ Minimize Initial Cost
○ Minimize Operating Cost

Initial Installation Cost

Unit Cost

Capacitor   0 $/kvar
Inductor   0 $/kvar

Operating Cost

Loss Factor

Capacitor   1   %

PF Correction

Existing PF   Desired PF   Load MVA
99.64 %   99.99 %   0.9

Result

| Size Filter | 1-Ph | 63.61 | kvar | Vc | 0.367 | kV (ASUM) |
| Substitute | XI | 0.05 | ohm/phase | IL | 322.9 | Amp (RMS) |

Help   OK   Cancel

Figure 2: Harmonics filter sizing

Figure 1 The harmonic spectrum indicates dominance of the 5th harmonic component, which is typical in industrial systems employing 6-pulse rectifier based variable frequency drives. Characteristic harmonics generated by such converters follow the order $h = 6k \pm 1$, making the 5th harmonic the lowest and most significant component.

Additionally, the negative sequence nature of the 5th harmonic contributes to increased motor heating and losses. The presence of capacitor banks in the network further increases the possibility of parallel resonance near the 5th harmonic frequency, resulting in amplification of distortion at Load Centre-01.

After installing the filter, the current THD at the bus reduced from 22.18% to 6.83%, bringing the harmonic distortion within acceptable IEEE 519 limits. The post-mitigation results confirm the effectiveness of the filter, with THD reduced below IEEE 519 recommended limits. Additionally, no adverse resonance amplification was observed in the impedance scan, validating the stability of the proposed mitigation strategy. This solution has improved power quality, reduced the thermal stress on cables and transformers, and ensured regulatory compliance.
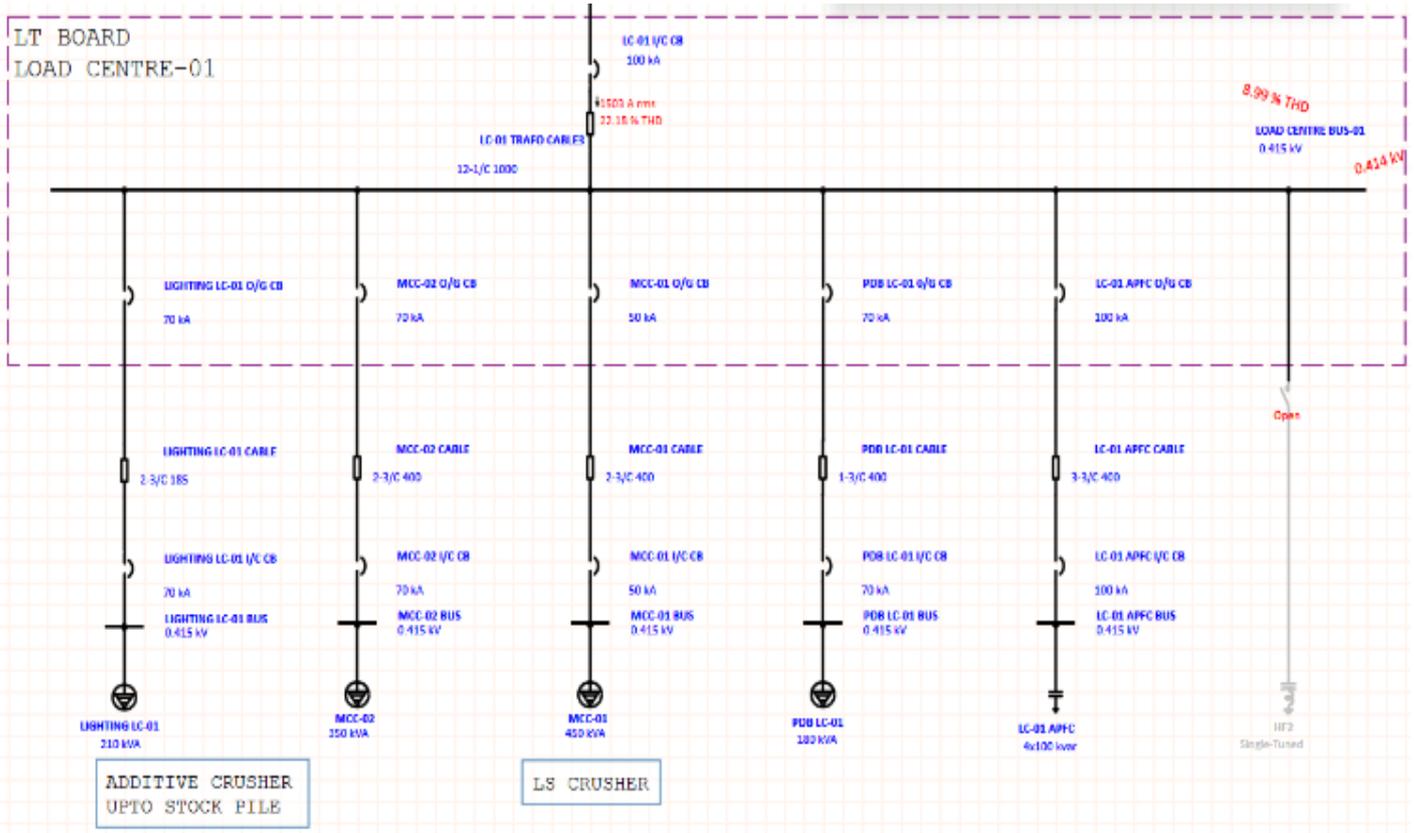
Figure 3: THD level at Load Centre-01 bus before mitigation

Figure 4: THD level at Load Centre-01 bus after mitigation

Bus Location	THD-I Before (%)	THD-I After (%)	IEEE 519 Limit	Compliance
Load Centre-01	22.18	6.83	8%	Achieved

Table 2: THD level at Load Centre 01 bus

Importantly, the addition of the filter did not introduce any new parallel resonance issues. This is because the system's parallel resonance frequency was located near the 3rd harmonic (~150 Hz), and 3rd harmonic components are negligible in the system due to the absence of their sources.

Harmonic analysis was also performed at other major buses in the plant. Both current and voltage THD levels were found to be within the permissible limits specified by IEEE 519-2014. No significant harmonic distortion or resonance issues were observed at these locations, so no additional mitigation measures were required.

From a practical perspective, passive filters offer lower installation and maintenance costs compared to active harmonic mitigation techniques, making them suitable for cement industry applications where harmonic sources are predictable and dominant harmonic orders are well defined.

Suggestion-02:

Parallel Resonance at Load Centre-02 Bus:During the harmonic analysis at Load Centre-02 bus, a parallel resonance condition was detected due to the connection of a 600 kVAR capacitor bank. The system's Thevenin impedance at the bus was calculated using the following formula:

$$Z_{th} = \frac{V}{(\sqrt{3} \times Isc)} \qquad (4)$$

$$Z_{th} = \frac{415}{(\sqrt{3} \times 44990)}$$

$$Z_{th} = 0.0053 \ \Omega$$

where

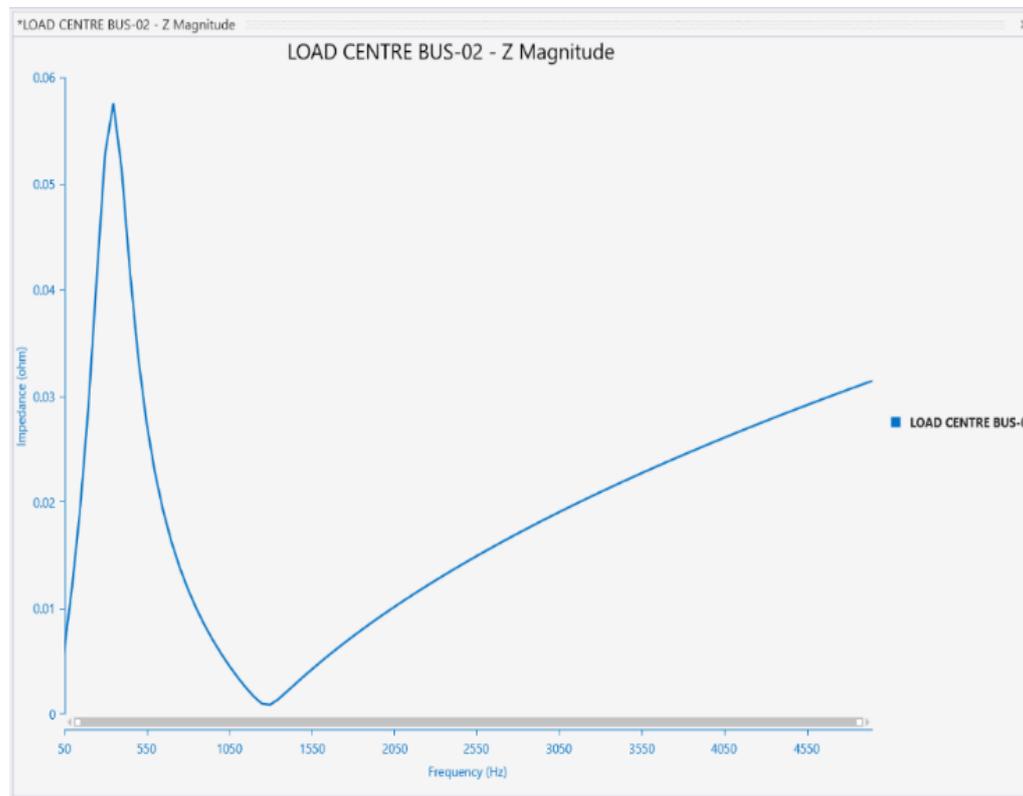Z_{th}= Thevenin equivalent impedance at the bus (Ω)

V= line-to-line voltage (V)

I_{sc}= short-circuit current (A)

voltage (V)

I_{sc}= short-circuit current (A)

Figure 5: Parallel Resonance condition

The frequency scan results indicated a resonance peak near the 7th harmonic frequency (≈350 Hz), where the system impedance increased to approximately 0.057 Ω. The Thevenin impedance at the bus was calculated as 0.0053 Ω, resulting in a resonance amplification factor exceeding 10. According to industrial harmonic mitigation practices, such impedance magnification indicates a high risk of harmonic voltage amplification even when THD levels remain within IEEE 519 limits.

The resonance condition was primarily caused by the interaction between the 600 kVAR capacitor bank and the upstream system inductance. Although measured THD values were acceptable, sustained operation under this condition could lead to capacitor overstressing, insulation degradation, and possible protection maloperation. Therefore, frequency scan analysis is essential in addition to THD assessment when capacitor banks are present in industrial distribution systems.

To mitigate this issue, a detuned reactor was installed in series with the capacitor bank. The original capacitive reactance was calculated as Xc=0.287 Ω. A 7% detuning factor was selected, resulting in an inductive reactance

of XL=0.0179 Ω. The addition of this series inductance shifted the resonance frequency from the 7th harmonic to approximately the 3rd harmonic (≈150 Hz), where harmonic content in the system is negligible.

This detuning strategy successfully eliminated the resonance risk while preserving the reactive power compensation benefits of the capacitor bank without introducing significant additional losses or cost.

CONCLUSION

This research addressed key power quality issues in an industrial cement plant by conducting a detailed harmonic analysis using ETAP software. The study focused on identifying and mitigating Total Harmonic Distortion (THD) and parallel resonance conditions that can adversely affect equipment performance and system stability. At one major load center, excessive current harmonics were identified and mitigated using a passive filter tuned to the dominant harmonic frequency. The filter successfully reduced distortion levels and improved overall power quality without introducing new resonance risks, as the system's resonance frequency remained in a safe range.

Another critical observation was a parallel resonance condition caused by the interaction of a capacitor bank with the system impedance. Though THD levels were within limits, the resonance risk was mitigated by detuning the capacitor bank with a series reactor, effectively shifting the resonance point to a non-problematic harmonic.

Harmonic assessments at other buses showed compliance with IEEE 519 standards, confirming that no further mitigation was necessary. The results emphasize the value of detailed harmonic studies in identifying hidden power quality challenges and implementing cost-effective solutions that enhance system reliability and longevity.

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