Advanced Harmonic Analysis in Industrial Power Systems: Its Impact on Enhancing Power Quality and System Performance

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Abstract:

This paper presents an advanced harmonic analysis of industrial power systems, focusing on its impact on enhancing power quality and system performance. The study investigates the harmonic distortions caused by nonlinear loads, particularly those introduced by Variable Frequency Drives (VFDs), in a manufacturing plant. Measurements of key electrical parameters, such as voltage, current, and Total Harmonic Distortion (THD), were recorded and analysed. The results reveal significant harmonic distortion levels, exceeding industry standards, which can lead to reduced equipment efficiency and potential damage. By adhering to IEEE 519 guidelines and implementing harmonic mitigation strategies, such as filters and power factor correction, the paper demonstrates how power quality can be improved. The findings provide a foundation for future simulation and optimization efforts aimed at reducing harmonic distortion and enhancing system performance.

Keywords: Total Harmonic Distortion (THD), Harmonic Analysis, Power Quality, Industrial Power Systems, Current Distortion.

Introduction:

The use of alternating current (AC) circuits in electrical power systems has been a foundational practice for decades. Historically, the primary loads in these systems were constant power, constant impedance, and constant current devices, which resulted in nearly pure sinusoidal voltage and current waveforms. However, with the advancement of modern industrial technologies, this is no longer the case. The widespread use of nonlinear and time-varying devices has introduced significant distortions in both voltage and current waveforms. As a result, both electric utilities and end users are increasingly concerned about the degradation of power quality[1-3].

Power quality refers to the stability and consistency of electrical parameters, including voltage, current, and frequency, within defined limits that allow equipment to operate without compromising performance or reducing its lifespan. The Institute of Electrical and Electronics Engineers (IEEE) defines power quality in IEEE Standard 1100 as the ability to power and ground sensitive electronic equipment in a manner suitable for its proper function[4-5]. In simpler terms, power quality problems occur when deviations in voltage, current, or frequency lead to equipment malfunction or failure.

Power quality issues are a growing concern in industrial settings, where the operation of critical devices ranging from motors and transformers to computers and communication equipment—can be severely impacted by poor power quality. As industries increasingly rely on power converters and other nonlinear loads, the presence of harmonics in the electrical system becomes a significant challenge[6,11]. Harmonics, which are voltage or current waveforms with frequencies that are integer multiples of the fundamental frequency, are one of the primary sources of power quality problems in industrial power systems.

To address these challenges, standards like IEEE 519 have been implemented to regulate harmonics in electrical systems. First issued in 1991 and revised in 1992, IEEE 519 provides guidelines for limiting harmonic distortion, recommending a 5% voltage distortion limit for systems below 69 kV and specifying current distortion limits between 2.5% and 20%, depending on system voltage and customer size. These standards are crucial for maintaining power quality and ensuring the efficient operation of industrial power systems.[7-8]

This paper focuses on the role of harmonic analysis in industrial power systems and its impact on improving power quality. By understanding and mitigating harmonics, industries can enhance system performance, reduce equipment failure, and ensure compliance with established power quality standards.

Description of the Industrial Plant and Power Network:

The plant under study is a manufacturing unit specializing in the production of steam-cured sand-lime bricks and paving blocks. The primary operations within the plant are driven by electric motors, which typically operate on short, periodic duty cycles, necessitating frequent switching on and off. In addition to conventional motor operations, some motors are equipped with Variable Frequency Drives (VFDs) to enhance control and efficiency. Currently, one VFD-assisted motor is in use, specifically for operating the presses.

The plant's main electrical supply is provided by the Maharashtra State Electricity Distribution Company Limited (MSEDCL) through a 250 kVA transformer. During periods of load shedding or when additional power is required, the plant utilizes a backup generator (DG) with a capacity of 125 kVA.

A Single Line Diagram (SLD) provided in the following section illustrates the overall configuration of the plant's electrical power system, detailing the integration of both grid and backup power sources.

Measurement and Results:

The electrical parameters of the plant's power system are continuously monitored using the YOKOGAWA CW240 Clamp-on meter. This device is capable of recording extensive data at specified intervals. For this study, data was collected at one-minute intervals, providing detailed insights into the plant's power consumption and quality.

The key parameters recorded include:

- Voltage (V)
- Current (A)
- Active Power (kW)
- Reactive Power (kVAR)
- Apparent Power (kVA)
- Power Factor
- Frequency (Hz)
- Harmonic Distortion (THD)

These measurements are crucial for assessing the plant's power quality, identifying harmonic distortions, and ensuring the efficient operation of electrical equipment.[9-10]

The same data is plotted in the form of various graphs, providing a visual representation of the trends and patterns over time. These plots illustrate the variations in voltage, current, power factors, harmonic levels, and other key parameters, facilitating a deeper understanding of the power quality issues in the plant.

To ensure data collection, the following events were conducted for measurements:

Day 1:

- **Event 1 (16:30 Hrs – 16:55 Hrs):**

  Transformer supply with capacitor bank and Variable Frequency Drive (VFD). After 16:55 Hrs, capacitors are progressively reduced one by one.

- **Event 2 (17:10 Hrs – 20:50 Hrs):**

  Transformer supply without capacitor bank but with VFD.

- **Event 3 (20:50 Hrs – 6:00 Hrs):**

  Transformer supply without capacitor bank and without VFD.

Day 2:

- **Event 1 (20:15 Hrs – 21:05 Hrs):**

  Diesel Generator (DG) supply with 100% lighting load.

- **Event 2 (21:05 Hrs – 22:10 Hrs):**

  Transformer supply with 50% lighting load.

- **Event 3 (22:10 Hrs – 22:35 Hrs):**

  Transformer supply with 100% lighting load.

- **Event 4 (22:35 Hrs – 23:05 Hrs):**

  Transformer supply with 50% lighting load.

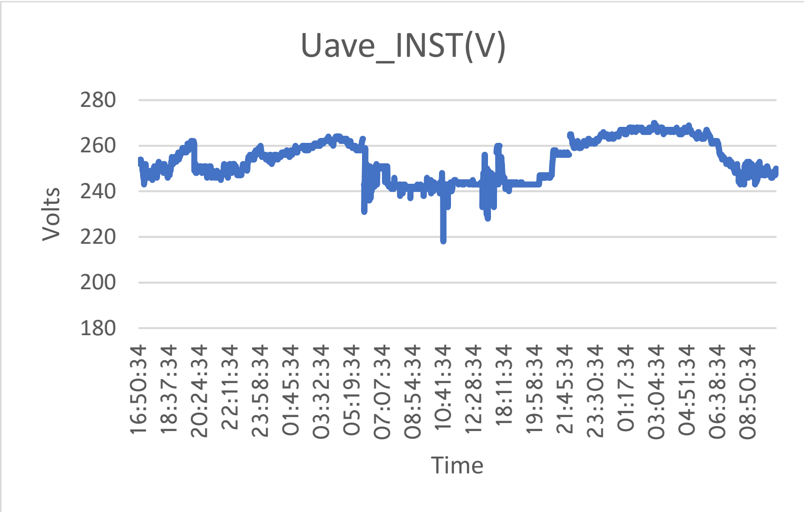

Fig. 1: Voltage Variation Over Time

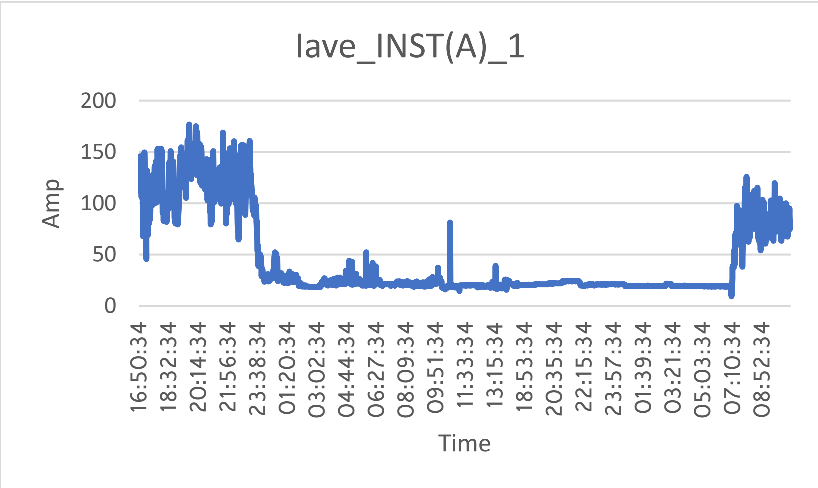

Fig. 2: Current Variation Over Time

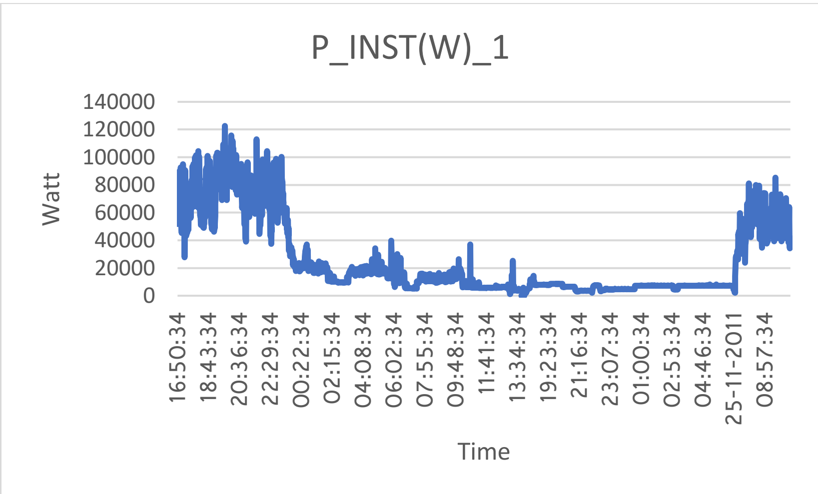

Fig. 3: Active Power (kW) Variation Over Time

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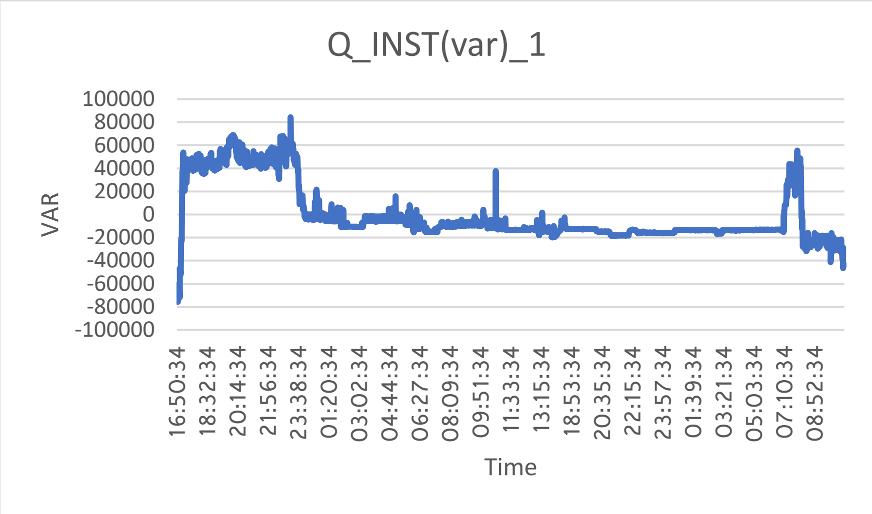

Fig. 4: Reactive Power (kVAR) Over Time

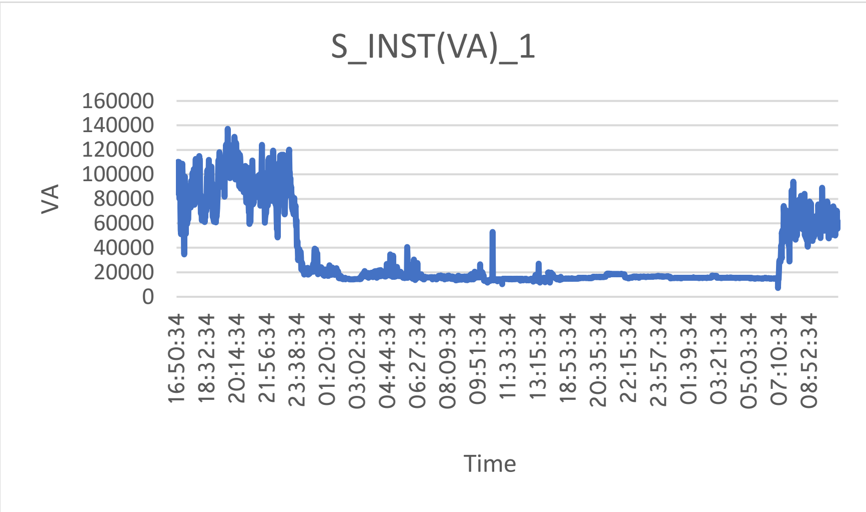

Fig. 5: Apparent Power (kVA) Variation Over Time

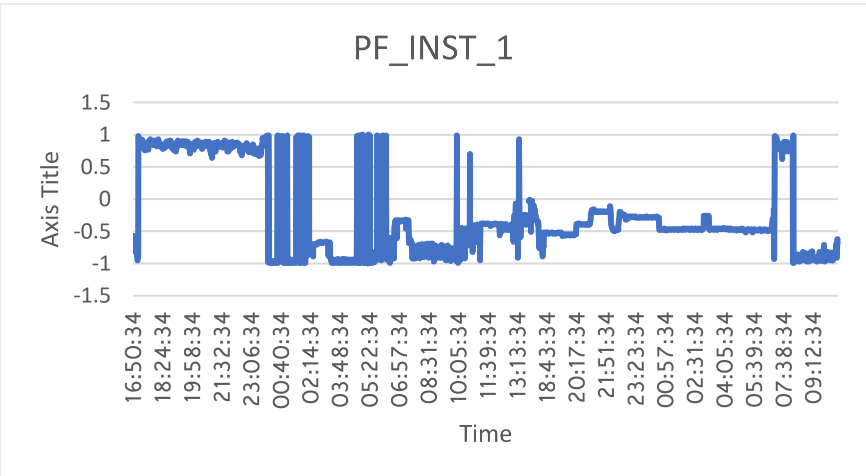

Fig. 6: Power Factor Variation Over Time

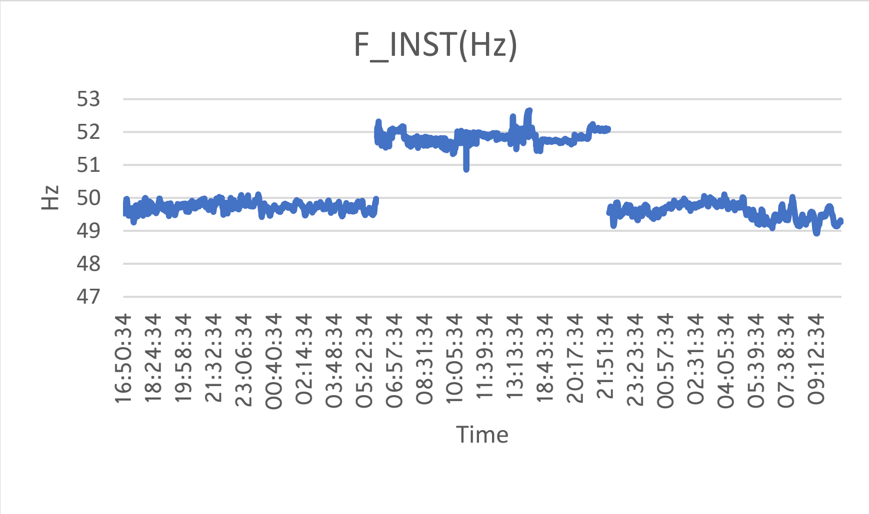

Fig. 7: Frequency (Hz) Fluctuation Over Time

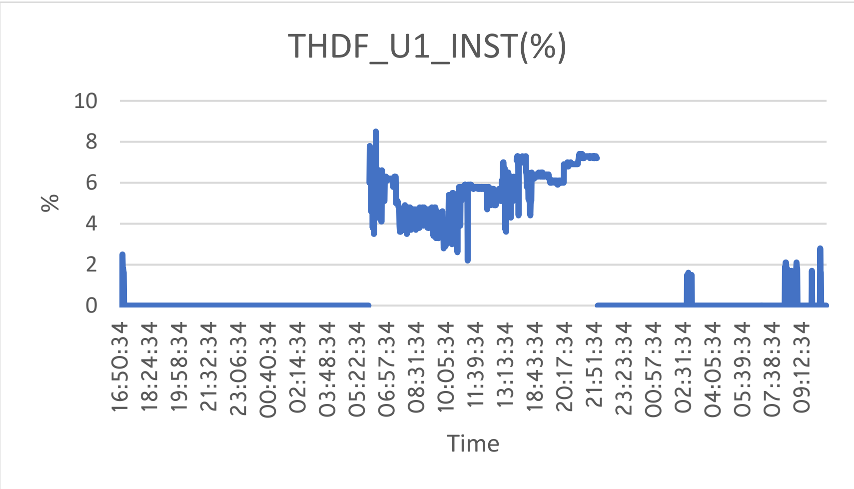

Fig. 8: Total Harmonic Distortion (THD) for Voltage phase 1

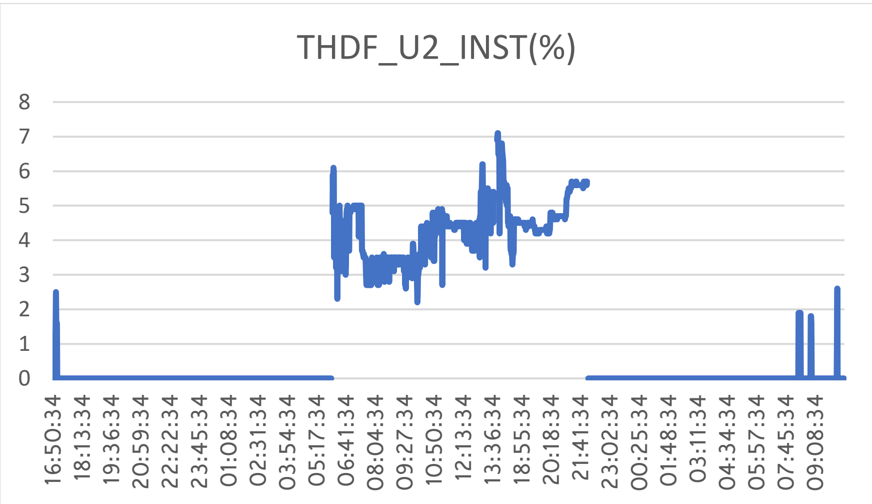

Fig. 9: Total Harmonic Distortion (THD) for Voltage phase 2

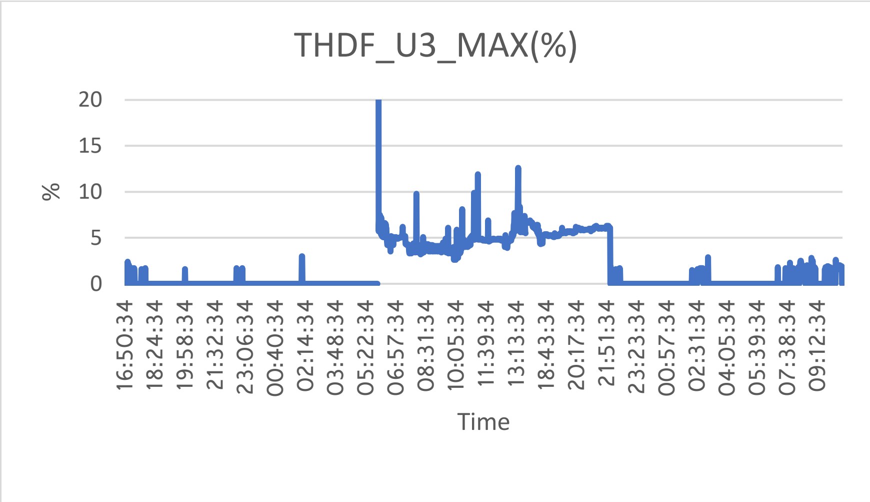

Fig.10: Total Harmonic Distortion (THD) for Voltage phase 3

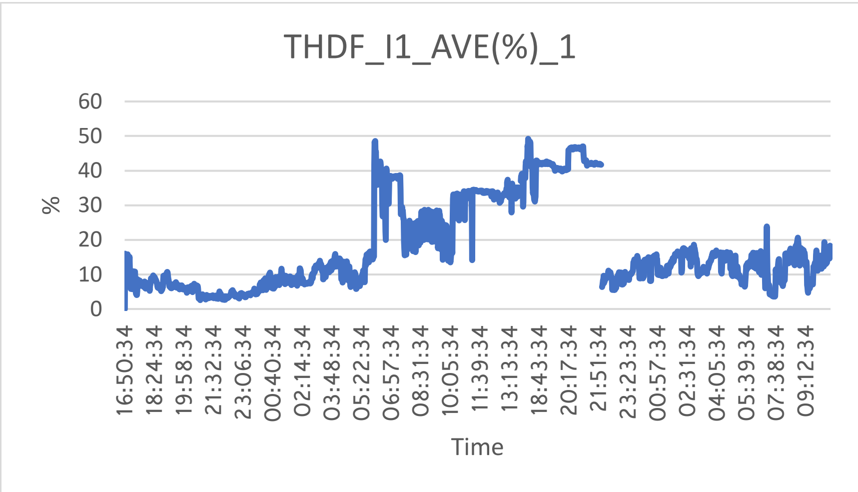

Fig. 11: Total Harmonic Distortion (THD) for Current phase 1

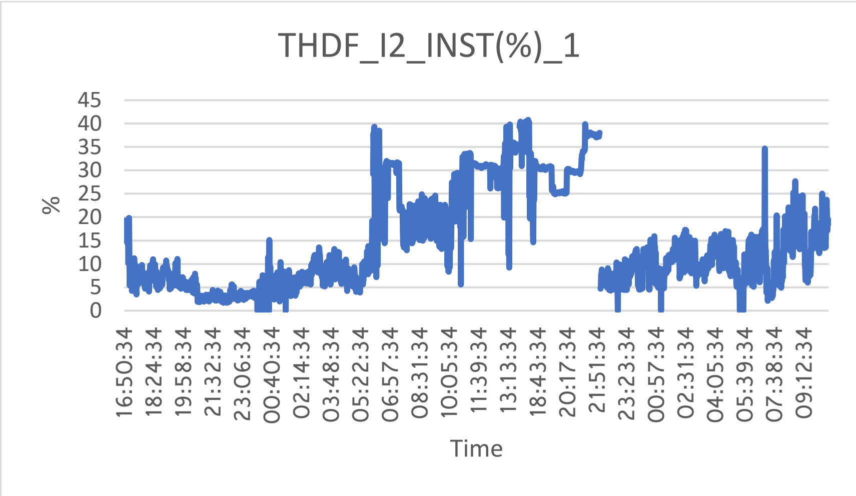

Fig. 12: Total Harmonic Distortion (THD) for Current phase 2

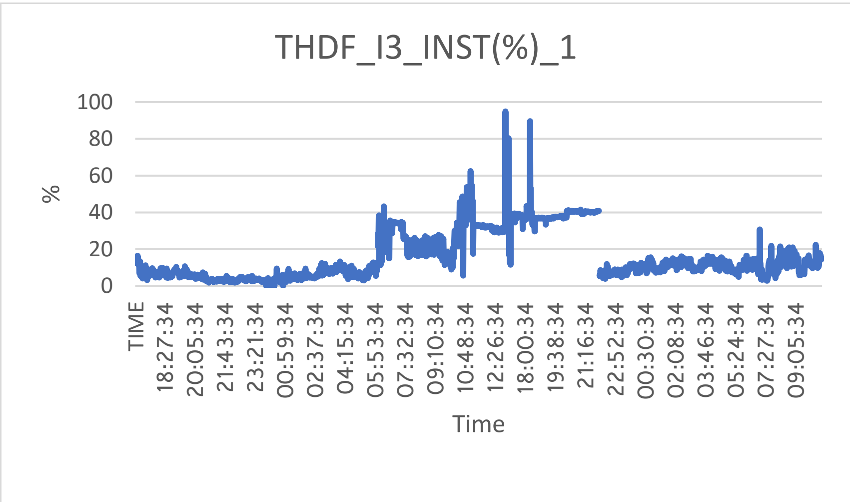

Fig. 13: Total Harmonic Distortion (THD) for Current phase 3

The graphical representations show the variations in power quality parameters across different events. Voltage, current, and power factor trends reveal how operational changes impact these parameters over time.

Total Harmonic Distortion (THD): The THD values recorded in both voltage and current phases show significant deviations from industry standards, especially during VFD operation. The high THD (9% to 28%) for current during VFD use indicates potential issues with harmonic interference, which can lead to heating and stress on electrical components, ultimately reducing their lifespan. This highlights the importance of implementing harmonic filters or other corrective measures.

Power Factor and Reactive Power: Variations in reactive power and power factor across events demonstrate the influence of capacitive and inductive loads on the system. A stable power factor is essential for efficiency, as low power factors can increase transmission losses and demand charges.

Frequency Stability: While frequency remained largely stable across events, the DG operation introduced minor fluctuations, underlining the need for robust frequency regulation when switching from grid to generator supply, especially with sensitive equipment in the system.

Conclusion:

The analysis of the plant's power system reveals that operating with the transformer supply and VFDs generates current harmonic distortion (THD) between 9% and 28%, exceeding industry standards. The dominant 5th and 7th harmonics from motive loads contribute significantly to this distortion, indicating the need for targeted harmonic mitigation measures. While the voltage and frequency are stable, the high THD levels can lead to inefficiencies and potential equipment damage.

The data gathered is also valuable for further simulation and modelling in MATLAB, providing a basis for developing corrective strategies such as harmonic filters and power factor correction to improve power quality and overall system performance.

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