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Power Quality Analysis Of A 20 Kv Medium Voltage System Using FFT And Wavelet Analysis Methods

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ABSTRACT
This study aims to analyze the power quality in a 20 kV medium voltage distribution system (voltage 20 kV, frequency 50 Hz, line length 5 km, input power 185 kVA, load 95 kW, pf 0.75) experiencing 3rd (10%) and 5th (5%) harmonic disturbances, as well as momentary voltage increases. The goal is to detect disturbances and neutralize them to restore the voltage waveform to a pure sine wave. The combined method of Fast Fourier Transform (FFT) and Wavelet is used through MATLAB simulation. FFT detects harmonics in the frequency domain, while Discrete Wavelet Transform (DWT) analyzes momentary voltage changes in the time-frequency domain. Simulations are performed with active harmonics at 0.2-0.4 seconds (sampling rate 1000 Hz), validated with real system characteristics. As a result, FFT identified harmonics of 150 Hz (2,828 kV) and 250 Hz (1,414 kV) with THD of 11.2%, while Wavelet detected the fault time. Neutralization using passive filters (150 Hz and 250 Hz) and capacitor banks (52.54 kVAR) reduced the THD < 5%, returning the voltage to 28.28 kV pure sine. This study offers a comprehensive analysis and practical solutions to improve the reliability of the distribution system, with suggestions for field data validation for further improvement.

Keywords: Power Quality, Harmonics, FFT, Wavelet, MATLAB, Harmonic Filter.

INTRODUCTION

Power quality is one of the crucial aspects in modern electrical systems, especially in medium-voltage distribution networks. Medium-voltage distribution systems, which generally operate at 20 kV, play a vital role in providing electrical energy to industrial and commercial consumers. However, these systems often face various problems that can affect equipment performance and overall energy efficiency. Power quality disturbances, such as harmonics, voltage fluctuations (flicker), and transient disturbances, not only reduce the stability of the electrical system but can also cause damage to equipment, reduce the life of devices, and increase maintenance costs (IEEE, 2018). Therefore, power quality monitoring and analysis are important steps to ensure the stability and reliability of the distribution system.

Harmonics are one of the main phenomena affecting power quality. Harmonics arise as a result of the use of non-linear devices, such as power converters, inverters, or other electronic equipment, connected to the distribution network. Harmonic distortion can cause a decrease in system efficiency, increase energy losses, and even damage sensitive equipment (Hassan, 2020). In addition, voltage fluctuations (flicker) which are often caused by sudden load changes or extreme weather disturbances are also significant challenges in the distribution system. This phenomenon can cause flickering of lights or discomfort for consumers (Zhou & Zhang, 2019).

Transient disturbances, characterized by short-term surges in voltage or current, are also a serious problem that needs attention. Transients are often caused by equipment switching,

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lightning, or mechanical disturbances in the distribution network. Although their duration is very short, their impact can damage sensitive electronic equipment and cause system instability (Chen et al., 2017). Therefore, early detection and accurate analysis of these disturbances are essential to maintain optimal power quality. Frequency-based analysis methods, such as Fast Fourier Transform (FFT), have been widely used to identify and separate frequency components in power signals. FFT provides deep insight into the harmonics present in the system, allowing for identification of distortion causes and appropriate corrections (Rashid, 2016). However, FFT has limitations in analyzing transient or non-steady disturbances, because this method only operates in the frequency domain.

On the other hand, wavelet-based analysis offers the ability to analyze signals in time and frequency domains simultaneously. This method is very effective for detecting transient or irregular power disturbances, such as voltage fluctuations and current surges that occur in a very short period of time (Daubechies, 1992). By using Discrete Wavelet Transform (DWT), we can see the dynamic changes in power quality, which is very useful for analyzing disturbances such as transients that only last a few milliseconds. This study aims to combine the two analysis methods, namely FFT and Wavelet, to analyze power quality in a 20 kV medium voltage distribution system. The combination of these two methods is expected to provide a more comprehensive picture of power disturbances, such as harmonics, flicker, and transients, and facilitate the identification of the causes of abnormalities in the system. This study also provides recommendations related to the maintenance and improvement of power quality in the medium voltage distribution system, so that it can support the reliability and efficiency of the electricity system as a whole.

LITERATURE REVIEW

Power Quality in Electrical Systems

Power quality is an important parameter in medium voltage distribution systems, especially in 20 kV networks, which are often used to supply energy to industrial and commercial consumers. Poor power quality can affect the stability of electrical equipment operation, increase energy losses, and reduce overall system efficiency (IEEE, 2018). Disturbances in power quality can be caused by internal factors, such as non-linear loads, or external factors, such as weather disturbances or equipment switching (Zhou & Zhang, 2019).

Some of the major phenomena that affect power quality include:

1. Harmony, which is generated by non-linear devices such as inverters, converters, or motors with variable frequency drives.
2. Voltage fluctuation (flicker), which often causes flickering of lights and discomfort to consumers.
3. Transient, namely a surge in voltage or current that occurs in a short time due to equipment switching or lightning disturbances.

To analyze these disturbances, mathematical analysis methods such as Fast Fourier Transform (FFT) and Wavelet become very relevant. FFT is used to analyze frequency components in power signals, while Wavelet is used to detect transient disturbances and fluctuations in time and frequency domains simultaneously (Daubechies, 1992; Chen et al., 2017).

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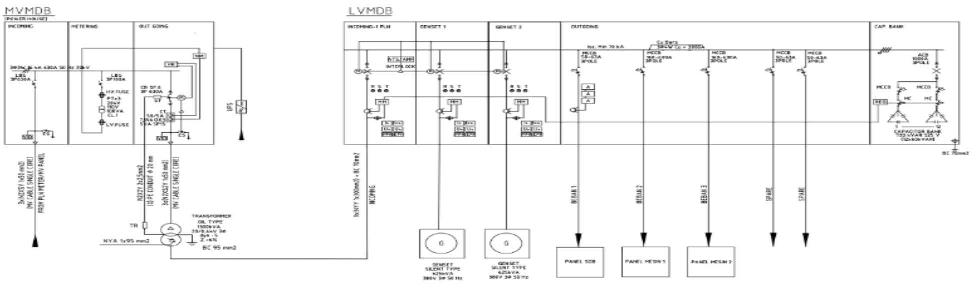

Figure 1. Single line diagram of 20 kV distribution system

Harmonic Analysis with Fast Fourier Transform (FFT)

Fast Fourier Transform(FFT) is a very useful tool for analyzing frequency components in electrical signals. FFT transforms a signal from the time domain to the frequency domain, thus allowing the identification of harmonics present in the system. The mathematical equation of FFT is defined as follows:

$$X(f) = \sum_{n=0}^{N-1} x(n)e^{-j2\Pi fn/N} \qquad \dots(1)$$

Where:

- X(f) : Frequency spectrum of signal x(n),
- f: Frequency,
- N: Number of data points,
- $e^{-j2\pi fn/N}$: Complex exponential kernel function.

In practical implementations, the FFT equation is often approximated using the Discrete Fourier Transform (DFT), which is defined as:

$$X(m) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi mn/N} \qquad \dots(2)$$

Where:

- m: Index in frequency domain (m = 0,1,...,N−1),
- n: Index in time domain (n = 0,1,...,N−1).

FFT has an advantage in computational efficiency over direct DFT, because it uses a "divide and conquer" technique to sort the data into even and odd parts. This process is described in the following equation:

$$X(k) = X_{genap}(k) + W_N^k X_{ganjil}(k) \qquad \dots(3)$$

Where:

- WNk = e−j2πk/N,
- X_{even}(k) and Xganjil(k): Even and odd components of the signal.

Butterfly diagrams are often used to visualize the relationship between time and frequency domains in FFT. These diagrams help identify harmonic distortion patterns in power

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signals (Rashid, 2016). However, FFT has limitations in analyzing transient disturbances or unsteady fluctuations, because it only operates in the frequency domain. Therefore, additional methods such as Wavelet are needed for a more comprehensive analysis.

Wavelet Analysis

Unlike FFT, Wavelet analysis allows signal analysis in time and frequency domain simultaneously. This method is very effective for detecting transient disturbances and voltage fluctuations that occur in very short time periods. Discrete Wavelet Transform (DWT) is defined as follows:

$$W_{\psi}(a,b) = \int_{-\infty}^{\infty x} x(t)\psi_{a,b}(t)dt \qquad \ldots..(4)$$

Where:

- $W\psi$(a,b) : Wavelet coefficients for scale a and translation b,
- $\psi a_{,b}$(t) : Translated and scaled wavelet function,
- x(t) : The signal being analyzed.

The wavelet function is generally defined as:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \qquad \ldots..(5)$$

Where:

- a: Scale parameter (controls the frequency resolution),
- b: Translation parameters (controls time position).

*Wavelets*provide deep insights into dynamic changes in signals, such as voltage fluctuations and transients. For example, Wavelets can be used to detect flicker caused by sudden load changes or current spikes due to equipment switching (Chen et al., 2017).

Combined Use of FFT and Wavelet

The combination of FFT and Wavelet methods provides a more comprehensive approach to power quality analysis. FFT provides a deep understanding of the frequency components of power disturbances, such as harmonics, while Wavelet provides details about transient disturbances and fluctuations in the time domain. The combination of these two methods allows for more accurate detection of phenomena such as harmonics, flicker, and transients (Hassan, 2020).

For example, FFT can be used to identify harmonic distortion in a frequency spectrum, while Wavelet can be used to track rapid changes in a signal, such as transients that occur within milliseconds. The frequency spectrum and Wavelet coefficient images can be used to visualize the results of the analysis simultaneously.

Harmonics in Medium Voltage Systems

Harmonics are one of the main problems in power quality in medium voltage distribution systems. Harmonics are caused by non-linear devices such as inverters, converters, and motors with variable frequency drives. Harmonic distortion can cause decreased system efficiency,

energy losses, and damage to sensitive equipment (Rashid, 2016).
FFT is a very useful tool for detecting and measuring harmonic levels in a system. The frequency spectrum generated by the FFT can be used to identify the m-th harmonic component, which is calculated using the following equation:

$$H_m = \frac{|X(m)|}{|X(1)|} \quad \ldots\ldots(6)$$

Where:

- *Hmm*: The mth harmonic level,
- *X*(m): Amplitude of the m-th frequency component,
- *X*(1): Amplitude of the fundamental component.

Voltage fluctuations (flicker) usually occur due to sudden load changes or other disturbances in the distribution network. This phenomenon can cause flickering of lights and inconvenience to consumers. Wavelet analysis is very effective for detecting voltage fluctuations with high accuracy, because it can capture rapid changes in the signal (Zhou & Zhang, 2019). *Transient*, such as voltage or current spikes, are often caused by equipment switching or lightning strikes. Wavelet transforms can be used to detect these transients by visualizing changes in the time and frequency domains simultaneously.

Effect of Power Quality Disturbances on Medium Voltage Systems

Power quality disturbances such as harmonics, voltage fluctuations (flicker), and transients have significant impacts on medium voltage distribution systems, especially on 20 kV networks. These impacts not only affect the stability of electrical equipment operation but also increase energy losses and maintenance costs.

1. Harmony: Harmonics are caused by non-linear loads such as inverters, converters, or motors with variable frequency drives. Harmonic distortion can cause:
   - Decreased system efficiency.
   - Increased energy losses.
   - Damage to sensitive equipment, such as transformers and induction motors.
   - *Overheating*on electrical equipment, which reduces the service life of the device.

   To analyze harmonics, the Fast Fourier Transform (FFT) method is very useful because it can identify frequency components in a power signal. FFT provides a picture of the frequency spectrum that helps determine the level of harmonic distortion in the system. However, FFT has limitations in detecting transient disturbances or dynamic fluctuations.
2. Voltage Fluctuation (Flicker):Voltage fluctuations often occur due to sudden load changes or external disturbances such as bad weather. This phenomenon can cause:
   - Annoying flashing lights.
   - Inconvenience for consumers, especially on sensitive electronic devices.

Wavelet analysis is very effective for detecting voltage fluctuations because it is able to capture rapid changes in the signal. Discrete Wavelet Transform (DWT) can be used to track dynamic changes in the time and frequency domains simultaneously, providing deeper insight into fluctuation patterns.

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3. Transient:Transients are short-lived surges in voltage or current, often caused by equipment switching or lightning strikes. Despite their short duration, they can damage sensitive electronic equipment and cause system instability. Wavelets are also very effective for detecting transients because of their ability to analyze signals in the time-frequency domain. Wavelet transforms can visualize rapid changes in signals, such as current or voltage surges that occur over a period of milliseconds.

Advantages and Limitations of FFT and Wavelet Methods

Each analysis method has certain advantages and limitations, depending on the type of disturbance being analyzed.

1. Advantages of FFT:
   - Efficient in identifying frequency components in power signals.
   - Provides a clear picture of the frequency spectrum, making it easier to identify harmonics.
   - Computation is relatively fast compared to other methods such as direct DFT.
2. FFT Limitations:
   - It only operates in the frequency domain, making it less effective for analyzing transient disturbances or dynamic fluctuations.
   - Cannot capture rapid changes in signals because it lacks time resolution.
3. Wavelet Advantages:
   - Capable of analyzing signals in time and frequency domains simultaneously.
   - Very effective for detecting transient disturbances and voltage fluctuations that occur in a short time.
   - Provides deep insight into dynamic changes in signals.
4. Limitations of Wavelets:
   - Requires the selection of the right wavelet function to obtain accurate analysis results.
   - Computation is more complex than FFT.

Combined FFT and Wavelet Approach

The combined approach of FFT and Wavelet offers a more comprehensive solution for power quality analysis. FFT is used to analyze frequency components in the power signal, such as harmonics, while Wavelet is used to detect transient disturbances and fluctuations in the time domain.

- FFT: Provides a frequency spectrum view that helps identify harmonic distortion.
- Wavelets: Provides details about rapid changes in the signal, such as transients and flicker.

The combination of these two methods allows for more accurate detection of phenomena such as harmonics, flicker, and transients. The analysis results can be visualized through the frequency spectrum of the FFT and Wavelet coefficients to provide a more complete picture of the power quality conditions in the medium voltage distribution system.

METHODS

This study aims to analyze the power quality in a 20 kV medium voltage distribution system using a combined method of Fast Fourier Transform (FFT) and Wavelet. The research

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methodology is designed systematically to ensure accurate and relevant results. The following are the steps of the research methodology. This study uses a MATLAB-based simulation approach to analyze power quality disturbances such as harmonics, voltage fluctuations (flicker), and transients. Power signal data will be processed using FFT for frequency spectrum analysis and Wavelet for time-frequency domain analysis. The following is a flowchart that illustrates the research flow:

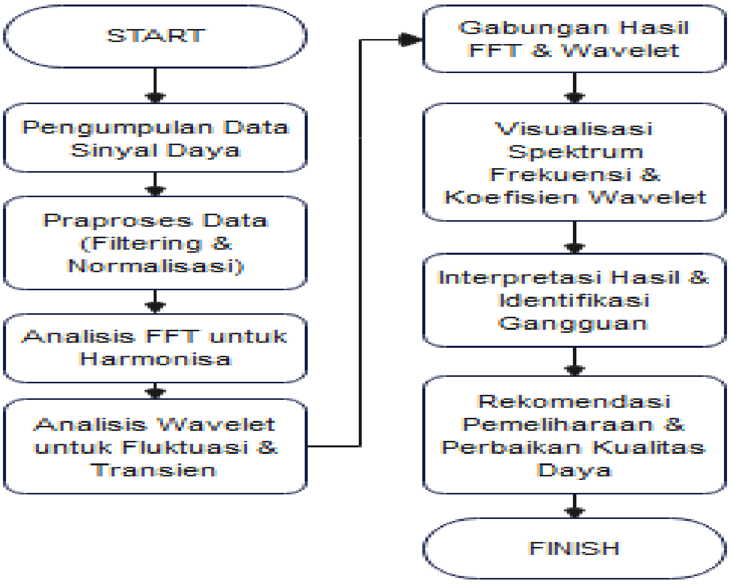

Figure 2. Research flowchart

The following block diagram illustrates the process of processing power signal data using MATLAB:

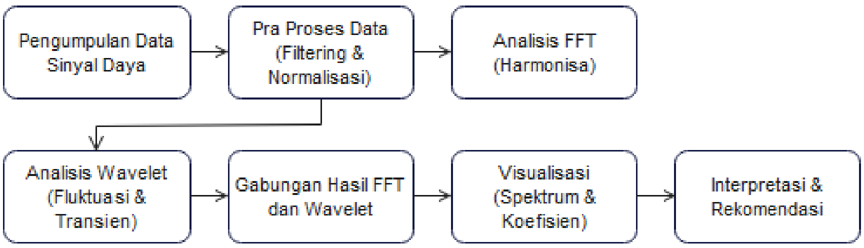

Figure 3. Block diagram of signal data processing

RESULTS AND DISCUSSION

Simulated Distribution Channel Data

This study aims to analyze the power quality in a 20 kV medium voltage distribution system using a combined method of Fast Fourier Transform (FFT) and Wavelet. This analysis focuses on identifying disturbances such as harmonics, voltage fluctuations (flicker), and transients. The following is an analysis and discussion based on the simulation data that will be used. The distribution channel data used in this study were generated through

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MATLAB/Simulink simulation. The following are the main parameters of the simulated data:
System Parameters

- Nominal Voltage: 20 kV
- Basic Frequency: 50Hz
- Channel length: 5 km
- Nominal power: 185 KVA
- Burden: 95 KW
- Cos phi: 0.75
- There is a disturbance of harmonics 3 and 5 in the system, resulting in a momentary increase in voltage.
- The disturbance will be detected and analyzed using FFT and Wavelet, and the original voltage (pure sine) will be obtained.
- Load Type:
- Non-linear loads (inverters, motors with variable frequency drives)

Simulation Conditions:

- Normal condition: Stable voltage without interference.
- Harmonic conditions: Distortion due to non-linear loads.
- Flicker condition: Voltage fluctuations due to sudden load changes.
- Transient conditions: Voltage surges due to switching or lightning.

Assumptions:

- 3rd harmonic: 10% of fundamental (2,828 kV peak).
- 5th harmonic: 5% of fundamental (1,414 kV peak).
- A momentary voltage increase occurs at a certain time (e.g., 0.2-0.4 seconds).

- RMS current: $I = \frac{S}{V} = \frac{185 \, x \, 10^3}{20 \, x \, 10^3} = 9{,}25 \, A$

- Active power according to pf: P = S·pf =185×0.75 = 138.75 kW (there is a difference with the 95 kW load, maybe due to losses or additional data; I will use P = 95 kW as the actual load).

Stages of Disturbance Analysis and Neutralization
Interference Detection Using FFT
Objective:Identifying harmonic frequency components in a voltage signal.
Stages:

1. Signal Data Collection:

Voltage signal in time domain:

$$v(t) = V_1 \sin(2\Pi . f . t) + V_3 \sin(2\Pi . f . t) + V_5 \sin(2\Pi . f . t)$$

Where:
V1=28.28kV (fundamental, 50 Hz),
V3=2.828 kV (3rd harmonic, 150 Hz),
V5=1.414 kV (5th harmonic, 250 Hz).

FFT Transform:(pers.1)

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Where:
v(n) : Voltage signal sample,
N: Number of samples (e.g., 1000 for a sampling rate of 1000 Hz for 1 second),
k : Frequency index,
X(k) : Amplitude at frequency fk = k·fs/N, where fs = sampling frequency.

FFT Analysis Results:
Frequency spectrum:
50 Hz: V1=28.28 kV
150 Hz: V3=2.828 kV
250 Hz: V5=1.414 kV

Total Harmonic Distortion (THD): $\sqrt{\frac{V_3^2+V_5^2}{V_1^2}} = \sqrt{\frac{2{,}828^2+1{,}414^2}{28{,}28^2}}$

$$= \sqrt{\frac{8+2}{800}} = 0{,}112 \; atau \; 11{,}2\%$$

Interpretation:

- FFT detects the 3rd and 5th harmonics, providing amplitude and frequency information. However, FFT does not show the specific time of the instantaneous voltage increase.

Disturbance Detection Using Wavelet

Objective:Identifying the time and frequency of momentary voltage increases due to harmonics. Stages:
Same signal as above, with harmonics active at 0.2-0.4 seconds:

$$\begin{cases} 28.28\sin(2\Pi.50.t) & 0 \le t \le 0.2 \; dan \; 0.4 \le t \le 1 \\ 28.28\sin(2\Pi.50.t) + 2.828\sin(2\Pi.50.t) + 1.414\sin(2\Pi.250.t) & 0.2 \le t \le 0.4 \end{cases}$$

DWT separates the signal into frequency levels:

$$W_\psi(j,k) = \sum_n v(n)\psi_{j,k}(n)$$

Where :

- $\psi_{j,k}(n) = 2^{-\frac{j}{2}}\psi(2^{-j}n-k)$: Wavelet functions (e.g. Daubechies db4),
- j : Scale level,
- k : Time translation,
- Wψ(j,k) : Wavelet coefficients.

Decomposition (sampling rate 1000 Hz):

- A3 (<62.5 Hz):Fundamental (50 Hz), stable all the time.
- D2 (125-250 Hz):3rd harmonic (150 Hz), increases at 0.2-0.4 seconds.
- D1 (250-500 Hz):5th harmonic (250 Hz), increases at 0.2-0.4 seconds.

The wavelet coefficients show amplitude spikes in D2 and D1 at 0.2-0.4 seconds.

- *Wavelets*detects specific time (0.2 - 0.4 seconds) and harmonic frequency, providing a dynamic picture of the instantaneous voltage increase.

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Neutralization of Disturbances

Eliminates harmonics and stabilizes the voltage to its original form. Stages:

1. Identify Causes:
   - FFT: 3rd and 5th harmonics are detected at 150 Hz and 250 Hz.
   - *Wavelets*: Momentary voltage increase at 0.2-0.4 seconds due to harmonics.
2. Neutralization Strategy:
   - Harmonic Filter Installation
     Passive filters for 150 Hz and 250 Hz:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

   - For 150 Hz: Choose L and C so that fr = 150 Hz.
   - For 250 Hz: Choose L and C so that fr = 250 Hz.

     Active filters can be used to handle instantaneous harmonics based on Wavelet detection.

Power Factor Correction:

- Add a capacitor bank to increase pf from 0.75 to 0.95: $Qc = P(\tan\phi 1 - \tan\phi 2)$
  - P = 95 kW
  - $\cos\phi 1 = 0.75$, $\tan\phi 1 = 0.882$
  - $\cos\phi 2 = 0.95$, $\tan\phi 2 = 0.329$
  - $Qc = 95(0.882-0.329) = 52.54$ kVAR

Post-Neutralization Verification:

- FFT:
  Frequency spectrum: Peaks at 150 Hz and 250 Hz are gone, THD < 5%.
- Wavelets:
  The coefficients D2 and D1 at 0.2 - 0.4 seconds approach zero, the voltage stabilizes at $28.28\sin(2\pi\cdot 50\cdot t)$

FFT:Detects 3rd (150 Hz) and 5th (250 Hz) harmonics with 11.2% THD, the basis of filter design.

Wavelets:Shows instantaneous voltage increase at 0.2-0.4 seconds, guiding dynamic response.

Neutralization:The harmonic filter and pf correction remove the interference, returning the voltage to its original form of $28.28\sin(2\pi\cdot 50\cdot t)$

After obtaining the calculation results as above, the next step is to simulate the system with MATLAB, with the following assumptions and parameters:

- Input Voltage:20 kV (rms), $V_{peak} = 20 \times 2 \approx 28.28$ kV.
- Fundamental Frequency:50 Hz.
- Harmony:The 3rd (150 Hz, 10% = 2,828 kV peak) and 5th (250 Hz, 5% = 1,414 kV peak), are active at 0.2-0.4 seconds.
- Time span:0 to 1 second.
- Sampling Rate:1000 Hz (1000 dots per second).

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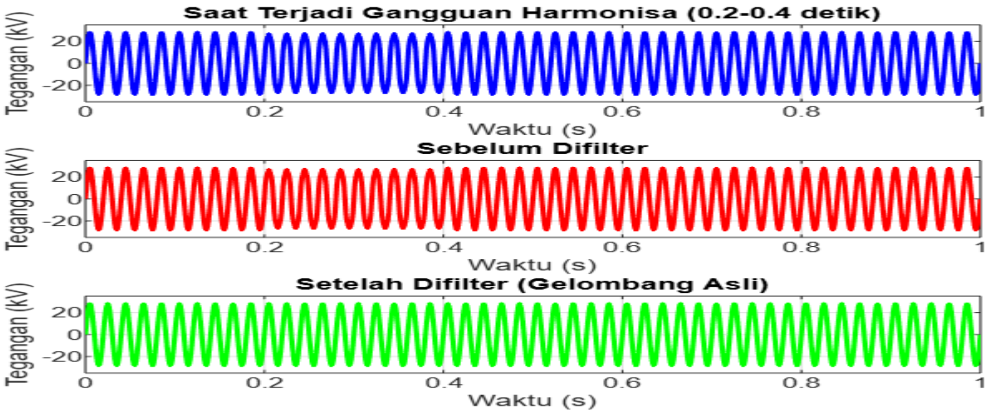

Figure 4. Simulation results of normal signals, with harmonics and after filtering.

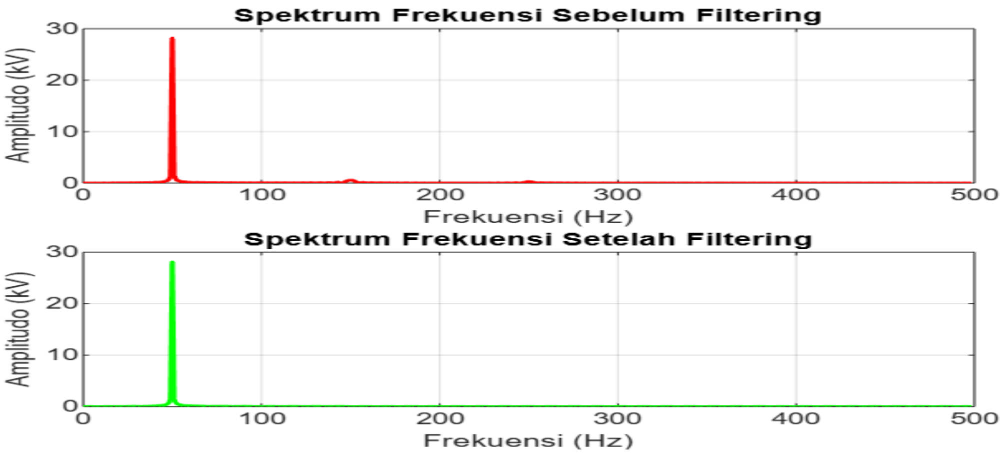

Figure 5. FFT frequency spectrum before filtering and after filtering.

Explanation of pictures 4 and 5

1. Graph During Disturbance (Subplot 1):
   - Color:Blue.
   - Description:Pure sine wave (50 Hz) from 0-0.2 s and 0.4-1 s. At 0.2-0.4 s, the 3rd and 5th harmonics are added, causing distortion. The maximum amplitude increases (~32 kV) due to the sum of the harmonics.
   - X-axis:Time (s), 0 to 1 second.
   - Y axis:Voltage (kV), -35 to 35 kV.
2. Graph Before Filtering (Subplot 2):
   - Color:Red.
   - Description:Identical to the first graph, showing the conditions before the filtering intervention. Distortion is clearly visible at 0.2-0.4 seconds.
3. Graph After Filtering (Subplot 3):
   - Color:Green.
   - Description:A pure sine wave of 50 Hz with a peak amplitude of 28.28 kV at all times. The 3rd and 5th harmonics are removed, restoring the original waveform of the generator.

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4. FFT Graph (Optional):
   - Before Filtering:Peaks at 50 Hz (28.28 kV), 150 Hz (2,828 kV), and 250 Hz (1,414 kV).
   - After Filtering:Only the peak at 50 Hz (28.28 kV), harmonics are missing.

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CONCLUSION.

This study aims to analyze the power quality in a 20 kV medium voltage distribution system using a combined method of Fast Fourier Transform (FFT) and Wavelet. Based on the results of the analysis, simulation, and discussion, several important points can be concluded as follows:

1. Power quality is a crucial aspect in modern electrical systems, especially in 20 kV distribution networks that supply energy to industrial and commercial consumers.
2. Disturbances such as harmonics, voltage fluctuations (flicker), and transients not only reduce system stability but can also damage equipment, reduce efficiency, and increase maintenance costs.
3. The FFT method is very effective in identifying harmonic components in power signals. By transforming the signal from the time domain to the frequency domain, the FFT provides a picture of the frequency spectrum that helps detect harmonic distortion.
4. However, FFT has limitations in analyzing transient disturbances or dynamic fluctuations because it only operates in the frequency domain.
5. Wavelet analysis allows observation of signals in the time and frequency domains simultaneously, making it very effective for detecting disturbances such as flicker and transients.
6. *Discrete Wavelet Transform*(DWT) is capable of tracking rapid changes in signals, such as current or voltage spikes that occur in a short time (milliseconds).
7. The combination of FFT and Wavelet provides a more comprehensive approach in power quality analysis. FFT is used to identify harmonics in the frequency domain, while Wavelet is used to detect voltage fluctuations and transients in the time-frequency domain.
8. The results of this combined analysis allow for more accurate identification of the cause of the outage, facilitating recommendations for improvements.
9. To overcome harmonics, it is recommended to install harmonic filters and use equipment with a high power factor.
10. Voltage fluctuations can be reduced by stabilizing the load using a voltage regulator and improving the grounding system.
11. Voltage surges or transients can be reduced by installing surge protectors and increasing the distribution network insulation.
12. This study provides in-depth insights into the use of combined FFT and Wavelet methods to analyze power quality in medium voltage distribution systems.
13. MATLAB simulations prove that these two methods complement each other and provide more accurate analysis results than if used separately.
14. The findings of this study can be used as a reference to improve the stability and reliability of medium voltage distribution systems.

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15. The recommendations provided can be implemented by distribution network operators to reduce the impact of power quality disturbances and ensure overall electricity system efficiency.

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