COMPARATIVE MODELING OF HARMONIC WAVE REDUCTION ON PERIODIC SIGNALS THROUGH FOURIER SERIES INTEGRATION AND PASSIVE FILTER EFFECTIVENESS

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Abstract: Harmonic distortion is a crucial problem in electric power systems caused by the use of non-linear loads, this study presents a comparative modeling of harmonic wave reduction on periodic signals through Fourier Series integration and the use of passive filters, research methodology involves collecting real data in the field using a power quality analyzer FLUKE 435 series II on a distribution panel to identify the critical load profile. Load characteristics are analyzed through individual current decomposition (IHDi) from the 3rd to 23rd order. The observation results show that load has the highest fundamental current peak of 0.541 A with dominant distortion in the 3rd and 5th orders. The implementation of a specifically tuned RLC passive filter is proven to be effective in improving the current waveform to a pure sinusoidal in the time domain with a fundamental frequency of 50 Hz. Overall, the integration of this mathematical model is able to suppress harmonics to meet the international standard IEEE 519, ensuring the efficiency and stability of the electric power distribution system, The results of the data analysis and modeling conducted indicate that Fourier series integration is highly effective in representing the characteristics of nonlinear loads in electric power systems, determining filter values that will reduce harmonics and the appropriate filter models.
Keywords: harmonics; Fourier series; passive filter; power quality

Abstrak: Distorsi harmonik merupakan masalah penting pada sistem tenaga listrik yang disebabkan oleh penggunaan beban non-linier. Studi ini menyajikan pemodelan komparatif pengurangan gelombang harmonik pada sinyal periodik melalui integrasi deret Fourier dan penggunaan filter pasif, metodologi penelitian melibatkan pengumpulan data dunia nyata di lapangan menggunakan power quality analyzer FLUKE 435 series II pada panel distribusi untuk mengidentifikasi profil beban kritis, karakteristik beban dianalisis melalui dekomposisi arus individual (IHDi) dari orde ke-3 hingga ke-23. Observasi menunjukkan bahwa Beban memiliki arus puncak fundamental tertinggi sebesar 0,541 A, dengan distorsi dominan pada orde ke-3 dan ke-5. Implementasi filter pasif RLC yang disetel secara khusus terbukti efektif dalam meningkatkan bentuk gelombang arus menjadi sinusoidal murni dalam domain waktu dengan frekuensi fundamental 50 Hz. Secara keseluruhan, integrasi model matematika ini mampu menekan harmonik untuk memenuhi standar internasional IEEE 519, memastikan efisiensi dan stabilitas sistem distribusi daya listrik. Hasil analisis data dan

pemodelan yang dilakukan dapat disimpulkan bahwa integrasi deret fourier sangat efektif dalam merepresentasikan karakteristik beban non-linier dalam sistem daya listrik untuk menentukan nilai filter yang akan mengurangi harmonik dan model filter yang dapat digunakan.

Kata kunci: harmonisa; deret Fourier; filter pasif; kualitas daya

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Introduction

Harmonic distortion is a sinusoidal component of a periodic wave that has a frequency that is a multiple of a positive integer from the fundamental frequency. Harmonics are defined as components with frequencies that are multiples of the fundamental frequency, the fundamental frequency of the first harmonic is 50 or 60 Hz.The second harmonic and so on are a combination of the fundamental frequency, namely 100 or 120 Hz and so on, Alternating current electrical signals which are periodic functions are widely used in electricity which must be in the form of a sinusoidal input signal, but in the process of implementing electricity, many input signals are not sinusoidal due to the influence of harmonic distortion on the electric power system. Harmonic distortion is also caused by non-linear devices. Non-linear devices are devices with disproportional currents. Harmonics have several indices that are generally used as indicators of how much impact harmonics occur. Harmonic indices can be observed through individual harmonic distortion (IHD) and (THD) total harmonic distortion (Qaisar, M et al 2025), IHD is the ratio between the RMS value of each harmonic current compared to the RMS value of the fundamental current or the first harmonic. In a single-phase electrical circuit that uses a sinusoidal input signal, analysis can be done easily using the phasor method, we can analyze square waves and truncated sine waves such as the output waveform of a rectifier circuit, both half-wave and full-wave rectifiers. The input signal in an alternating current waveform that is a function must be sinusoidal to maximize its usefulness in an electrical load (Priyadarshini, M, et al 2023).

The Fourier series is a series containing sine and cosine terms used to describe periodic functions. The Fourier series is often used as an aid in solving differential equations, both ordinary differential equations and partial differential equations. the Fourier series can describe periodic functions by being represented as an infinite sum of a series of sinusoidal quantities. A function f(t) is said to have period T or is periodic with period T if for each period (t) it is written as f (t+T) = f(t) (Khajouei, J. et al 2020), where T is a positive constant. The smallest value of T is called the smallest period or abbreviated as period f(t). The image displays the graph of each harmonic of the function f(t) done using the MATLAB version R2020a (version

9.8) program. the program to display the first, second, third and fourth harmonic waves of the function f(t) (Wen, J. 2025).

This study uses industrial-grade power quality measurement instruments to obtain accurate harmonic distortion data in electric power systems. The main device used in the data acquisition process is the FLUKE 435 series II Power Quality Analyzer. This instrument functions to monitor and record electrical parameters in real-time, especially on non-linear loads that produce non-sinusoidal waves. Measurements are focused on capturing the Root Mean Square (RMS) value of the fundamental current and harmonic components at critical points in a single-phase circuit to identify the occurrence of square waves or truncated sinusoids. The data processing and wave simulation processes are carried out using MATLAB software. The initial data obtained from the measuring instrument is imported into the MATLAB environment for frequency spectrum analysis. The use of this software allows the decomposition of periodic signals through Fourier transforms, so that the fundamental frequency components 50 Hz or 60 Hz. This simulation is also used to compare the characteristics of ideal sinusoidal input with the actual output distorted by non-linear devices. The data analysis method is carried out by calculating the harmonic index as the main indicator of power quality through the Individual Harmonic Distortion (IHD) and Total Harmonic Distortion (THD) parameters. This measurement aims to evaluate the extent to which the deviation of the input signal from a pure sinusoidal form affects the efficiency of power distribution to the electrical load.

Method

This research is quantitative by conducting measurements with a case that can be shown is the current signal used as an input signal on the electrical network load with a non-linear load, namely a distorted current wave signal. The wave signal will be sought for its mathematical equation by the Fourier series circumference approach, to determine the total harmonic distortion (THD), Fourier series analysis is used for voltage and current as a function of time used for measurement analysis and written in equation 1. 2.. (Shang, H. et al 2016) (Zhu, J., Wang, S., & Li, Q 2025)

$$\mathrm{v(t)} = V_0 + \sum_{n=1}^{\infty} V_n Cos(n\omega t + \theta_n) \dots\dots\dots\dots\dots\dots (1)$$

$$\mathrm{i(t)} = I_0 + \sum_{n=1}^{\infty} l_n Cos(n\omega t + \varphi_n) \dots\dots\dots\dots\dots (2)$$

determine the periodic function f(t) = f(t)+T in equation 3

$$f(t) = \frac{1}{2} a_0 + \sum_{h=1}^{\infty} (a_n \cos(h\omega_0 t) + b_n \sin(h\omega_0 t) \dots.(3)$$

a_n and b_n are the coefficients of the Fourier series

$$a_n = \frac{2}{T} \int_0^T f(t) \cos(h\omega_0 t)\, dt \quad \text{.....(4)}$$

$$b_n = \frac{2}{T} \int_0^T f(t) \sin(h\omega_0 t)\, dt \quad \text{.....(5)}$$

the current is in the form of a symmetrical alternating wave, then the wave has an odd function, then the wave has an odd function if f (t) = - f (-t), then the function f (t) equations 6,7.

$$a_n = 1 \quad \text{.....(6)}$$

$$b_n = \frac{4}{T} \int_0^{T/2} f(t) \sin(h\omega_0) \quad \text{.....(7)}$$

analysis with Fourier series for voltage and current (Zhao, F. et al 2025).

$$f(t) = f_0 + f_{ml} \sin(\omega_0 t + \varphi_1) + \ldots + f_{mh} \sin(h\omega_0 t) + \varphi_h \quad \text{..(8)}$$

$$v(t) = v_0 + \sum_{n=1}^{\infty} v_n \cos(n\omega t \ \emptyset_n) \quad \text{.....(9)}$$

$$i(t) = I_0 + \sum_{n=1}^{\infty} I_n \cos(n\omega t + \varphi_n) \quad \text{.....(10)}$$

RMS voltage and current analysis of sinusoidal waves, namely the peak value of the wave divided by √2 and in a Fourier series for voltage and current.

$$v_{(t)} = V_0 + \sum_{n=1}^{\infty} \sqrt{2}\, V_n \sin(n\omega_0 t + \theta_n) \quad \text{.....(11)}$$

$$i_{(t)} = I_0 + \sum_{n=1}^{\infty} \sqrt{2}\, I_n \sin(n\omega_0 t + \delta_n) \quad \text{.....(12)}$$

the DC part (V_0 and I_0) is analyzed and ignored to simplify the calculation, where the Vn and In values are the RMS values for the nth order harmonics for each voltage and current, so the RMS value is obtained in one period of a pure sinusoidal waveform with period T.

$$V_{(t)} = V_m \sin \omega t \quad \text{.....(13)}$$

$$V_{RMS} = \sqrt{\frac{1}{2} \int_0^T [V(t)]^2 \, dt} \quad \text{.....(14)}$$

Result

Load measurement on a 150 kVA distribution transformer is a crucial instrument in collecting primary data that serves as an indicator of the health of electrical assets. Through periodic observation of current (I), voltage (V), and neutral current parameters, system managers can map daily load profiles to

determine whether the transformer is operating within optimal efficiency limits or approaching saturation point (overload). This periodic data analysis allows early identification of the phenomenon of load imbalance between phases that often triggers the emergence of neutral currents and overheating in the transformer windings, load balancing or planning transformer mutations to larger capacities before insulation failure occurs Fig. 1.

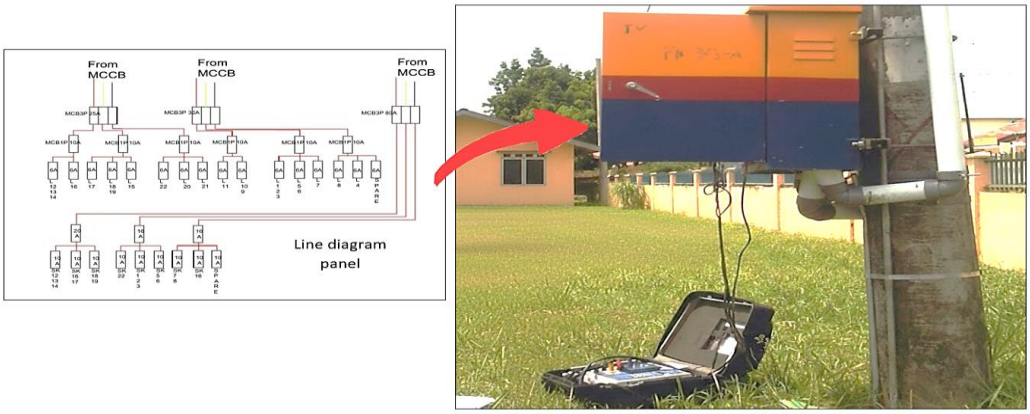


Figure 1. Load measurement on a 150 kVA distribution transformer

Individual voltage and current harmonics based on comparisons with the IEEE 519-1992 standard show no conformity. This condition can also be interpreted that the voltage and current in this study have disturbances that must be repaired due to harmonics and conditions must be reduced to reduce harmonics so that the plate works optimally (table 1).

In the implementation of appropriate harmonic mitigation strategies, such as the installation of passive or active filters. The use of passive filters consisting of a combination of inductors and capacitors can be designed to absorb certain dominant harmonic orders, while active filters can provide dynamic compensation for current distortion fluctuations in real-time. By reducing harmonic components to below the IEEE 519 tolerance limit, the waveform will return to being close to a pure sinusoidal shape, which will ultimately minimize electromagnetic interference and ensure the distribution of electrical energy throughout the system works stably and optimally.

Table 1. Individual voltage and current harmonics

IHD Ordo	IHD_I-L1 (%)	IHD_I-L2 (%)	IHD_I-L3 (%)	Standard IEEE 519-1992	
1	100	100	100	100	normal
3	2,2	2,46	2,83	7	over
5	14,22	14,48	12,84	7	over
7	2,35	3,52	2,14	7	over
9	0,84	0,38	0,75	7	over
11	1,21	1,7	1,77	3,5	over

IHD Ordo	IHD_I-L1 (%)	IHD_I-L2 (%)	IHD_I-L3 (%)	Standard IEEE 519-1992	
13	1,03	1,1	0,83	3,5	over
15	0,49	0,4	0,13	3,5	over
17	0,84	0,54	0,79	2,5	over
19	1,2	1,13	0,78	2,5	over
21	0,24	0,14	0,15	2,5	over
23	0,81	0,31	0,68	2,5	over
THD total	**25,43**	**26,16**	**23,69**		

Fourier series representation of any periodic wave:

$$a_0 = \frac{1}{2}\left(\int_0^1 4\,dt + \int_2^2 -4\,dt\right) \text{.....(15)}$$

The square waveform will be obtained by adding each term of f(t) which is the Fourier series description of the square wave, coefficient an is calculated for n = 1, 2, 3, …with the following calculation:

$$a_n = \frac{1}{2}\int_0^1 4\cos n\pi t\,dt + \int_1^2 -4\cos n\pi t\,dt \text{ ..... (16)}$$

$$b_n = \frac{2}{2}\int_0^1 4\sin n\pi t\,dt + \int_1^2 -4\sin n\pi t\,dt \text{ ..... (17)}$$

$$f(t) = \frac{16}{\pi}\left(\frac{\sin \pi}{1} + \frac{\sin\ 3\pi 3}{3} + \frac{\sin\ 5\pi 3}{5} + \frac{\sin\ 7\pi 3}{7} + \ldots\right) \text{..... (18)}$$

This simulation model integrates the Fourier Series principle by representing signal distortion through a series of odd-order current sources (h3 to h23) connected in parallel on the load side. This approach allows for precise comparative analysis because each harmonic order can be amplitude-controlled according to the Fourier coefficients of the specific nonlinear load characteristics. By modeling the harmonic spectrum up to the 23rd order, this simulation is a close representation of the periodic waveforms in the real-world grid system to the load, while also testing the system's resilience to high-frequency distortion before and after filter intervention (fig. 2).

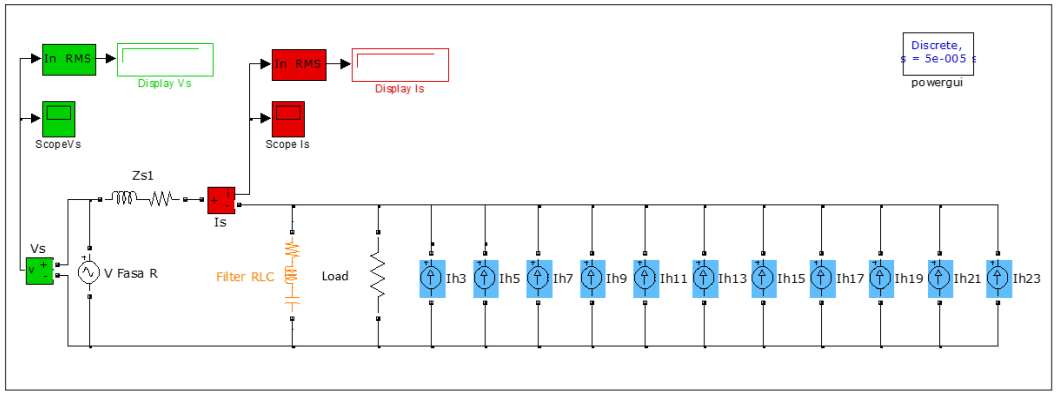


Figure 2. Distorted current simulation with filter

A visual representation of a periodic waveform in the time domain that has undergone harmonic distortion due to the use of a non-linear load. Technically, the waveform is no longer a pure sinusoid, but instead exhibits significant undulations or ripples at the positive peaks, negative peaks, and the area around the zero crossing point. Based on the scale on the horizontal axis, one full cycle of the waveform is completed in 0.02 seconds, indicating that the system is operating at a fundamental frequency of 50 Hz. Waveform amplitudes reaching numbers above 400 units indicate peak values of the electrical signal being analyzed, where the jagged shape is the result of the superposition of the fundamental frequency with various harmonic orders fig. 3.

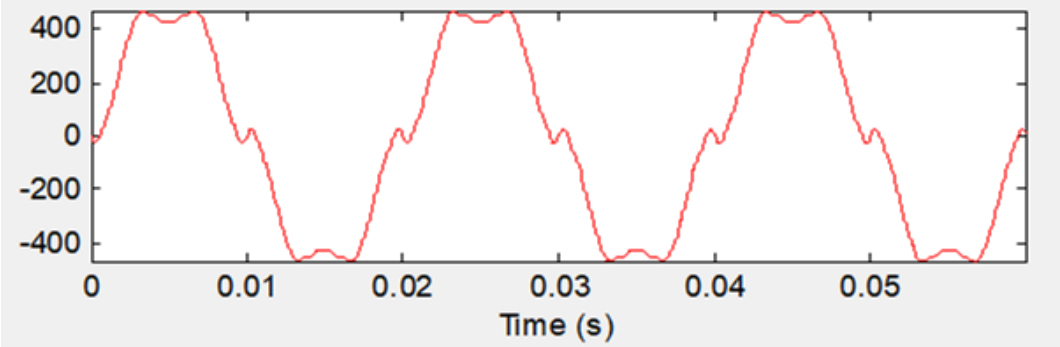


Figure 3. Distorted sinusoidal wave

The simulation results effectively implement a harmonic current model, where the non-linear load is represented through a series of discrete current sources (h3 to h23) based on the Fourier Series analysis decomposition. Among the evaluated analyses, Load D is identified as the most critical condition, exhibiting the highest fundamental current magnitude of 0.541 A as well as significant spectral peaks at the 3rd and 5th orders. Based on the individual current measurement data (IHDi), there is a significant variation in distortion among the five tested load scenarios. The current spectrum visualization shows a consistent pattern of decreasing amplitude with increasing order, directly validating the mathematical

convergence of the Fourier series in representing real periodic signal distortion. The linear progression of the spectral data reveals a characteristic of decreasing amplitude with increasing harmonic order, validating the mathematical convergence of the periodic signal model. The integration of a shunt-connected passive RLC filter demonstrates superior mitigation efficiency, achieving a significant reduction in Total Harmonic Distortion (THD) to a final level of 1.806%. Quantitative analysis confirms that all individual harmonic orders are successfully suppressed below the threshold of 3.0%, especially reducing the 3rd and 5th orders to 0.41% and 0.77% respectively. The output image of a nearly pure sinusoidal waveform in the time domain waveform analysis is as shown in (fig. 4).

Passive Filter Performance Evaluation on Periodic Waveforms to mitigate the detected distortion, the system is equipped with a passive filtration mechanism designed to improve the current waveform. Time-domain analysis shows that the resulting periodic signal has good stability, with a period of approximately 0.02 seconds, corresponding to a fundamental frequency of 50 Hz. Although small ripples remain at the waveform peaks due to residual high-order harmonics, the use of the filter successfully maintains signal integrity, maintaining a nearly pure sinusoidal shape with consistent peak values within the ±400 range.

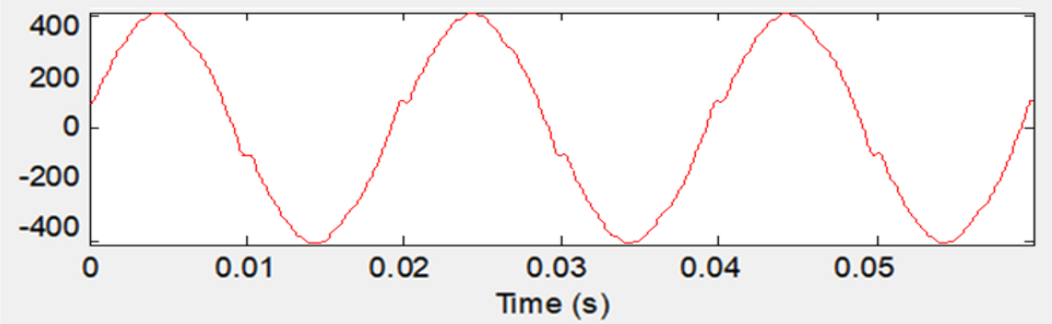


Figure 4. Reduced sinusoidal wave

System analysis shows the achievement of a Total Harmonic Distortion (THD) value of 1.806%, which is well below the critical threshold of 5.0%. All individual harmonic components are also recorded below the standard limit of 3.0%, so that the system is declared to meet the qualifications of the international standard IEEE 519. Further success through time domain analysis, where the initially distorted current waveform is transformed into a nearly pure sinusoidal signal, guarantees the stability and efficiency of power distribution in the system as shown in (fig. 5).

The successful transformation of the waveform into a pure sinusoidal signal also reflects the effectiveness of the compensation or filtration strategies implemented in the system. The resulting power distribution stability not only improves energy efficiency but also optimizes the overall system capacity utilization by reducing excessive neutral currents in multi-phase systems.

Operationally, this result ensures that the plates and other mechanical components can operate at their maximum efficiency without the repetitive torque disturbances (torque pulsations) often triggered by the presence of low-order current harmonics.

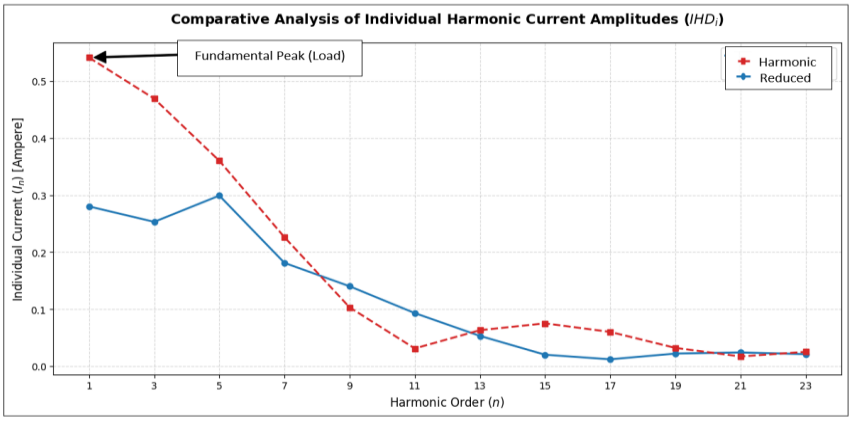


Figure 5. Time domain analysis

Conclusion

The fundamental current reaches 0.541 A, and significant distortion levels are observed in low-order harmonics, especially the third and fifth harmonics. These findings provide a strong technical basis to demonstrate that frequency spectrum noise attenuation is crucial before determining power quality mitigation measures in distribution panels. The implementation of passive filters in this study is proven to provide optimal mitigation performance by suppressing all odd harmonic components to meet the IEEE 519 international standard. Analysis using Fourier series in the time domain confirms that harmonic attenuation can be done by adding passive circuits to reduce distortion in the current, the use of passive filters successfully converts the initially distorted signal into a stable and pure sinusoidal waveform with a period of 0.02 seconds or a frequency of 50 Hz. The combination of appropriate mathematical modeling and a suitable passive filtration system is a reliable solution to maintain operational efficiency and stability in electrical distribution systems serving non-linear loads.

Conflict of Interest

Conflict of Interest Statement The authors declare no commercial financial interests or personal relationships that could appear to be construed as appearing in the work reported in this study.

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