

Hybrid Double-Tuned and High-Pass Filter for Harmonic Mitigation in Inverter HVAC Systems

Filter Hybrid Double-Tuned dan High-Pass untuk Mitigasi Harmonisa pada Sistem HVAC Inverter

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ABSTRACT — Inverter-based Heating, Ventilation, and Air Conditioning (HVAC) systems are increasingly utilized in industrial settings for their superior energy efficiency and controllability. Despite these advantages, nonlinear switching in inverters generates significant harmonic distortion, particularly at lower-order frequencies such as the 3rd and 5th, which can compromise power quality, reduce system lifespan, and lead to non-compliance with regulatory standards. This study proposes a hybrid passive filter solution—combining a Double Tuned Filter (DTF) and a High Pass Filter (HPF)—to mitigate harmonic distortion in an industrial HVAC system. Field data collected using a Power Quality Analyzer (PQA) revealed a 3rd-order Individual Harmonic Distortion of Current (IHDi) of 12.9%, far exceeding the 4.0% threshold specified in IEEE 519:2022. The hybrid filter was analytically designed and validated through MATLAB/Simulink simulation. Post-simulation results demonstrated effective mitigation of Total Harmonic Distortion (THD) to 3.45%, with the 3rd-order IHDi mitigated to 3.42%, achieving full compliance with IEEE 519:2022. Furthermore, the hybrid filter preserved voltage waveform quality and suppressed high-order harmonics without incurring additional energy losses or resonance issues. The combination of DTF and HPF offers wide-spectrum harmonic mitigation and enhanced power system stability. This solution is well-suited for high-load, scalable infrastructures aligned with Industry 4.0 requirements. The study concludes that passive hybrid filters are a reliable and cost-effective strategy for harmonic suppression, and future work should explore real-time adaptive control and hybrid active-passive configurations for enhanced dynamic performance.

KATA KUNCI — Mitigasi Distorsi Harmonik, Filter Pasif Hibrid, Filter Tuned Ganda, Filter High-Pass, Sistem HVAC Berbasis Inverter.

INTISARI — Sistem Pemanas, Ventilasi, dan Penyejuk Udara (HVAC) berbasis inverter semakin banyak digunakan di lingkungan industri karena efisiensi energi dan kemampuannya dalam pengendalian beban. Namun, proses pensaklaran nonlinier pada inverter menghasilkan distorsi harmonik yang signifikan, terutama pada frekuensi rendah seperti harmonik orde ke-3 dan ke-5. Hal ini dapat menurunkan kualitas daya, memperpendek umur peralatan, serta menyebabkan ketidaksesuaian terhadap standar regulasi. Studi ini mengusulkan solusi filter pasif hibrida—menggabungkan Double Tuned Filter (DTF) dan High Pass Filter (HPF)—untuk mitigasi distorsi harmonik pada sistem HVAC industri. Pengukuran lapangan menggunakan Power Quality Analyzer (PQA) menunjukkan bahwa distorsi harmonik individu Arus (IHDi) orde ke-3 mencapai 12,9%, jauh melebihi ambang batas 4,0% yang ditetapkan oleh IEEE 519:2022. Filter hibrida ini dirancang secara analitis dan divalidasi melalui simulasi MATLAB/Simulink. Hasil simulasi menunjukkan mitigasi efektif terhadap Total Harmonic Distortion (THD) menjadi 3,45%, dengan IHDi orde ke-3 berkurang menjadi 3,42%, sehingga memenuhi standar IEEE 519:2022. Selain itu, filter ini mampu menjaga kualitas gelombang tegangan dan meredam harmonik orde tinggi tanpa menyebabkan rugi-rugi daya tambahan atau risiko resonansi. Kombinasi DTF dan HPF memberikan mitigasi harmonik spektrum luas dan meningkatkan stabilitas sistem daya. Solusi ini sangat sesuai untuk infrastruktur berskala besar dan berdaya tinggi dalam konteks Industri 4.0. Studi ini menyimpulkan bahwa filter pasif hibrida adalah strategi yang andal dan hemat biaya untuk mitigasi harmonik, serta menyarankan penelitian lanjutan pada kontrol adaptif waktu nyata dan konfigurasi aktif-pasif untuk kinerja yang lebih dinamis.

KEYWORDS — Harmonic Distortion Mitigation, Hybrid Passive Filter, Double-Tuned Filter, High-Pass Filter, Inverter-based HVAC Systems.

I. INTRODUCTION

Inverter-based HVAC (Heating, Ventilation, and Air Conditioning) systems have become a preferred solution in both residential and commercial sectors due to their ability to enhance energy efficiency and user comfort [1], [2], [3]. The inverter technology enables precise control of compressor and motor speed, resulting in more stable operation and reduced energy consumption [4], [5]. However, despite these advantages, inverter-driven HVAC systems are not without technical challenges—particularly in the form of harmonic distortion, which can degrade power quality and overall system performance [6], [7], [8].

Harmonic distortion refers to the presence of unwanted frequency components (harmonics) in electrical waveforms, deviating them from the ideal sinusoidal form. Inverter-based HVAC systems are known sources of harmonic currents and voltages, especially

at low to mid-order frequencies [9]. These harmonics can interfere with other electronic equipment connected to the same power network, such as computers, televisions, lighting systems with electronic ballasts, and other sensitive devices [10].

Operationally, harmonics can significantly reduce the efficiency of HVAC systems by increasing power losses, reducing power factor, and causing overheating in components due to non-fundamental current flow. Moreover, harmonics contribute to higher values of Total Harmonic Distortion (THD) in both voltage and current, which is a key indicator of degraded power quality [11]. Failure to comply with harmonic standards may lead to technical penalties, system instability, or shortened equipment lifespan [12].

To mitigate these issues, passive filters are widely adopted due to their reliability and effectiveness in targeting specific harmonic frequencies. Among various filter configurations, the combination of Double-Tuned Filters (DTFs) and Second-Order High-Pass Filters (HPFs) has shown promising results in selectively attenuating dominant harmonic orders while maintaining power system stability [13]. DTFs are tuned to specific harmonic frequencies, while second-order HPFs are effective in suppressing higher-order harmonics and improving power factor [14], [15].

In this study, power quality data were collected from the sub-distribution panel of an inverter-driven HVAC system using a Power Quality Analyzer integrated with an intelligent control system. The measurements, processed using Power Vision software, revealed that the Individual Harmonic Distortion of Current (IHD_i) on phase L2 at the 3rd harmonic order reached 12.9%, significantly exceeding the 5% limit specified by IEEE Std 519-2022. These findings underscore the importance of identifying harmonic sources and implementing effective mitigation techniques to ensure optimal HVAC system performance and compliance with power quality standards.

II. LITERATURE REVIEW

A. HARMONIC DISTORTION IN INVERTER-BASED HVAC SYSTEMS

In inverter-based HVAC systems, harmonic distortion is a consequence of the nonlinear switching process inherent to inverters. The inverter converts direct current (DC) into alternating current (AC) using high-speed switching techniques such as Pulse Width Modulation (PWM) to control compressor speed [16]. This process results in load current waveforms that are no longer purely sinusoidal, but instead contain higher-order harmonic component [17]. Such harmonic distortion leads to an increase in Total Harmonic Distortion (THD), imposes additional stress on the electrical network, and may compromise system stability if not properly compensated (see Figure 1).

To mitigate harmonics, the system employs a combination of a Double-Tuned Filter (DTF) and a High-Pass Filter (HPF), both of which are passive filters [4], [18]. The DTF is specifically designed to resonate at targeted harmonic frequencies, while the HPF effectively attenuates a broader range of high-order harmonics. These filters generate a compensation current that absorbs the harmonic components of the load current, resulting in a supply current that is closer to a sinusoidal waveform [19]. Through the implementation of these passive filters, the system significantly enhances power quality, reduces THD, and ensures the reliable operation of inverter-based HVAC systems without the need for complex active control mechanisms.

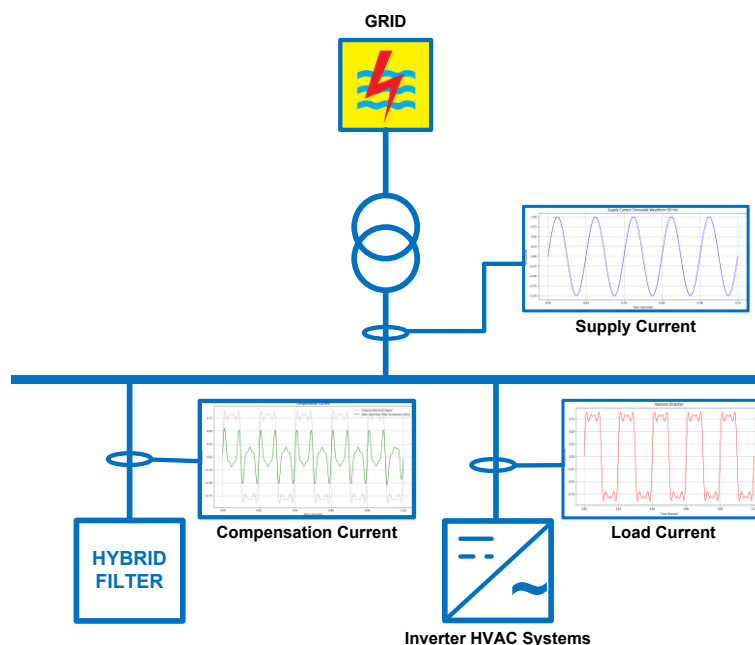


Figure 1. Block diagram of Hybrid Filter in operation Inverter HVAC Systems

B. DOUBLE-TUNED FILTER

The Double-Tuned Filter (DTF) is a passive filter topology specifically designed to attenuate two distinct harmonic frequency components in electrical power systems [20]. The impedance-versus-frequency characteristic shown in the figure demonstrates two clear minima, indicating the presence of dual resonant frequencies. At these frequencies, the filter presents very low impedance, allowing harmonic currents to be diverted through the filter to ground rather than flowing into the main power network [21]. In

contrast, at other frequencies—particularly at the fundamental frequency—the filter maintains high impedance to ensure that the fundamental current continues to flow to the load without interference (see Figure 2a).

On the right-hand side of the figure, two equivalent DTF circuit configurations are presented. The first consists of two parallel branches, each comprising a series connection of an inductor, capacitor, and damping resistor, individually tuned to specific frequencies. The second configuration is a more compact variant, where both branches are connected to a common central node while still maintaining equivalent filtering performance [22]. These configurations are designed to provide sharply selective low-impedance paths at the targeted frequencies, enabling effective harmonic mitigation (see Figure 2b). As a passive filtering solution, the DTF offers advantages in simplicity, operational reliability, and energy efficiency, making it highly suitable for use in systems with nonlinear loads such as inverter-based HVAC systems [23].

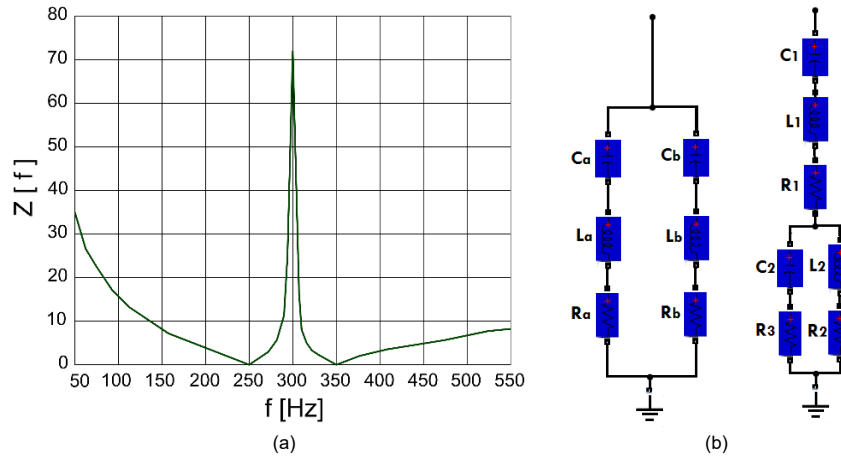


Figure 2. (a) Characteristics of Double-Tuned Filter (b) Design Double-Tuned Filter.

The additional reactive power required to improve the power factor is determined by the following expression:

$$\Delta Q = P(\tan \phi 1 - \tan \phi 2) \quad (1)$$

To determine the appropriate value of the compensation capacitor in each filter branch, the relationship between system voltage and the required reactive power for each frequency component is applied [24]. Specifically, the capacitive reactance for each branch, denoted as XC_a and XC_b , can be computed using the following expressions:

$$XC_a = \frac{V_s^2}{\Delta Q_a}, \quad XC_b = \frac{V_s^2}{\Delta Q_b} \quad (2)$$

Once the capacitive reactance XC_a and XC_b are determined for each filter branch, the corresponding capacitance values C_a and C_b can be calculated using the standard formula for capacitive reactance:

$$C_a = \frac{1}{2\pi f XC_a}, \quad C_b = \frac{1}{2\pi f XC_b} \quad (3)$$

The total capacitance for the filter branches can then be expressed as:

$$C_1 = C_a + C_b \quad (4)$$

Additionally, a secondary equivalent capacitance C_2 , which accounts for the interaction between the inductive and capacitive branches in the filter, is given by the following derived expression:

$$C_2 = \frac{C_a C_b (C_a + C_b) (L_a + L_b)^2}{(L_a C_a - L_b C_b)^2} \quad (5)$$

In a double-tuned passive filter (DTPF), the values of inductance in each branch must be appropriately tuned to resonate at the desired harmonic orders. This tuning is achieved by adjusting the inductive reactance based on the targeted harmonic number H_o . The inductive reactance for each filter branch is determined by:

$$XL_a = \frac{XC_a}{H_o^2}, \quad XL_b = \frac{XC_b}{H_o^2} \quad (6)$$

After calculating the reactance, the corresponding inductance values are derived using the fundamental relation:

$$L_a = \frac{XL_a}{2\pi f}, \quad L_b = \frac{XL_b}{2\pi f} \quad (7)$$

To model the combined inductance behavior of the two parallel branches, an equivalent inductance L_1 is calculated as:

$$L_1 = \frac{L_a L_b}{L_a + L_b} \quad (8)$$

This represents the parallel inductance resulting from the interaction between L_a and L_b . Furthermore, an effective inductance L_2 can be calculated to account for the mutual effect of capacitance and inductance within the filter topology, defined as:

$$L_2 = \frac{(L_a C_a - L_b C_b)^2}{(C_a + C_b)^2 (L_a + L_b)} \quad (9)$$

To evaluate the resistor values necessary for an optimal performance of a Double-Tuned Filter (DTF), the analytical approach incorporates fundamental relationships among the circuit parameters, including resonance frequency, inductance, capacitance, and

quality factor (Q) [25]. The resistances R_a , R_b , and R_1 represent the equivalent series resistances (ESR) corresponding to individual inductive branches within the DTF topology. These resistances are computed as follows:

$$R_a = \frac{2\pi \times f \times H_o \times L_a}{Q}, R_b = \frac{2\pi \times f \times H_o \times L_b}{Q} \quad (10)$$

$$R_1 = \frac{2\pi \times f \times L_1}{Q} \quad (11)$$

The total effective resistance R_2 and R_3 are obtained through harmonic impedance synthesis, incorporating the interaction of multiple resonance paths. These are calculated using the following composite expressions:

$$R_2 = R_a \left[\frac{a^2 (1 - x^2)}{(1 + a)^2 (1 + x^2)} \right] - R_b \left[\frac{1 - x^2}{(1 + a)^2 (1 + x^2)} \right] + R_1 \left[\frac{a(1 - a)(1 - x^2)}{(1 + a)^2 (1 + x^2)} \right] \quad (12)$$

$$R_3 = -R_a \left[\frac{a^2 x^4 (1 - x^2)}{(1 + ax^2)^2 (1 + x^2)} \right] - R_b \left[\frac{1 - x^2}{(1 + ax^2)^2 (1 + x^2)} \right] + R_1 \left[\frac{(1 - x^2)(1 - ax^2)}{(1 - x^2)(1 - ax^2)} \right] \quad (13)$$

The parameter a represents the ratio of the capacitance values between the two tuned branches of the filter. This value influences the distribution of reactive energy and directly determines the position and sharpness of the resonance frequencies [26]. Selecting an appropriate value of a allows for a balanced harmonic attenuation across all filter sections while avoiding impedance mismatches that could reduce the filter's overall effectiveness. This parameter can be mathematically expressed as follows:

$$a = \frac{C_a}{C_b} \quad (14)$$

The parameter x is a normalized coupling factor associated with frequency. This value reflects the proportional relationship between the inductive and capacitive elements in each filter branch. Specifically, x represents the resonant energy balance between the branches and plays a crucial role in tuning the Double-Tuned Filter (DTF) to effectively suppress specific harmonic orders [27]. The magnitude of this parameter directly influences the filter's bandwidth and the selectivity of its notch characteristics. The expression for this parameter can be formulated as follows:

$$x = \sqrt{\frac{L_b C_b}{L_a C_a}} \quad (15)$$

C. HIGH-PASS FILTER

The high-pass filter (HPF) is a type of passive filter widely used in electrical power systems to mitigate harmonics, particularly lower-order harmonics such as the 3rd, 5th, and 7th. The filter is designed to present high impedance at the fundamental frequency (e.g., 50 or 60 Hz) while offering significantly lower impedance at higher frequencies corresponding to harmonic components [28]. As a result, the HPF diverts harmonic currents away from the main distribution system and toward grounding paths or harmonic traps, thereby reducing the propagation of harmonic distortion across the network [29].

Technically, the HPF is typically implemented using RLC components (resistor, inductor, and capacitor) arranged to establish a cut-off frequency above the system's fundamental. In power systems incorporating inverter-based technologies—where harmonic distortion is commonly present—the implementation of HPFs significantly enhances power quality by reducing the Total Harmonic Distortion (THD) [30]. The performance of the HPF is determined by its design parameters and tuning accuracy relative to the target harmonic spectrum. Due to its passive characteristics, the HPF is widely favored for its operational stability, reliability, and cost-effectiveness compared to active harmonic mitigation techniques [31], [32].

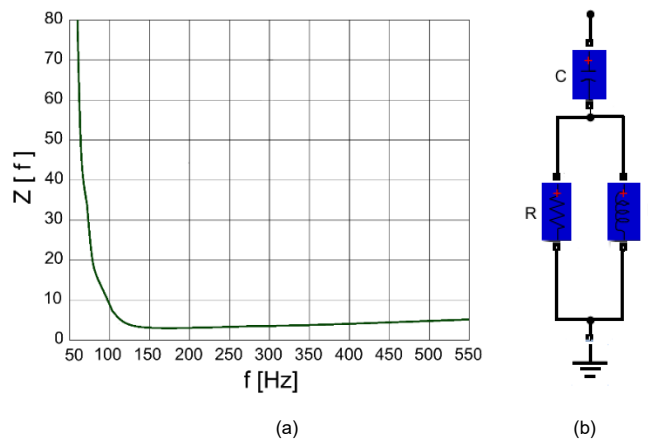


Figure 3. (a) Characteristics of High-Pass Filter (b) Design High-Pass Filter.

To evaluate the power factor correction and determine the required capacitance for the filter, the reactive power Qf is calculated using the following equation:

$$\Delta Q = P(\tan \phi 1 - \tan \phi 2) \quad (16)$$

Subsequently, the capacitive reactance X_C can be determined by:

$$X_c = \frac{V_s^2}{Qf} \tag{17}$$

The corresponding capacitance (C) value is then derived as:

$$C = \frac{1}{2\pi f X_c} \tag{18}$$

To account for harmonic mitigation at a specific harmonic order $H0$, the required inductive reactance X_L is calculated as:

$$X_L = \frac{X_c}{H0^2} \tag{19}$$

and the inductance (L) is obtained by:

$$L = \frac{X_L}{2\pi f} \tag{20}$$

For damping purposes, the characteristic impedance X_n of the LC filter is expressed as:

$$X_n = \sqrt{\frac{L}{C}} \tag{21}$$

Finally, the resistance (R) needed to achieve the desired quality factor (Q_{Filter}) is given by:

$$R = X_n \times Q_{Filter} \tag{22}$$

III. METHODOLOGY

A. RESEARCH FLOWCHART

In this study, harmonic distortion analysis was conducted on the AC distribution system, specifically at the outgoing panel of the Sub Distribution Panel (SDP). The electrical parameters were recorded using a Power Quality Analyzer (PQA), namely the MYeBOX, which was wirelessly operated through a tablet interface. Measurements were performed during the operation of the HVAC system to capture real-time load conditions.

The recorded data were subsequently transferred to a personal computer and analyzed using Power Vision software, focusing on harmonic spectrum evaluation. The analysis was guided by the IEEE 519-2022 standard, which specifies that the Total Harmonic Distortion of current (THDi) must not exceed 5%. Should the measured THDi surpass this threshold, harmonic mitigation becomes necessary.

To address excessive harmonic levels, a hybrid passive filtering approach was adopted by combining a Double-Tuned Filter (DTF) and a High-Pass Filter (HPF). The design of these filters was carried out through analytical methods, followed by simulation and performance verification using MATLAB/Simulink.

The research methodology is illustrated in Figure 4. The left branch of the flowchart describes the measurement and compliance verification workflow, while the right branch details the filter design, simulation, and iterative refinement process. Compliance with the IEEE 519-2022 standard was used as the evaluation benchmark both in the measurement phase and in the simulation environment to ensure effectiveness and alignment with international power quality standards.

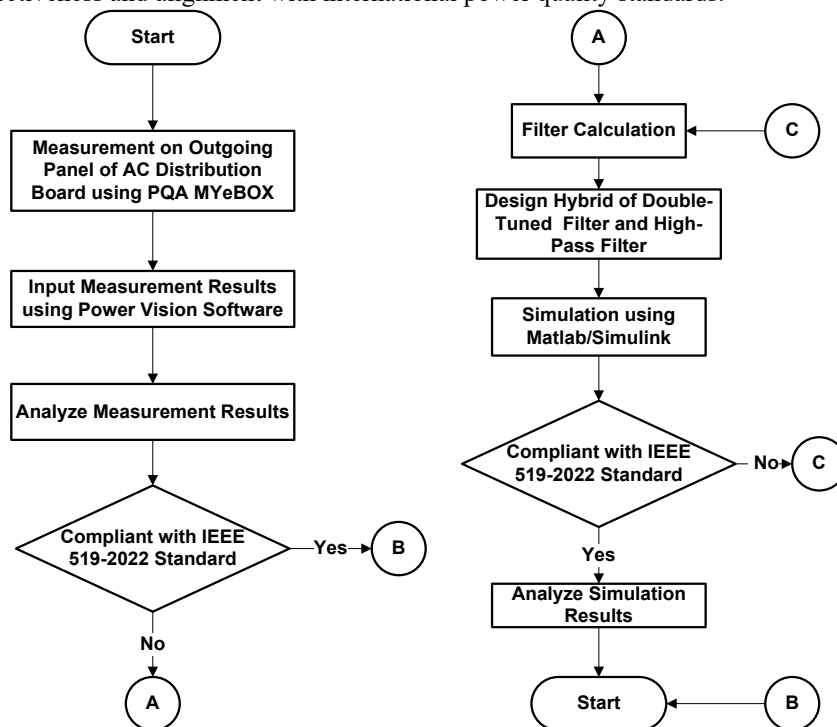


Figure 4. Research Flowchart.

B. IHDi MEASUREMENT RESULTS

Measurements obtained using a Power Quality Analyzer revealed that the observed current waveform deviates significantly from a pure sinusoidal form due to the presence of harmonic components. This distortion is predominantly attributed to the 3rd-order harmonic, which exhibited a high Individual Harmonic Distortion of Current (IHDi) of 12.9%, far exceeding the 4% limit prescribed by IEEE 519:2022. The dominance of this odd harmonic suggests the influence of nonlinear loads such as inverters, fluorescent lighting, and switching power supplies. These harmonics distort the current waveform, resulting in increased power losses, excessive heating of equipment, and potential malfunction of protective devices. Consequently, the mitigation of the 3rd-order harmonic is critical, and the application of passive filtering techniques is considered an effective strategy to restore power quality within acceptable limits.

TABLE 1
 MEASURED INDIVIDUAL HARMONIC DISTORTION OF CURRENT (IHDi)

Harmonic Order	Frequency (Hz)	IHDi (%)	IEEE 519:2022 Limit (%)	Compliance Status
3	150	12.9	4.0	Non-Compliant
5	250	1.5	4.0	Compliant
7	350	0.9	4.0	Compliant
9	450	0.9	4.0	Compliant
11	550	0.9	2.0	Compliant
13	650	0.8	2.0	Compliant
15	750	0.8	2.0	Compliant
17	850	0.7	1.5	Compliant
19	950	0.7	1.5	Compliant
21	1050	0.7	1.5	Compliant
23	1150	0.7	0.6	Non-Compliant
25	1250	0.7	0.6	Non-Compliant
27	1350	0.7	0.6	Non-Compliant
29	1450	0.6	0.6	Compliant
31	1550	0.7	0.6	Non-Compliant
33	1650	0.6	0.6	Compliant
35	1750	1.3	0.3	Non-Compliant
37	1850	1.3	0.3	Non-Compliant
39	1950	1.2	0.3	Non-Compliant
41	2050	1.2	0.3	Non-Compliant
43	2150	1.3	0.3	Non-Compliant
45	2250	1.1	0.3	Non-Compliant
47	2350	1.8	0.3	Non-Compliant
49	2450	1.9	0.3	Non-Compliant

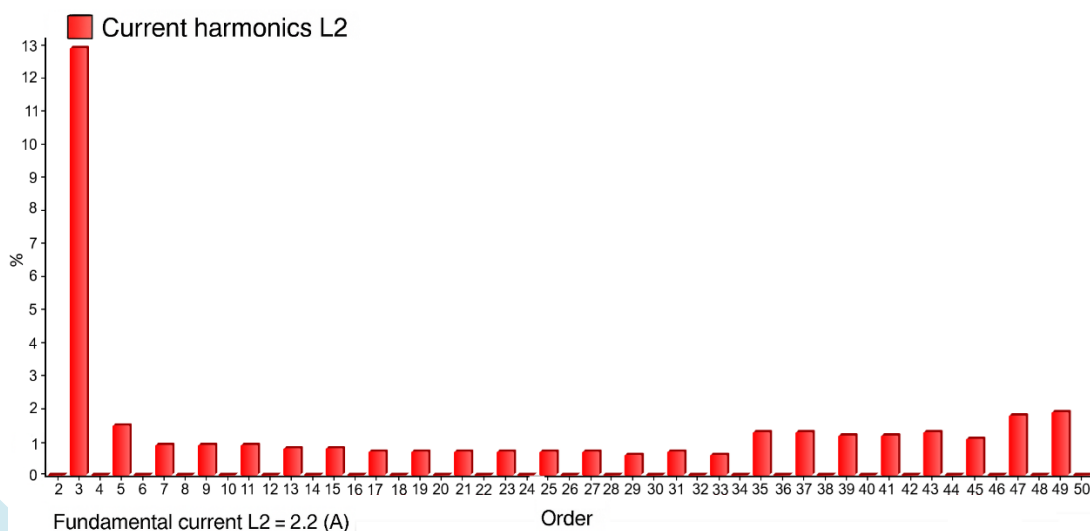


Figure 5. IHDI Measurement Results.

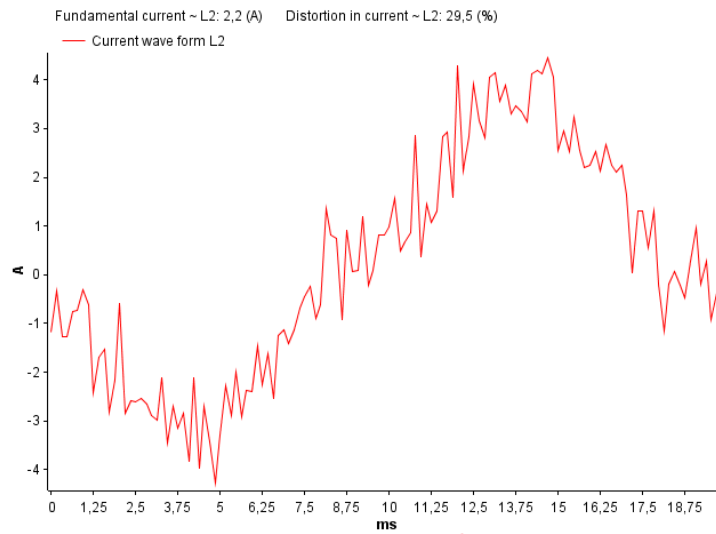


Figure 6. Measured Non-Sinusoidal Current Waveform

C. DESIGN HYBRID FILTER

Figure 7 illustrates the design of a hybrid filter topology composed of a Double Tuned Filter (DTF) and a High Pass Filter (HPF), connected in parallel between the power grid and a nonlinear HVAC load. This hybrid configuration is developed to reduce dominant harmonic components, particularly the 3rd, 5th, 37th, and 39th orders, which are commonly found in industrial power systems due to the operation of power electronic devices and nonlinear loads. The DTF functions as a selective resonant filter with RLC parameters specifically tuned to absorb certain harmonic frequencies without affecting the fundamental component. In parallel, the HPF complements the system by attenuating high-frequency harmonics through its characteristic of low impedance at high frequencies and high impedance at the fundamental frequency.

Table 2 shows that each filter stage has customized RLC configurations based on the targeted harmonic order. The DTF maintains a constant capacitance value of 5.64873×10^{-4} F across all orders, while resistance and inductance values are varied to achieve resonance at the desired frequency. In the HPF, the inductance values are significantly smaller than those in the DTF, while the capacitance values are relatively larger for certain harmonic orders such as the 5th and 39th, with values of 1.296×10^{-3} F. This configuration allows the HPF to provide a low-impedance path for high-frequency harmonics, diverting them away from the main supply line.

The hybrid filter design offers advantages in selectively mitigating low-order harmonics while also providing wideband attenuation of high-order harmonics, which can lead to overheating, electromagnetic interference, and reduced equipment lifespan. In addition, the parallel connection between the DTF and HPF ensures minimal power losses and maintains system stability under varying load conditions. Overall, this hybrid filter enhances power quality, reduces total harmonic distortion, and improves the operational reliability of HVAC systems in industrial environments. The design aligns with harmonic control guidelines defined by the IEEE-519 standard and provides an effective solution for modern power systems facing increasing harmonic pollution.

TABLE 2
RLC PARAMETERS OF DTF AND HPF HYBRID FILTER DESIGN

Order	Filter	R (Ω)	L (H)	C (F)
3rd	DTF	39.24	0.208811	5.64873×10^{-4}
	HPF	9.396	0.001995	5.64873×10^{-4}
5th	DTF	0.289	0.004600	5.64873×10^{-4}
	HPF	0.805	1.470×10^{-5}	1.296×10^{-3}
37th	DTF	0.258	0.0013726	5.64873×10^{-4}
	HPF	0.760	1.310×10^{-5}	5.64873×10^{-4}
39th	DTF	0.191	8.71193×10^{-5}	5.64873×10^{-4}
	HPF	0.650	9.710×10^{-6}	1.296×10^{-3}

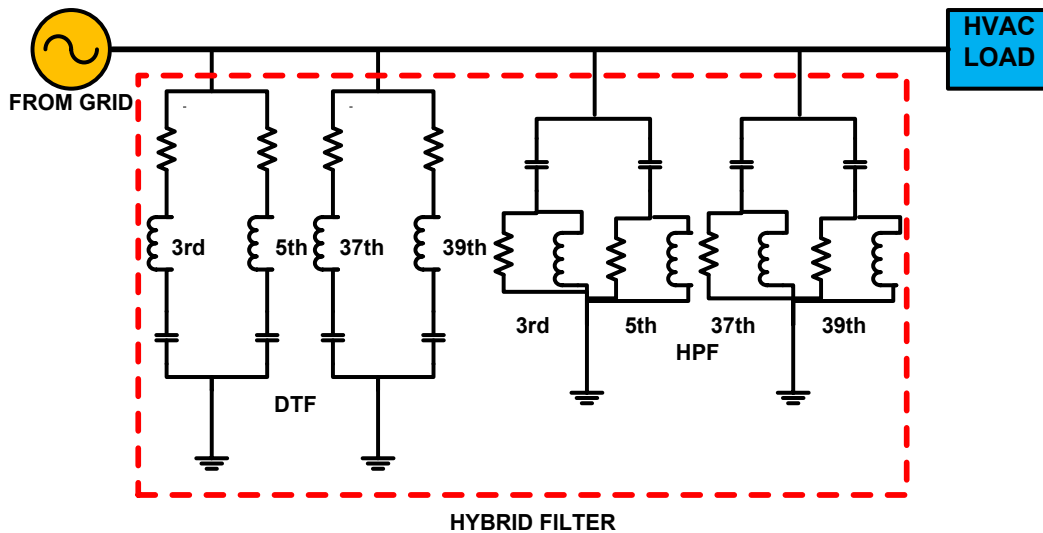


Figure 7. Design Hybrid Filter

IV. ANALYSIS AND DISCUSSION

A. HARMONIC MITIGATION USING HYBRID FILTER IN HVAC SYSTEMS

Figure 8 illustrates the overall configuration of the electrical system, where a hybrid filter is installed between the utility grid (PLN) and the industrial HVAC load. The system, simulated using MATLAB/Simulink, integrates a hybrid filter consisting of two types of passive filters, namely the Double Tuned Filter (DTF) and the High Pass Filter (HPF), each designed to target specific harmonic orders and attenuate high-frequency harmonics across a wide range. This combination aims to enhance power quality, minimize harmonic distortion, and protect HVAC equipment from the adverse effects of harmonic interference. The system also includes metering and monitoring components to track power quality parameters in real time.

Following the implementation of the hybrid filter in the Simulink-based model, the harmonic spectrum of the filtered current is shown in Figure 9. The fundamental frequency component at 50 Hz accounts for 90.12% of the total signal magnitude, while the Total Harmonic Distortion (THD) is reduced to 3.45%. This significant reduction reflects the effectiveness of the harmonic mitigation strategy. Lower-order harmonics, such as the 3rd and 5th, which typically dominate distortion in industrial systems, have been successfully attenuated below critical thresholds. Further details are presented in Table 3, which summarizes the Individual Harmonic Distortion of Current (IHDi) for each harmonic order and compares the results with the maximum allowable limits defined by IEEE 519:2022. For the 3rd harmonic, the IHDi is 3.42%, remaining within the acceptable limit of 4.0%. All measured harmonics up to the 49th order fall well below their respective limits, with all values marked as “Compliant,” indicating that the hybrid filter implemented in the MATLAB/Simulink environment effectively ensures compliance with international power quality standards.

The impact of harmonic mitigation is further confirmed by the time-domain waveform shown in Figure 10, which displays the current signal after filtering. The waveform exhibits a clean sinusoidal shape with a full cycle of 20 ms and a peak current of approximately -2 A. This result aligns with the spectral analysis and demonstrates that the system has been restored to a nearly ideal fundamental waveform condition. Overall, the MATLAB/Simulink-based simulation and analysis confirm that the proposed hybrid filter configuration is highly effective in eliminating both low-order and high-order harmonics. The system successfully restores waveform purity, enhances power quality, and meets the harmonic distortion limits specified by IEEE 519:2022. This solution is particularly well-suited for industrial applications such as HVAC systems, where voltage and current stability, energy efficiency, and regulatory compliance are critically important.

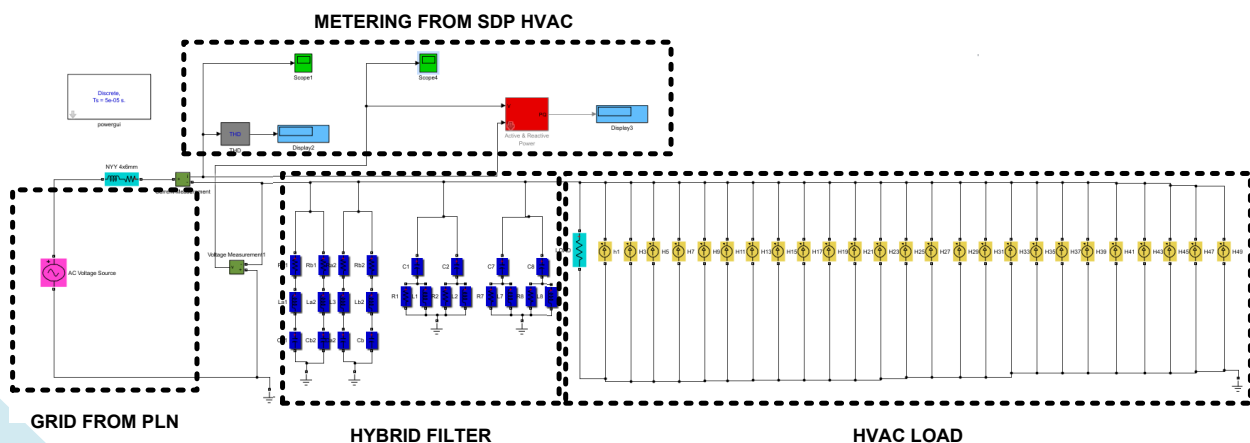


Figure 8. HVAC Electrical System Model with Hybrid Filter in Simulink

TABLE 3
 SIMULATED IHDI RESULTS USING HYBRID FILTER BASED ON IEEE 519:2022

Harmonic Order	Frequency (Hz)	IHDI (%)	IEEE 519:2022 Limit (%)	Compliance Status
3	150	3.42	4.0	Compliant
5	250	0.36	4.0	Compliant
7	350	0.13	4.0	Compliant
9	450	0.09	4.0	Compliant
11	550	0.06	2.0	Compliant
13	650	0.05	2.0	Compliant
15	750	0.04	2.0	Compliant
17	850	0.03	1.5	Compliant
19	950	0.02	1.5	Compliant
21	1050	0.01	1.5	Compliant
23	1150	0.02	0.6	Compliant
25	1250	0.02	0.6	Compliant
27	1350	0.01	0.6	Compliant
29	1450	0.01	0.6	Compliant
31	1550	0.01	0.6	Compliant
33	1650	0.02	0.6	Compliant
35	1750	0.03	0.3	Compliant
37	1850	0.03	0.3	Compliant
39	1950	0.03	0.3	Compliant
41	2050	0.03	0.3	Compliant
43	2150	0.04	0.3	Compliant
45	2250	0.07	0.3	Compliant
47	2350	0.07	0.3	Compliant
49	2450	0.08	0.3	Compliant

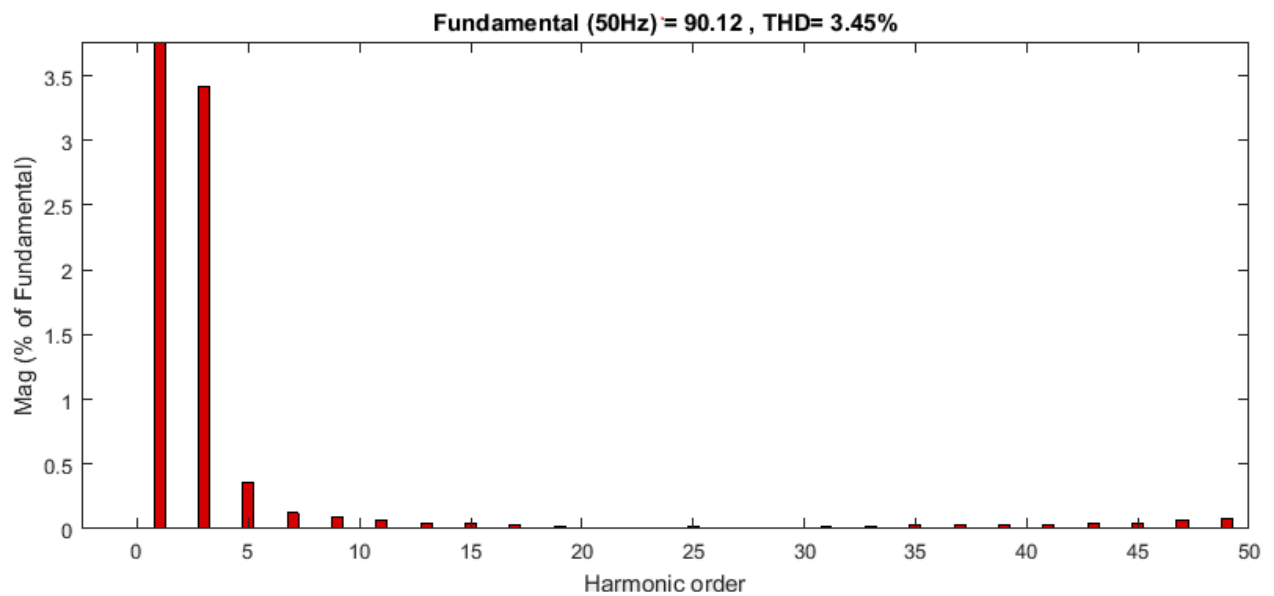


Figure 9. IHDI Spectrum After Simulation

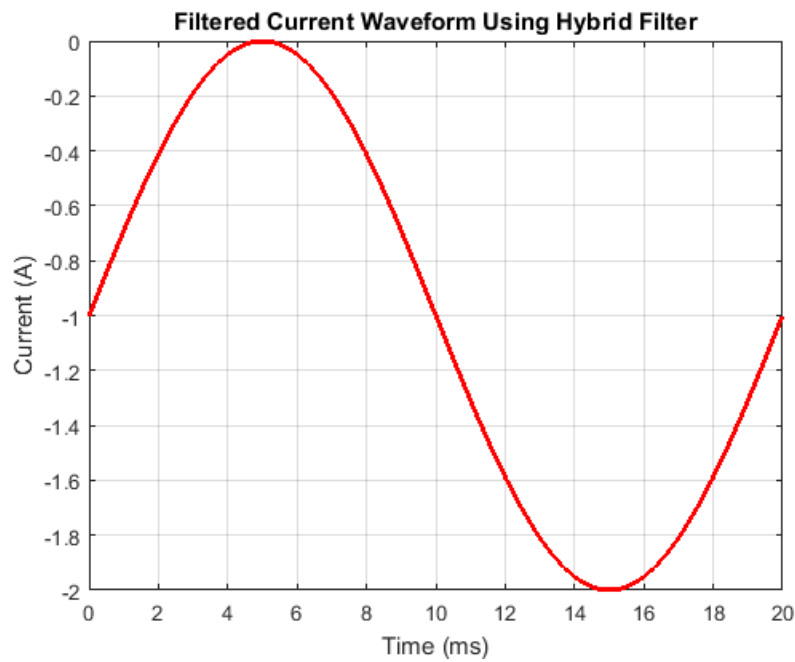


Figure 10. Current Waveform After Harmonic Mitigation with a Hybrid Filter

B. ANALYSIS OF TEST RESULTS

Figure 11 illustrates the comparative performance of harmonic distortion levels represented by the Individual Harmonic Distortion of Current (IHDi) for odd harmonic orders ranging from the 3rd to the 49th. The graph presents three datasets: (1) Measured IHDi values using a Power Quality Analyzer (PQA) under actual operational conditions of an industrial HVAC system, (2) IEEE 519:2022 standard limits, and (3) Simulated IHDi values after the implementation of a hybrid filter composed of a Double Tuned Filter (DTF) and a High Pass Filter (HPF).

The most critical distortion was observed at the 3rd harmonic, where the IHDi measured 12.9%, significantly exceeding the IEEE 519:2022 permissible limit of 4.0%. This confirms the dominance of triplen harmonics (especially 3rd-order) in HVAC systems, mainly caused by nonlinear power electronic devices such as variable frequency drives. Additionally, measured IHDi values for the 5th, 7th, 9th, and 11th harmonic orders are relatively close to the standard thresholds, with values ranging from 0.8% to 1.5%, indicating persistent low-order harmonic disturbances in the system.

After the application of the hybrid filtering system, the simulated IHDi values show a remarkable attenuation across all harmonic orders. The 3rd harmonic is reduced from 12.9% to 3.42%, successfully falling below the IEEE threshold. The 5th and 7th harmonics are attenuated from 1.5% and 0.9% to 0.36% and 0.13%, respectively. Higher-order harmonics such as the 35th through 49th, which initially recorded moderate distortion levels between 1.1% and 1.9%, are also reduced significantly to values as low as 0.07–0.08%, demonstrating the wide-spectrum effectiveness of the filter.

The DTF component of the hybrid filter effectively targets specific low-order harmonics due to its narrow band tuning, while the HPF component ensures suppression of high-frequency harmonic noise by providing low impedance paths above the corner frequency. This combination not only addresses harmonic magnitudes but also ensures system stability by avoiding resonance phenomena common in conventional passive filters.

The comprehensive mitigation observed across all harmonic orders underscores the robustness of the hybrid filter design in improving power quality. By reducing IHDi to below IEEE standards, the system minimizes additional thermal stress on electrical components such as transformers, capacitors, and distribution cables. This directly translates into improved energy efficiency, extended equipment lifespan, and reduced maintenance intervals in HVAC-dominated industrial facilities.

In conclusion, the experimental and simulated results validate the hybrid filter as an effective solution for harmonic mitigation in HVAC systems. Its ability to reduce dominant and residual harmonic components ensures compliance with international power quality standards, enhances operational reliability, and supports the broader objectives of energy-efficient and sustainable industrial automation.

The implementation of hybrid filters in HVAC systems also demonstrates a significant positive impact on voltage stability and the reduction of parallel resonance risks, which are commonly observed in electrical networks with high levels of nonlinear load penetration. By stabilizing the harmonic distortion profile to exceptionally low levels, the system effectively minimizes voltage fluctuations that could adversely affect the performance of sensitive components, such as automatic control systems and HVAC sensors. Moreover, the filter's capability to suppress harmonics up to high-order components indicates that the design is not only optimized for low-order harmonic-dominant conditions but is also inherently adaptable to dynamic variations in the harmonic spectrum. This adaptability provides the necessary flexibility and scalability for long-term deployment in large-scale HVAC infrastructures, which are continuously evolving to meet the complex demands of Industry 4.0 and the sustainable, human-centric innovations of Industry 5.0.

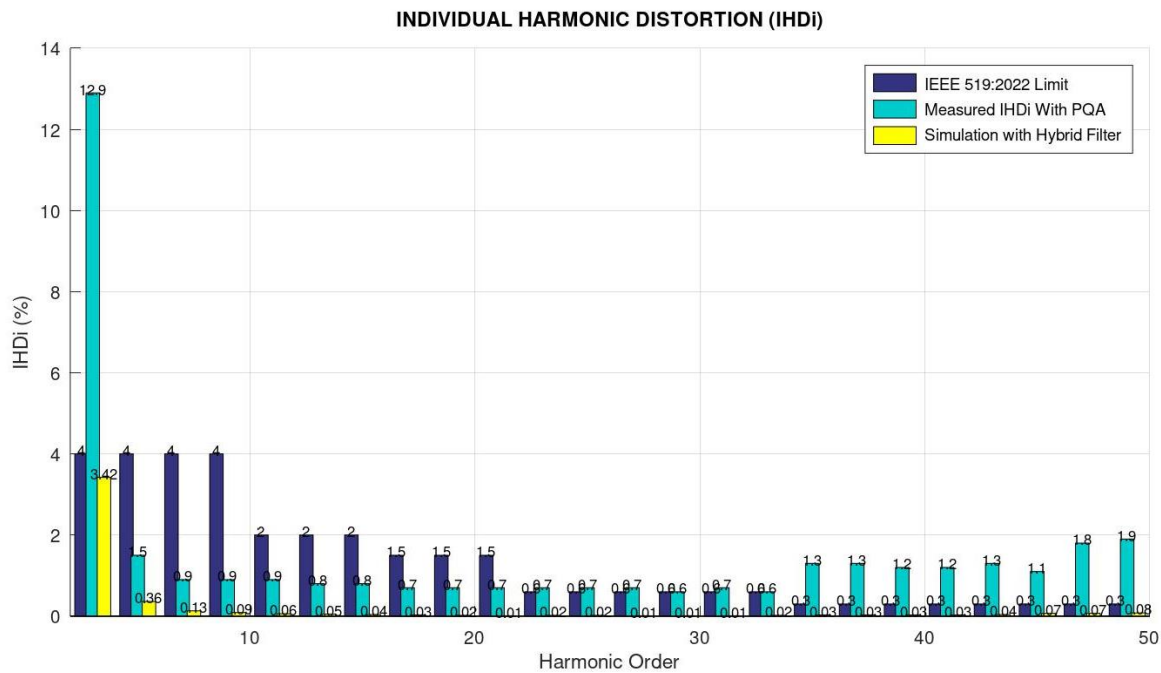


Figure 11. IHDi Comparison of Measurement, Simulation, and IEEE 519:2022 in an HVAC System

V. CONCLUSION

This study presents a comprehensive approach to harmonic mitigation in industrial HVAC systems through the implementation of a hybrid passive filter composed of a Double Tuned Filter (DTF) and a High Pass Filter (HPF). Empirical measurements conducted using a Power Quality Analyzer (PQA) revealed significant harmonic distortion, particularly at the 3rd-order harmonic, which recorded an Individual Harmonic Distortion of Current (IHDi) of 12.9%, exceeding the IEEE 519:2022 compliance threshold. Such findings emphasize the pressing need for effective harmonic control strategies in nonlinear load-dominated environments. The proposed hybrid filter, designed and validated through MATLAB/Simulink simulations, demonstrated exceptional performance in attenuating both low- and high-order harmonic components. Post-simulation results showed a substantial reduction in IHDi across all targeted harmonic orders, with the Total Harmonic Distortion (THD) reduced to 3.45%, well below the maximum allowable limit of 5%. Notably, the 3rd harmonic was mitigated to 3.42%, thereby ensuring full compliance with international standards. Beyond harmonic suppression, the hybrid filter design also contributed to improved voltage waveform quality, enhanced system stability, and reduced risk of resonance, without introducing significant additional losses. This not only supports the operational reliability of HVAC systems but also promotes energy efficiency, reduced thermal loading, and extended equipment lifespan.

In summary, the hybrid filtering strategy effectively addresses the challenges posed by harmonic distortion in industrial power systems and fulfills the technical requirements stipulated IEEE 519:2022 standards. The proposed approach offers a scalable and adaptable solution for modern HVAC infrastructures, aligning with the evolving demands of Industry 4.0 and the sustainable, human-centric principles of Industry 5.0. Future research may extend this work by implementing real-time filter control strategies and exploring active-passive hybrid solutions for even greater flexibility and dynamic adaptability in power quality enhancement.

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