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Comprehensive Analysis and Reduction of Total Harmonic Distortion in Grid-Connected Renewable Energy Systems

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ABSTRACT: This paper presents an effective approach for the analysis and mitigation of total harmonic distortion (THD) in a hybrid renewable energy system integrating solar photovoltaic (PV) and wind turbine sources connected to an AC grid. The presence of non-linear loads introduces significant harmonic distortions in the grid current, adversely affecting power quality and system stability. To overcome this challenge, a harmonic extraction and adaptive filtering control scheme is proposed. The method utilizes a Synchronous Reference Frame (SRF) transformation to convert three-phase grid currents into the d–q domain, facilitating accurate separation of fundamental and harmonic components. An adaptive filtering technique based on the Least Mean Square (LMS) algorithm is employed to dynamically estimate and suppress harmonic components through continuous adjustment of error signal weights. The extracted harmonics are used to generate a compensating current, which is injected into the grid via an Active Power Filter (APF) inverter to effectively cancel distortions caused by non-linear loads. The performance of the proposed system is evaluated through simulation using measurement and Fast Fourier Transform (FFT) analysis to assess harmonic spectra before and after compensation. The results demonstrate a substantial reduction in THD, along with improved power quality and enhanced grid stability. These findings validate the effectiveness and robustness of the proposed adaptive control strategy for harmonic mitigation in renewable energy-based power systems.

KEYWORDS: Total Harmonic Distortion (THD), Hybrid Renewable Energy System, Synchronous Reference Frame (SRF), Least Mean Square (LMS) Algorithm, Active Power Filter (APF).

I. INTRODUCTION

The increasing penetration of renewable energy sources into modern power systems has significantly transformed the structure and operation of electrical grids. Among these sources, solar photovoltaic (PV) and wind energy systems have gained widespread adoption due to their environmental benefits, sustainability, and decreasing installation costs. However, the integration of these renewable energy systems into conventional AC grids introduces several power quality challenges, particularly when combined with non-linear loads [1]. These loads, which include power electronic devices, variable speed drives, and rectifiers, are major contributors to harmonic distortion in power systems. Harmonics are undesirable frequency components that distort the ideal sinusoidal waveform of voltage and current. The presence of harmonics leads to increased losses, overheating of equipment, malfunction of sensitive devices, and reduced overall system efficiency. One of the key indicators used to quantify harmonic distortion is Total Harmonic Distortion (THD). Maintaining THD within acceptable limits, as specified by power quality standards, is essential for ensuring reliable and efficient grid operation [2]. In hybrid renewable energy systems, where multiple distributed energy resources are interfaced through power electronic converters, the issue of harmonic distortion becomes even more pronounced.

To address these challenges, advanced harmonic mitigation techniques are required. Among various approaches, Active Power Filters (APFs) have emerged as an effective solution for compensating harmonic currents and improving power quality. APFs operate by injecting compensating currents into the system to cancel out harmonic components generated by non-linear loads [3]. However, the effectiveness of APFs largely depends on the accuracy and speed of harmonic detection and extraction methods used in the control strategy. In this context, the Synchronous Reference Frame (SRF) method has been widely utilized for harmonic extraction due to its capability to transform three-phase quantities into a rotating reference frame. This transformation simplifies the separation of fundamental and harmonic components, making it easier to identify and isolate distortions. Nevertheless, conventional SRF-based methods may face limitations

under dynamic operating conditions, such as fluctuations in renewable energy generation or sudden load variations. To enhance the performance of harmonic detection, adaptive filtering techniques have been introduced. In particular, the Least Mean Square (LMS) algorithm offers a simple and efficient approach for real-time estimation and minimization of harmonic components [4]. By continuously updating filter coefficients based on the error signal, the LMS algorithm provides improved adaptability and robustness under varying system conditions. When integrated with the SRF framework, this approach enables precise harmonic extraction and effective compensation.

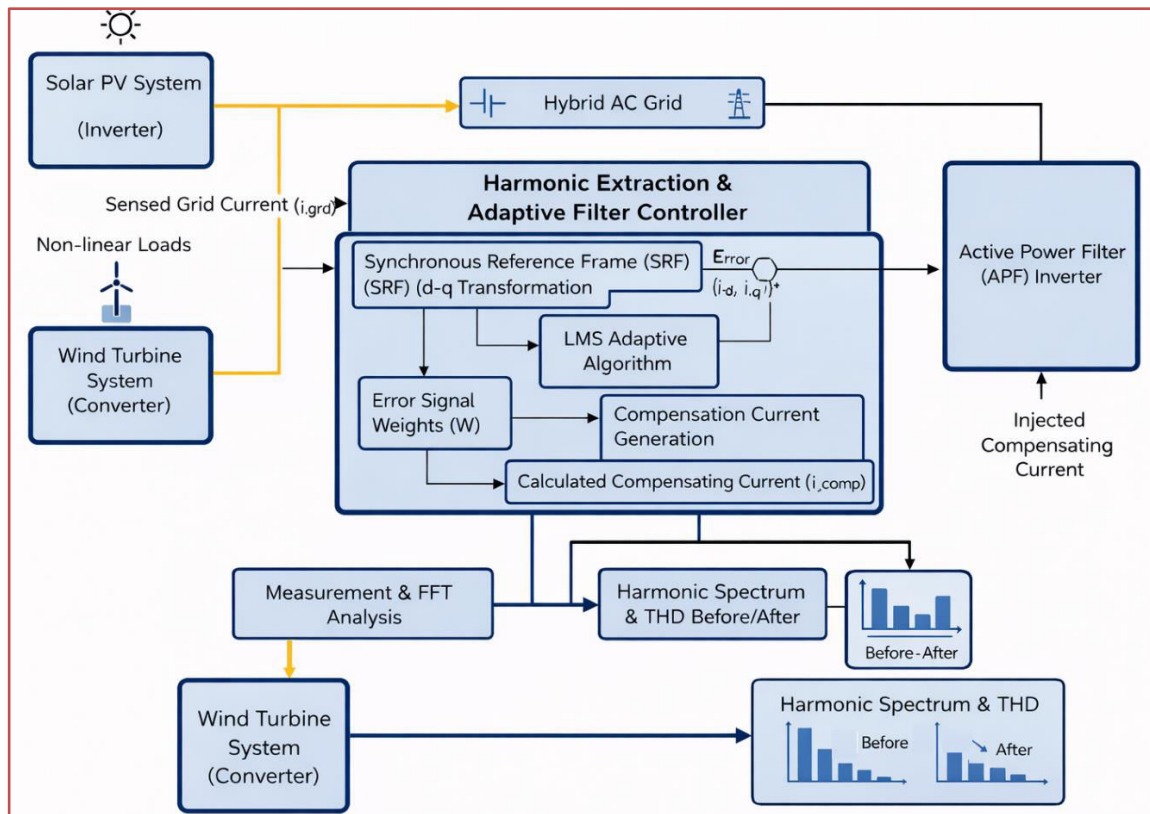


Fig. 1 Block Diagram of SRF–LMS Based Active Power Filter for Harmonic Reduction [4] [5]

This paper proposes a hybrid control strategy (as per figure 1) that combines SRF transformation with an LMS-based adaptive filtering algorithm for harmonic mitigation in a grid-connected renewable energy system. The extracted harmonic components are used to generate a compensating current, which is injected into the grid through an Active Power Filter (APF). The proposed system is designed to operate under the influence of non-linear loads, ensuring improved power quality and reduced harmonic distortion [5]. The performance of the proposed method is evaluated through simulation studies. Measurement and Fast Fourier Transform (FFT) analysis are employed to assess the harmonic spectrum and quantify THD before and after compensation. The results demonstrate a significant reduction in harmonic distortion, validating the effectiveness of the proposed control strategy. Overall, this work contributes to the development of reliable and efficient power quality enhancement techniques for modern renewable energy-based power systems [6].

II. PROPOSED CONTROL METHODOLOGY

The proposed methodology aims to mitigate Total Harmonic Distortion (THD) in a hybrid renewable energy system by integrating Synchronous Reference Frame (SRF) theory with a Least Mean Square (LMS)-based adaptive filtering algorithm and an Active Power Filter (APF). Initially, the three-phase grid currents are transformed into the d–q reference frame using SRF transformation, enabling effective separation of fundamental and harmonic components. The LMS adaptive algorithm is then employed to continuously estimate and minimize harmonic content by updating filter weights based on the error signal. This process ensures accurate extraction of harmonic components under dynamic operating conditions [7]. The identified harmonics are used to generate a reference compensating current,



which is converted back to the abc frame. Finally, the APF inverter injects this compensating current into the grid to cancel distortions caused by non-linear loads. This integrated approach significantly reduces THD, improves power quality, and enhances the overall stability and performance of the hybrid renewable energy system.

The three-phase grid currents (i_a, i_b, i_c) are transformed into the rotating d-q reference frame using Park's transformation [8]. This allows separation of fundamental and harmonic components.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos \left(\theta - \frac{2\pi}{3} \right) & \cos \left(\theta + \frac{2\pi}{3} \right) \\ -\sin \theta & -\sin \left(\theta - \frac{2\pi}{3} \right) & -\sin \left(\theta + \frac{2\pi}{3} \right) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

In the synchronous reference frame, the fundamental component is represented as a constant (DC) value. In contrast, harmonic components appear as oscillating signals with varying frequencies.

The Least Mean Square (LMS) adaptive filter is employed to estimate the fundamental component and effectively extract harmonic content from the distorted signal [9]. The error signal, representing the difference between the desired signal and the estimated output, is expressed as:

$$e(n) = d(n) - y(n)$$

where $d(n)$ denotes the measured (desired) current and $y(n)$ represents the estimated fundamental component. The adaptive filter updates its weight vector iteratively to minimize this error using the LMS algorithm, defined as:

$$w(n+1) = w(n) + \mu e(n) x(n)$$

where $w(n)$ is the filter weight vector, μ is the step size controlling the convergence rate, and $x(n)$ is the input signal. Through continuous adjustment of weights, the LMS algorithm minimizes the error signal and accurately isolates harmonic components, ensuring effective harmonic mitigation under varying system conditions.

The harmonic components extracted in the d-q reference frame are utilized to generate the reference compensating current required for harmonic mitigation. This compensating current in the d-q frame is given by:

$$i_{comp}^{dq} = i_{harm}^{dq}$$

The obtained reference current is then transformed back into the three-phase (abc) frame using the inverse Park's transformation to produce the final compensating current signals:

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = f^{-1}(i_d, i_q)$$

This process ensures that the extracted harmonic components are accurately converted into time-domain compensating currents, which can be injected into the system by the Active Power Filter (APF) to effectively cancel distortions and improve power quality [10].

The Active Power Filter (APF) inverter plays a crucial role in harmonic mitigation by injecting the required compensating current into the grid to counteract distortions introduced by non-linear loads. By generating a current equal in magnitude and opposite in phase to the harmonic components, the APF effectively cancels these distortions, resulting in improved current waveform quality. The relationship between source, load, and compensating currents is expressed as:

$$i_{source} = i_{load} - i_{comp}$$

As a result, the source current becomes nearly sinusoidal with significantly reduced harmonic content, leading to lower Total Harmonic Distortion (THD) and enhanced overall power quality of the system [10].

Total Harmonic Distortion (THD) is a key parameter used to quantify the level of harmonic distortion present in a signal and is typically evaluated using Fast Fourier Transform (FFT) analysis. FFT decomposes the signal into its fundamental and harmonic frequency components, allowing accurate measurement of their magnitudes [11]. THD is



defined as the ratio of the root mean square (RMS) value of all harmonic components to the RMS value of the fundamental component, expressed as a percentage. A lower THD value indicates better power quality and a waveform closer to an ideal sinusoidal shape.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100\%$$

The proposed SRF - LMS based control method effectively extracts harmonic components and generates accurate compensating currents. When implemented with an APF, it significantly reduces THD, improves power quality, and enhances the stability of the hybrid renewable energy system [12] [13].

III. SIMULATION SETUP AND PARAMETERS

The simulation model represents a hybrid renewable energy system integrating a 20-kW wind energy conversion system and a 20-kW solar photovoltaic (PV) system connected to a common grid through a Voltage Source Converter (VSC). The wind system consists of a wind turbine coupled with a generator and power electronic interface, while the PV system includes a PV array with maximum power point tracking (MPPT) and a DC–DC converter for optimal power extraction. Both sources are connected to a common DC link, which is interfaced with the AC grid via a three-phase VSC. The grid is modelled with appropriate voltage and current measurement blocks to monitor system performance. Non-linear loads are connected at the point of common coupling (PCC) to introduce harmonic distortion.

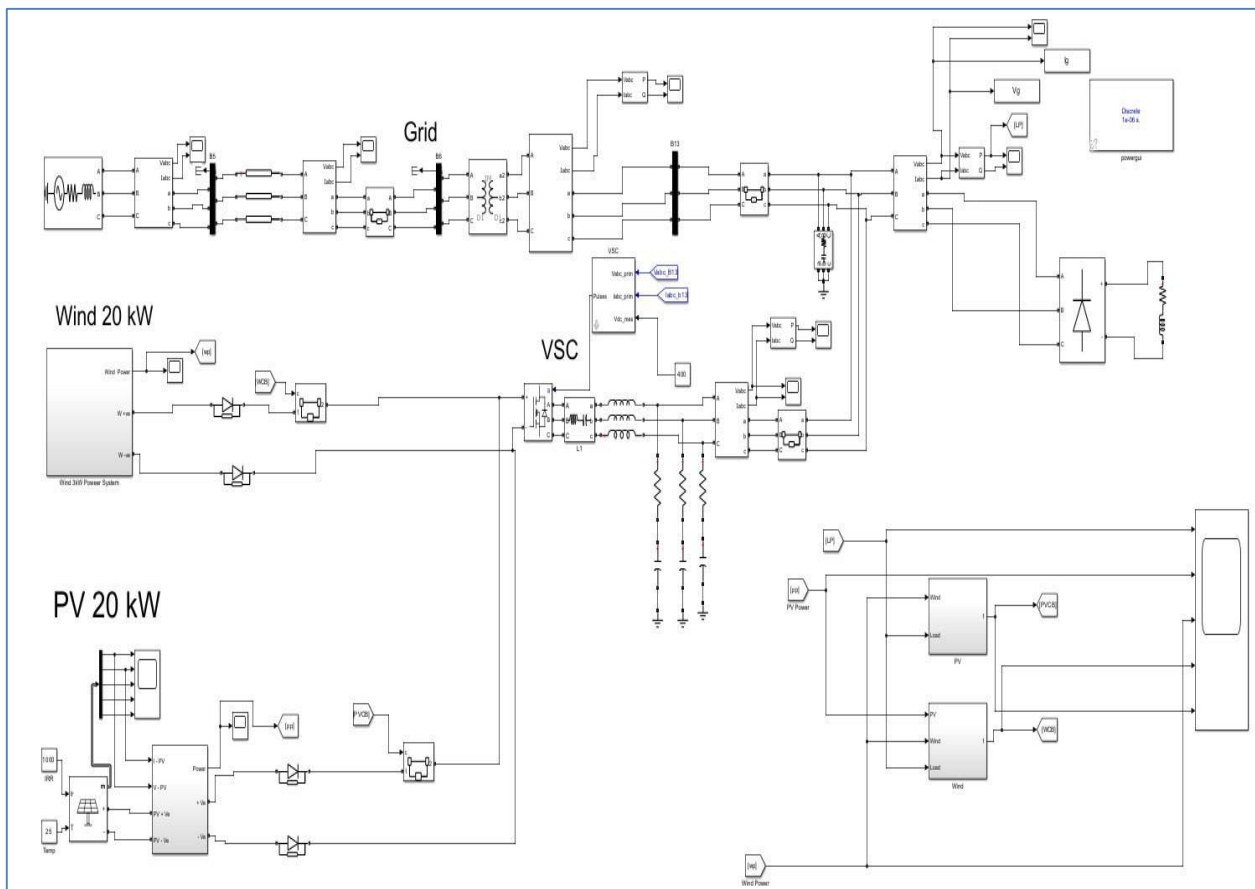


Fig. 2 Proposed Simulation for Solar PV-WES Hybrid Renewable system with Grid Connection

The VSC is equipped with filtering components, including inductors and capacitors, to reduce switching ripples. Control blocks are implemented to regulate DC-link voltage and manage power flow from both renewable sources.



Additionally, measurement and signal processing units, including FFT analysis, are incorporated to evaluate harmonic content and Total Harmonic Distortion (THD) before and after compensation. The system parameters are selected to ensure stable operation, efficient power transfer, and effective harmonic mitigation under varying load and generation conditions [14].

IV. RESULTS ANALYSIS AND DISCUSSION

The simulation results of the hybrid renewable energy system integrating 20 kW solar PV and 20 kW wind energy sources demonstrate effective power sharing and significant improvement in power quality. The system is evaluated under non-linear load conditions, which introduce harmonic distortions into the grid current.

The simulation results illustrate the dynamic performance of load, PV, and wind power over time. The load power initially fluctuates and then stabilizes with minor oscillations after 0.1 seconds. Here, PV power output remains nearly constant, indicating stable solar generation under steady conditions. Moreover, PV switching signal shows rapid ON - OFF operation, representing PWM-based control behaviour. The wind power gradually increases in steps and reaches a steady-state value after approximately 0.2 seconds. The wind system ON - OFF signal indicates initial switching activity followed by stable operation. Overall, the results demonstrate coordinated operation of PV and wind sources with stable power delivery to the load.

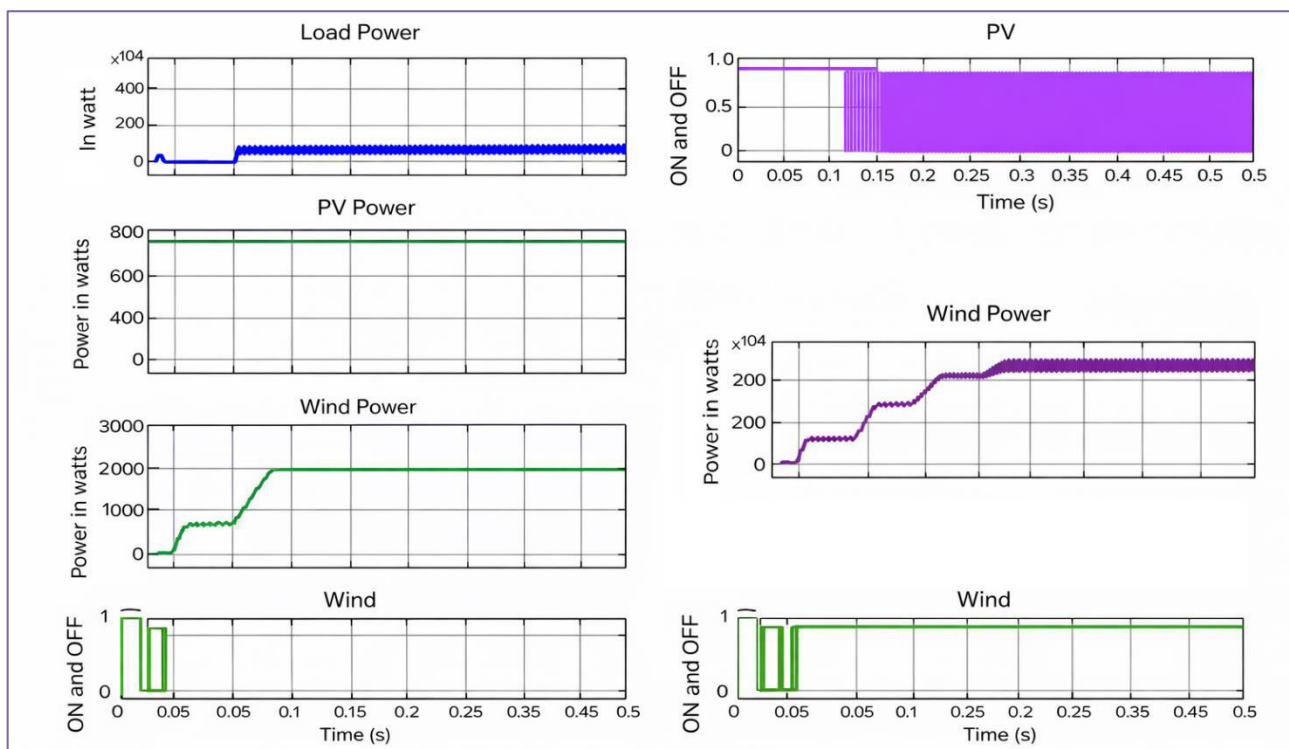


Fig. 3 Waveform analysis for the SPV and Wind power with load power

After the connection of the Active Power Filter (APF), the three-phase voltage and current waveforms become balanced and sinusoidal. The distortion present in the current waveform is significantly reduced, resulting in smooth and stable sinusoidal currents. The voltage waveform also shows improved quality with minimal harmonic distortion after compensation. The phase currents are properly synchronized with the corresponding voltages, indicating improved power factor. Overall, the APF effectively reduces THD and enhances power quality and system stability

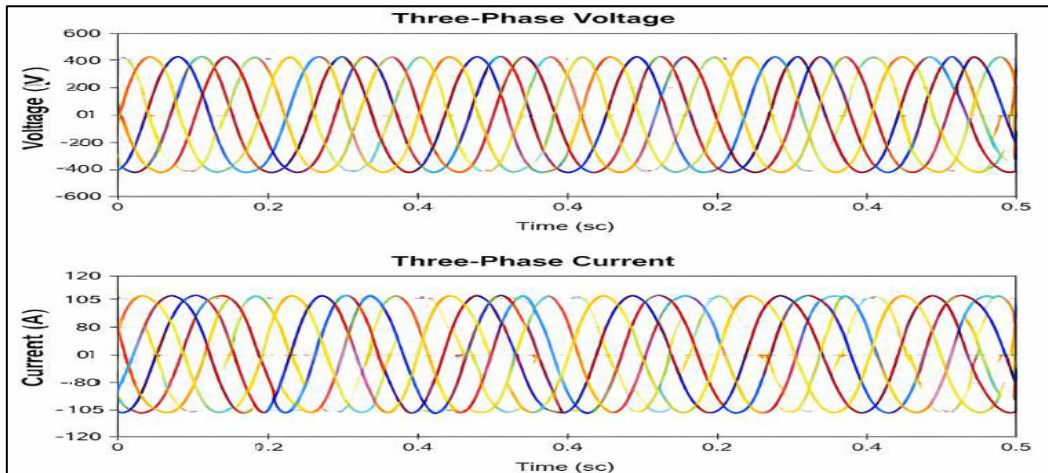


Fig. 4 Voltage and current waveform after connection of APF

The Total Harmonic Distortion (THD) analysis clearly demonstrates the effectiveness of the Active Power Filter (APF) in improving power quality. Without the APF, the voltage waveform exhibits a high THD of 16.24%, while the current waveform shows a distortion level of 12.71%, indicating significant harmonic presence due to non-linear loads. These elevated THD values result in poor waveform quality and reduced system efficiency. However, after the integration of the APF, a substantial reduction in harmonic distortion is observed. The THD of the voltage waveform decreases to 2.14%, and the current waveform THD is reduced to 1.63%, both of which fall within acceptable standards. This significant improvement confirms that the APF effectively compensates harmonic components and restores near-sinusoidal waveforms.

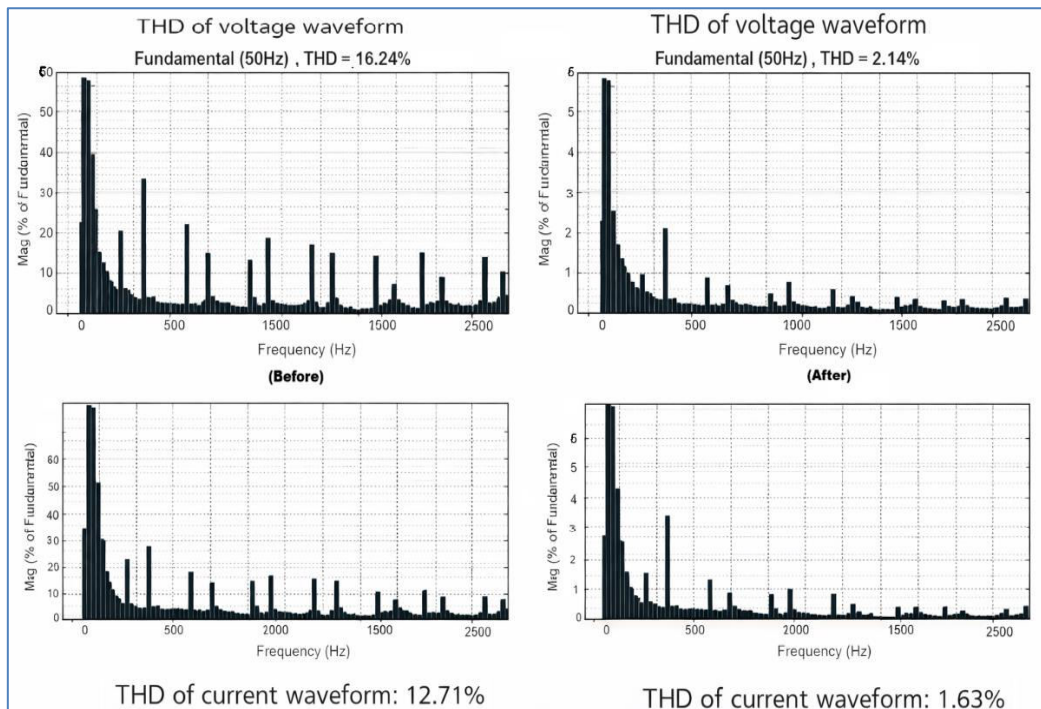


Fig. 5 THD analysis (Before APF and After APF)

Consequently, the overall system performance is enhanced, ensuring better power quality, reduced losses, and improved reliability of the hybrid renewable energy system.



V. FUTURE SCOPE OF WORK

The proposed SRF–LMS based Active Power Filter (APF) control strategy has demonstrated effective reduction of Total Harmonic Distortion (THD) and improvement in power quality for hybrid renewable energy systems. However, future work can focus on enhancing the adaptability and intelligence of the control scheme under highly dynamic grid conditions. Advanced control techniques such as Artificial Intelligence (AI), Machine Learning (ML), and neural network-based adaptive filters can be integrated to improve harmonic detection accuracy and response speed [15]. Additionally, the implementation of real-time hardware systems using FPGA or DSP platforms can be explored to validate the practical feasibility and performance of the proposed method beyond simulation environments.

Further research can also extend the proposed system to larger and more complex power networks, including microgrids and smart grids with multiple distributed energy resources. The inclusion of energy storage systems such as batteries or supercapacitors can enhance system stability and support during transient conditions. Moreover, the impact of varying environmental conditions, grid faults, and unbalanced loads can be investigated to improve system robustness [16]. Optimization of controller parameters and reduction of computational complexity can also be considered to make the system more efficient and cost-effective for real-world applications.

VI. CONCLUSION

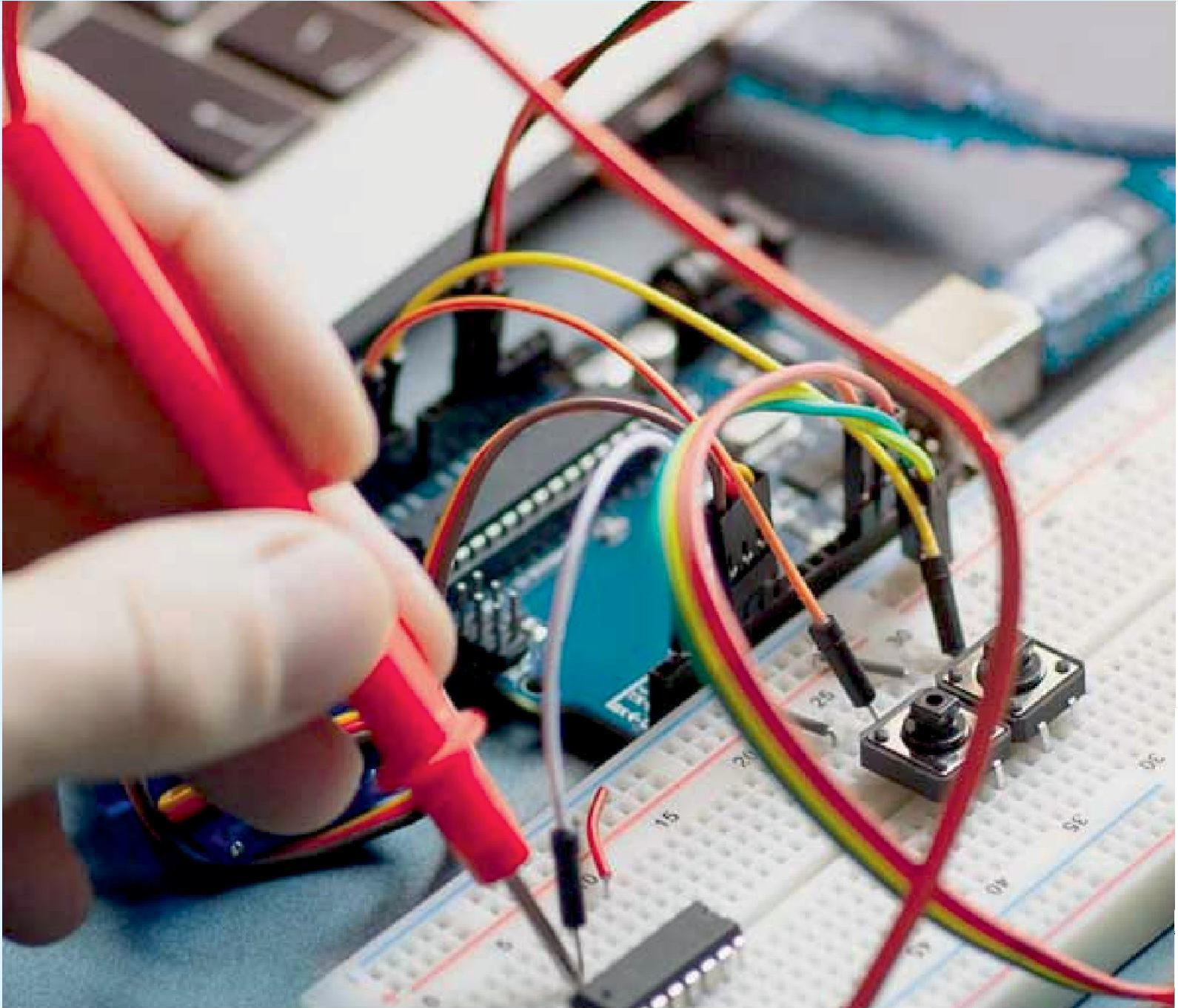
The proposed SRF–LMS based Active Power Filter (APF) control strategy has been successfully implemented and evaluated for harmonic mitigation in a hybrid renewable energy system integrating solar PV and wind sources. The results clearly indicate a significant improvement in power quality, as the Total Harmonic Distortion (THD) of the voltage waveform is reduced from 16.24% to 2.14%, and the current waveform THD is decreased from 12.71% to 1.63% after APF compensation. These values fall well within standard acceptable limits, confirming the effectiveness of the proposed approach. Additionally, the system achieves balanced three-phase voltage and current waveforms with near-sinusoidal characteristics, demonstrating proper harmonic suppression. Furthermore, the coordinated operation of the Voltage Source Converter (VSC) ensures stable DC-link voltage and efficient power sharing between the solar PV and wind energy systems. The LMS-based adaptive filtering technique provides fast convergence and accurate harmonic extraction under varying load conditions.

REFERENCES

- [1] Kumar, N. (2024). Scalable Harmonic Compensation Techniques for Active Power Filters in Renewable Energy Systems. *THE REVIEW OF CONTEMPORARY SCIENTIFIC AND ACADEMIC STUDIES: The Review of Contemporary Scientific and Academic Studies*, 4(9).
- [2] Panpean, C., Homjan, J., Udomsuk, S., & Areerak, K. (2025). Control Strategy Improvement of Active Power Filters for Harmonic Elimination in Heavy Rail Systems With Installed PV Arrays. *IEEE Access*.
- [3] Shah, P. K. (2025). *Custom Power Device Based Power Quality Enhancement and Power Flow Management in Solar PV Based Grid Tie Renewable System* (Doctoral dissertation, Gujarat Technological University).
- [4] Karthikeyan, M., Sharmilee, K., Balasubramaniam, P. M., Prakash, N. B., Babu, M. R., Subramaniaswamy, V., & Sudhakar, S. (2020). Design and implementation of ANN-based SAPF approach for current harmonics mitigation in industrial power systems. *Microprocessors and Microsystems*, 77, 103194.
- [5] Sharma, S. K., Gali, V., & Gupta, S. K. (2024). Investigation of multifunctional grid-tied PV inverter with even and odd order harmonic mitigation using active and harmonic power weight control strategy. *Energy Systems*, 1-23.
- [6] Meraouah, M., Hassaine, S., Kaddari, F., Moreau, S., Mihoub, Y., & Benkhaled, A. (2026). Ripple reduction and power quality improvement in photovoltaic and wind integration using hybrid intelligent nonlinear control with a shunt active power filter. *Electrical Engineering*, 108(1), 65.
- [7] Israni, R. K., & Parekh, C. (2024). Power quality enhancement in hydroelectric-solar PV-based hybrid system by exploiting CPD. *International Journal of Smart Grid and Green Communications*, 2(3), 231-248.
- [8] Chitra, M., & Sakthivel, P. (2025). Power quality optimization in hybrid renewable energy system using MDNSOGI-based predictive control. *Electrical Engineering*, 107(11), 14735-14754.
- [9] Kundu, S., Singh, M., & Giri, A. K. (2024). SPV-wind-BES-based islanded electrical supply system for remote applications with power quality enhancement. *Electrical Engineering*, 106(1), 279-294.



- [10] Tyagi, M., Meena, D. C., & Kundu, S. (2026, January). Next-Generation Control Strategy for Renewable Microgrids with Bidirectional Battery Support. In *2026 International Conference on Electric Power and Renewable Energy (EPREC)* (pp. 1-6). IEEE.
- [11] Chakraborty, S., Modi, G., & Singh, B. (2022, October). A robust IMFOGI control for power quality enhancement of a dual stage SPV-BES-BDC-SyRG DG set based standalone microgrid. In *2022 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 1-8). IEEE.
- [12] Shukla, D. M., Zaveri, N., & Sutikno, T. (2023). The performance of a multilevel multifunctional solar inverter under various control methods. *Bulletin of Electrical Engineering and Informatics*, 12(5), 2717-2732.
- [13] Singh, B. (2018, December). Improved Damped Quadrature SOGI Control algorithm for Solar PV-Hydro Battery Based Microgrid. In *2018 8th IEEE India International Conference on Power Electronics (IICPE)* (pp. 1-6). IEEE.
- [14] Govil, V. K., Sahay, K., Tripathi, S. M., Sinha, A., Kumar, N., Ibraheem, I. K., & Smerat, A. (2026). Power Quality Control in PV Systems with DSTATCOM: Methods and Performance Evaluation. *Smart Grids and Sustainable Energy*, 11(1), 28.
- [15] Al-Jame, F., & Btia, J. (2025). AI-Driven Control Strategies for Power Converters in Solar–Wind Hybrid Energy Systems: Enhancing Efficiency, Reliability, and Grid Resilience. *Transactions on Power Electronics and Renewable Energy Systems*, 1-7.
- [16] mohammadi, H., Radmehr, M., Nouri, T., & Ghafouri, A. (2026). Optimization of maximum power point tracking in a wind-solar hybrid power plant by neural networks for reducing total harmonic distortion (THD). *Energy Informatics*.



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