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Article

Strengthening Power Quality in Active Distribution Network via Harmonics filters Integration

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Abstract: Rapid urbanization and changing energy demands have made the delivery of clean and reliable electricity increasingly critical. Renewable systems have also become more popular in recent years owing to the increased demand for clean energy sources. Wind systems have the advantage of being able to utilize the abundant and free energy provided by the wind. However, the harmonics produced by the fluctuating incident energy from renewable sources could lead to subpar system performance. Both power producers and consumers now consider power quality to be a significant concern. The frequent use of power electronic devices and nonlinear loads in regular usage schedules introduces harmonic distortions into the electrical distribution network. Power quality is negatively impacted by harmonics in multiple ways, including decreased power-generating efficiency, voltage distortion, increased operating expenses, equipment overheating, transformer saturation, electromagnetic interference, etc. To address these issues, it is pivotal to use a well-suited filtration technique and to evaluate its performance in the context of harmonic reduction. The integration of filters is one of the foremost methods for harmonic mitigation. Since the mission is always to increase power quality while using the fewest possible filtering units, this study presents a harmonic mitigation framework for an IEEE 33-bus active distribution network (ADN) comprising a wind farm, a battery energy storage system (BESS), and an electric vehicle (EV) charging station. Harmonic propagation is assessed by evaluating the Total Harmonic Distortion (THD) across all buses in distribution network, enabling identification of the most vulnerable buses. Based on the harmonic assessment, Single-Tuned Filters (STFs) are strategically deployed at Buses 15, 29, and 33 to suppress the dominant fifth-order harmonic. Simulation results demonstrate a maximum THD reduction of **65.38%** at Bus 33.The proposed STF allocation significantly mitigates harmonic distortion across the network; however, a limited number of buses continue to exhibit THD values exceeding the **IEEE 519** recommended limit of **5%**, indicating scope for further optimization or complementary harmonic mitigation measures. Overall, the proposed selective STF placement strategy effectively enhances power quality, offering a practical and economically viable solution for harmonic mitigation in renewable-integrated active distribution networks.
Keywords: Total Harmonic Distortion, Single tuned filter (STF), Active Distribution Network, Power Quality, Battery Energy Storage System, Electric Vehicle Charging Station, Wind farm

1. Introduction

The global transition towards sustainable and low-carbon energy systems has accelerated the deployment of renewable energy resources within electrical distribution networks. Among various renewable technologies, wind energy has emerged as one of the most promising alternatives owing to its environmental benefits, technological maturity, and abundant energy potential. Simultaneously, BESSs and EVCSs are increasingly being integrated into modern distribution grids to enhance renewable energy utilization, improve system flexibility, and support future electrification initiatives. Consequently, conventional passive distribution systems are evolving into ADNs, where multiple converter-interfaced distributed energy resources (DERs) operate in a coordinated manner to improve energy efficiency, reliability, and sustainability.

Despite these advantages, the extensive use of power electronic converters introduces significant power quality challenges. Unlike conventional rotating machines, converter-based renewable energy systems, battery storage units, and EV chargers behave as nonlinear sources that inject harmonic currents into the network. The simultaneous operation of these devices modifies harmonic propagation characteristics and may lead to excessive voltage and current distortion throughout the distribution feeder. Moreover, the widespread use of nonlinear consumer loads, including adjustable-speed drives, switched-mode power supplies, and industrial electronic equipment, further aggravates harmonic distortion. Excessive harmonics deteriorate voltage quality, increase network losses, reduce transformer and motor efficiency, accelerate insulation ageing, cause equipment overheating, interfere with communication systems, and may trigger maloperation of protection devices. Consequently, maintaining harmonic levels within the limits prescribed by IEEE Std. 519 has become an essential requirement for ensuring reliable and secure operation of modern power distribution systems.

Recent research has investigated numerous techniques for harmonic mitigation in distribution networks. Passive harmonic filters remain the most widely adopted solution owing to their simple structure, low installation cost, and high effectiveness in suppressing dominant low-order harmonics. Various filter topologies, including Single-Tuned Filters (STFs), Double-Tuned Filters (DTFs), C-type filters, and high-pass filters, have demonstrated satisfactory performance under different loading conditions. In parallel, Active Power Filters (APFs) and Hybrid Active Power Filters (HAPFs) have attracted considerable attention because of their superior compensation capability, adaptive control strategies, and ability to mitigate multiple harmonic orders simultaneously. However, these advanced filtering technologies generally require sophisticated control algorithms, higher converter ratings, increased switching frequencies, and substantial investment costs, thereby limiting their practical implementation in medium- and low-voltage distribution systems.

To improve both technical performance and economic feasibility, recent studies have increasingly focused on optimization-based harmonic filter allocation. Metaheuristic algorithms, such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Whale Optimization Algorithm (WOA), and other evolutionary techniques, have been successfully employed to determine the optimal size and location of passive filters while simultaneously minimizing harmonic distortion, improving voltage profiles, reducing active power losses, and enhancing power factor. Although these approaches have demonstrated promising results, most investigations have been conducted on conventional radial distribution systems or networks containing a single renewable energy source. Comparatively fewer studies have examined harmonic interactions arising from the simultaneous integration of wind generation, battery energy storage systems, and electric vehicle charging infrastructure within a unified ADN. Furthermore, existing optimization studies generally prioritize loss minimization or voltage profile improvement, whereas filter placement based primarily on the severity of harmonic distortion across individual buses has received relatively limited attention.

Motivated by these observations, this work investigates harmonic propagation and mitigation in an IEEE 33-bus ADN integrating a wind farm, a BESS, and an EVCS. Firstly, Harmonic propagation is done to identify the buses most susceptible to harmonic amplification. Subsequently, Single-Tuned Filters are strategically designed and installed at the most severely affected buses (Buses15, 29 and 33) to suppress the dominant fifth-order harmonic while limiting the number of installed filtering devices. Unlike conventional approaches that employ extensive filter deployment or computationally intensive optimization algorithms, the proposed methodology provides a practical and cost-effective framework for targeted harmonic mitigation, significantly reducing harmonic reduction and improving power quality across the network.

The principal contributions of this work are summarized as follows:

- Development of an active IEEE 33-bus distribution network integrating a wind farm, BESS and EVCS.
- Comprehensive harmonic assessment of converter-interfaced renewable energy sources.
- Identification of the most harmonically vulnerable buses based on network-wide THD assessment.

- Design and selective placement of STFs for effective suppression of dominant fifth-order harmonics with minimum filter deployment.
- Comparative evaluation of the network before and after filter installation, demonstrating significant THD reduction and improvement in overall harmonic performance.
- Demonstration of a technically effective and economically viable harmonic mitigation strategy for renewable-integrated ADNs.

The remainder of this paper is organized as follows. Section 2 presents the system configuration and problem formulation for the IEEE 33-bus ADN. Section 3 describes the proposed harmonic assessment and Single-Tuned Filter design methodology. Section 4 discusses the simulation results and evaluates the effectiveness of the proposed harmonic mitigation strategy. Finally, Section 5 concludes the paper and outlines potential directions for future research.

2. Problem Formulation

2.1. Test Distribution System

The effectiveness of the proposed harmonic mitigation strategy is evaluated using the standard IEEE 33-bus radial distribution system, which is widely recognized as a benchmark for assessing planning and operational methodologies in ADNs. Owing to its radial topology, realistic loading conditions, and extensive adoption in the literature, the IEEE 33-bus system provides an appropriate platform for investigating harmonic propagation and evaluating power quality enhancement techniques.

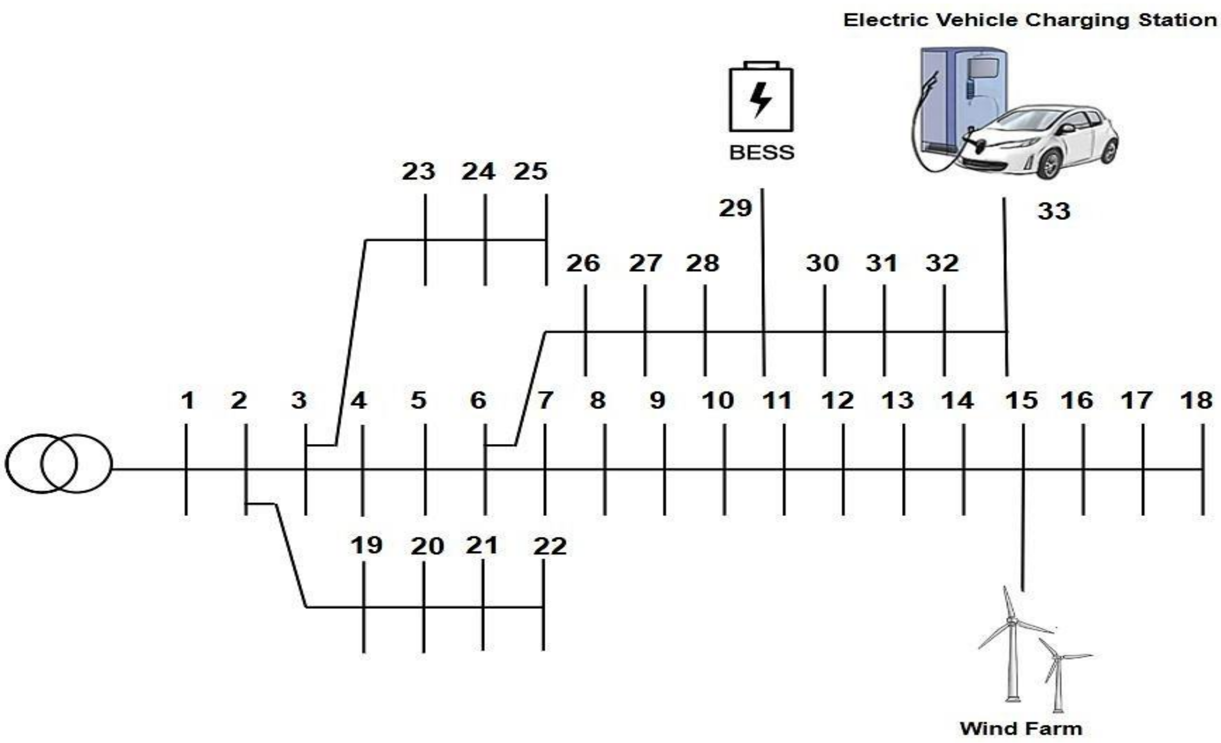

Fig.1: Single-line diagram of the Proposed IEEE-33 bus system.

The test system consists of **33 buses** interconnected through **32 distribution lines** operating at a nominal voltage level of **12.66 kV**. An infinite bus connected at **Bus 1** serves as the slack bus, supplying power to the entire distribution network. The total connected load of the system is **3.715 MW** and **2.30 MVAr**, representing typical operating conditions of a medium-voltage radial distribution feeder. The single-line configuration of the proposed test system is illustrated in **Fig.1**. Unlike the conventional IEEE 33-bus network, the proposed active distribution system incorporates three major converter-interfaced components: a **wind farm**, a **Battery Energy Storage System (BESS)**, and an **Electric Vehicle Charging Station (EVCS)**. These resources represent key elements of future smart distribution networks, enabling improved renewable energy utilization, enhanced operational flexibility, and increased electrification of transportation. Although these technologies offer significant operational and environmental benefits, their dependence on power electronic converters introduces nonlinear current characteristics that become major sources of harmonic distortion. The simultaneous operation of renewable generation, battery storage, and EV charging infrastructure modifies harmonic propagation throughout the feeder and may lead to harmonic amplification at electrically weak buses. Consequently, the network experiences deterioration in power quality, manifested through increased voltage and THD, higher feeder losses, transformer overheating, accelerated insulation ageing, reduced equipment lifetime, voltage regulation issues, and possible malfunction of protection and metering devices.

Therefore, the harmonic assessment of the proposed ADN is essential for identifying the buses most susceptible to harmonic distortion. This assessment guides the deployment of STFs at identified critical buses, enabling effective suppression of the dominant fifth-order harmonic with a limited number of filter installations.

3. Harmonic Filtration Module Modelling

3.1. Single Tuned Filter

Single-tuned filters, also known as single-tuned passive filters, are a type of passive filter. Passive filters area traditional technology used to reduce harmonics. These filters depicted in Fig. 2, are composed of an inductor (reactor) and a capacitor, which usually provide harmonic currents produced by the nonlinear load with an alternate impedance path, which lowers the harmonic current components in the utility current. It can be tuned to lower-order harmonics at resonances, such as the fifth, seventh, eleventh, and thirteenth. Higher-order harmonics are not a good fit for this type of filter because tuning at higher orders becomes difficult to achieve reliably. Most passive filters must be specially designed to account for particular system impedances, background voltage distortion, load current harmonics, and interactions with adjacent sources and loads. At resonance, inductive and capacitive reactances are equal, which lowers the total impedance and creates a way to the resonance frequency (f_h) with low impedance, thereby eliminating the harmonics caused by nonlinear loads. Additionally, it helps increase the power factor. As shown in Fig. 3, that depicts Impedance Characteristics of STF, at normalized resonance frequency ($\omega_h = 1$), net reactance vanishes, and the circuit impedance drops to minimum value that is purely resistive, $i.e.\, R_h$. If the operating frequency is higher than the resonance frequency, the circuit is inductive; if it is lower than the resonance frequency, the circuit is capacitive.

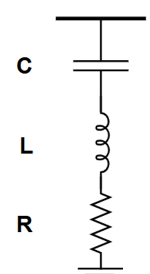

Fig. 2: Single Tuned Filter Circuit

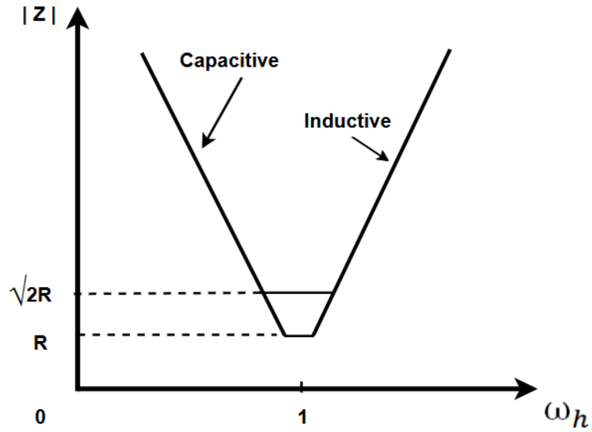

Fig. 3: Single Tuned Filter Impedance Characteristics

the resonant frequency f_h is defined as:

$$f_h = \frac{1}{2\Pi\sqrt{L_h C_h}} \tag{1}$$

and the filter's impedance is given by

$$Z_h = R_h + j\,(\omega L_h - \frac{1}{\omega C_h}) \tag{2}$$

At the resonance frequency,

$$\omega_h L_h = \frac{1}{\omega_h C_h} \tag{3}$$

Substituting equation (3) in equation (2), we got:

$$Z_h = R_h$$

The quality factor (Q_f) determines the filtering sharpness i.e. how sharply the filter is tuned, filter may be either high or low (Q_f). The filter with low (Q_f) is sharply tuned to one of the lower harmonic frequencies. The range is $30 < Q_f < 60$.

In the case of tuned filter, Q_f is defined as ratio of inductance or capacitance to resistance at the resonant frequencies, i.e.

$$Q_f = \frac{X}{R} \tag{4}$$

As shown in Fig. 3, the filter pass band (PB) is defined as being bounded by the frequencies at which the filter reactance is equal to resistance; i.e., the impedance angle is 45 degree and magnitude is $\sqrt{2R}$. Relationship between the quality factor and pass band can be expresses as:

where ω is tuned angular frequency (rad/s)

The complete modeling of STF is depicted in Figure 4.

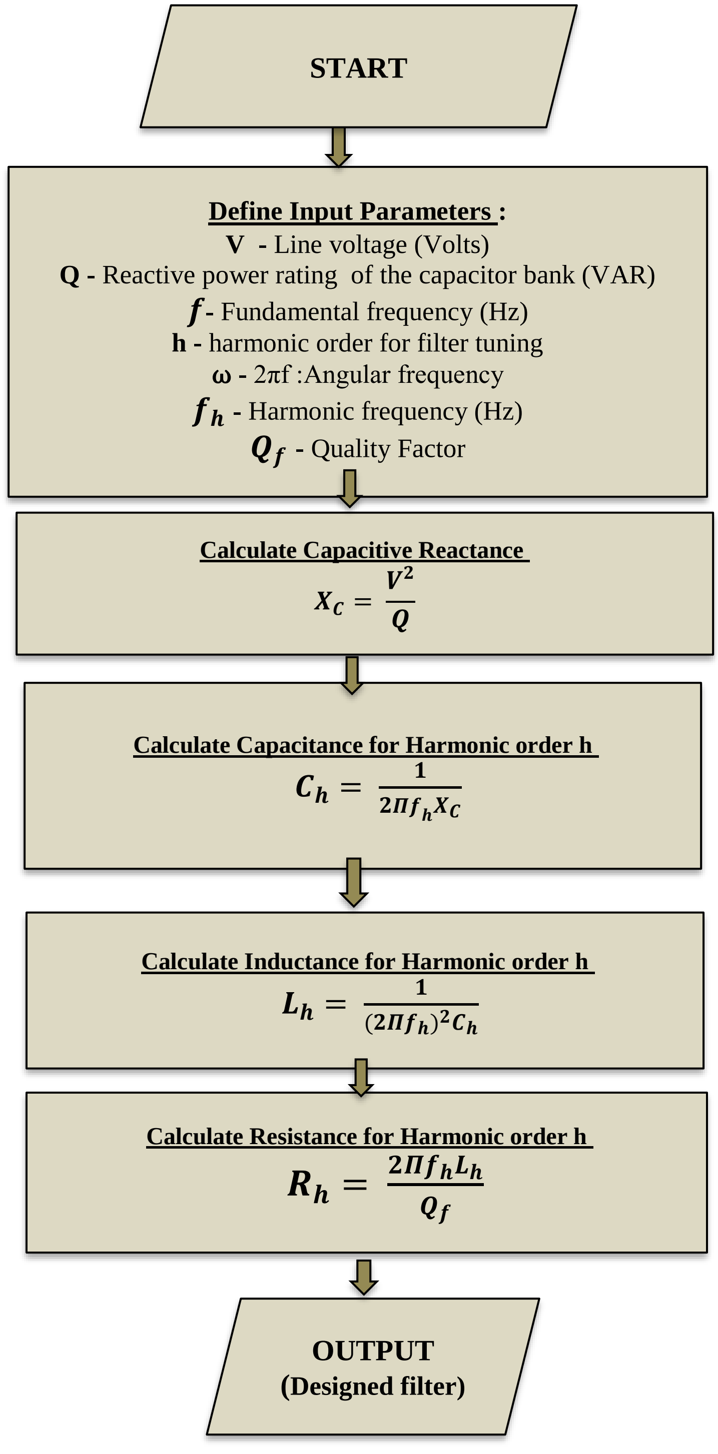

Fig. 4: Modelling of Single Tuned Filter

4. Results and Discussion

The proposed harmonic mitigation strategy was validated on the IEEE 33-bus ADN. The benchmark feeder comprises 33 buses and 32 radial branches operating at 12.66 kV with a total connected load of 3.715 MW and 2.3 MVAr. The network was transformed into an ADN by integrating a 225 kW wind farm (Bus 15), a 775 kW BESS (Bus 29), and an EV charging station (Bus 33).

Parameter	Value
Test system	IEEE 33-bus
Voltage	12.66 kV
Load	3.715 MW / 2.3 MVAr
Wind farm	225 kW @ Bus 15
BESS	775 kW @ Bus 29
EVCS	50 kW @ Bus 33

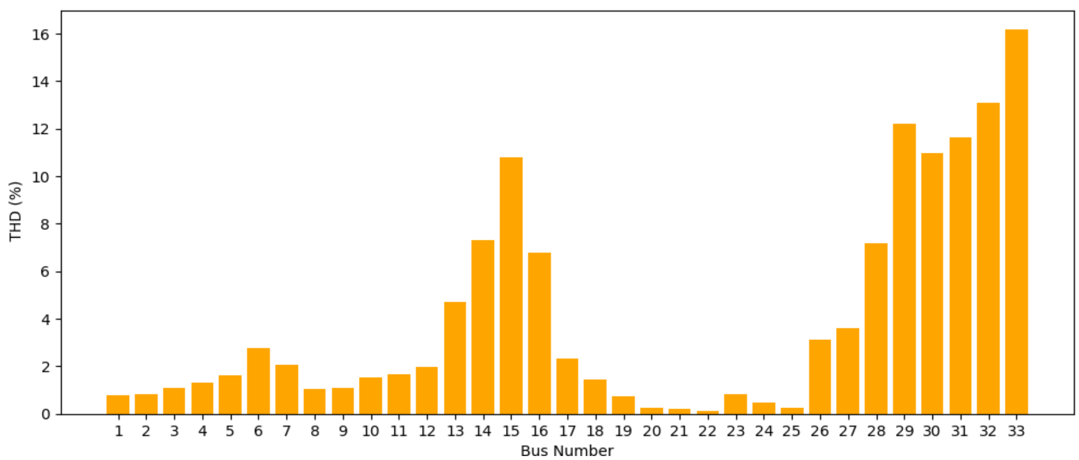

Fig. 5: Pre mitigation THD profile of the IEEE 33- bus ADN

Fig. 5 illustrates the THD profile of the IEEE 33 bus ADN before the STFs implementation. The ADN incorporates the converter-interfaced harmonic sources, that is wind farm (Bus 15), BESS (Bus 29), and an EV charging station (Bus 33).These converter-interfaced sources infuse harmonic currents into the network, resulting in varying THD across different buses.

It is clearly visible in Fig. 5 that the buses hosting wind farm (Bus 15), BESS (Bus 29), and EV charging station (Bus 33), and its nearby buses shows comparatively high THD values and violate the IEEE 519 standard. According to the IEEE 519 standard, the Total Harmonic Distortion must be less than 5% and should be monitored if it exceeds this value.

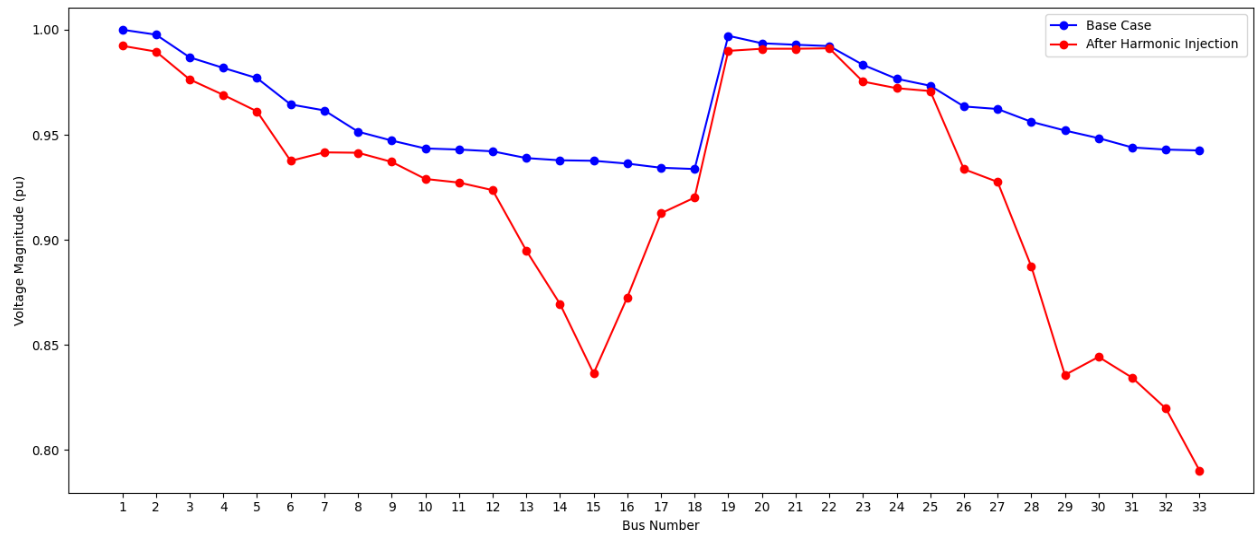

Fig. 6: Voltage profile comparison: Base vs. after harmonic injection

Fig. 6 compares the voltage profile of the IEEE 33 bus system before and after integrating the wind farm, BESS, and EV charging station. The blue trace represents the base case (no integration), while the red trace represents the system with renewable and storage integration. Following integration, buses 15, 29, and 33 exhibit significant voltage sags that fall outside the 0.95–1.05 p.u. operating range specified by IEEE Std 1547 for distributed energy resource interconnection. These violations are primarily attributed to the additional power injections and altered power flow conditions introduced by the integrated renewable energy sources and EV charging station. The results highlight the impact of renewable integration on feeder voltage regulation and emphasize the importance of coordinated power quality assessment and harmonic mitigation in active distribution networks.

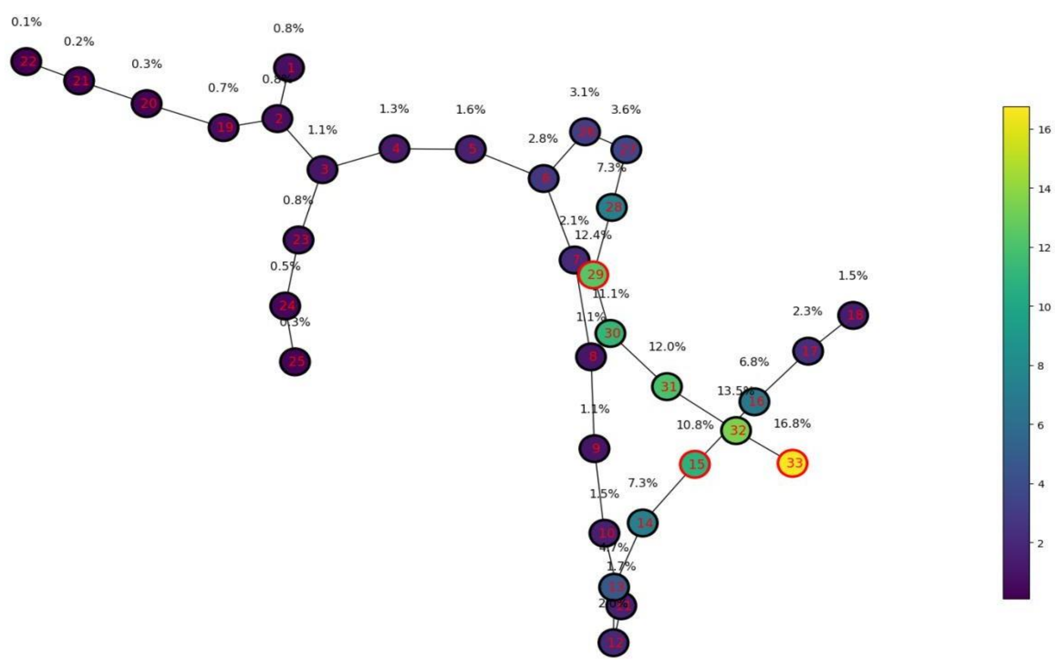

Fig. 7: Network Graph: THD distribution across IEEE 33 Bus ADN

As shown in the network graph of IEEE 33 bus ADN in Fig. 7, the node colour represents the THD magnitude at each bus, with dark purple representing lower THD values and green-to-yellow indicating higher THD values. The buses that depict green and yellow colours are the ones of main exasperate for us, as they indicate higher THD levels that can be mitigated by installing STFs.

Table 1 lists the top five buses with the highest THD% before filter implementation. The table identifies the most harmonically affected locations in the network providing overview of harmonic severity. However, STF placement is determined by the locations of the major harmonic sources wind farm (Bus 15), BESS (Bus 29), and an EV charging station (Bus 33) rather than solely by the magnitude of THD, enabling effective mitigation of harmonics at their points of origin. Installing filters at the harmonic source buses effectively suppresses the injected harmonics and reduces distortion throughout the surrounding network.

Table 1: Top 5 Buses with highest THD (%) before filter implementation

Bus No.	THD (%)
33	16.17
32	13.07
29	12.22
31	11.61
30	10.98

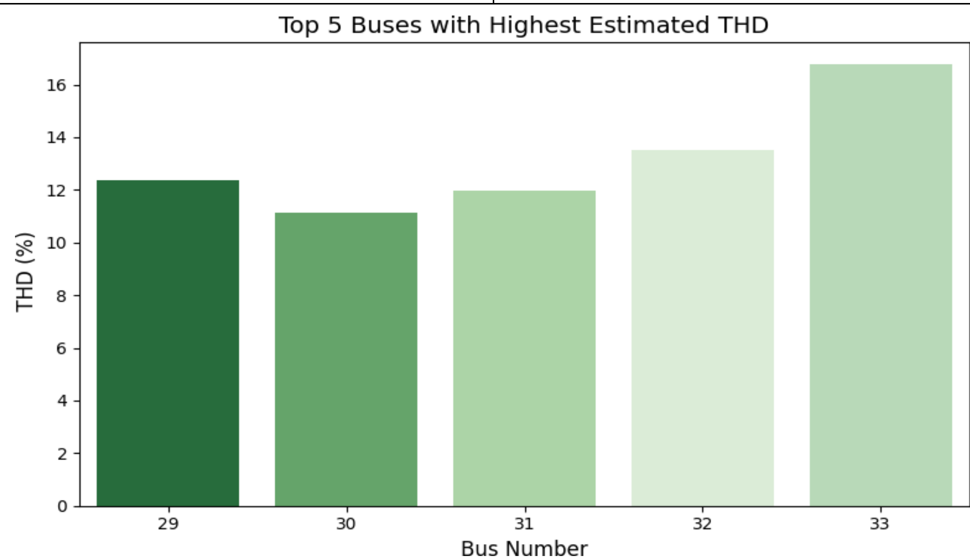

Fig. 8: Top five buses according to their THD%.

Fig. 8 also depicts the estimated THD% of the top five buses with the highest harmonic distortion among the 33 buses. The results indicate that bus 33 has the highest harmonic distortion with a THD of 16.17 %, followed by buses 32 and 29 with THD % of 13.07 and 12.22, respectively.

The Single Tuned Filter is intended to reduce any single-order harmonics. Consequently, we designed our filter to reduce the 5th-order harmonics, which are the primary source of concern in the considered system. The capacitance, resistance, and inductance values of STF are determined by considering the design methodology depicted in Fig. 4. The filter's impedance was evaluated using equation (2). The value of the quality factor $Q_f = 50$ was considered to balance filter sharpness against bandwidth: the bandwidth of STF is

$$BW = \frac{f_h}{Q_f} = \frac{250}{50} = 5Hz$$

, which is narrow enough to attenuate inter-harmonics adjacent to the 5th order while remaining tolerant to $\pm 0.5\ Hz$ grid frequency drift typically observed in the distribution network [15] report $BW = 5.2\ Hz$ at the same tuned frequency for the same application context. The STF was then connected in shunt to the distribution network's line, thus generating a low impedance path at the tuned harmonic frequency. This configuration empowers the STF to absorb the targeted harmonic current and thus mitigates harmonic disturbance.

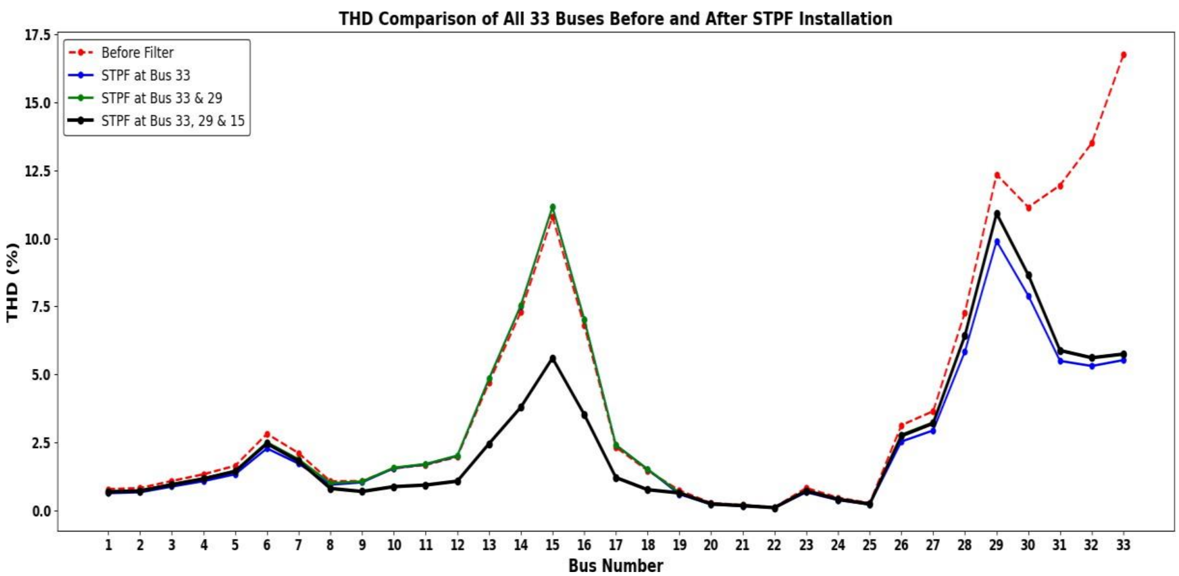

Fig. 9: THD comparison after filter installation

Fig. 9 illustrates the comparison of Total Harmonic Distortion (THD) levels in the proposed IEEE 33-bus ADN before and after the installation of STFs at selected buses. Overall, the Fig. 9 confirms that progressive installation of Single Tuned Filters substantially reduces harmonic distortion, limits harmonic propagation throughout the network, and enhances power quality performance in the ADN. Initially, the red dashed curve represents the THD profile of the system before filter installation. It can be observed that buses near the harmonic sources, particularly buses 15, 29, and 33, exhibit significantly high THD values. The maximum THD is observed at bus 33, reaching approximately 16%, which exceeds the IEEE 519 permissible limit of 5%. Bus 15 corresponds to the wind farm integration point, whereas Bus 29 is the point of connection of the BESS. Both converter-interfaced sources contribute to harmonic injection into the distribution network; both interfaces therefore inject 5th- and 7th-order harmonics under partial loading.The blue curve represents the THD profile after installing an STF at bus 33. A noticeable reduction in THD is observed near bus 33 and adjacent buses, indicating that the filter effectively suppresses harmonic propagation originating from the EV charging station. The green curve illustrates the THD profile after additional STF installation at buses 33 and 29.Finally, the black curve shows the THD profile after installing STFs at buses 33, 29, and 15 simultaneously. The THD values across the network are significantly reduced, and most buses operate within or close to the IEEE 519 harmonic limit. The largest reduction is observed at bus 33, followed by bus 32, 31, 17, 16, 15,as shown in Table 2 which shows the Top 10 buses with highest THD reduction, demonstrating the effectiveness of the proposed STF-based harmonic mitigation approach.

After the implementation of harmonic filters, a substantial reduction in THD is observed across the entire network. The THD at Bus 33 decreased from 16.17% to 5.59%, resulting in the highest THD reduction of 65.38%. Similarly, Bus 32 experienced a reduction of 58.03%, while Buses 31, 15, 16, and 17 exhibited reductions of more than 48%. This indicates that the filters were highly effective at buses located close to the major harmonic injection points.

Table 2: Top 10 buses with the highest THD reduction

Bus Number	THD Before Filter (%)	THD After STF at Bus 33, 29 & 15 (%)	THD Reduction %
33	16.17	5.59	65.38
32	13.07	5.48	58.03
31	11.61	5.76	50.34
17	2.32	1.20	48.17
16	6.80	3.52	48.15
15	10.79	5.59	48.15
18	1.45	0.75	48.11
14	7.28	3.78	48.06
13	4.69	2.44	47.80
12	1.96	1.06	45.62

Table 3 presents the comparison of THD % at all buses of the IEEE 33-bus ADN before and after the implementation of STFs. Moderate THD reductions were observed at Buses 8–14 and Bus 30, where the reduction ranged approximately from 22% to 48%. In contrast, buses located farther from the harmonic sources, such as Buses 1–7 and 19–28, showed comparatively lower reductions of around 12–14%, indicating lower harmonic severity in those regions even before filter installation. Although the STF installed at Bus 29 reduces harmonic distortion, the reduction is less pronounced than that observed at Buses 15 and 33. This behavior suggests that the harmonic mitigation effectiveness varies with the characteristics of the harmonic source, network configuration, and local operating conditions. Nevertheless, the proposed STF placement achieves a significant overall improvement in the harmonic performance of the ADN. Overall, the results confirm that the proposed harmonic mitigation approach effectively suppresses harmonic distortion throughout the IEEE 33-bus distribution system. The filters significantly improve power quality and reduce THD levels, especially at buses heavily affected by converter-interfaced renewable energy sources and EV charging loads. The obtained results demonstrate the suitability of the proposed filter design for improving the harmonic performance and overall power quality in renewable-integrated ADN.

Table 3: THD comparison of IEEE 33 ADN after filters implementation

Bus Number	THD Before Filter (%)	THD After STF at Bus 33, 29 & 15 (%)	THD Reduction %
1	0.71	0.67	12.91
2	0.81	0.70	12.99
3	1.07	0.93	12.95
4	1.31	1.14	12.92
5	1.62	1.41	12.90
6	2.79	2.42	12.94
7	2.08	1.78	14.01

8	1.05	0.79	24.73
9	1.07	0.69	35.94
10	1.54	0.86	43.69
11	1.67	0.92	44.51
12	1.96	1.07	45.62
13	4.69	2.45	47.80
14	7.29	3.78	48.06
15	**10.79**	**5.59**	**48.15**
16	6.80	3.53	48.15
17	2.32	1.20	48.17
18	1.46	0.76	48.11
19	0.72	0.63	12.89
20	0.26	0.23	12.98
21	0.19	0.17	12.56
22	0.11	0.09	12.26
23	0.81	0.71	12.95
24	0.46	0.39	13.10
25	0.26	0.23	12.74
26	3.09	2.70	12.72
27	3.61	3.16	12.45
28	7.19	6.34	11.87
29	**12.22**	**10.78**	**11.76**
30	10.98	8.54	22.20
31	11.61	5.77	50.34
32	13.07	5.48	58.03
33	**16.17**	**5.59**	**65.38**

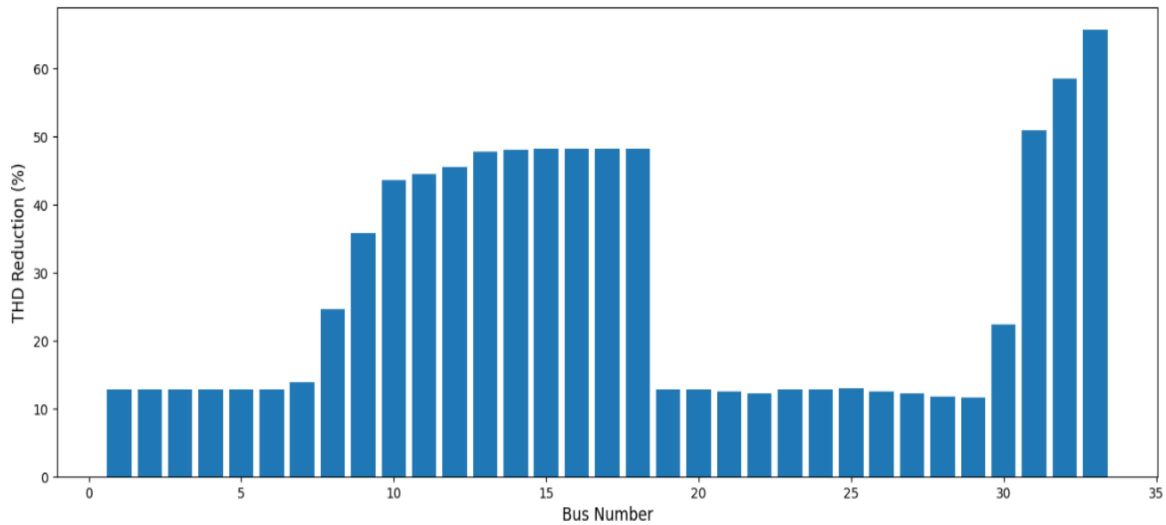

Fig. 10: THD reduction across all 33 Buses after STF installation

Fig. 10 represents the % THD reduction at all buses following filters implementation. Buses 32 and 31 achieved reductions exceeding 50 %, while Bus 33 recorded the maximum reduction of approximately 65.38 %. Buses 12–18 also exhibited consistently high harmonic suppression. In contrast, Buses 1–7 and 19–29 showed comparatively lower reductions in the range of approximately 12–14 %.

5. CONCLUSIONS

This study quantified harmonic distortion in an IEEE 33-bus ADN integrating a wind farm, a BESS and an EV charging station, then assessed the effectiveness of strategically placed STFs for harmonic mitigation. Prior to filter installation, the maximum voltage THD reached 16.17 % at Bus 33, exceeding the 5 % IEEE Std 519-2022 limit for the 12.66 kV class by a factor of more than three. Three STFs, tuned to the dominant 5th-order harmonic at 250 Hz, with design parameters verified to satisfy $f_h = \frac{1}{2\Pi\sqrt{L_h C_h}}$, were installed at the locations of the major harmonic source buses (33, 29, and 15). Following STFs installation, THD at Bus 33 decreased to 5.59 %, representing the maximum THD reduction of 65.38 % ,The Buses 15, 32, and 33 cluster recorded reductions of 48.15 –65.38 %. Although a limited number of buses continued to exhibit THD values above the IEEE Std. 519-2022 recommended limit, the proposed selective STF placement strategy significantly improved the harmonic performance and overall power quality of the renewable-integrated distribution network. The results demonstrate that strategically placing STFs at major harmonic source locations provides an effective and practical approach for mitigating dominant fifth-order harmonics in ADN. Future work may investigate optimization-based filter placement and hybrid passive–active filtering techniques to achieve further reductions in harmonic distortion

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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