



MITIGATION OF SUPRAHARMONICS IN MICROGRIDS USING PARABOLIC CARRIER-BASED PWM-CONTROLLED SHUNT ACTIVE FILTERS

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Abstract

Microgrids (MGs) are having more difficulty sustaining power quality (PQ) as renewable energy sources (RES) become more widely integrated. The issue of supraharmonics (SH), characterized by high-frequency emissions spanning from 2 kHz to 150 kHz, holds significant importance. The switching processes used in these RES power electronic converters are to blame for these harmonics. Traditional passive filters and capacitor banks are ill-equipped to deal with the dynamic changes in system characteristics that occur at the PCC. Voltage swell, unbalance, and power factor problems result from this. The Shunt Active Filter (SAF) has shown superior efficacy in mitigating harmonic issues in power systems. Nonetheless, its performance is contingent upon the rapidity and precision of its control algorithms. This paper employs the parabolic carrier-based pulse-width modulation (PWM) technique to regulate current in SAF, thereby minimizing SH. This method incorporates using a pair of positive and negative parabolic PWM carriers to control the switching states of the two switches in the converter phase leg, simultaneously constraining the current tracking error within the nonlinear parabolic region. The proposed filter is designed using the MATLAB/Simulink environment and used in a modelled MG with specified ratings. The results of the harmonic analysis showed a distortion contribution in the SH range of merely 0.03%. The minimal increase

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in THD when extending the analysis up to 150 kHz demonstrates the active filter's effectiveness in suppressing SH.

Keywords: Harmonic Mitigation, Microgrid, Parabolic PWM, Power Quality, Shunt Active Filter, Supraharmonics.

I. Introduction

The problems of power quality (PQ) deterioration have grown increasingly apparent as renewable energy sources (RES) find a growing presence in contemporary power systems. The occurrence of supraharmonics (SH), which are harmonic distortions in the frequency range of 2 kHz to 150 kHz, is one of the main problems related to integrating distributed generation (DG) systems. These disturbances may destroy system efficiency, create failures in power-electronic converters, and interfere with the sensitive equipment of Microgrids (MGs). Effective treatment of these high-frequency aberrations is a challenge for both traditional passive and conventional active filters. MGs may function both on and off the grid, and they can include various RES like solar photovoltaic (PV) systems, wind turbines, and battery storage [XVI]. Due to their cheap installation costs, PV systems have been the most popular power source in MGs [VII]. Notwithstanding these benefits, there are still a lot of obstacles to overcome when integrating solar PV systems into MGs, particularly in terms of PQ. The development of SH is one of the main problems resulting from the integration of solar PV systems. It is produced by power electronic-based converters, which are crucial parts of PV systems. SH may result in significant issues, including elevated power outages, communication system interference, device overheating, and PQ deterioration [I].

Active filters are critical elements in power systems, engineered to reduce harmonic distortions and enhance PQ. Diverse topologies have been created to tackle certain issues in various applications. Active filter topologies for PQ enhancement offer a comprehensive examination of various systems. Shunt Active Filters (SAFs) are extensively employed to mitigate current harmonics and reactive power in electrical systems. They are arranged in parallel with the load and introduce compensating currents to mitigate harmonics. **Figure 1** describes the action of SAF in an MG.

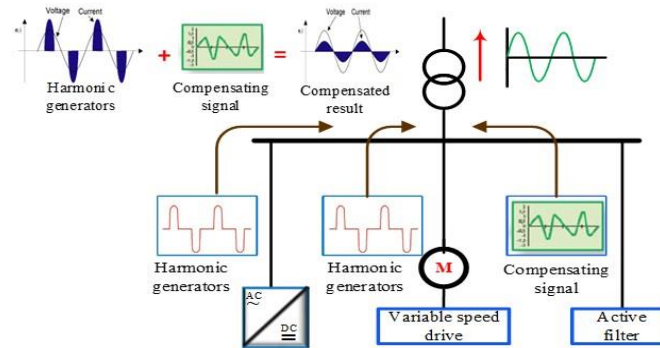


Fig. 1. The role of SAF in an MG [I]

This architecture effectively mitigates harmonics and is frequently utilized in industrial applications. Nevertheless, SAFs may encounter difficulties in dynamic contexts characterized by quickly fluctuating load levels. Series-active harmonic filters are integrated into the power line and primarily mitigate voltage harmonics. Nonetheless, this category of filters may be more intricate to apply and may require elevated voltage ratings for the components utilized. A passive filter generally addresses lower-order harmonics, whereas an active filter mitigates higher-order harmonics and dynamic disturbances. This combination facilitates superior performance across an extensive frequency spectrum and increases efficiency. The design and tuning of these filters can be intricate, necessitating meticulous attention to the interplay between active and passive components. SAFs based on parabolic pulse-width modulation (PWM) have shown great promise in effectively reducing SH. It uses a parabolic reference signal for switching control, unlike more traditional PWM techniques, which depend on sinusoidal references. Through an optimal switching pattern of the voltage-source inverter (VSI), this special modulation approach improves the dynamic response of the active filter and reduces Total Harmonic Distortion (THD), hence enhancing SH suppression.

In this paper, the design, implementation, and performance investigation of a parabolic PWM-based SAF for SH reduction in an MG are presented. MATLAB/Simulink models and simulations of the proposed system help to assess its performance relative to conventional filtering methods. For next-generation MG applications, the research shows that parabolic PWM-based active filtering offers better harmonic attenuation, reduced power losses, and enhanced voltage quality, therefore making it a perfect alternative.

The remainder of this paper is set up as follows: Section 2 offers a survey of the literature on active filtering methods for SH reduction. Section 3 addresses parabolic PWM-based active filter mathematical modeling and design. Results of the simulation and performance analysis are presented in Section 4. Section 5 finishes the study and lists future avenues of inquiry.

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II. Literature review

Recent advancements in solar PV technology have significantly increased its penetration of MGs. However, the integration of solar PV systems can introduce SH, predominantly in the range of 2 kHz to 150 kHz, which can compromise the stability and efficiency of these systems [I]. SH, unlike traditional lower-order harmonics, are less studied and present unique challenges in terms of detection and mitigation. Many works in literature, as seen in references [XX], [VIII], [IX], [XII], and [V], tackled various PQ issues, particularly the harmonic distortion concerns. Other authors, as references [XII], [XXII], [XXIII], [XIX], [III], [IV], and [VI] have researched the topic as it is a major power system engineers since the beginning of the last decade. Various techniques were used to address this concern, as shown in comparative **Table 1**, where harmonic mitigation methods are compared to show the merits and drawbacks of each. Every harmonic-reducing technique has advantages and disadvantages. The application, the kinds of harmonics present, and the system setup will all determine the option. A potential remedy for reducing SH in power systems that primarily rely on power electronics is the application of hybrid approaches in filter design. Although passive filters prove to be effective in the suppression of low-order harmonic distortions, records reported that they were ineffective in the SH range of distortions [VI]. Using a passive part to reduce grid fundamental frequency voltage drops and a linear amplifier for dynamic SH compensation, these designs greatly lower the active part's operating loss and output capacity [V].

Table 1: Comparison of various harmonic mitigation techniques

Ref.	Technique Used	Benchmarked Results	Limitations
[XX]	Various control techniques for VSI in grid-integrated PV MGs.	Evaluation under the IEEE-519 standard shows that synchronous reference frame control gives the best result for THD (=1.85%).	SRF control responds slower than least-mean square towards harmonics mitigation.
[VII]	Hybrid active power filters.	An effective combination of filters reduces overall costs and improves band mitigation.	Narrow compensation range, requires higher DC-link operation voltage, losing low inverter rating characteristics.
[IX]	Passive and active filtering.	Reduced THD levels to within national standards.	High-accuracy current transducers are needed for active filters.
[XII]	Multistage harmonic oscillator.	Not detailed, focus on adaptive control under non-ideal conditions.	Complexity in adaptive control under varying grid conditions.
[V]	Hybrid control method with energy storage integration.	Current THD reduced from 150% to about 10%, voltage THD from 4.5% to 0.25%.	Complexity and cost of hybrid systems, reliance on energy storage.

[XX I]	A hybrid filter combining a linear amplifier-based active filter in series with a passive high-pass filter.	This configuration compensates for supra-harmonics while reducing the active part's burden. Reduction in THD from 6.70% to 1.35% in simulations and from 6.34% to 2.73% in experiments with fast dynamic response and improved system efficiency.	Efficiency may decrease under low-voltage PCC conditions; parasitic resistance in passive components limits full cancellation; system cost and complexity increase due to added analog circuitry.
[XV III]	Multifunctional capabilities of inverter-interfaced DGs.	Focuses on improving PQ by mitigating harmonics.	Cost and bulkiness of traditional filters.
[XX II]	Active harmonic filtering with selective overcurrent limitation.	Reduced voltage THD below 2%, harmonic current controlled to prevent VSI overload.	High VSI harmonic current leading to potential overload, complex control for dynamic harmonic mitigation.
[XX III]	Hybrid approach combining a Thyristor-Controlled Transformer (TCT) and Fixed Capacitor (FC) for real-time reactive power management.	Better power factor adjustment. Enhanced voltage stabilization. Harmonic distortion reduction. Faster reaction time and better control accuracy than reactive power compensation techniques.	The system may be limited under highly dynamic load scenarios that need quicker reaction times. Integration of thyristor control may complicate maintenance. It may cost more to deploy than capacitor-based compensating solutions.
[XI X]	SAF in cascaded power converters.	Reduced harmonic current from 6.8A to 3.7A, 45% reduction.	Limited reduction in high-frequency harmonics, more effective at lower harmonics .
[III]	Frequency analysis of VSR using PWM and FFT to study supra-harmonics.	Supra-harmonics cluster around the switching frequency.	Focused on steady-state and limited grid interaction modeling.

Active filters have become the key solution for handling harmonic problems because of their versatility and efficiency over a broad range of frequencies. References [VII], [XIV], [XXIV], [XXV], [X], and [XVII] have provided evidence about the effectiveness of active filters in reducing conventional harmonics as well as SH. Various controlling techniques are being employed to operate these filters, which could be visualized as follows:

- Parabolic PMW technique.
- Neural Synchronous Reference Frame (SRF) technique.

- Negative Feedback Phase Locked Loop (NFPLL), Modified Synchronous Reference Frame (MSRF), Fuzzy Inverted Error Deviation (FIED), and Adaptive Fuzzy Hysteresis Current Controller (AFHCC).
- Least Mean Square (LMS) and Second Order Generalized Integrator (SOGI) technique.

By stabilizing switching frequency and reducing switching losses, parabolic PWM enhances active filter performance. Harmonic suppression and power factor rise help to define power system stability and efficiency. Though complex control techniques could improve dynamic responsiveness, PWM performs well in steady-state applications. Industrial application is adequate for the method response time. Using standard PWM controllers, this technique is simple to develop and needs little computer resources, hence facilitating incorporation into current systems. Though effective within its operational range, parabolic PWM could find it difficult to fit varied system conditions or load profiles without modification or adjustment. Because of their straightforward control techniques and widespread component availability, parabolic PWM systems are less expensive to install and keep running.

Neural-SRF's control system employs neural networks for exact harmonic extraction and correction. This might lower THD and satisfy IEEE-519 PQ requirements. Neural networks boost system parameter adaptation and load responsiveness. This accelerates filter adjustment, hence lowering power system impact during transients. Control systems based on neural networks are more complex and need signal processing knowledge as well as machine learning. Higher computing demands might call for advanced processing units or specialized technology. Operational data increases the performance and flexibility of neural networks, and despite it being more expensive, advanced hardware and software might help to mitigate higher energy losses and system reliability. In the NFPLL technique, MSRF, FIED, and AFHCC technologies provide dynamic and adaptable pulses. The integrated approach maintains power quality with non-linear loads and distorted sources by eliminating harmonics, hence removing harmonics. Dynamic control methods provide quick load disturbance reaction. Modern control techniques used together provide a sophisticated, precise, adaptable system. Handling different scenarios, the whole control method adjusts to load and source changes. The intricacy of technology might increase expenses. In LMS and SOGI, reference current generation enhances load current decomposition into fundamental components for precise filtering. By changing frequency component learning rates, the LMS algorithm increases dynamic responsiveness. Additionally, this medium-complexity approach offsets harmonic and reactive power and lowers computational load.

A comparative summary of the main features of these techniques is provided in **Table 2**. This table presents a concise comparison of the techniques used in controlling active filters for harmonic suppression in RES-based MGs.

Table 2: Comparison of active harmonic filters control techniques

Control technique	Parameter		
	Effectiveness	Response time	Complexity
Parabolic PWM	Good efficiency and effective harmonic suppression	Adequate for typical conditions	Simpler and lower computational demand
Neural-SRF	Superior in reducing THD and ensuring compliance	Faster and adaptable	More complex, requiring advanced computation
NFPLL, MSRF, FIED, and AFHCC	Highly effective, especially under varying conditions	Quick, especially with load changes	Moderate, focused on computational efficiency
LMS and SOGI	Effective in harmonic reduction and power factor improvement	Improved dynamic response with tailored learning rates	Moderate, focused on computational efficiency

Generally, it is reported that active filters offer a more complete solution that can be adjusted to the different frequencies and load situations seen in solar PV MGs, while passive filters are more economical for fixed frequency disturbances [X], [XVII], and [IV]. Even with significant advancements, SH mitigation in solar PV MGs is still a challenging area that needs more investigation. International standards such as IEEE Standard 519 and EN Standard 61000-3-2 guide allowable levels of harmonic distortions to guarantee the dependability and safety of MG operations [XIII], [V], [II], and [XV]. These guidelines place a strong emphasis on the necessity of keeping harmonic levels within designated thresholds to avoid operational inefficiencies and equipment deterioration.

III. Research framework

3.1 Theoretical Background

Parabolic PWM is a specialist modulation method used in power electronics and control applications to improve waveform quality, minimize harmonics, and increase converter and filter efficiency. Unlike typical sinusoidal or space vector PWM approaches, parabolic PWM modulates the pulse width of switching signals using a parabolic function, resulting in improved harmonic suppression and dynamic responsiveness. Instead of using a fixed or sinusoidal reference wave, a parabolic reference wave is utilized to locate switching occurrences. Smoother transitions provide fewer high-frequency harmonics, allowing for improved pulse localization. As well as being suitable for integrating RES, this PWM technique is also suitable for harmonic abatement in MGs, shunt APFs, power inverters, and converters. It reduces switching losses and improves PQ, making it superior to conventional PWM systems for controlling voltage and current waveforms. The technique proceeds as follows:

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1. The reference signal used in Parabolic PWM is a parabolic function defined by Equation (1) below.

$$V_{ref}(t) = A \left(1 - \left(\frac{2t}{T} - 1\right)^2\right) \quad (1)$$

Where:

$V_{ref}(t)$ is the instantaneous value of the parabolic reference signal.

A is the peak amplitude of the modulation signal.

T is the modulation period corresponding to the switching cycle.

t is the time within the switching cycle, $0 \leq t \leq T$.

2. This function generates a concave downward parabolic shape, symmetric around $T/2$.
3. A high-frequency triangular carrier signal is used to generate the switching pulses as defined by Equation (2).

$$V_{tri}(t) = B \left| \frac{4t}{T} - 2 \right| \quad (2)$$

Where:

$V_{tri}(t)$ is the instantaneous value of the triangular carrier wave.

B is the peak amplitude of the carrier wave.

This triangular waveform has constant frequency and linearly varying amplitude. The switching logic for Parabolic PWM is determined by comparing the parabolic reference signal with the triangular carrier wave, as defined by Equation (3).

$$S(t) = \begin{cases} 1, & \text{if } V_{ref}(t) > V_{tri}(t) \\ 0, & \text{if } V_{ref}(t) \leq V_{tri}(t) \end{cases} \quad (3)$$

Where:

$S(t) = 1$ stands for the electronic switch (MOSFET or IGBT) being ON.

$S(t) = 0$ stands for the electronic switch (MOSFET or IGBT) being OFF.

This comparison modulates the width of the pulses, adjusting the duty cycle dynamically based on the parabolic waveform.

4. The harmonic content of a PWM waveform can be expressed as a Fourier series given by Equation (4).

$$V_{PWM}(t) = \sum_{n=1}^{\infty} V_n \sin(n\omega t + \Phi_n) \quad (4)$$

Where:

V_n is the magnitude of the harmonic component.

$\omega = 2\pi f$ is the angular switching frequency.

Φ_n is the phase shift of the n^{th} harmonic.

For Parabolic PWM, the harmonic spectrum is optimized to suppress higher-order harmonics by modifying the duty cycle distribution.

change to choose harmonic frequencies, active components actively move to offset more complicated and changeable harmonic content. An active filter in a control system tracks and modulates higher-order harmonics. This part balances harmonics by injecting currents, therefore producing a steadier power supply. Design depends critically on real-time harmonic detection and active filter adjustment. By using the FFT detection technique, the filter examines the current waveform to find harmonic distortion. The control system produces suitable correction signals to help lower distortions. Real-time feedback dynamically changes compensation to meet harmonic levels and modifies the output of the active filter by tracking system harmonic content. This guarantees low harmonic contents independent of load and power consumption. This method is crucial for SH that are difficult to control with passive filters for exact harmonic correction. MATLAB/Simulink simulation starts the design process to assess filter performance under many load and harmonic environments. Before hardware, simulation maximizes control tools and filter components. Including THD reduction and PQ enhancement, the MATLAB/Simulink model replaces the real-world performance of the AHF. Another vital factor is filter efficiency, as harmonics must be lowered without power loss.

A low-voltage MG model is developed in MATLAB/Simulink, incorporating renewable energy sources, power electronic converters, and nonlinear loads that contribute to supraharmonics. The power system configuration is designed to simulate real-world operating conditions, ensuring a representative test environment. To simulate parabolic PWM in MATLAB/Simulink, the first step is to define the MATLAB parameters. This step consists of defining the switching period (T), the switching frequency (f_s), the peak amplitude of the parabolic reference (A), the peak amplitude of the triangular wave (B), and the time vector (t). Then the parabolic reference signal (V_{ref}) and the triangular carrier wave (V_{tri}) are calculated as given by Equations (1) and (2). The PWM signal is then generated by comparing the signals in the former equations, and the three signals are plotted as well. The second step is to model the following Simulink components, and the details of both steps are shown in **Figure 3**, as follows:

1. Signal Generation Block, where the parabolic reference and triangular carrier wave are generated.
2. Comparator Block, where (V_{ref}) and (V_{tri}) are compared to produce the PWM signal.
3. Switching Control, where the PWM signal is used to control IGBT/MOSFET switches in the active filter circuit.
4. Output Analysis, where harmonic distortion is measured using the FFT Analyzer.

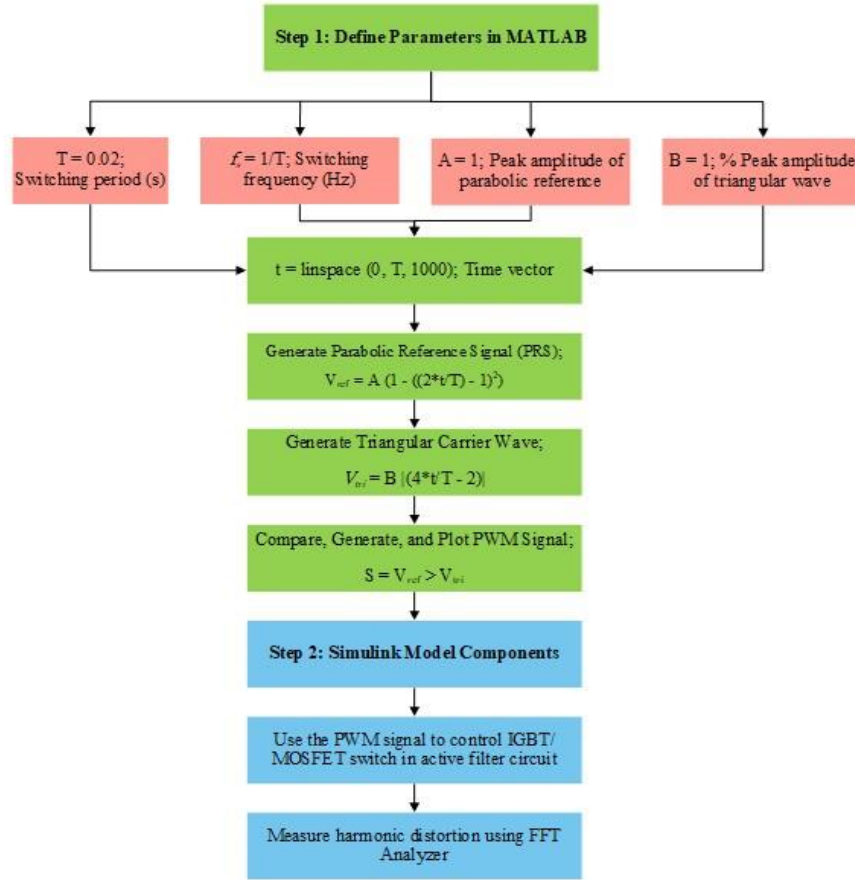


Fig. 3. MATLAB/Simulink methodology flowchart

IV. Application and results

4.1 MG Network Configuration

Figure 4 illustrates that the system used for the active filtering of high-frequency harmonic mitigation has the following components: The Solar PV system functions as the primary renewable energy source inside the microgrid. It consists of four panels of the brand (Trina Solar TSM-250PA05), which are linked in series to create a string. Four strings are interconnected in parallel to augment the current output. **Table 3** presents the solar panel ratings with irradiance and ambient temperature parameters set at 1000 W/m² and 25 °C, respectively. The PV system is outfitted with essential instruments for monitoring voltage, current, and power. The graphical user interface, which is the POWERGUI block, alongside discrete power system simulations, offers a continuous method suitable for rapid dynamic systems necessitating accurate outcomes. In discrete mode, it enables modeling with specified step sizes, enhancing compatibility with digital

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controllers. A DC link capacitor and a DC-to-DC boost converter are connected, with the PWM controller delivering a pulse to the electronic switch of the one-quadrant converter. The duty cycle defines the proportion of the pulse duration during which the output is activated. This controller is calibrated at a sampling interval of 5 microseconds. **Figure 5** illustrates the SAF arrangement in a block diagram format, and the parameter settings for simulation are as given in **Table 4**.

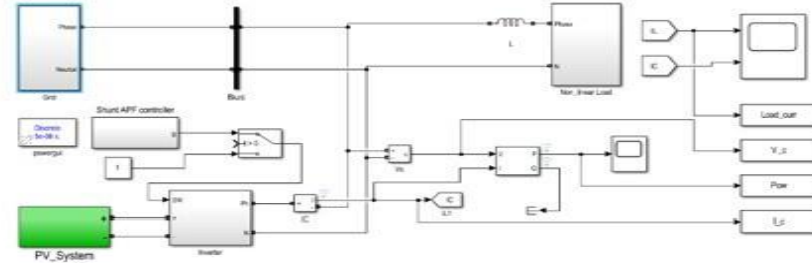


Fig. 4. MG configuration with SAF.

Table 3: Solar array and modules ratings (brand TSM-250PA05)

Peak power watts (Wp)	249.86 W	PTC rating	227.5 W
Series modules/string	4	Parallel strings	4
Power output tolerance	0/+3 %	Cells per module	60
Max. power voltage (V_{MP})	31 V	Open-circuit voltage (V_{OC})	37.4 V
Max. power current (I_{MP})	8.06 A	Short-circuit current (I_{SC})	8.55 A
Light-generated current (I_L)	8.5728 A	Diode saturation current (I₀)	9.646*10 ⁻¹¹ A
Temperature Coeff. of V_{OC}	-0.3297 (%/C°)	Diode idealist factor	0.96295
Shunt resistance	286.8727 Ω	Series resistance	0.2351 Ω
Module efficiency (η)	15.3%		

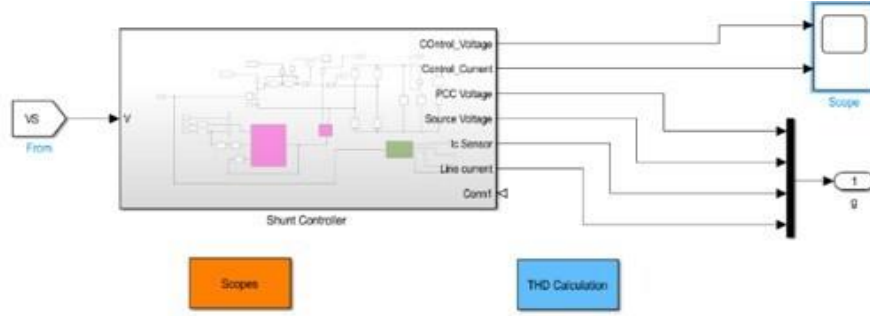


Fig. 5. Block configuration of the AHF.

Table 4: Parameter settings of the SAF model design

DC boost converter		Inverter MOSFET		MPPT P&O algorithm		Nonlinear load	
Diode R_{ON}	0.001 Ω	R_{ON}	0.1 Ω	D initial	0.4	RL Source	100 Ω
Diode V_{ON}	0.8 V	Diode R_{ON}	0.01 Ω	D max	0.9	side L	300 mH
Snubber R	500 Ω	Snubber R	100 k Ω	D min	0.1		1.2 mH
Snubber C	0.25 μ F	Snubber C	infinity	ΔD	2×10^{-5}		
Series L	0.3 mH	Inverter filters		MPPT PWM		Load bridge	
MOSFET R_{ON}	0.1 Ω	DC side R	0.01 m Ω	Switching f	5 kHz	Diode R_{ON}	0.001 Ω
Diode R_{ON}	0.01 Ω	DC side C	2300 μ F	Sample time	5 μ Sec.	Diode V_{ON}	0.8 V
Snubber R	100 k Ω	AC side R	48 Ω			Snubber R	500 Ω
Snubber C	infinity	AC side L	2.5 mH			Snubber C	0.25 μ F

Figure 6 illustrates the arrangement of the nonlinear load inside the Simulink model. The characteristics of loads significantly influence the generation and transmission of harmonics. Resistive loads are devices like heaters and incandescent light bulbs that exhibit stable resistance and do not produce harmonics inside the system. Inductive loads include motors, transformers, and certain industrial machines. Inductive loads cause phase shifts between voltage and current, which may result in low-order harmonics, but generally do not directly generate supraharmonics. Nonlinear loads, including rectifiers, computers, and power electronics, generate harmonics because of their non-sinusoidal current consumption. These loads are a substantial source of both low-order and higher frequency SH.

4.2 Active Filter control algorithm

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4.3 Results and discussion

Assessing the system performance and collecting data on harmonic content is essential for operational efficiency and subsequent analysis. The system employs many measuring instruments; voltage and current waveforms at various locations are presented on Oscilloscopes. These instruments measure the instantaneous voltage and current levels at critical locations within the MG, such as at solar PV inverters, loads, and the filter connection at PCC. Analyzers for PQ measure the amount of harmonic distortion, which includes THD and certain harmonic orders. Data acquisition systems gather data from sensors and analyzers and transmit it to control systems for real-time decision-making. We also preserve the data for long-term examination of system performance. All these parts work together to enhance the MG system to control and reduce harmonic distortions, especially SH, in a long-lasting and effective way. This section analyzes the performance of the proposed parabolic PWM-based AHF through visualized results obtained at the PCC within the microgrid environment. The investigation focuses on both the mitigation of low-order harmonic distortions and the reduction of SH content in the presence of non-linear PV-induced loads. **Figure 8** shows the waveforms of the distorted load current and the filtered line current in part (a), and the current harmonic spectrum at PCC for low-order frequencies up to 2 kHz in part (b). **Figure 9** and **Figure 10** show the current spectra at PCC with various ranges of SH up to the upper limit of 150 kHz.

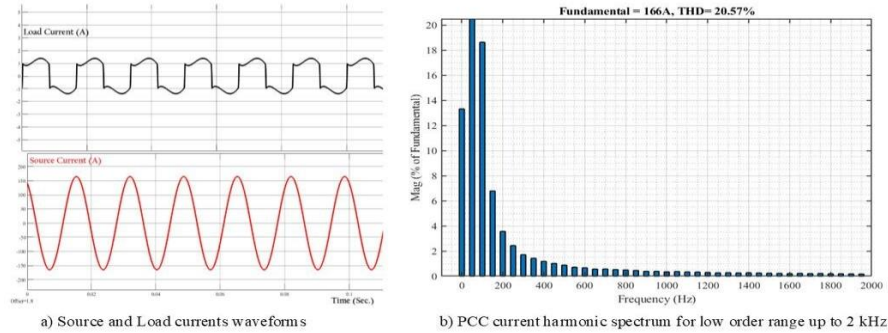


Fig. 8. Current results: a) Load current and source current waveforms, and b) PCC current harmonic spectrum with low order range up to 2 kHz.

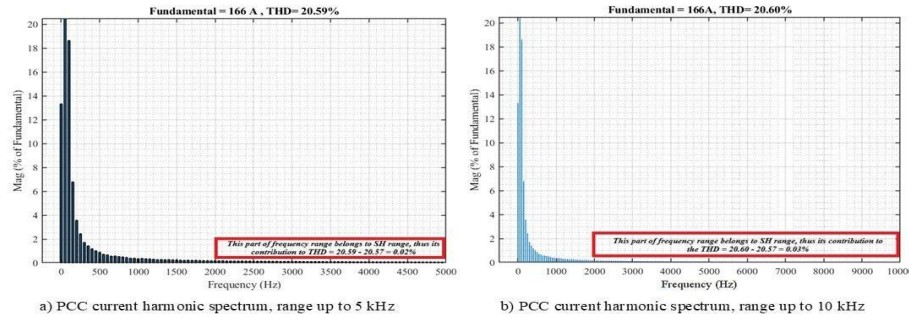


Fig. 9. PCC current harmonic spectrum a) with SH's range up to 5 kHz, and b) with SH's range up to 10 kHz

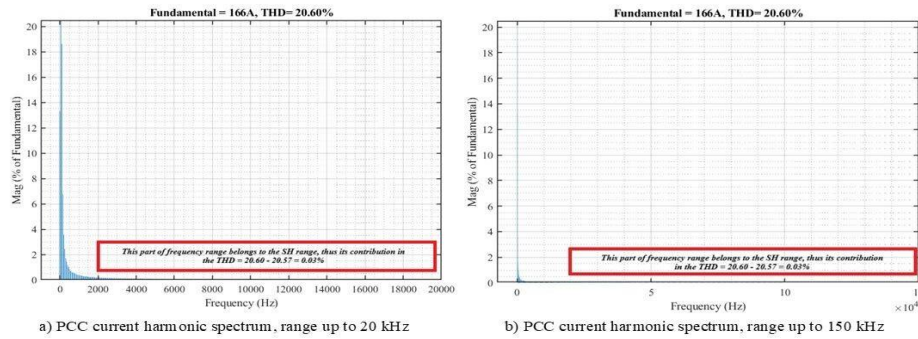


Fig. 10. PCC current harmonic spectrum a) with SH's range up to 20 kHz, and b) with SH's range up to 150 kHz

For current waveform evaluation, as depicted in **Figure 8-a**, a comparative observation between the distorted load current and the filtered source current confirms the filtering efficacy of the proposed SAF. The load-current waveform is significantly distorted due to the injection of harmonics from switching converters connected to solar PV units. These distortions manifest severe waveform deformation and high peak amplitudes. Conversely, the source current waveform exhibits a marked improvement in terms of shape regularity and sinusoidal integrity. This observation clearly demonstrates the SAF's real-time compensation capability, wherein the harmonic current components demanded by the load are effectively supplied by the filter, leaving the source to supply predominantly the fundamental component.

For harmonic spectrum evaluation, the harmonic spectra at the PCC represented in **Figure 8-b**, **Figure 9**, and **Figure 10** offer a more profound insight into the filter's performance across a wide frequency range. **Figure 8-b** (0–2 kHz) and **Figure 9-a** (0–5 kHz) show that the bulk of harmonic distortion resides within the conventional low-order harmonic range (up to the 50th order for a 50 Hz system). The total harmonic distortion (THD) in this range is around 20.59% to 20.60%, of which the majority is attributed to harmonics below 2 kHz. The contribution of THD from harmonics beyond this point is minimal. **Figure 9-b** and

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Figure 10 (a and b), expanding the frequency analysis up to 10 kHz, 20 kHz, and 150 kHz, respectively, provide a clear breakdown of SH components. It is evident that the contribution of SH to the overall THD remains marginal, as highlighted in the plots. The observed increase in THD from 20.57% to 20.60% when including frequencies up to 150 kHz quantifies the SH contribution as approximately 0.03%. These outcomes regarding SH mitigation show that SH contributes relatively little numerically to the overall THD, which reveals that the ability of the SAF to suppress SH is evident in the smooth spectral roll-off beyond 2 kHz. This behavior validates the effectiveness of the parabolic PWM strategy, ensuring the minimization of high-frequency harmonic energy without the need for bulky passive filters. Additionally, the attenuation curve seen in **Figure 9-b** and **Figure 10 (a and b)** demonstrates that the filter does not exhibit resonance amplification or switching noise injection at high frequencies, which is a common concern in poorly designed filters.

V. Conclusions

This study successfully demonstrates the design and implementation of an active filter to minimize supra-harmonics in a microgrid with solar PV. The filter significantly improves power quality and system reliability, providing a viable solution to a critical challenge in renewable energy integration. The findings have several important implications:

- The active filter can be integrated into MG designs to enhance PQ and reliability. Improved PQ leads to longer equipment life, reduced maintenance costs, and better overall performance.
- The filter facilitates the broader adoption of solar PV by addressing one of its major drawbacks. By mitigating SH, the active filter supports the integration of RES into MGs.
- The research supports the development of standards and policies promoting the use of active filters in RES. Standardized guidelines can help ensure consistent and effective implementation of active filters.
- Parabolic PWM-based AHF achieves significant suppression of SH, reducing source current distortion and improving PQ.
- SH mitigation, although contributing minimally to THD numerically, is effectively addressed, ensuring better EMC (electromagnetic compatibility) and grid compliance.
- The system maintains THD levels with a marginal rise from the SH spectrum, validating the filter's high-frequency performance.

The combined waveform and spectral evidence confirm that the proposed control strategy not only complies with harmonic standards such as IEEE 519 in terms of current quality but also contributes to broader power conditioning by addressing emerging supra-harmonic concerns. This makes it particularly suited for solar PV-integrated MGs, where inverter-driven distortions are prominent across both traditional and high-frequency domains. Future research should focus on scaling active filter design for larger systems and exploring

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its application in other RE integrations. Additionally, advancements in control algorithms and digital signal processing can further enhance the filter's performance. Research into cost-effective solutions for active filter implementation can also support broader adoption.

Conflict of Interest

There was no relevant conflict of interest regarding this paper.

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