Compensation of Harmonics in Microgrids: A Review

Osita U. Omeje[1], Phoebe O. Umukoro[2], Daniel E. Okojie[3], and Gerard N. Obiora[4]
[1,2,4]*Department of Electrical and Electronics Engineering, University of Lagos, Akoka-Yaba, Lagos, Nigeria*
[1,3]*Department of Electrical and Electronic Engineering, Pan-Atlantic University, Ibeju-lekki, Lagos, Nigeria*

***Abstract*—The integration of flexible loads and distributed energy resources (DERs) into microgrids is increasing the complexity and uncertainty of these systems. This has led to challenges in the control and operation of microgrids, as well as opportunities for novel data-driven methods to address these challenges. One such method is harmonic compensation, It involves minimizing the distortion of the current and voltage waveforms brought on by non-linear loads. There are numerous techniques for harmonic compensation that can be used in both islanded and grid-connected microgrids. This paper provides a comprehensive review on harmonic compensation in microgrids. The paper begins by discussing the basics of harmonics and their impact on microgrids. It then reviews the different methods of harmonic compensation, including passive, active, and hybrid methods. The paper also discusses the challenges and future trends in harmonic compensation in microgrids. The paper concludes by providing a summary of the key findings and recommendations. The findings of this paper suggest that harmonic compensation is a promising method for improving the operation and control of microgrids.**

***Index Terms*—microgrids, harmonic compensation, non-linear loads, harmonics, power electronic devices.**

I. INTRODUCTION

With the growing consumer expectations and growing environmental concerns, the production of electricity is changing quickly. A collection of distributed generation (DG) units, loads, communication systems, safety devices, and distributed energy storage systems that act as one controlled entity is known as a microgrid (MG). Low voltage grids known as microgrids can function in both autonomous and non-autonomous modes. Meaning that microgrids can be operated in grid-tied and islanded modes [1]. Due the growing use of distributed energy production systems, microgrids are one of the viable options to integrate the various DERs with the utility grid [2]. The use of non-linear load can result in harmonic contamination of the distribution system. Harmonic issues in distribution networks have given rise to various filtering approaches. These methods are designed to compensate for the cyclic distortions in the output voltage resulting from the distorted load current and its harmonic components, with power electronics converters serving as interfaces between renewable energy sources (RESs) and the grid [2]. Recently, RESs based DGs have enhanced the world's energy supply networks. The utility grid's deployment of DERs is rapidly expanding both in developed and developing countries [1]. DGs can run in a MG mode or concurrently with the main grid. Grid-connected inverters are primarily utilized by these DGs to transmit clean energy such as photovoltaic (PV) electricity [2].

The concept of microgrids is extremely encouraging as a potential solution to the issue of future fossil fuel shortages in traditional power generation. It is also effective in mitigating the effects of the current generating system on the environment.

Due to non-linear load interruptions, as well as increase in the use of power electronic devices, the power quality (PQ) domain has attracted a lot of interest in microgrid systems and the development of RESs. It is anticipated that implementing microgrids will improve PQ, ease network congestion, minimize radiations, and power losses, potentially improving the system's profitability, and increase energy efficiency [3].

Various strategies have been suggested for compensation of harmonics in island and grid connected MGs. Harmonic currents produced by non-linear electronic loads raise end-user energy costs and power system heat losses. These harmonic-related losses raise power and cooling costs, decrease system effectiveness, and lead to overheating of apparatus [4]. By monitoring total harmonic distortion (THD) at different crucial microgrid sites, it is feasible to assess the harmonics effect on PQ across various points. Examples are load connection points, Point of Common Coupling (PCC), and DERs interfaces [5]. Voltage quality issues account for at least 50% of power quality issues with 18% caused by harmonics. THD of the grid must be kept at a low level per industrial norms [6]. In addition to harmonic distortion mitigation, harmonic current sharing is crucial for enhancing the power quality of microgrids [7]. Transformers, electric motors, and other networked equipment, as well as electronic appliances, are all susceptible to damage arising from the presence of harmonics [8].

II. MICROGRID

A microgrid consists of interconnected loads and DERs that act as a unified, manageable system which can be operated in grid connected or freestanding mode. Thus, MGs have the ability to connect to or disconnect from the grid [9]. Thermal power plants, microturbines, solar panels, wind turbines, and microturbines are some of the DERs that makes up a typical MG structure [10]. Using microgrids makes it possible to employ RESs while enhancing PQ, reducing transmission congestion, minimizing emissions, and reducing energy losses [6]. Harmonic currents produced by nonlinear devices like switched mode power supply (SMPS), variable-speed motors, drive systems, computers, and power electronic inverters, are applicable to MGs and thus, needs to be mitigated [5]. Figure 1 depicts a typical MG architecture.

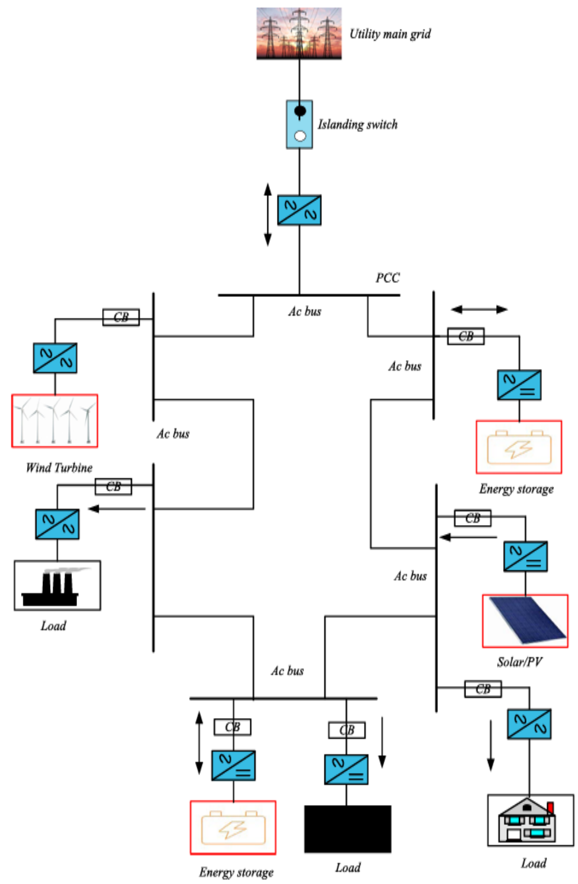

Fig 1. Microgrid Architecture [11]

III. MICROGRID OPERATION MODES

There are two ways a microgrid power system can run islanded mode and grid-connected mode:

A. Freestanding

The utility grid does not supply any electricity when the static switch is open. Thus, a MG can function independently when the utility grid is down, preventing power outages [9]. Microgrids without PCC are referred to as isolated microgrids, or simply independent microgrids. This grid category encompasses remote locations that remain unconnected to the main utility grid due to technical or economic constraints. In such areas, independent MGs can be employed to supply power. Achieving island status improves service, power quality, and dependability while reducing outages. Islanding may occur accidentally or on purpose. Islanding can happen during scheduled maintenance or when the utility main grid's power quality endangers the performance and quality of the microgrid. On the other hand, in the MG, faults and other unpredictable events may lead to unintentional islanding. [12].

B. Grid-connected

In this mode, electricity is connected to the microgrid. There are two types of grid connection. One type is linked to the grid without generating excess electricity for it, while the other type produces power for the utility grid. When connected to the utility grid, a static switch is closed. The utility grid has established all the necessary connections, allowing the microgrid to contribute surplus electricity to the main grid [9]. In order to transfer power without experiencing any technical issues, the frequency needs to be coordinated with the main electric grid. The main and mini grids must be disconnected and connected at the PCC [12].

IV. CONTROL OF MICROGRID

Three hierarchical control structure of MGs exists and they are the primary, secondary and tertiary control methods [13].

A. Primary Control

This is the local control action by the local controllers at the grid/load interfacing converters terminals. It provides internal control of the converters' output voltage and current, as well as power-sharing using centralized and decentralized control techniques. As the primary control is the fastest among all the control levels, it also includes islanding detection, power-sharing, output control and subsequent change of controller modes. Voltage and current control are the two primary types of local control used in MG systems to manage power electronic converters [13]. They are typically organized in a cascaded structure with and outer voltage loop and an inner current loop.

i. Current control: Several methods of control have been developed to enhance PQ by way of adjusting the MG [14]. A current control loop is responsible for managing the grid current within the grid-side electrical converter. In the case of the current-controlled voltage source inverter (VSI), pulse width modulation (PWM) techniques are applied to control both the active and reactive components of the current supplied to the grid. A current controller is less susceptible to grid voltage distortion and voltage phase shifts. The most popular technique for the grid linked mode to manage the output voltage and frequency inside confinement sites is current control [9]. Thus, implies that this method of control is applicable in grid-tied mode.

P,Q control, a type of current control, delivers constant active and reactive power to the microgrid by DGs. P,Q control is utilized especially for wind and solar based DGs to extract maximum available energy. Inverters in this control category functions as a voltage source with current control [15].

ii. Voltage control: This type of control is essentially about maintaining stable voltage levels within the acceptable range despite fluctuations in generation, load, and other factors. Whether the microgrid operates in island mode or connected to the main grid, this helps to assure its dependability, stability, and efficiency. Large harmonic currents may develop if the grid voltage is distorted, and voltage regulation is sensitive to even small phase errors [9]. There are diverse voltage control strategies but in this study, emphasis will be made on V/f and droop control. Both find application in islanded operation mode of MGs.

Droop Control is a type of decentralized control since it uses local information only and the energy available in DG is more than the demand. For a synchronous generator, if the active power output increases, its load angle increases thereby decreasing the frequency. Similarly, if the reactive power drawn increases, its terminal voltage decreases. This frequency and voltage droop characteristics are assigned to the inverters and they are made to imitate the behaviour of synchronous generators. For an inverter in a microgrid, if we are required to increase the active power drawn from it, its frequency is reduced as per the frequency droop characteristic. The case is similar with reactive power also. The whole idea of this machine mimicking is to make the microgrid look more like a normal utility grid run by synchronous generators. In this mode, the MG inverter will work as VSI and operates in parallel with other inverters [16].

For V,f control, also known as VSI. Here, the inverter is operated as a voltage source with controllable magnitude and frequency [15]. When a power sharing process occurs, the voltage and frequency deviates from their nominal values as per the droop characteristics of the inverters. V,f control helps in bringing back the frequency and voltage to their nominal values. It further plays a vital role during synchronization - switching between islanded mode to grid connected mode [16].

B. Secondary Control

This is the energy management system (EMS) of the microgrid. It is responsible for power quality enhancement, restoring frequency and voltage in the microgrid caused due to primary level droop control actions. It is also responsible for resynchronization of microgrid to the utility grid and ensuring optimal and coordinated operation of DER units within the microgrid [13].

C. Tertiary Control

The purpose of tertiary control is to manage the power flow between the microgrid and utility grid and to optimize the operation of a microgrid. It coordinates the operation of multiple microgrids and communicates the requirements such as voltage and frequency regulation from the host grid. Tertiary control receives power references from the distribution management system (DMS) and processes the error between the actual and reference values. It is however, the slowest control in the hierarchy [13].

V. CLASSIFICATION OF MICROGRID

Microgrids exist in three categories: direct current (DC) microgrids, alternating current (AC) microgrids and hybrid microgrids [12].

A. AC microgrids

Since it requires additional power conversion equipment and uses a plug-in method for all DERs, the AC microgrid is the most popular of the three [12]. AC microgrids are microgrids that operate and supply AC electricity to the utility system with which they are integrated. Power generation sources, storage devices, and various system components are interconnected with the AC network to meet the demands of AC loads. These microgrids can be readily integrated into existing electricity grids and do not require any special control methods. Single-phase, grounded three-phase, and ungrounded three-phase are the three types of AC microgrids [17] .

B. DC microgrids

DC loads including communication/computing equipment, liquid crystal displays, and variable speed drives are most suited for DC microgrids since they require the fewest power conversion components [12]. DC microgrids use the concept of generating and storing power in DC forms. These microgrids employ a variety of converters and power electronic devices to communicate with the current distribution system. When feeding DC loads, DC microgrids are more efficient and need less conversion than AC microgrid systems. Certain commercial applications of DC microgrids include telephony, electric vehicles, naval power systems, and so on. DC microgrids are further classed as mono-polar, bi-polar, and homo-polar microgrids [17].

C. Hybrid microgrids

A hybrid microgrid is an energy system composed of multiple power sources such as photovoltaic panels, wind turbines, fossil-fuel generators, converters, battery storage systems, and an EMS that guarantees stability and balance of the entire system. According to the system operation and the meteorological conditions, the microgrid can be linked to the electrical grid or work as a standalone system [18]. The most popular type is the AC/DC hybrid MG [19].

VI. HARMONIC DISTORTION

Harmonics have a multitude of negative consequences for power system loads and components. Power electronic loads regulate power flow by pulling current only at specific intervals of the 50/60 Hz cycle. This causes the load current waveform to be non-sinusoidal. Thus, when the system impedance and the non-sinusoidal current interact, this results in distortion [20]. The presence of harmonic currents from nonlinear loads results in voltage distortion at the PCC due to losses induced by the grid-side inductors of microsource inverters [21]-[22]. Through the distortion of waveform in both voltage and current, nonlinear loads can produce harmonics. The effective value of the harmonic voltage $(THD)_V$ or current $(THD)_I$ is measured as THD. In contrast to high value harmonics that have a high chance of having disruptive effects, low value harmonics with a low possibility, can be found in utility networks. Voltage distortions are expected to remain below limitations for 95% of the 10-min averages collected in a week, according to EN 50160, which specifies harmonic standards. When an AC source is used to power a nonlinear load with h harmonics, the root mean square (rms) voltage is calculated using Equation (1) as shown in [14].

$$V_{rms} = \frac{1}{\sqrt{2}}\sqrt{V_1^2 + V_2^2 + V_3^2 \ldots . V_{h_{max}}^2} = \sqrt{V_{1,rms}^2 + V_{2,rms}^2 + V_{3,rms}^2 \ldots . V_{h_{max,rms}}^2} \quad (1)$$

The peak intensities of the first, second, third and higher order current harmonics are denoted by the letters V1, V2, V3...Vh. The current's corresponding rms value is represented by

$$I_{rms} = \frac{1}{\sqrt{2}}\sqrt{I_1^2 + I_2^2 + I_3^2 \ldots . I_{h_{max}}^2} = \sqrt{I_{1,rms}^2 + I_{2,rms}^2 + I_{3,rms}^2 \ldots . I_{h_{max,rms}}^2} \quad (2)$$

The fundamental voltage and current harmonic levels are known as THDs. THD in voltage and current are represented by Equation (3) and (4).

$$THD_V = \left(\sqrt{\sum_{h>1}^{h_{max}} V_{h,rms}^2}\right)/V_1 = \frac{\sqrt{V_2^2 + V_3^2 \ldots . V_{h_{max}}^2}}{V_1} \quad (3)$$

$$THD_i = \left(\sqrt{\sum_{h>1}^{h_{max}} I_{h,rms}^2}\right)/V_1 = \frac{\sqrt{I_2^2 + I_3^2 \ldots . I_{h_{max}}^2}}{I_1} \quad (4)$$

Harmonics in voltage and current fall between h=2 and $h_{max,}$ with V_1 or I_1 standing for the rms value of fundamental voltages or currents. A distorted voltage and current waveform's rms value is given by

$$V_{rms} = \left(\sqrt{\sum_{h=1}^{h_{max}} V_h^2}\right) = \sqrt{V_1^2 + \sum_{h>1}^{h_{max}} V_h^2} \quad (5)$$

$$I_{rms} = \left(\sqrt{\sum_{h=1}^{h_{max}} I_h^2}\right) = \sqrt{I_1^2 + \sum_{h>1}^{h_{max}} I_h^2} \quad (6)$$

The rms values of the harmonic components are V_h and I_h. THD can be related to the rms values of distorted voltage and current waveforms by

$$V_{rms} = V_1\sqrt{1 + (THD/100)^2} = V_1\sqrt{1 + THD_{PU}^2} \quad (7)$$

$$I_{rms} = I_1\sqrt{1 + (THD/100)^2} = I_1\sqrt{1 + THD_{PU}^2} \quad (8)$$

VII. EFFECT OF VOLTAGE AND CURRENT HARMONICS

The presence of harmonics (current or voltage) is detrimental to any electrical power system. The following are some of the negative effects of the presence of either voltage or current harmonics: equipment overheating, affects fuses and circuit breaker interruption abilities, leads to motor performance deterioration, leads to transformer losses by way of eddy current or core losses, causes electromagnetic interference, decreased efficiency, measurement error [23]-[24].

A. Voltage Harmonics

In most power systems, voltage harmonic distortion THDv is less than 5%, and the size of harmonic components is minor when compared to the fundamental. According to ANSI-C.27-1920, the losses caused by voltage harmonics are indicated as follows if harmonic distortion is substantial and needs to be taken into account [25].

$$P = P_M\left[P_h + P_{ec}\left(\frac{V_{hrms}}{V_{rms}}\right)^2\right] \quad (9)$$

Where V_{rms} and V_{hrms} are the rms values of fundamental voltage and harmonic voltage, respectively, P is the losses under fundamental voltage, P_M is the losses under harmonic voltage, P_h denotes the hysteresis losses and P_{ec} is eddy current losses.

B. Current Harmonics

Current harmonics is more significance in the majority of power systems. Increased losses in the transformer are caused by current harmonics. Due to the presence of current harmonics, the load current increases, increasing losses proportional to the square of the current [25].

VIII. HARMONIC REDUCTION TECHNIQUES UTILIZED IN MICROGRIDS

To achieve a high level of reliability, it is imperative to enhance the performance of microgrids in both isolated and grid-connected modes. Numerous researchers have explored the impact of harmonics in microgrids across various operational modes, as well as diverse approaches for mitigating these harmonics.

Some of the various strategies used to mitigate harmonics will be discussed in this section.

A. Virtual Impedance

Inverter control loops can reduce voltage harmonic distortion at the PCC by using a capacitive virtual impedance loop [26]. The study executed by [22] focused on selective harmonic correction in islanded microgrids. The authors were able to enhance the virtual impedance loop at the PCC in order to minimize voltage harmonics. Thus, voltage THD was reduced from 3.36% to 2.57% while for the study carried out by [26], V_{THD}decreased from 24.3% to 1.826%.

B. Virtual Admittance

The fundamental objective of the virtual admittance strategy is to distribute the required actions among several parallel connected inverters in order to reduce the harmonic content and unbalances at the PCC in microgrids. Because microgrids commonly incorporate non-linear loads (NLL), harmonic components are regularly detected at the PCC [27].

C. Zero-Sequence Control

A zero-sequence control method is capable of removing current and voltage harmonics without the need of active and passive filters. This strategy was employed by [28] to achieve 0.3% and 0.2% voltage and current THD from 5.73% and 27.41% respectively. In this method, the controller uses a specific control loop to manage the zero-sequence current circulating between the microgrid inverter and the grid.

D. Filtering Methods

Passive and active power filters have long been utilized to mitigate harmonics within a system [29]. Passive filters have proven effective in attenuating harmonic currents and voltages. Their simplicity and reliability make them a viable choice for applications where harmonic sources are relatively constant. Another approach for diminishing and ultimately eradicating the harmonic amplitudes in current and voltage is through the utilization of the active power filter module (APFM). This module optimizes control coefficients and applies them to harmonic loops associated with voltage, current, and the controller error [30]. APFs can be categorized as series or shunt according to their topology. Shunt APFs for instance can be employed to compensate for reactive power and unbalanced current in addition to reducing harmonic currents brought on by NLLs. Furthermore, active compensation techniques remarkable dynamic response capabilities. They enable real-time harmonic mitigation, making them suitable for situations where harmonic sources vary rapidly. The common types of passive filters are presented in Fig. 2 while the general block diagram of an APF is shown in Fig. 3. In addition to using individual passive or active filters for harmonic suppression, passive as well as active filter topologies (series and parallel) can be hybridized for more effective performance. This hybrid combination of passive or active filters or both are now employed for addressing harmonic problems in microgrids [24]. Hybrid solutions that combine passive and active methods offer enhanced flexibility and performance. They can address a broader range of harmonic scenarios and provide synergistic benefits.

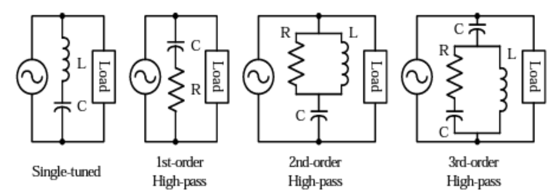

Figure 2: Common type of passive filter and their configuration [31]

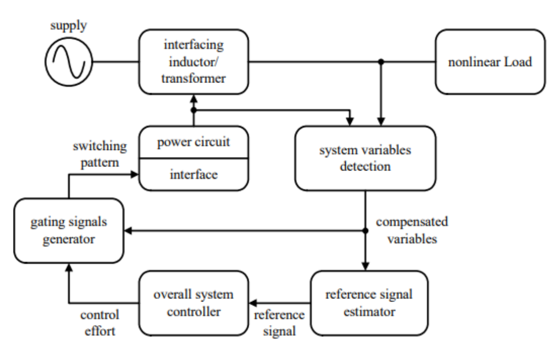

Figure 3: General block diagram for an APF [24]

E. Current Control Method

This method can also be employed to achieve harmonic compensation. Thus, in a microgrid, this approach can effectively accomplish harmonic compensation within the Distributed Generation (DG) unit(s). To attain harmonic suppression in the study carried out by [32], the DG line current was adjusted based on the need for harmonic compensation and the inverter's available power rating. Owing to the fact that compensations for voltage and current harmonics are connected, compensation for current harmonics significantly reduces the amount of distortion in the voltage at the PCC [33].

F. Voltage Control Method

This method is also an appropriate technique for achieving harmonic compensation in microgrids. With this technique, the fundamental voltage reference signal, V_{ref_f}, can be generated through droop control mechanisms like real power-frequency (P-f) droop and reactive power-voltage (Q-V) droop. This enables effective power distribution among multiple DG units when they are interconnected within the system [32].

The current and voltage control methods can be hybridized to achieve harmonic minimization and this strategy was employed in the studies executed by [2], [34]-[35].

G. Hybrid Voltage and Current method (HCM).

An adaptive hybrid voltage and current controlled technique (HCM) has been proposed in [2]. It demonstrates the ability of the proposed adaptive Hybrid Control Method (HCM) to reduce the number of low-pass/bandpass filters required in the digital controller of the DG unit. In cases where DG units are equipped with converters employing LCL filters, a hybrid approach that combines voltage and current control techniques (HCM) was implemented [34]. The suggested control strategy manages harmonic line currents to account for the specific harmonic loads in the vicinity and enhance the quality of line currents at the selected harmonic frequencies. Fundamental voltage tracking is employed alongside droop control to govern the fundamental power flow of the DG unit. The HCM also ensures changeover between islanding and grid-connected operation modes [34]. For a grid-connected PV inverter to perform a variety of functions, a hybrid control technique was developed. Despite the intermittent nature of solar energy, this method guarantees reliable energy delivery. Power quality methods such as harmonic elimination and power factor enhancement also contribute to the reduction of power output. The control strategy comprises a voltage control loop founded on proportional-integral principles, ensuring reliable operation even during intermittent or zero-generation scenarios. Additionally, it incorporates a current control loop grounded in passivity theory, enhancing the quality of power from the inverter [35].

H. Repetitive-based controller

A positive feedback strategy for the delay line is examined for the repeating method, instead of placing it in the direct path like other recorded repetitive schemes, it is placed in the feedback path. [36]. An illustration of a repetitive-based control technique is presented for a boost-based power factor pre-compensator, guaranteeing swift adjustment of the output voltage to a predetermined constant level while achieving a power factor that closely approaches unity [37].

A novel recurring technique created to account for the harmonics, $6\ell \pm 1$ $(\ell = 0,1,2,\dots,\infty)$ of the fundamental frequency ω_0. "This approach was devised to incorporate a positive-feedback repeating system within a synchronous frame that rotates at the frequency ω_0. The objective of the positive-feedback method was to generate a continuous sequence of resonant peaks centered at $6\ell\omega_0$, which, due to frequency shifts resulting from the rotations in the synchronous frame, produce a resonant peak at $(6\ell \pm 1)\omega_0$ [38]. A new repetitive-based control system has been introduced for the pulse-width modulated (PWM) boost converter with the aim of diminishing the output voltage fluctuations arising from harmonic distortions in the input voltage [36]. As a controller, the cascade connection of inner and outer loops has been considered [39]. The inner loop was designed using a repeating scheme and a standard proportional term, whereas the outer loop was designed using a low pass filter and an integral term. The repetitive technique was devised to offset the odd harmonic elements arising from periodic distortion in heavily distorted loads. Even in the presence of distorted and imbalanced load currents, a three-phase inverter managed to produce an approximately sinusoidal and well-balanced voltage, thanks to the implementation of a repetitive-based controller. The repetitive method is designed to counteract the periodic distortion in the output voltage resulting from the distorted load current and its atypical harmonic components. In the repeating scheme, which included a feedforward loop and a negative feedback structure, only odd harmonics were analyzed for compensation [40].

IX. FINDINGS AND RECOMMENDATION

This section presents the findings derived from the comprehensive analysis of various harmonic compensation methods:
Passive filters have proven effective in attenuating harmonic currents and voltages. Their simplicity and reliability make them a viable choice for applications where harmonic sources are relatively constant. Active compensation techniques, including shunt and series compensators, exhibit remarkable dynamic response capabilities. They enable real-time harmonic mitigation, making them suitable for situations where harmonic sources vary rapidly while hybrid solutions that combine passive and active methods offer enhanced flexibility and performance. They can address a broader range of harmonic scenarios and provide synergistic benefits. Advancements in control techniques, such as model predictive control and artificial intelligence-based strategies, offer potential for improved accuracy and adaptability in harmonic compensation systems. Based on the findings and insights presented in this review paper, the following recommendations are made for future research and practical implementations in the field of harmonic compensation:
Researchers and practitioners should focus on integrating cutting-edge control strategies such model predictive control and artificial intelligence-based techniques into harmonic compensation systems. These strategies can enhance the adaptability and precision of compensation systems, ensuring efficient harmonic mitigation. Exploration of hybrid and distributed harmonic compensation solutions is encouraged. These approaches leverage the strengths of both passive and active methods while aligning with the trend of decentralized energy resources. Investigating their performance in diverse scenarios and their scalability in larger systems is crucial.

X. CONCLUSION

This review paper meticulously explored various harmonic compensation methods to counter the adverse effects of harmonics on power systems. Passive harmonic compensation methods, such as passive filters, were examined for their effectiveness in attenuating harmonic currents and voltages. Active harmonic compensation techniques, encompassing different control strategies for shunt and series compensators, were thoroughly analyzed for their dynamic response capabilities. Furthermore, the advantages of hybrid harmonic compensation approaches, which amalgamate passive and active techniques, were underscored for their ability to deliver enhanced performance and flexibility. The impact of harmonic compensation on power system operation, stability, and reliability was thoroughly evaluated. It became evident that harmonic compensation plays a pivotal role in mitigating power quality issues and grid disturbances caused by harmonics.
Advancements in control techniques, such as model predictive control (MPC) and artificial intelligence (AI)-based strategies, offer potential for improved accuracy and adaptability in harmonic compensation systems. Thus, future researchers and stakeholders interested in this study area should focus on integrating these cutting-edge control strategies into harmonic compensation systems. These strategies can further ensure efficient harmonic mitigation.

REFERENCES

[1] N. Kannan, ‘‘Microgrid,’’ in Research Trends and Challenges in Smart Grids, London, United Kingdom: IntechOpen, 2020, ch. 6, pp. 103-118, http://dx.doi.org/10.5772/intechopen.77415

[2] J. He, Y. W. Li and F. Blaabjerg, “Flexible microgrid power quality enhancement using adaptive hybrid voltage and current controller,” IEEE Transactions on Industrial Electronics, vol. 61, no. 6, pp. 2784-2794, 2014, doi: https://doi.org/10.1109/TIE.2013.2276774

[3] A. F. Ali, W. H. Zayer and S. S. Shukir, “Power Quality Prolems and Improvement Techniques,” Journal of Engineering and Applied Sciences, vol. 14, no. 16, pp. 5888–5898, 2019, doi: https://doi.org/10.36478/jeasci.2019.5888.5898

[4] Eaton (2008). Harmonics in your electrical system. Available: https://www.newark.com/pdfs/techarticles/eaton/

Eaton_Technical_Articles/UPS_Training/Powerware_Training/HarmonicsInYourElecSystem.pdf

[5] P. Basak, S. Chowdhury, S. H. N. Dey and S. P. Chowdhury, “A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid,” Renewable and Sustainable Energy Reviews, vol. 16, no. 8, pp. 5545–5556, 2012, doi: https://doi.org/10.1016/j.rser.2012.05.043

[6] Q. Zhong and T. Hornik, “Cascaded current-voltage control to improve the power quality for a grid-connected inverter with a local load,” IEEE Transactions on Industrial Electronics, vol. 60, no. 4, pp. 1344–1355, 2013, doi: https://doi.org/10.1109/TIE.2012.2187415

[7] F. Chang, G. Song, S. Li, B. Li, Z. Lou, Y. Liang, D. Wang and Y. Zhang, ‘‘Harmonic power sharing control method for microgrid inverters based on disturbance virtual impedance,’’ Energies, vol. 19, no. 4, p. 1015, 2026, doi: https://doi.org/10.3390/en19041015

[8] M. Savaghebi, A. Jalilian, J. C. Vasquez, J. M. Guerrero and T. Lee, “Voltage harmonic compensation of a microgrid operating in islanded and grid-connected modes,” in Proceedings of the 19th Iranian Conference on Electrical Engineering, Tehran, Iran, 2011. [Online]. Available: https://vbn.aau.dk/files/58333889/PREPRINT_voltage_harmonic_compensation_of_a_microgrid.pdf

[9] M. M. Prakash and J. Paul, “Control of microgrid for different modes of operation,” International Journal of Engineering Research & Technology, vol. 5, no. 5, pp. 815-820, 2016. [Online]. Available: https://www.ijert.org/research/control-of-microgrid-for-different-modes-of-operation-IJERTV5IS051001.pdf

[10] M. Uddina, H. Mo, D. Dong, S. Elsawah, J. Zhu, and J. M. Guerrero, ‘‘Microgrids: A review, outstanding issues and future trends,’’ Energy Strategy Reviews, vol. 49, p. 101127, 2023, doi: https://doi.org/10.1016/j.esr.2023.101127

[11] S.T. Saranya and P. Bhowmik, ‘‘A comprehensive review of microgrid architectures, power management and resilient operation,’’ Energy Reports, vol. 15, p. 109021, 2026. doi: https://doi.org/10.1016/j.egyr.2025.109021

[12] V. Saravanan, K. M. Venkatachalam, M. Arumugam, M. A. K. Borelessa, and K. T. M. U. Hemapala, “Overview of microgrid systems,” International Journal of Advances in Applied Sciences, vol. 10, no. 4, pp. 378-391, 2021, doi: http://doi.org/10.11591/ijaas.v10.i4.pp378-391

[13] S. K. Sahoo, A. K. Sinha and N. K. Kishore, ‘‘Control techniques in AC, DC, and hybrid AC-DC microgrid: A review’’, IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 6, no. 2, pp. 738-759, 2018, doi: https://doi.org/10.1109/JESTPE.2017.2786588

[14] M. T. L. Gayatri, A. M. Parimi and A. V. P. Kumar, “A review of reactive power compensation techniques in microgrids,” Renewable and Sustainable Energy Reviews, vol. 81, part 1, pp. 1030–1036, 2018, doi: https://doi.org/10.1016/j.rser.2017.08.006

[15] A. S. Dobakhshari, S. Azizi, and A. M. Ranjbar, ‘‘Control of Microgrids: Aspects and Prospects’’, in Proceedings of the 2011 International Conference on Networking, Sensing and Control, Delft, the Netherlands, pp. 38-42, 2011, doi: https://doi.org/10.1109/ICNSC.2011.5874892

[16] B. Satish, and S. Bhuvaneswari, ‘‘Control of Microgrid - A Review’’, in Proceedings of the 2014 International Conference on Advances in Green Energy, Trivandrum, pp. 18-25, 2014, doi: https://doi.org/10.1109/ICAGE.2014.7050138

[17] S. Chandak and P. K. Rout, “The implementation framework of a microgrid: A review,” International Journal of Energy Research, vol. 45, pp. 3523–3547, 2021, doi: https://doi.org/10.1002/er.6064

[18] Z. Ullaha, S. Wanga, J. Lai, M. Azam, F. Badshah, G. Wu, and M. R. Elkadeem, ‘‘Implementation of various control methods for the efficient energy management in hybrid microgrid system’’, Ain Shams Engineering Journal, vol. 14, p. 101961, 2023, doi: https://doi.org/10.1016/j.asej.2022.101961

[19] F. Chang, J. O’Donnell, and W. Su, ‘‘Voltage Stability Assessment of AC/DC Hybrid Microgrid’’, Energies, vol. 16, no. 1, p. 399, 2023, doi: https://doi.org/10.3390/en16010399

[20] J. Kaur and S. K. Bath, ‘‘Harmonic distortion in power systems due to electronic control and renewable energy integration: A comprehensive review,’’ Discover Electronics, vol. 2, no. 67, 2025, doi: https://doi.org/10.1007/s44291-025-00111-9

[21] A. Alduraibi, J. Yaghoobi and F. Zare, ‘‘Impacts of grid voltage harmonics amplitude and phase angle values on power converters in distribution networks,’’ IEEE Access, vol. 9, pp. 92017-92029, 2021, doi: https://doi.org/10.1109/ACCESS.2021.3093026

[22] A. Micallef, M. Apap, C. Spiteri-Staines and J. M. Guerrero, “Selective virtual capacitive impedance loop for harmonic voltage compensation in islanded microgrids,’’ in Proceedings of the 39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, 2013, doi: https://doi.org/10.1109/IECON.2013.6700464

[23] G. N. Obiora, F. O. Oghenegweke, G. O. Igbinosa, T. Obidire, C. B. Fiemobebefa and O. A. Bamido, ‘‘Reduction of power quality perturbations: A review,’’ European Journal of Applied Science, Engineering and Technology, vol. 3, no.3, pp. 174-190, 2025, doi: https://doi.org/10.59324/EJASET.2025.3(3).11

[24] G. N. Obiora, A. S. Alayande and O. U. Omeje, ‘‘Utilization of filters and other methods for harmonic distortion mitigation in electricity networks tied to renewable energy sources: A review,’’ Nigerian Journal of Tropical Engineering, vol. 19, no. 1, 2025, doi: https://doi.org/10.59081/njte.19.1.001

[25] J. S. Maan, S. Singh, and A. Singh, “Impact of harmonics on power transformer losses and capacity using open DSS,” International Journal of Emerging Electric Power Systems, vol. 20, no. 4, p. 20180349, 2019, doi: https://doi.org/10.1515/ijeeps-2018-0349

[26] A. Micallef, M. Apap, C. Spiteri-Staines and J. M. Guerrero, “Mitigation of harmonics in grid-connected and islanded microgrids via virtual admittances and impedances,” IEEE Transactions on Smart Grid, vol. 8, no. 2, pp. 651–661, 2017, doi: https://doi.org/10.1109/TSG.2015.2497409

[27] C. Blanco, D. Reigosa, J. C. Vasquez, J. M. Guerrero and F. Briz, “Virtual admittance loop for voltage harmonic compensation in microgrids,” IEEE Transactions on Industry Applications, vol. 52, no. 4, pp. 3348–3356, 2016, doi: https://doi.org/10.1109/TIA.2016.2547362

[28] A. Naderipour, Z. Abdul-Malek, M. R. Miveh, M. J. H. Moghaddam, A. Kalam, and F. H. Gandoman, “A harmonic compensation strategy in a grid-connected photovoltaic system using zero-sequence control,” Energies, vol. 11, no. 10, p. 2629, 2018, doi: https://doi.org/10.3390/en11102629

[29] Y. W. Li and J. He, “Distribution system harmonic compensation methods: An overview of DG-interfacing inverters,” IEEE Industrial Electronics Magazine, vol. 8, no. 4, pp. 18–31, 2014, doi: https://doi.org/10.1109/MIE.2013.2295421

[30] N. Khosravi, H. R. Abdolmohammadi, S. Bagheri and M. R. Miveh, “Improvement of harmonic conditions in the AC/DC microgrids with the presence of filter compensation modules,” Renewable and Sustainable Energy Reviews, vol. 143, p. 110898, 2021, doi: https://doi.org/10.1016/j.rser.2021.110898

[31] E. Mhawi, H. Daniyal and M. H. Sulaiman, ‘‘Advanced Techniques in Harmonic Suppression via Active Power Filter: A Review;’’ International Journal of Power Electronics and Drive System, vol. 6, no. 2, pp. 185-195, 2015, doi: http://doi.org/10.11591/ijpeds.v6.i2.pp185-195

[32] X. Liang and C. Andalib-Bin-Karim, “Harmonics and mitigation techniques through advanced control in grid-connected renewable energy sources: A review,” IEEE Transactions on Industry Applications, vol. 54, no. 4, pp. 3100–3111, 2018, doi: https://doi.org/10.1109/TIA.2018.2823680

[33] M. El-Habrouk, M. K. Darwish and P. Mehta, “A survey of active filters and reactive power compensation techniques,’’ in Proceedings of the Eighth International Conference on Power Electronics and Variable Speed Drives, pp. 7-12, 2000, doi: https://doi.org/10.1049/cp:20000211

[34] J. He and Y. L. Wei, “Hybrid voltage and current control approach for DG-grid interfacing converters with LCL filters,” IEEE Transactions on Industrial Electronics, vol 60, no. 5, pp. 1797-

1809, 2013, doi: https://doi.org/10.1109/TIE.2012.2190374

[35] M. Reveles-Miranda, M. Flota-Banuelos, F. Chan-Puc, V. Ramirez-Rivera and D. Pacheco-Catalan, “A hybrid control technique for harmonic elimination, power factor correction, and night operation of a grid-connected PV inverter,” IEEE Journal of Photovoltaics, vol. 10, no. 2, pp. 664-675, 2020, doi: https://doi.org/10.1109/JPHOTOV.2019.2961600

[36] G. Escobar, J. Leyva-Ramos, P. R. Martínez, and A. A. Valdez, “A repetitive-based controller for the boost converter to compensate the harmonic distortion of the output voltage,” IEEE Transactions on Control Systems Technology, vol. 13, no. 3, pp. 500–508, May 2005, doi: 10.1109/TCST.2004.841666.

[37] G. Escobar, P. R. Martínez, J. Leyva-Ramos, A. A. Valdéz, and M. Hernández-Gómez, “A Repetitive-Based Controller for a Power Factor Precompensator with Harmonic Compensation.”

[38] G. Escobar, P. G. Hernandez-Briones, P. R. Martinez, M. Hernandez-Gomez, and R. E. Torres-Olguin, “A repetitive-based controller for the compensation of $6\ell \pm$ harmonic components,” IEEE Transactions on Industrial Electronics, vol. 55, no. 8, pp. 3150–3158, 2008, doi: 10.1109/TIE.2008.921200.

[39] G. Escobar, R. Ortega, A. Astolfi, M. F. Martínez, and J. Leyva-Ramos, “A repetitive based controller for a shunt active filter to compensate for reactive power and harmonic distortion.”

[40] G. Escobar, A. A. Valdez, J. Leyva-Ramos, and P. Mattavelli, “Repetitive-based controller for a UPS inverter to compensate unbalance and harmonic distortion,” IEEE Transactions on Industrial Electronics, vol. 54, no. 1, pp. 504–510, Feb. 2007, doi: 10.1109/TIE.2006.888803.