

HARMONIC COMPENSATION AND ACTIVE POWER INJECTION WITH PV AND BATTERY INTEGRATED PARALLEL ACTIVE POWER FILTER

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Abstract

In recent days, the harmonic distortion plays crucial power-quality issues which proliferates the distribution system and also worrying the power system engineers. These harmonics distortions are mostly injected into system by employing non-linear power-electronic loads in several domestic and industrial applications. In this regard, active power filters are found to have considerable interest at distribution system so as to maintain harmonic-free and also enhance distribution system stability. The shunt-Active Power Filter utilizes the single voltage-source inverter for compensation of harmonic currents in source current is maintained to be sinusoidal, linear and balanced in shape. But, the single VSI have some technical limitations over the dual-Voltage Source Inverter's are connected as parallel to attain current sharing, low switch stress, reduced switching losses and maximizing the over-all efficiency, so on. In this work, the dual-VSIs-based parallel connected APF (Active Power Filter) has been proposed for reducing harmonic current distortions, power-quality enhancement in Power Quality-mode. It injects the active power by employing the solar and battery connected energy storage system under DG connected mode by using DG-SRF control algorithm (Distributed Generation - Synchronous Reference Frame control algorithm). The performance of dual-VSIs based parallel connected APF is verified in both PQ (Power Quality) and DG (Distributed Generation) integrated modes by using Matlab/Simulink software tool, results are presented with comparisons.

Keywords: Active power injection; Battery energy storage system; DG-SRF theory; Harmonics; Parallel Active Power Filter; Solar-PV system

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Introduction

A grid's capability to deliver clean power is commonly referred to as power quality. Clean power is characterized by low noise, a sinusoidal waveform, and a frequency within allowable tolerance. The evolution of power electronics has simplified many tasks in the electrical sector. However, an increase in power-electronic components can introduce disturbances that degrade the power quality delivered to loads (Kai *et al.*, 2019). Disturbances on the source side may also make other connected devices more vulnerable. Harmonics, reactive power issues, transients, oscillations, and flicker are common disturbances. Poor power quality can reduce production rates, increase system losses, raise energy consumption, and reduce system efficiency and lifetime (Wu *et al.*, 2018).

Nowadays, it is increasingly common to install distributed generation (DG) in the grid. DG can improve stability, energy security, and reliability; however, power quality remains a concern as DG penetration increases. DG systems often employ power-electronic inverters, which can introduce harmonics into the system. Shunt active power filters (SAPFs) act as compensating devices that mitigate these disturbances to maintain a near-sinusoidal waveform at the source side.

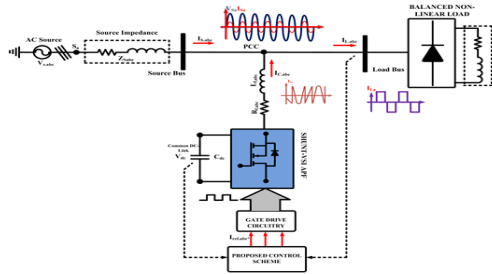


Figure 1. Block diagram of Shunt-Connected APF

The evolution of power electronics has made many tasks easier in the electrical sector. The block diagram of a shunt-connected APF (Suslov *et al.*, 2018) is shown in Figure 1. This paper presents a parallel-connected APF configuration for harmonic elimination and active power injection using energy sources. Active power generated from a solar system and a battery is fed into the distribution system through the parallel-connected APF. The parallel-connected APF performs two functions: harmonic compensation and active power injection. The parallel active power filter is controlled using the DG-SRF control algorithm (Peter *et al.*, 2018). Different simulation test cases are discussed, and the

proposed system is developed using a computer simulation software tool. The detailed characteristics of the photovoltaic (PV) panels used include:

1. **Technical Specifications:** Information such as the type of PV panels (e.g., monocrystalline or polycrystalline), efficiency, size, and rated power output should be detailed.

2. **Operating Conditions:** Environmental factors such as temperature, irradiance levels, and any assumptions made about ideal or suboptimal conditions should be clearly stated.

3. **System Integration:** Details on how the PV panels interact with other components in the system, including the battery and the active power filter, would add clarity and value to the research.

The paper include:

1. **System Description:** Provide a detailed overview of the system, highlighting its unique characteristics and components. This could include diagrams or schematics to visually depict the configuration.

2. **Modeling Details:** Clearly present the mathematical or computational models used for the system, including assumptions, equations, and parameters. This will ensure transparency and enable reproducibility.

3. **Control Strategy:** Specify the control techniques employed, including their design rationale and contribution to system performance. Comparisons with traditional approaches could further emphasize the novelty of the research.

Active Power Injection in Distribution System

The idea of a grid-connected PV system allows for a more flexible and efficient use of generated power. PV system use is growing quickly in the distribution network, and power quality issues have been found that could impair network performance. Harmonics are typically the primary cause of network distortions in power distribution system, which reduce quality power delivering to consumers (Jadhav *et al.*, 2016; Medina-Rios *et al.*, 2007). Filters are the fundamental correction mechanism used to overcome various types of power quality issues. PV-APF has been used in tandem for a number of years. This PV-APF system has the ability to correct power factor, current imbalances, current harmonics, as well as inject solar system power with low THD. Figure.1 shows the circuit

diagram for active power filter connected to the DG systems. Here, the aim of APF is to mitigate the problems in DG system caused by non-linear loads. The major elements of parallel connected APF consist of active compensating device, power electronic converter and shunt transformer (Ramos-Carranza *et al.*, 2008). In this paper, the parallel connected APF configuration has been developed for injecting the active power into distribution network. The power generated from solar system and battery is fed to distribution system through parallel APF's. The Parallel connected APF's carryout two functions like compensating harmonics and active power injection. Parallel active power filter is controlled using DG-SRF control algorithm. Figure 2 represents the PV integrated APF in power network

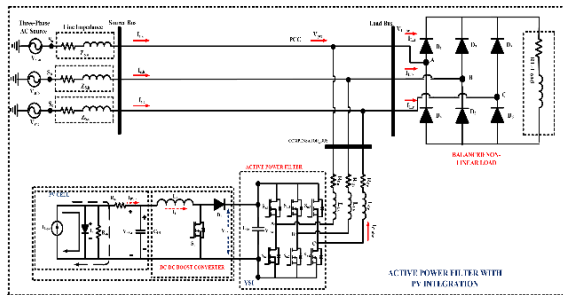


Figure 2. PV integrated APF in power network

The VSC integrated by the APF should provide a better harmonic removal and reactive power compensation solution while also injecting the maximum amount of solar system power. This work proposes an instantaneous power theory to govern this (Somayajula *et al.*, 2014; Cai *et al.*, 2016). Grid voltages, non-linear load currents, VSC output currents, injected currents via APF, and dc-link voltages are used to provide reference signals for this controller. Using Clark's transformation method, it is possible to determine the load current and voltages' instantaneous active and reactive powers (Ribeiro *et al.*, 2001). Figure 3 shows the Synchronous Frame Theory based control diagram for DG based APF. The Synchronous Reference Frame Theory (SRFT) for a Distributed Generation (DG)-based Active Power Filter (APF) is designed to improve power quality by eliminating harmonics and compensating reactive power in a grid-connected system. The control process begins by measuring the three-phase load currents at the point of common coupling (PCC). These currents are then transformed from the stationary abc frame to the rotating dq0 frame using Park transformation, synchronized with the grid voltage angle provided by a Phase-Locked Loop (PLL). In this rotating frame, the DC components of the d-axis and q-axis

currents represent the fundamental active and reactive power, respectively. These components are extracted using a low-pass filter (LPF), while the harmonic and reactive components are identified by subtracting the DC part from the original signals. The resulting reference compensation currents are then transformed back into the abc frame through an inverse Park transformation to generate three-phase reference currents. A current controller (such as hysteresis or PI) compares these reference currents with the actual APF output currents and produces the necessary switching signals for the Voltage Source Inverter (VSI). The VSI then injects the required compensating currents into the system to cancel harmonics and improve the power factor, ensuring the grid current remains sinusoidal and balanced, even under nonlinear or unbalanced loading conditions.

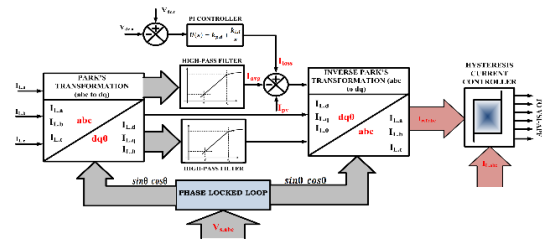


Figure 3. Synchronous Frame Theory based control diagram for DG based APF

PV-Battery Integrated Parallel APF In DG System With Active Power Injection

In previous section, implementation of APF's is discussed, but have some disadvantage such as high rating compensating devices, which leads to economic burden and also produces the reactive power distortions in the system (Molina *et al.*, 2006). Also during fault condition or any damages, the APF is unable to do compensation. To avoid these problems, in this work a concept of parallel connected APF's has been proposed. If any failures in anyone APF, the compensation can be done by the second APF, so that it improves the reliability and durability of the compensating devices (Zhang *et al.*, 2004). Figure 4 shows the PV-Battery Integrated Parallel APF.

A hysteresis controller is used to generate the required gate pulses for both APF circuits. The reference signal required to generate the gate pulses is generated by synchronous reference frame theory (Mahela *et al.*, 2019; Reddy *et al.*, 2021). Parks transformation technique is used to convert load current in three coordinates into two-axis components. Here, a dc-link voltage controller is designed to identify the reference current and made

a comparison with actual load currents to track the distortions and harmonic content. The complete control diagram for two parallel APF circuit is illustrated in Figure 5 (McGrath *et al.*, 2007).

Fundamental Equations of Park's transformation:

$$\begin{bmatrix} x_d \\ w_q \\ x_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos \left(\theta - \frac{2\pi}{3} \right) & \cos \left(\theta + \frac{2\pi}{3} \right) \\ -\sin \theta & -\sin \left(\theta - \frac{2\pi}{3} \right) & -\sin \left(\theta + \frac{2\pi}{3} \right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

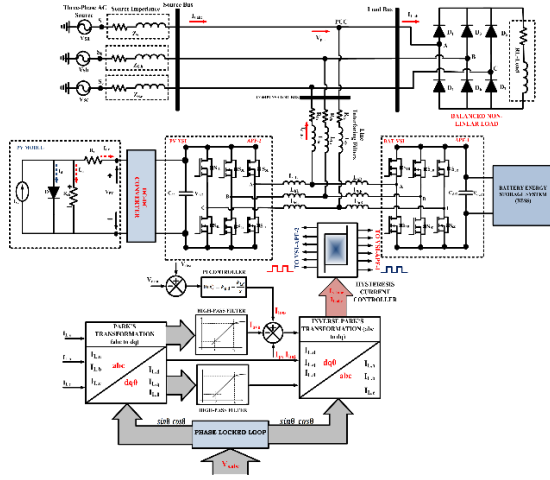


Figure 4. PV-Battery Integrated Parallel APF

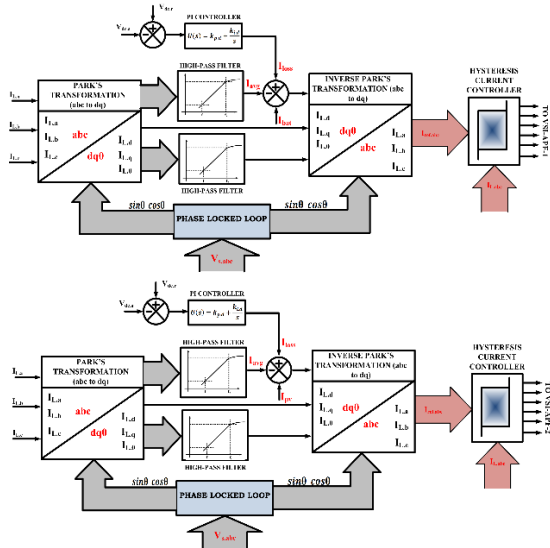


Figure 5. Control Diagram for two parallel APF circuits with DG system

The capacitor voltages at each cluster are added to determine the control target (Satyanarayana *et al.*, 2013a; Satyanarayana *et al.*, 2015a; Karthikumar *et al.*, 2021; Rayaguru *et al.*, 2021; Renduchintala *et al.*, 2021; Eswara *et al.*,

2021). The voltage reference, which is separated into V_1 and V_2 , is obtained from the dc capacitor and is utilized to produce a u-phase overall voltage signal. This control approach is expanded in the feature to include N-phase H-bridge cascaded inverters (Satyanarayana *et al.*, 2013b; Varma *et al.*, 2014; Satyanarayana *et al.*, 2015b; Kumar *et al.*, 2017; Bhavani *et al.*, 2019; Lakshmi *et al.*, 2020; Ganesh *et al.*, 2020).

Babu *et al.* (2022) showcases the power system's harmonic correction in relation to energy storage battery systems. In order to increase the system's dependability, this work primarily introduces a parallel APF idea for harmonic compensation (Rajesh *et al.*, 2022).

Simulation Results and Analysis

The capacitor voltages at each cluster are added to determine the control target. The voltage reference, which is separated into V_1 and V_2 , is obtained from the dc capacitor and is utilized to produce a u-phase overall voltage signal. This control approach is expanded in the feature to include N-phase H-bridge cascaded inverters. The proposed system is developed and simulated through proper system specifications are illustrated in Table 1.

Table 1. System Specifications

Parameter	Value
Source Voltage	$V_s=415V_{rms}$, 50Hz
Source Impedance	0.1 Ohms, 0.9mH
Interfacing Filter	0.1 Ohms, 5mH
Load Impedance	20 Ohms, 20mH
Battery Type	Lead-Acid type
Battery Nominal Voltage	750V
Battery rated Capacity	100 Ah
Battery Nominal	43.47 A
Discharge Current	
Battery initial SoC	80%

Case-1: Parallel Connected APF Without PV and Battery Integration

Figures 6(a) and 6(b) show the MATLAB/Simulink model of the parallel-connected APF system operating without PV and battery integration in a 415 Vrms, 50 Hz low-voltage distribution network. The corresponding simulation results are presented in Figure 7 under non-linear load conditions.

Although the source voltage remains sinusoidal at 340 V (line-to-neutral), 50 Hz, the non-linear load draws a highly distorted current, resulting in poor power quality and a non-unity power factor at the grid side. Such distortion increases losses and stresses grid-connected equipment.

To mitigate these effects, two APFs connected in parallel inject a total compensating current of 10 A (5 A each). This compensation effectively cancels the harmonic and unbalanced components of the load current. As a result, the source current is restored to a near-sinusoidal waveform (Figure 7(a)), while the load current remains distorted, demonstrating that the APFs decouple load-induced distortions from the grid.

The compensated source current is also aligned in phase with the source voltage (Figure 7(b)), ensuring unity power factor operation and improved

system efficiency. Stable DC-link voltages of 800 V for both inverters (Vdc1 and Vdc2), shown in Figure 7(c), confirm reliable VSI operation and effective control.

FFT analysis further validates the performance: the load current exhibits a THD of 19.43% (Figure 7(d)), whereas the source current THD is reduced to 2.36% after compensation (Figure 7(e)). This meets IEEE-519 limits, confirming the effectiveness of the parallel APF configuration in restoring grid-side power quality.

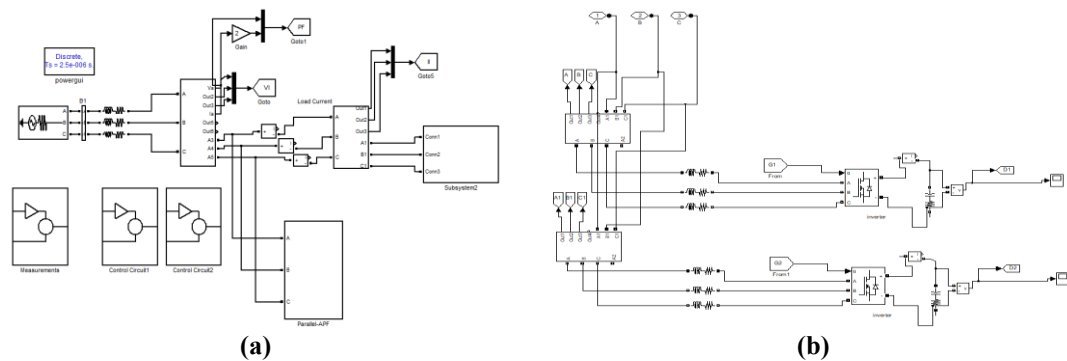


Figure 6. Matlab/Simulink Diagram of Parallel Connected APF without PV and Battery Integration

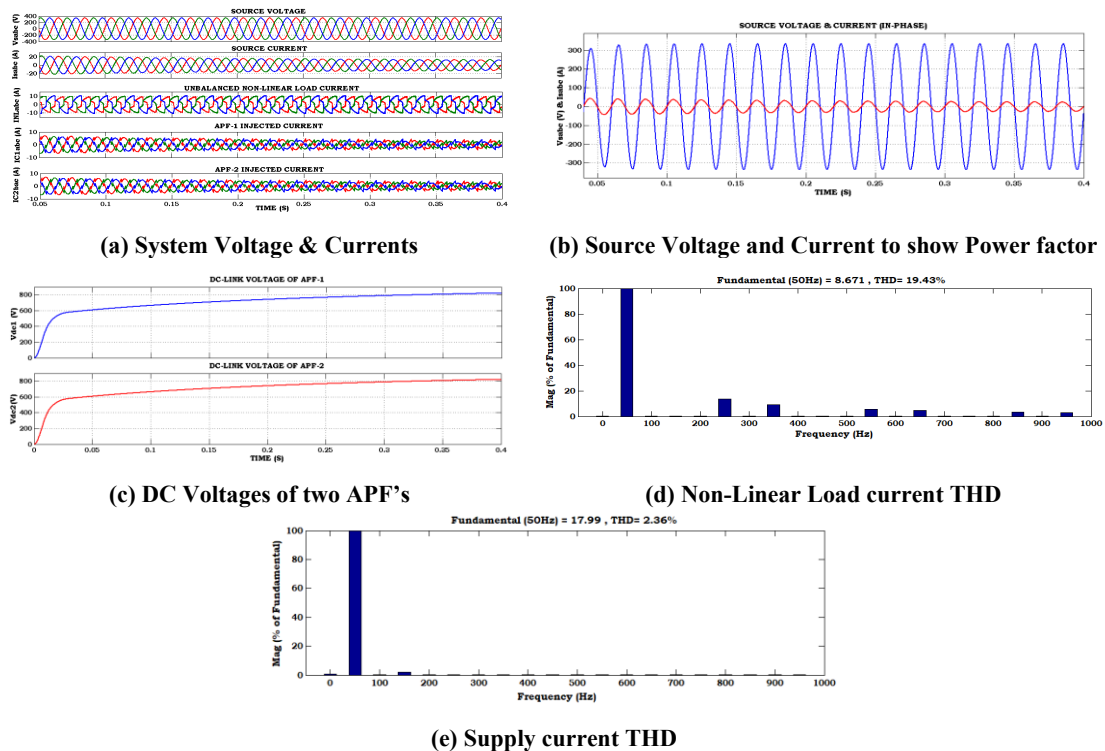


Figure 7. Simulation Waveforms of Parallel Connected APF without PV and Battery Integration

Case-2: Parallel APF with PV and Battery Integration with Battery Discharge

The MATLAB/Simulink diagrams shown in Figure 8(a) and 8(b) illustrate a parallel-connected Active Power Filter (APF) system operating in a low-voltage distribution network under non-linear load conditions, but without PV or battery integration. The system is modeled with a supply voltage of 415 Vrms at 50 Hz, reflecting typical utility standards. The simulation waveforms in Figure 9 provide insight into the system's behavior under these loading conditions.

In this configuration, a sinusoidal source voltage of 340 V (line-to-neutral) at 50 Hz is applied to a non-linear load, which induces significant current distortion due to the generation of harmonic components. This results in a highly distorted source current, deviating from its ideal sinusoidal form and leading to poor power quality and non-unity power factor. These distortions not only affect the efficiency of power transfer but also pose a risk to other equipment on the network by increasing heating, reducing lifespan, and causing electromagnetic interference.

To mitigate these adverse effects, the proposed system employs two parallel-connected APFs, each injecting a compensating current of 5 A, summing to a total of 10 A. These filters are configured to

cancel harmonic and unbalanced components of the load current, thereby isolating the distortion from the source. As depicted in Figure 9(a), the source current is restored to a near-ideal sinusoidal waveform, even though the load current remains distorted and unbalanced. This clearly illustrates the decoupling effect of the APFs: while they do not alter the nature of the load, they effectively shield the grid from the associated distortions.

A critical implication of this compensation is the improved phase alignment between the source voltage and current, as shown in Figure 9(b). This alignment results in unity power factor operation, which minimizes reactive power flow and enhances overall system efficiency an essential requirement for optimized grid performance.

Another key performance indicator is the DC-link voltage stability in the APF inverters. As shown in Figure 9(c), the DC-link voltages are regulated and remain constant at 800 V for both APFs (Vdc1 and Vdc2). This voltage regulation confirms the robustness of the control strategy and the ability of the system to supply consistent compensation current under varying load conditions.

The system's effectiveness is further validated by FFT-based harmonic analysis. The load current exhibits a high Total Harmonic Distortion (THD) of 19.43%, as shown in Figure 7(d), which is typical

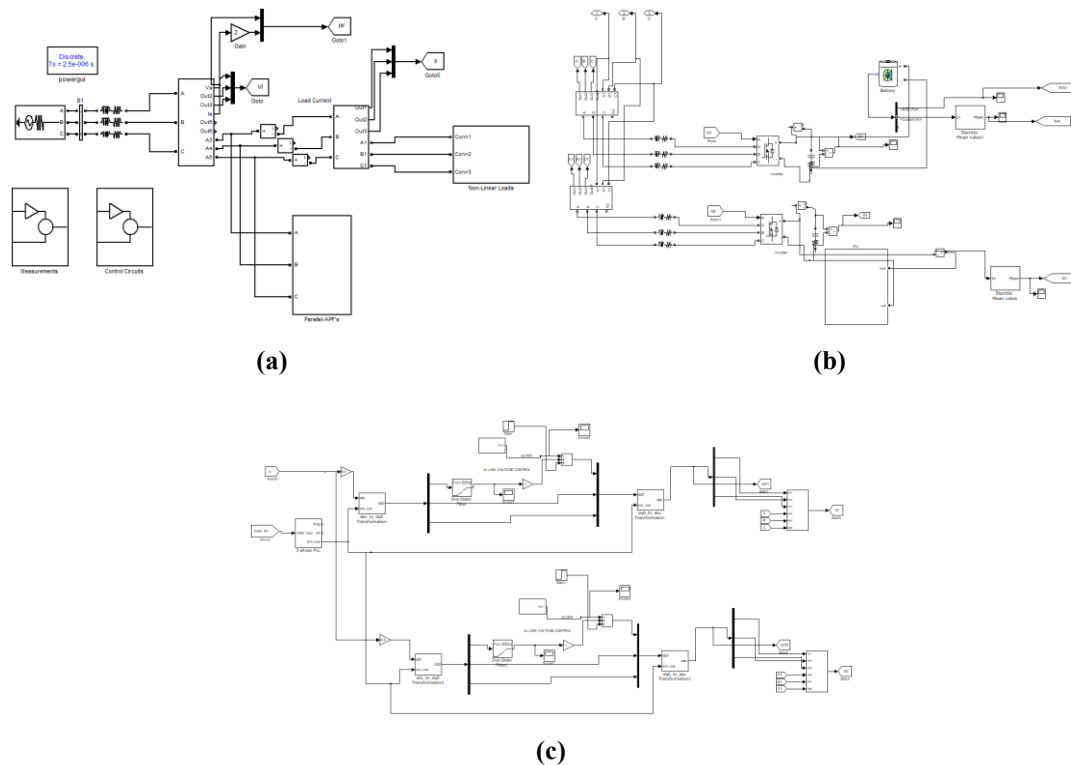


Figure 8. Matlab/Simulink Diagram of Parallel Connected APF with PV and Battery Integration under Battery Discharge

for non-linear loads. However, the THD of the compensated source current is significantly reduced to just 2.36%, as illustrated in Figure 7(e). This reduction places the source current well within the IEEE-519 recommended limit of 5%, demonstrating that the parallel APFs successfully enhance power quality to acceptable standards

Figures corresponding to Case-2 present the operation of the parallel-connected APF system when integrated with a photovoltaic (PV) source and a battery energy storage system operating in discharge mode. Unlike the base configuration, the DC-link of the APF inverters is actively supported by the PV array, while the battery supplies supplemental energy to maintain DC-link regulation and compensation capability during discharge conditions.

In this operating mode, the battery delivers power to the common DC bus, ensuring uninterrupted APF operation even when PV generation is insufficient or fluctuating. This integration enables the APFs to simultaneously perform power-quality compensation and local energy support, reducing dependence on the utility grid. As a result, a portion of the real power demanded by the non-linear load is supplied by the PV-battery subsystem, while the grid primarily

supplies fundamental active power with minimal distortion.

The coordinated control of the PV and battery stabilizes the DC-link voltage during discharge, despite dynamic load and compensation requirements. This stable DC-link directly enhances the APFs' ability to inject accurate compensating currents, ensuring effective harmonic and reactive power mitigation. Consequently, the source current remains nearly sinusoidal and closely aligned with the source voltage, indicating sustained unity power factor operation even under battery discharge conditions.

Harmonic analysis further confirms the benefit of PV-battery integration in Case-2. While the load current continues to exhibit significant harmonic content due to its non-linear nature, the compensated source current maintains low total harmonic distortion within recommended standards. This demonstrates that the inclusion of PV and battery storage does not compromise compensation performance; instead, it enhances system resilience and operational flexibility by combining renewable energy utilization, energy storage support, and active power filtering within a unified framework.

In Case-2, the distinguishing feature of the system is the active participation of the photovoltaic

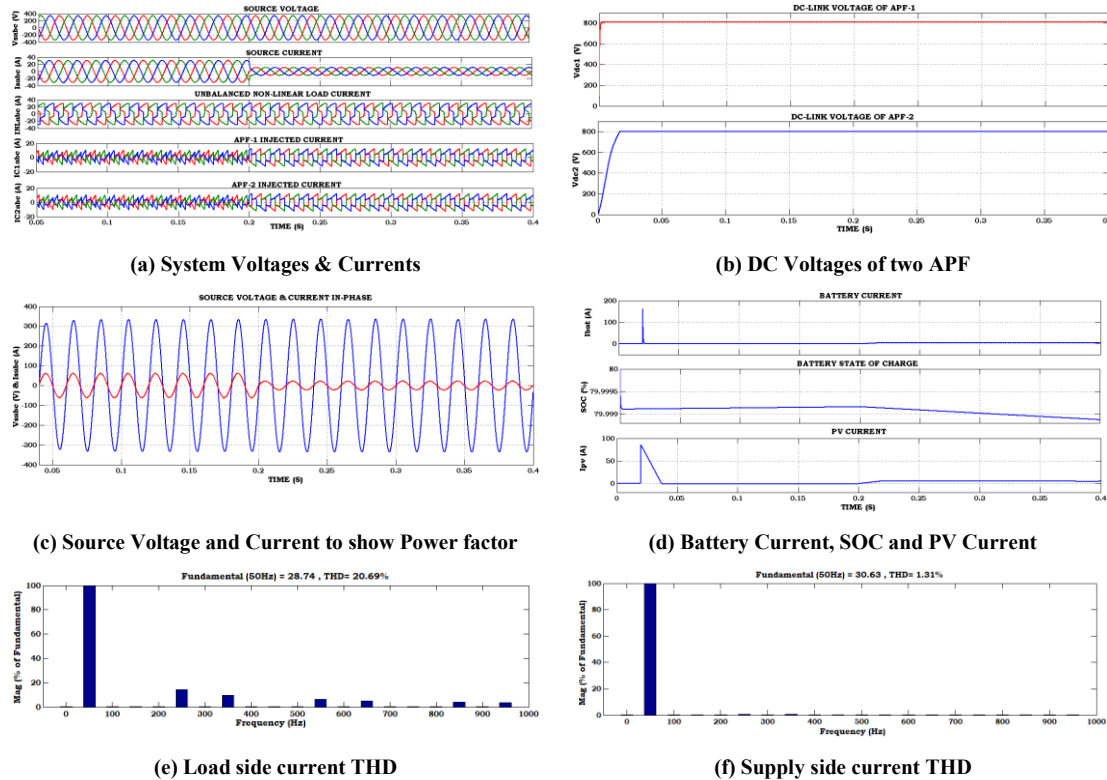


Figure 9. Simulation Waveforms of Parallel Connected APF with PV and Battery Integration under Battery Discharge Condition

(PV) array and the battery energy storage system in supporting the APF during battery discharge operation. Unlike the non-integrated case, the DC-link power is no longer maintained solely through grid interaction; instead, it is supplied jointly by the PV source and the discharging battery, which directly influences current flow, power sharing, and harmonic performance.

The PV array injects a steady DC current into the common DC-link through its interfacing converter, operating near its maximum power point. This PV current contributes directly to the real power required for both APF operation and partial load supply. When PV generation alone is insufficient to sustain the DC-link voltage and compensation demand, the battery provides additional DC current. During this interval, the battery current is positive in the discharge direction, clearly indicating energy delivery from the battery to the DC-link. The combined PV–battery current ensures uninterrupted compensating current injection by the APFs.

The battery state of charge (SOC) exhibits a gradual and controlled decrease during this mode of operation, confirming sustained discharge to support both harmonic compensation and active power injection. The smooth SOC trajectory reflects effective energy management and prevents abrupt battery stress, demonstrating that the proposed

control strategy maintains battery health while enabling grid-support functions.

This coordinated energy injection has a direct impact on active power flow. A portion of the load's active power demand is supplied locally by the PV–battery subsystem, thereby reducing the active power drawn from the grid. As a result, the grid source current magnitude decreases while remaining nearly sinusoidal and in phase with the source voltage, indicating unity power factor operation with reduced grid burden.

From a power-quality perspective, the integration of PV and battery does not degrade harmonic performance; instead, it enhances overall system robustness. The non-linear load continues to draw a highly distorted current, exhibiting high THD. However, the APFs now energetically supported by the PV-battery system successfully isolate these harmonics from the grid. The source current THD is significantly reduced and maintained well within IEEE-519 limits, despite simultaneous active power injection and battery discharge. This confirms that Case-2 achieves effective harmonic mitigation while simultaneously delivering renewable-based active power support, highlighting the multifunctional capability of the proposed PV-battery-assisted APF system.

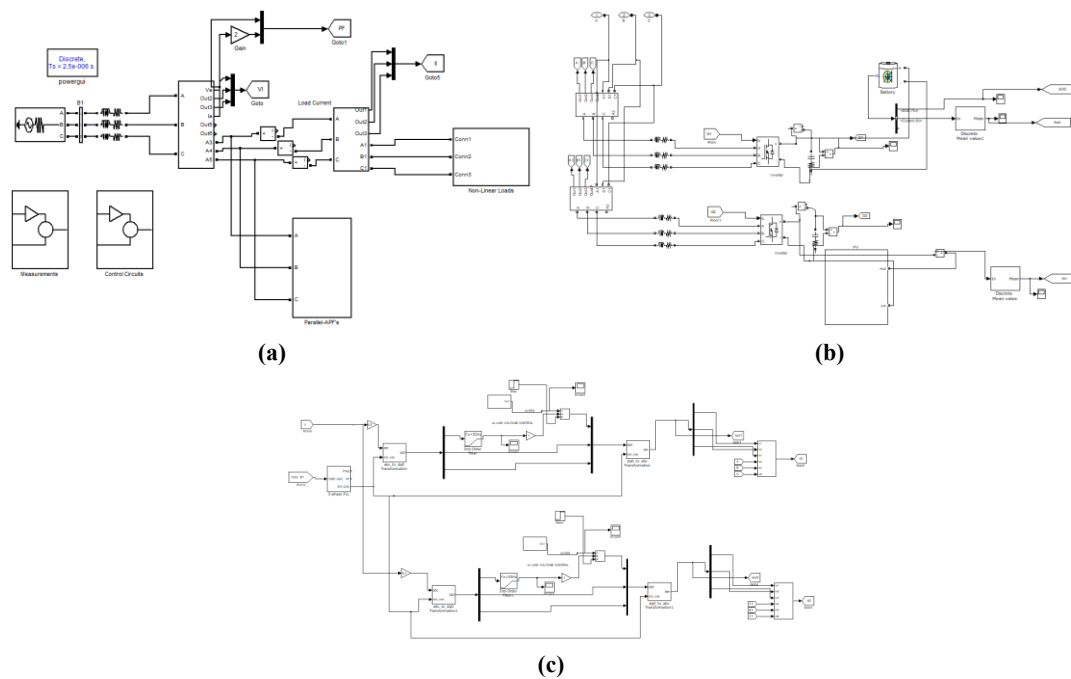


Figure 10. Matlab/Simulink Diagram of Parallel Connected APF with PV and Battery Integration under Low Current Battery Charge Mode

Case-3: Parallel APF with PV and Battery Integration with Battery Charge with Low Current Charge Mode

The MATLAB/Simulink diagrams for the parallel-connected Active Power Filter (APF) with PV and battery integration under low battery charge conditions are shown in Figure 10 (a-c). The simulation waveforms of this configuration, which operates in a distribution system with a supply voltage of 415 Vrms and a frequency of 50Hz, are presented in Figure 11. In this system, the source voltage is maintained as a sinusoidal waveform at 340 V, 50 Hz, which drives the non-linear load during a time period of $t = 0.2$ seconds. This non-linear load causes harmonic current distortions in the source current.

Before $t = 0.2$ seconds, the harmonic current distortions in the source current are compensated by the proposed parallel-connected APF, with compensation currents of 32A. The load current remains distorted and unbalanced at 30A. The two parallel-connected APFs inject compensation currents of 10A each to restore the source current to a sinusoidal and balanced shape, as shown in Figure 11(a). During this period, the source current remains in-phase with the source voltage, ensuring a unity power factor, as shown in Figure 11(b). The DC

capacitor voltages are kept constant at 800V for both Vdc1 and Vdc2, as shown in Figure 11(c). Before $t = 0.2$ seconds, due to the availability of PV energy, the battery has a low charge, and the total load current is supplied by the source current, as shown in Figure 11(d).

After $t = 0.2$ seconds, the harmonic current distortions in the source current are compensated by the parallel-connected APF, with compensation currents of 20A. The load current remains distorted and unbalanced at 30A. The two parallel-connected APFs inject compensation currents of 13.5A each to maintain the source current as sinusoidal and balanced, as shown in Figure 11(a). During this period, the source current continues to be in-phase with the source voltage, representing a unity power factor, as shown in Figure 11(b). The DC capacitor voltages are maintained as constant at 800V for both Vdc1 and Vdc2, as shown in Figure 11(c).

After $t = 0.2$ seconds, the battery begins to charge from the available PV or source current, with a charging current of -4.2A. This reduces the reliance on the source current when PV or other energy sources are available. During the low battery charge period, the state of charge (SOC) of the battery increases slightly to 79.99%, while the PV system continues to supply the required current of

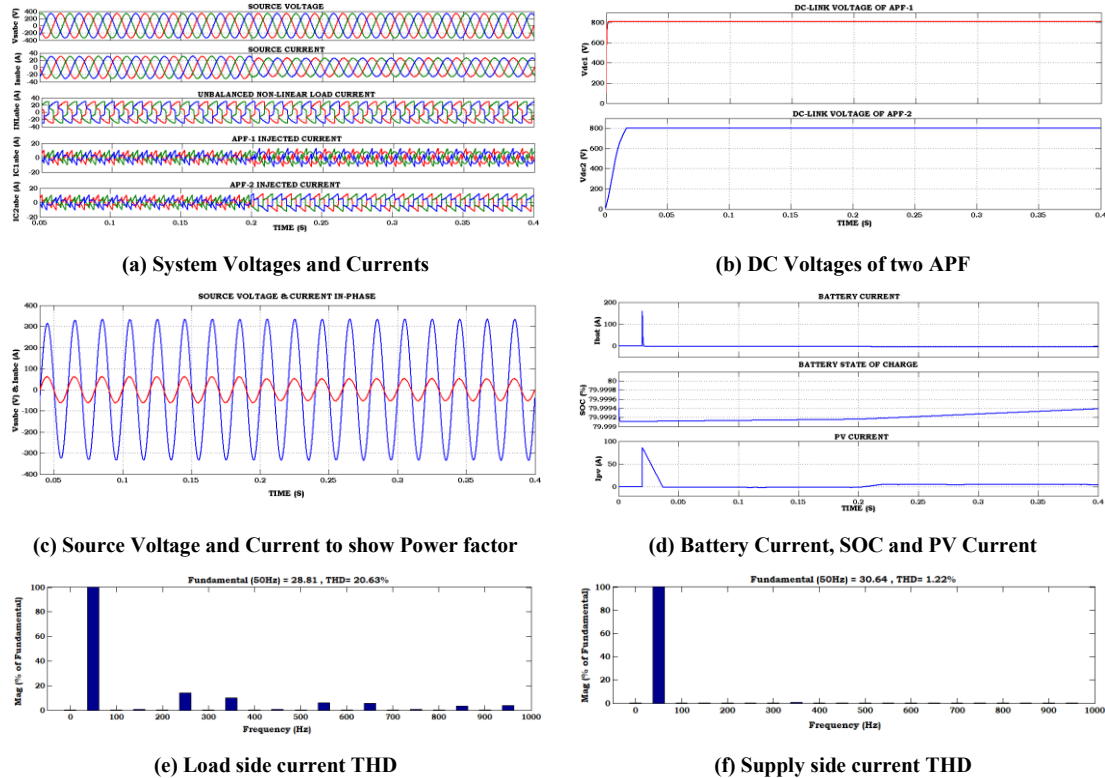


Figure 11. Simulation Waveforms of Parallel Connected APF with PV and Battery Integration under Low Current Battery Charge Mode

5.5A to the load, ensuring continuous active power injection to the load through the available energy sources in DG integration mode, as shown in Figure 11(d). The Total Harmonic Distortion (THD) of the non-linear load current, measured using FFT analysis, is 20.63%, indicating the presence of harmonic distortions, as shown in Figure 11(e). The THD of the supply current is reduced to 1.22%, which is well within IEEE-519 standards, thanks to the compensation currents produced by the two parallel-connected APFs powered by the PV-battery system in DG mode, as shown in Figure 11(f).

Case-4: Parallel APF with PV and Battery Integration with Battery Charge with High Current Charge Mode

The MATLAB/Simulink diagrams for the parallel-connected Active Power Filter (APF) with PV and battery integration under high battery charge conditions are shown in Figure 12 (a-c). The simulation waveforms of this configuration, which operates in a distribution system powered by a voltage of 415Vrms and a frequency of 50Hz, are presented in Figure 13. In this system, the source voltage is maintained as a sinusoidal waveform at 340V, 50Hz, used to drive the non-linear load during a time period of $t = 0.2$ seconds. This non-linear load causes harmonic current distortions in the source current.

Before $t = 0.2$ seconds, the harmonic current distortions in the source current are compensated by

the proposed parallel-connected APF, with compensation currents of 32A. The load current remains distorted and unbalanced at 30A. The two parallel-connected APFs inject compensation currents of 10A each to restore the source current to a sinusoidal and balanced shape, as shown in Figure 13(a). During this period, the source current remains in-phase with the source voltage, ensuring a unity power factor, as shown in Figure 13(b). The DC capacitor voltages are maintained constant at 800V for both Vdc1 and Vdc2, as shown in Figure 13(c). Before $t = 0.2$ seconds, due to the availability of PV energy, the battery is in a low charge state, and the total load current is supplied by the source current, as shown in Figure 13(d).

After $t = 0.2$ seconds, the harmonic current distortions in the source current are compensated by the parallel-connected APF, with compensation currents of 26A. The load current remains distorted and unbalanced at 30A. The two parallel-connected APFs inject compensation currents of 12A each to maintain the source current as sinusoidal and balanced, as shown in Figure 13(a). During this period, the source current continues to be in-phase with the source voltage, ensuring a unity power factor, as shown in Figure 13(b). The DC capacitor voltages are maintained constant at 800V for both Vdc1 and Vdc2, as shown in Figure 13(c).

After $t = 0.2$ seconds, the battery begins to charge with the available PV or source current, with a charging current of -4.2A, which reduces the

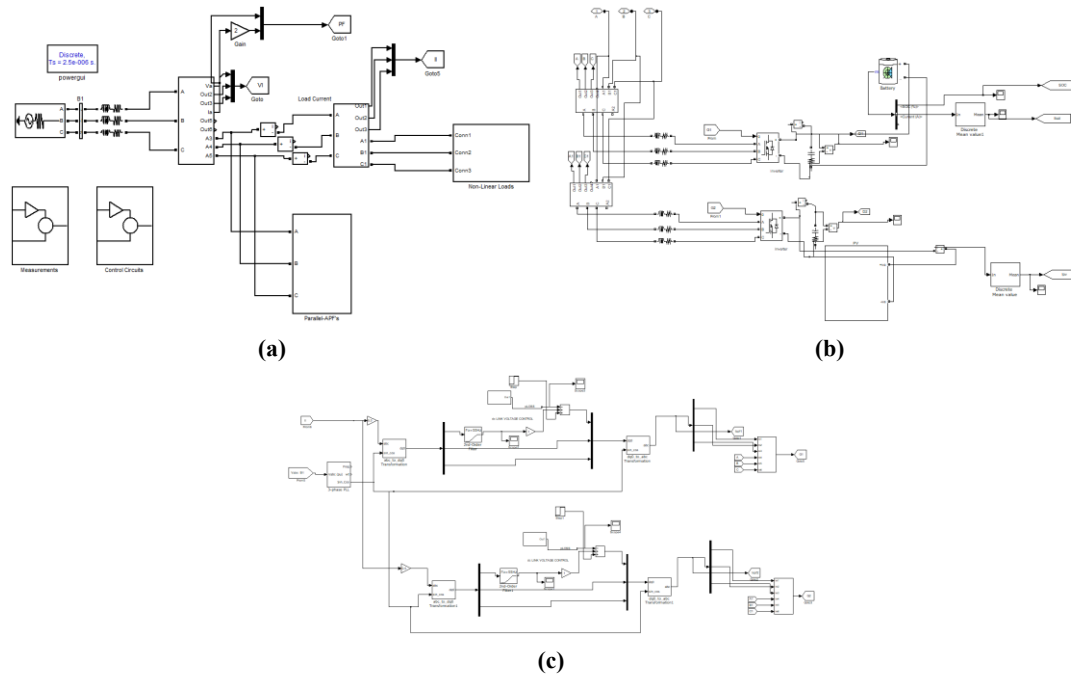


Figure 12. Mat lab/Simulink Diagram of Parallel Connected APF with PV and Battery Integration under High Current Battery Charge Mode

reliance on the source current when PV or other energy sources are available. During the high battery charge period, the state of charge (SOC) of the battery increases slightly to 79.99%, while the PV system continues to supply the required current of 5.5A to the load, ensuring continuous active power injection to the load through the available energy sources in DG integration mode, as shown in

Figure 13(d). The Total Harmonic Distortion (THD) of the non-linear load current, measured using FFT analysis, is 20.81%, indicating the presence of harmonic distortions, as shown in Figure 13(e). The THD of the supply current is reduced to 1.54%, which is well within IEEE-519 standards, thanks to the compensation currents produced by the two parallel-connected APFs powered by the PV-battery

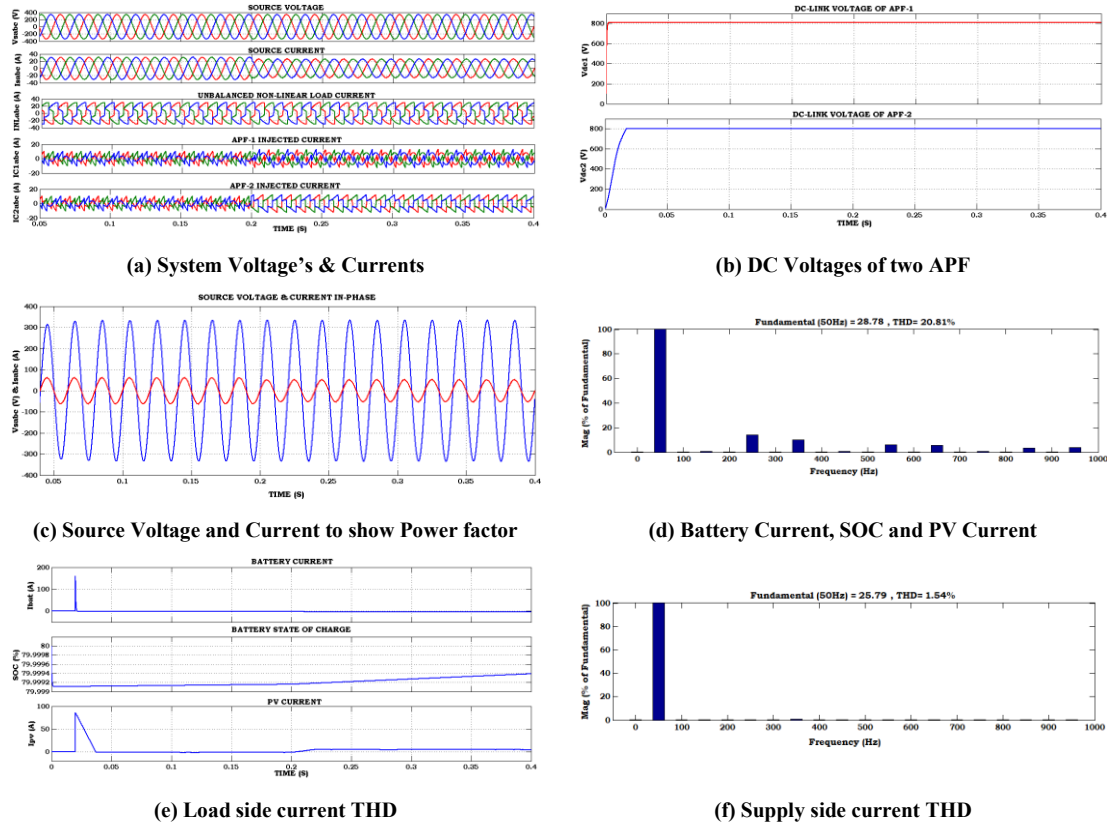


Figure 13. Simulation Waveforms of Parallel Connected APF with PV and Battery Integration under High Current Battery Charge Mode

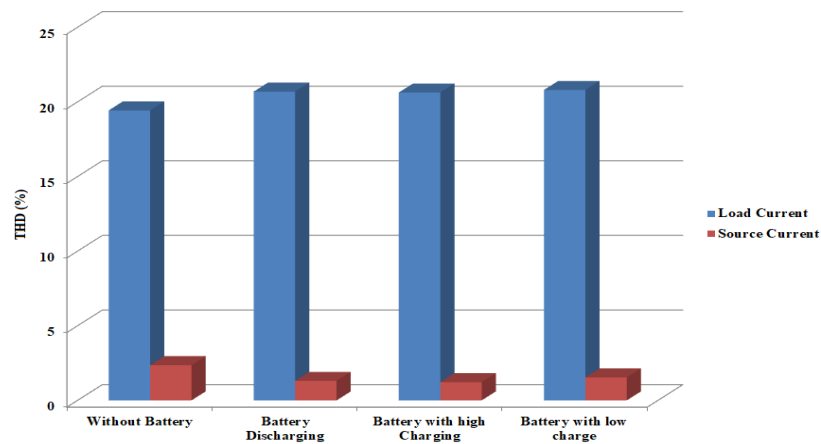


Figure 14. Graphical View

system in DG mode, as shown in Figure 13(f). The THD values for both the load side and supply side are summarized in Table 2, and the corresponding bar graph of these THD values is shown in Figure 14 under various conditions. Due to the presence of the APF, the supply side current THD is always maintained within the prescribed range of 5%. The load current, however, exhibits a higher degree of distortion due to its non-linear nature.

Table 2. Comparison of Measured THD Values of Load Current and Source/Supply Current

THD	Source Current	Load Current
Without Battery	2.36%	19.43%
Battery Discharging	1.31%	20.69%
Battery with high Charge	1.22%	20.63%
Battery with low charge	1.54%	20.80%

Across all scenarios, the load current THD remains consistently high, ranging between 19.43% and 20.80%. This is expected, as the non-linear load introduces harmonics independent of the energy storage conditions. These values confirm the presence of significant harmonic content in the load, reinforcing the need for active compensation.

In contrast, the THD of the source current varies across scenarios, reflecting the effectiveness of the APF under different battery operating states:

- **Without Battery (2.36%):** This scenario serves as a baseline. Though compensation is still provided by the APF (powered by the source or PV alone), the absence of battery support limits the dynamic response and increases reliance on the grid, resulting in a slightly higher THD. However, the value still complies with IEEE-519 standards (<5%).
- **Battery Discharging (1.31%):** When the battery is discharging, it actively supplies energy to support the APF and reduce the burden on the grid. This leads to a significant reduction in THD, showing that battery support enhances APF performance, especially during periods of higher compensation demand.
- **Battery High Charge (1.22%):** This scenario represents the most optimized condition. With the battery fully charged and the system in distributed generation (DG) mode, surplus PV energy and stable DC-link voltages ensure smooth APF operation. This produces the lowest THD, confirming that well-managed energy storage maximizes power quality performance.
- **Battery Low Charge (1.54%):** Here, the battery begins charging after $t = 0.2$ s, initially offering limited support. Though the APF still compensates effectively, the THD slightly increases compared to the high charge and discharging cases.

This reflects the trade-off between charging the battery and supplying compensation current, which can slightly affect filtering efficiency.

Conclusion

This research introduces the battery-integrated dual APF's for power-quality improvement and also injecting active power through energy sources. Controlling and managing the power flow interchange between the APF and the PCC which is made possible by managing the active power in a certain manner. Insufficient main power from supply side is injected into load/PCC, while surplus power in supply side is used for battery charging purposes. The source current harmonics are additionally compensated by APF's; the THD evaluations for various conditions are tabulated. Due to the presence of APF, the THD of supply side current is always under the prescribed range of 5%. Load current has a much higher degree of distortion because it is non-linear in nature. Illustrated is a control technique for the battery-integrated APF.

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