International Journal of Applied Power Engineering (IJAPE)
Vol. 15, No. 3, September 2026, pp. 965~974
ISSN: 2252-8792, DOI: 10.11591/ijape.v15.i3.pp965-974

Mitigation of grid harmonics using active filters with adaptive energy valley optimization (AEVO) control techniques

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Article Info

Article history:

Received Dec 18, 2024
Revised Apr 17, 2026
Accepted Jun 10, 2026

Keywords:

Active power filters
Adaptive energy valley optimization
Harmonics
Power quality
Total harmonic distortion

ABSTRACT

Many nonlinear devices are linked to the power grid as the fast development of the power electronics sector causes serious harmonic pollution of the grid voltage. Active power filter (APF), which can detect the harmonics at the installation location, is the tool used for the harmonic voltage treatment. While considering the surplus of APF active devices to guarantee effective and stable operation of APF, the harmonic sources at each node will change with time and need the injection of fresh harmonic compensation commands. This work intends to offer a dynamic adjustment approach of distributed harmonic compensation based on the computation model of active device margin of APF. First, for certain harmonic combinations, the APF active device loss and injection temperature model is developed to compute in real time whether the harmonic injection command satisfies the active device margin. Furthermore, the adaptive energy valley optimization method is applied to derive new harmonic injection commands for the power grid with harmonic source changes, which on one hand lowers the total voltage harmonic distortion rate of the power grid, and on the other hand satisfies the active device margin to guarantee stable operation of APF.

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1. INTRODUCTION

Maintaining power quality and dependability has become somewhat difficult in recent years as nonlinear loads and power electronic devices proliferate in contemporary electrical systems. As well as contribute to higher energy losses and decreased system efficiency, the presence of harmonic currents and voltage distortions brought about by these loads can negatively influence the performance and lifetime of electrical equipment. These difficulties have made the creation and application of sophisticated power quality control methods absolutely essential. Among the several approaches used to solve power quality problems, shunt active power filters (SAPFs) have become rather flexible and successful [1]. Through dynamic compensation for the reactive and harmonic currents produced by nonlinear loads, SAPFs are meant to reduce harmonic distortions and raise the general power factor [2]. Modern power systems would benefit much from their capacity to adjust to different load conditions and offer real-time compensation [3]. This research article explores shunt active power filters' design, analysis, and performance evaluation. Investigating the most recent developments in SAPF technology—along with creative control strategies, better filtering methods, and more system integration—is the main goal [4]. This work attempts to give a complete knowledge of several optimization and possible uses in modern electrical systems by analyzing the theoretical foundations, actual implementations, and performance measures of SAPFs [5].

Although the existence of PV on the network is occasionally regarded as one of the harmonic distortion resources [6], in this study, we aim to use PV as a solution to lower the total harmonic distortion (THD) level. On the other hand, the primary function of power electronic devices, which are used as interfaces for RES such as PVs, is delivering the power with the necessary degree of power quality. Apart from their primary function, their technical traits and the particular operator decisions indicate that they can also play auxiliary roles, e.g., harmonic reduction employing the virtual harmonic damping impedance concept [7], and selective harmonic elimination pulse-width modulation technique [8]. Recent studies [9], [10] often find that active distribution networks commonly use distributed generations (DGs) as a tool for problem-solving. Pricing strategy is one of the efficient ways that makes use of the DGs as instruments of problem-solving [11]. This approach eliminates the need for a further charge, equipment addition or removal, or network configuration modification [12]. Apart from the typical issues of harmonic pollution, harmonic flowing in transmission lines and feeders not only consumes lines capacity but also the transmission loss is growing [13]. This can lead theirs to unforeseen congestion. Consequently, there is direct connection between the locational marginal pricing (LMP) process and the effects of harmonic pollution [14]. This work mostly helps to minimize the detrimental consequences of harmonic pollution by means of intentional LMP DG pricing [15].

Harmonic pricing in power networks has been studied a few times. Compared to other technical indices like loss pricing, the total quantity of articles is far less [16]. Using harmonic voltage magnitude [17], the harmonic pricing is applied. This cost is stated as a cost function whereby the harmonic voltages provide a negative effect. Harmonic pricing comes first. Using harmonic pricing in [18], consumers want to lower their harmonic levels. One can either install filters at the point of common coupling (PCC) or replace nonlinear loads with linear ones. Should consumers not engage in any of these circumstances, they will be liable for penalties. The influence of harmonic losses on the pricing process has not been precisely and directly observed in these works. Furthermore, the approaches of these papers are obligatory and failed to solve the problem of voluntary involvement. Under the suggested strategy, the DGs' ownership is regarded as private; so, the process of providing incentives—that is, a price rise for DGs—is carried out with a fair game-theoretic approach. Based on adaptive energy valley optimization (AEVO) approach, considering the benefits and drawbacks of the articles mentioned in the literature review, by means of intentional DG utilizing in the form of LMP pricing, the total loss and the THD of the network are simultaneously reduced simultaneously without any changes in the network configuration, adding or removing equipment, or budget extension.

2. LITERATURE SURVEY

Harmonic distortion is one of the primary effects that must be considered when connecting a PV system to the grid for operation. Harmonics are defined as the deviation of currents and voltages from their original or unaltered sinusoidal waveform. The harmonics are essential multiples of the fundamental frequency [19]. It arises due to an active photoelectrochemical component inside the photovoltaic system. The modification of DC-AC is achieved by utilizing an inverter that introduces current and voltage harmonics into the network, resulting in power harmonics [20]. Augmenting the capacity of inverters leads to increased energy consumption in capacitor-banks and transformers, resulting in a more unstable and unpredictable system [21]. The primary factor contributing to voltage fluctuations in grid-connected PV systems is the unpredictable performance of solar panels. Discrepancies in solar irradiances result from transient cloud cover, photovoltaic installation, and some areas of reflection or incidence. The criteria together facilitate the PV-scheme in achieving uniformity by addressing voltage disparities [22]. The decrease in voltage over a short period is referred to as "voltage sag". (The voltage is within a range of 10-90 percent of the usual root mean square volt value). Periods in which root mean square (rms) voltages above 110 percent of the typical range for less than 1 minute are referred to as "voltage swell". Significant decrease in root mean square (rms) voltage below the threshold of a noticeable or total voltage failure is referred to as voltage interruptions [23]. An interruption lasting less than 1 minute is referred to as a short-interruption, whereas an interruption lasting more than 1 minute is referred to as a long duration interruption [24]. Though the term "interruption" is often used to describe short-interruptions, the term "sustained" is used to indicate long-interruptions [25]. In the context of electrical loads, harmonics refer to significant deviations from sinusoidal waves, sometimes known as choppy or non-sinusoidal/non-linear currents. These are fundamental frequency elements together with their corresponding integer multiples, such as 2f and 3f, of the fundamental frequency [26]. Numeral or integer multitudinous operations are essentially higher orders of fundamental frequency elements. Harmonics encompass two phenomena: current distortion under harmonics and voltage distortion under harmonics [27]. Voltage distortion is a consequence of current distortion [28]. When the harmonic current passes through the network impedance, it produces a voltage drop at a frequency exactly equal to that of the harmonic current. Harmonics modification of common current/voltage waveforms is often elucidated by the concept of "total harmonic distortion (THD)," which is defined as the ratio of the root of square of the sum of squares of the magnitude values of each harmonic component to the magnitude of the fundamental component [29].

Harmonics in a PV grid-connected system arise from two sources: firstly, from the PV system itself, and secondly, from non-linear loads connected to the system [30]. The application of power electronic equipment and the intermittent power flow from photovoltaic systems contribute to the introduction of harmonics in power distribution systems [31]. Another cause of current harmonics being drawn from the distribution network is the presence of non-linear loads, which results in vibration pollution [32].

3. MODELING AND DESCRIPTION OF THE SYSTEM

As modern networks include a greater spectrum of distributed energy sources, including solar photovoltaic (PV) systems, wind farms, and electric vehicles (EVs), effective management of power quality in electrical grids becomes more important. The above-described changes are producing high harmonics in power systems, which are distortions of the electrical waveforms caused by non-linear loads. A range of technical and financial issues, including equipment overheating, insulation degradation, increased losses, and maybe sensitive system failure can arise from amplification of harmonics. These challenges lead to the concept of adaptive energy valley optimization (AEVO) emerging as a strong tool. AEVO is the term used to describe a set of methods and technologies meant to improve energy efficiency during low demand, sometimes referred to as valley periods, by reducing the harmonic generation and therefore their possible impact on the electrical grid. The whole method for implementing AEVO to achieve harmonic reduction in power networks is presented in this part. It offers a thorough explanation of every level, together with the related technology and approaches as shown in Figure 1. Park's transformation (PT) applied after the control signal capture will produce the whole mathematical model.

$$\begin{bmatrix} V_{Btd} \\ V_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -X_B \\ X_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \frac{m_B \cos(\delta_B) V_{dc}}{2} \\ \frac{m_B \sin(\delta_B) V_{dc}}{2} \end{bmatrix} \quad (1)$$

$$\frac{dV_{dc}}{dt} = \frac{3m_E}{4c_{dc}} [cos\ \delta_E \quad sin\ \delta_E] \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4c_{dc}} [\text{cosine}(\delta_B) \quad \text{sine}(\delta_B)] \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \quad (2)$$

The resulting mathematical model is used in the Simulink blocks for controller design.

$$Y_a^{New1} = Y_a\big(Y_{CT}(y_a^b)\big), \begin{cases} a = 1,2 \ldots o \\ b = indexalpha1 \end{cases} \quad (3)$$

$$E_a^c = \sqrt{(y_2 - y_1)^2 + (z_2 - z_1)^2}\ , \begin{cases} a = 1,2, \ldots o \\ c = 1,2, \ldots o - 1 \end{cases} \quad (4)$$

$$Y_a^{New2} = Y_a\big(Y_{oh}(y_a^b)\big), \begin{cases} a = 1,2 \ldots o \\ b = indexgama1 \end{cases} \quad (5)$$

The position upgrading process is done to improve the exploitation and exploration phase of the AEVO algorithm. The position upgrading process is stimulated as shown in (6).

$$Y_a^{New2} = Y_a + (s3 \times Y_{CT} - S_4 \times Y_{oh})\ a = 1,2,..o \quad (6)$$

Consequently, it causes random displacement in the particles, as formulated below.

$$Y_a^{New2} = Y_a + s,\ a = 1,2, \ldots o$$

Here, at the given search space, the a[th] particles forthcoming and the existing position vector are represented as Y_a^{New}, Y_a, respectively.

$$(THD_{out})_i = (\textstyle\sum_{J=I}^{n} THD_{inj})_i - (\sum_{J=I}^{n} THD_{gen_j})_i \quad (7)$$

$$(I_{GEN})_i = (\textstyle\sum_{J=I}^{n} I_{out_j})_i - (\sum_{J=I}^{n} I_{in_j})_i \quad (8)$$

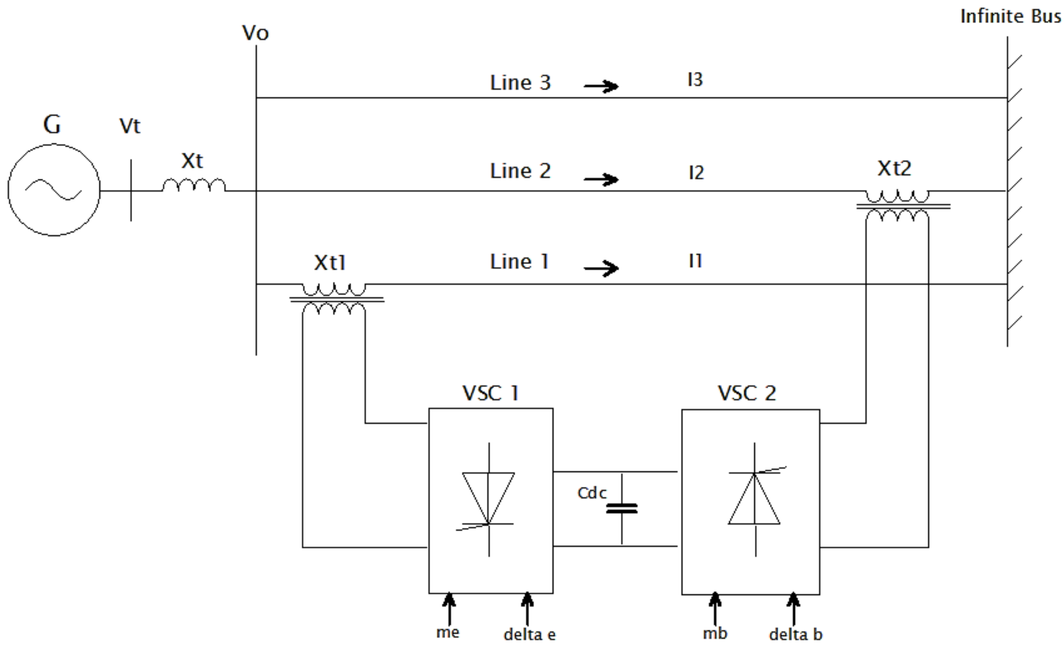

Figure 1. System model of the APF

4. EXPERIMENTAL RESULTS AND ANALYSIS

The experimental setup and the corresponding waveforms of the shunt active filter with controller setup are shown in Figure 2. From Figures 3 and 4, the effective ruling method is required to clear the non-linear character of source voltage and current. To validate SAF proposed algorithm, the hardware was built-up.

Figure 5 shows the voltage waveforms at the PCC. The DC capacitor voltage waveform is shown in Figure 5. The quality of load current with voltage components was shown in this work. Using the AEVO with time delay controller technique, the value of THD was reduced to 0.73%. Figure 6 shows the load current waveform before and after compensation. At 0.4 s, the opposite harmonic is injected into the system; thereby sinusoidal waveform is obtained by reducing the effect of harmonics.

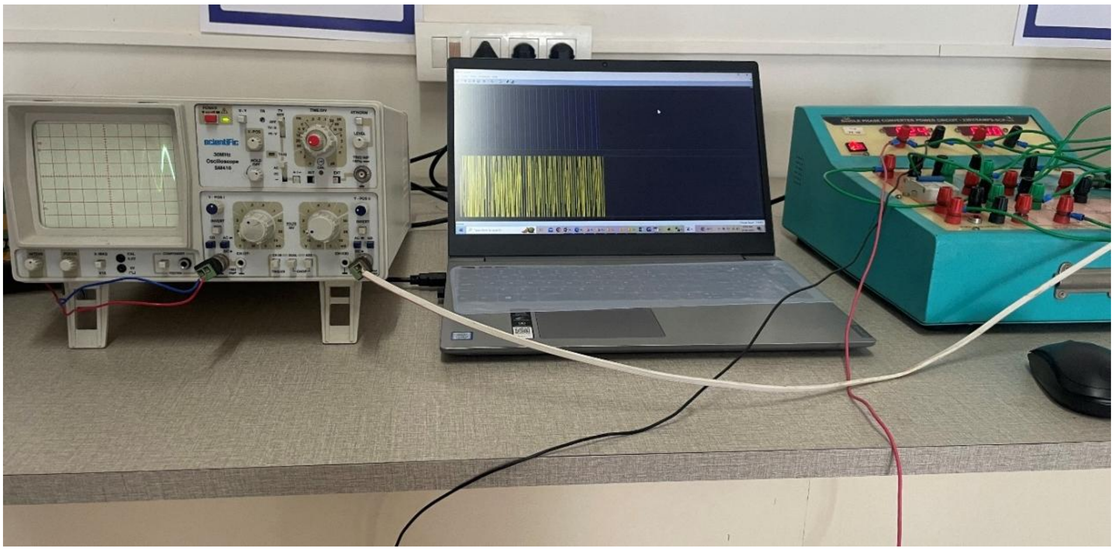

Figure 2. Hardware setup of the APF for AEVO

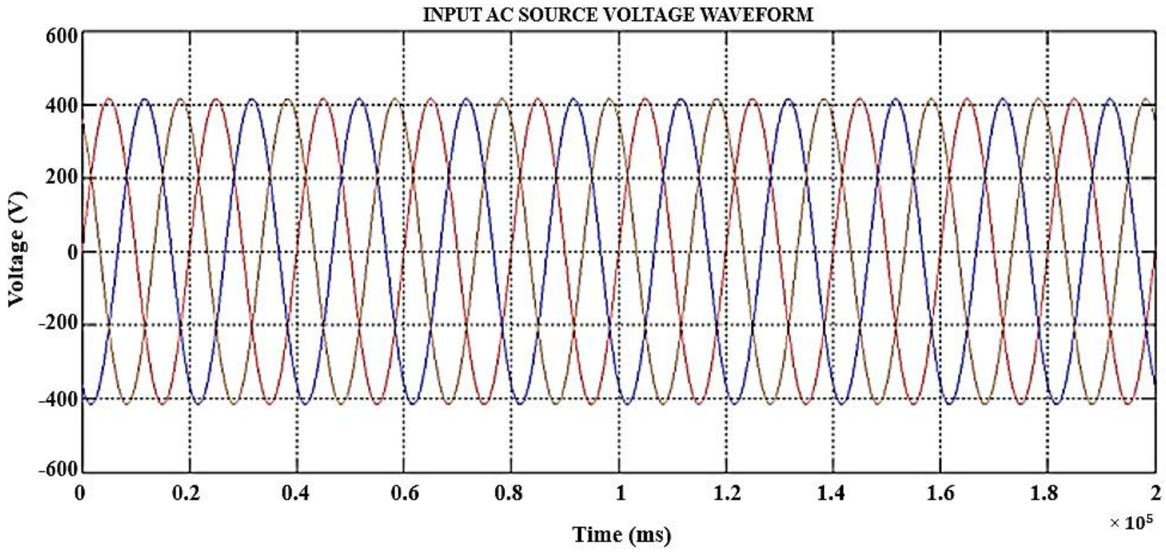

Figure 3. Input AC source voltage waveform

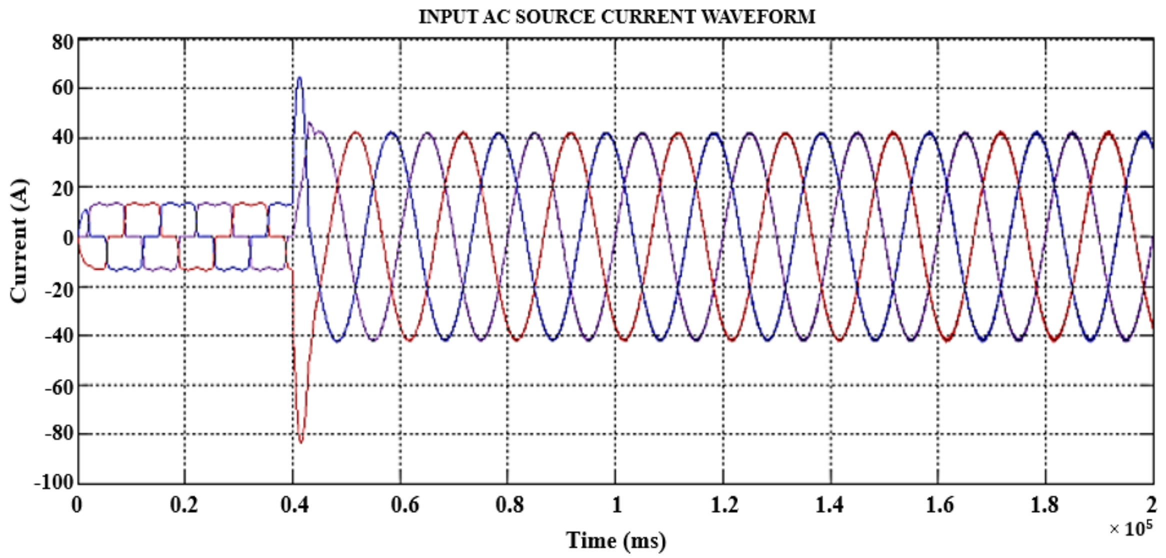

Figure 4. Input AC source current waveform

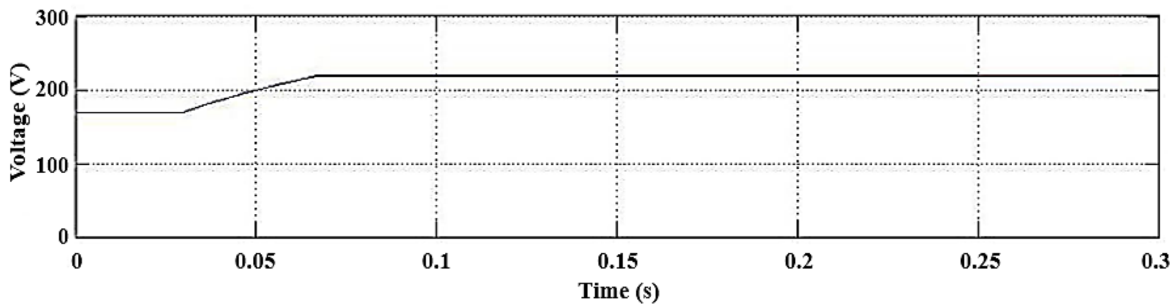

Figure 5. DC capacitor voltage waveform

Figure 7 shows the opposite current harmonics injected to the point of common coupling. The decoupled double synchronous reference frame theory produces sinusoidal harmonic opposite to that of load harmonic and inject it to the power system, thereby reducing the effect of harmonics. The state delay controller is used to reduce the delay between the compensation time for power injection and generation of reference signal. The load current after compensation using AEVO is shown in Figure 6. The unbalanced load consists of three- phase diode rectifier circuit and has shown THD of 26.16% without SAF as shown in Figure 8 and THD of 0.73% with SAF as shown in Figure 9.

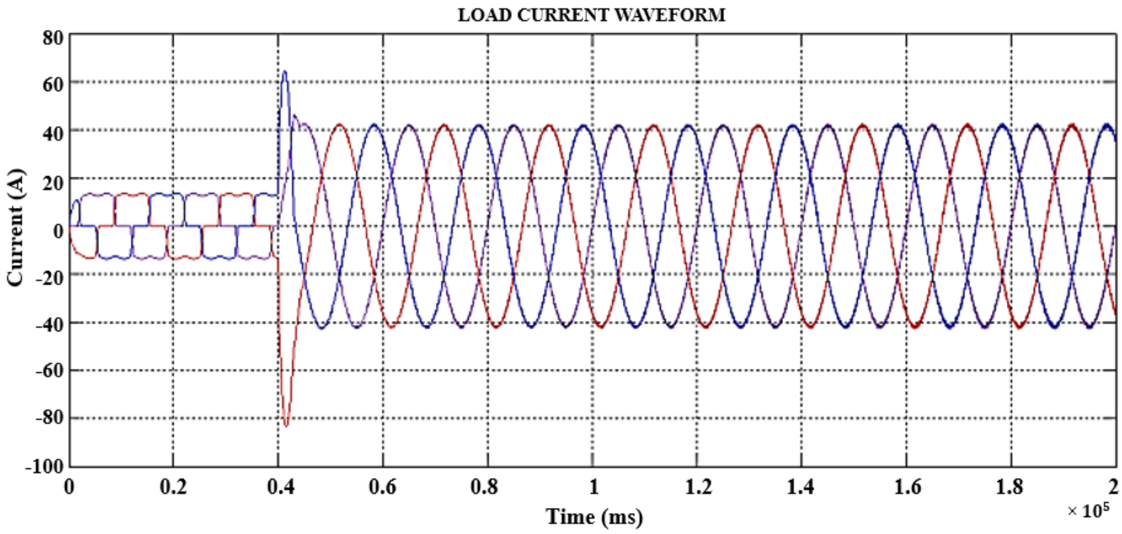

Figure 6. Load current waveform

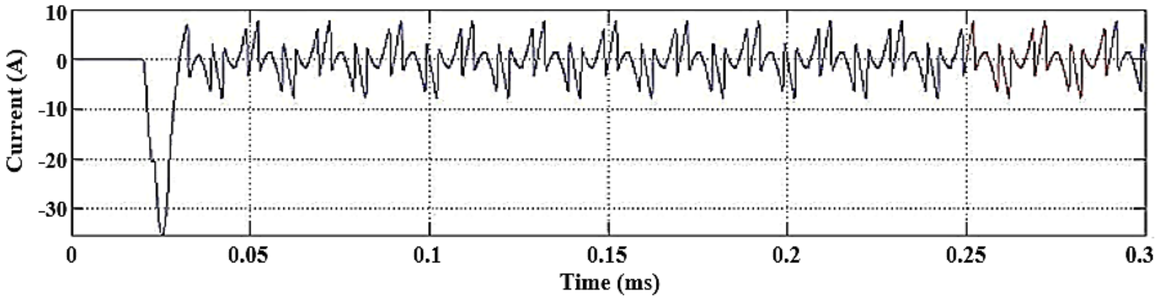

Figure 7. Opposite current harmonics injected at PCC

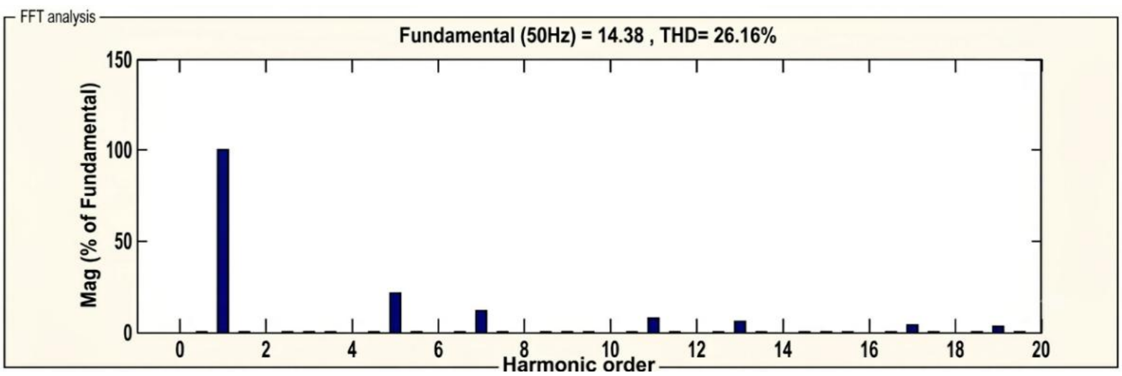

Figure 8. THD spectrum of load current before compensation

Figure 10 depicts an imbalanced three-phase source voltage and current profile consisting of current harmonics (THD) in phase 'a'. Figures 10-12 display the hardware outputs of the system after appropriate remedial measures have been implemented. Measurements of the phase and line magnitude of the RMS voltage and current of an imbalanced load are displayed in Figure 10. The total harmonic distortion (THD) of the load current is lowest (23.85%) in phase 'c' and highest (25.13%) in phase 'a' when there is no injection of compensating current in the power conversion converter (PCC) or when the second-arm filter (SAF) is not connected. The reduced harmonic components utilizing SAF are shown in Figures 11 and 12. This study validates the performance enhancement of an AEVO-based method that incorporates time delay prediction of the dq1 and dq2 components of positive sequence PQ and negative sequence PQ power consumed by load. The harmonics in phase 'c' are decreased to 0.923%, which is below the suggested target value set by IEEE. SAF successfully overcomes the challenges of unbalanced load operation during transient operating conditions. The SAF is evaluated under transient conditions within a time frame of 82 milliseconds, as depicted in Figure 12.

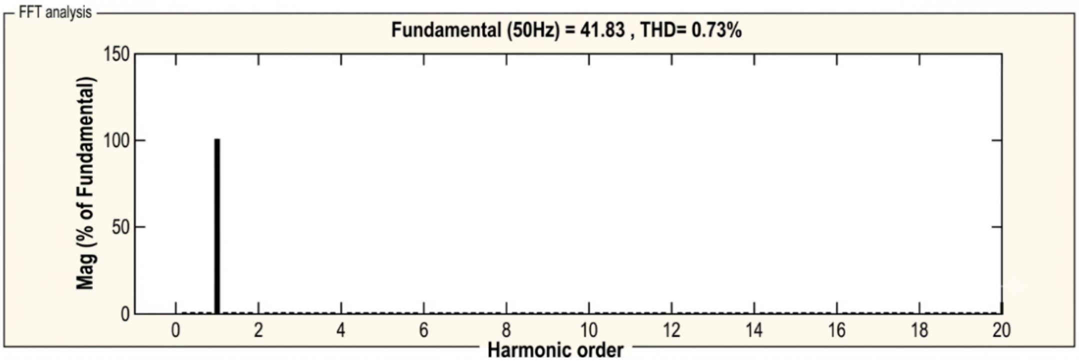

Figure 9. THD spectrum of load current after compensation

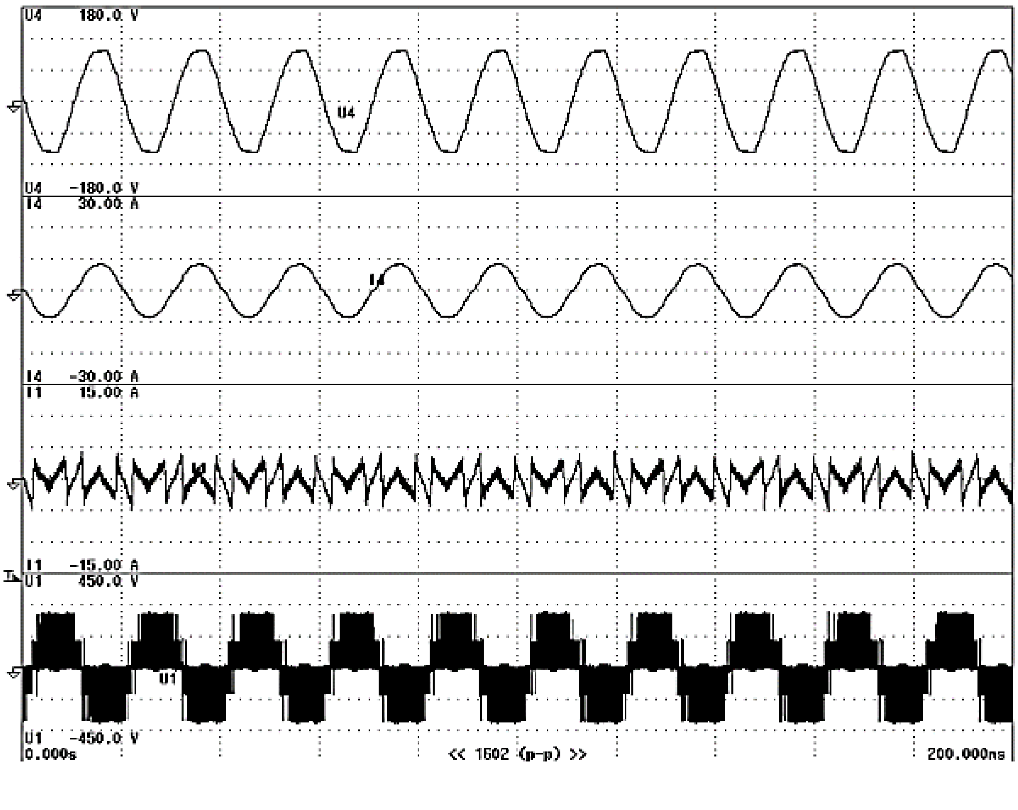

Figure 10. Three-phase source voltage, current, and opposite harmonics injected at the PCC

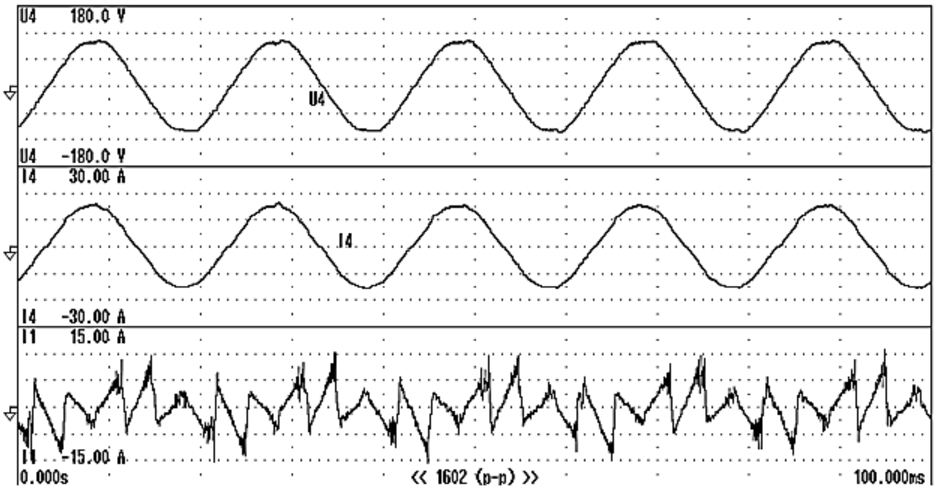

Figure 11. Three-phase load voltage, current, and opposite harmonics for one phase

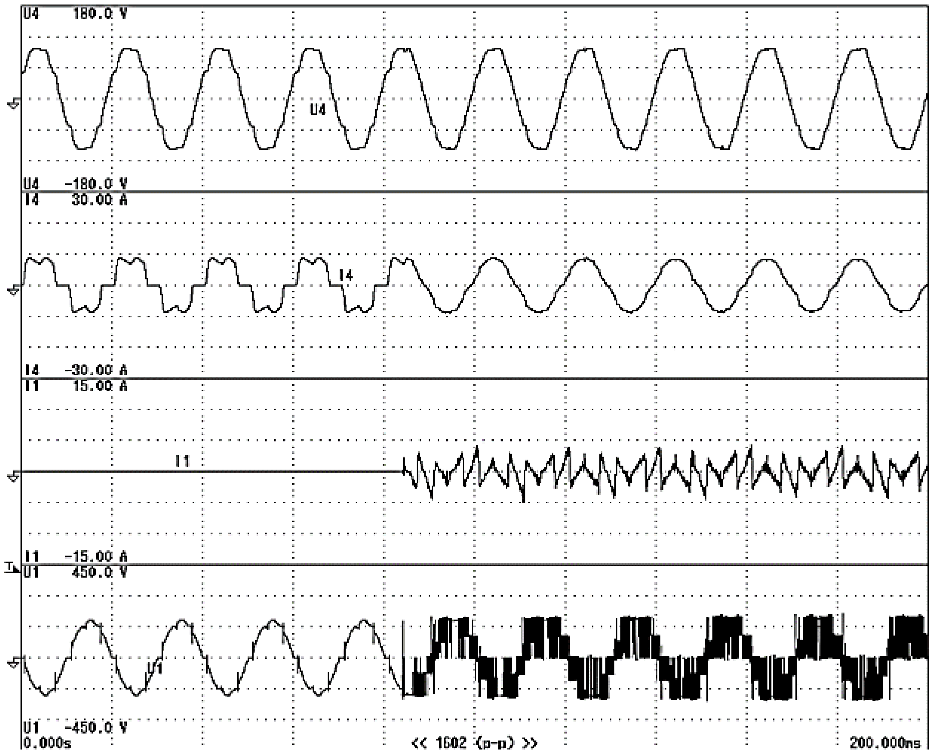

Figure 12. Load voltage and current, AEVO based APF compensation current and voltage

5. CONCLUSION

Energy valley optimization provides a comprehensive framework for mitigating harmonics in power grids by leveraging advanced monitoring, control systems, demand-side management, distributed generation, and energy storage technologies. By systematically identifying valley periods and deploying appropriate measures, utilities can effectively manage harmonic levels, improve power quality, and enhance the overall stability and efficiency of the grid. Continuous evaluation and adjustment of strategies are essential to adapt to the ever-changing dynamics of modern power systems and to achieve sustainable harmonic mitigation. Further the system can be used and implemented in high voltage power transmission and distribution networks for the mitigation and control of harmonics. The system is stable and efficient for mitigating harmonics.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Nagaraja Bodravara	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Ezhilarasan Ganesan	✓	✓			✓	✓		✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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