IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

POWER QUALITY IMPROVEMENT IN PV POWERED UNIFIED ACTIVE POWER FILTER USING INTELLIGENT ANN CONTROLLER

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Abstract: The growing integration of renewable energy sources, particularly solar photovoltaic (PV) systems, into the power grid has introduced complexities in power quality management. Traditional active power filters, though effective, often struggle in dynamic environments with varying loads and fluctuating power generation. This paper proposes a PV-powered unified active power filter (UPF) equipped with an intelligent Artificial Neural Network (ANN) controller to improve power quality (PQ). The system utilizes a series and shunt converter configuration to efficiently manage both linear and nonlinear loads. A switched inductor boost-Luo converter, positioned at the core of the system, enhances the voltage output from the PV module (V_{PV} and I_{PV}). Pulse Width Modulation (PWM) pulses, generated through a dedicated PWM generator using D-Q theory, enable the conversion process. Control mechanisms include an ANN controller and a modified Red Kite optimized Proportional-Integral (PI) controller, ensuring precise tracking of reference power (Pref) and actual power (Pact). The system maximizes energy efficiency, responding dynamically to varying loads while maintaining optimal PV system performance. This design enhances solar power integration into existing electrical grids and addresses key PQ issues such as harmonic distortions, voltage fluctuations, and reactive power imbalance. This paper is implemented using MATLAB 2021a**.**

Index Terms **- Renewable energy integration; Solar Photovoltaic (PV) Systems; Power Quality (PQ); Unified Active Power Filter (UPF)**

I. INTRODUCTION

Photovoltaic (PV) systems utilize photovoltaic cells to directly convert sunlight into electrical power. These cells function based on the photovoltaic effect, which occurs when sunlight excites electrons in a material, pushing them into a higher energy state and generating an electric current. Typically, PV cells are made from semiconductor materials like silicon. A standard PV system consists of solar panels (modules), inverters, batteries, mounting systems, and power controllers. Solar panels capture sunlight and convert it into direct current (DC) power, but inverters are needed to convert DC into alternating current (AC), which is commonly used in residential and commercial applications. Batteries are included in off-grid systems to store excess energy produced during daylight hours for use when the sun is not shining [1].

Charge controllers regulate the flow of electricity to and from the battery to prevent overcharging or discharging. PV systems can be deployed on various scales, from small rooftop installations on homes to large utility-scale solar farms spanning vast areas. One of the main advantages of PV systems is their ability to provide clean, renewable energy with zero greenhouse gas emissions during operation, making them vital for addressing climate change and transitioning toward low-carbon energy. Furthermore, once installed, PV systems are cost-effective to operate and maintain, as sunlight is a free and abundant resource in many parts of the world. Over recent years, improvements in photovoltaic technology have made solar energy more competitive with traditional fossil fuels in terms of efficiency, cost, and integration into existing power grids.

The efficiency of a PV system is influenced by several factors, including geographical location, local weather conditions, and the orientation and angle of the solar panels. Systems in regions with high solar irradiance, such as deserts or tropical areas, typically produce more energy than those located in cloudier or less sunny areas. Tracking devices can further enhance energy capture by adjusting the panels' position to follow the sun's movement throughout the day. Moreover, innovations in materials, such as perovskites and bifacial panels, which capture sunlight from both sides, are helping to increase system efficiency.
Despite these benefits, several challenges remain in the widespread adoption of PV systems. The intermittent nature of solar energy, dependent on sunlight availability, poses a significant challenge. To address this issue, many PV systems are integrated with energy

storage systems or connected to the power grid, allowing energy to be supplied during night time or cloudy periods. Additionally, while the cost of PV systems has decreased over the years due to economies of scale, technological advancements, and government incentives, the initial installation cost may still be a barrier for some users.

Looking ahead, further advancements in PV technology will play a crucial role in achieving global renewable energy goals, reducing reliance on non-renewable sources, and promoting a more sustainable energy future. The continued development of efficient materials, enhanced storage solutions, and better integration with power grids will help overcome current limitations and make solar energy a cornerstone of the world's clean energy transition.

II. LITERATURE SURVEY

Using a PV-powered Unified Active Power Filter (UPF) in conjunction with an Intelligent Artificial Neural Network (ANN) Controller is a promising way to address power quality concerns in contemporary electrical networks. The increased usage of non-linear loads and power electronic devices has led to an increase in power quality issues such reactive power difficulties, voltage swings, and harmonics. These issues reduce power systems' stability and efficiency, particularly in grid-connected configurations. An advanced power electronic device called a Unified Active Power Filter (UPF) improves the system's overall power quality by compensating for reactive power, harmonic currents, and unbalanced loads all at once. In addition to addressing power quality concerns, this system promotes the use of renewable energy sources, making it sustainable and eco-friendly when powered by a photovoltaic (PV) source. An Intelligent ANN Controller is employed to maximize the UPF's performance.

Shaik Rafi Kiran et al [2022] proposed a step Size variability Maximum Power Point Tracking (MPPT), a technology based on artificial neural networks (ANNs), is used to improve the efficiency of solar photovoltaic (PV) systems in partial shadowing conditions (PSCs). By assessing factors like steady-state behavior, settling time, power point tracking speed, MPP oscillations, and operating efficiency, this method is compared with a number of other MPPT techniques, such as Adaptive Perturb & Observe (AP&O), Adaptive Feed Forward Neural Network Controller (AFFNNC), ANN-based P&O, ANN-based Incremental Conductance (ANN-based IC), ANN-based Hill Climb (ANN-based HC), and Radial Basis Functional Controller-based Fuzzy (RBFC-based Fuzzy).

Koganti Srilakshmi et al [2022] proposed a Controlling a Unified Power Quality Conditioner (UPQC) that is connected to solar photovoltaic (PV) and battery storage systems using a hybrid artificial intelligence approach is intended to enhance power quality by removing aberrations in voltage and current. To control DC-link voltage, the control approach creates a Neuro-Fuzzy Hybrid Controller (NFHC) by combining an Artificial Neural Network (ANN) with a Fuzzy Logic Controller (FL-C).

Hina Mahar et al [2022] presented a Controlling a Unified Power Quality Conditioner (UPQC) integrated with a grid-connected microgrid using artificial neural networks (ANNs) aims to improve power quality while lowering system complexity and expense. Efficiency is increased by the ANN controller, which does away with costly hardware like DSPs and FPGAs and complicated mathematical transformations. Taking into account voltage problems like sag and swell, the system is assessed under nonlinear unbalanced loads and harmonic supply voltage. Stable dc-link voltage and efficient reference signals are provided by the ANN controller, which was trained using the Levenberg-Marquardt backpropagation technique.

Mostafa M. Shibl et al [2023] presented a two-phase machine learning-based energy dispatch management system for hybrid power plants (HPPs) that combines backup systems like diesel generators and energy storage with renewable energy sources like wind and photovoltaic (PV). In order to minimize power variation and achieve peak shaving and valley filling, the second stage of the system coordinates energy dispatch from reserve and backup sources. The first stage anticipates the power output from renewable sources and load demand. For predicting, the system makes use of Long Short-Term Memory (LSTM), which performs exceptionally well with low mean squared error and high explained variance.

Ahmed Hussain Elmetwaly et al [2023] proposes a sophisticated Power Management System (PMS) for an AC micro grid (MG) that incorporates renewable energy sources including diesel generators (DG), permanent magnet wind generators (PMWG), and solar photovoltaic (PV) panels. To provide stable operation, energy balance, lower fossil fuel use, and voltage stability, the system uses an adaptable Artificial Neural Network (ANN), with the ANN weights optimized using the Enhanced Bald Eagle Search (EBES) method.

Devi Prasad Acharya et al [2023] presented a Deep Auto Regressive Exogenous Output Neural Network (KDNARX) controller is based on kernels and is intended to handle power quality (PQ) problems in a complicated three-phase microgrid situation. This microgrid incorporates a number of distributed energy resources (DERs), including battery energy storage systems, fuel cells, wind turbines, and solar cells. Voltage sag/swell, imbalance, power factor (PF), total harmonic distortion (THD), communication delay, and impedance fluctuations are among the PQ factors that are improved by the KDNARX controller.

Musa Yilmaz et al [2023] introduced an Adaptive Reference Voltage (ARV) technique for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems that is based on Artificial Neural Networks (ANN). This voltage-controlled method maximizes power extraction from PV panels by adjusting to changing environmental factors like temperature and solar radiation. In MATLAB/Simulink simulations, the effectiveness of the ANN-based ARV approach is contrasted with conventional control strategies, such as the popular Perturb and Observe (P&O) and Incremental Conductance (INC) approaches, as well as standard Proportional-Integral (PI) and anti-windup PI controllers.

Belqasem Aljafari et al [2024] presented to solve power quality (PQ) problems, a Unified Power Quality Conditioner (UPQC) that is fueled by solar photovoltaic (PV) and battery energy storage devices was created. Instead of using more conventional techniques like instantaneous power (p-q) and synchronous reference frame (SRF) methods, the control strategy uses the Honey Badger Optimization Algorithm (HBOA) to optimize the weights and biases of an artificial neural network (ANN) for reference signal generation and DC capacitor voltage regulation. In order to reduce total harmonic distortion (THD), increase power factor (PF), and lessen voltage disturbances including flicker, sag, swell, and imbalances, HBOA is also used to adjust the parameters of shunt and series filters.

Mohammad Amir et al [2024] introduced during grid outages, a Fuzzy Q-Learning (FQL) algorithm is used to manage Distributed Generations (DGs) in EV parking lot charging systems. This algorithm responds to disturbances in both grid-connected (GC) and standalone (SA) modes in real-time by dynamically adjusting control signals for grid synchronization and islanding detection. The FQL guarantees smooth transitions between grid states and improves system performance by continuously learning from faults and disruptions. Real-time hardware-in-loop (HIL) simulations of a grid-integrated photovoltaic (PV) sub-system with different load profiles are used to test the method and show that it handle both linear and nonlinear load scenarios.

D. K. Nishad et al [2024] presented Power quality problems in electrified railway systems are addressed by a Dynamic K-factor PI (DKPI) algorithm and an Artificial Intelligence-based Unified Power Quality Conditioner (AI-UPQC). Due mostly to the extensive usage of power electronic converters in contemporary traction drives, these systems encounter issues including resonance, harmonics, and voltage swings. The AI-UPQC significantly improves system performance by using Artificial Neural Networks (ANNs) to produce the best reference signals for managing shunt and series active power filters. To assess the efficacy of the AI-UPQC, a comprehensive model of a traction power supply system is created using MATLAB/Simulink.

Objectives:

- To implement PV powered unified active power filter with intelligent ANN controller for PQ improvement
- To design a PWM generator based on D-Q theory for enhanced performance of series and shunt converters.
- To establish an ANN controller for dynamic adjustment of PWM signals to ensure stable operation under varying load conditions.
- To utilize a modified Red Kite optimized PI controller for precise voltage, minimizing losses and improving overall system reliability.

III. SYSTEM DESCRIPTION

This paper proposes a PV-powered unified active power filter with an intelligent ANN controller for power quality (PQ) improvement. The system uses a converter to regulate and condition the voltage from the AC source. The PV system, represented by a solar panel, generates DC voltage (Vpv) and current (Ipv) under sunlight. This output is fed into a Switched Inductor Boost-Luo Converter, which steps up the voltage to a desired level. The converter then produces Pulse Width Modulation (PWM) pulses that control the output voltage. These PWM pulses are processed by a PWM generator based on D-Q theory, optimizing the control signals for the converters.

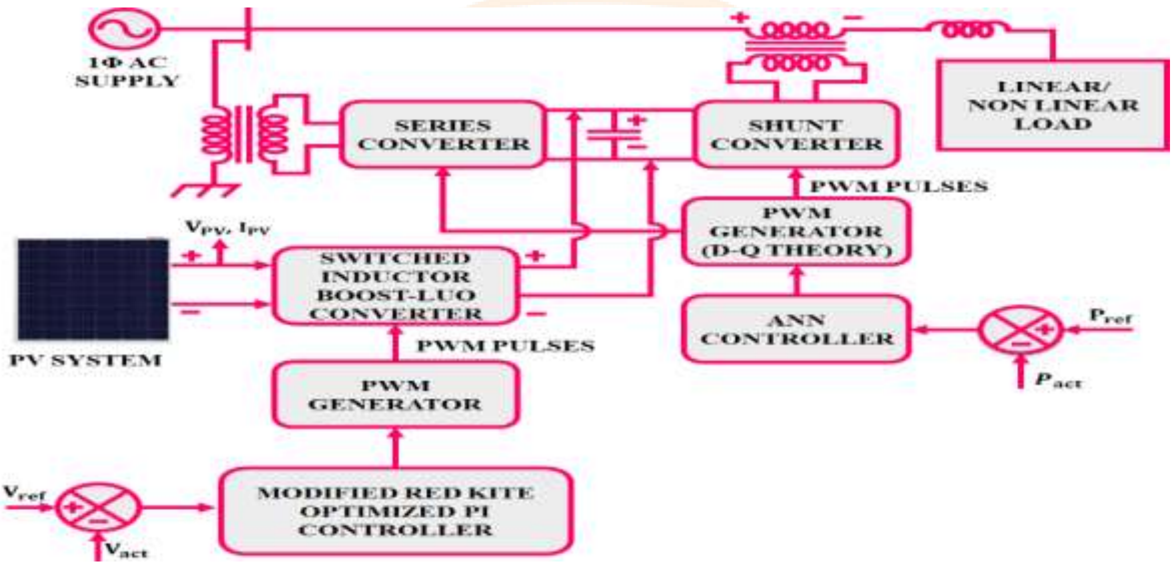

Figure 1 Block Diagram of Proposed System

An Artificial Neural Network (ANN) controller is incorporated to adjust the converter's operation based on system performance. The controller compares the actual output (Pact) with a reference power level (Pref) to minimize error. Additionally, a modified Red Kite optimized PI controller fine-tunes the system's response by adjusting the PWM signals according to the difference between the reference voltage (Vref) and the actual voltage (Vact) at the load. This ensures efficient utilization of the power generated by the PV system, while maintaining stability and performance, even when supplying linear or nonlinear loads.

A. PV System

A photovoltaic (PV) system generates electricity by directly converting sunlight into direct current (DC) power. The process begins when sunlight is absorbed by solar panels made of photovoltaic cells, typically composed of semiconductor materials such as silicon. When sunlight strikes the cells, the energy excites the electrons in the semiconductor, allowing them to move freely, generating an electric current. The interconnected cells in the PV modules work together to produce DC electricity [12].

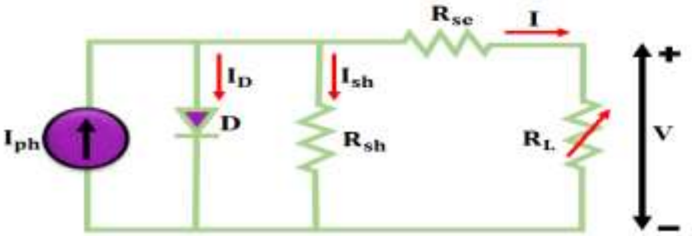

Figure 2 PV Circuit Diagram

B. Switched Inductor Boost Luo Converter

The Switched Inductor Boost Luo Converter is a highly efficient DC-DC power converter that boosts a lower input voltage to a higher output voltage through a sequence of switching operations. Initially, when the switch is closed, energy is stored in the inductor's magnetic field as current flows through it. When the switch opens, the stored energy is released and transferred to the output circuit, increasing the voltage. The converter's use of multiple inductors enables higher voltage gain and improved energy transfer, ensuring that the output voltage is consistently higher than the input [13,14].

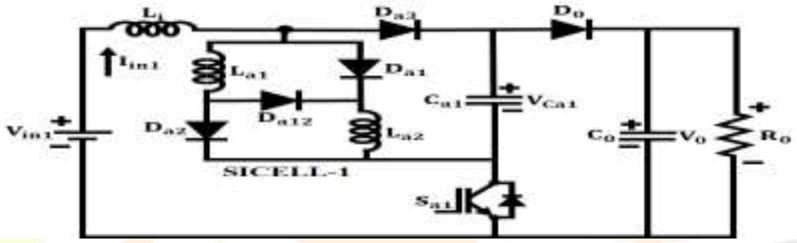

Figure 3 Switched Inductor Boost Luo Converter

Mode 1:
In operating mode-l, the gate-drive circuitry generates gate pulses that are supplied to switch Sal, activating it. The input DC voltage Vin is applied to charge inductors Lal and La2 within the Sl cells, with the help of the corresponding diodes Dal and Da2.

Mode 2:
The diode Da12 and the output diode Do facilitate the release of energy stored in the Sl cell-1 inductors Lal, La2, and the boost capacitor Ca1. Using the input voltage Vin1, the system employs a series discharge method to transfer energy to a resistive load. Consequently, the voltage across the two inductors in the Sl cell, Lal and La2, represented as - VL1 and -VL2, aligns with the voltage of the boost capacitor, ensuring efficient energy delivery to the load.

C. Series and Shunt Converters

The series converter controls voltage and current in a power system using a switching mechanism. When the switch is closed, current flows from the input source to the load, maintaining a stable voltage level. Upon opening the switch, energy is stored in an inductor, helping regulate the output voltage. This energy is then released to the load when the switch closes again, ensuring continuous power flow. The converter adjusts the duty cycle of the switching to manage voltage output, adapting to load variations for efficient energy transfer.

D. PWM Generator (D-Q Theory)

A Pulse Width Modulation (PWM) generator based on D-Q (Direct-Quadrature) theory is vital for precise control of voltage and current in modern power electronic systems. By splitting AC signals into two orthogonal components—the direct axis (D-axis) and the quadrature axis (Q-axis)—D-Q theory simplifies controlling three-phase AC systems. This transformation allows for DC-like management, improving accuracy and efficiency. The PWM generator uses these D-Q components to generate high-frequency switching pulses, which control power devices like converters and inverters.

F. ANN Controller
An artificial neural network (ANN) controller is an AI-based control system that manages complex, nonlinear, and time-varying systems. Unlike traditional control methods that rely on mathematical models, an ANN controller learns from data to adjust control parameters. This makes it ideal for applications where modeling is difficult, such as in renewable energy systems and power electronics. The ANN controller works by training a neural network to map inputs (e.g., voltage, current) to desired outputs (e.g., control signals for converters or inverters).

IV. RESULTS AND DISCUSSIONS

The simulation results were analyzed using the program called MATLAB/SIMULINK. MATLAB is a language that can be used to calculate, visualize and compute in the user environment, where the problem and its solution are expressed using the information method. MATLAB is the best tool for signal analysis. The proposed work is implemented in MATLAB simulation are shown in figure 4.

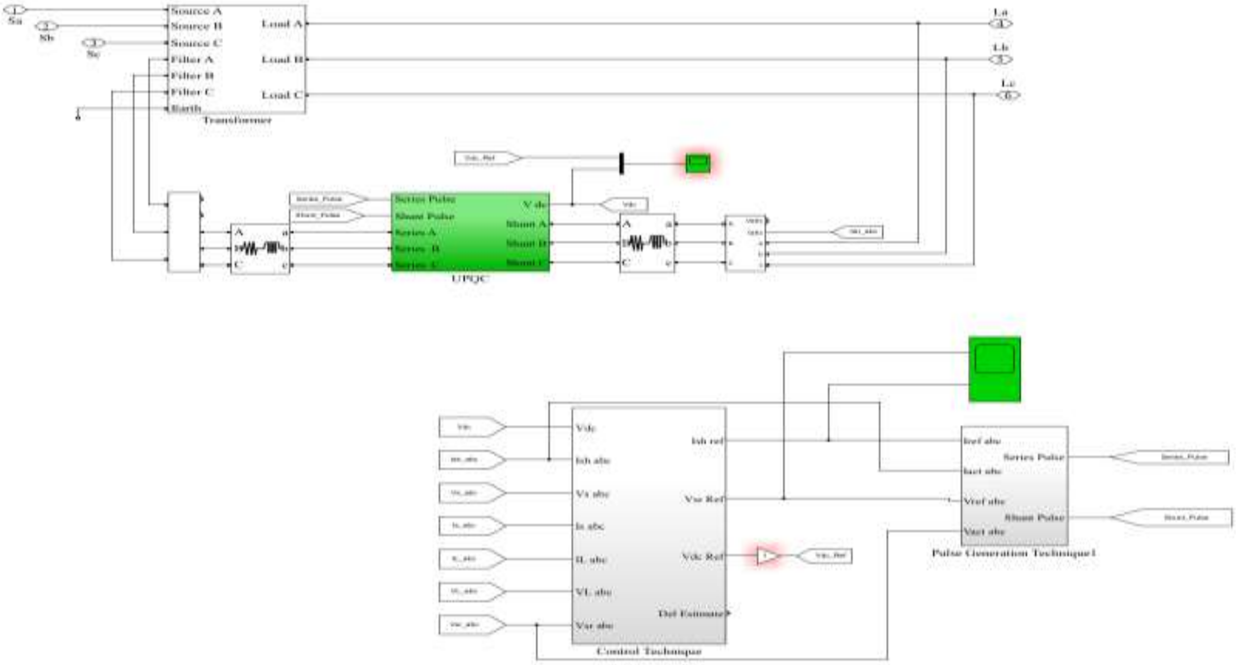

Figure 4 Overall Simulation Block Diagram

Case 1: Step Magnitude (-0.4)

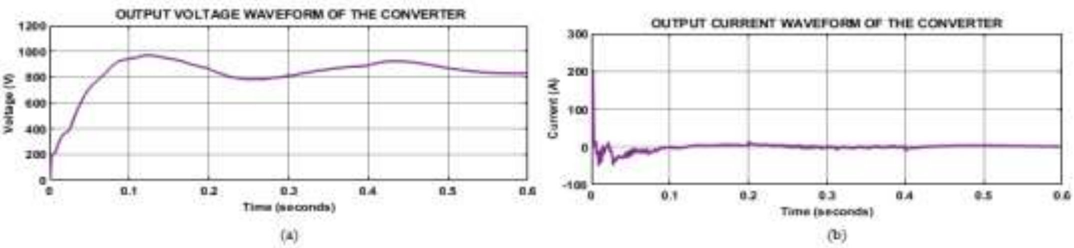

Figure 5 Output Waveform of Converter

Figure 5 presents the voltage waveform (a), which stabilizes around 200 V after an initial rise, demonstrating effective voltage regulation. The output current waveform (b) shows a steady flow of approximately 10 A, indicating a consistent load throughout the operation. This stability in both voltage and current highlights the converter's ability to maintain desired output levels efficiently, ensuring reliable performance under the given conditions.

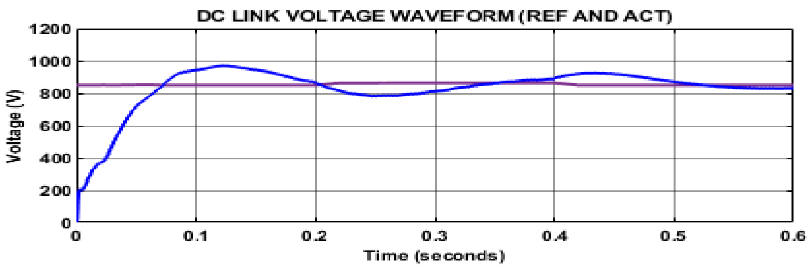

Figure 6 DC Link Voltage Waveform

As shown in Figure 6, the DC link voltage waveform, which illustrates the converter's output process, stabilizes around 800 V after an initial oscillation. This stability indicates that the converter is effectively regulating and controlling the voltage. By maintaining a steady voltage level, the converter ensures peak performance, thereby enhancing the overall efficiency of the system.

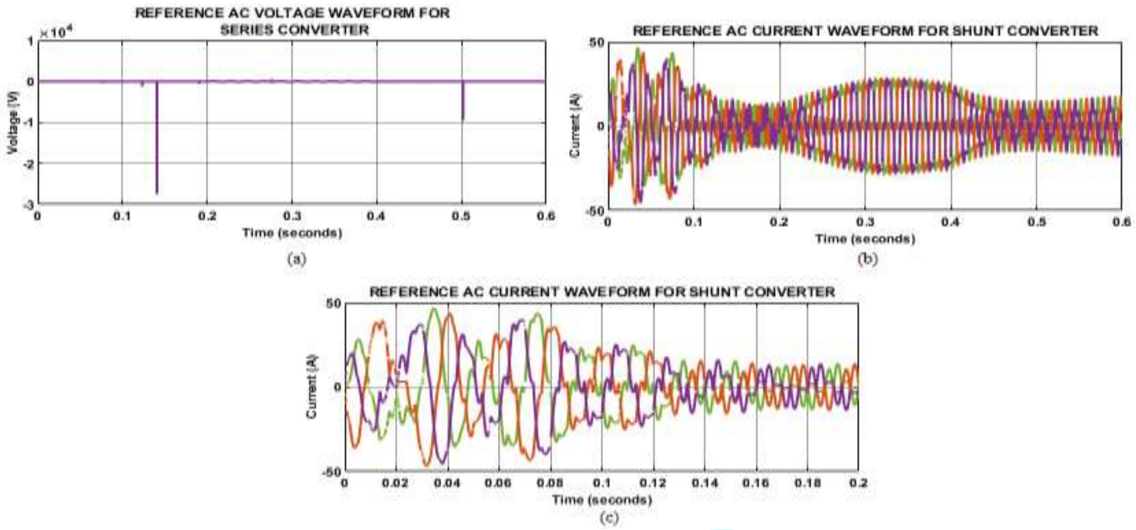

Figure 7 Waveform of UAPF

Figure 7 illustrates the converter's process, where the reference AC voltage waveform stabilizes at approximately 50 V after an initial spike. The current waveform of the shunt converter shows oscillations, peaking around ±30 A, indicating dynamic adjustments in response to varying load conditions. These fluctuations reflect the converter's ability to regulate the current efficiently in real-time, ensuring the system adapts to changing demands.

Case 2: Step Magnitude (+0.4)

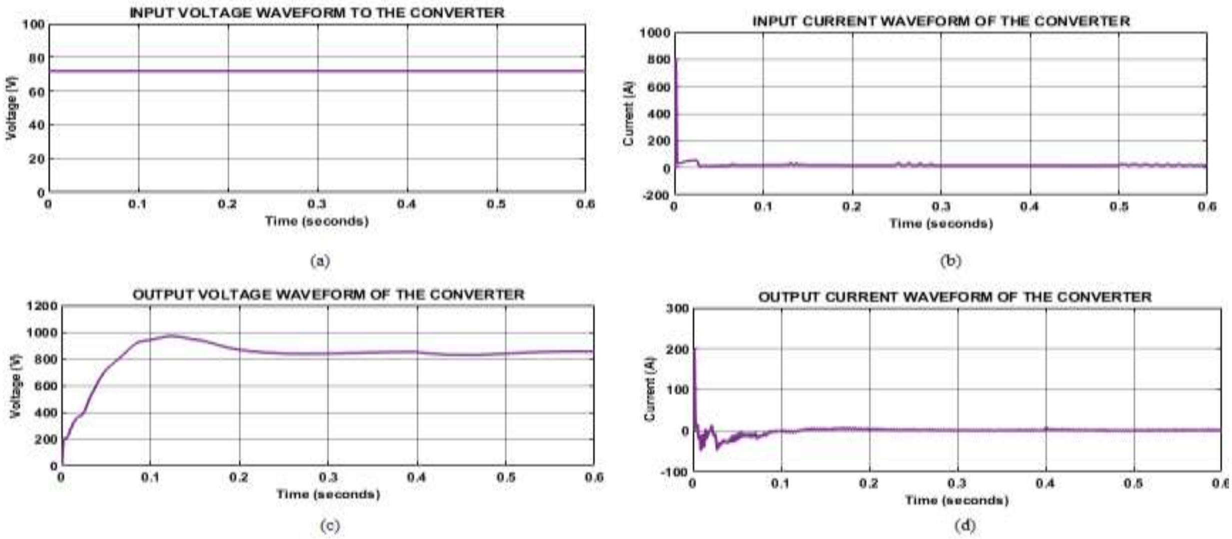

Figure 8 Waveform of Converter

While the load current fluctuates between ±30 A. This behavior highlights the system's ability to adjust to dynamic load changes, ensuring consistent voltage and current levels. The steady waveforms indicate the converters' reliable performance and their capacity to maintain optimal operation under varying conditions, confirming the system's efficiency and stability during dynamic load adjustments.

The waveform shown in figure 8 illustrates the AC source voltage stabilizing around 200V.

In contrast, the shunt converter's current waveform fluctuates between ±50 A, indicating dynamic load adjustments. These values highlight the system's capability to maintain voltage stability while adapting to changing load conditions, demonstrating the converter's efficiency in regulating performance under varying operational circumstances.

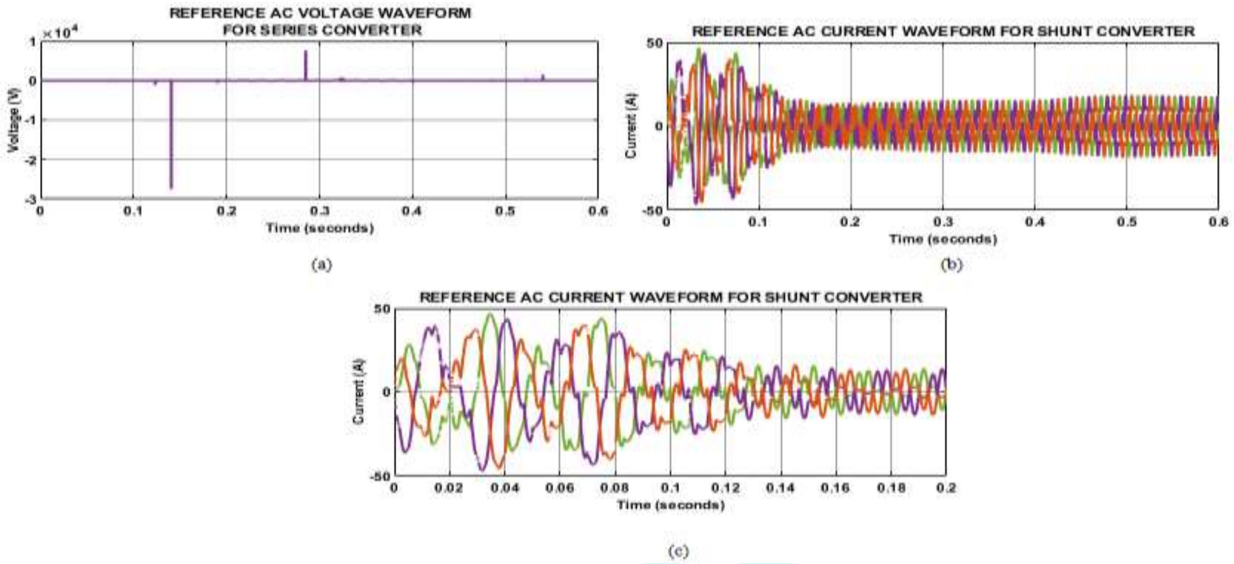

Figure 9 Waveform of UAPF

V. CONCLUSION

In conclusion, the proposed PV-powered unified active power filter with an intelligent ANN controller provides an effective solution to common power quality (PQ) challenges in modern electrical systems. By integrating a switched inductor boost-Luo converter and utilizing advanced control techniques like the ANN and modified Red Kite optimized PI controller, the system achieves efficient harmonic suppression, voltage regulation, and reactive power compensation. The use of series and shunt converter configurations improves the management of both linear and nonlinear loads. With implementation in MATLAB 2021a, the design's precision is validated, demonstrating improved PQ and energy efficiency, while facilitating the seamless integration of solar power into grids for sustainable energy solutions.

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