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PQ management and control with Hybrid source based UPQC with neural controller for on grid microgrid

1 T. Aravind,2 S.Tarun,3 P. Raj kumar,4 V. Bhavana,5 M.Vara Prasad,6 Dr. N. Dharani Kumar
1,2,3,4,5 PG Scholar, Department of Electrical and Electronics Engineering
6, Assistant Professor, Department of Electrical and Electronics Engineering
R.V.R & J.C Engineering College, Chowdavaram, Guntur(Dt), AP, India.
polankirajkumar2003@gmail.com

Abstract:

This research presents an innovative approach to enhancing power quality in photovoltaic-battery storage systems (PVBSS). The proposed method leverages Unified Power Quality Conditioners (UPQCs) controlled by Artificial Neural Networks (ANNs) integrated with Fractional Order Control (FOC), eliminating the need for conventional abc-to-dq0 transformations. The system employs Levenberg-Marquardt-trained ANN controllers (ANNCs) to generate direct reference signals for both shunt and series converters.

To optimize energy harvesting from photovoltaic (PV) sources, a Maximum Power Point Tracking (MPPT) algorithm based on High-Frequency Switching Modulation Control (HFSMC) is implemented. A Battery Storage System (BSS) maintains a stable DC link voltage, allowing for rapid response to fluctuations in load and solar irradiance.

This architecture effectively mitigates grid voltage disturbances such as spikes and sags, improves power factor, and reduces current harmonics. Compared to traditional Proportional-Integral Controllers (PICs), the proposed system significantly lowers Total Harmonic Distortion (THD) and achieves faster settling of the DC link voltage. Future work will focus on applying heuristic optimization techniques to fine-tune system parameters and further enhance overall efficiency.

Key Words: Photovoltaic system, Battery energy storage system, UPQC, MPPT, FO-ANN and HFSMC.

I. Introduction

Currently, power quality (PQ) issues in distribution systems (DS) arise from the presence of harmonics generated by power electronic-based appliances, drives, and other nonlinear loads. In order to mitigate the effects of PQ-related problems, a solution was suggested: the use of an active power filter (APF). The UPQC was introduced to effectively address power quality (PQ) issues in distribution networks that are associated with voltage and current. This is achieved by integrating a shut active power filter (SHAPF) and a series active power filter (SAPF) through a shared DC link. Various control methods have been developed for unified power quality conditioners, such as PIC, artificial intelligence (AI) techniques like ANNs and fuzzy logic, park's and Clarke's transformations approaches, and others (Fujita and Akagii, 1998).

The PQ enhancement debates encompassed the design and research of unified PQ conditioners, which integrate both SHAPF and SAPF along with a dynamic voltage restorer

(Kolhatkar, Errabelli, and Das 2005; Mosaad et al. 2022). In order to address the issue of harmonics and grid voltage compensation, a new control mechanism and a fuzzy hysteresis band voltage methodology were implemented for the Unified Power Quality Conditioner (UPQC) (Drozdov et al., 2018). Furthermore, the purpose of UPQC is to produce the required reactive power to meet the demand, with the aim of minimizing the overall expenses of operation (Khadkikar and Chandra, 2008). A PIC-based artificial neural network (ANN) hybrid controller was then created for the Unified Power Quality Conditioner's (UPQC) Series Hybrid Active Power Filter (SHAPF) to effectively regulate current (Kinhal, Agarwal, & Gupta, 2011).

In order to minimize power loss in the converter, the UPQC (Leon et al., 2011) incorporated the optimal linearization feedback control method, which involved determining the most suitable angle for the load voltage. Furthermore, a comprehensive examination was conducted on the advanced techniques and remuneration strategies employed in the Unified Power Quality Conditioner (UPQC) as outlined by Khadkikar in 2012. In order to reduce PQ difficulties, costs, and losses, it was suggested that UPQCs be strategically positioned utilizing the differential evolution technique (Taher and Afsari, 2012). Furthermore, Yang, Soh, and Yap (2019) provide a design for a 3-level inverter architecture that utilizes Unified Power Quality Conditioner (UPQC) with Fuzzy Logic Control (FLC) to mitigate voltage fluctuations and minimize harmonic distortions.

In order to reduce fluctuations in voltage and current in distribution systems, a PV integrated UPQC was created (Gopal Murthy, and Sreenivas, 2016). Gadgune and Waware (2014) proposed an Integral-plus-SMC based controller for the voltage regulator in UPQC to maintain a constant voltage across the DC connection (Vdc) with a faster settling time and no overshoot. Nevertheless, a recent study conducted by Kalair et al. in 2017 scrutinized the body of literature pertaining to harmonic removal approaches, total harmonic distortion (THD) analysis, and power factor correction procedures. Furthermore, the integration of UPQC with the micro-grid effectively addressed PQ related issues for different types of loads, as demonstrated by Samal and Hotaa in 2017. A comparison was conducted between the Total Harmonic Distortion (THD) performances of Unified Power Quality Conditioner (UPQC) and Distribution Static Compensator (DSTATCOM) at a steel plant that operates an induction furnace load (Saggu et al., 2018). The development of an SMC-based hybrid controller for UPQC was required in order to reduce current THD and grid-voltage distortion (Yavari, Edjtahed, and Taher, 2018).

The Levenberg Marquardt (LM) back propagation trained artificial neural network (ANN) method was created for the five level unified power quality conditioner (UPQC) in order to eliminate the requirement for intricate calculations and the construction of reference signals for DC Link balancing and current generation (Vinnakoti and Kotaa, 2018). Dash and Ray (2018) proposed a PV-tied UPQC topology with LCL filters and integrated sliding mode control to address voltage and current problems related to PQ. In order to further decrease the Total Harmonic Distortion (THD) and improve the power factor, the 5-level Unified Power Quality Conditioner (UPQC) was implemented. This implementation, as described by Nagireddy, Kota, and Ashok Kumar in 2018, utilizes the fuzzy-back-propagation controller technique. The predator-prey based firefly optimization (PPFO) technique was developed by Mahaboob, Ajithan, and Jayaramann to reduce total harmonic distortion (THD) and enhance the voltage profile in the design of a SHAPF (Selective Harmonic Active Power Filter).

In their study, Nandhini and Sivaprakasamm (2020) analyzed the benefits and drawbacks of different PWM control systems that utilize Space Vector Pulse Width Modulation (SVPWM).

The DC connection supported by PV and BSS connected UPQC was designed to mitigate current harmonics caused by fluctuations in the grid voltage (Mansor et al., 2020).

II. System deign

UPQC research has recently focused on micro-grids and distributed power generation. Unified power quality conditioners are of greater significance for a solar photovoltaic system compared to a conventional grid-connected voltage source converter. Important objectives include safeguarding sensitive loads from disturbances originating from the power grid and ensuring that the converter has a high level of competency in handling abrupt changes in electrical conditions. When employing a combined PV system with a UPQC, it is not possible to determine the neural phase for signal-phase loads, as they are considered mutual loads in a distribution system. Generating a reference signal is essential in the context of UPQC. The signal-generation techniques outlined in the literature.

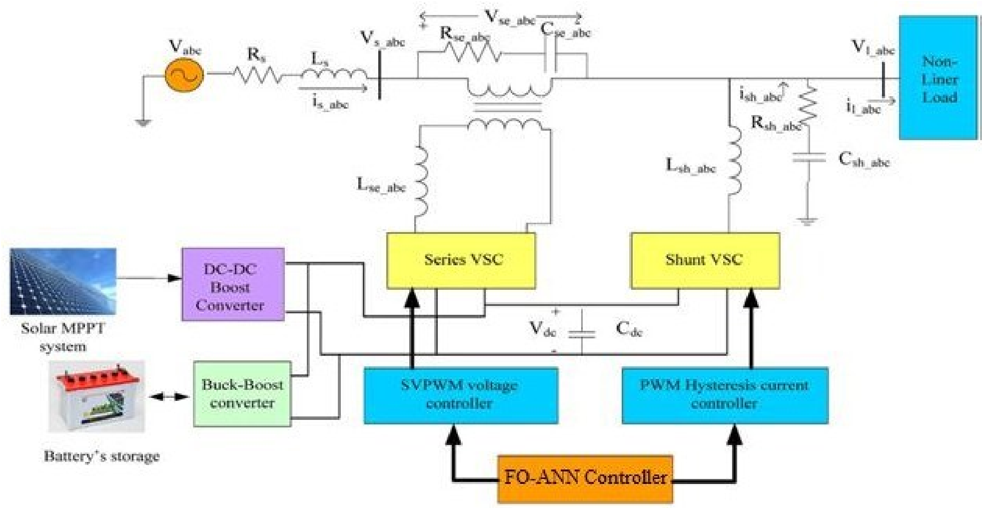


Figure 1. Proposed UPVBSS configuration.

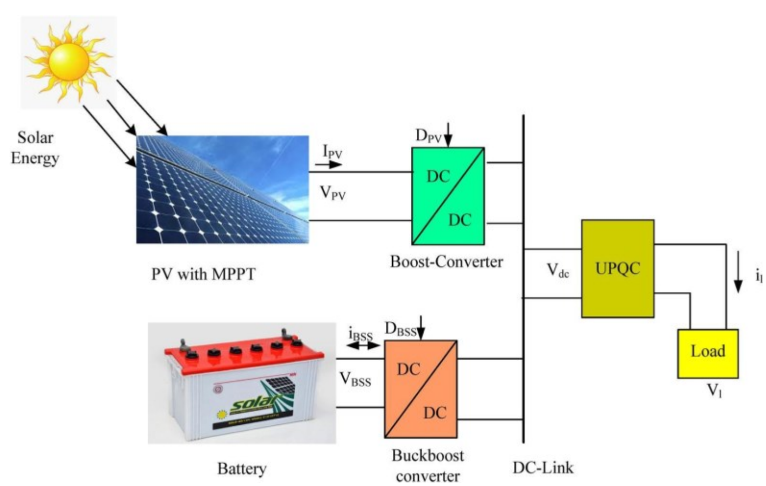


Figure 2. RES connected DC link for UPQC

The series compensator and shunt compensator of UPQC and PV utilize advanced approaches in the time and frequency domains as a basis for their operation. Time domain-based methodologies are commonly embraced in real-time applications because of their minimal processing demands. Methods such as instantaneous symmetrical component theory, instantaneous reactive power theory, and synchronous reference frame theory are commonly used.

The presence of a second harmonic component in the d-axis current is a disadvantage of the synchronous-based reference frame theory in the case of unbalanced loads. The low pass filter (LPF) is employed to eliminate the double harmonic component by utilizing a low cutoff frequency.

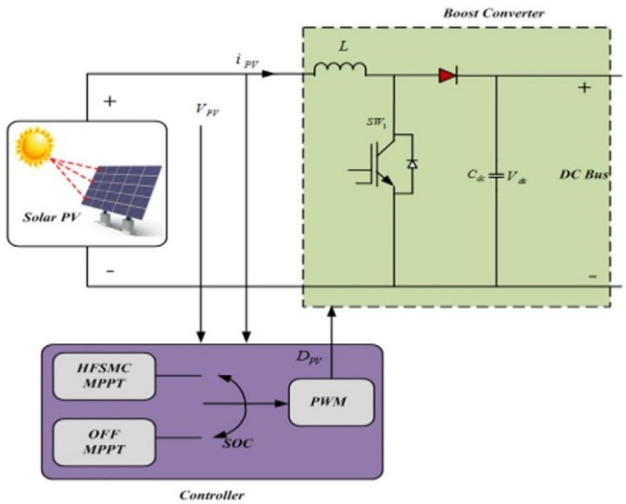


Figure 3. PV solar system controller.

a) Proposed UPVBSS Configuration

Figure 1 illustrates the proposed UPVBSS configuration. The BSS is linked to the UPQC's DC connection via a buck-boost converter, while the solar PV is connected to the UPQC's AC link using a boost converter. Va, Vb, and Vc stand for variables A, B, and C respectively.

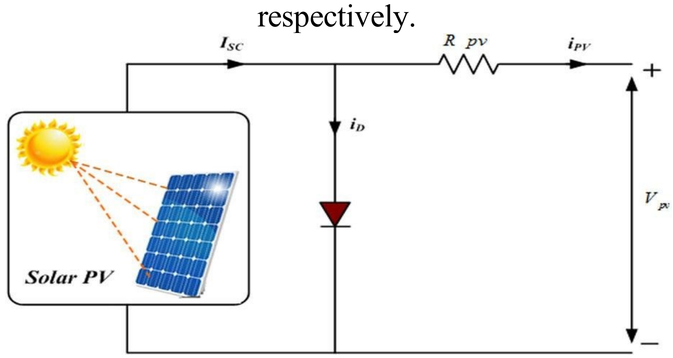


Figure 4 PV power system configuration

If Vsa, Vsb, and Vsc represent the voltages of the source bus for the a, b, and c phases of the grid, then Vl, il represent the current and voltage at the load. Source resistance is denoted by Rs, and source inductance by Ls. The UPQC combines series and shunt VSCs into a single unit.

By injecting the correct compensating voltage Vse through the transformer, series APF can solve grid-voltage-related issues. Resistor Rse, inductor Lse, and capacitor Cse make up the RLC filter; resistance Rsh, inductance Lsh, and capacitance Csh connect the SHAPF to the grid. By injecting a compensating current, SHAPF can stabilise the Vdc with minimal settling time and lower the harmonic content of the current waveform.

b) PV Power Plant

The SPG system harnesses sun photons and transforms them into practical energy. The main elements of the system consist of B-C and PV arrays that are arranged in either a series or parallel arrangement, utilizing MPPT technology. The performance of the Solar Power Generator (SPG) is dependent on the intensity of solar radiation received by the strategically positioned Photovoltaic (PV) cells. Incorporating a solar system into the DC link can decrease the ratings, burden on power converters, and utility consumption. Figure 4 illustrates the configuration of a photovoltaic (PV) power system. The efficiency of a solar photovoltaic (PV) system is determined.

$$P_{PV} = V_{PV} \times i_{PV}$$

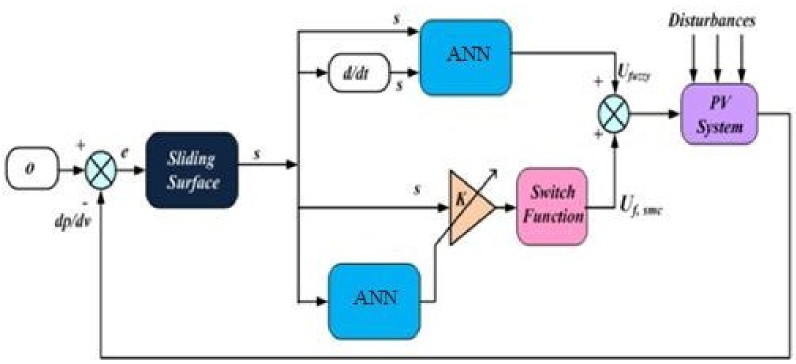


Figure 5 Proposed ANN control system.

VPP and IPP denote the voltage and current generated by a photovoltaic (PV) array. In order to optimize the output power and regulate the duty-cycle (D) of the boost converter, the High-Frequency Switching Modulation Controller (HFSMC) is suggested as the Maximum Power Point Tracking (MPPT) method.

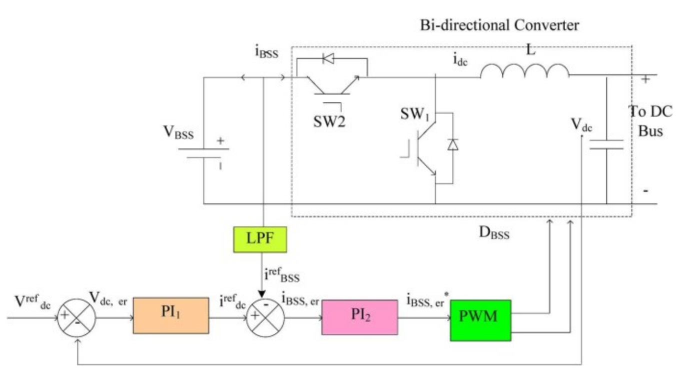


Figure 6. BSS controller with Buck-Boost.

b) Proposed hybridised control

The main objective of this technology is to optimize the output of a photovoltaic panel by implementing Maximum Power Point Tracking. The control system proposed is depicted in Figure 5, where Fuzzy and sliding-mode control are combined.

$$U = U_{Fuzzy} + U_{flsmc}$$
$$U = U_{fuzzy} + K.Satu(s(x))$$

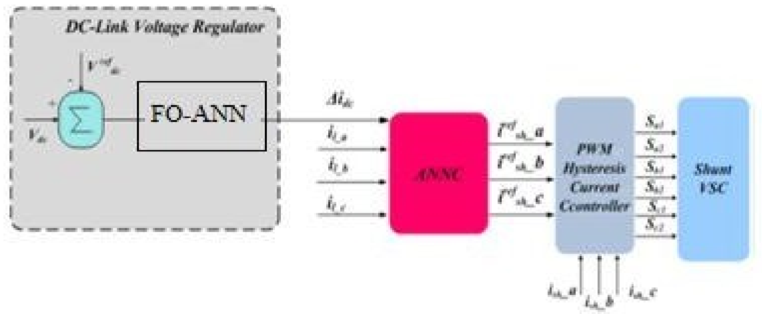


Figure 7 Shunt VSC Controller.

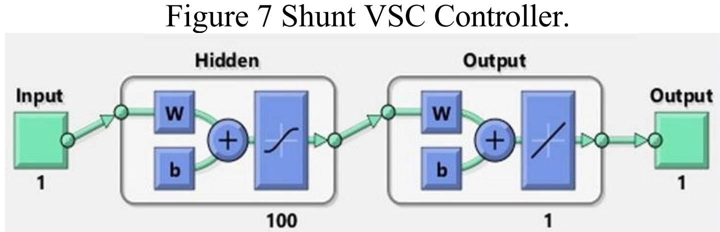
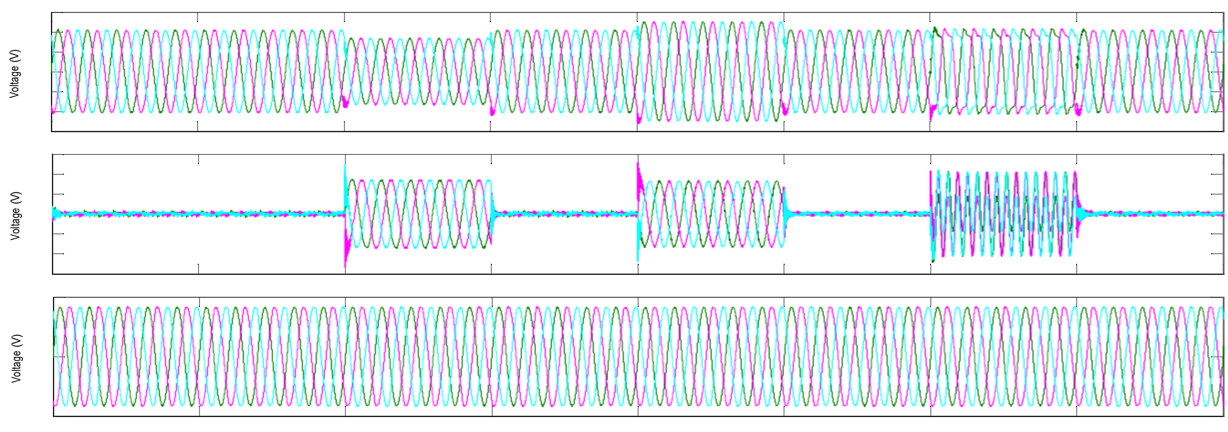
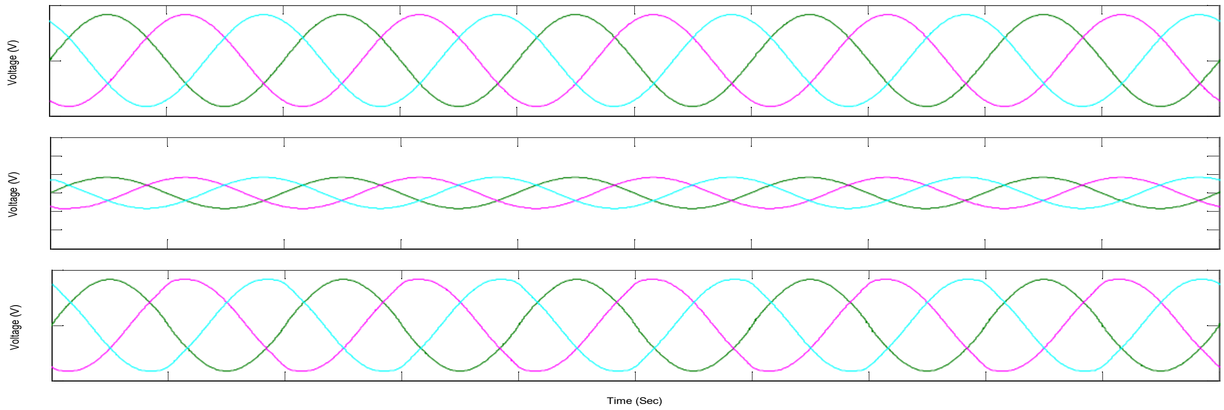


Figure 8 Switched-Shunt Voltage-Stabilized-Current Controller.

III. Simulation Result Analysis



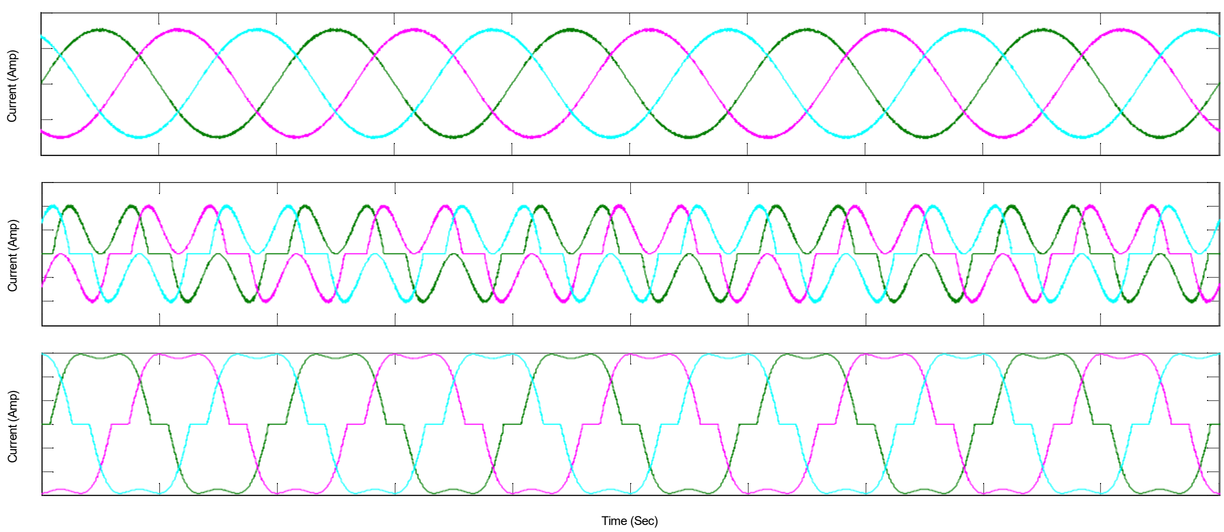
(a) Vs, Vse and Vl



(b) Vs, Vse and Vl

Figure 9 Case1 (a) and (b)

Figure 9(a) illustrates the planned UPVBSS, including the loads and grid. Figure 9(b) shows a solar PV model with fluctuating irradiance. Figure 9(c) offers the suggested ANNC technique for the SHAPF and SAPF. The system and UPQC parameters are displayed in Table 4. In order to showcase the exceptional efficiency of the designed Artificial Neural Network Controller (ANNC) on the developed Uninterruptible Power and Voltage Balancing System (UPVBSS), five different scenarios were examined.



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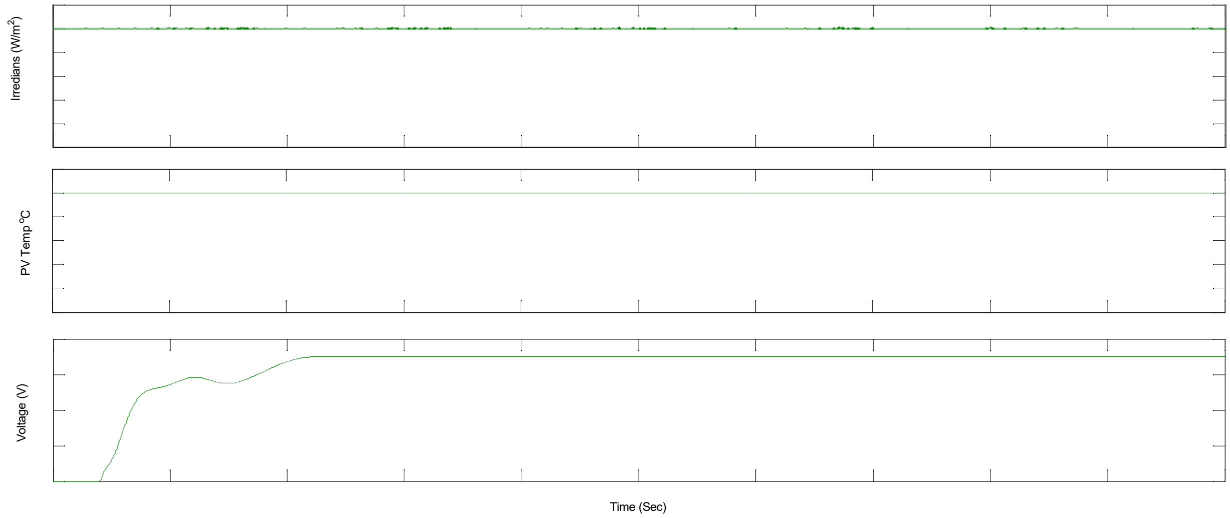
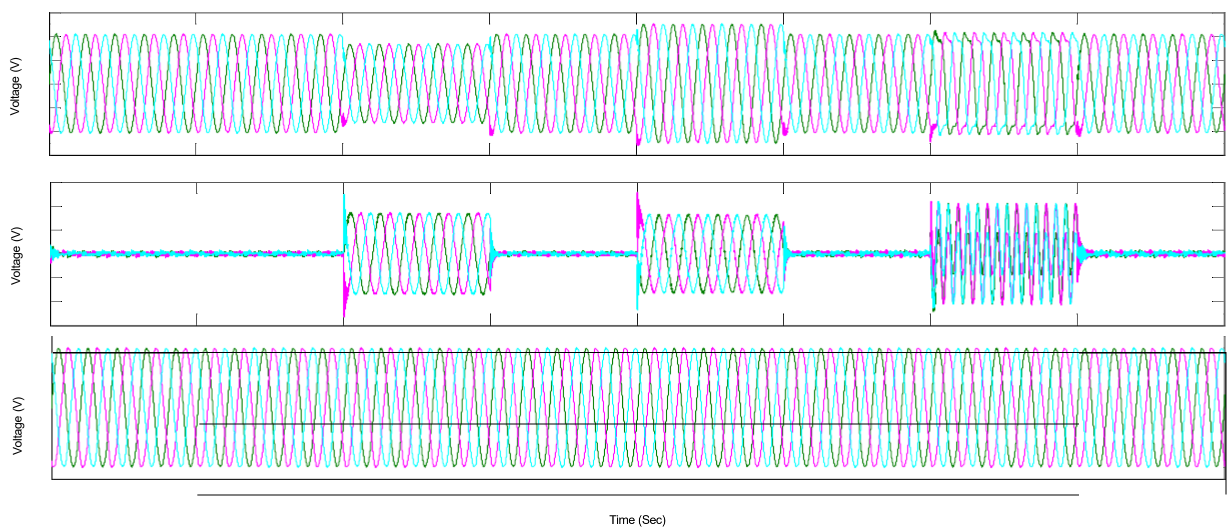
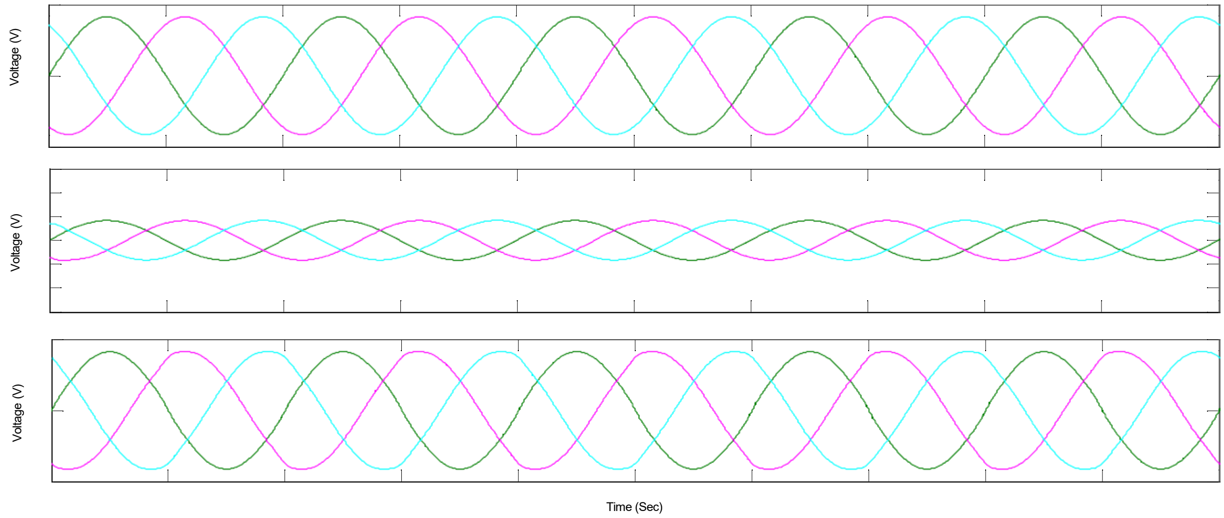


(d) PV_irr, PV_temp and Vdc
Figure 9 Case1 (c) and (d)

In scenario 1, the voltage source (VS) is considered to be in equilibrium. To evaluate the performance of the SAPF, a 30% decrease and increase in voltage, known as sag and swell, respectively, are introduced. These conditions are illustrated in Figure 9(a). In order to mitigate the effects of voltage drop, voltage increase, and disturbance, ANNC employs a coupling transformer to introduce a compensatory voltage, thus maintaining a stable voltage level at the load terminals. Figure 9(b) illustrates the voltage waveforms during steady-state conditions.



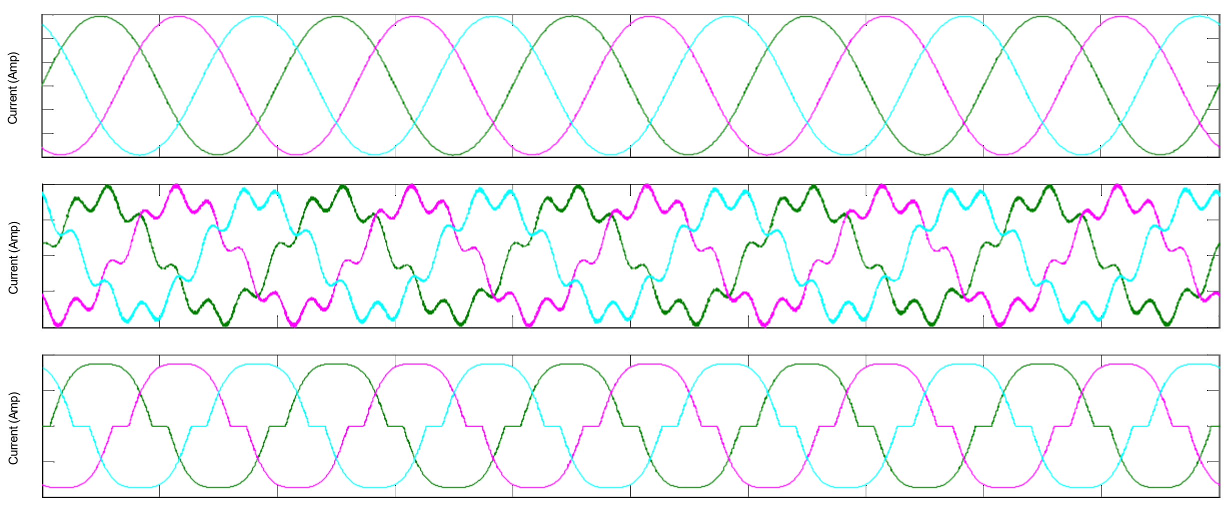
(a) Vs, Vse and Vl



(b) Vs, Vse and Vl

Figure 10 Case2 (a) and (b)

The system assumes a balanced voltage source and introduces a disturbance of 30% sag and swell to evaluate the performance of SAPF. Figure 10(a) demonstrates the effective compensation achieved by the suggested technique, whereas Figure 10(b) displays the steady-state voltage waveforms. In example 2, we keep all other factors constant except for the irradiance, which decreases from 1000 W/m2 to 800 W/m2, while maintaining the temperature at 250 C. Figure 10(c) illustrates the il waveform, which was found to be non-sinusoidal but nonetheless evenly distributed. The proposed method effectively reduces the Total Harmonic Distortion (THD) of the current from 8.88% to 3.55%, surpassing the performance of the Power Inverter Converter (PIC).



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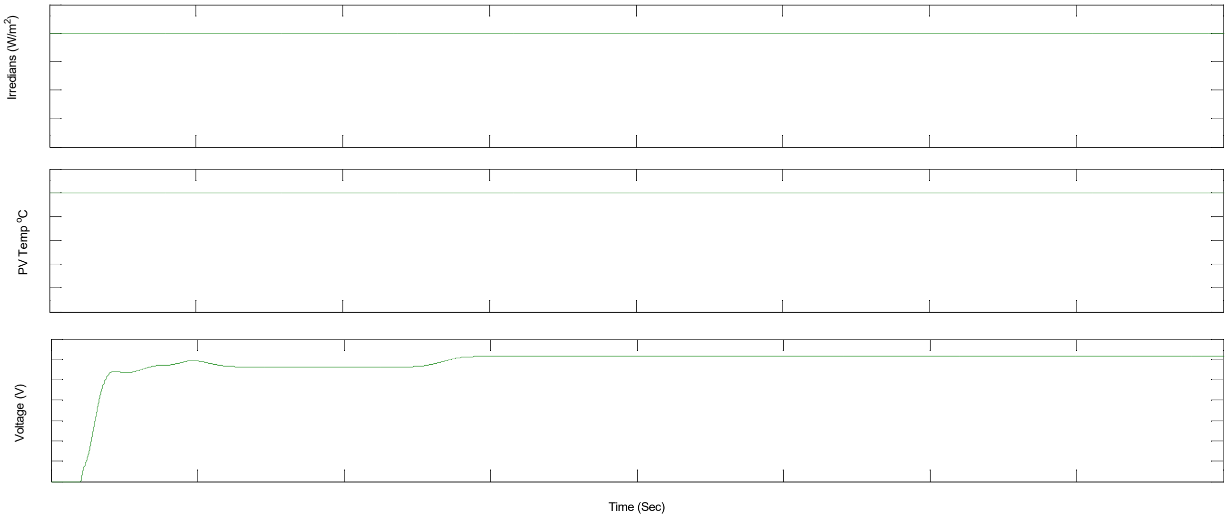
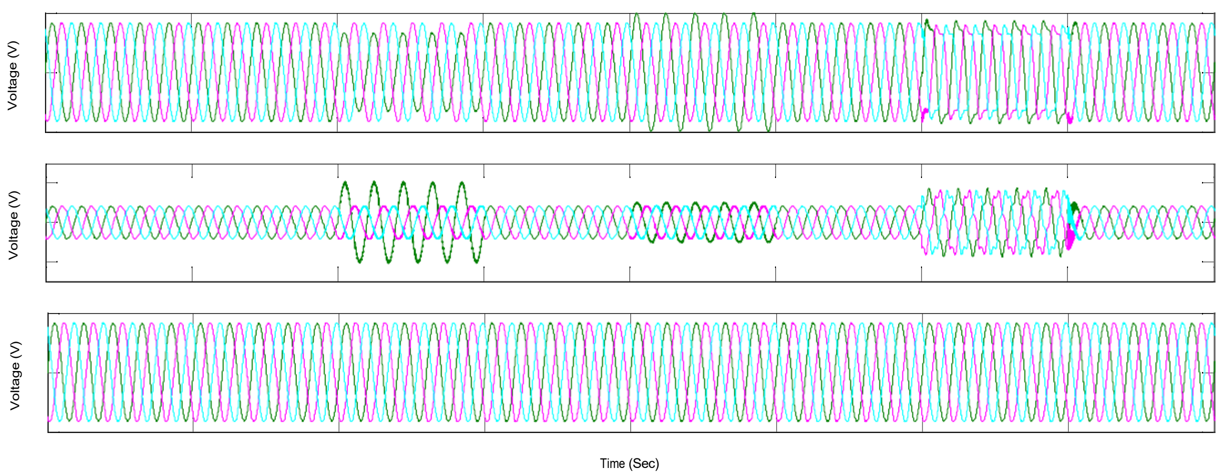


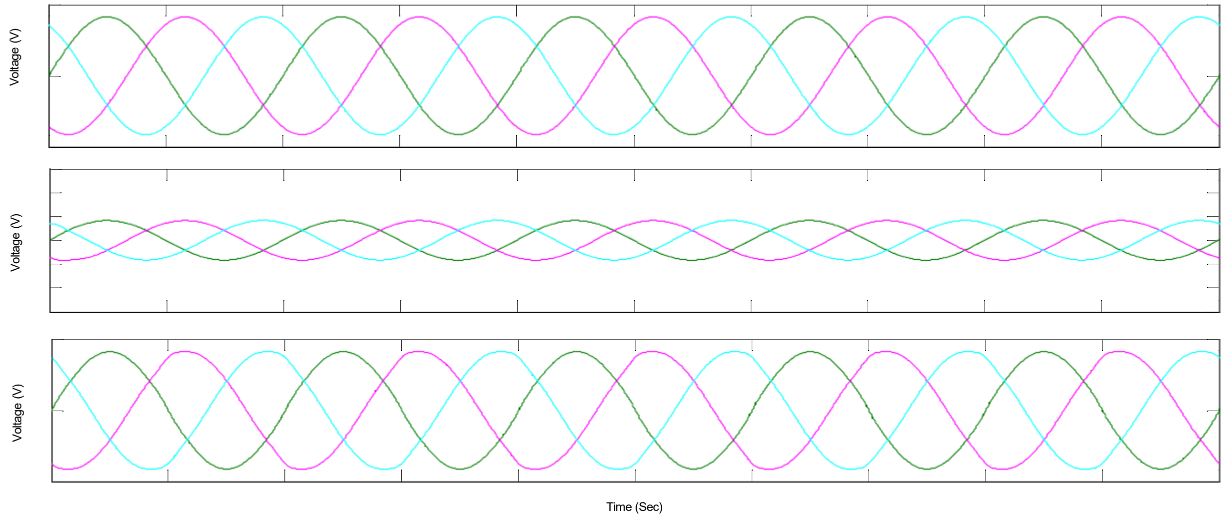
(d) PV_irr, PV_temp and Vdc

Figure 10 Case2 (c) and (d)

In Case 3, we evaluate the effectiveness of SAPF by subjecting a balanced voltage source to a 30% decrease, a 30% increase, and a 30% disturbance in source voltage. ANNC has the capability to identify voltage drop, voltage increase, and disruption produced by an unbalanced two-phase power source. It effectively resolves these issues by injecting the required compensating voltage. Figure 11(b) depicts the voltage waveforms during a stable condition. Figure 10(c) demonstrates that when an unbalanced load was assessed to analyze the efficiency of SHAF, the il waveform was determined to be sinusoidal but imbalanced in one phase. The proposed methodology rectifies existing waveform anomalies.



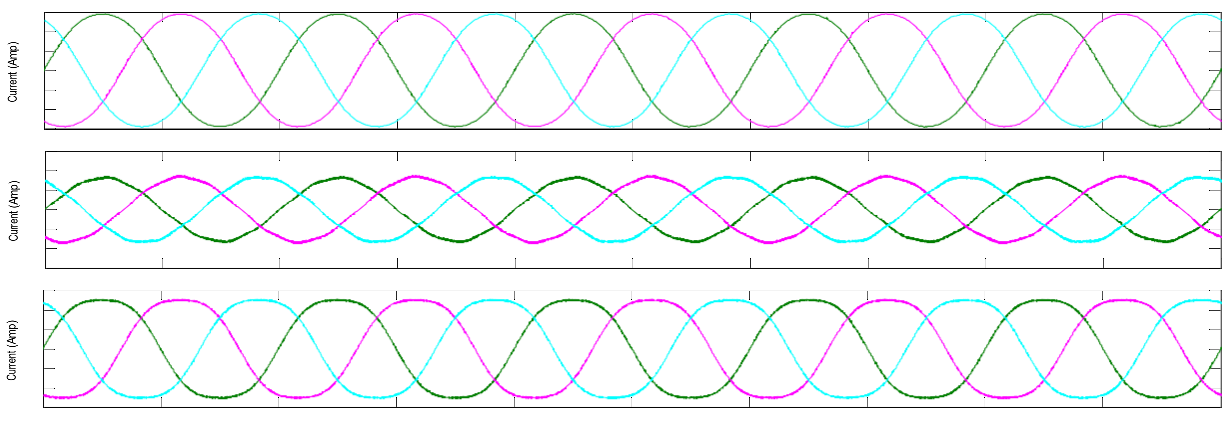
(a) Vs, Vse and Vl



(b) Vs, Vse and Vl

Figure 11 Case3 (a) and (b)

In the event of an unbalanced VS, as illustrated in Case 4 of Figure 12(a), the ANNC-controlled SAPF will identify the issue and rectify it by providing a voltage boost. Considering the balanced load, the il waveform depicted in Figure 12(b) was found to be non-sinusoidal but balanced. As can be observed in Figure 12(c) for 1000 W/m2 irradiation and 250c constant temperature, the suggested controller reduces the current THD from 5.33% to 3.24%.



(c) Is, Iinj and Il

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(a) Vs, Vse and Vl

(d) PV_irr, PV_temp and Vdc

Figure 11 Case3 (c) and (d)

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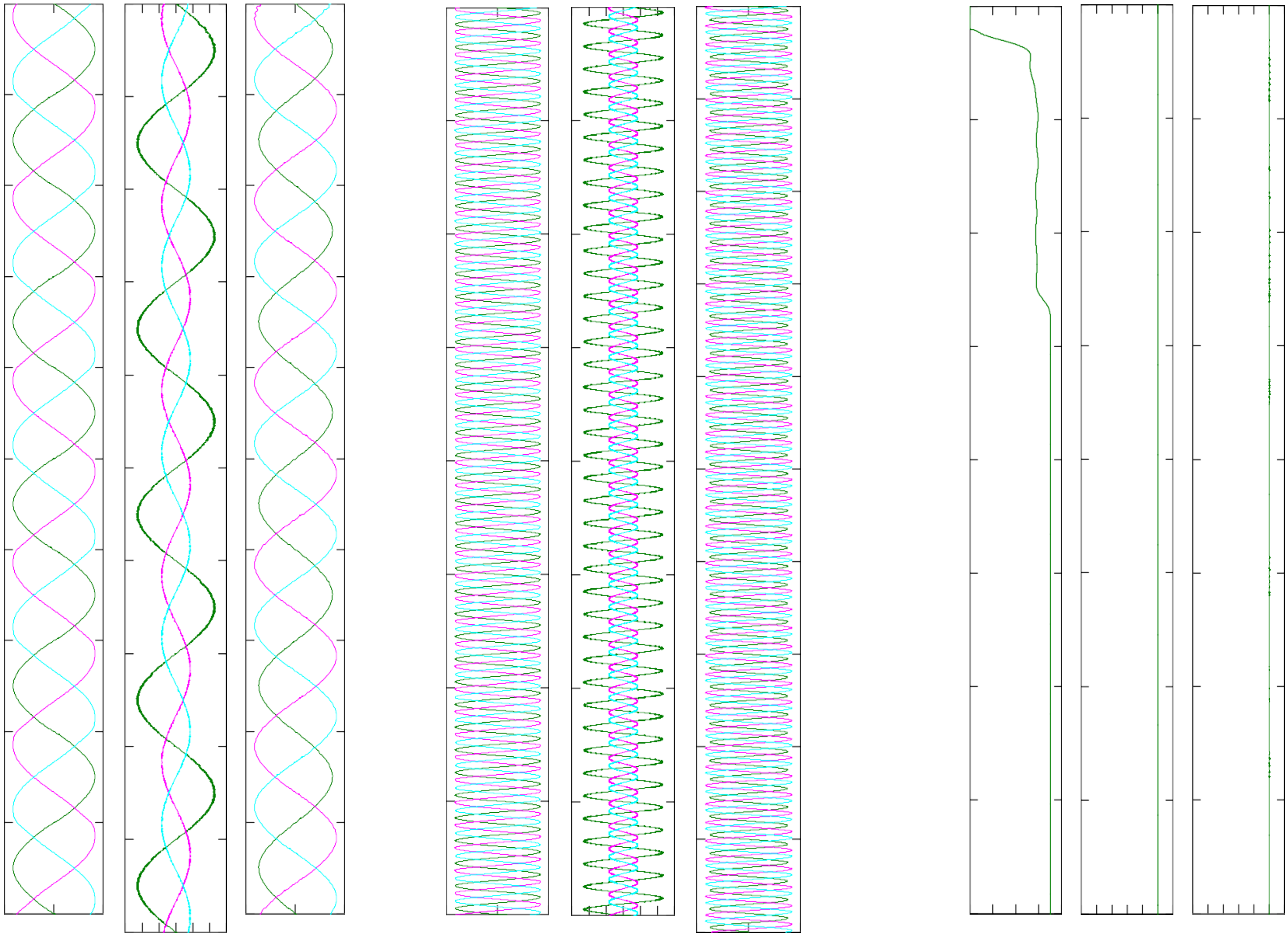
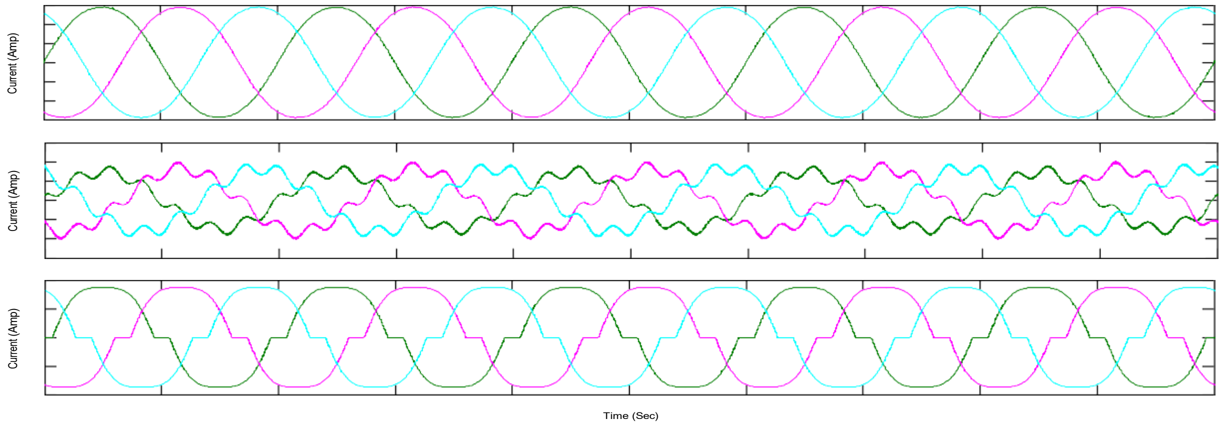


(b) Vs, Vse and Vl



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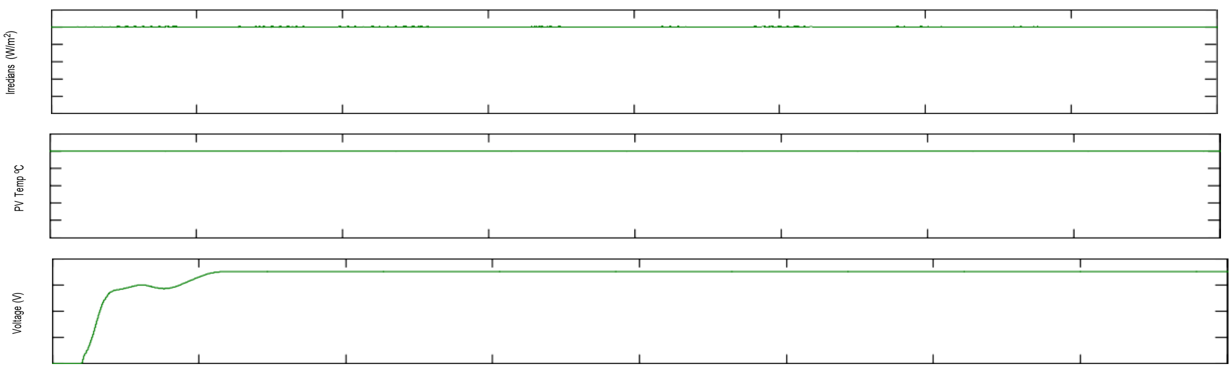
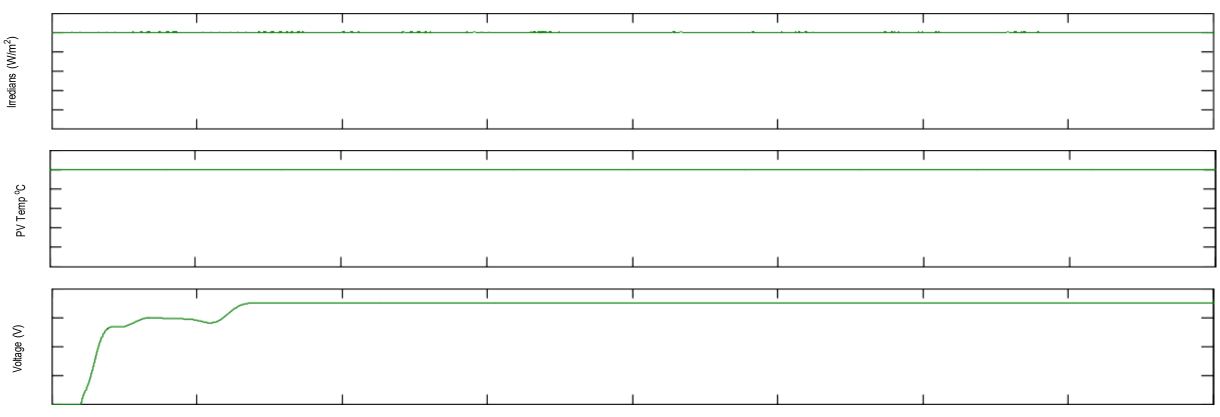


(d) PV_irr, PV_temp and Vdc



(e) Case 5 PV_irr, PV_temp and Vdc

Figure 12 Case4 (a), (b), (c), (d) and case 5 (e)

IV. Conclusion

In conclusion, the proposed power quality management strategy for PVBSS systems—integrating Fractional Order Control with Artificial Neural Networks—offers substantial improvements in both reliability and efficiency. By eliminating the need for traditional abc-dq0 transformations and utilizing UPQCs controlled by Levenberg-Marquardt-trained ANNCs, the system enables direct reference signal generation for shunt and series converters, resulting in a more streamlined and effective control scheme. The incorporation of a High-Frequency Switching Modulation Control (HFSMC)-based MPPT algorithm ensures optimal PV power extraction, while the Battery Storage System stabilizes the DC link voltage and enhances system responsiveness under dynamic conditions. Compared to conventional PIC-based methods, the proposed approach significantly reduces Total Harmonic Distortion (THD), improves power factor, and accelerates DC link voltage settling. Future work will focus on heuristic optimization techniques to fine-tune system parameters, further enhancing performance and making this methodology a compelling solution for power quality improvement in solar-powered microgrids.

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