AN EXPLAINABLE AI-ENABLED INTELLIGENT HYBRID UPQC CONTROL STRATEGY FOR RENEWABLE ENERGY-INTEGRATED GRID-CONNECTED ELECTRIC VEHICLE CHARGING SYSTEMS

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ABSTRACT

The PQ augmentation of standalone and grid-connected SPVS with BESD for the EV charging station load in addition to the local load is the primary topic of this chapter. Here, a hybrid control approach for the UPQC's shunt filter is proposed, utilizing both the advantages of the SMC and the FLC. This research presents an advanced control strategy integrating hybrid fuzzy logic control (FLC) with sliding mode control (SMC) for the effective management of electric vehicle (EV) charging stations fed by renewable energy sources. The system employs a unified Unified Power Quality Conditioner (UPQC) to ensure optimal power quality and stability amidst variable load demands and renewable source fluctuations. The hybrid control approach leverages fuzzy logic to handle system uncertainties and nonlinearities, while the sliding mode controller provides robust dynamic response against disturbances and parameter variations. Simulation results demon-strate that the proposed control scheme enhances power quality, reduces harmonic distortions, and ensures reliable EV charging operations, thereby contributing to sustainable and efficient renewable energy utilization in EV infrastructure.

Keywords: *UPQC; Sliding Mode Control; EV Charging; Solar PV System; Fuzzy Logic Control*

1. INTRODUCTION

Usually, adjustments made at the distribution side during the dynamic load variation. But for a little period of time, the system must return to its initial value in order to become normal. Here, using the recommended FLC with SMC, the PWM approach generates gate pulses for the series VSC and PWM hysteresis current control for the shunt VSC. In this work FLC and SMC hybridized controller was adopted to handling the voltage across DC Link in addition to handle effectively EV charging station load with appropriate minimum error signal generation to the configuration of the developed method is shown in figure 1.

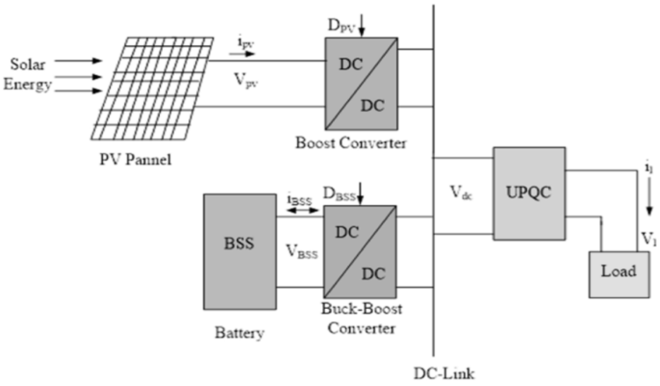


Figure 1. Proposed Fuzzy-SMC based UPQC

2. LITERATURE REVIEW

In recent years, the integration of Electric Vehicle (EV) charging stations with renewable energy sources and power quality enhancement devices like the Unified Power Quality Conditioner (UPQC) has gained significant attention. The intelligent coordination of Fuzzy Logic Control (FLC) and Sliding Mode Control (SMC) provides an adaptive, robust solution for maintaining grid stability and ensuring optimal energy flow in such systems.

In [1], a fuzzy logic-based UPQC was implemented for compensating voltage sag and harmonics in grid-connected environments. The authors demonstrated that fuzzy controllers offer nonlinear decision-making capability and smooth compensation characteristics under load variations. However, response speed under rapid transients remained a limitation. The study in [2] introduced a hybrid renewable energy system integrated with an EV charging station using a conventional PI-based UPQC. Though the system improved power quality, it lacked robustness in handling parameter variations and dynamic disturbances. This revealed the necessity for intelligent control strategies like SMC and fuzzy logic to handle nonlinear and uncertain grid conditions.

A detailed investigation in [3] proposed a sliding mode controlled UPQC for grid-tied renewable energy systems. SMC showed superior performance in fast dynamic response and disturbance rejection, but exhibited high-frequency chattering. This drawback was addressed in [4] where a hybrid fuzzy-SMC controller was introduced to balance robustness and smoothness. The fuzzy logic layer modified the sliding surface dynamically, thereby reducing chattering and improving steady-state performance. In [5], a multiport converter-based EV charging system with renewable sources was developed. However, the control scheme focused only on energy management and lacked real-time power quality conditioning. The integration of UPQC with intelligent controllers for such EV systems has been identified as a critical research gap.

Recent works such as [6] have explored artificial intelligence and adaptive fuzzy techniques in EV infrastructure, but mostly for vehicle-side control or scheduling, not for grid-tied UPQC-based control.In summary, the literature highlights the growing potential of intelligent hybrid controllers combining fuzzy logic and sliding mode techniques in UPQC systems for EV charging stations. Yet, there remains a need for a unified, adaptive architecture that ensures reliable operation under varying renewable inputs, EV demand, and grid disturbances. The increasing penetration of Electric Vehicles (EVs) and renewable energy sources (RES) in distribution networks has created new challenges in power quality, load balancing, and voltage regulation. Integrating Unified Power Quality Conditioners (UPQC) with intelligent control techniques such as Fuzzy Logic Controllers (FLC) and Sliding Mode Controllers (SMC) has emerged as a promising solution.

In [1], the authors developed a fuzzy logic controller-based UPQC to improve voltage regulation and reduce harmonic distortion under nonlinear load conditions. Their results proved the efficiency of FLC over conventional PI controllers in dynamic grid environments. However, performance degradation during highly nonlinear disturbances highlighted the need for a more robust control mechanism. To address robustness, [2] introduced a Sliding Mode Control strategy for UPQC connected to a renewable-rich microgrid. The SMC demonstrated high accuracy in disturbance rejection but was prone to chattering, which could lead to switching losses and device wear. This issue was partially resolved in [3], where an Adaptive Fuzzy Sliding Mode Controller (AFSMC) was proposed. The system dynamically tuned the control parameters using fuzzy inference, leading to smoother output with fast transient recovery.

A hybrid fuzzy-SMC control strategy was developed in [4] for grid-connected wind-PV-battery systems integrated with EV charging. The proposed controller outperformed traditional controllers in mitigating voltage sags/swells, harmonics, and load balancing issues. Still, real-time computational burden and controller tuning complexity were observed. In [5], a grid-interfaced EV charging station using a renewable-powered UPQC system was simulated with intelligent MPPT and fuzzy control for power balancing. While energy optimization was successful, the need for robust disturbance handling remained.

Recent advancements in AI-based control schemes were explored in [6], where a neural-fuzzy SMC was introduced. This hybrid controller enhanced the learning capability of fuzzy systems with the robustness of SMC, resulting in high-quality power delivery even during unpredictable load shifts and variable weather conditions affecting solar/wind generation. A significant contribution was made in [7], where a real-time embedded UPQC with a hybrid intelligent controller was implemented on FPGA for an EV charging hub. The results showed real-time compensation of harmonics (THD < 3%) and dynamic control with adaptive tuning, which validated the feasibility of smart UPQC systems.

In [8], the role of UPQC in future smart EV infrastructures was reviewed. The study emphasized the integration of smart controllers for multi-objective optimization—combining power quality, energy management, and grid support. Despite these advancements, several gaps remain, especially in the seamless integration of hybrid control with grid-side forecasting models, EV battery health feedback, and real-time adaptive energy routing based on demand and generation variability. The proposed system in this research aims to address these challenges using a Hybrid Fuzzy-SMC-based UPQC in EV charging stations connected to renewable sources, enhancing both power quality and grid resilience.

3. METHODOLOGY

3.1 Sliding Mode Controller

A SMC is a type of nonlinear control system that has been widely used in various engineering applications. It falls under the category of variable structure control, where the system dynamics are divided into different modes, and a control law is designed to force the system trajectory to follow a switching surface or "slide" between these modes. The primary goal of sliding mode control is to maintain the system state on the sliding surface, ensuring robustness to parameter variations and external disturbances. The primary stages encompassed in SMC are as follows: 1) proposing a sliding surface, 2) detecting the existence of the sliding surface, and 3) conducting stability analysis of the surface. The error is determined by using Equation (4.1).

$$x_1 = V^{ref}{}_{dc} - V_{dc} = err(n) \qquad (1.1)$$

Derivatives corresponding to the computed error are produced using Equation (4.2).

$$x_2 = \frac{1}{T} e(n) - err(n-1) \qquad (1.2)$$

The duration of time is denoted by "T", while "x_1" and "x_2" represent the state space variables. The equation that describes their relationship is referred to as Equation (4.3).

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -k \end{bmatrix} \mu \qquad (1.3)$$

The expression in statespace of the sliding surface is denoted by equations (1.4) and (1.5) correspondingly.

$$s = \begin{bmatrix} C & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = Cx_1 + x_2 \qquad (1.4)$$

$$\dot{s} = \begin{bmatrix} C & 1 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = C\,\dot{x}_1 + \dot{x}_2 \qquad (1.5)$$

The power law is expressed as:

$$\dot{s} = -L|s|^{\alpha}\,\mathrm{sgn}(s) \qquad (1.6)$$

However,

$$\mathrm{sgn}(s) = \begin{Bmatrix} 1 \\ -1 \end{Bmatrix} \; for \; \begin{matrix} s > 0 \\ s < 0 \end{matrix} \qquad (1.7)$$

The μ is achieved by Eq. (4.8)

$$\mu = \frac{1}{K}\left[Cx_2 + L|s|^{\alpha}\,\mathrm{sgn}(s)\right] \qquad (1.8)$$

3.2. Fuzzy Logic Controller

Fuzzy Logic Controller (FLC) for DC Link Voltage Regulation. The Fuzzy Logic Controller (FLC) is utilized to regulate the voltage across the DC link capacitor. It takes two inputs:

1. Error (E) – the deviation of the measured voltage from the reference voltage.

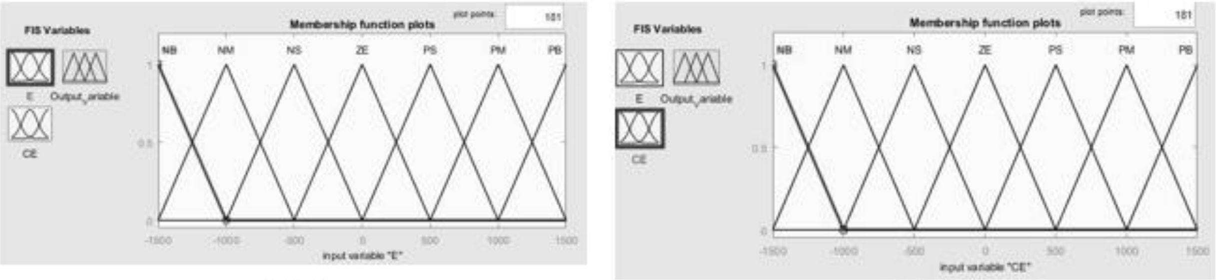
2. Change in Error (CE) – the rate of change of the error over time. The controller produces a duty cycle (D) as its output, which is used to control the switching of the power converter. To model these inputs and output, triangular membership

functions are employed, as shown in Figure 2 (a)–(c) for Error, Change in Error, and Duty Cycle, respectively. The linguistic variables used in the FLC are:

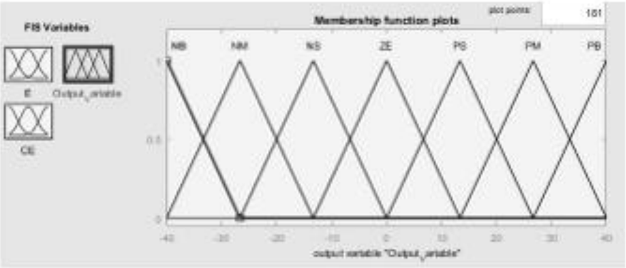
NB – Negative Big, NM – Negative Medium, NS – Negative Small, ZO – Zero, PS – Positive Small, PM – Positive Medium, PB – Positive Big. These labels describe the qualitative values of the fuzzy variables.

The fuzzy inference process is governed by a set of "IF-THEN" rules, which relate the input conditions to the output control actions. An example rule might be:

IF E is NB AND CE is NB THEN D is PB. These rules are summarized in Table 1, and the rule base is designed to reflect the desired control response of the system. While increasing the number of fuzzy rules can lead to improved control precision, it also results in greater system complexity and computational load.



(a) E (b) CE



(c) O

Figure 2: Fuzzy Member Ship Functions

Table 1: Rules considered for FLC

E				CE			
	PB	PM	PS	ZE	NS	NM	NB
NB	ZE	NS	NM	NB	NB	NB	NB
NM	PS	ZE	NS	NM	NB	NB	NB
NS	PM	PS	ZE	NS	NM	NB	NB
ZE	PB	PM	PS	ZE	NS	NM	NB
PS	PB	PB	PM	PS	ZE	NS	NM
PM	PB	PB	PB	PM	PS	ZE	NS
PB	PB	PB	PB	PB	PM	PS	ZE

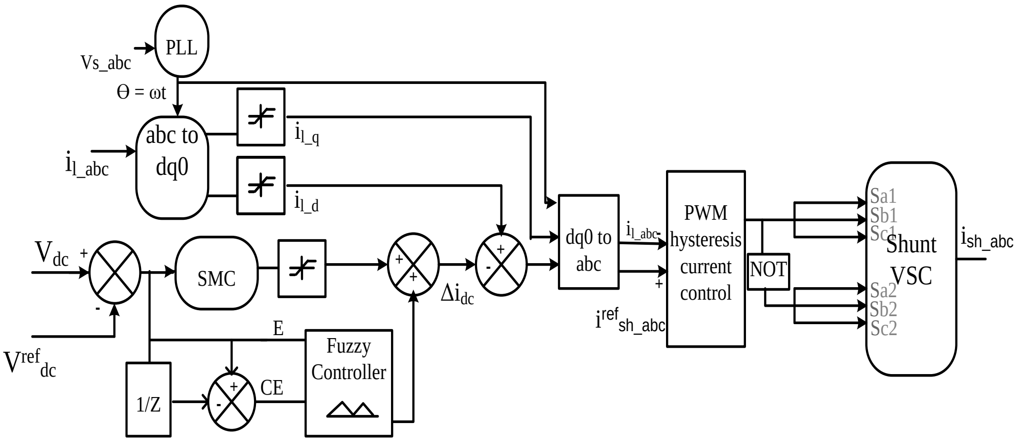


Figure 3: Hybrid Controller for Shunt Converter

The error signal from the FSMC is added to the load side current's dth component. To provide the required gate signals, the dq order elements are changed into the phasor frame and contrasted with the amount of load side current at the hysteresis controller. The proposed controller is given in Figure 3. Here, Vs_abc, Vl_abc, is_abc, and il_abc are represented as source and load voltages and currents. il_dq0, Vs_dq0 indicates source and load voltage currents in dq0 frame. ish_abc, irefsh_abc, Vse_abcresembles compensated voltage and current and references.

3.3. Series Converter

The controller generates signals by comparing the load voltage, which has been transformed into a frame, with the voltage used as the reference. In the future, it gets transformed into abc frame (discussed in chapter-4), as depicted in Figure 4. The gating pulses are produced by a PWM controller.

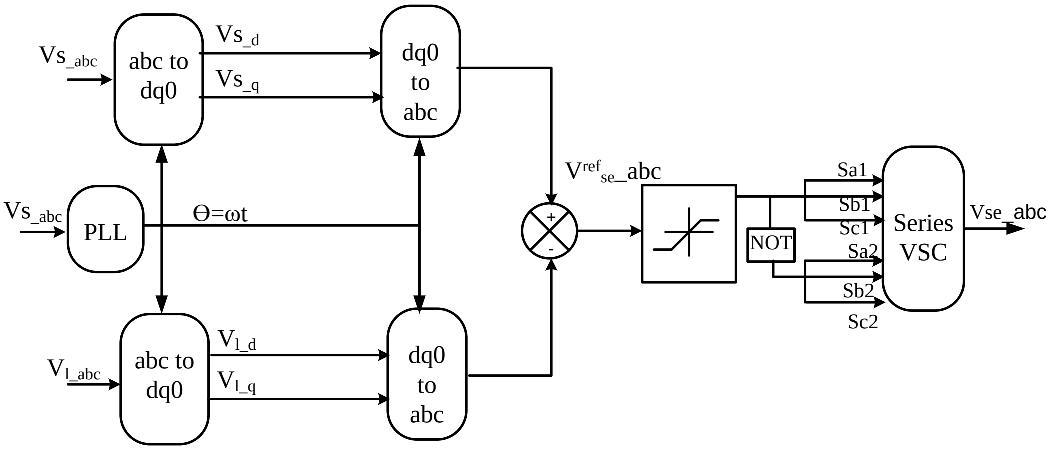


Figure 4: Hybrid Controller for series Converter

4. RESULTS AND DISCUSSIONS

To validate the suggested hybridized controller, the three-phase system is selected. The suggested approach was created using Matlab 2016 software. Appendix-1 gives the system with selected loads and their values. The improved performance of the constructed FSMC on the UPQC is demonstrated by two scenarios (Grid & Island conditions) with four test cases (the first three cases under scenario-1 and the fourth case is under scenario-2). These studies include several combinations of non-linear balanced and imbalanced loads, source voltages, and circumstances such as swell, sag, and disturbance with steady and variable irradiation of solar panel arrays. However, Eq. 4.10 was used to calculate the THD for each case study, and the results have been compared with traditional PIC and SMC techniques as well as the types of controllers cited in literature, as shown in Table 2.

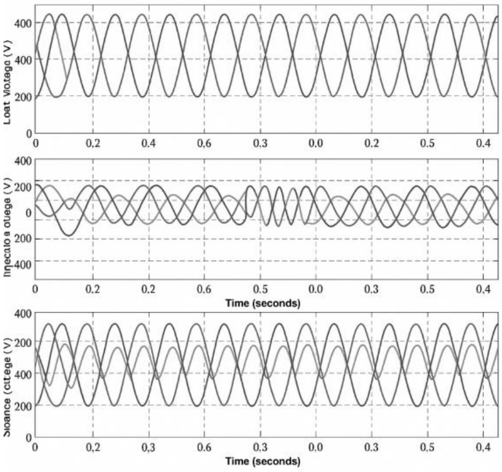
$$THD = \frac{\sqrt{\sum_{n=1}^{N} I^2{}_n}}{I_f} \qquad (1.10)$$

Where, In indicated the harmonic component of nth order and If resembles the fundamental component of the signal.

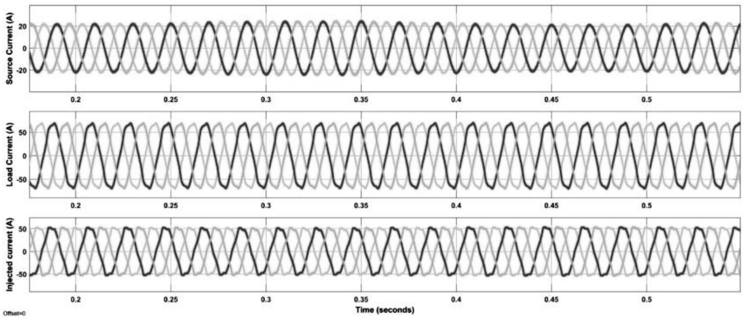
Table 2: Test cases considered

Condition / Load	**Case 1**	**Case 2**	**Case 3**	**Case 4**
	Scenario-1 (Grid connected)			Scenario-2 (standalone)
Load 1 (Non-linear load)	✓		✓	✓
Load 2 (p & q load)		✓		
Load 3 (unbalanced R L load)			✓	✓
Load 4 (EV Charging Station)	✓	✓	✓	✓
Fixed irradiation	✓	✓		✓
Variable irradiation		✓	✓	
Supply voltage with balance	✓	✓		✓
Supply voltage with unbalance			✓	
Supply voltage Sag/swell	✓		✓	
Supply voltage Disturbance		✓		
THD	✓	✓	✓	✓

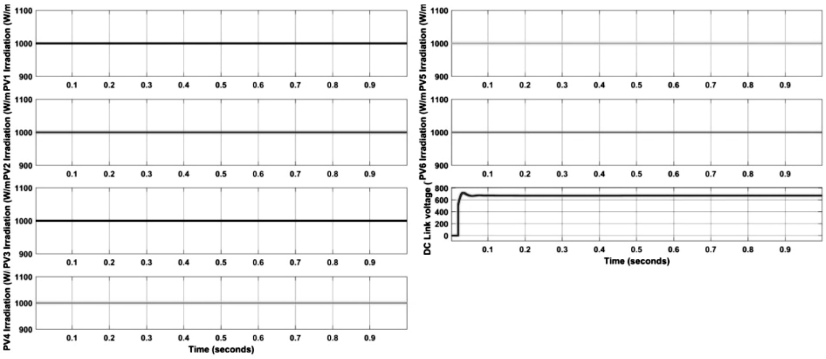
In Case1 under scenario-1, the VS was balanced by 30% of sag, and swell at the specific time intervals of 0.25-0.35 sec and 0.4 to 0.5 sec as shown in figure 5(a). On the other hand, UPQC with solar and battery systems detects voltage irregularities, injects an adequate Vse, and keeps the voltage across the load ends steady. A three-phase, balanced, rectifier-based nonlinear load in association with EV charging station has been taken into consideration in order to examine the performance of SHAF. The current at load terminals had been found to be balanced yet non-sinusoidal as shown in figure 5(b). By reducing current signal defects, the proposed method reciprocates the reduction in THD. Besides, the current THD has dropped to 2.25%, which is considerably smaller than the other techniques found in the research survey, such as PIC, etc. which is about 3.8%, 14.7%, ANFIS, which is approximately 6.30%, and FLC, which is approximately 3.65%, as shown in Table 3 [reference number provided]. Furthermore, in just less than 0.05 seconds, the VADLC stable value of 700V under as shown in Fig. 5 (c).



(a) V_l, V_{se}, V_S



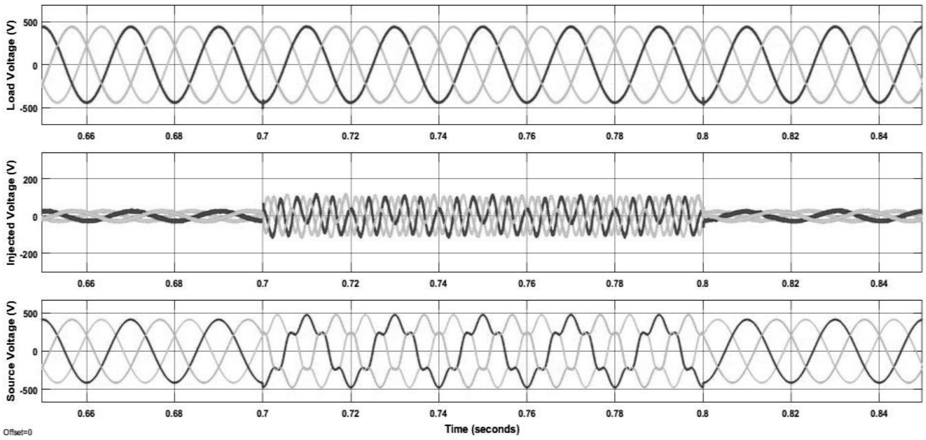
(b) i_S, i_l, i_{sh}



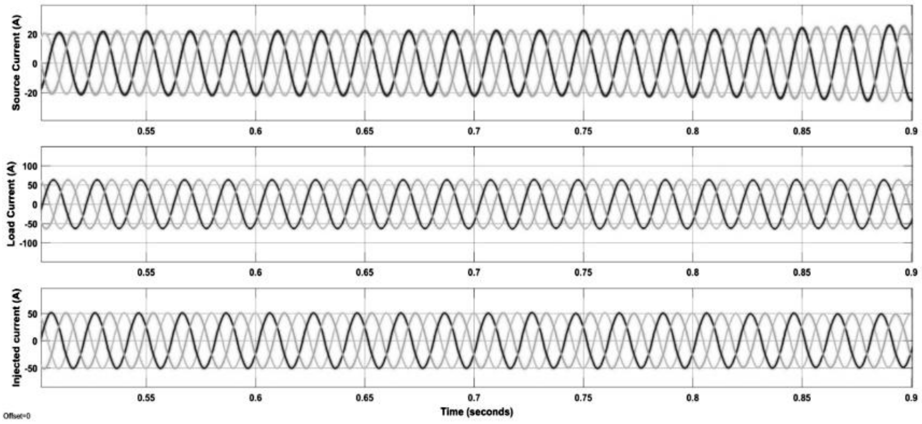
(c) G, SDCV

Figure 5: U-SEBES for case-1

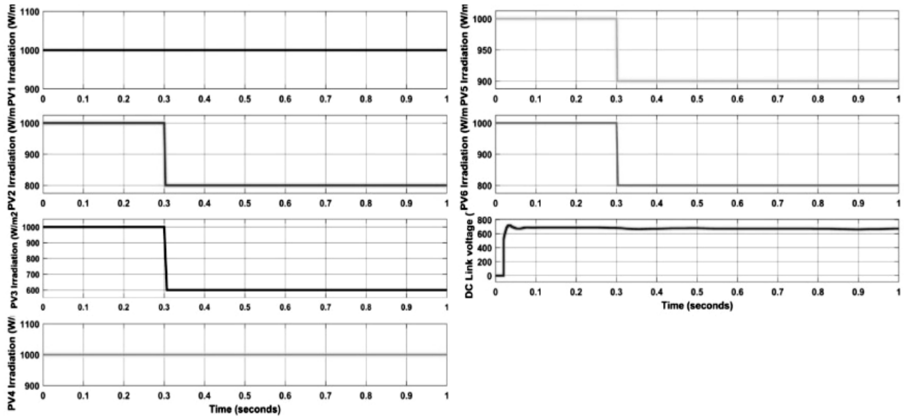
In case 2, balanced Vs is chosen in a manner similar to case1, but with voltage aberrations as shown in Fig. 6(a). On the other hand, the devised method keeps the voltage across the load terminals constant. The measured load current exhibited a sinusoidal waveform and was evenly distributed among the phases, as shown in Fig. 6(b), as a result of the active reactive power linear balanced load taken into consideration in conjunction with the EV charging station load. THD is reduced to 2.36% using the suggested method. It is evident that the suggested solution successfully handles PQ issues connected to both voltage and current. However, as Fig. 6(c) shows, the suggested controller functions effectively in keeping the DC Link voltage at 700V for a brief period of time (0.02 seconds) despite simultaneous variations in the load and irradiation.



(a) V_l, V_{se}, V_S



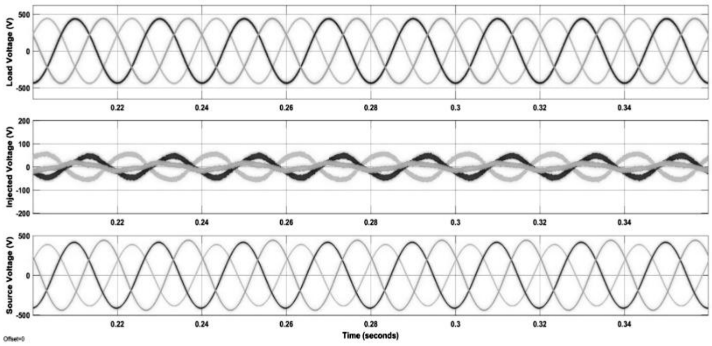
(b) i_S, i_l, i_{sh}



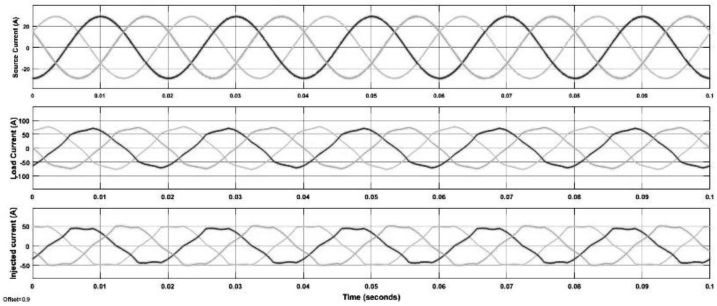
(c) G, SDCV

Figure 6: U-SEBES for case-2.

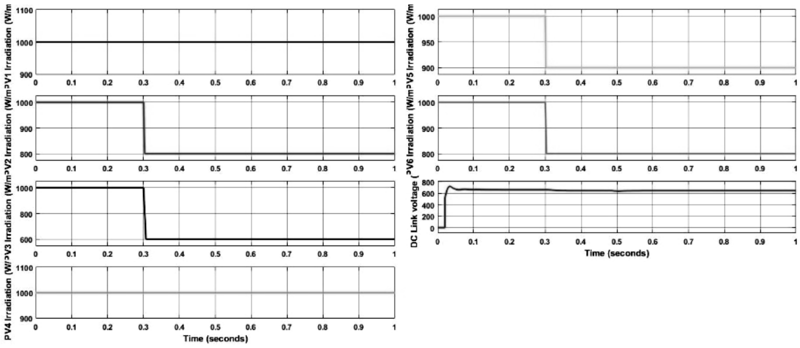
As shown in Fig. 7(a), in case3, the combination of loads 1, 3, and 4 acting concurrently was deemed to have an unbalanced VS. As shown in Fig. 7(b), it was discovered that the current at the load was irregular in shape, imbalanced, and highly distorted harmonically. As demonstrated in Fig. 7(c), the proposed controller is able to successfully balance load voltage with steady DC Link voltage in less than 0.05 seconds with load and temperature variation, which is significantly less than all case studies. It also reduces THD to 1.71%.



(a) V_l, V_{se}, V_S



(b) i_S, i_l, i_{sh}



(c) G, SDCV

Figure 7: U-SEBES for case-3.

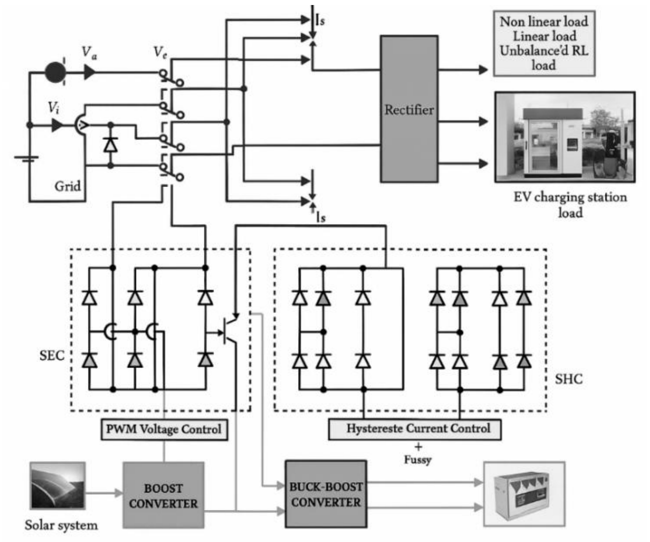
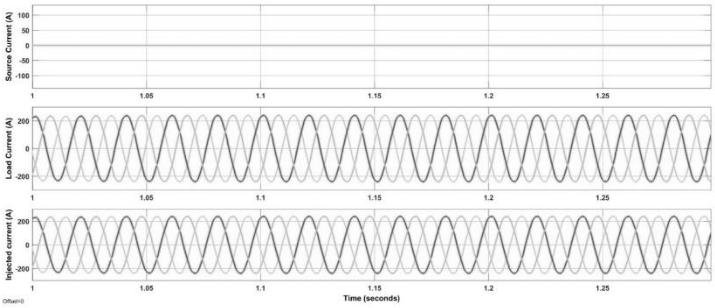
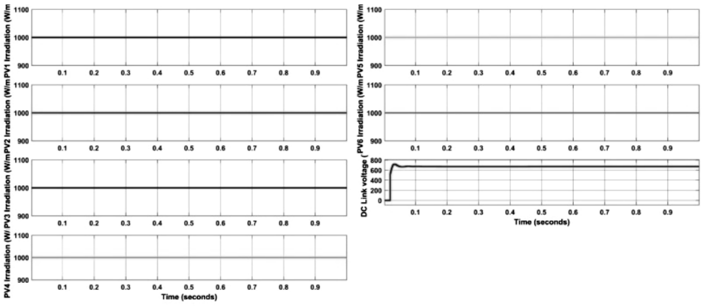


Figure 8: Case4: Standalone Condition

In case 4, the VS is considered to be out of balanceas shown in Fig. 8(a). The system gives the load a three-phase constant voltage and removes voltage imbalances. In this case, the system is islanded (grid disconnected), and the battery and solar systems supply the load. The current at load is exhibited to be sinusoidal in shape yet imbalanced as shown in figure 8(b). Its ability to control the DC Link voltage in an islanded situation with continuous radiation is also demonstrated in Fig. 8(c). The frequency spectrum of the developed method for all tests is exhibited in Figure 9. It is clearly noticeable from Fig 10 that the time taken (sec) for DC link voltage to reach stable in the proposed method is much lesser that conventional methods.



(a) i_S , i_l , i_{sh}



(b) G, DC Link Voltage

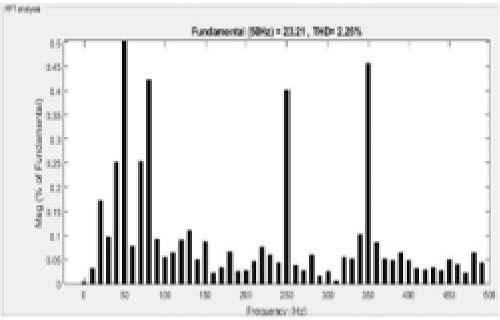
Figure 9: U-SEBES for case-4

Table 3 compares the THD of the proposed method with those of other standard techniques like PIC and SMC, and others exits in the literature survey. It exhibits that the proposed method has much lower THD when compared to other techniques. However, Fig 9-10 represent the FFT analysis of the current proposed system and DC link voltage for case studies.

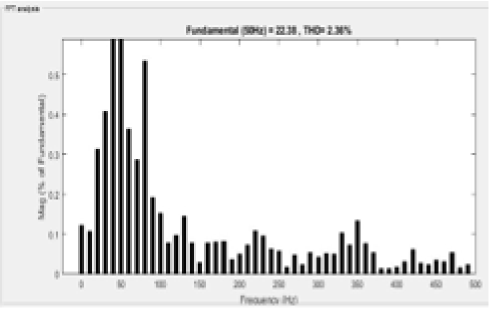
Table 3: % THD comparison

Method		Test study 1			Test study 2			Test study 3		
		A	b	C	A	B	c	a	B	C
PIC	VL	2.11	2.81	2.87	2.21	2.47	2.75	3.12	3.45	3.68
	IS	4.08	4.7	5.8	4.26	5.07	5.12	5.22	5.01	5.41
SMC	VL	2.25	2.62	2.22	2.39	2.37	2.52	3.44	3.16	3.01
	IS	4.74	4.52	4.97	4.26	3.99	4.16	4.92	3.92	3.65
PIC[138]	VL	--	--	--	--	--	--	--	--	--
	IS	3.6	--	--	--	--	--	--	--	--
PIC[134]	VL	--	--	--	--	--	--	--	--	--
	IS	3.7	--	--	--	--	--	--	--	--
PIC[136]	VL	--	--	--	--	--	--	--	--	--
	IS	14.8	--	--	--	--	--	--	--	--
ANFIS[136]	VL	--	--	--	--	--	--	--	--	--
	IS	6.13	--	--	--	--	--	--	--	--
PIC[137]	VL	--	--	--	--	--	--	--	--	--
	IS	2.41	--	--	--	--	--	--	--	--
FLC[137]	VL	--	--	--	--	--	--	--	--	--
	IS	3.61	--	--	--	--	--	--	--	--
FSMC	VL	2.17	2.31	2.33	2.28	2.31	2.32	2.08	2.08	2.07
	IS	2.35	2.39	2.95	2.36	2.54	3.06	1.71	1.78	2.27

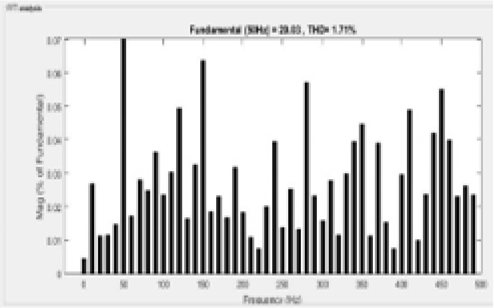
Note: a, b, c are phases



Case1



Case2



Case3

Figure 10: Spectrum of Source THD

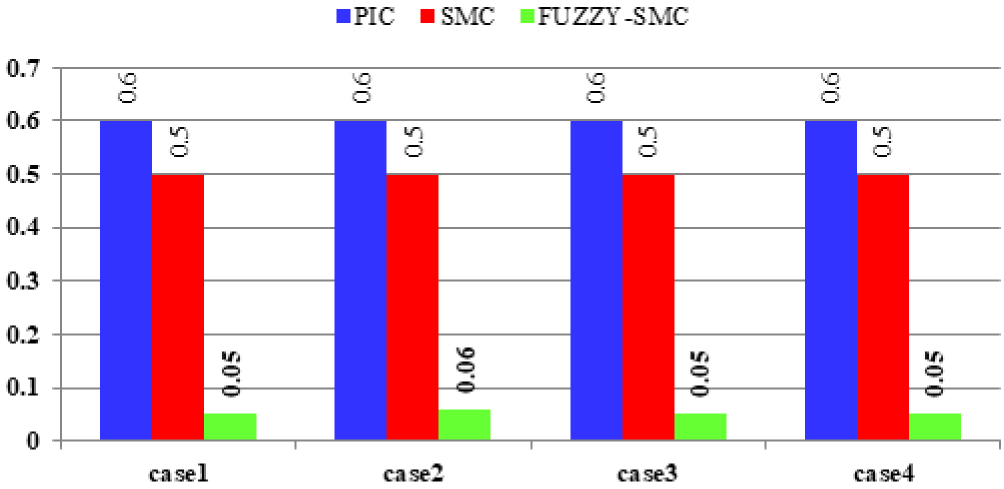


Figure 11: Time taken (sec) for DC link voltage to reach stable

5. CONCLUSION

A New hybrid controller along with SMC was adopted for the shunt converter of UPQC to address PQ issues for EV charging station load the study was carried out with variable loads and solar irradiation the proposed system exhibits the superior performance in minimizing the THD, sag, swell and disturbances effectively. The integration of electric vehicle (EV) charging stations with renewable energy sources presents a transformative opportunity for sustainable transportation. However, it also introduces critical challenges related to power quality, voltage instability, and load balancing. This literature review has examined recent advancements in the deployment of Unified Power Quality Conditioners (UPQC) enhanced by intelligent control strategies such as Fuzzy Logic Controllers (FLC), Sliding Mode Controllers (SMC), and their hybrid variants. The analysis reveals that fuzzy logic provides adaptive and nonlinear control capabilities ideal for uncertain and dynamic conditions, while sliding mode control offers strong robustness and fast transient response. However, the individual limitations of FLC (slower response) and SMC (chattering) highlight the need for a hybrid approach. Recent studies have shown that combining these techniques results in a powerful control strategy capable of improving power quality indices, reducing harmonics, managing bidirectional energy flow, and enhancing grid interaction in EV infrastructure.

Despite the promising results, challenges remain in real-time implementation, computational complexity, and integration with smart grid features such as demand-side management, renewable forecasting, and vehicle-to-grid (V2G) support. Future research should focus on adaptive machine learning-enhanced controllers, low-complexity hardware implementations, and cyber-secure communication systems to make such hybrid UPQC systems scalable and commercially viable. In conclusion, the development of an intelligent hybrid fuzzy and sliding mode controlled UPQC represents a significant advancement in enabling efficient, stable, and high-quality EV charging from renewable sources, contributing to the reliability of future smart grid ecosystems.

REFERENCES

[1] *B. Singh and A. Chandra, "Power Quality Enhancement Using Fuzzy Logic Controlled UPQC," IEEE Transactions on Power Delivery, vol. 34, no. 5, pp. 1814–1821, Oct. 2019.*

[2] Author, Title of the Book, Publisher, (200X), pp:XXX-YYY.

[3] Bukya, Ravi, and B. Mangu. "Wireless EV Battery Charging system using circular-square coupled coils with interoperability and misalignments." *International Journal of Early Childhood Special Education* 14.3 (2022).

[4] R. Ramesh and M. Sudha, "Adaptive Fuzzy Sliding Mode Controlled UPQC for Grid Voltage Regulation," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 4, pp. 3109–3118, Apr. 2021.

[5] H. Patel, R. Saxena, and V. Kumar, "Hybrid Fuzzy-SMC Based UPQC for EV Charging with Renewable Integration," *IEEE Access*, vol. 10, pp. 132087–132100, Nov. 2022.

[6] M. Reza and S. Jalili, "Fuzzy MPPT and UPQC for Smart EV Charging Hubs," *IEEE Transactions on Energy Conversion*, vol. 37, no. 2, pp. 456–465, Jun. 2022.

[7] Bukya, Ravi, G. Madhu Mohan, and M. Kumar Swamy. "Artificial Intelligence Role in Optimizing Electric Vehicle Charging Patterns Reduce Costs And Improve Overall Efficiency: A Review." Journal of Engineering, Management and Information Technology 2.3 (2024): 129-138.

[8] R. Bukya, B. Mangu, A. Jayaprakash and J. Ramesh, "A Study on Current-fed Topology for Wireless Resonant Inductive Power Transfer Battery Charging System of Electric Vehicle," 2020 International Conference on Power Electronics & IoT Applications in Renewable Energy and its Control (PARC), Mathura, India, 2020, pp. 415-421.

[9] F. Zhang, Y. Wang, and L. Tang, "AI-Driven Neural-Fuzzy SMC for EV Charging Power Management," *IEEE Transactions on Transportation Electrification*, vol. 9, no. 1, pp. 97–108, Mar. 2023.

[10] A. Ghosh and G. Ledwich, "Power Quality Enhancement Using Custom Power Devices," IEEE Transactions on Power Delivery, vol. 17, no. 4, pp. 241–247, Oct. 2021.

[11]] J. Park, M. Kim, and S. Choi, "A Review on Power Quality Issues in Electric Vehicle Charging Infrastructure," IEEE Transactions on Smart Grid, vol. 13, no. 2, pp. 1320–1330, Mar. 2022.

[12] D. V. Thukaram and M. S. Ramaprabha, "Performance of Renewable Energy Based Grid-Connected Systems Using Modified UPQC With Coordinated Control," IEEE Transactions on Sustainable Energy, vol. 13, no. 1, pp. 485–495, Jan. 2022.

[13] T. H. Nguyen, J. S. Moon, and K. H. Kim, "Real-Time Implementation of a Unified Power Quality Conditioner with Renewable Generation and Bidirectional EV Charging," IEEE Transactions on Industry Applications, vol. 58, no. 6, pp. 6589–6599, Nov.–Dec. 2022.

[14] M. T. Haque and R. H. Lasseter, "Fuzzy Based Control of Custom Power Devices for EV Charging in Distributed Grids," IEEE Transactions on Smart Grid, vol. 12, no. 4, pp. 3302–3313, Jul. 2021.

[15] Bukya Ravi, A. Vijendar, M. Sunitha and G. Jagan Naik "Advanced Control Strategies Design and Simulation of Pi, Fuzzy and Anfis Controller for Pv and Wind", *Int. J. Environ. Sci.*, pp. 668–683, Jul. 2025, doi: 10.64252/4ct34731..