Hybrid ANFIS-PI Control for Enhanced Power Quality in PV Grid Integration

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Abstract-- The unpredictable nature of photovoltaic (PV) energy introduces various power quality challenges when integrated into the grid, including voltage deviation, harmonics, and voltage fluctuations. With increasing penetration of renewable energy sources, maintaining high power quality at every stage of power conversion has become crucial. Unlike traditional grids, PV grid integration requires robust control mechanisms to ensure stable power delivery while adhering to power quality norms. However, the high switching frequency of inverters introduces harmonics, necessitating efficient control techniques for mitigation. This research addresses these challenges by implementing functional variations in power conversion stages and introducing hybrid control techniques. A novel hybrid approach utilizing Fuzzy-PI and Adaptive Neuro-Fuzzy Inference System (ANFIS)-PI controllers is proposed to enhance power quality, voltage stability, and harmonic reduction. The study focuses on optimizing the voltage source converter (VSC) through an intelligent dq controller-based grid synchronization technique to achieve lower total harmonic distortion (THD) at the point of common coupling (PCC). The system topology integrates a Perturb and Observation-based Maximum Power Point Tracking (MPPT) algorithm with a controlled VSC at the grid interface. Simulations were conducted using the MATLAB-Simulink platform to compare the performance of traditional PI controllers with hybrid Fuzzy-PI and ANFIS-PI controllers. Key performance metrics include output voltage, active and reactive power, and THD at the PCC. The results indicate that hybrid ANFIS-PI controllers outperform traditional methods, significantly improving THD and overall power quality in PV grid synchronization.

Keywords-- *PV Grid Integration, Power Quality Improvement, Total Harmonic Distortion (THD), Adaptive Neuro-Fuzzy Inference System (ANFIS-PI), Voltage Source Converter (VSC), MATLAB-Simulink Simulation.*

I. INTRODUCTION

Due to significant population growth, experts predict a 45% rise in electricity consumption by the end of 2035. A significant proportion of global electrical energy use (75%) is derived from non-renewable energy sources, such as fossil fuels, which substantially impact the environment. A reliance on fossil fuels for future electrical energy needs presents a sufficiency issue. Deforestation, pollution, and other environmentally damaging factors are obvious in this circumstance, along with greenhouse gas emissions.

The dimensions of photovoltaic systems vary based on the end user, ranging from tiny to extensive power distribution systems. Islanding and grid-connected modes are two methods for using photovoltaic energy. The first kind is the standalone system, whereby electricity generation is optimal during nighttime hours. Consequently, this system requires energy storage capacity. The second kind of electricity generation is grid-connected solar photovoltaic panels. The photovoltaic system produces alternating current in conjunction with the utility power system .

Despite the availability of several nonrenewable energy resources inside power systems, solar and wind energy remain the predominant renewable resources in contemporary distribution networks. The solar integration topology with the main grid generator includes the maximum power point tracking (MPPT) converter and the grid-side converter. The Voltage Source Converter (VSC) employed for grid synchronization must be regulated to ensure the stability of the power quality sent to the grid. A controller capable of effectively supplying energy in a steady state is employed, and the outcomes will be studied. The energy efficiency is contingent upon a larger power range. Therefore, even a minor enhancement in power quality must be utilized. The limitations of traditional controller architecture result in increased losses at the generating end and the creation of harmonics.

To address the identified deficiency, superior controllers capable of resolving dynamic synchronization issues is examined. The dimensions and expense of the circuit are augmented. The dynamic stability of the system is entirely contingent upon the controller employed in the grid-connected system. Decoupled dq control is typically employed to manage synchronization with the grid. PI/PID controllers are employed for the minimizing of steady-state error. Certain literature demonstrates that PI/PID controllers do not operate intelligently and have prolonged response times. The rapid reaction is crucial in solar power generating systems characterized by stochastic behavior.

II. OBJECTIVES OF THE RESEARCH:

A stable and rapid grid synchronization technique has been devised, focusing on optimal power supply at the Point of Common Coupling (PCC).

- To adopt a control strategy in the Grid Side Converter (GSC) of grid-connected photovoltaic production to provide enhanced power quality and regulated output with minimal distortion.

- To study and implement a Maximum Power Point Tracking (MPPT) method in a converter to harvest the maximum possible power from the photovoltaic (PV) system.
- To devise a control methodology for a Grid Side Converter (GSC) to ensure efficacy.
- Synchronize with the utility grid and manage the DC link voltage, as well as the active and reactive power flow across the grid, while minimizing THD values.
- The power delivery at each stage of the conversion must be steady.

III. LITERATURE REVIEW

Sheetal Singh; Sanju Saini; S. K. Gupta [1] This research illustrates the regulatory capabilities of a substantial photovoltaic farm functioning as a solar-PV inverter to alleviate chaotic electrical, electromechanical, and torsional oscillations, including subsynchronous resonance, in a turbogenerator-based power system. The oscillations encompass variations in machine speed, rotor angle, voltage fluctuations (resulting in voltage collapse), and torsional modes.

Manoja Kumar Behera; Lalit Chandra Saikia [2] Solar photovoltaics (PVs) are progressively infiltrating rural area electricity infrastructures. Nonetheless, the detrimental impact of pulse power demands and variable photovoltaic generation induces significant grid instability. Consequently, a proposal is put up for a hybrid energy storage system (HESS) that integrates a hydrogen/bromine redox flow battery (RFB) and supercapacitor (SC) for grid-connected photovoltaic (PV) systems to enhance energy and power support. The system incorporates an antiwindup mixed-order generalized integrator (AWMOGI), an enhanced sparrow search algorithm (ISSA) optimized tilt integral–derivative with filter (TIDF) controller, and a rapid adaptive dc-link power-based energy management control. AWMOGI captures essential elements of grid voltage and is resistant to noise and grid disturbances.

Md. Masudur Rahman; Shuvra Prokash Biswas [3] This paper proposes an innovative nonlinear control technique for a three-phase grid-connected inverter and a solar photovoltaic (PV) system integrated with a dc–dc converter. The suggested control methodology relies on a nonlinear adaptive integral backstepping technique.

Muhamad Najib Kamarudin; Tengku Juhana Tengku Hashim [4] As the need for alternative renewable resources increases to address environmental concerns associated with conventional production, it is crucial for the solar PV system to maintain its connection to the grid under diverse load and fault situations. This research examines the effects of a grid-connected large-scale solar photovoltaic system with varying sizes linked to the IEEE 9 bus system.

Balachandra Pattanaik; Ruthramurthy Balachandran [5] The design methodology founded on the stated principle of PV-STATCOM is executed. The primary objective for enhancing the dependable integration of distributed energy resources into the grid necessitates a paradigm shift to augment both efficiency and overall system performance.

Chinmoy Roy; Tushar Kanti Roy; Liton Chandra Paul [6] This study presents a grid-connected solar photovoltaic (SPV) system utilizing a rapid power convergence law-based robust backstepping integrated terminal sliding mode controller. An output LCL filter is recommended in lieu of L filters to enhance the quality of injected power. Although an LCL filter can enhance the quality of injected power, it will induce a resonance issue.

Saraban Nazifa; Roubaiath Islam; Md. Ahsan Kabir [7] In response to the rising electricity demand, distributed generation (DG) has been included into the power grid. The integration of distributed generation with the utility grid significantly compromises system stability in the face of shocks, resulting in diminished power quality. The integration of large-scale photovoltaic systems into the grid, among other distributed generation sources, results in increased stability issues due to the reduction of the system's total inertia.

T. K. Roy; F. Akter; S. K. Ghosh [8] A rapid power reaching law-based integral robust backstepping sliding mode controller is presented for a grid-connected single-phase inverter solar photovoltaic (PV) system integrated with an LCL filter. It is important to mention that an LCL filter is utilized instead of the L filter to enhance the quality of injected electricity. Conversely, the LCL filter will produce a resonance issue.

M. P. Thakre; S. Shinde Sayali; Jain A. M [9] This article discusses and analyzes the stability and Total Harmonic Distortion (THD) of the grid-integrated photovoltaic (PV) array using two distinct maximum power point (MPPT) tracking techniques. This experiment employed a photovoltaic array connected to the grid via a voltage source inverter and a boost converter. The PSCAD environment simulated structures, using MPPT techniques for Incremental Conductivity (InC) and Perturbation & Observation (P&O).

Oluwaseun M. Akeyo; Vandana Rallabandi; Nicholas Jewell [10] Solar inverters generally limit or "clip" the power output from the photovoltaic (PV) system when it surpasses the maximum alternating current capacity. This article examines a battery system linked to the DC bus of an inverter for the recovery of photovoltaic energy. In contrast to traditional methods that utilize two dc-dc converters—one for the battery and another for the solar PV system—the suggested arrangement employs a single dc-dc converter that functions concurrently as a charge controller and a maximum power point tracking (MPPT) device.

IV. METHODOLOGY

The examination of power quality in the solar photovoltaic model is conducted. The solar photovoltaic panel system is linked with the electricity grid. Power quality concerns in the dispersed network are addressed by traditional and intelligent strategies in the conducted research. The power quality study is conducted using conventional converters such as controllers, and the performance is evaluated with hybrid Fuzzy-PI controllers and ANFIS-PI controllers.

The conventional PI controller employs manual tuning, but the advanced controller utilizes adaptive tuning to adjust the gain settings of the PI controllers through the ANFIS controller. The comprehensive modeling of the grid-connected photovoltaic system, inclusive of all controllers, has been built, and results have been acquired for comparative analysis.

4.1. Hybrid Fuzzy-PI controller implementation

The integration of the hybrid Fuzzy PI with the Fuzzy Logic Controller and the PI controller yields a cumulative output. This hybrid controller, termed the supplemental controller, utilizes the outputs of both the Fuzzy and PI controllers to derive the reference voltage for the PWM controller. Figure 4.1 illustrates a supplemental fuzzy controller utilized for current regulation.

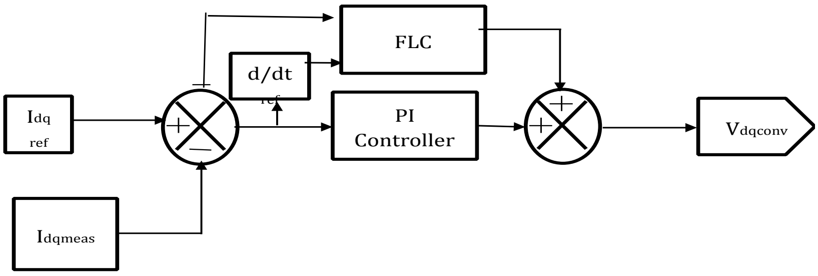


Figure 1: Supplementary Fuzzy Controller for Current Regulation

The auxiliary Fuzzy PI controller, or the hybrid Fuzzy-PI approach, generates output from both the Fuzzy controller and the PI controller. The contributions of both controllers are equally considered for the output reference voltage and aggregated.

The error and its variation in the dq domain serve as inputs to the Fuzzy Logic Controller (FLC), which generates output values from the inference engine, while the Proportional-Integral (PI) controller concurrently creates output as well. Both operate concurrently to achieve optimal Total Harmonic Distortion (THD) for the voltage at the Point of Common Coupling (PCC).

The specifications of the photovoltaic array, boost converter, transformer, and grid, including power, voltage, and current ratings, are presented in Table 4.1.

Table 1: Simulation Parameters

Components	Parameters	Values
PV array	Product ID	Sun Power spr-305-WHT
	Vmpp	54.7 V
	Impp	5.58a
	V_{oc}	64.2 V
	Isc	5.92 A
	Number of panels in series	5
	Number of panels in parallel	34
Boost converter	Inductor	5mH
	Capacitor	12000µF
	Frequency	5kHz
Filter	Inductor	1.5mH
	Resistor	2mΩ
Transformer	KVA rating	100
	Low voltage side	415V
	High voltage side	11kV
	Frequency	50Hz
Grid	MVA rating	100
	Voltage	11kV
	Frequency	50Hz
Three phase RL Load	Active power	30kW
	Reactive power	22000 vars

4.2 Membership functions and rules of FLC

The power quality assessment is conducted using a hybrid fuzzy-PI controller. The selected membership functions for the Fuzzy Logic Controller (FLC) are low, medium, and high.

4.3 ANFIS tuned PI Current Controller for Power Quality Improvement

A detailed comparative examination of the PI controller alongside the hybrid Fuzzy-PI and ANFIS-PI controllers is presented. The methodologies employed to assess the impact of big photovoltaic systems on the functioning of the distribution network are examined and determined to need further enhancement. This research proposes a hybrid method combining the Adoptive Neuro Fuzzy Inference System (ANFIS) with a Proportional-Integral (PI) controller to identify the gain parameters of the PI controller. This thesis delineates the contextual theory and extensive modeling of many components of a grid-connected photovoltaic system, including the photovoltaic source, maximum power point tracking (MPPT) approaches, DC/DC converters, and DC/AC inverter control algorithms utilized in this research. A proper model for analyzing various voltage quality and harmonic effects is required for such a scheme. The model of the proposed system and the numerous software tools utilized in this research are delineated.

V. RESULTS AND DISCUSSION

The enhancement of power quality through the application of adaptive PI tuning strategies is discussed. The detailing of ANFIS-based PI tuning. The synchronization of 11 kV photovoltaic generation with the grid has been conducted, and the outcomes are analyzed for various controllers, employing the Direct Quadrature (dq) approach for synchronization. A comparison is conducted among the three controllers: the classic PI controller, the adaptive PI tuning utilizing ANFIS-PI controllers, and the supplemental control based on the Fuzzy-PI hybrid controller. The obtained findings demonstrate an improved Total Harmonic Distortion (THD) and a significantly steady DC link voltage. The voltage control at the DC link and the current regulation at the inverter both enhance the total harmonic distortion (THD) at the point of common coupling (PCC). The ANFIS-PI hybrid technique has distinctly demonstrated its superiority among the three employed controllers.

Figure 2 (a) illustrates the comparison of grid power utilizing PI, Fuzzy-PI, and ANFIS-PI methodologies. Figure 2(b) illustrates a magnified version of Figure 2(a). The efficacy of ANFIS is enhanced due to its precise current regulation. The fuzzy-Pi and PI controllers yield results that are comparable, however the former exhibits more oscillations in power. Figure 3(a) illustrates the comparison of D.C. link voltage among PI, Fuzzy-PI, and ANFIS-PI controllers. Figure 3(b) presents a magnified view of Figure 3(a). The DC connection voltage is regulated in ANFIS-PI, as seen by this figure. However, both the PI controller and Fuzzy-PI exhibit distortions. Figure 4 (a) illustrates the comparison of input power among PI, Fuzzy-PI, and ANFIS-PI. Figure 4 (b) presents an enlarged version of Figure 4 (a). The chart illustrates that the input power of ANFIS-PI remains relatively stable compared to PI and Fuzzy-PI.

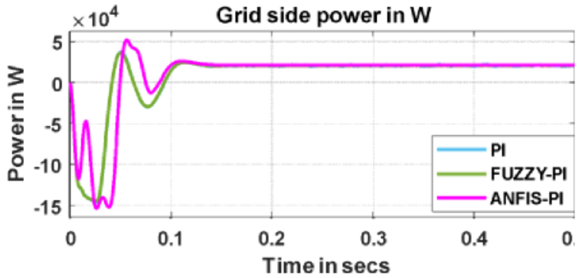


Figure 2 (a): Grid power comparison with PI, Fuzzy-PI and ANFIS-PI

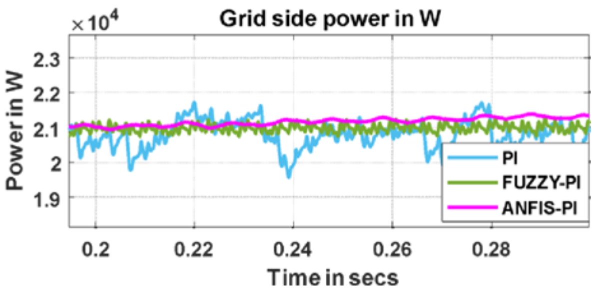


Figure 2(b): Zoomed view of fig. 5.15 (a)

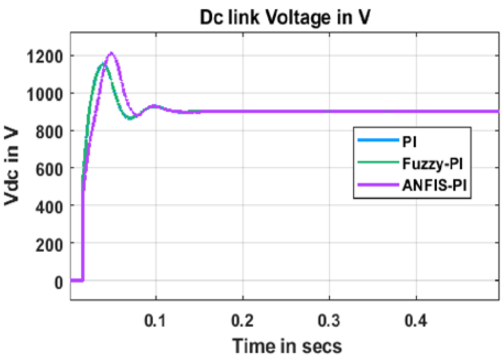


Figure 3 (a): Dc link Voltage comparison with PI, Fuzzy-PI and ANFIS-PI

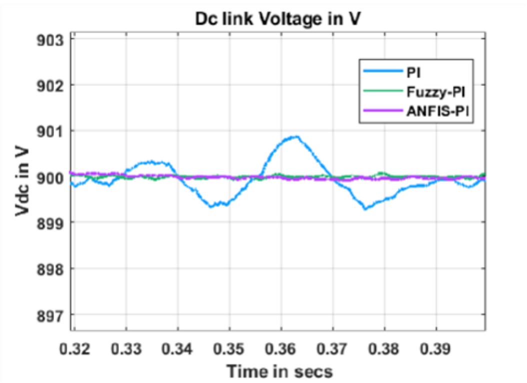


Figure 3(b): Zoomed view of fig. 5.16 (a)

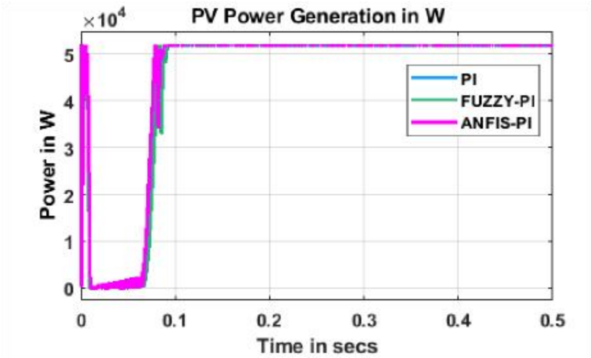


Figure 4 (a): Input power comparison with PI, Fuzzy-PI and ANFIS-PI

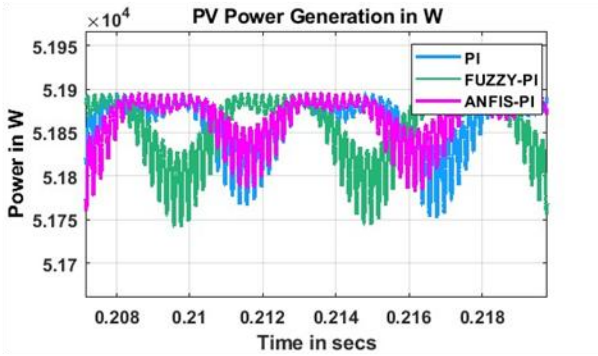


Figure 4(b): Zoomed view of fig. 5.17 (a)

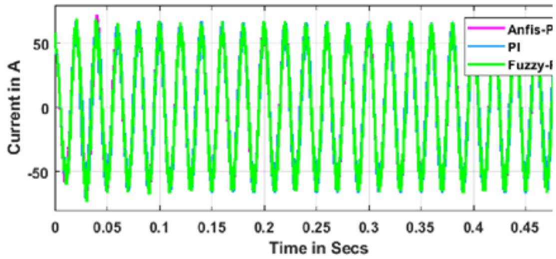


Figure 5 (a): Current at phase A comparison with F Fuzzy-PI and ANFIS-PI

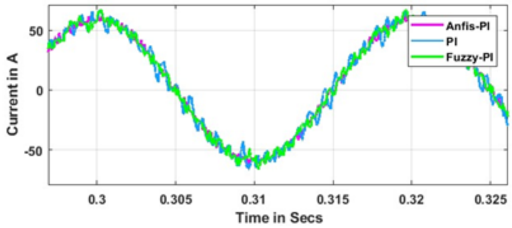
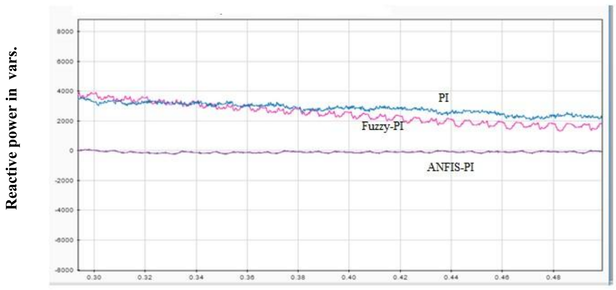


Figure 5(b): Zoomed view of fig. 5.18 (a)

Figure 5 (a) displays a single phase of the three-phase currents measured. The overall fluctuations of the grid current are significantly diminished using the ANFISPI controller. Figure 5(b) distinctly illustrates an expanded view of the current waveform, effectively differentiating the current oscillations of each approach. Figure 6 illustrates the comparison of reactive power among the three controllers. This chart clearly indicates that the reactive power provided by the grid with the PI and Fuzzy-PI controllers is somewhat greater than that with the ANFIS-PI controller and approaches zero in steady-state circumstances. The reactive power provided by the grid with the ANFIS-PI controller is zero, indicating that the grid operates at a unity power factor with the ANFIS-PI controller.



Times in secs

Figure 6: Comparison of reactive power using PI, Fuzzy-PI, and ANFIS-PI

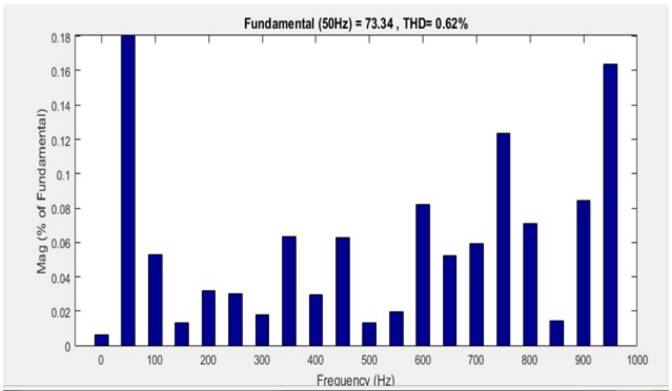


Figure 7: Present harmonic spectrum with a PI controller

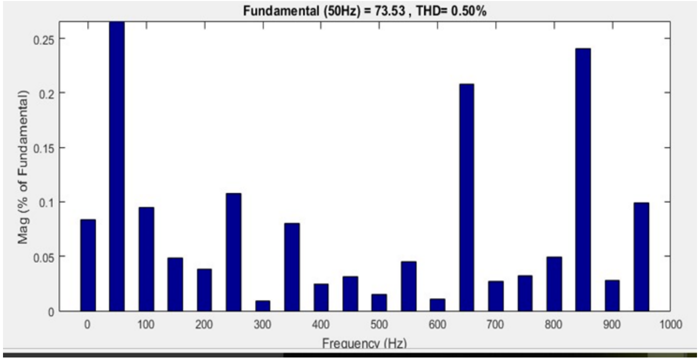


Figure 8: Present harmonic spectrum via Fuzzy-PI controller

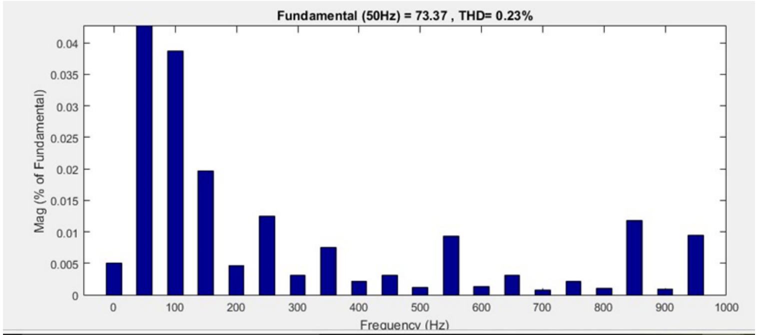


Figure 9: Present harmonic spectrum with ANFIS-PI controller

Upon comparing Figure 8 with Figures 6 and 7, it is apparent that the Total Harmonic Distortion (THD) achieved through the implementation of the ANFIS-PI controller demonstrates a significant performance enhancement relative to both the Fuzzy-PI controller and the PI controller. It is advisable to employ an ANFIS-PI controller in areas with significant sensitive load usage. The total harmonic distortion (THD) is kept within IEEE standards across all utilized controllers.

Table 2 presents the percentage of current Total Harmonic Distortion (THD) values acquired using different methodologies.

Table 2: Current THD values of PI, Fuzzy-PI, ANFIS-PI techniques

Solution techniques	THD (%)
PI	0.62
Hybrid Fuzzy-PI	0.5
Hybrid ANFIS-PI	0.23

In the foundational paper, the current Total Harmonic Distortion (THD) was 15.06%.

The THD values for various approaches were observed using a resistive load. Table 3 presents the percentage of current total harmonic distortion (THD) values for a resistive load at an active power demand of 30 kW.

Table 3 Present THD values for PI, Fuzzy-PI, and ANFIS-PI algorithms applied to resistive load

Solution techniques	THD (%)
PI	12.86
Hybrid Fuzzy-PI	7.9
Hybrid ANFIS-PI	4.9

Upon comparing Table 2 and Table 3, it is evident that the total harmonic distortion (THD) for the RL load in Table 5.1 is lower than that for the resistive load, as inductance mitigates current fluctuations. An inductor functions as a filter for current harmonics, resulting in a smoother current waveform and a reduction in current total harmonic distortion (THD).

The duration for execution in the Matlab simulation, namely the time required for compiling and executing all three controllers, is presented in Table 4.

Table 4. Duration of execution in Matlab simulation employing several methodologies

Solution techniques	Time taken for execution(sec)
PI	6
Hybrid Fuzzy-PI	9
Hybrid ANFIS-PI	10

Table 4 presents the comparative observations of several parameters for the PI controller, Fuzzy-PI controller, and ANFIS-PI controller approaches.

Table 5: Observations of various parameters utilizing PI controller, Fuzzy-PI controller, and ANFIS-PI controller approaches.

Parameter	Observations
Solar power generation	From the input power comparison with PI, Fuzzy-PI and ANFIS-PI controller techniques, it is seen that the input power of ANFIS-PI is not much disturbed compared to PI and Fuzzy-PI controller techniques.
Active power supplied to the grid	Observing the Grid power comparison with PI, Fuzzy-PI and ANFIS-PI. it is seen that the power supplied using ANFIS-PI is higher . Whereas with the fuzzy-pi and PI controller is also near to the results but it shows more oscillation in power.
Reactive power supplied to the grid	It is observed that, with ANFIS controller, reactive power supplied to the grid is zero and it is operating at unity power factor. Whereas with PI controller and Fuzzy-PI controller techniques, reactive power supplied to the grid is tending to zero under steady state conditions.
D.C link voltage	Observing the DC link voltage comparison with PI, Fuzzy-PI and ANFIS-PI controllers it is seen that the DC link voltage in maintained in ANFIS-PI. But the PI controller and Fuzzy-PI controller has distortions.
Current	Observing the single phase of the three phase currents obtained, it is seen that the overall oscillations of the current are largely reduced with ANFIS-PI controller.
Current THD	Comparing THD values, it is evident that the THD obtained while implementing the ANFIS-PI controller has clearly shown lesser value when compared to Fuzzy-PI controller and PI controller.

CONCLUSION

PV grid synchronization is executed with various controllers, encompassing both standard and innovative types. The analysis of power quality enhancement through the utilization of both traditional and sophisticated controllers, namely the adaptive PI tuning using the ANFIS-PI controller, the supplemental Fuzzy-PI, and the conventional PI controller. The power quality enhancement using the advanced controller, in comparison to the classic controller, is seen to be superior. The Total Harmonic Distortion (THD) and the stability of the DC link voltage are much superior in the hybrid controller, ANFIS-PI controller, as compared to the Fuzzy-PI and PI controllers. The total harmonic distortion (THD) of all controllers is within the standard range established by IEEE STD 519-1992, with the ANFIS-PI controller exhibiting the lowest THD. The active controller and the smaller passive filter reduce harmonics in the PCC.

The voltage at the DC link and the harmonics at the point of common coupling are regulated using PWM control in the inverter. The reference voltage and the phase angle derived from the grid must be meticulously monitored using the controllers. The DC link reference voltage must be achieved with minimal ripples. The performance examination of the PI, Fuzzy-PI, and ANFIS-PI controllers indicates that the ANFIS-PI outperformed the other controllers. The ANFIS-PI controller outperformed the other controllers, demonstrating superior total harmonic distortion (THD) and voltage regulation when employed.

FUTURE SCOPE

1. AI-Enhanced Adaptive Control: Utilizing deep learning or reinforcement learning with ANFIS-PI for real-time adaptive optimization to enhance grid stability.
2. Advanced Harmonic Mitigation: Incorporating hybrid active filters and predictive compensation methods for enhanced harmonic suppression.
3. Smart Grid Integration: Creating AI-powered autonomous controllers for flawless synchronization in smart grid systems.
4. Real-Time Hardware Implementation: Employing Digital Signal Processors (DSP) to execute and evaluate grid integration algorithms, hence providing practical viability and performance verification.
5. Energy Storage Integration: Integrating ANFIS-PI with battery storage for improved frequency management and consistent power supply.

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