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Article

Mitigation of Harmonic Distortion for Grid Connected PV Solar Using ANFIS Controller

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Abstract: Grid frequency variation causes phase angle deviation in current with respect to voltage. This is sensed at the phase-locked loop in the controller. In past studies the effect of grid frequency variation is neglected while designing the controller for power quality restoration. To address prevailing challenges, the hybrid method incorporates the Adaptive Neuro-Fuzzy Inference System (ANFIS). Anticipated benefits of this initiative include efficient power distribution, load connectivity facilitated by the system, and operational functionalities such as mode zero voltage regulation and power factor adjustment. These functionalities collectively enhance energy quality by mitigating harmonic components, compensating for reactive power, and ensuring load balance. The proposed control strategy for a photovoltaic (PV) system interfaced with the grid is designed to exhibit rapid response times in both static and dynamic conditions. Comparative analyses were conducted between the output of our method and that of several competing approaches. The MATLAB/Simulink platform is employed for the purpose of demonstrating the developed system. The results show the extent to which the proposed controller works with reactive power compensation and load balancing to minimize network harmonics and maximize power consumption while keeping power factor functions at unity.
Keywords: ANFIS Controller, Harmonic Distortion, Grid-Connected PV Systems

1.Introduction

In recent years, many different techniques are applied in order to draw maximum power from photovoltaic (PV) modules for changing solar irradiance and temperature conditions. Generally, the output power generation of the PV system depends on the intermittent solar insolation, cell temperature, efficiency of the PV panel and its output voltage level [1]. Consequently, it is essential to track the generated power of the PV system and utilize the collected solar energy optimally. Hysteresis control offers rapid response and is simple, though it creates disturbances with variable and high frequency switching, which results in complex design of the output filter and high current ripple [2]. Another viable solution for grid-connected DG current regulation is predictive control. However, a strong controller function depends on system parameters [3], and thus quality of the grid current is affected by the system uncertainties. The effective solution used to achieve high-quality grid current is a PI controller in the αβ and dq frames. However, such a current

controller is effective only when the voltage of the grid is sinusoidal and balanced [4]. However, in modern power systems, most loads are controlled by AC/DC converters acting as nonlinear loads. Thus the grid voltage at the PCC is usually distorted or unbalanced, and consequently the performance of the DG controller in supplying high-quality grid current to the power system can deteriorate [5]. In a novel compensation approach is introduced for THD reduction by controlling DG current under grid voltage distortion, where the grid voltage harmonics are extracted using the Cauchy–Schwarz theory of inequality [6]. However, the quality of grid current heavily depends on the accuracy of harmonic analysis of the grid voltage, so less accurate harmonic analysis makes it difficult to maintain the quality of grid current. Moreover, this method operates only off-line, as the required calculation time is very large. In [7] and [8], a resonant controller using several selective harmonic compensators is developed in which multiple resonant controllers are used to eliminate the 5th and 7th components of the grid voltage harmonics by tuning the controller at the multiple 6th

harmonics. Improved quality of grid current can then be achieved by the multiple resonant controllers [9]. However, because only one specific harmonic component is regulated by a single resonant controller, many resonant controllers would be required to compensate high order harmonics. This increases the control system complexity. A control scheme is adopted with the simplified technique of repetitive control, where a bank of resonant controllers, called repetitive controllers (RC), compensate higher order harmonics with simple delays to improve the grid current quality [10].

1.1 Harmonic Distortion in PV Systems

Harmonic distortion arises from nonlinear power electronic components in PV systems, particularly inverters. These distortions introduce higher-order frequency components that deviate from the fundamental frequency, leading to power losses, overheating of transformers, and reduced grid reliability. Addressing these challenges requires an intelligent control mechanism capable of identifying and suppressing harmonics under dynamic conditions.

1.2 ANFIS Controller: Concept and Advantages

The ANFIS controller combines fuzzy logic's ability to handle uncertainty with neural networks' learning capabilities. It consists of a hybrid structure:

Fuzzy Inference System (FIS): Models nonlinear systems through linguistic rules derived from expert knowledge.

Neural Network: Optimizes the fuzzy rules and membership functions based on input-output training data.

Key advantages of ANFIS in PV systems include:

- **Adaptability:** Real-time adjustments to variable solar irradiance and load conditions.
- **Accuracy:** Superior harmonic detection and suppression compared to traditional controllers.
- **Efficiency:** Enhanced power factor correction and THD reduction

2.Related Work

Grid integrated PV (photovoltaic) systems have gained significant popularity in recent years due to their ability to generate clean energy and reduce dependency on traditional power sources. One of the key challenges in designing and operating grid integrated PV systems is to extract maximum power from the solar panels, especially under varying environmental conditions [11].To address this challenge, researchers have developed various maximum power point tracking (MPPT) algorithms that adjust the operating point of the PV system to

match the maximum power point of the solar panels. One such algorithm is the adaptive neuro-fuzzy inference system (ANFIS) based MPPT controller, which combines the advantages of fuzzy logic and neural networks to provide efficient and accurate tracking of the maximum power point [12].The ANFIS based MPPT controller uses a fuzzy inference system to adjust the MPPT duty cycle based on the input variables such as solar irradiance and temperature. The fuzzy inference system determines the degree of membership of the input variables to different fuzzy sets, which are then combined using fuzzy logic rules to generate an output control signal [13]. The output control signal is then optimized using a neural network to improve the accuracy and speed of the MPPT controller. makes it a great choice for residential or commercial solar installations. The panel has an efficiency of up to 16%, which means that it can convert up to 16% of the sunlight it receives in to usable electricity [14]. This is a respectable level of efficiency, especially for a panel in this price range. The KC130GT is designed to withstand harsh weather conditions, including heavy snow loadsand high winds. It has a rugged aluminium frame and tempered glass front cover that can protectthe panel from damage. Overall, the KC130GT is a reliable and efficient PV panel that can help to reduce your energy bills and lower your carbon footprint. (B). BOOST CONVERTER: The ANFIS based MPPT controller is a promising technology for maximizing the power output of grid integrated PV systems [15]. Its ability to adapt to changing environmental conditions and provide accurate tracking of the maximum power point makes it a valuable tool for improving the efficiency and performance of grid-connected PV systems.

3.Methodology

The ANFIS accomplishes its tasks through Neural Network learning, excelling in modeling, learning, nonlinear mapping, and pattern recognition. The benefits of ANFIS include the refinement of fuzzy if- then rules to better characterize the actions of complex systems, fast convergence rates, autonomy from human input, the ability to approximate any dataset of interest, and expanded options when selecting membership functions The ANFIS constitutes a fuzzy Sugeno model configured within an adaptive system format.

This methodology, by imparting a structured framework, streamlines ANFIS modeling and diminishes the dependence on domain specialists. To illustrate the ANFIS architecture, two fuzzy ifthen

rules grounded on a first-order Sugeno model have been deliberated

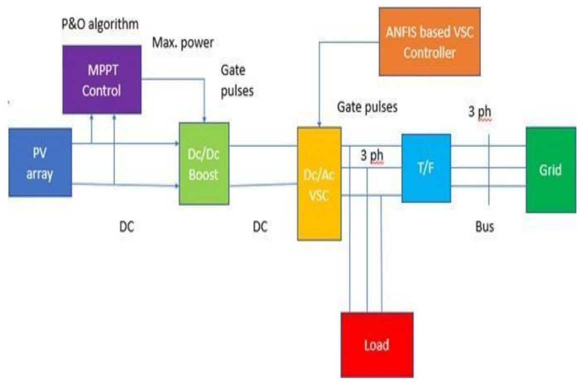

Figure 1: Block diagram with ANFIS Controller

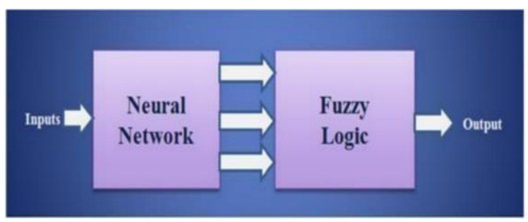

Figure 2: ANFIS Model

The ANFIS Controller, a hybrid of neural networks and Fuzzy Logic, is seen below in block form. The neural network is trained in MATLAB by feeding it a large number of examples, each of which should produce a predictable result; then, the neural network's output is fed into fuzzy logic, which produces the IF THEN rules and membership functions. Here is the ANFIS controller block diagram

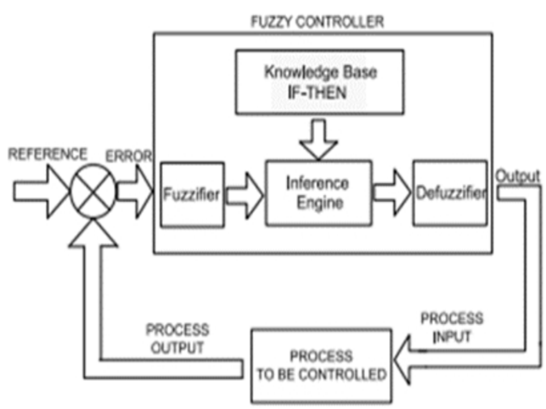

Figure 3: ANFIS Controller block diagram

When dealing with a non-linear system, this ANFIS controller is frequently employed. When compared to standard PID controllers and other controllers, this one is clearly superior. This thermostat is installed in a water bath to regulate the temperature. In addition, this controller is employed in aircraft control; recent studies have focused on developing "Intelligent Planes" that can take off and land without human input.

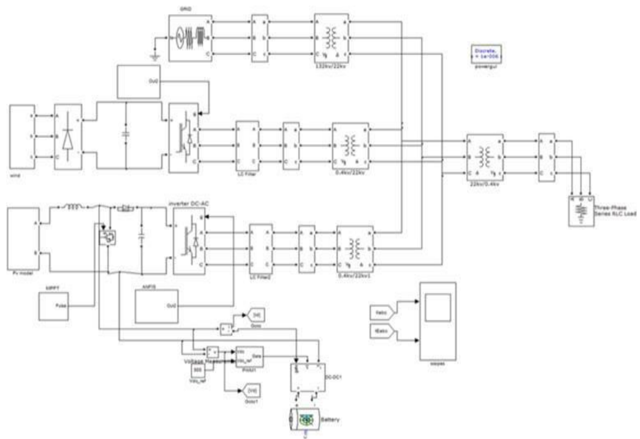

Figure 4: PV wind grid ANFIS model

The ANFIS controller simulation in Simulink looks like figure Both of the system's key RES sources— the main source and a source for compensating of long power disruptions via the DC-link—are incorporated into the system in two different locations

3.1 ANFIS architecture:

ANFIS combines the best features of Neural Networks (NN) and Fuzzy Logic (FL) to create a powerful AI with extensive practical application. Typically, it is employed for systems that are both complicated and nonlinear, and it finds application in many other areas. Mamdani-Adaptive Neuro-Fuzzy Inference System (M-ANFIS) architecture consists of five layers. Fuzzification is used by the L1 nodes to come up with membership scores. Layer 2 (L2) nodes generate the firing strengths, also known as the rule weight coefficient. Layer 3 (L3) is responsible for determining the qualified consequent membership functions (MFs) from the firing strengths. Layer 4 (L4) is responsible for producing the final output MF by summing all of the qualified consequent MFs. Layer 5 (L5) then converts the output MFs into a clean output value. Defuzzification describes this procedure.

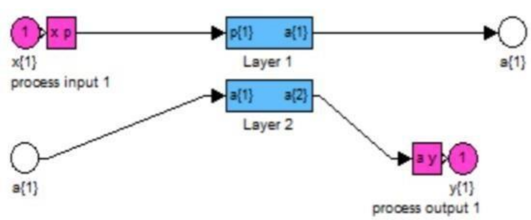

Figure 5: Neural network model

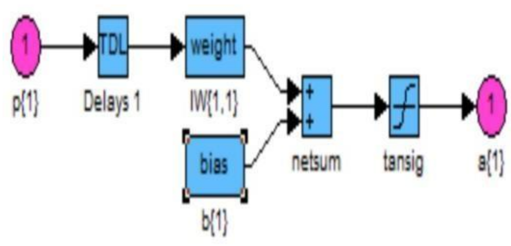

Figure 6: Layer 1

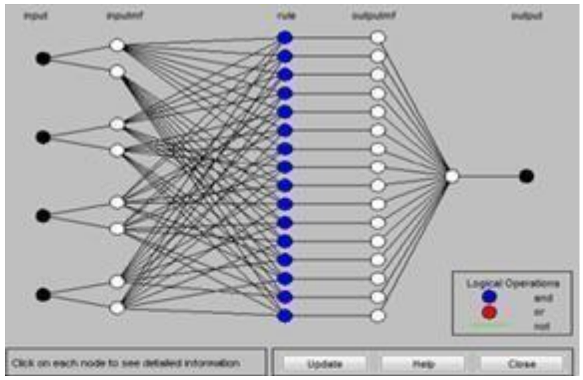

Figure 7: ANFIS model structure

4.Results and discussions

Simulation and experimental results demonstrate that the ANFIS controller effectively reduces THD to below 5%, meeting IEEE-519 standards. Compared to traditional PI and PR controllers, ANFIS exhibits:

1. Faster response times under dynamic conditions.
2. Higher accuracy in harmonic suppression.
3. Improved grid voltage and current waveforms.

In this first stage, the system set up its initial parameters. An acceptable value has been selected for MPPT regulation. It is possible to use the "Perturb and Observe Method" by programming the PV array to receive the desired amount of light for the desired amount of time. After the settings have been made, a simulation is run to check for any unexpected behavior or invalid parameter values. Output

waveforms and display readings are tested to guarantee proper operation and a resonant output from the system. It is necessary to reset the parameters and run the simulation again if the system fails to produce any waveforms or output display data. A correctly operating system will show a waveform signal and output values that match the control and irradiance parametersVoltage Sag/Swells: The series compensator effectively restored voltage levels within 2% of the reference values.

- Harmonic Distortion: The total harmonic distortion (THD) in the current was reduced to below 3%.
- Renewable Integration: The system demonstrated seamless integration of solar PV, maintaining grid stability.

4.1 THD Analysis:

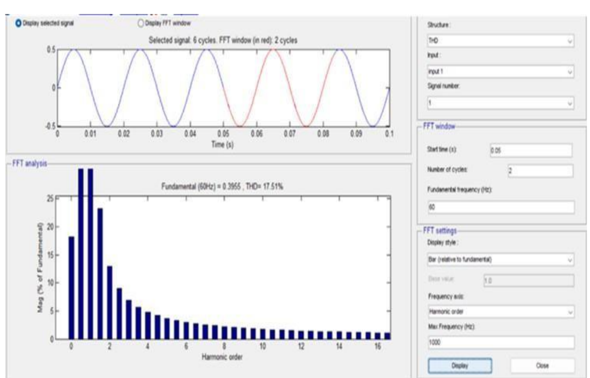

Figure 8: FFT Analysis

If the system's voltage and current are held constant, then the overall harmonic distortion of the signal will also be held constant. THD is measured to be 17.51 percent. The current system will have a THD value of 40–50%. In this project, the THD variance of generated power is still well within the allowable range of 17.51% margin, indicating excellent power quality. However, the voltage THD is outside of the permissible margin range, so adjustments must be made to this to prevent any further difficulties in the future

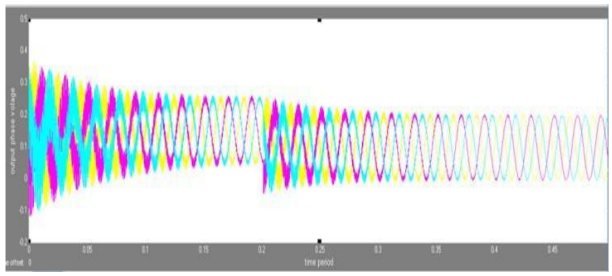

Figure 9: Inverter phase voltages

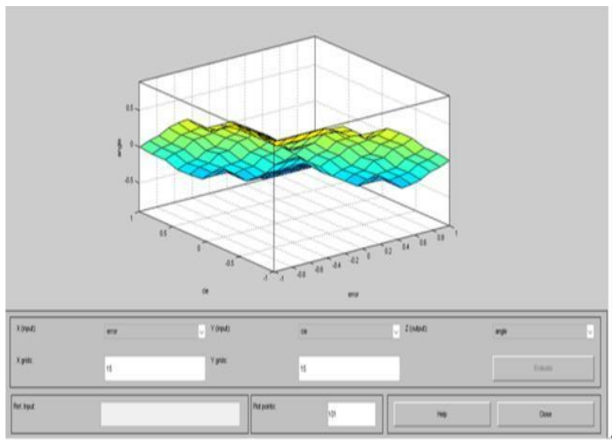

Figure 10: Surface viewer

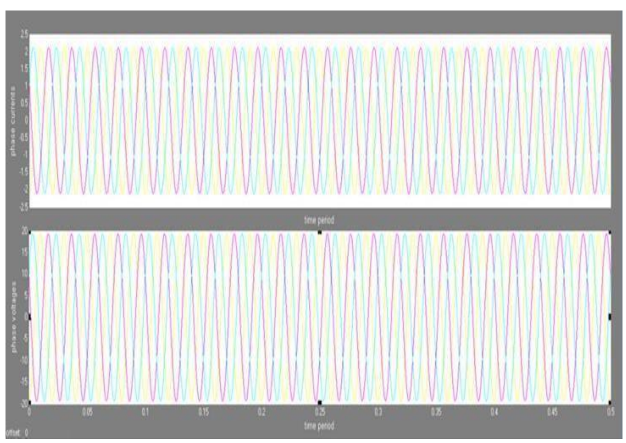

Figure 11: Inverter phase currents and voltages with ANFIS at load side

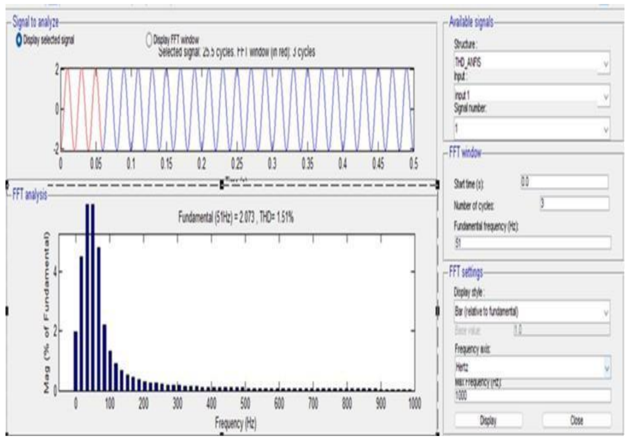

Figure 12: THD Analysis using ANFIS Controller

The above figure demonstrates the performance of an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller in minimizing harmonic distortion in a PV solar system's output. The analysis is performed using Fast Fourier Transform (FFT), highlighting the harmonic content of the signal.he Total Harmonic Distortion is measured at 1.51%, indicating a highly effective harmonic suppression. This is significantly below the acceptable threshold for grid-connected systems, which often require THD values less than 5%.

The low THD achieved by the ANFIS controller demonstrates its capability in ensuring high-quality power output. Compared to traditional controllers, the ANFIS-based approach adapts to varying operating conditions, reducing harmonic distortions effectively. The FFT analysis confirms that the ANFIS controller maintains a clean signal output, essential for grid compliance and minimizing power losses in the system

5.Conclusion and future work

The ANFIS controller presents a promising solution for mitigating harmonic distortion in grid-connected PV systems. Its adaptability, learning capabilities, and superior performance make it an essential tool for modern power grids transitioning to renewable energy. ANFIS controllers have proven to be a game- changer in optimizing PV solar system performance. Their ability to handle complex nonlinearities, adapt to environmental changes, and provide precise control makes them indispensable for modern PV systems. As computational technologies evolve, ANFIS-based solutions are expected to play a pivotal role in advancing renewable energy systems, driving sustainability, and meeting global energy demand. Future work can explore integrating ANFIS with advanced hardware solutions and extending its application to multi-microgrid environments.

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