International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING

ISSN:2147-6799 www.ijisae.org Original Research Paper

An Adaptive Quadrant Filter-based PLL Approach for a Three-Phase System with Adoptive Neuro-Fuzzy Interface System (ANFIS)

Naveen Kumar Diddi, **Dr. KVNS. Pavan Kumar**

Submitted: 28/08/2024 **Revised:** 10/10/2024 **Accepted:** 18/10/2024

Abstract: In recent Grid synchronization of electricity systems is required for Phase-Locked Loop (PLL) technologies, particularly when connecting renewable energy and improving power quality. Traditional Proportional-Integral (PI) controllers tend to face challenges in dynamic grid conditions, leading to slow responses and phase tracking instability. The work introduces an Adaptive Quadrant Filter-based Using a Synchronous Reference Frame Phase-Locked Loop (AQF-SRF-PLL) combined with an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller, enhance tracking accuracy and robustness. The proposed approach employs the adaptive learning characteristics of ANFIS to adapt to grid variations, ensuring fast convergence, smaller steady-state error, and robustness against disturbance such as voltage sags and harmonics. Comparative simulations show that the ANFIS-based PLL outperforms the conventional PI-based PLL in terms of reaction time, stability of phase synchronization, and system longevity as a whole, and hence is a better solution for modern grid applications. The Matlab /Simulink simulation model is built, & the results. The simulations are presented to ensure that the mathematical analysis is correct.

Keywords: *Phase-Locked-Loop (PLL), Synchronous Reference Frame, Adaptive Quadrature Filter Harmonic Distortion, Unbalanced Components, Adoptive Neuro-Fuzzy Interface System (ANFIS).*

1 Introduction:

The use of power electronic systems for grid connection like active rectifier, generator/motor control, wind/solar power, APF, FACT, and UPS requires proper considerations of positive sequence components and synchronization of phases with utility voltage [1]. For frequency variation systems, it is essential to precisely and quickly monitor the utility voltage, phase angle, and frequency to apply phase synchronisation, active power factor correction, harmonic current compensation, and system protection [2]. The basic diagram is represented in Figure 1. Moreover, the power flow computations, variable conversions to rotating reference frames, and synchronisation of the inverter output variables all depend on the positive sequence or element. Nevertheless, a growing number of non-linear electronic loads are put into the utility grid system, which pollutes the power system with harmonics. Since the loads aren't always balanced, genuine industrial application utilities often include certain imbalanced components.

Research Scholar, Dept of EEE Chaitanya deemed to be University Hyderabad Telangana, naveen.d5218 @gmail.com
Associate Professor,Dept of EEE Chaitanya deemed to be University Hyderabad Telangana, kollimarla.pavankumar@chaitanya.edu.in

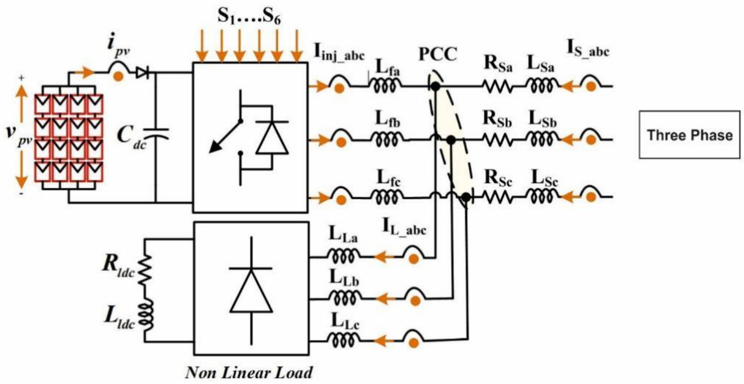

Figure 1. The Basic Three Phase circuit diagram with Non-Linear Loads

Utility voltage frequency fluctuates due to several variables. One such aspect is the greater penetration of wind power systems, which may result in significant variations in utility frequency. Ultimately, random sounds are an inevitable part of observed signals for synchronisation [3]. Hence, the signals aren't quite sinusoidal anymore. PLL systems are often used to implement synchronisation. There are many PLL technologies put out in the literature. The zero crossings detecting method is the most straightforward of these techniques. By instantaneously identifying the line voltage's zero crossing places, it records the grid phase angle [4]. It is susceptible to frequency distortion, however, and the angle identification mechanism does not take phase variations into account. Furthermore, there has been a significant delay of one-fourth of the whole time of one quarter [5]. SRF-PLL, or the most popular approach is the so-called asynchronous reference frame technique. used PLL technology. The loop filter and phase detector components make up the two primary components of the conventional SRF-PLL system. By converting natural points of reference to a synchronized reference edge, phase detection is achieved. The PLL system's dynamics are set by the loop filter [6]. Thus, for the typical SRF-PLL, choosing the loop filter the bandwidth involves a trade-off between dynamic responsiveness and filtering performance. Regretfully, the traditional SRF-PLL is unable to fully address all of the issues it encounters, particularly about the imbalanced elements along lower-order consonant alterations in the perceived source signals. To get an enhanced presentation, many refined SRFPLLs are suggested. To abstract a positive sequencing module in the imbalanced scenario, the PLL structure is given. For the goal of extraction, this approach employs 3 all-pass filters in every stage. But this PLL does not filter out sounds or harmonic distortion. Its sensitivity to variations in grid frequency is another drawback [7]. An upgraded PLL (EPLL) is offered in an attempt to address the issues. Having an optimistic sequence removal element across the whole PLL method and four EPLL components makes the EPLL structure too complicated. With a reduced dynamic response, low-pass filters provide superior filtering performance. After switching from a stationary to a synchronous reference frame, a new approach is given that uses an all-pass filter [8]. Its use of two all-pass filters rather than three is its lone benefit. Double decouple SRF-PLL (DDSRF-PLL) is disclosed in this article. Both the positive and negative sequences decoupling computational unit of the DDSRF-PLL, which is utilised to solve the imbalanced issue, is its major component [9]. To filter harmonic distortion and random sounds, the DDSRF-PLL has four additional low-pass filters in addition to two decoupling computational units. A reported PLL for active power filtering application used the sinusoidal signal integrator (SSI). In stationary rotating reference frame situations, SSI-PLL integrates harmonic filtering with positive sequence extraction [10]. This strategy still compromises the filtering performance and dynamic responsiveness. The SSI unit consists of four resonant filters and is an example of a two-input, two-output filter network. Its use is significantly limited as a result of these restrictions. Another approach that utilises the SSI principle is a filtering and phase angle extract block that uses a single resonates filter architecture [11]. Despite its user-friendliness, it is limited to monitoring the phase angle and does not allow for the proper entry of the sequence of positives [12].

This research proposes an innovative method for SRF-PLL that relies on adaptive quadrature filters and is built using technologies for synchronous reference frame transitions [13]. Section II explores the concept of AQF-SRF-PLL and the construction of the simulation model. In section III, the Matlab /Simulink simulation results are used to verify the AQF-SRFPLL performance [14]. It is argued that the outcomes in Section IV are meritorious [15].

2 Background

Adoptive Neuro-Fuzzy Interface System (ANFIS)

A system for fuzzy inference and an artificial neural network are both components of the intelligent combination approach known as ANFIS. In addition, ANFIS integrates the benefits of both models into a cohesive solution method for addressing engineering challenges[1]. Below given figure 2.1 illustrates A diagram showing the architecture of the ANFIS. ANFIS is a nonlinear model that characterizes the input-output connection of a real system by using the learning capabilities of a neural network inside a fuzzy system framework[2] .

ANFIS enables adaptive modelling by integrating learning capabilities from both paradigms, allowing it to approximate complicated and non-linear functions. It has the capability to autonomously adjust the controller settings and regulations in real time for optimal control. ANFIS controllers have exceptional proficiency under varying load situations. This control approach is very versatile and applicable to several types of DC-DC converters beyond buck converters. The Sugeno model is used for the ANFIS controller. The inputs are first fuzzified and then processed by a "product" fuzzy operator. Subsequent to defuzzification into constant values (linear relation) derived from its own knowledge base of relational rules. Every rule has a weight that establishes its precedence. The regulations and their significance are established via the training of the artificial neural network. The data used for training the ANFIS may be derived from the buck converter's open-loop response in response to a ramp input.

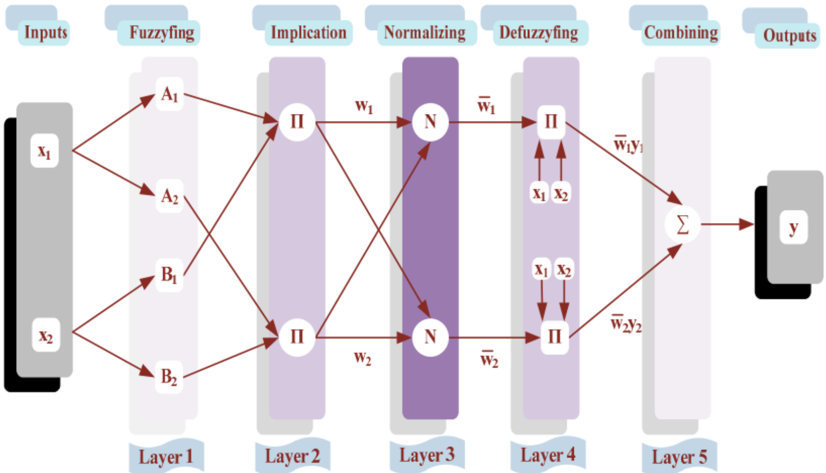

Figure 2.1 Schematic diagram of ANFIS architecture[3]

The fundamental principle of ANFIS, with two inputs x1 and x2, and a single output y, may be articulated as follows.

Rule 1: if x_1 is A_1 and x_2 is B_1, then $y_1=p_1x_1+q_1x_2+r_1$

Rule 2: if x_1 is A_2 and x_2 is B_2, then $y_2=p_2x_1+q_2x_2+r_2$

The fuzzy set parameters for each input in part-if (permissive portion) are Ai and Bi, while the linear parameters in part then are Pi, qi, and ri(consequent peart).

Fuzzifying Layer 1: In this layer, each node is thought of as flexible, and its output is as follows.

$$O_i^1 = \mu A_i(X_1)\,, for\ \ i = 1{,}2$$

$$O_i^1 = \mu B_{I-2}(X_2),\ for\ \ i = 3{,}4$$

Implication Layer 2: The nodes are called fixed nodes, or π, which denotes that they serve as fundamental multipliers. Each node's output, which is based on incoming signals, represents a rule's firing power:

$$O_i^2 = W_i = \mu A_i(X_1)\mu B\ _i(_{X_2}\ \ , for\ \ i = 1{,}2$$

Normalizing Layer 3: In this layer, every node is a fixed node that has been assigned the number N. The signal that is produced $\overline{W_i}$ of the ith node is established by dividing the ith rule's firing intensity by the sum of the firing strengths of all the rules.:

$$O_i^3 = \overline{W_i} = \frac{W_i}{W_1 + W_2}\ \ , for\ \ i = 1{,}2$$

Defuzzifying Layer 4: In this layer, each node i is adaptive and has a node function that includes the resulting parameters (pi, qi, and ri). W_i is a standardized firing frequency from the layer before it.:

$$O_i^4 = \overline{W_i}y_i = \overline{W_i}(P_ix + q_iy + r_i)\ \ , for\ \ i = 1{,}2$$

Combining Layer 5: A single fixed node in this last layer, called Σ, combines every input signal to calculate the total final output in the manner described below.:

$$O_i^5 = y = \sum_i (\overline{W_i} y) = \frac{\sum_i W_i y_i}{\sum_i W_i}$$

3 Principle of the proposed AQF-SRF-PLL

3.1 Problems of Conventional SRF-PLL Faced

Figure 3.1 illustrates the framework of the traditional SRF-PLL method.

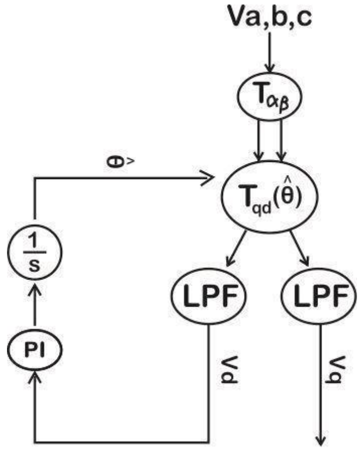

Figure 3.1 Conventional SRF-PLL configuration with LPF

Where,

$$T_{\alpha\beta} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}$$

$$T_{qd}(\hat{\theta}) = \begin{bmatrix} \cos(\hat{\theta}) & -\sin(\hat{\theta}) \\ \sin(\hat{\theta}) & \cos(\hat{\theta}) \end{bmatrix}$$

The typical SRF-PLL fails to provide correct phase angle, electrical frequency, and positive sequence components for unbalanced and harmonically distorted input signals, resulting in inadequate dynamic responsiveness [13]-[16]. A novel technique is required to enhance PLL performance.

3.2 Filter Block with Adaptive Quadrature

[27] presents a comprehensive filter block that encompasses notch, band-pass, low-pass, and high-pass filters, depending on where the output nodes are placed. The filter block indicates that we may move the resultant node points of V2 and V3 to the new locations while also changing the parameter "–K" in [27] alongside K. The updated filter block is shown in Fig 3.2.

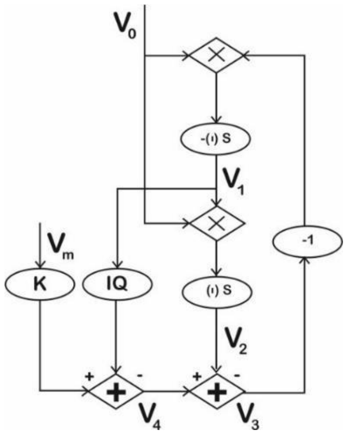

Figure 3.2 Updated General Filter Block

In Fig. 2, V_1, V_2, V_3, and V_4 stand for the output node voltages, V_c for the pole with zero control voltage, and V_{in} for the input voltage. The following transfer functions are offered by the enhanced general filter block.

Band Pass:

$$\frac{V_1}{V_{in}} = \frac{K\omega_p S}{S^2 + \left(\frac{\omega_p}{Q}\right)S + \omega_p^2}$$

Low Pass:

$$\frac{V_2}{V_{in}} = \frac{K\omega_p^2}{S^2 + \left(\frac{\omega_p}{Q}\right)S + \omega_p^2}$$

High Pass:

$$\frac{V_3}{V_{in}} = \frac{KS^2}{S^2 + \left(\frac{\omega_p}{Q}\right)S + \omega_p^2}$$

Notch:

$$\frac{V_4}{V_{in}} = \frac{K\omega_p^2\left[\left(\frac{s}{\omega_z}\right)^2 + 1\right]}{S^2 + \left(\frac{\omega_p}{Q}\right)S + \omega_p^2}$$

Where,

$$\omega_p = \omega_z = \frac{V_c\omega_o}{V_m}$$

V_c stands for the control voltage, ω_p for the pole frequency, ω_z for the zero frequency, and V_m for the multiplier constant

Since the grid frequency is the only factor influencing the poles and zeros in our investigation, the control voltage Vc has no bearing on the PLL application. Only nodes V1 and V2 are left after ignoring output nodes V3 and V4. You can see the next filter block in Fig. 3.3. At the pole frequency positions, there is a quadrature phase shift in the two filters that are visible from V1 and V2 to Vin, respectively.

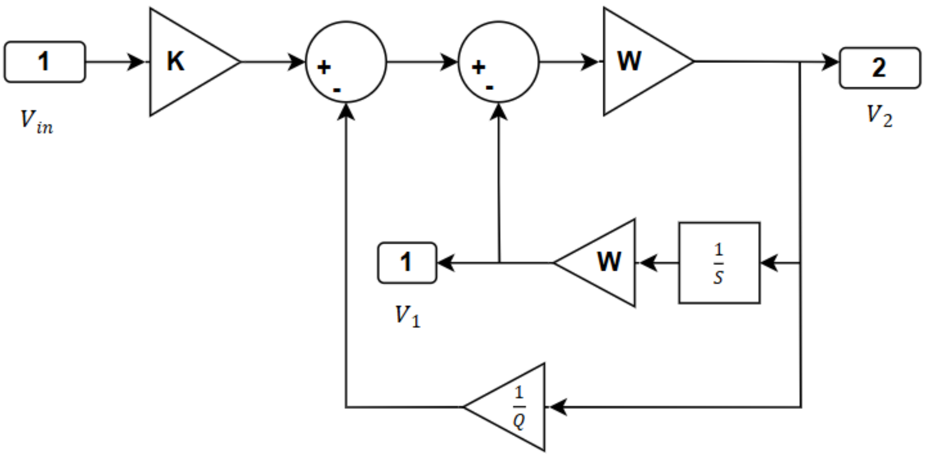

Figure 3.3 Derived quadrature filter block

In this field of study, gains at the frequency of the pole should be equal to one. This can be guaranteed by maintaining Q=1/k. Then, both transfer functions have the shape of the equations below.

$$\frac{V_1}{V_{in}} = \frac{K\omega s}{S^2 + K\omega s + \omega^2}$$

$$\frac{V_2}{V_{in}} = \frac{K\omega^2}{S^2 + K\omega s + \omega}$$

The dynamic response and the band-pass filter's filtering efficacy are determined by the value k.

Since the grid frequency is the sole factor that determines the zeros and poles in the study, the control voltage Vc into account while using the PLL application. There are now just the nodes V1 as well as V2 remaining; ignore the output nodes V3 and V4. The predicted electrical frequency is used for the pole frequency to apply the band-pass & low-pass filters' capacity to adapt. The predicted electrical frequency will then automatically modify the pole frequency. It is known by researchers as the adaptable quadrature filter (AQF). The forecast electrical frequency is a variable that may be changed and self-tunes to the variable grid frequency. The α-axis & β-axis elements of the positive order estimator, which are examined below, have been assigned labels to the inputs and outputs.

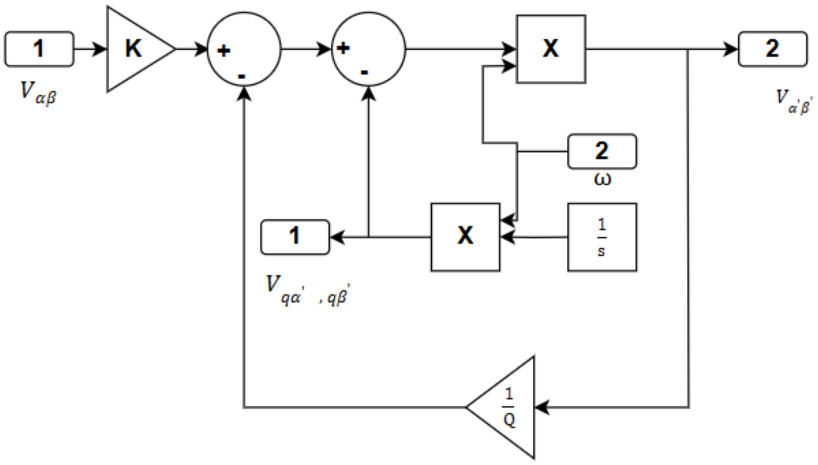

Figure 3.4 AQF Filter Block

3.3 Estimating Positive Sequence

The positive sequence components of The changes shown in the α-axis and β-axis are the source of equation (10).

$$\begin{pmatrix} v_\alpha^p \\ v_\beta{}^p \end{pmatrix} = T_{\alpha\beta}\begin{pmatrix} v_a^p \\ v_b^p \\ v_c^p \end{pmatrix} = T_{\alpha\beta}T_{abc\_p}\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} = T_{\alpha\beta}T_{abc\_p}T_{\alpha\beta}^{-1}\begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 & -q \\ q & 1 \end{pmatrix} v_{\alpha\beta}$$

Where,

$$\begin{pmatrix} v_a^p \\ v_b^p \\ v_c^p \end{pmatrix} = T_{abc\_p}\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix}$$

$$T_{abc\_p} = \frac{1}{3}\begin{pmatrix} 1 & a^2 & a \\ a & 1 & a^2 \\ a^2 & a & 1 \end{pmatrix}$$

$$a = e^{-j\frac{2\Pi}{3}}$$

$$q = e^{-j\frac{\Pi}{2}}$$

The positive sequence estimator depends on the examination of the aforementioned AQF with the positive sequence extraction calculation approach. The AQF unit and the positive sequences calculation element make up the positive sequence estimator. Its three primary tasks are positive sequence estimation, harmonic removal, and quadrature component extraction. It plays the most important part in the suggested PLL system.

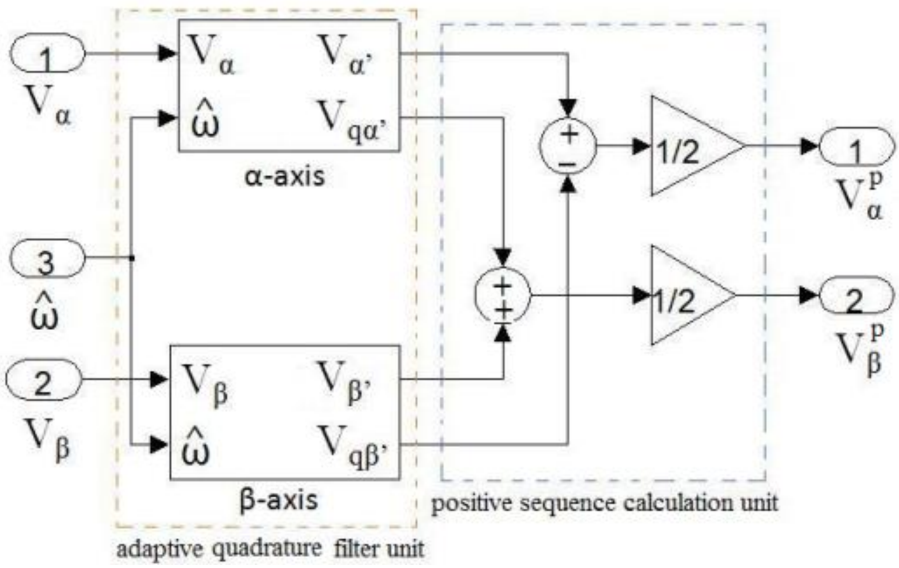

Figure 3.5 Positive sequence estimator

3.4 Proposed ANFIS controller with AQF-SRF-PLL Scheme

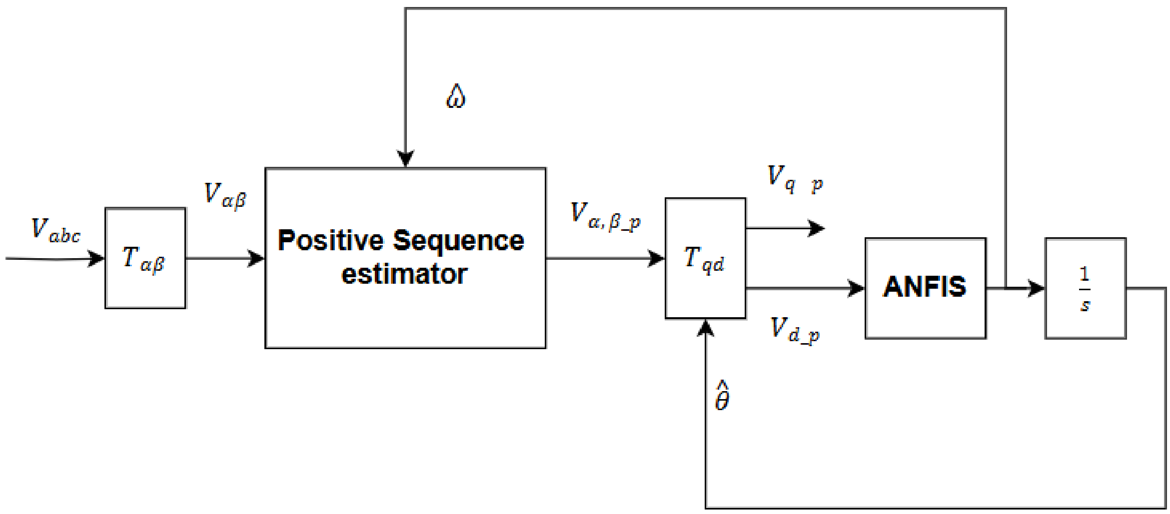

Figure 3.6 Proposed model

The ANFIS-based AQF-SRF-PLL technique is intended for precise phase estimation in three-phase systems experiencing distortion and imbalance. The input three-phase voltage (V_{abc}) is initially converted into the stationary $\alpha\beta$ frame utilizing Clarke transformation ($T_{\alpha\beta}$), subsequently followed by a Positive Sequence Estimator that isolates the fundamental positive sequence component while eliminating harmonics and disturbances. The altered voltage (V_{α,β_p}) is then transferred into the spinning dq-frame by Park transformation (T_{qd}) utilizing the approximated phase angle ($\hat{\theta}$). The quadrature-axis voltage ($V_{q,p}$) is input into an ANFIS controller, which dynamically modifies and enhances the phase angle estimate. The ultimate phase angle ($\hat{\theta}$) is derived by integrating the ANFIS output and is then reintegrated into the transformation block to maintain continuous phase tracking. This system improves phase estimation precision, harmonic resistance, and flexibility, making it suitable for grid synchronization, renewable energy integration, and enhancement of power quality.

4 Results and Discussion

The outcome reflects the outcome of the simulations carried out to examine the efficiency of the suggested adaptive quad filter-based PLL technique for a three-phase system using ANFIS controller.

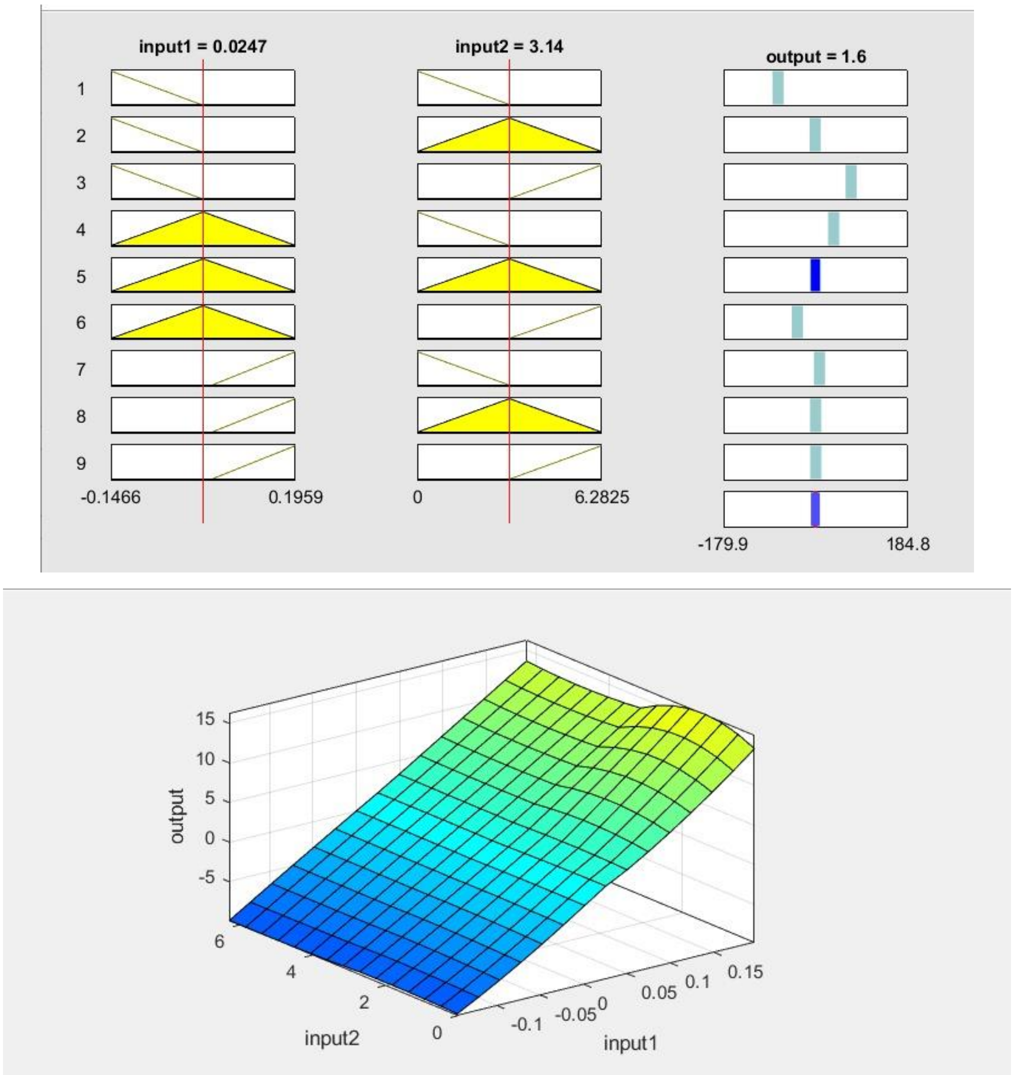

Figure 4.1 Training of ANFIS

ANFIS

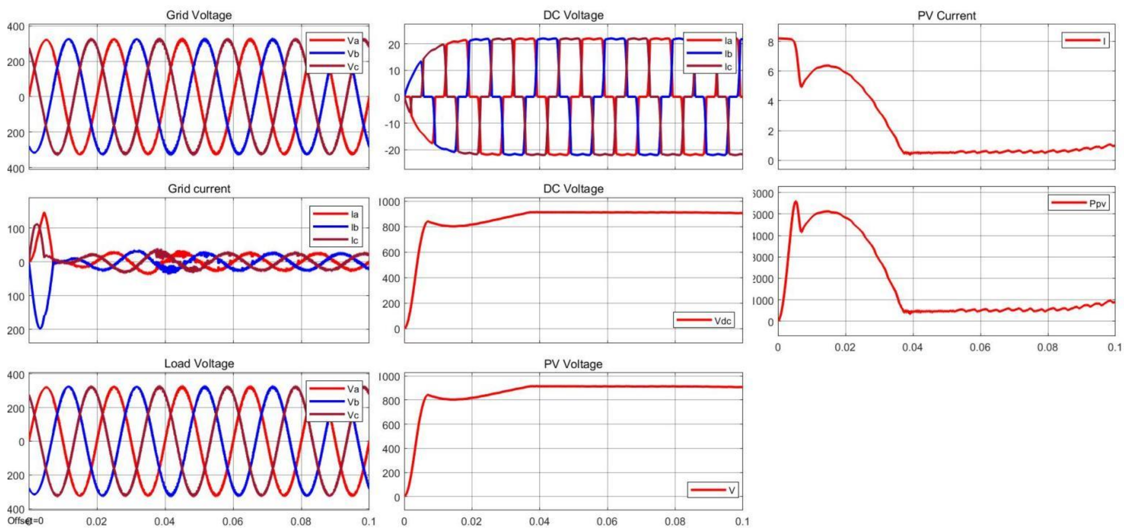

Figure 4.2 Waveforms of ANFIS

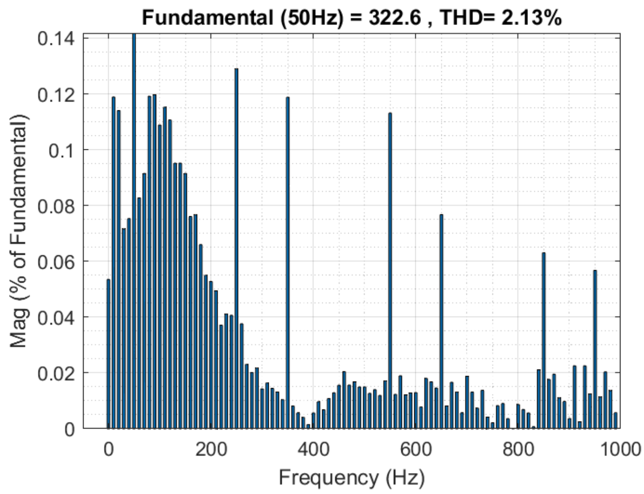

Figure 4.3 Shows the THD% result of ANFIS

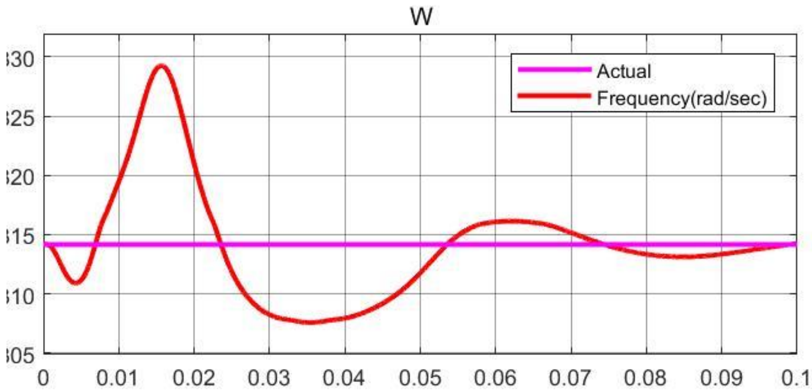

Figure 4.4 Frequency of ANFIS

The ANFIS controller demonstrates improved tracking capacity with much smaller phase error under dynamic conditions. In comparison to the conventional PI control, ANFIS responds to input disturbances and nonlinearities by adapting, promoting faster convergence and reducing steady-state error. The proposed method efficiently alleviates frequency and phase fluctuation resulted from voltage sags, harmonics, and power system noise. The simulation results validate that the ANFIS controller facilitates smooth phase synchronization, even in cases of severe grid parameter fluctuations. The fast response time of the system and low overshoot validate the efficacy of the ANFIS method to ensure stable PLL performance under severe grid conditions.

PI

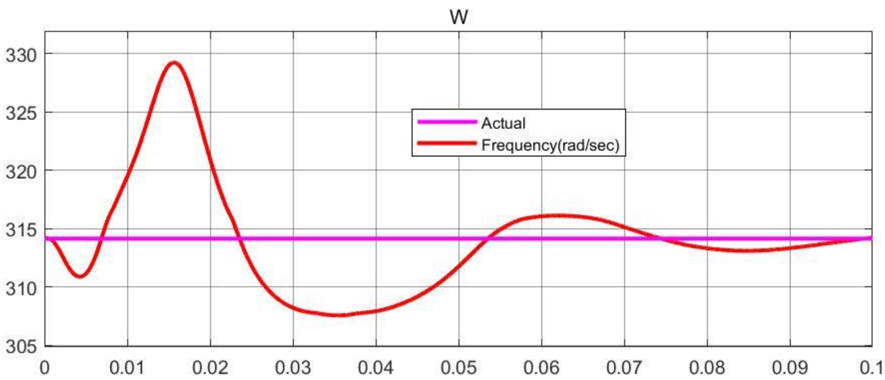

Figure 4.5 Frequency of PI

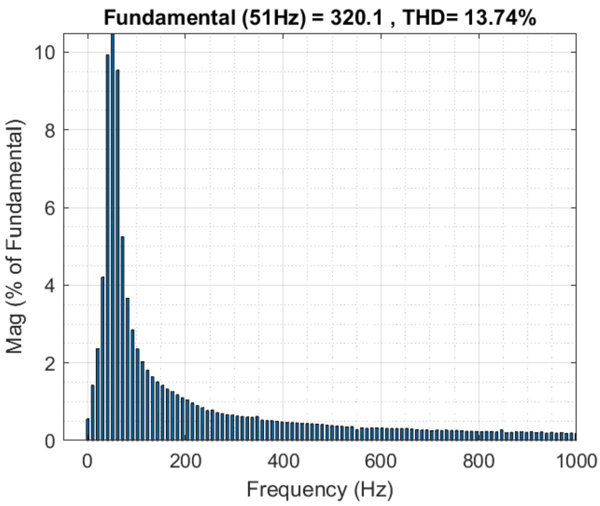

Figure 4.6 Shows the THD% result of PI

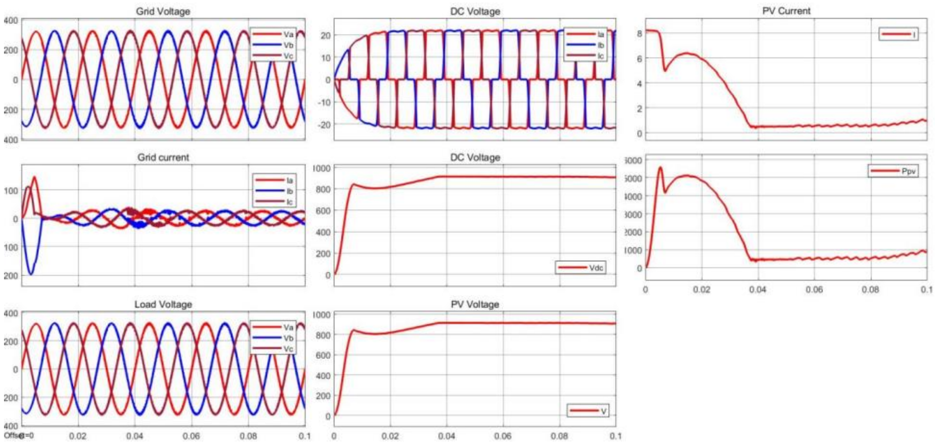

Figure 4.7 Waveforms of PI

The PI controller, despite its widespread use in PLL systems, is deficient in effective management of grid disturbances. Under dynamic conditions, the PI-based PLL exhibits greater phase deviations and slower convergence rate than the ANFIS method. The steady-state error is more significant with greater settling times when dealing with abrupt phase jumps or harmonic distortions. Furthermore, the PI controller is not suitable for high frequency changes, and thus not suitable for all those applications that demand a high resistance to grid variation. The PI approach, while efficient in stable scenarios, lacks the critical adaptability required for the current power systems based on rising uncertainty and unpredictability.

4.1 Discussion

The comparative analysis of ANFIS and PI controllers highlights the adaptive control techniques' role in implementing PLL. The fixed setting of static gains of conventional PI controllers, though widely used, strongly hinders them from efficient control of grid disturbances. PI-based PLL under dynamic conditions is differentiated by phase lag, high settling times, and higher susceptibility to harmonics, which make it less trustworthy under changeable grid conditions. The ANFIS controller demonstrates greater flexibility through learning from previous input-output data and adapting control settings accordingly. The adaptive nature of the ANFIS-based PLL leads to faster convergence, lower phase errors, and better transient response, especially under voltage distorted and frequency oscillatory conditions.

One of the strongest advantages of the ANFIS-based PLL is its capability for synchronization under non-ideal grid conditions. While the PI controller is subject to manual tuning and is troubled by system nonlinearities, ANFIS optimizes control actions adaptively in real-time, offering superior accuracy and reliability. Besides, the new AQF-SRF-PLL design enables removal of unwanted harmonics and noise, thus ensuring higher phase detection accuracy. The characteristics of ANFIS-based PLL make it a perfect candidate for applications demanding reliable grid synchronization, including renewable energy systems, microgrids, and industrial automation.

The results of the research indicate that intelligent control techniques, such as ANFIS, provide significant performance enhancement over traditional techniques in PLL systems. Through adaptive learning and nonlinear control features, ANFIS-based PLLs provide improved phase synchronization, enhanced stability, and increased robustness, making them a state-of-the-art solution for enhancing power systems.

5 Conclusion:

This study demonstrates that the ANFIS-based AQF-SRF-PLL method outperforms conventional PI-based PLL controllers for phase tracking and grid synchronization. The dynamic adaptation of ANFIS to fluctuating grid conditions leads to better response times, lower steady-state error, and enhanced immunity against voltage disturbances and harmonics. Comparative study reveals that the PI controllers, although superior in stable grid operation, fail to control the dynamic and nonlinear conditions and thus are not satisfactory for the current power systems. The ANFIS-based proposed approach provides powerful and intelligent control and thus becomes a best-fitting solution to those applications seeking high accuracy and flexibility. Future research can emphasize enhanced optimization and real-time hardware implementation to test the performance of the system in practical applications. The use of ANFIS-based PLLs in power electronics and renewable energy systems can greatly improve grid reliability and efficiency in the new paradigm of smart power systems.

References:

1) Diddi, Naveen Kumar, and KVNS Pavan Kumar. "An Adaptive Quadrant Filter-based PLL Approach for Grid Connected Multifunctional Inverter." *2023 First International Conference on Advances in Electrical, Electronics and Computational Intelligence (ICAEECI)*. IEEE, 2023.

2) Kumar, K. Sunil Ratna, et al. "Iot and data mining techniques to detect and regulate solar power systems." 2023 International Conference on Inventive Computation Technologies (ICICT). IEEE, 2023.

3) Karim, Shahid, et al. "Current advances and future perspectives of image fusion: A comprehensive review." Information Fusion 90 (2023): 185-217.

4) R.Senthamil Selvan, "Tumor Infiltration of Microrobot using Magnetic torque and AI Technique" by 2023 2nd International Conference on Vision Towards Emerging Trends in Communication and Networking Technologies (ViTECoN), ISSN:0018-9219,E-ISSN:1558-2256,26June2023,10.1109/ViTECoN58111.2023.10157336.

5) Hong, Weidong, et al. "Novel Phase-locked loop Method for three-phase power grid based on double complex coefficient filter via cross decoupling." *2023 2nd International Conference on Smart Grids and Energy Systems (SGES)*. IEEE, 2023.

6) Meraj, Sheikh Tanzim, et al. "An Advanced Frequency Adaptive PLL for Grid Connected Inverters Under Abnormal Grid Conditions." *2023 IEEE International Conference on Energy Technologies for Future Grids (ETFG)*. IEEE, 2023.

7) Gassara, Khalil, Bilel Gassara, and Ahmed Fakhfakh. "Enhanced dqPLL Architecture based on THD Compensation Blocs used in Three-Phase Smart Grid Synchronization." *2022 IEEE 21st International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA)*. IEEE, 2022.

8) Hamouda, Noureddine, et al. "Predictive control of a grid-connected PV system incorporating active power filter functionalities." *2019 1st International Conference on Sustainable Renewable Energy Systems and Applications (ICSRESA)*. IEEE, 2019.

9) Lee, Kyoung-Jun, et al. "A novel grid synchronization PLL method based on adaptive low-pass notch filter for grid-connected PCS." *IEEE transactions on industrial electronics* 61.1 (2013): 292-301.

10) Avudaiappan, Saravana Kumar, et al. "A high-speed frequency adaptive grid synchronization technique for single-phase inverter under distorted grid conditions." *Sādhanā* 47.2 (2022): 69.

11) Ambikapathy, A., et al. "Identification of Suitable PLL Technique for Grid-Connected PV System." *Advances in Power Systems and Energy Management: Select Proceedings of ETAEERE 2020*. Springer Singapore, 2021.

12) Bhuyan, Anshuman, et al. "Fuzzy logic control-based maximum power point tracking for a three-phase grid-connected PV system." *Smart Energy and Advancement in Power Technologies: Select Proceedings of ICSEAPT 2021, Volume 2*. Singapore: Springer Nature Singapore, 2022. 135-144.

13) Ehtesham, Md, and Majid Jamil. "Control Techniques to Optimize PV System Performance for Smart Energy Applications." *Smart Cities—*

Opportunities and Challenges: Select Proceedings of ICSC 2019. Springer Singapore, 2020.

14) Mohammed, Zerouali, and Tidhaf Belkassem. "Single-phase photovoltaic grid-connected inverter based on fuzzy Variable Step Size P&O control." *2021 Fifth International Conference On Intelligent Computing in Data Sciences (ICDS)*. IEEE, 2021.

15) Yada, H. K., M. R. Anumandla, and A. A. J. Basha. "An Adaptive Frequency PLL Approach for Grid Connected Multifunctional Inverter for Residential Applications." *Journal of Physics: Conference Series*. Vol. 2070. No. 1. IOP Publishing, 2021.