Power Quality Analysis of Grid-Tied PV System Using Fuzzy Controller

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Abstract: **Power quality is crucial in three-phase grid-connected solar systems to prevent interruptions and financial losses. The Point of Common Coupling (PCC) is an important location in interconnected energy systems. Power quality that reaches the electrical load connected at PCC is essential for equipment to function properly and prevent damage. For a PV inverter to operate efficiently with fewer harmonic distortions, a suitable grid synchronization strategy must be connected to a capable controller. The study employs fuzzy-based Direct Quadrature control for Pulse Width Modulation inverter control and a Direct Quadrature Phase Locked Loop (DQ-PLL) for grid synchronization. It intends to evaluate how well a fuzzy controller regulates the energy flow, preserves stability, and complies with grid standards in the setting of variable and intermittent renewable energy sources.**

Using MATLAB/Simulink software, this study critically analyzes power quality issues. Total Harmonic Distortion was used as the performance criterion. Using the IEEE 519-2014 standard for harmonic level, the total demand distortion for a fixed resistance-inductive load linked at the point of common coupling is confirmed to be acceptable. Consequently, the findings show that it may be applied successfully as one of the appropriate techniques for incorporating renewable energy into electrical grids, which is dependable with respect to shifts in the dynamics of the power grid.

Keywords: **Grid tied PV, Reference signal generation, Phase Locked Loop, DQ, FLC and Total Harmonic Distortion.**

1. INTRODUCTION

Many sources of renewable energy, such as solar, wind, hydro, geothermal, tidal, and wave energy, came into use in the recent years as they are environmentally friendly and are capable of meeting the increasing energy demands in the upcoming years. Many types of renewable energy technologies are emerging with the aim of renewable power generation at a low cost. The integration of renewable energy into a grid system necessitates the use of power electronic converters. These power electronic converters perform the action of supplying the power generated by RES to the grid. However, many control techniques are implemented to transfer this power in a suitable form. Suitable form here implies smooth power with fewer ripples. This issue is termed as power quality issue [1-3]. The electrical properties of the power supply, such as waveform purity, necessary frequency, and voltage stability, are referred to as power quality. Power plant operating range is determined by grid regulations and standards, which allow grid-connected PV systems to manage power flow to the utility grid and remove storage [4]. Harmonic distortions can cause transformer overheating, protective device malfunctions, and communication signal interference. High power quality is crucial for efficient electrical equipment, while low quality can lead to inefficiencies and equipment damage.

It arises due to a rise in excess harmonic content in the generated power. The harmonics arise mainly due to the non-linear devices, which are power electronic converters and non-linear loads. The researchers had created a variety of current management techniques to reduce harmonics in the inverter's output current waveform and voltage waveform. PI control, proportional resonant control, hysteresis control, and sliding mode control are a few of the essential current control techniques. Three-phase inverters that are connected to the grid are an example of how PI controllers are used. The difficulty of adjusting the controller's gains is the issue with PI control. PR control is characterized by a delayed dynamic reaction. Lastly, there is the hysteresis control, which produces more harmonics by operating at a high switching frequency. These are some of the important controllers [5-8]. Therefore, maintaining power quality in grid-tied PV systems requires an understanding of and commitment to reducing harmonic disturbances.

2. LITERATURE REVIEW

2.1 Ali M. Eltamaly, Almoataz Y. Abdelaziz , "Modern Maximum Power Point Monitoring Methods for Photovoltaic Energy Systems"

PVEs, or solar photovoltaic energy systems, are utilized in remote loads and central power plants. By boosting energy generation and enhancing performance, research seeks to lower energy expenses. One tool that uses controlled methods to monitor the maximum power from PVES is the Maximum Power Point Tracker (MPPT). Partial shading makes traditional techniques like hill climbing and progressive conductance ineffective. Soft computing, metaheuristic methods, and artificial intelligence can all assist in getting beyond these restrictions.

To optimize PVES power, MPPT regulates power electronics converters. For unshaded PVES, conventional techniques such as hill climbing and incremental conductance are sufficient. Local peaks, however, may result from partial shade. This limitation can be lifted by metaheuristic methods, soft computing, and artificial intelligence. Several metaheuristic methods are covered in this book, such as genetic algorithms, particle swarm optimization, gray wolf optimization, ant colony optimization, whale optimization, and simulated annealing. A summary of PVES modeling and performance features is also given, along with an introduction to hybrid approaches.

The development of maximum power point tracking (MPPT) in PV systems from 1954 to 2018 is examined in this book, with an emphasis on the advantages and disadvantages of different strategies. It looks at things like tracking precision, speed, cost, efficiency, number of sensors, complexity, and cost. Monitoring the development of MPPT in PV systems is the goal of the study. Almost all of these optimization strategies have their own disadvantages. Despite having a better theoretical design of the Grey Wolf Optimization (GWO) technique, it has a poorer optimal solution and premature convergence. Recent years have seen a thorough examination of the GWO by Peifeng Niu et al. (2019). "When GWO solves the same optimization function, the farther the function's optimal solution is from 0, the worse its performance" is one of the main drawbacks of using GWO to solve tasks in the real world [9-10].

2.2 Mahammad A. Hannan; Zamre ABD. Ghani; Md. Murshadul Hoque; Pin Jern Ker; Aini Hussain; Azah Mohamed, "Fuzzy logic inverter controller in photovoltaic applications: Issues and recommendations"

Grid-tied PV systems' inverter control systems seek to reduce THD while preserving the AC output voltage at a predetermined frequency and level. To ensure tracking accuracy based on the controller's capabilities, the controller modifies the duty cycle of power devices to follow the reference voltage signal.

Inverter control problems, internal power losses, system nonlinearity, power fluctuation, environmental variation, low PV efficiency, harmonic distortion, DC-bus voltage fluctuation, electromagnetic interface, and unity power factor maintenance have all been extensively studied. Consequently, it is difficult to create an effective inverter controller that will improve a PV system's overall performance. In PV inverter systems, several PID and PI controllers have been used. However, the traditional PID, PI, and other controllers have drawbacks when it comes to intelligent application, grid frequency, and large-scale output filtering. Researchers and developers are using intelligence applications in controllers, such as neural networks, fuzzy logic, and neuro-fuzzy, since PV inverter systems need adaptive control. For three-phase grid-connected PV inverter systems, a supervisory control using an adaptive neuro-fuzzy interface system (ANFIS) can be created to meet grid power demands. However, there are certain network training issues with the ANFIS in a lot of data sets. Meanwhile, because they simplify the process of managing the system's nonlinearity and the mathematical model analysis problem, intelligent controllers may be in high demand in PV inverter systems.

The best intelligent controller for inverter control applications is the fuzzy logic controller (FLC), which outperforms conventional controllers in terms of resilience, sensitivity to changes, and reaction speed. The difficulty of the PV system's implementation depends on the kind of inverter and switching architecture. While complicated inverters

necessitate complex algorithms and higher switching costs, many inverters simplify system design and control. An inverter is essential for connecting a DC power source to an AC load. It converts energy through a control algorithm, ensuring successful power conversion and efficient filtering. The inverter's performance relies on the appropriate controller [11].

3. METHODOLOGY

This study uses a Direct Quadrature (DQ) frame based Fuzzy logic controller for grid synchronization and power quality improvement in Grid tied PV system. A proper grid synchronization approach is needed to be interlinked to a competent controller for the efficient operation of a PV inverter with reduced harmonic distortions. The proposed topology uses DQ PLL synchronization technique is used due to its simple structure, fast, accuracy, and easy implementation. In addition, Fuzzy Logic Controller (FLC) is used for reference signal generation as it outperforms conventional controllers in terms of resilience, sensitivity to parameter and load changes, and reaction time. The result is improved responsiveness and reduction in harmonic distortions at Point of Common Coupling (PCC). The control system is validated by MATLAB Simulation. According to literature [12-14], the PVS is represented by a single diode model.
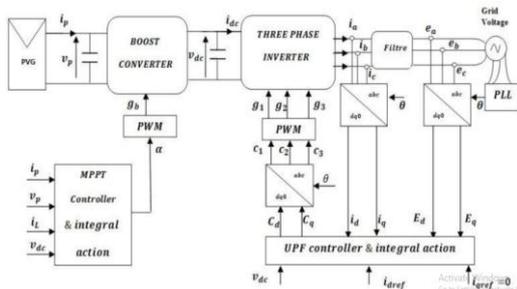

Fig. 1 A three phase grid tied PV system

PV array parameters (997 KW)	
Number of Parallel strings	238
Number of Series-connected Modules per string	79
Maximum Power (W)	53.07
Number of Cells per module	80
Open circuit voltage Voc (V)	21.5
Short-circuit current Isc (A)	3.33
Grid Parameters (Yg- Star grounded connection)	

Grid Frequency (Hz)	60
Phase-to-phase voltage (Vrms)	400
3 phase short-circuit level (MVA)	100

Table. 1 System parameters

3.1 Boost Converter

A boost converter is a power processing tool that enhances the voltage at the inverter's input, enabling a PV panel to transmit power to the utility grid. Pulse width modulation (PWM) technology is used to maximize power output from this converter [15]. Here, the boost converter Switching frequency is 10 kHz.
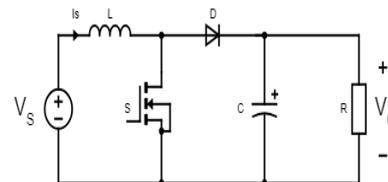

Fig. 2 Boost Converter

By using solar array voltage and current to calculate dI/dV and dP/dV, the MPPT control algorithm integrates a regulator into the incremental conductance approach, reaching the extreme power point when dP/dV is zero. This approach is better than other tracking strategies and works well in scenarios with regularly changing solar radiation [16].

3.2 Phase Locked Loop

A phase lock loop (PLL) is a closed-loop control method used to synchronize the phase and frequency of a utility network with the inverter output specifications. PLLs consist of phase detectors, loop filters, and voltage-controlled oscillators, with SRF PLL being the most commonly used due to its simplicity and speed. It maintains a unity power factor by setting the q-axis current reference to zero [17].
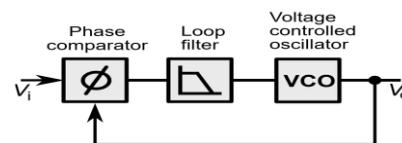

Fig. 3 Phase locked loop

3.3 Reference signal generation

The three-phase instantaneous active and reactive powers, which are produced by a periodic sequence of three-phase voltages and currents, are shown in the dq0 reference frame. In the equations, id and iq are DC variables while Psr and Qsr are continuous signals. The dq-frame control system uses DC variables, as one might anticipate [18].

$$\text{Psr(t)} = 3/2 \; \text{Vsd}(t) \; \text{id}(t) \quad (3.1)$$

$$\text{Qsr(t)} = 3/2 \; \text{Vsd}(t) \; \text{iq}(t) \quad (3.2)$$

The reference currents idr and iqr are the controller's output. The dq-axis reference currents and the corresponding dq-axis instantaneous currents, id and iq along with Vsd and Vsq are operated in dq frame to decouple the dynamics of id, iq. Decoupling the dynamics is done with control inputs Wd and Wq [19]. Vsd and Vsq are the d,q equivalent components of grid voltage.

$$L \; di\text{d}/dt - \text{Lw}(t) \; iq + (R\text{eq}) \; is\text{d} + Vsd = Vtd \quad (3.3)$$

$$L \; diq/dt + L\text{w}(t) \; id + (R\text{eq}) \; isq + Vsq = Vtq \quad (3.4)$$

Following equations are two decoupled linear systems of first order, Wd and Wq, control id and iq.

$$L \; di\text{d}/dt + (R\text{eq}) \; id = \text{Wd} \quad (3.5)$$

$$L \; diq/dt + (R\text{eq}) \; iq = \text{Wq} \quad (3.6)$$

The control loop's equivalent resistance and inductance are denoted by Req and L. In the dq frame, md (12) and mq (13) are the modulation indices as mentioned.

$$md = (2/VDC) * (\text{Vtd}) \quad (3.7)$$

$$m\text{q} = (2/VDC) * (\text{Vtq}) \quad (3.8)$$

Fuzzy Logic Controller

FLC utilizes a fuzzifier, rule base, inference engine, and defuzzifier.

a)   Fuzzification

In this process, the crisp set is used as input data and is fuzzified utilizing membership functions, fuzzy linguistic terms, and linguistic variables to create a fuzzy set.

b)   Rule Base or Membership function

A rule base controls output variables, containing error and change in error, using IF-THEN rules with membership functions. The fuzzy rule base is impacted by input modification.

c)   Defuzzification

By defuzzifying the fuzzy set output of the FLC, non-fuzzy values can be controlled. [20]
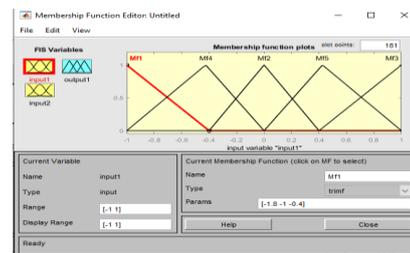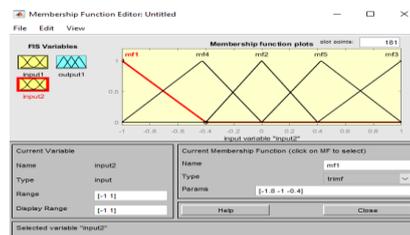

Fig. 4 FIS input variable 1: Error

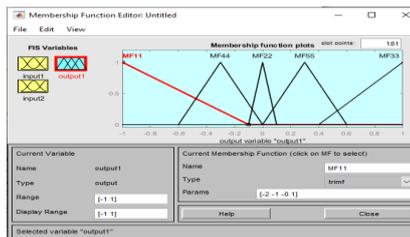Fig. 5 FIS input variable 2: Change in Error

Fig. 6 FIS Output variable

4. RESULTS AND DISCUSSION

A foundation for harmonic limitation is provided by IEEE Standard 519 2014: Recommended Practices and Requirements for Harmonic Control in Electric Power Systems. For a Bus voltage V at PCC ≤ 1.0 kV, the Individual harmonic (%) is 5.0 and Total harmonic distortion THD (%) is 8.0 while considering distortion in voltage [21].
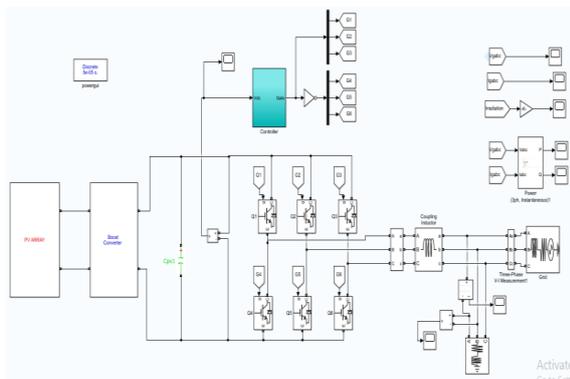
Fig. 7 Simulation model of proposed system

On the other hand, the distortion in current when the ratio (Isc/IL)>1000, the THD is less than or equals to 20.0%

Where, ISC is maximum short-circuit current at PCC, IL is maximum demand load current at PCC under normal load operating conditions.
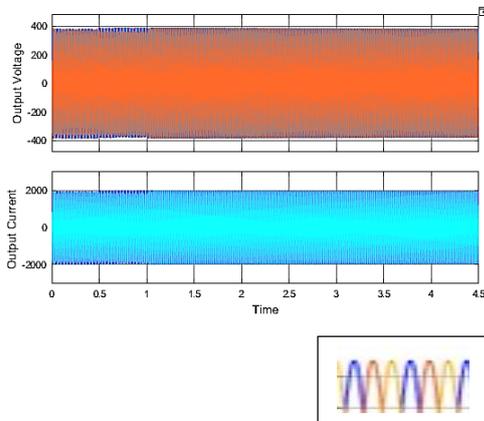

Fig. 8 Three phase a) output voltage b) output current

Voltage and current output from the grid at the Point of common coupling (PCC), are as shown in the fig. 8(a), fig. 8(b) respectively and are sinusoidal waveforms. They are found to be unbalanced till 1.035 [s], after which they are balanced.
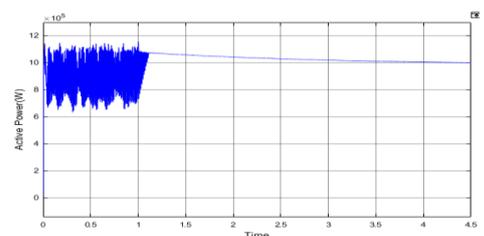
Fig. 9 Three phase output Active power

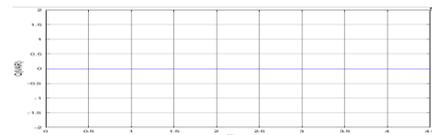The p is oscillating between 10 to 12 (*10^5) as seen in Fig. 9.
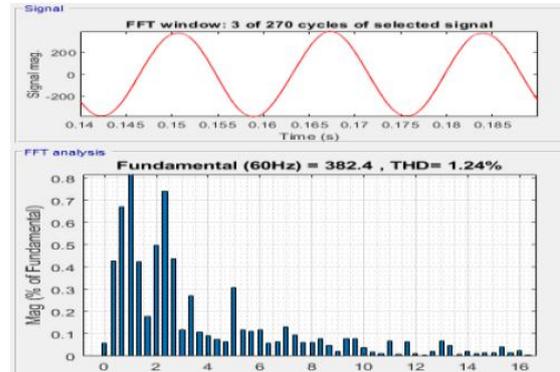

Fig. 10 Q (KVAR)

Fig. 11 Output Voltage THD

As shown in Fig. 11, THD of output voltage is 1.24% & 5th harmonic is 0.3% which is highest among other odd nth harmonics.
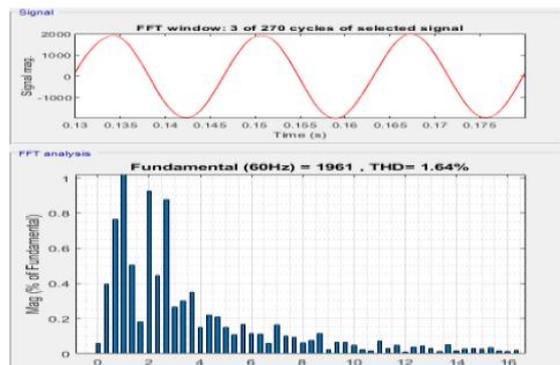

Fig. 12 Output Current THD

As shown in Fig. 12, THD of output current is 1.64% 3rd harmonic is 0.28% and it is highest among other odd harmonics.
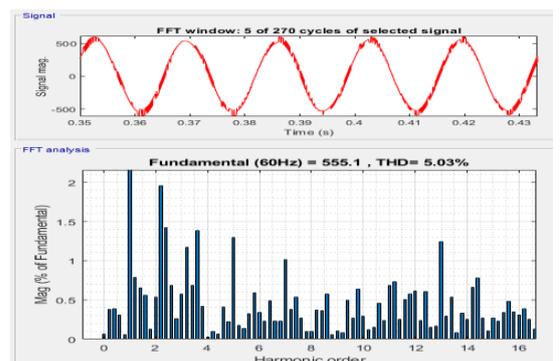

Fig. 13 Load Voltage THD

As shown in Fig. 13, the load voltage distortions are as seen from FFT window and THD is 5.03%. The odd harmonics are present in the percent's of 0.6%, 1.3%, 1%, 0.025, 0.25%, 0.25% between $3 \leq h < 17$.
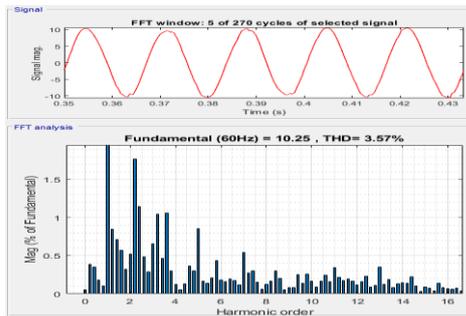

Fig. 14 Load Current THD

The THD of load current is 3.57% as shown in Fig. 14, with significant odd harmonics as 3rd with 0.53% and 5th with 0.57%. Remaining harmonics are very less.
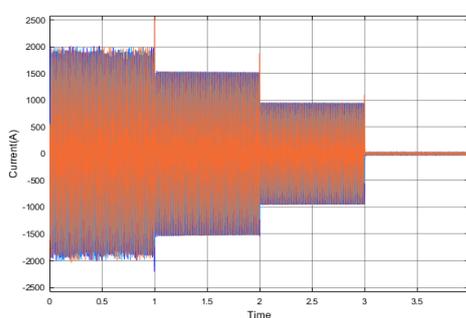

Fig. 15 Output current under varying temperature

Ambient temperature of the PV array is varied from 25'C to 55'C in the steps of 10'C for every 1[s] time duration and the effect on grid parameters is studied.
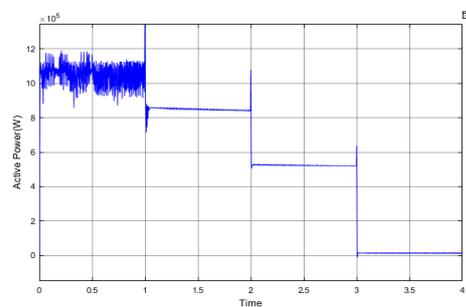

Fig. 16 Active power under varying temperature

From the Figures 15 and 16, it can be observed that output current and output active power of grid is reduced with increase in the ambient temperature of PV array.
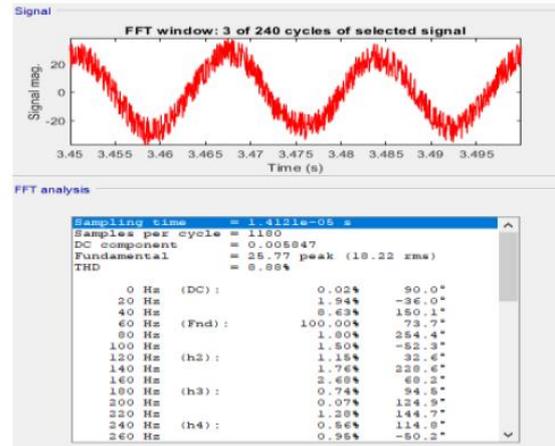

. Fig. 17 Output Current THD at 55'C

As shown in Fig. 17, from FFT window, it can been observed that current distortion is significant and high at an increased temperature of 55 degrees Celsius. At t=3.45[s], THD = 8.88%.
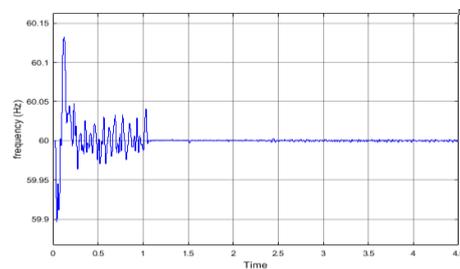

Fig. 18 Frequency(Hz) versus time (s)

Figure 18 shows that the system's operational frequency variation is likewise within the acceptable range of ±0.5% for a 60Hz fundamental frequency according to US grid standards.

5. CONCLUSION

For the efficient operation and quick response of the VSC, a robust and dependable controller is required. The FLC outperforms conventional controllers in terms of robustness and settling time. With a switching frequency of 10 kHz of the converter, this study intends to investigate the nominal current and voltage outputs at Standard Test Conditions (STC).

THD of output parameters and load parameters at PCC is analyzed and validated with the IEEE 514 2014 standard. The output voltage and current THD's are 1.24% and 1.64%, respectively, and their total and individual harmonics are within limits. The load voltage and current THD's are 5.03% and 3.57%, respectively. The total harmonics are within

limits. The lower-order odd harmonics, like the 3rd and 5th, are significant and found to be within the limits. Harmonics were significantly increased at high temperatures.

6. FUTURE SCOPE

Simulation results reveal the inverter's harmonic generation due to the resonating network. Therefore, Hybrid control strategies can be investigated to reduce harmonic generation, further control output current, active and reactive power. Research into adverse control techniques based on a reduced level of complexity is necessary to meet the evolving challenges of the diverse demands of grid-connected PV systems in an efficient way. The number of micro-grids installed and their integration into LV distribution systems will rise sharply in the next few years. So, appropriate control mechanisms need to be created to account for this variation.

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