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A COMPREHENSIVE REVIEW ON HARMONIC REDUCTION IN INTEGRATED SOLAR–WIND ENERGY SYSTEMS USING FACTS CONTROLLERS

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Abstract- The increasing global demand for sustainable and clean energy has accelerated the integration of renewable energy sources such as solar photovoltaic (PV) and wind energy into conventional power systems. However, the combination of these variable energy sources introduces power quality issues, particularly harmonic distortion, due to nonlinear switching devices and fluctuating generation patterns. Harmonics adversely affect system stability, efficiency, and the lifespan of electrical components, making their mitigation a crucial aspect of hybrid renewable system design. This review paper provides a comprehensive analysis of harmonic generation mechanisms in integrated solar–wind energy systems and evaluates the role of Flexible AC Transmission System (FACTS) controllers in minimizing these distortions. Various FACTS devices such as Static VAR Compensators (SVC), Static Synchronous Compensators (STATCOM), and Unified Power Flow Controllers (UPFC) are discussed in terms of their operational principles, control strategies, and harmonic suppression capabilities. The paper also compares conventional control methods with advanced techniques like fuzzy logic, artificial neural networks, and adaptive controllers used in FACTS-based harmonic mitigation. Furthermore, the study explores grid codes, IEEE standards for power quality, and recent trends in hybrid renewable grid interfacing. The review concludes that the coordinated operation of FACTS controllers significantly enhances power quality, voltage stability, and harmonic reduction efficiency in integrated renewable systems. Future research directions focus on the development of intelligent hybrid control strategies and cost-effective FACTS configurations optimized for large-scale renewable integration.

Keywords: Harmonic Reduction, Integrated Solar–Wind System, FACTS Controllers, Power Quality Improvement, STATCOM, Renewable Energy Integration

I. INTRODUCTION

1.1 SOLAR WIND HYBRID POWER SYSTEM

A Solar-wind hybrid system is a combination of two power sources together i.e Two types of Renewable Energy (Solar Power and Wind Energy) will ensure better sustainability and sufficiency power supply. These combine the fact that both solar and wind resources vary naturally, which means a weakness of one is oftentimes balanced by strength in another source if they are taken together. Key Components of Solar-Wind Hybrid Systems as shown in Fig.1.1

- PV Panels
- Wind Turbine
- Controllers
- Inverter & converter
- Energy Storage System
- Filter

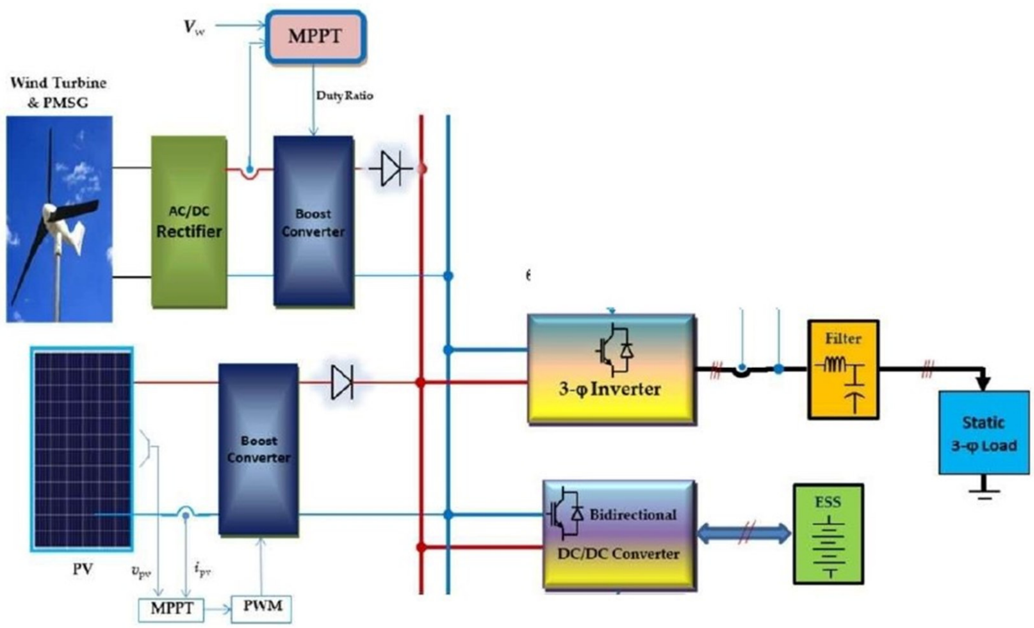

Fig. 1. Block Diagram of Hybrid Solar Wind Power System

1.2 WORKING PRINCIPLE

A solar-wind hybrid system is a combination of two power generating systems i.e. both, the solar panels and wind turbines generate electricity depending upon sunlight availability, or less predictive functions for energy cost-effective frequency time are included in this research work. This electricity can be efficiently supplied to loads, charged into energy storing elements.

- Solar panels use sunlight to create electricity and wind turbines can generate power during high-wind days.

- Nighttime with Wind: The wind turbines can generate electricity while solar panels are inactive.
- Low Wind and Sunlight: During such times, stored energy in batteries is used to maintain power supply, or backup generators may be activated.

Solar-wind Hybrid Systems for Clean and Reliable Power Generation — A Promising Solution Integrating the more consistent power of solar and wind resources, these systems can provide a less volatile source of energy while decreasing reliance on fossil fuels. With continuous improvements in control techniques and storage solutions, solar-wind hybrid systems keep contributing significantly towards the world transition to other renewable power supplies.

II. REVIEW OF LITERATURE

Khazaal et. al. proposed a multi-port bidirectional DC- DC converter, to address the issue of power transfer across wind, solar, and battery subsystem. The power balance and voltage stability of the whole wind-solar complementing system have been improved using a distributed model predictive control technology. This reduces the number of DC-DC converters required and their total cost. As shown in the studies, the distributed model predictive control approach seems to be compatible with the DC-DC converter type wind/solar complementing system. In comparison to the conventional method of regulating things, its optimization rate is high and the system's safety and reliability are taken care. [3]

Kumar and Balakrishna analysed hybrid fuzzy logic MPPT controller for solar PV systems under partial shading conditions. It explores advanced techniques like the Modified Differential Step Grey Wolf Optimization (MDSGWO) combined with a fuzzy logic controller to enhance the efficiency of solar energy extraction in challenging conditions such as partial shading. [5]

Jun Mei et. al. discussed an energy storage system-friendly, non-isolated, bidirectional dc-dc converter. These two boost converters, which are linked together in series, make up the power source for this converter. A switched-capacitor cell is set up on the side with a lot of electricity. One of the converter's low-voltage sides has two separate inductors removed in favor of one that is linked together. [6]

Lazar et. al. developed fault-tolerant systems for current-fed dual active bridge converters (CF-DAB) since the main and secondary sides are not identical. Adding blocking capacitors on both sides of the transformer is one technique to ensure that the frozen phase solution is fault-tolerant. Blocking capacitors are employed to prevent the DC current component of the filter inductor from passing through the transformer and causing it to fail, which would be detrimental to the transformer. When the frozen-phase fault-tolerant approach is applied, the DC blocking capacitors assist in isolating the non-functioning phase. [7]

Chen et. al. developed a digital adaptive frequency modulated bidirectional dc-dc converter that can be used in an energy management system. The frequency has to meet the Zero Voltage System (ZVS) criterion every time. Because this method doesn't need a Zero Crossing Detector (ZCD) circuit, it can be used with a lot of different circuit designs. In order to meet the zero voltage system criterion, the suggested system can handle a wide range of battery and bus voltages (between 12 V and 24 V). It can also handle a wide range of loads. An interleaved bidirectional dc-dc converter topology is used to test the digital adaptive frequency regulation that was suggested. Interleaving reduces effective conduction loss and current ripple, which makes the converter more efficient and effective. [8]

Subrahmanya et. al. proposed a new bidirectional DC-DC converter for dual voltage automotive systems that doesn't use any power when switching. Two extra switches are used with two resonant inductors and two capacitors to make an even better DC-DC converter. This converter's main job is to change low-voltage input signals into high-voltage output signals. Two extra resonant networks are used to run the ZCS procedures. ZCS can also be turned on and off with extra switches because the extra costs are so small. In this study, the operating principles and design simulation analysis are shown to show that the theoretical analysis is correct. It is done on a converter system that has a 100/350V/500W system with a 75kHz switching frequency. [9]

Tariq et al. presented an effective control strategy for supplying electricity to marine loads, primarily lighting and heating, using a PV-powered hybrid energy storage system (HESS) integrated with a traditional diesel generator. Furthermore, considering the irregularity of PV generation, multiple feasible operating modes for achieving optimal performance are outlined and validated using simulation findings. Meanwhile, the suggested control strategy makes significant contributions such as maximum power extraction from PV panels, power factor single functioning of the utility grid, and increased dependability of associated loads.[10]

Moumani et al explained the modelling and management of WECS' PMSG (Permanent Magnet Synchronous Generator) (Wind Energy Conversion System). A Non-Linear control method based on backstepping is used to control the RSC (Rotor Side Converter). The ultimate goal is to extract as much power as possible from WT (Wind Turbine). This is accomplished by independently controlling the PMSG's active and reactive power. The Matlab/Simulink software environment was utilised to assess and simulate the performance of this control technique. As a result, the performance of the system is judged in terms of its ability to withstand random variations in wind speed and other parametric anomalies. Simulations reveal that this approach outperforms more traditional linear controllers in terms of overall performance. [11].

Cao et al. discussed the basic technique for modelling the microgrid as a multi-negative feedback system (MIMO) integration into the overall system structure was created based on the communication method (CCM) to separate the inverter and the passive network system. The features of the measured inverter terminals can be used to examine the low-low relative to baseline frequency by applying Generalized Nyquist Stability Criteria (GNC) to the echo rate and the predawn matrix of the MIMO system model. The 37-bus microgrid analysis and simulation validate the effectiveness of the stability analysis method. [12]

III. MAXIMUM POWER POINT TRACKING

Maximum Power Point (MPP) is defined as the point at which the solar module produces the most electricity. Maximum current and maximum voltage are the current and voltage related to this point (I_{mpp} and V_{mpp}). During regular operation, the solar panel does not produce its full power. It is preferable to use a clever algorithm to maximise conversion efficiency. It is also critical to connect the module to the load such that the maximum load power is accessible. Fig. 2 depicts the block diagram of the Maximum Power Point Tracking (MPPT) for solar system.

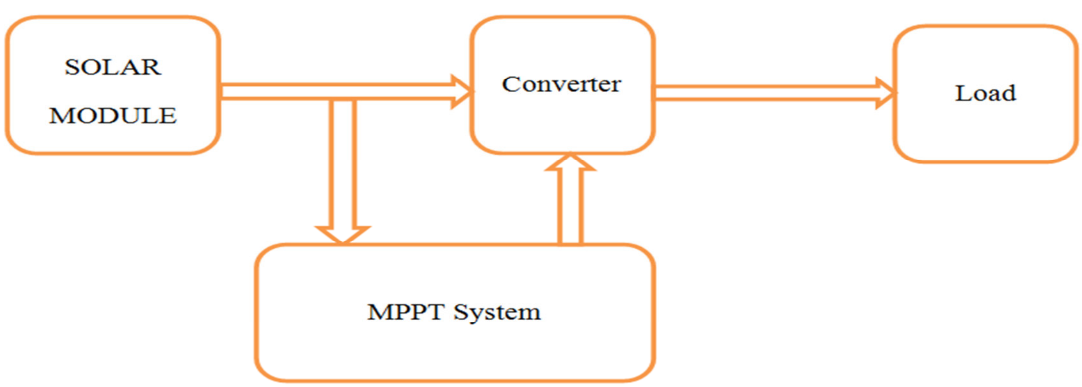

Fig. 2. Block Diagram of MPP Tracking for Solar System

3.1 MPPT TECHNIQUES

In this section we will cover the different MPPT techniques and the proposed technique Fuzzy Logic Control.

3.1.1 FUZZY LOGIC CONTROL MPPT TECHNIQUE

One important component of solar power systems is Maximum Power Point Tracking (MPPT), which continuously modifies the operating point to the maximum power point to guarantee the solar panels run as efficiently as possible. MPPT approaches can benefit from the application of Fuzzy Logic Control (FLC), a control strategy that can improve performance, particularly in scenarios where the operating conditions are unpredictable or dynamic.

An outline of how Fuzzy Logic Control can be used with MPPT is provided below:

- Design of a Fuzzy Logic System

  Inputs: In an MPPT system, the solar irradiance (G) and the variation in solar irradiance are usually the main inputs to the fuzzy logic controller.

  Output: The output is the duty cycle or operational point where the solar cell produces the maximum amount of power.

  Membership Functions: Specify language variables (such as low, medium, and high) for inputs and outputs that correspond to the various system states.

- Base of Rules

  Create a map between the input and output variables using a set of fuzzy rules. These guidelines are derived from empirical observations or professional knowledge.

  Example rule: Increase duty cycle IF irradiance is high AND irradiance change is positive.

- System of Inference

  Utilise fuzzy logic inference techniques (such as Sugeno or Mamdani) to ascertain each input's degree of membership in the fuzzy sets that the membership functions have defined.

  Integrate the fuzzy rules to produce a clear result.

- Defuzzification

  Transform the indistinct output into a distinct control action. This can be the duty cycle modification required in the MPPT situation.

- Implementing a Controller

  Use the MPPT algorithm's fuzzy logic controller. This entails incorporating the fuzzy logic block into the MPPT system's control loop.

Advantages of MPPT's Fuzzy Logic Control

- Robustness: Fuzzy logic controllers exhibit robustness in varying climatic conditions due to their ability to handle uncertainties and variances in the solar power system.
- Adaptability: The tracking accuracy of fuzzy logic systems can be enhanced by their ability to adjust to the dynamic and nonlinear properties of the solar panel system.
- Ease of Implementation: Compared to certain other control systems, FLCs are comparatively simple to implement, and they frequently call for less accurate mathematical models of the system.

Steps for Fuzzy Inference System.

Step 1. Define input and output variables.
Step 2. Specify membership functions for each variable.
Step 3. Create fuzzy rules based on expert knowledge.

3.1.2 PERTURB AND OBSERVED MPPT TECHNIQUE

The Perturb and Observe (P&O) algorithm is also known as "climbing," however depending on its application, both terms relate to the same method. The correction consists of interrupting the power cycle of the power converter and P&O, as well as interrupting the working power of the DC link between the photovoltaic array and the power converter. On the plus side, tripping the circuit breaker on the power converter changes the DC link between the PV array and the power converter, allowing one technology to refer to the same technology. The final turbulence and the rise in the final turbulence signal are used in this method, to forecast the upheaval that will follow. The trial and error method, also known as the P&O method, works by changing the terminal voltage of the solar array by one small step V. It then compares whether the array's power output grows or decreases. The V of the following disturbance cycle is eliminated or added depending on the outcome. Furthermore, because V is fixed in size. A small step size produces sluggish but correct results, whereas a large step size produces slow but accurate results. Furthermore, because the P&O process constantly monitors the power output, i.e. increases and decreases the terminal voltage, the correct MPP will never be achieved. Rather, it oscillates about the MPP. Overall, the P&O method works effectively. The step size, on the other hand, determines tracking and accuracy. Furthermore, unpredictable behaviour was observed when a rapid shift was tracked and the MPP searched in the wrong direction. The algorithmic steps as per flowchart shown in Fig. 3 is as follow.

Step 1: Measure the two consecutive values of voltages and currents of solar PV.

Step 2: Calculate the powers P(n) and P(n-1).

Step 3: If the powers are increasing, then decrease the duty cycle.

Step 4: If the powers are decreasing, then increase the duty cycle.

Step 5: Go to step 1."

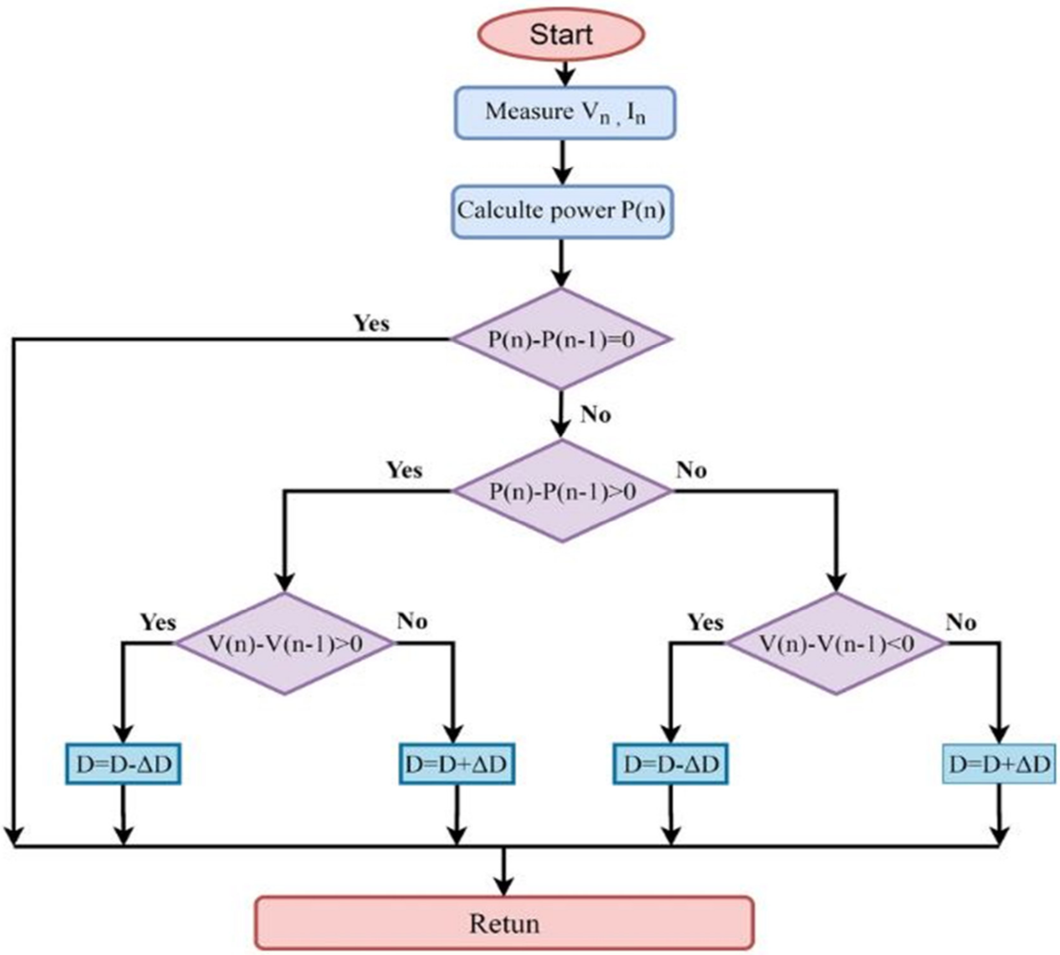

Fig. 3. The Flowchart of the P&O Algorithm [8]

3.1.3 INCREMENTAL CONDUCTANCE

The Incremental Conductance Maximum Power Point Tracking (MPPT) technique is one of the most efficient algorithms used to maximize the power output of photovoltaic (PV) systems. Its primary function is to dynamically adjust the operating point of the PV system to ensure that it operates at or near the maximum power point (MPP), even as environmental conditions such as temperature and irradiance change.

Key Principles of Incremental Conductance MPPT.

(i) Relationship between Power and Voltage - The maximum power point occurs when the derivative of the power with respect to voltage (dP/dV) is zero. The power can be expressed as

$$P = V \times I$$

Where, P is power, V is voltage and I is current.

(ii) Derivative Analysis - By differentiating the power equation with respect to voltage.

$$dP/dV = d(V \times I)/dV = I + V \times dI/dV$$

- At the MPP: $dP/dV = 0$ which leads to the condition $I = -V \times dI/dV$
- If $dP/dV > 0$, the operating point is to the left of the MPP (lower voltage).
- If $dP/dV < 0$, the operating point is to the right of the MPP (higher voltage).

(iii) Basic Idea: The Incremental Conductance method works by comparing the instantaneous conductance (I/V) and the incremental conductance (ΔI/ΔV). Depending on the result of this comparison, the algorithm adjusts the voltage or current to track the MPP:

- If $\Delta I/\Delta V = -I/V$, the system is at the MPP.
- If $\Delta I/\Delta V > -I/V$, the voltage is too low, and the operating point is to the left of the MPP.
- If $\Delta I/\Delta V < -I/V$, the voltage is too high, and the operating point is to the right of the MPP.

(iv) Tracking the MPP: The algorithm continuously measures the change in current and voltage and adjusts the duty cycle of the DC-DC converter (such as a boost converter) to bring the PV system to its optimal power point.

The algorithmic steps as per flowchart shown in Fig. 1.4 is as follow.

Step 1: Sense the voltages and current of solar PV

Step 2: Calculate the incremental changes in voltage (ΔV) and current (ΔI).

Step 3: Compare the incremental conductance with the instantaneous conductance.

Step 4: Adjust the operating voltage or current based on the comparison to approach the MPP.

Step 5: Repeat continuously to adapt to changes in environmental conditions i.e. go to step 1.

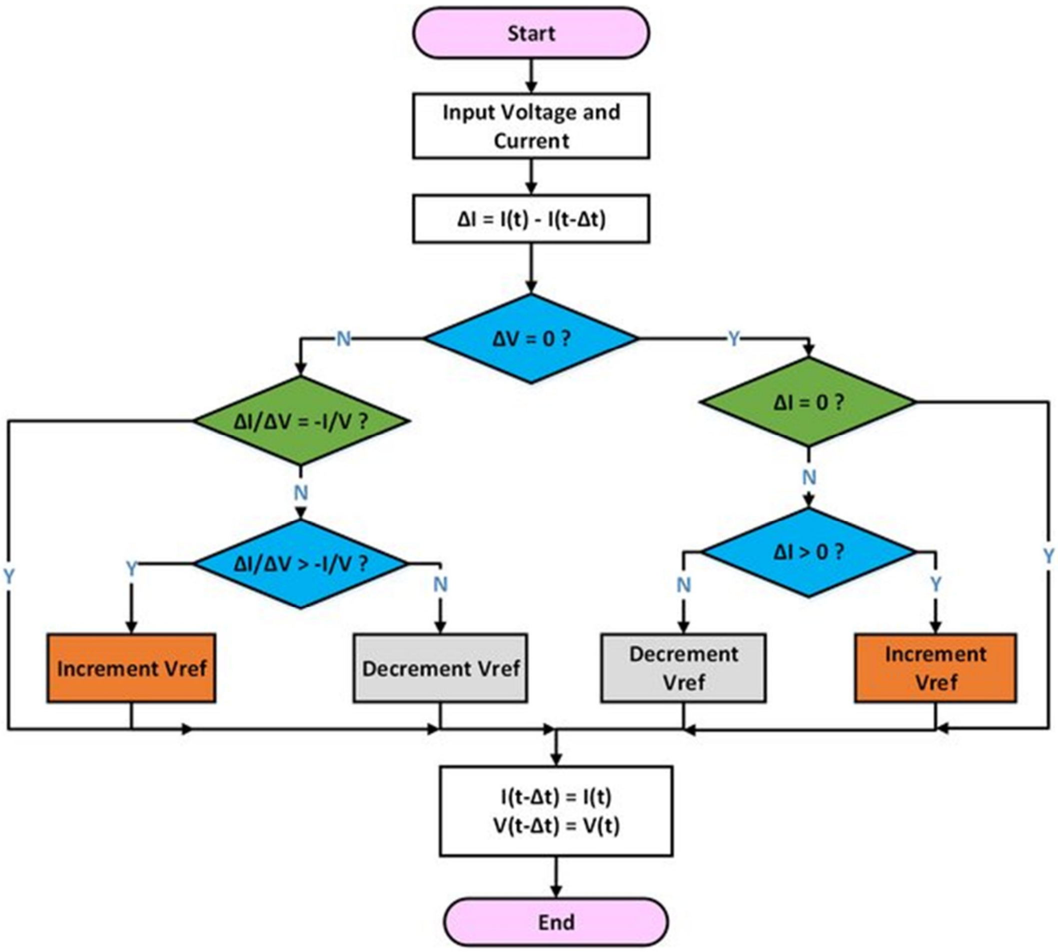

Fig. 4. The Flowchart of the Incremental Conductance Algorithm

This is the result of the control voltage or current in the MPP failing to oscillate continuously. The magnitude of the oscillation depends on the magnitude of the orientation voltage's rate of change. The greater the magnitude of the oscillation's amplitude, the more crucial it is. However, the rate of MPP acquisition also depends on the conversion rate, and this dependence increases as the power gain increases. Standard technique is the consensus: if the rise is minimal, the oscillation decreases and the MPP arrives slowly, and vice versa. In recent years, initiatives involving abrupt changes in environmental conditions have been initiated to address these restrictions. In which additional measurements were taken devoid of moderate and current restrictions. In this method, all three successive samples are used to estimate the effect of the (current) power surge and the influence of the change in conditions, so that the power rise utilized by the algorithm is

IV. CONCLUSION

The integration of solar and wind energy systems into existing electrical grids presents significant challenges related to power quality, primarily due to the nonlinear nature of converters and inverters. The reviewed literature indicates that harmonic distortion levels increase with the penetration of renewable energy sources, particularly under variable load and generation conditions. FACTS controllers have emerged as an effective solution to address these challenges by providing dynamic voltage regulation, reactive power compensation, and harmonic filtering.

Among the various FACTS devices, STATCOM and UPFC demonstrate superior harmonic mitigation capabilities due to their fast response and adaptability to changing grid conditions. SVCs are widely used for cost-effective reactive power control but show limitations under dynamic harmonic loads. Advanced control strategies such as fuzzy logic, artificial neural networks (ANNs), and model predictive control (MPC) further enhance the performance of FACTS devices by enabling real-time optimization and adaptive operation. The discussion also highlights that the effectiveness of harmonic reduction depends not only on the type of FACTS controller but also on the placement strategy, control algorithm, and coordination with renewable energy converters.

However, challenges remain in terms of the economic feasibility, complexity of control, and scalability of FACTS-based systems in large-scale hybrid renewable grids. Recent research trends indicate a growing interest in hybrid compensation systems, where multiple FACTS controllers operate in coordination to achieve both power quality improvement and voltage stability. Moreover, the incorporation of artificial intelligence and machine learning algorithms in control design has shown promising results in predicting and mitigating harmonic distortion dynamically.

V. FUTURE SCOPE

The current feature of the reduction in the Hormones of the Solar-Hurry Hybrid Power System with Fuzzy Logic Control MPPT technique shows the effectiveness of intelligent control to optimize power extraction and improve power quality. Construction of this research, the following future development is proposed:

1. Real -time implementation

Future work can focus on the development and testing of the proposed system using real -time hardware such as DSP, FPGA or microcontroller. This will help to validate the simulation results and assess practical challenges in control, stability and hormonic deficiency.

2. Integration of energy storage systems

Including battery energy storage systems (BESS) or supercapacitors can help handle fluctuations in power generation, the reliability of the system can improve, and load can support balance, especially in standalone or weak web applications.

3. Advanced Hybrid MPPT algorithms

The performance of fuzzy logic-based MPPT can be compared to other intelligent algorithms such as artificial nerve networks (Ann), adaptive neuro-fuzzy invention system (ANFIS) or hybrid methods, which will further increase MPPT-efficiency in rapidly changed environmental conditions.

4. Expansion of web -connected operation

The current model works in standalone mode. Future work can detect landscapes associated with networks, focus on voltage and frequency control synchronization, contribution requirements, match code for grid code and advanced control strategies.

5. Use of increased power quality equipment

While DVR has been used for hormonic mitigation, future research may evaluate and compared to equipment for other facts such as Unified Power Quality Conditioner (UPQC), static synchronous compensator (STATCOM) or hybrid filter for better power quality and dynamic compensation.

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