ADVANCED ENERGY MANAGEMENT AND POWER QUALITY CONTROL OF HYBRID RENEWABLE ENERGY SYSTEMS USING AN ANFIS-BASED COORDINATED CONTROLLER

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Abstract: Significant issues pertaining to power imbalance, power quality deterioration, voltage variations, frequency deviations, and intermittent power generation have been brought about by the growing incorporation of renewable energy sources into contemporary electrical grids. One efficient way to increase the use of renewable energy and the reliability of the system is to install a hybrid renewable energy system (HRES), which combines various renewable energy sources like wind and solar photovoltaics (PV) with energy storage batteries (BESSs). An advanced strategy for managing energy and controlling power quality in a hybrid renewable energy system is proposed in this paper. The controller is based on an Adaptive Neuro-Fuzzy Inference System (ANFIS). To optimize power flow management and improve power quality, the suggested controller integrates artificial neural networks' learning capabilities with fuzzy logic's decision-making capabilities. In response to fluctuations in renewable power output and load demand, the ANFIS controller dynamically adjusts the power transferred between the PV system, wind energy conversion system, battery energy storage system, grid, and load. Additionally, the suggested method of control enhances current quality, harmonic performance, power factor, and voltage regulation in response to dynamic operating circumstances. In MATLAB/Simulink, the system is modeled and tested under various operational situations, such as variations in renewable energy, changes in load, and disruptions to the grid. In comparison to traditional control methods, the anticipated outcomes show that the suggested ANFIS-based coordinated control strategy improves energy utilization, system stability, power quality disturbances, and dynamic performance.

Index Terms— Power Quality, Energy Management, Renewable Energy Integration, Solar PV, Wind Energy, ANFIS, Coordinated Control, and Battery Energy Storage Systems are all parts of a hybrid renewable energy system.

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I. INTRODUCTION

Growing environmental concerns and the ever-increasing need for electricity have hastened the incorporation of renewable energy sources into contemporary power grids. Due to their vast availability and environmentally friendly operation, solar photovoltaic and wind energy systems have become some of the most popular renewable energy technologies. Nevertheless, there are a number of technological hurdles in running the power system that are brought about by the intermittent and unpredictable character of renewable energy production. Power fluctuations, voltage deviations, frequency variations, and poor power quality can be caused by changes in sun irradiation, temperature, wind speed, and load demand.

When compared to standalone renewable energy systems, the benefits of integrating several renewable energy sources into a hybrid system are substantial. With a hybrid system, you may take use of the best features of many renewable energy sources. For instance, photovoltaic (PV) systems typically produce their most electricity during the day, but wind turbines may keep turning even when the sun isn't shining. When used in tandem, these technologies can increase the availability of renewable energy sources while decreasing reliance on traditional grid electricity. Achieving dependable operation, however, requires excellent coordination among loads, energy storage devices, renewable energy sources, and the utility grid. Renewable energy sources, load demands, battery charging status, and grid operating circumstances are all factors that must be considered by the energy management system in order to ascertain the best power-sharing method. Performing poorly in extremely nonlinear and dynamic operating situations is a common problem with traditional control systems that rely on fixed proportional-integral (PI) controllers.

The use of control techniques based on artificial intelligence has garnered a lot of interest for renewable energy applications. Adaptive Neuro-Fuzzy Inference System is one such method that combines the best features of neural networks with fuzzy logic. Even while it still uses rules to make decisions, ANFIS is able to discover nonlinear connections from data used for training. So, it's a good fit for creating smart systems for controlling power quality and managing energy.

In order to improve power quality and implement advanced energy management in a hybrid renewable energy system, this research suggests a coordinated control technique based on ANFIS. All of the following components make up the suggested system: photovoltaic (PV) panels, wind turbines, batteries, grid connection, and loads on the ground. The ANFIS controller is responsible for coordinating the subsystems' operations and, depending on the operating conditions, determining the proper commands for the flow of power.

Here are the key points of this work:

1. Constructing a solar photovoltaic (PV) system that integrates with wind power, battery storage, the grid, and the load.
2. The creation of a coordinated controller for intelligent energy management that is founded on ANFIS.
3. Integrated management of power flow among renewable energy sources, energy storage batteries, the grid, and the load.
4. Harmonic performance, power factor, current quality, and voltage control are all enhanced.
5. Assessment of the suggested control approach in relation to different loads and levels of renewable generation.

II. SYSTEM CONFIGURATION

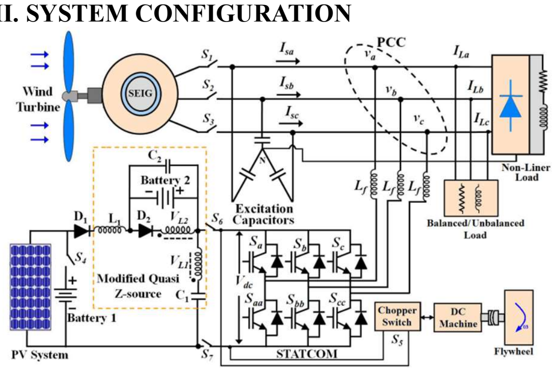

Fig1. The wind energy conversion system with qZSI-STATCOM integrated.

Here are the main parts of the renewable energy hybrid system that has been proposed:

- Power plant that uses solar energy
- Conversion mechanism for wind energy
- Converters for direct current to direct current power sources
- Power storage system using batteries
- Turnkey battery charger
- DC-coupled capacitor
- DC-powered energy converter
- current and direct current loads
- ANFIS-based controller that is coordinated

Operating in grid-connected mode is the intended operation of the entire system. When there is an abundance of power, the renewable energy sources take over. When renewable energy sources aren't producing enough electricity, the battery energy storage system steps in to fill the gap. In addition to supplying additional electricity, the grid may also soak up surplus power, all dependent on the approach to energy management.

Our hybrid system's power balance is defined as

$$P_{PV} + P_{wind} + P_{bat} + P_{grid} = P_{load} + P_{loss}$$

where P_PVis the power produced by the photovoltaic (PV) system, P_windis the power produced by the wind energy conversion system, P_batis the power produced when the batteries are charged or discharged, P_gridis the power produced by the grid, and P_loadis the demand for load.

In order to decide on the best power-sharing instruction, the controller constantly checks these power variables.

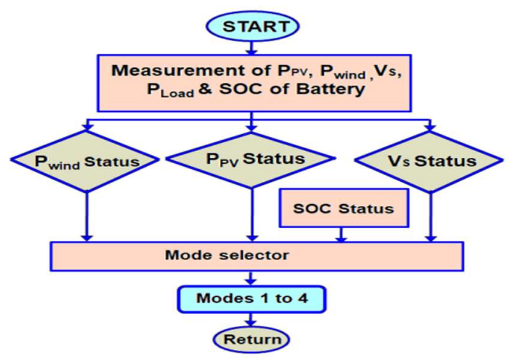

Fig. 2: Operating mode selection flowchart for PV-qZSI-STATCOM.

III. SOLAR PV GENERATION SYSTEM

Solar photovoltaic (PV) subsystems transform solar radiation into usable electricity. Solar radiation and cell temperature affect the PV array's output power. A DC-DC converter controls the operating voltage and draws the most power from the PV array.

One way to express the power that PV modules produce is

$$P_{PV} = V_{PV} I_{PV}$$

Considering the PV voltage (V_PV) and the PV current (I_PV).

In order to get the most out of the solar array, the PV converter might have a maximum power point tracking algorithm installed. Changes in temperature and sun irradiation cause a constant variation in the maximum power point. To maximize the use of solar power, the suggested system integrates the PV subsystem with an energy management controller based on ANFIS.

IV. WIND ENERGY CONVERSION SYSTEM

The mechanism for converting wind energy uses the kinetic energy of the wind to generate electricity. Depending on the setup of the system, either a squirrel-cage induction generator or a permanent magnet synchronous generator can be used.

The mechanical power that the wind turbine produces is provided by

$$□_{□□□□} = \frac{1}{2}□□□_{□}(□,□)□^{3}$$

When it comes to:

- □how dense the air is,
- □equals the turbine's swept area,
- $□_{□}$ is the coefficient of power,
- □ does the ratio of tip speed
- □ is an angle at which the blades are pitched, and
- □ represents the velocity of the wind.

Power output is dynamic due to the fact that wind speed is always changing. In response to changes in both generating capacity and load demand, the suggested coordinated controller regulates the wind system's power contribution.

V. BATTERY ENERGY STORAGE SYSTEM

To make up for the fact that renewable energy output isn't constant, the battery energy storage technology is implemented. There are two main things it does:

Charging Mode

There will be a surplus of renewable energy when it outstrips the demand for electricity.

$$□_{□□} + □_{□□□□} > □_{□□□□}$$

The battery is charged using the surplus energy.

Discharging Mode

When power from renewable sources is inadequate,

$$□_{□□} + □_{□□□□} < □_{□□□□}$$

Recharging the battery fills the power gap.

One key metric in energy management is the battery's charge level. A rough approximation of the state-of-charge connection is

$$□□□(□) = □□□(□_{0}) + \frac{1}{□_{□□□}}\int_{□_{0}}^{□} □_{□□□}(□)□□$$

in which $□_{□□□}$in which $□_{□□□}$ symbolizes the current flowing through the battery.

To keep the battery state of charge (SOC) within specified parameters, the battery converter is regulated. This stops the battery from being overcharged or discharged too much.

VI. PROPOSED ANFIS-BASED COORDINATED CONTROL STRATEGY

A. ANFIS Controller Structure

In order to provide appropriate control commands depending on the state of the system, the suggested controller employs an Adaptive Neuro-Fuzzy Inference System.

There are five main layers that make up the ANFIS controller:

Layer 1: Fuzzification

We transform the input variables into fuzzy membership values. Common variables used as inputs consist of:

- Generation of electricity from renewable sources
- Demand for load
- Battery charging status
- Error in DC-link voltage
- AC voltage inaccuracy
- Disparity in power

Layer 2: Rule Layer

It is the input variables' relationships to the necessary control action that the fuzzy rules establish.

One common way to express a rule is:

Assuming a high state of charge (SOC) and low renewable power, the discharge power from the battery will be modest.

Layer 3: Normalization Layer

Each rule's relative contribution is determined by normalizing its firing strength.

Layer 4: Defuzzification Layer

To create the controller output, the normalized rule outputs are mixed.

Layer 5: Adaptive Output Layer

By optimizing adaptive parameters during training, the final control signal is formed.

B. ANFIS Inputs and Outputs

The following inputs could be utilized by the proposed ANFIS controller:

$$□_{□} = □_{□□□} - □_{□□□□}$$
$$□_{□□□} = □□□_{□□□} - □□□$$

This is where the power imbalance (e_P) and the battery state-of-charge error (e_SOC) are defined.

The ANFIS controller produces the following outputs:

- Reference for charging and discharging batteries
- Electricity grid reference
- Duty ratio of converters
- Voltage reference inverter
- A resource for reactive power correction

Because of this synchronized controller, energy management and power quality enhancement may happen at the same time.

ENERGY MANAGEMENT STRATEGY

Under these circumstances, the suggested energy management system will function.

Case 1: Excess Renewable Power

If

$$□_{□□} + □_{□□□□} > □_{□□□□}$$

If the battery's state of charge is lower than its upper limit, the surplus renewable energy is first used to charge the battery.

It is possible to export any excess power to the grid after the battery is charged to full capacity.

Case 2: Renewable Power Deficit

If

$$\square_{\square\square} + \square_{\square\square\square\square} < \square_{\square\square\square\square}$$

When the state of charge (SOC) of the battery exceeds the lowest allowable value, it will fill the gap.

Power is drawn from the grid when the battery state of charge drops too low.

Case 3: Low Renewable Generation and Low Battery SOC

The grid steps in to meet the remaining load demand when renewable power sources are exhausted and the battery reaches its minimum state of charge.

Case 4: High Renewable Generation and Full Battery

When the battery's state of charge (SOC) is full, any extra renewable energy is sent back to the grid, if the system permits power export.

This well-coordinated plan enhances the usage of renewable energy sources while reducing needless grid power exchange.

POWER QUALITY IMPROVEMENT CONTROL

The grid-connected inverter is also a part of the power quality management system that is suggested. Here are some tasks that the inverter can complete:

- control of voltage across DC-link
- Active management of power
- Adaptive power regulation
- Enhancement of the power factor
- Harmonic reduction in current
- Controlling voltage

The system's active and reactive power needs determine the inverter reference current generation. When the load or renewable generation changes, the ANFIS controller updates the reference values.

To determine the total harmonic distortion, one uses the formula

$$\square\square\square = \frac{\sqrt{\square_2^2 + \square_3^2 + \cdots + \square_{\square}^2}}{\square_1} \times 100$$

The fundamental current component is denoted as I_1, whereas the harmonic components are represented by I_2, I_3,..

Reducing harmonic distortion and keeping the grid current near a sinusoidal waveform are the goals of the suggested controller.

CONTROL OPERATION OF THE PROPOSED SYSTEM

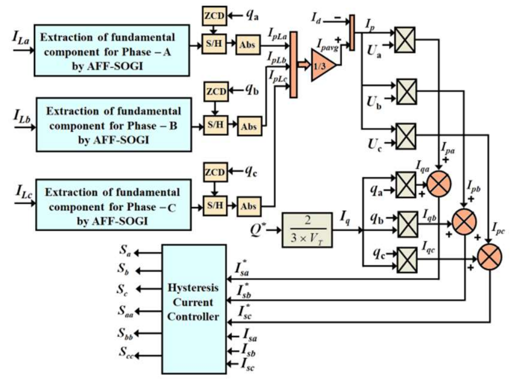

Fig 3. Control strategy for qZSI-STATCOM using AFF-SOGI

the steps involved in the control process are as follows:

1. Take readings of the following: PV power, wind power, load power, state of charge (SOC) of the batteries, voltage across the DC-link, voltage across the AC lines, and current within the grid.
2. Determine the overall balance of renewable electricity.
3. Ascertain the current power excess or deficit.
4. The trained ANFIS controller should be instructed to use the measured variables.
5. Make a reference for the grid power and the battery power.
6. Manage the battery converter that can convert DC to AC.
7. Produce reference currents for inverters.
8. Direct the voltage and reactive power of the DC-link.
9. Minimize current harmonics and keep power factor close to unity.
10. Keep the energy management decision up-to-date based on the current system operating circumstances.

Optimal energy utilization and stable system performance are guaranteed by the coordinated operation of all subsystems.

VII. MATLAB/SIMULINK MODEL IMPLEMENTATION

It is possible to model the suggested renewable energy hybrid system using MATLAB/Simulink. Down below, you can see the simulation model.

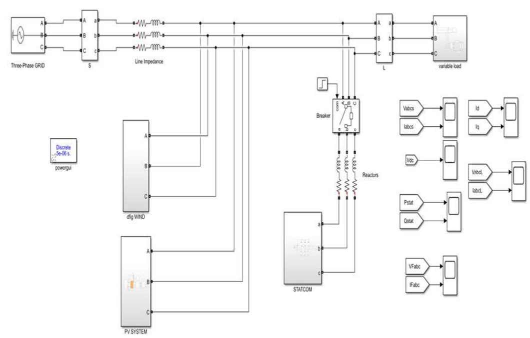

Fig 4. Simulation circuit model

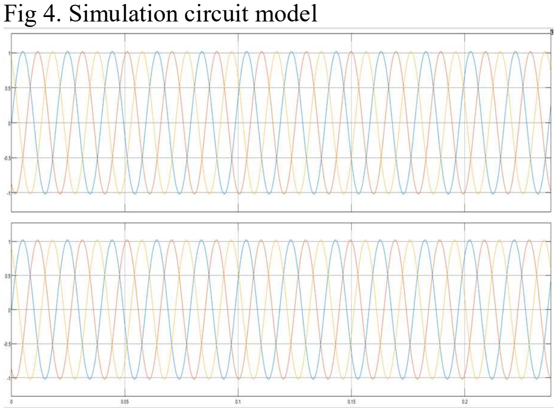

Fig 5. Grid voltage and currents in pu

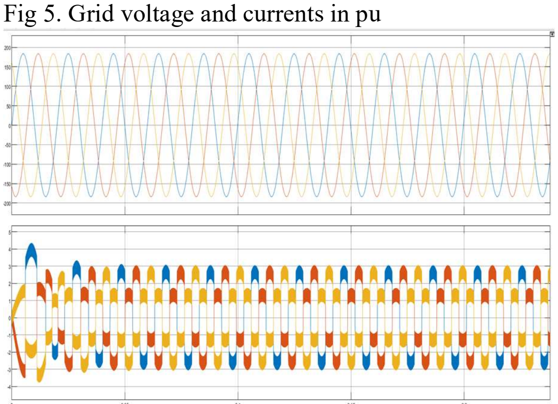

Fig 6. Load voltage and currents

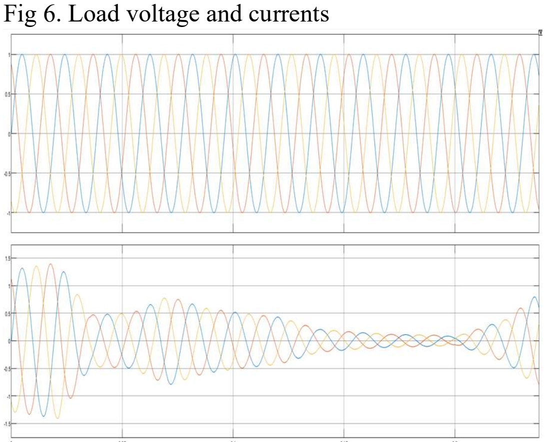

Fig 7. Dstatcom voltage and currents in pu

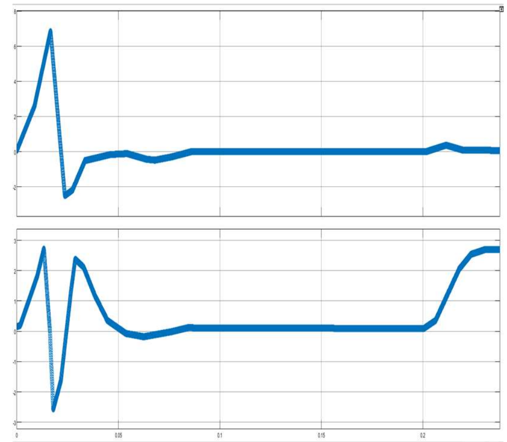

Fig 8. Load active and reactive powers

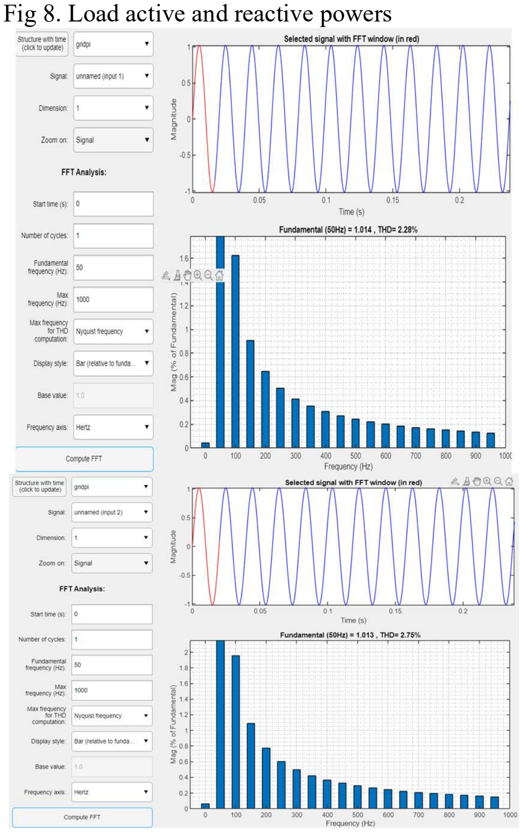

Fig 9. Impact of THD on grid voltage and current It is believed that the suggested controller would outperform traditional PI or fixed-rule controllers in terms of transient performance. Because of its adaptive learning capabilities, ANFIS can manage nonlinear interactions among grid power, load demand, battery state of charge, and renewable generation.

ADVANTAGES OF THE PROPOSED SYSTEM

Among the many benefits of the suggested system are:

1. Enhanced harnessing of renewable energy sources.
2. Managing electricity flows intelligently.
3. Less reliance on the power grid.

4. Enhanced control over charging and draining batteries.
5. Enhanced control of DC-link voltage.
6. A higher power factor.
7. Distortion of harmonics decreased.
8. Improved reliability of the system.
9. Dynamic reaction during swings in renewable power is improved.
10. Adaptive control capabilities under nonlinear operating circumstances.

VIII. CONCLUSION

Using an ANFIS-based coordinated controller, this article offered a solution for enhanced energy management and power quality control in a hybrid renewable energy system. Solar photovoltaic (PV) power generation, wind energy conversion, energy storage in batteries, grid connection, and locally applied loads are all components of the suggested system. Power quality improvement and efficient coordination of renewable energy sources, battery storage, grid, and load are the key goals of the suggested control technique.

When it comes to controlling power flow under changing renewable energy and load situations, the ANFIS controller offers sophisticated decision-making capacity. When renewable power is available and the battery state of charge is known, the controller will decide how to charge or discharge the batteries and how to interchange electricity with the grid. The grid-connected inverter also improves power factor, decreases harmonics, regulates voltage, and compensates for reactive power.

The suggested way of control outperforms more traditional approaches in terms of dynamic reaction and flexibility. Future smart-grid and microgrid applications that rely on renewable energy sources will find the suggested system to be an ideal fit due to its coordinated framework integration of intelligent energy management and power quality control. To further improve performance, future work might concentrate on integrating electric vehicle charging systems, demand-side management, advanced battery technologies, and optimization algorithms like Particle Swarm Optimization, Genetic Algorithm, or Deep Reinforcement Learning.

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