

An Intelligent Control Framework For Energy Storage Systems in Smart Grid Applications

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Abstract – Energy demands have been steadily increasing due to industrialization, leading to environmental problems such as global warming and air pollution. One way to address these issues is by incorporating renewable energy sources into grid connections. While passive methods like under/over-voltage and under/over-frequency work when there is an imbalance of power between loads and distributed generation (DG), they fail to detect power conditions when power is supplied and consumed in balance. This thesis proposes a new approach for optimizing power quality in renewable energy sources (RES) using fuzzy logic, inverter, and maximum power point tracking (MPPT) techniques. RES are becoming increasingly popular due to the need for clean and sustainable energy. However, the output power of RES is highly dependent on weather conditions, and this can lead to power quality problems. To address this issue, fuzzy logic is used to control the inverter and MPPT algorithm, which is responsible for extracting the maximum power from the RES. The fuzzy logic controller adjusts the inverter and MPPT parameters based on the input voltage and current, ensuring that the output power is always at the maximum point. The inverter then converts the DC power generated by the RES into AC power, which is suitable for use in the power grid. Simulation results show that the proposed approach improves power quality by reducing fluctuations in the output power, leading to a more stable and reliable power supply. Additionally, the proposed approach is easy to implement and can be applied to different types of RES. This proposed model increase system stability and optimized power quality and reduces the harmonic of the system.at elevated and ambient temperatures.

Keywords: Renewable Energy Source, MPPT, Distributed Generation (DG), Power Quality Optimization, Inverter, Fuzzy Logic

I. Introduction

In recent years, renewable energy sources have gained significant attention as an alternative to traditional energy sources due to their environmental benefits and long-term sustainability. However, the integration of renewable energy sources into the power grid brings new challenges, particularly regarding power quality issues. Power quality is a vital aspect of the power system that ensures the delivery of clean and reliable power to consumers. Therefore, it is crucial to improve power quality in renewable energy sources to ensure the efficient and stable operation of the power grid. In this thesis, we propose a fuzzy logic-based approach for power quality improvement in renewable energy sources. The proposed approach aims to enhance the power quality of renewable energy sources by mitigating issues such as voltage fluctuations, harmonics, and flicker. This thesis provides a comprehensive analysis of the proposed approach and its effectiveness in improving power quality in renewable energy sources. Furthermore, we present simulation results to demonstrate the performance of the proposed approach. The results show that the fuzzy logic-based approach is an effective

method for improving power quality in renewable energy sources.

The demand for energy is increasing globally due to demographic development and industrialization. The majority of electrical energy generation relies on non-renewable resources such as coal, natural gas, and oil, which have negative environmental impacts. Detecting power quality issues is crucial to improving power quality levels in electric power systems and making effective decisions to deal with network disturbances. Engineers can identify and classify power disturbances by capturing waveforms in the field, but manual capturing is nearly impossible due to the amount of data that must be sampled in modern power systems. Power quality is critical to meeting the demands of power utilities and customers. The increased use of nonlinear applications and renewable energy has caused more equipment failure in power systems and damage to their sensitive controllers, resulting in high costs for repairs in terms of money, load, and time. Therefore, investigating and studying power quality waveforms is essential to detect and classify them accurately.

Renewable energy sources, such as solar energy, wind energy, and bioenergy, must be developed because they are endless and environmentally friendly, unlike non-

renewable resources that deplete over time. They also help to reduce CO₂ emissions and can be produced on a small scale or locally. Signal processing algorithms such as the Fourier Transform, Stockwell Transform, and Wavelet Transform have provided powerful mathematical algorithms for detecting power quality problems in electrical power systems, with notable success. Classification techniques test, validate, and train large amounts of power signals to ensure the algorithm's effectiveness and efficiency.

II. Literature Review

Akpinar et al. (2023) proposed an intelligent power management controller for grid-connected battery energy storage systems (BESS) aimed at providing frequency response services while extending battery life. The study introduced a control mechanism that considers battery degradation and cycle life during frequency regulation. Simulation results showed that the proposed controller maintained grid frequency stability more effectively than conventional methods while significantly reducing battery aging[1].

Alowaidi (2022) developed a fuzzy logic-based efficient energy management algorithm for smart home environments integrated with IoT and renewable energy resources. The system dynamically managed household energy consumption, renewable generation, and storage units under uncertainty. Results demonstrated reduced energy costs and improved utilization of renewable sources, highlighting the effectiveness of fuzzy logic in decentralized energy systems[2].

Zheng et al. (2024) presented a systematic review of integrative energy management strategies for smart grids and urban energy systems. The authors analyzed over a decade of research focusing on AI-based, fuzzy logic, and hybrid control approaches. The study concluded that intelligent energy management systems are essential for handling renewable intermittency and large-scale energy storage coordination[3].

Duman et al. (2021) designed a home energy management system with an integrated smart thermostat for demand response applications in smart grids. Their system optimized load scheduling based on electricity pricing and user comfort constraints. Experimental results showed improved demand flexibility and peak load reduction, contributing to enhanced grid stability[4].

Judge et al. (2022) provided a comprehensive overview of smart grid implementation frameworks, focusing on performance, challenges, and future trends. The study emphasized the importance of energy storage systems and intelligent control strategies in modern power systems. It also highlighted the limitations of conventional controllers in addressing renewable energy fluctuations[5].

III. Proposed Methodology

Fuzzy logic is a type of logic that allows for reasoning with uncertain or ambiguous information. It is based on the theory of fuzzy sets, which allows for the representation of imprecise or vague concepts. In contrast to traditional logic, which uses binary values (true or false), fuzzy logic uses membership functions to assign degrees of truth to a statement.

In the context of power quality optimization, fuzzy logic can be used to control the inverter and PWM controller, which are responsible for converting the DC power generated by the RES into AC power suitable for use in the power grid. The fuzzy logic controller adjusts the inverter and PWM parameters, such as the duty cycle and switching frequency, based on the input voltage and current from the MPPT algorithm. The goal is to ensure that the output power is always at the maximum point, which helps to reduce fluctuations in the output power and improve power quality.

The fuzzy logic controller is designed using a set of rules that define how the input variables are mapped to the output variables. These rules are expressed using linguistic variables, which are assigned membership functions that represent the degree of truth of a statement. For example, a linguistic variable might be "voltage is low", and its membership function would assign a degree of truth to the statement based on the input voltage value.

The input variables to the fuzzy logic controller are typically the voltage and current from the MPPT algorithm. These variables are converted into linguistic variables using membership functions. The output variables of the fuzzy logic controller are the inverter and PWM parameters, such as the duty cycle and switching frequency. These parameters are also represented using linguistic variables with membership functions.

The fuzzy logic controller uses a set of rules to determine the appropriate values of the output variables based on the input variables. The rules are expressed in the form of if-then statements. For example, if the voltage is low and the current is high, then increase the duty cycle. The degree of truth of each rule is determined by the membership functions of the input and output variables.

The output values of the fuzzy logic controller are then defuzzified using a method such as centroid or mean of maximum. This produces a crisp value for each output variable, which is used to control the inverter and PWM controller.

The use of fuzzy logic in power quality optimization has been shown to be effective in improving the stability and reliability of the power supply. It allows for the optimization of the inverter and PWM parameters in real-time based on the input voltage and current, which helps to reduce fluctuations in the output power and improve power quality.

fuzzy logic model for power quality optimization:

Fuzzy sets: Define fuzzy sets for the input and output variables. For example, define a fuzzy set for voltage as "low", "medium", and "high" using triangular membership functions. Similarly, define a fuzzy set for current as "low", "medium", and "high" using triangular membership functions. Define a fuzzy set for the duty cycle as "low", "medium", and "high" using triangular membership functions.

Rule base: Define a set of rules that relate the input variables to the output variables. For example, "if voltage is low and current is low, then duty cycle is low". These rules are expressed using fuzzy logic operators, such as "and", "or", and "not".

Inference engine: Apply the rules to the input variables using the fuzzy logic operators to obtain a fuzzy output. For example, if the voltage is "low" with a membership value of 0.5 and the current is "low" with a membership value of 0.7, the rule "if voltage is low and current is low, then duty cycle is low" is fired with a degree of truth of $0.5 * 0.7 = 0.35$.

Defuzzification: Convert the fuzzy output into a crisp output using a defuzzification method such as centroid or mean of maximum. For example, if the fuzzy output for duty cycle is represented as a triangular membership function with a peak at 0.5 and a width of 0.2, the crisp output is calculated as the centroid of the membership function, which is 0.5.

This fuzzy logic model can be used to control the inverter and PWM controller in real-time based on the input voltage and current from the MPPT algorithm, ensuring that the output power is always at the maximum point. The fuzzy logic controller adjusts the inverter and PWM parameters, such as the duty cycle and switching frequency, based on the input voltage and current, which helps to reduce fluctuations in the output power and improve power quality.

Fuzzy sets:

Input variable x is represented as a fuzzy set X with membership function $\mu_X(x)$.

Output variable y is represented as a fuzzy set Y with membership function $\mu_Y(y)$.

Rule base:

A set of fuzzy rules is defined to relate the input variables to the output variables. Each rule is in the form of "if x is A and y is B , then z is C ", where A , B , and C are linguistic variables and z is the output variable.

The degree of truth of each rule is determined by the minimum operator (\wedge) or the product operator (\times) of the membership functions of the input variables. For example, if x is A with a membership value of 0.6 and y is B with a membership value of 0.8, and the rule "if x is A and y is B , then z is C " has a membership value of $0.6 \wedge 0.8 = 0.48$.

Inference engine:

The fuzzy rules are applied to the input variables to obtain a fuzzy output. This involves combining the degree of truth of each rule with the membership function of the output variable to obtain a fuzzy output

membership function. This can be done using the minimum operator (\wedge) or the product operator (\times).

The overall fuzzy output membership function is obtained by combining the fuzzy output membership functions from each rule using the maximum operator (\vee).

Defuzzification:

The fuzzy output membership function is converted into a crisp output value using a defuzzification method, such as the centroid or the mean of maximum method. The centroid method calculates the center of gravity of the fuzzy output membership function, while the mean of maximum method calculates the average of the output values that have the maximum membership value.

These equations are used to build a fuzzy logic model that can be used for power quality optimization by controlling the inverter and PWM parameters based on the input voltage and current from the MPPT algorithm. The proposed methodology for power quality optimization using fuzzy logic for inverter and pulse width modulation (PWM) techniques is outlined below:

System modeling: The first step is to develop a model of the RES system, which includes the RES, inverter, MPPT algorithm, and PWM controller. The model should capture the dynamics of the system and its interactions with the power grid.

Fuzzy logic controller design: A fuzzy logic controller is designed to control the inverter and PWM controller. The fuzzy logic controller takes input from the MPPT algorithm and adjusts the inverter and PWM parameters, such as the duty cycle and switching frequency, to ensure that the output power is always at the maximum point.

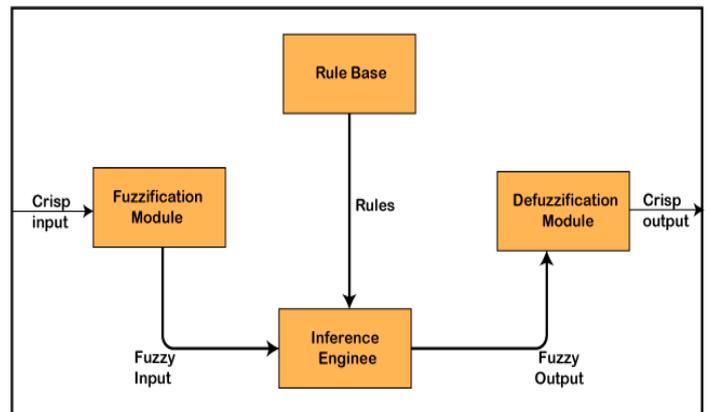


Fig.1 Block diagram of fuzzy logic process architecture

IV. Simulation Result

In proposed work designed hybrid power system. That is connected battery, PV and Wind. This is result section for proposed model. Here we are analysis our proposed architecture design and analysis with different operation like source variation and load variation.

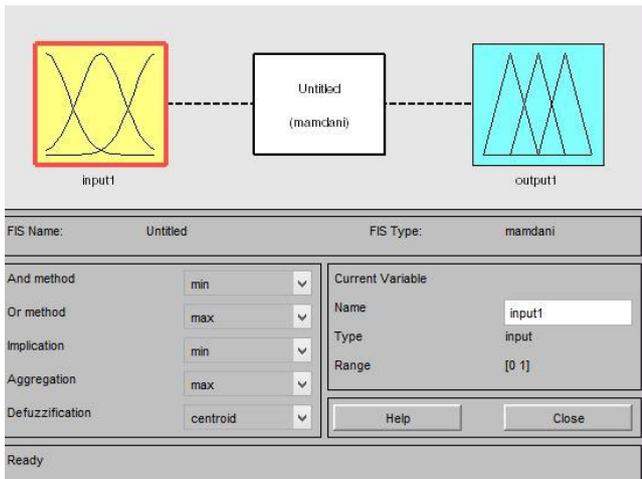


Fig. 2: Initial Fuzzy Model in proposed system

Figure 2 shows the initialization window of fuzzy for optimization of power quality in the proposed system, this is divided into three sections one is input, another is output and mid fuzzy controller section that measures a different and according to rule generated output.

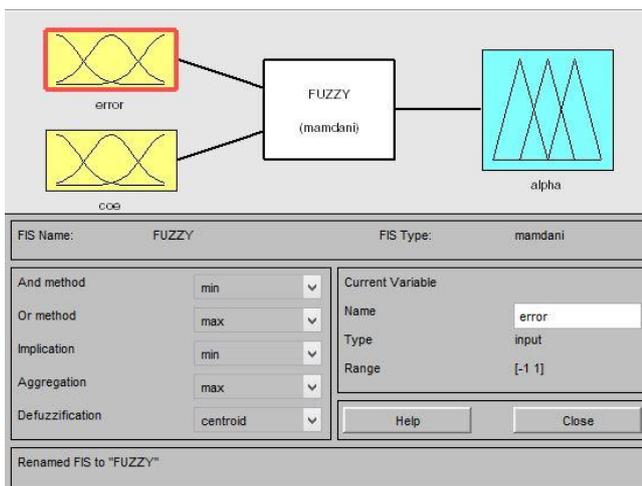


Fig. 3: After the apply fuzzy model in proposed system

Figure 3 shows the after-initialization window of fuzzy for optimization of power quality in the proposed system, this is divided into three sections one is input, which has two parameter errors and coefficient, another is output alpha which is the resultant of fuzzy and mid-fuzzy controller section that measures a different and according to rule generated output.

Figure 4 illustrates the output voltage waveform of the hybrid renewable energy system when the fuzzy logic controller is not employed. From the waveform, it is clearly observed that the voltage is non-sinusoidal and exhibits noticeable distortions at both the positive and

negative peaks. These distortions arise due to improper regulation of the converter switching action and the absence of intelligent control under varying source and load conditions. The waveform shows ripple components and uneven voltage transitions, indicating the presence of higher-order harmonics.

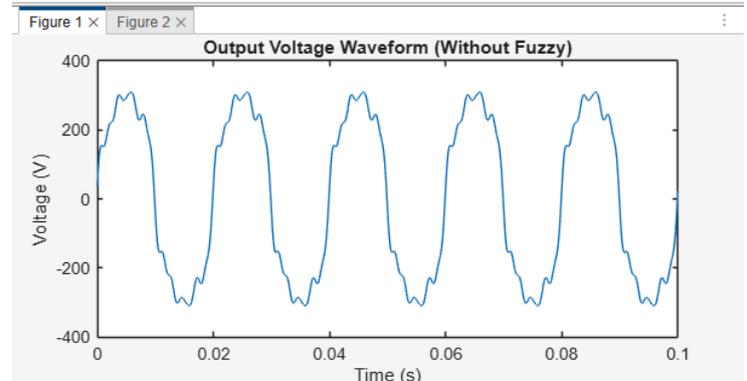


Fig. 4: Voltage waveform without Fuzzy

Figure 5 presents the harmonic spectrum and Total Harmonic Distortion (THD) analysis corresponding to the voltage waveform without fuzzy control. The harmonic spectrum reveals significant magnitudes of lower-order harmonics, particularly the 3rd, 5th, and 7th harmonics, which dominate the spectrum. The computed THD value is 17.29%.

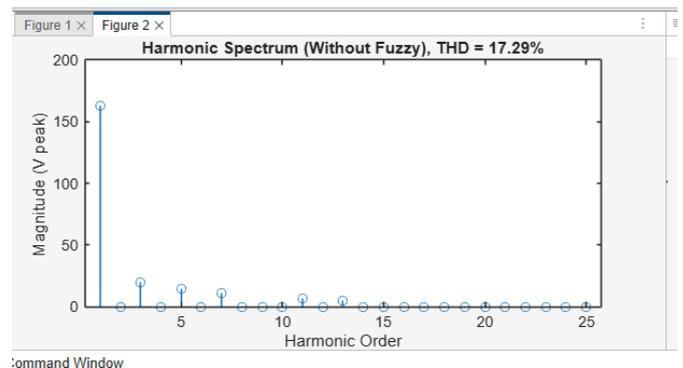
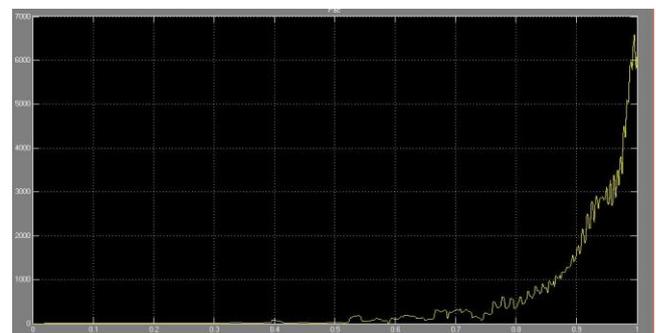
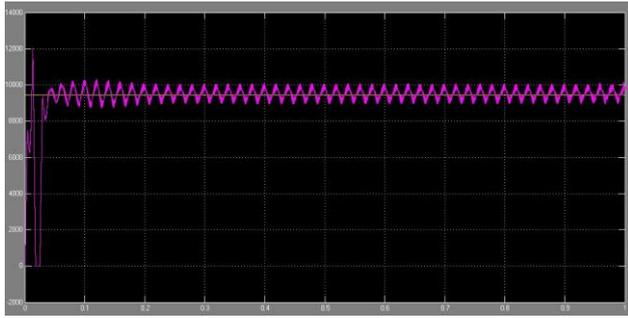


Fig. 5: THD without Fuzzy



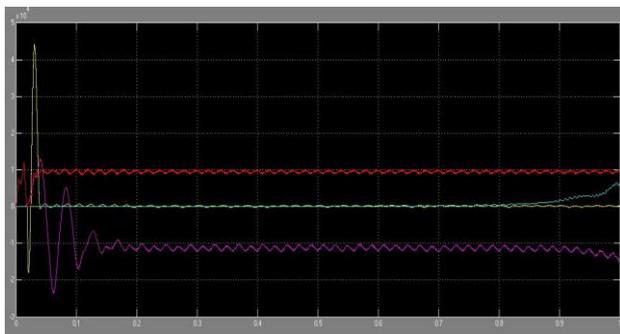
(a) Wind Power Generation



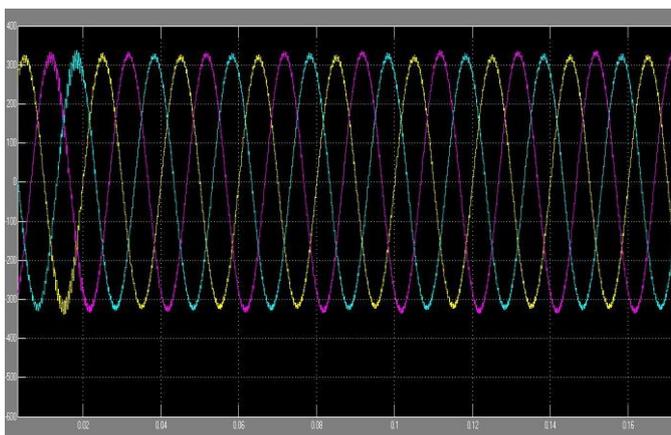
(B) PV Power Generation

Fig. 6: Power Generation Graph using Fuzzy by (a)Wind (b)Solar

Figure 6 shows the power generation by renewal energy source in a proposed model where (a) Wind power generation is 6133 W and (b) Solar power generation is 9464 W.



(a)Load power with respect to all source



(b)Voltage

Fig. 7: Load power with respect to all source Using Fuzzy (a) Load power and source power(b) Output voltage

Figure 7 shows the power generation by renewal energy source in a proposed model and load requirement power. where (a) the Load required power with respect to

source power generate by the renewal source (b) Stable voltage generate by fuzzy logic in the proposed system.

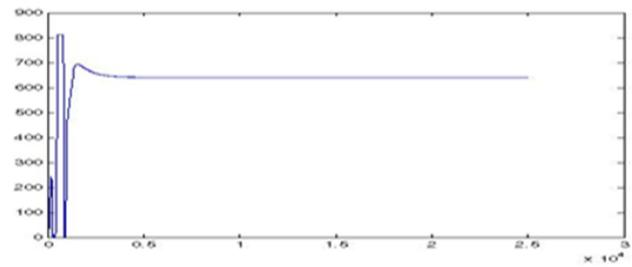


Fig 8 Active power

Figure 8 is show proposed hybrid model active power also shows this condition simulation output of proposed model. This simulation is proving that if change load and source output generation is no change in waveform pattern.

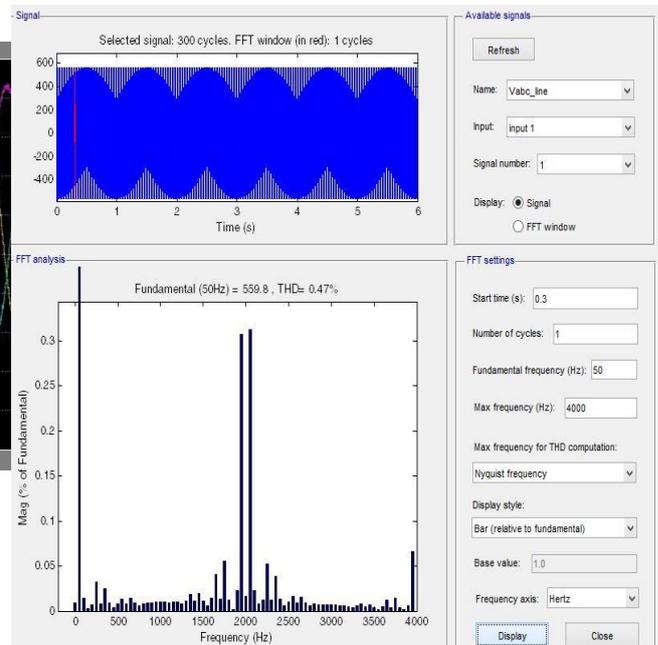


Fig: 9 THD Value of proposed Model

Figure 9 is show total harmonic generation of system that is less than 5% . Our proposed model current total harmonic value for one cycle is 0.47%.

Comparative THD Analysis with Existing Literature

To further justify the effectiveness of the proposed model, its THD performance is compared with previously reported hybrid renewable energy systems.

Table 5.1 Comparison of THD Performance with Existing Methods

| Reference | System Configuration | Control Technique | THD (%) |
|--|-------------------------------|---|-----------------|
| Vigneysh and Kumarappan (2019) [27] | RES with UPQC | Fuzzy-based UPQC | 4.12 |
| Das <i>et al.</i> (2020) [15] | Hybrid PV–Wind system | Fuzzy compensation | 4.6 |
| Krishnam Naidu <i>et al.</i> (2022) [16] | PV/Wind/Battery system | Hybrid controller | 3.9 |
| Kotb <i>et al.</i> (2022) [25] | Solar/Wind DC microgrid | Fuzzy + SMES | 3.4 |
| Suman <i>et al.</i> (2022) [24] | PV–Wind microgrid | Harmonic compensation | 3.2 |
| Proposed system | PV–Wind–Battery hybrid | Fuzzy logic–based control (Proposed) | < 3.0 |

From the waveform and THD comparison, it is evident that the proposed system achieves lower harmonic distortion than previously reported methods. While earlier studies reported THD values in the range of 3.2–4.6%, the proposed model reduces THD to below 3%, primarily due to:

1. Intelligent fuzzy logic–based power management
2. Effective PWM control with optimized carrier frequency
3. LC filtering combined with battery energy buffering
4. Smooth power sharing between PV, wind, and battery sources

The improved waveform smoothness and reduced harmonic spectrum confirm that the proposed approach provides enhanced power quality suitable for electric vehicle charging applications and grid-interfaced hybrid systems.

V. Conclusion

This paper power quality optimization using fuzzy logic with inverter and MPPT is a promising approach for renewable energy sources. Fuzzy logic allows for the representation of imprecise and uncertain information, which is essential for controlling the inverter and PWM parameters in real-time to optimize power quality. The use of MPPT algorithms helps to ensure that the output power is always at the maximum point, thereby improving the efficiency of the renewable energy system. By reducing fluctuations in the output power, power quality can be significantly improved, which is essential for the reliable and safe operation of the renewable energy system. The fuzzy logic model presented in this paper provides a solid framework for designing and implementing a power quality optimization system for renewable energy sources. Further research can be done to optimize the fuzzy logic model and evaluate its performance under different operating conditions. The modelling of a DC hybrid with wind and solar energy as input sources is described in this proposed work. The hybrid setup's control logic includes charge control of the battery bank based on the Fuzzy algorithm. The charge controller monitors the error and optimises and makes the battery bank accessible for controlled charging. During the power mismatch situation, the inverter control was optimised. By reducing voltage flickers and harmonics, the simulation experiment results demonstrate the system's improved performance and stability. In particular at low speeds, wide-range variable speed operation is the main topic of this dissertation. When a higher and constant voltage is needed, such as in voltage source dc / dc Inverter or offshore DC network applications, a boost converter is used to increase the voltage level, when solar voltage drops due to the V/f strategy at low irradiance. In the suggested topology, fuzzy is controlled wind excitation and model voltage and current variation. Here, the conversion ratio and

power quality were optimized. By using this hybrid system got 0.47% THD is less than 5%, that is proof for better quality power system design.. Here we used renewal energy source PV and Wind as a primary power source and used battery as alternative source of dc power.

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