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Fuzzy Logic-Based DSTATCOM for an Optimal Reactive Power Dispatch Solution in a Grid-Connected System

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ABSTRACT- In recent decades, there has been a substantial and dramatic implementation of renewable energy sources globally. Electrical systems should fulfill consumer load requirements while transmitting electricity with reduced loss, increased power quality, and dependability. However, the accessibility of steady and dependable electricity in emerging nations raises concerns about the depletion of energy production and the detrimental effects it has on the ecosystem. The most effective real-world and operational method to meet consumers' growing electricity requirements while upholding uncompromising ecological standards for power generation is to integrate a wind-solar-based microgrid into the distribution system. The microgrid system and a distribution network face severe issues, difficulties, and challenges. The fluctuation of hybrid renewable energies, namely wind and PV resources, causes issues including the occurrence of voltage dips and surges, voltage imbalances, and energy losses. The core objective of this research is to combine a microgrid network with a DSTATCOM controller to guarantee increased power flow and improve the voltage profile. The DSTATCOM is controlled using fuzzy logic controllers (FLC) and proportional integrals. By interconnecting to the primary distribution system, the effectiveness of DSTATCOM is evaluated with microgrid integration. Eventually, it is shown that DSTATCOM increases the distribution line's capability in the system.

Keywords: Voltage Profile, DSTATCOM, Fuzzy logic Controller, Solar PV, Wind energy module.

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1. INTRODUCTION

The use of fossil fuels has decreased in conservative power systems, even though the amount of energy consumed presently has been steadily increasing. Consequently, this puts electrical energy systems under strain all across the world, which negatively affects their dependability, power quality, frequency of power outages, and energy cost. The conventional electrical grid system is also highly hierarchical and a one-way pipeline. Nonetheless, research into renewable energy is being driven by factors such as increasing energy demands, rapid technological advancements, the energy crisis, blackouts, financial incentives, and social and cultural environmental understanding to improve the power system and its configuration. Due to variations in the weather and environment, renewable energy sources such as solar and wind energy are sporadic and unpredictable [1].

Furthermore, the network system shows notable output oscillations, which makes it dangerous to integrate the grid network into the transmission networks independently. Because of the power system's volatility, poor voltage management, decreased stability, and decreased efficiency, managing the network voltage profile is a challenging task [2].

Optimal *VAr* compensation has a detrimental effect on the performance and capability of the electrical network, resulting in a power drop and high costs. Static condensers and shunt capacitors have been utilized to address the issues related to power quality [3]. However, such VAR compensating devices do have downsides, including increased system losses, delayed response, stiffness, increased price, and large sizes. FACTS devices were proposed and developed in the 1980s to address power system operating difficulties relating to monitoring and control [4]. Conversely, digital architectures are required for Facts controllers to function precisely and to increase network security, dependability, integrity, and efficacy [5]. Because it implements a V*Ar* compensating device quickly and responds to control strategies, the static synchronous compensator is the most frequently used converter in the FACTS. It has a shunt connection and is a reactive-compensating device [6].

By increasing the capacity of the current lines, DSTATCOM lessens the need to build additional transmission lines. To enable the power system to operate within the required operational restrictions, many control mechanisms were put into place [7]. Conventional DSTATCOM controllers employ PI-type controllers, which have been standardized and determined to be appropriate for the acceptable responses they offer. As a result, the goal of flow research is to develop a DSTATCOM activity that is more versatile and resilient for a range of breakout electricity system topologies [8].

According to many researchers conducted recently, DSTATCOM has been used in microgrid systems to regulate the flow of DC electricity. It did not, however, address the issue of managing voltage variations; instead, it was only effective in controlling the integrated supply chain management system's current [9].

The integration of microgrid systems into radial distribution networks is being done to lower the quantity of electricity that is lost, as was indicated in [10]. However, the use of the FACTS controllers together with the integration of renewable energy sources has significantly enhanced the voltage profile and moderated instabilities. It is proposed in [11] that the voltage regulation achieved by using frequency and voltage support could be advantageous for a hybrid utility system. As mentioned in [10], the integration of microgrid systems into radial distribution networks is being done to reduce the amount of electricity that is lost. However, the voltage profile has significantly improved and instabilities have been controlled with the introduction of FACTS controllers in conjunction with the addition of renewable energy sources. A hybrid utility system may benefit from voltage regulation accomplished through the use of voltage and frequency support, as suggested in [11].

A review of the literature found that not much research has been done on the application of a *VAr* compensating device, specifically DSTATCOM, for enhancing optimal power flow in the microgrid system [15]. With more PV and wind-based distributed generation systems being constructed, there is a growing need for significant advancements in research and testing of the FACTS controllers across a range of operational conditions. A linearized set of equations that represented the system in its nominal load state was especially used to build the regulator's gains in the DSTATCOM controller [12]. Maintaining these control performances at their prior levels was a daily task for the DSTATCOM. The transmission grid, the imaginary part of the control circuit, and the good efficiency are all subject to change since the load varies throughout the course of a typical DSTATCOM performance day [16]. Hence, the controller should be adjusted in line with the system's requirements to preserve remarkably unique responses.

Artificial neural networks are advised in order to adjust to the DSTATCOM's controller gains [17]. However, they also demand offline instruction, which usually takes more time [19]. On the other hand, they introduce a fuzzy logic-based DSTATCOM controller, eliminating the need for an interpretation of output with an integrated electrical system network.

By utilizing more fuzzy logic in the controller, this objective will be achieved. Furthermore, the goal is to reduce power loss and voltage variations caused by the unpredictable nature of renewable energy sources [20].

Although numerous studies have examined the integration of DSTATCOM and the improvement of voltage profiles in microgrid systems, the proposed work differs from existing studies in the following aspects:

- To achieve the best reactive power dispatch, a DSTATCOM controller is coupled with a unified hybrid solar–wind microgrid model.
- To overcome the drawbacks of traditional fixed-parameter PI controllers, a fuzzy-PI-based control approach is developed to dynamically adjust DSTATCOM parameters under changing renewable generation conditions.
- The proposed approach uses an explicitly defined objective function to reduce both real power loss and voltage variation at the same time.
- In comparison to traditional PI-controlled DSTATCOM systems, comparative simulation findings show improved transient response, decreased power losses, and increased voltage stability.

2. PROBLEM FORMULATION

The main task in this research work is to improve the reactive power flow in an electrical network by reducing actual power loss and sum of load bus voltage variations [12]. The two optimization components and weights combine to generate a larger aim.

3. OBJECTIVE FUNCTION

The idea of this research is to determine the best configurations for reactive power compensation variables and to evaluate shunt var adjusting devices. As a result, the optimal control goal function may be written as:

$$P_i - jQ_i = \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \angle(\theta_{ij} + \delta_j - \delta_i) \quad (1)$$

Equating real and reactive parts,

$$P_i = \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \cos(\theta_{ij} + \delta_j - \delta_i) \quad (2)$$

$$Q_i = - \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \sin(\theta_{ij} + \delta_j - \delta_i) \quad (3)$$

From the above equation the optimal power flow equation can be obtained as

$$P_i = |V_i|^2 |Y_{ii}| \cos\theta_{ii} \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \cos(\theta_{ij} + \delta_j - \delta_i) \quad (4)$$

$$Q_i = - |V_i|^2 |Y_{ii}| \sin\theta_{ii} \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \cos(\theta_{ij} + \delta_j - \delta_i) \quad (5)$$

Where *Pi* is the real power flow across the i^{th} bus, *Qi* is the reactive power flow across the i^{th} bus, V_i,V_j are the magnitudes of the sending end and receiving end voltages of the line,

3.1. Constraints

In solving optimal reactive power dispatch an equal set of constraints are required.

3.1.1. Equality Constraints

3.1.1.1. Power Flow Constraint: The equality constraints can be stated as.

$$P_{gi} - P_{Di} = \sum_{j=1}^{NB} V_i V_j Y_{ij} \cos(\delta_{ij} + \gamma_j - \gamma_i) \quad (6)$$

$$Q_{gi} - Q_{Di} = \sum_{j=1}^{NB} V_i V_j Y_{ij} \sin(\delta_{ij} + \gamma_i - \gamma_j) \quad (7)$$

3.1.2. Inequality Constraints

The Inequality constraints of the system can be stated as

3.1.2.1. For Generator Constraints: The following equation represents the voltage variation limits starting from higher level to lower level of control variables. The equations are as follows.

$$V_{gbi}^{min} \leq V_{gbi} \leq V_{gbi}^{max} \quad i= 1,2,....N_G \quad (8)$$

$$Q_{gb1}^{min} \leq Q_{gb1} \leq Q_{gb1}^{max} \quad i= 1,2,....N_G \quad (9)$$

3.1.2.2. For Load bus Constraints: The least and utmost loading limits of the variables towards load bus voltages are given as follows

$$V_{L1}^{min} \leq V_{L1} \leq V_{L1}^{max} \quad i= 1,2,....N_L \quad (10)$$

3.1.2.3. For Transmission line Constraints: The net apparent power flow of the transmission line can be stated as

$$S_{L1} \leq S_{L1}^{max} \quad i= 1,2,...,N_{TL} \quad (11)$$

3.1.2.4. For Transformers tap settings Constraints: The loading limits of the transformer for attaining objective function can be stated as

$$T_i^{max} \leq T_i \leq T_i^{min} \quad i= 1,2,...,N_T \quad (12)$$

3.1.2.5. For Shunt compensator Constraints: The shunt VAr compensation of the system is provided with the operating limits as follows.

$$Q_{C_1}^{min} \leq Q_{C_1} \leq Q_{C_1}^{max} \quad i=1,2....,N_C \quad (13)$$

4. MODELING OF PROPOSED MODEL

The proposed method uses a fuzzy logic-based DSTATCOM controller to improve the voltage profile and lower power losses in a grid-connected hybrid microgrid. Initially, MATLAB/Simulink is used to model a microgrid that consists of a solar photovoltaic (PV) system and a wind energy conversion system based on a doubly fed induction generator (DFIG). While the wind system is modeled with the proper electrical parameters for reliable grid operation, the PV system is represented using a single-diode model combined with a maximum power point tracking (MPPT) method to ensure optimal power extraction. The Newton-Raphson approach is used to analyze load flow and assess power losses and the base-case voltage profile. The objective function is designed to satisfy the restrictions of the generator, transformer, shunt compensator, and transmission line while minimizing active power loss and voltage variation. In order to offer dynamic reactive power compensation, a DSTATCOM is then attached at the selected interface. The Mamdani-type Fuzzy-PI controller is developed to enhance control performance in nonlinear and fluctuating operating circumstances. The controller adjusts the PI gains adaptively by processing the voltage error and the error change. Until loss minimization and voltage profile improvement converge within reasonable bounds, an iterative process is employed.

The goal of this study is to build a typical microgrid model so that MATLAB can be used to analyze power flow. Furthermore, integrating microgrids with FACTS devices leads to improved power system efficiency, a lower loss, and an acceptable voltage profile.

5. MODELING OF SOLAR POWER SYSTEMS

PV cells are gadgets that convert solar radiation into electrical electricity. To improve voltage and boost current, solar photovoltaic cells are placed in a linear pattern. The relative circuit of a one-diode PV cell is comprised of phototransistors (Iph), series resistors (Rs), and shunt resistors (Rsh), as illustrated in [18]. The current flow in a PV system can be computed using the following formula. The computational formula for a solar PV system utilizing the observe and perturb method of the maximum power point tracking (MPPT) algorithm is described.

Table 1. Control variables of Solar PV connected to microgrid system

S. No.	Operating Component	Range Limit
1	System rating	8.0 MVA
2	Reference Voltage	1.055 p.u.
3	Time response of the Inverter (Tp, Tq)	Tp = 0.025, Tq = 0.02
4	Controller Gain voltage (Kv, Ki)	Kv = 0.0868, Ki = 50.9005

6. WIND POWER SYSTEM MODELLING

Currently, the preferred generator for wind power generation systems is the doubly fed induction generator (DFIG). It is the ideal generator to utilize in wind energy systems because of its ideal speed. When anything is "doubtfully fed," it means that the motor's rotor is supplying the voltage via the buck-to-buck converter. DFIG can be carried out in either conventional or breakdown situations by using different controllers to manage the buck-to-buck converters. The precise equivalent circuit of the system has been given. It has two progressive converters for grid and rotor control, according to the DFIG.

7. POWER FLOW ANALYSIS

The technique of examining each bus's voltage and current measurements as well as the reactive and active power flow along each line is known as the power flow analysis approach. In load flow analysis, the power flow methods most commonly utilized are fast-decoupled (FD), Gauss-Seidel (GS), and Newton-Raphson (NR). The most popular approach is the N.R.

algorithm since it converges accurately, takes less time to reach the goal, and performs well with complex systems.

Table 2. Control variables of Wind energy module connected to microgrid system

S. No.	Operating component	Range Limit
1	System rating	6.0 MVA
2	Reference Voltage	75 kv
3	Nominal Frequency	50Hz
4	Resistance across Stator	0.025 p.u
5	Reactance across Stator	0.005 p.u
6	Resistance across Rotor	0.025 p.u
7	Reactance across Rotor	0.09 p.u
8	Time Constant	Tp = 5 sec
9	Gain in Pitch Control mechanism	Kp = 15 p.u
10	Controller Gain voltage	Kv = 15 p.u

8. POWER FLOW IN DSTATCOM CONTROLLER

Synchronous condensers, sometimes referred to as DSTATCOMs, are simultaneous connection DC-to-AC converters. It absorbs reactive power, operates like an inductor, and stays in an under excited state. However, it functions like a capacitor, generates reactive power, and does not stop being overexcited. *Figure 1* shows the modified circuit model of DSTATCOM's connection to bus A. The equivalent circuit is used as the foundation for the calculation of the active and reactive power equations when DSTATCOM is coupled. The system must adjust the DC power of the capacitor to guarantee that the output AC voltage of the capacitor has the proper amplitude for providing the net reactive power to the system. The duty of the control system is to guarantee that the voltage generated by the AC stays in sync with the contents of the DSTATCOM connection bus. Because of this, the control method can decide whether to generate the *VAr* need for the system or not. A component that synchronizes the voltage and provides the necessary signal to the measurement equipment is referred to as a "phase-locked loop" (PLL). Phase-to-dq conversion and operating average are employed, respectively, to quantify the positive-sequence features of DSTATCOM voltage and current.

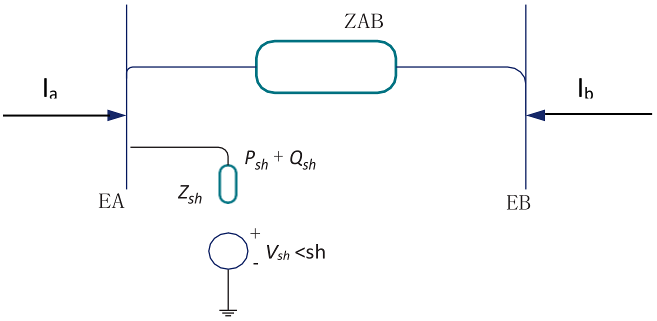

Figure 1. Modified equivalent circuit of DSTATCOM

Table 3. Control variables of DSTATCOM connected to microgrid system

S. No.	Operating component	Range Limit
1	Gain across Active power	300
2	Gain across Reactive Power	700
3	Gain of DC- Link Voltage	7.0
4	Reference Voltage	1.05 p.u.
5	Gain of Regulator	kp = 4, ki = 5
6	Controller Gain voltage (Kv, Ki)	Kv = 15, Ki = 250

9. FUZZY-PI CONTROLLER DESIGN FOR STATCOM CONTROLLER

Sequential PI controllers, which are commonly used as a benchmark against other controller types, are a major component of conventional control systems. PI controllers are usually not suited or trustworthy for significantly highly nonlinear since they are linear and have fixed parameters. Difficulties required the creation of an effective strategy to deal with these problems. Adaptive tuning of the proportional gain involves several ways that adjust the amplitude of the integral controller in response to each disturbance and alter the circuit architecture using fuzzy logic control. The fuzzy logic controller (FLC) is a versatile controller that performs effectively under a variety of circumstances. Boolean or crisp logic handles ambiguity and subtlety, much like fuzzy logic does. Fuzzy logic is a rule-based process that can readily handle any combination of inputs and outputs. The fundamental five elements of FLC's framework are shown in *figure 2*. Fuzzying is the process of converting the precise data in the input into language phrases that fit into the fuzzy set. A database with details about the plant and the related control goal is part of the level of expertise.

It provides thorough descriptions of every element needed for the fuzzy-making process. Fuzzy reasoning is used in conjunction with a rule basis by the expert system, also known as a fuzzy model, to produce accurate findings. The specifics of the data are converted into their linguistic equivalents throughout the fuzzification process in order to make them compatible with the fuzzy set. The effectiveness of the fuzzification technique is determined by the interference signal. The rule base is simply a representation of the program's control mechanism. It is mostly derived from master data or heuristics, which frequently take the shape of numerous if-then rules.

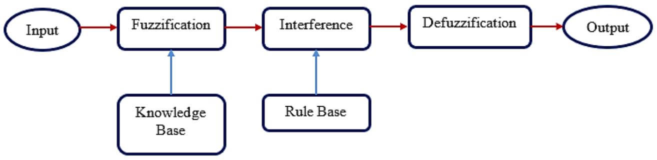

Figure 2. Fuzzy Logic Framework

9.1. Fuzzy Logic Control Structure

Included in the skill set is a database with details on the unit and related control objectives. It provides thorough explanations of all the necessary steps in the fuzzy-making process. The two most commonly used forms of fuzzification procedures are

Takagi-Sugeno and Mamdani fuzzy systems. The fuzzy paradigm, which applies fuzzy reasoning to a classification model to provide the correct result, is another term for the rule-base. Whereas Takagi-Sugeno is suitable for dynamic systems that change rapidly, Mamdani is best suited for dynamic systems that change slowly. In this work, the Mamdani fuzzy inference approach is used because of its wide appeal, ease of use, and special suitability for manual labor.

Defuzzification, which turns the spectrum of transfer functions into the corresponding universe system, allows one to assume a fuzzy process that changes the discrete values and generates a non-fuzzy performance of the controller. The architecture of the fuzzy system, which was used to represent the STATCOM device, is shown in *figure 3*. It has two connections, yet it only produces one result. The fuzzy logic controller of DSTATCOM governs the feedback controller, which sets the maximum voltage. Error and variation in error, represented by the errors e and de, were suitably computed and managed. The modified quantities of "e" and "de" are fed back to the fuzzy logic controller as feedback.

By calculating the output gain factor (k_p) to obtain the proportional derivative and the result of another gain (k_i) of the PI controller, which has been amplified and integrated to produce the proportional-integral, the fuzzy control signal is amplified with a PI controller and achieves improved performance. The fuzzy logic controller (FLC) produces a combination of proportional and integral action when both values are multiplied.

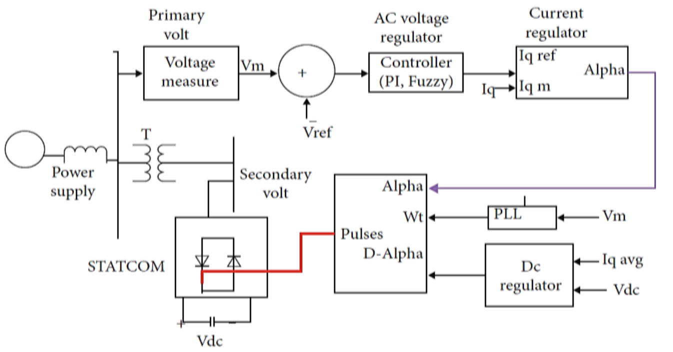

Figure 3. Architecture of Fuzzy System with DSTATCOM

10. RESULT AND DISCUSSION

The objective function involved in this research work is to enhance the voltage profile rating of the microgrid system interconnected with solar PV and wind energy modules connected with a fuzzy logic system, along with the DSTATCOM. The proposed method is being tested on the microgrid system using MATLAB software. The results produced are highly efficient and absolute in attaining the objective function. This research is novel because it combines a PI-controlled DSTATCOM for adaptive reactive power compensation in a hybrid solar–wind microgrid with a Mamdani-based fuzzy inference system. The proposed approach dynamically adjusts controller gains compared to traditional fixed-gain PI controllers, enhancing voltage stability and lowering oscillations under renewable fluctuations. The following *figure 4* shows that the Peak transient response waveforms are created in the initial condition in fuzzy-PI controllers because of the larger margins of gain in PI; therefore, the network is stabilized at 1 sec as opposed to 0.35 secs for the PI controller only.

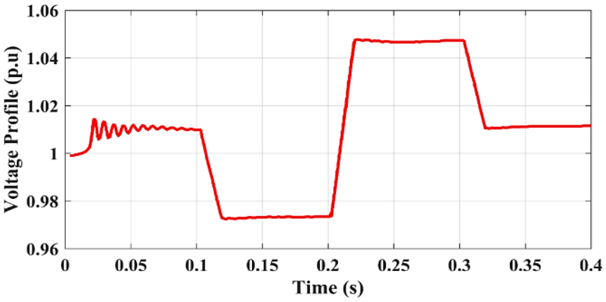

Figure 4. PI Controller-based Reactive Power

The effectiveness of the proposed methodology delivers a tremendous performance in attaining low peak overreach and rapid settling time, as shown in *figure 5*. The proposed controller proves to be effective in producing a better output than any other conventional method and efficient in reducing the system's sudden peak vibrations and stabilizing the result. Therefore, it has been demonstrated that in STATCOM systems, fuzzy-PI controllers perform better than PI controllers. In comparison to the traditional PI controller, the proposed fuzzy-PI controller exhibits better dynamic stability and adaptability under a range of load and generating situations by achieving faster settling time and reduced overshoot. When using a PI controller, the amplitude of the p.u voltage is 1.03, but when using a fuzzy-PI controller, it is shown in *figure 6* as 1.045. It has also been noticed that the proposed controller requires a considerable time limit to regain its initial set point for stabilization.

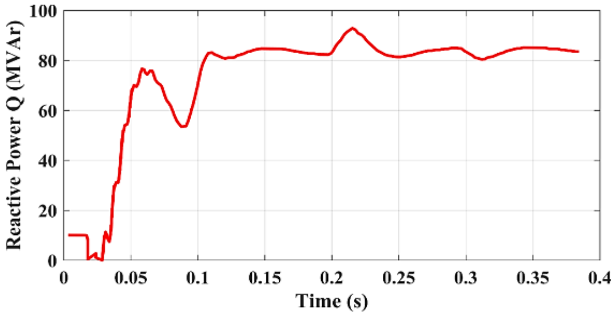

Figure 5. Fuzzy PI Controller-based Reactive Power

10.1. Implementation Procedure

Algorithm for solving the objective function is as follows.

Step 1: Initiate the Power flow studies along with the fuzzy inputs, along with the control parameters of the Wind and Solar PV module.

Step 2: Generate the power flow report by running the Newton-Raphson load flow analysis.

Step 3: Calculate the voltage profile ratings of the system.

Step 4: Validate the profile rating of the system to meet the objective function.

***Step 5*:** Store the results if the objective is attained, if the estimated results are not attained, reiterate the same process by updating the input data along with the DSTATCOM tuning parameters.
***Step 6*:** Repeat the same process until the estimated objective is attained.
***Step 7*:** Stop the iteration process and display the results.

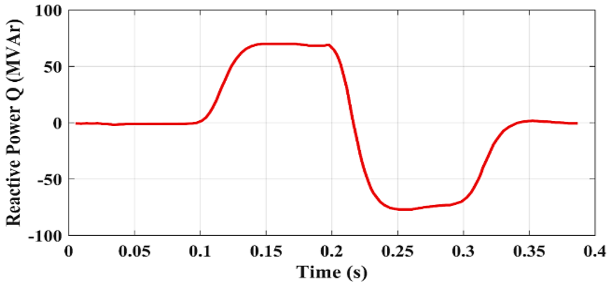

Figure 6. Voltage measurement with PI

The fuzzy-PI controller stabilizes the voltage profile of the system immediately, and there are no longer transitory instabilities. The waveforms are linear, and the attained voltage profile is contrast-generated effectively when the microgrid is connected with the fuzzy-PI controller, as shown in *figure 7*.

The implementation of the fuzzy logic technique for the voltage profile enhancement in the microgrid system using DSTATCOM has been proposed in a pictorial manner as follows in *figure 8*.

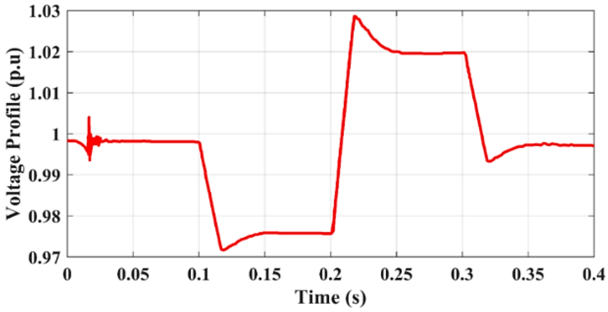

Figure 7. Voltage measurement with PI and Fuzzy Controller

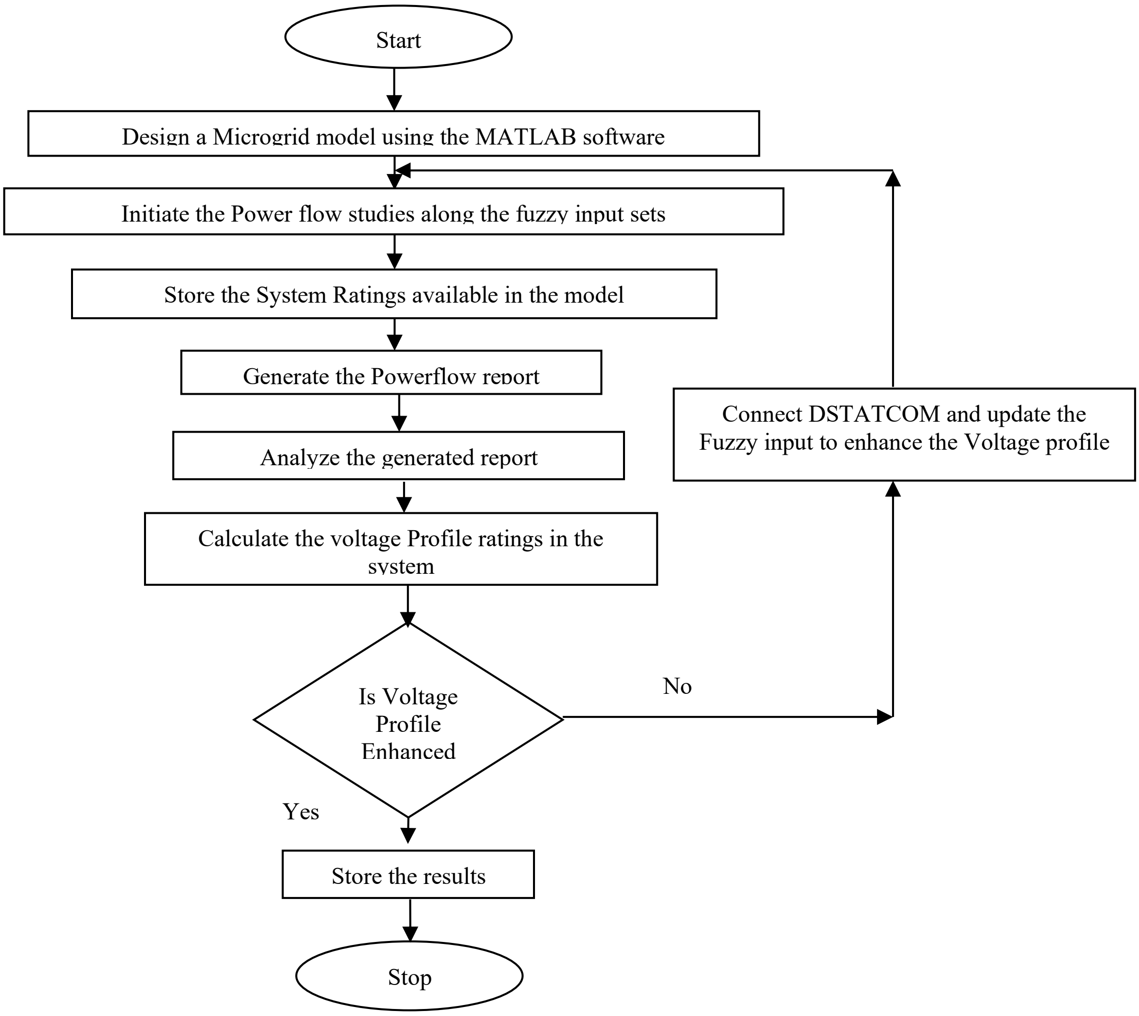

Figure 8. Flowchart for the proposed method

It is essential to stress that the voltage boost attained exhibits higher voltage stability properties in addition to a magnitude improvement. In spite of fluctuating load and generation conditions, the fuzzy-PI controller continuously keeps voltage levels nearer the reference value (1.03 p.u.). This indicates that the controller can increase overall power quality and network dependability by keeping voltage regulation within acceptable bounds.

Table 4. Minimization of the objective function

Parameter	Initial Case (p.u)	With DSTATCOM (p.u)	Fuzzy integrated DSTATCOM (p.u)
Net Real Power Generation	13.568	14.2589	15.7652
Net Reactive Power Generation	3.9456	4.2753	4.1235
Net Real Power at load	13.688	13.982	14.0245
Net Reactive Power at load	3.8564	3.9972	4.1273
Net Active Power Loss	0.4867	0.4134	0.3845
Net Reactive Power Loss	0.2479	0.2148	0.2037

10.2. Minimization of the Objective Function

The attainment of the objective function, *i.e.*, power loss minimization, is attained by implementing the fuzzy logic technique along with DSTATCOM in the microgrid system, as shown in *table 4*. With the fuzzy-integrated DSTATCOM, the net active power loss is quantitatively decreased from 0.4867 p.u. (initial case) to 0.3845 p.u., indicating a notable decrease in transmission losses. Reactive power losses also drop, ranging from 0.2479 p.u. to 0.2037 p.u. This dual improvement in loss minimization and voltage profile demonstrates that the proposed method effectively tackles the reactive power dispatch multi-objective optimization problem. The efficiency and novelty of the proposed fuzzy-logic-based DSTATCOM framework are confirmed by the coordinated increase in generation utilization, decreased line losses, and voltage enhancement.

The voltage profile enhancement in the hybrid renewable energy system integrated with a microgrid system strives to be effective and encouraging in implementing the fuzzy logic-based DSTATCOM for optimal power flow analysis. *Table 5* shows the comparison result of the voltage profile in the grid network. The results produced by the effect of PI-based Fuzzy controller are quite effective and efficient in handling the power system constraints, and the attained results are accurate, and the voltage profile values are outstanding when implementing the proposed system.

Table 5. Voltage profile enhancement

Time scale (sec)	Voltage Profile (p.u)		
	Initial Case (p.u)	With DSTATCOM (p.u)	Fuzzy integrated DSTATCOM (p.u)
0.05	1.042	1.047	1.053
0.1	1.024	1.031	1.049
0.15	1.032	1.038	1.069
0.2	1.051	1.056	1.081
0.25	1.033	1.042	1.062
0.3	1.053	1.061	1.079
0.35	1.047	1.053	1.078
0.4	1.036	1.042	1.08
0.45	1.034	1.044	1.069

Table 6. Comparative Performance Analysis

Performance Metric	PI Controller	Fuzzy-PI DSTATCOM	Improvement
Max Voltage (p.u.)	1.03	1.08	+4.85%
Active Power Loss (p.u.)	0.4867	0.3845	21.0%
Reactive Power Loss (p.u.)	0.2479	0.2037	17.8%
Voltage Stability	Moderate	High	Improved
Oscillation	Present	Reduced	Improved

A thorough performance comparison between the proposed Fuzzy-PI controlled DSTATCOM and the traditional PI controller is shown in *table 6*. There is a noticeable improvement of about 4.85% in the maximum voltage magnitude from 1.03 p.u. (PI controller) to 1.08 p.u. with the Fuzzy-PI controller. The active power loss is greatly decreased from 0.4867 p.u. to 0.3845 p.u., or a 21.0% reduction, in terms of loss minimization. Also, the reactive power loss improves by 17.8%, going from 0.2479 p.u. to 0.2037 p.u. Additionally, there is a significant boost in qualitative performance metrics like oscillatory behavior and voltage stability.

The proposed Fuzzy-PI DSTATCOM provides more stability with fewer oscillations than the PI controller, which shows moderate voltage stability with visible oscillations. The superiority of the proposed control technique in boosting dynamic performance, reducing transmission losses, and improving voltage regulation under fluctuations in renewable energy is quantitatively confirmed by these results.

Table 7 compares the proposed fuzzy-PI DSTATCOM with the current STATCOM/DSTATCOM control techniques. The delayed reaction and fixed settings of traditional PI controllers is drawbacks. Although ANN and GA-based techniques increase performance, they provide a high computational cost or training data requirement. Traditional FACTS controllers are not flexible enough to handle renewable fluctuations. However, without requiring complicated optimization or training, the proposed fuzzy-PI DSTATCOM offers adaptive tuning, quicker response, lower power losses, and enhanced voltage stability in a wind-solar microgrid.

Table 7. Comparison of Existing Methods and proposed Fuzzy-PI DSTATCOM

Reference Method	System Type	Controller Used	Key Objective	Limitations	Proposed Work Advantage
Conventional STATCOM control	Grid system	PI Controller	Voltage regulation	Fixed parameters, slow response	Adaptive fuzzy-PI tuning
ANN-based DSTATCOM	Microgrid	Neural Network	Reactive power control	Requires training data	No training required, rule-based control
GA-optimized STATCOM	Hybrid system	Optimization algorithm	Voltage stability	High computational cost	Simple implementation
FACTS-based compensation	Distribution network	Conventional control	Power quality improvement	Limited adaptability	Handles renewable fluctuations
Proposed Method	Wind–Solar Microgrid	Fuzzy-PI DSTATCOM	Voltage stability + Loss minimization	—	Adaptive, robust, fast response

In hybrid renewable-based microgrids, the proposed fuzzy-PI controlled DSTATCOM shows an efficient and innovative method for managing reactive power optimally. By combining adaptive control intelligence with power flow optimization, this research ensures higher dynamic stability, better voltage regulation, and lower power losses all at once, compared to conventional techniques.

11. DISCUSSION

According to the research's findings, the hybrid solar-wind microgrid's performance in terms of loss reduction and voltage stability is greatly improved by incorporating a fuzzy-PI controlled DSTATCOM. The maximum bus voltage is improved by about 4.85% with the proposed controller, according to simulation results, from 1.03 p.u. (traditional PI control) to 1.08 p.u. With less overshoot and a quicker settling time than the conventional PI controller, the dynamic response is also enhanced, reducing oscillatory behavior under variable renewable energy. Additionally, the fuzzy-integrated DSTATCOM achieves a 21% reduction in active power loss from 0.4867 p.u. in the initial level example to 0.3845 p.u., while reactive power loss drops by 17.8%. These outcomes demonstrate that the proposed adaptive fuzzy-PI control approach improves voltage regulation, efficiently distributes reactive power, and boosts network efficiency in general. The efficiency and originality of the proposed method for the best reactive power management in grid-connected microgrids are confirmed by the coordinated improvement in voltage profile, stability, and power loss reduction.

12. CONCLUSION

This research presented an effective approach for integrating a fuzzy logic-controlled DSTATCOM to improve reactive power management and voltage stability in a hybrid renewable energy-based microgrid system. Using MATLAB, a comprehensive microgrid model including solar PV and wind energy modules was created. The Newton-Raphson method was used to analyze power flow and assess system performance under various operating scenarios. The results show that incorporating DSTATCOM greatly enhances voltage management and lowers reactive and actual power losses. The proposed fuzzy-PI controller demonstrated better dynamic performance, including less overshoot, a quicker settling time, and an enhanced steady-state voltage profile, when compared to the traditional PI-controlled DSTATCOM. Under fuzzy-PI control, the voltage magnitude increased from 1.03 p.u. (PI controller) to 1.045 p.u., suggesting greater voltage stability. Furthermore, the fuzzy-integrated DSTATCOM decreased active power losses from 0.4867 p.u. in the initial scenario to 0.3845 p.u., demonstrating the efficacy of the proposed control approach. The fuzzy-PI controller minimizes voltage oscillations and ensures steady reactive power compensation by efficiently adjusting to nonlinear system fluctuations brought on by varying renewable energy sources. Overall, the combination of DSTATCOM with a fuzzy logic control framework enhances the operational stability of grid-connected microgrids, increases network capabilities, and improves power quality. In order to verify practical performance in field settings, future research will concentrate on real-time hardware implementation. The research can be expanded to include interconnected multi-microgrid systems with integrated energy storage and a greater penetration of renewable energy sources. Enhancing adaptive control techniques may also be a future development to boost system resilience in the event of significant grid disruptions.

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