REVIEW ON VOLTAGE CONTROL OF SOLAR-WIND HYBRID MICROGRID USING OPTIMIZED STATCOM

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ABSTRACT

The intermittent and unpredictable behaviour of renewable energy sources like solar and wind poses serious challenges to voltage stability and power quality in microgrids. To counteract these fluctuations, the integration of advanced reactive power compensators such as the Static Synchronous Compensator (STATCOM) has proven effective. This review explores the implementation and modeling of a solar-wind hybrid microgrid equipped with STATCOM, highlighting various control strategies, including conventional PI, Fuzzy Logic controllers. Comparative simulations demonstrate that while traditional PI controllers provide basic compensation, intelligent and adaptive controllers significantly enhance voltage regulation and system reliability. This paper offers a consolidated understanding of the improvements achieved through optimized control techniques, providing insights for future development in hybrid renewable microgrids.

Keywords: photovoltaic; Static Synchronous Compensator (STATCOM), PI controller, Solar PV-Wind Hybrid Micro-grid, Fuzzy Logic Controller

1. INTRODUCTION

Climate change and the responsible management of the world's depleting fossil fuel resources are the two greatest problems the planet now facing. Reducing our dependence on fossil fuels and significantly cutting down on emissions of greenhouse gases is necessary if we want to provide future generations with a safe planet. Investment in renewable energy has expanded significantly as the price of technologies drops and their efficiency keeps getting better; this is because renewable energy is an essential aspect of lowering global carbon emissions. [1]

Centralized power plants have several drawbacks: First, most power plants use fossil fuel, which increases CO2 emissions and wastes rejected heat; second, large amounts of power must be delivered using transformers and long transmission and distribution lines; third, power losses and voltage drop seem to be significant problems due to the length of the transmission lines and the transformers; and fourth, this does not offer a financially viable solution to supply power to poor and isolated communities. We can reduce our reliance on fossil fuels and our impact on the environment by switching to renewable energy sources like wind and solar photovoltaic (PV) generation.

Microgrids are small-scale power networks made up of renewable energy generators, battery storage, and end-use consumers. There are various benefits to using a microgrid, including more dependability, greater controllability, and higher quality electricity. There are two types of microgrids: those that are linked to the larger grid and those that are completely separate from it. Operating the grid-connected microgrid in tandem with a reliable electric power system means worrying less about unwanted frequency fluctuations. Therefore, from a financial perspective, microgrids that are linked to the grid need to focus on increasing electric power exchanges and profits. In contrast, without access to the larger electric grid, isolated microgrids have challenges with voltage and frequency fluctuation maintenance. [2]

Distributed microgrids based on renewable power generation techniques like solar, wind, and biogas can help meet the growing global demand for electricity while reducing the associated costs and emissions of harmful greenhouse gases (GHGs) from traditional central power plants that rely on fossil fuels. Use of renewable energy sources is the only viable option for creating a better, pollution-free planet. Producing electricity from renewable resources is feasible.

Conventional renewable sources are being used efficiently over the world to provide a long-term solution to the energy dilemma, and they include solar, wind, and hydro.

- **Development of Distributed Generation (DG)**

A major part of today's residential, commercial, and industrial power systems depends on the DG. Distributed generation (DG) offers an alternative to the conventional electrical power generating sources of today, such as oil, gas, coal, and water. Small-scale power generation (1 kW-50 MW) or, more colloquially, power generating units linked at distribution level closer to the load side is what is meant by "DG." [3] [4]

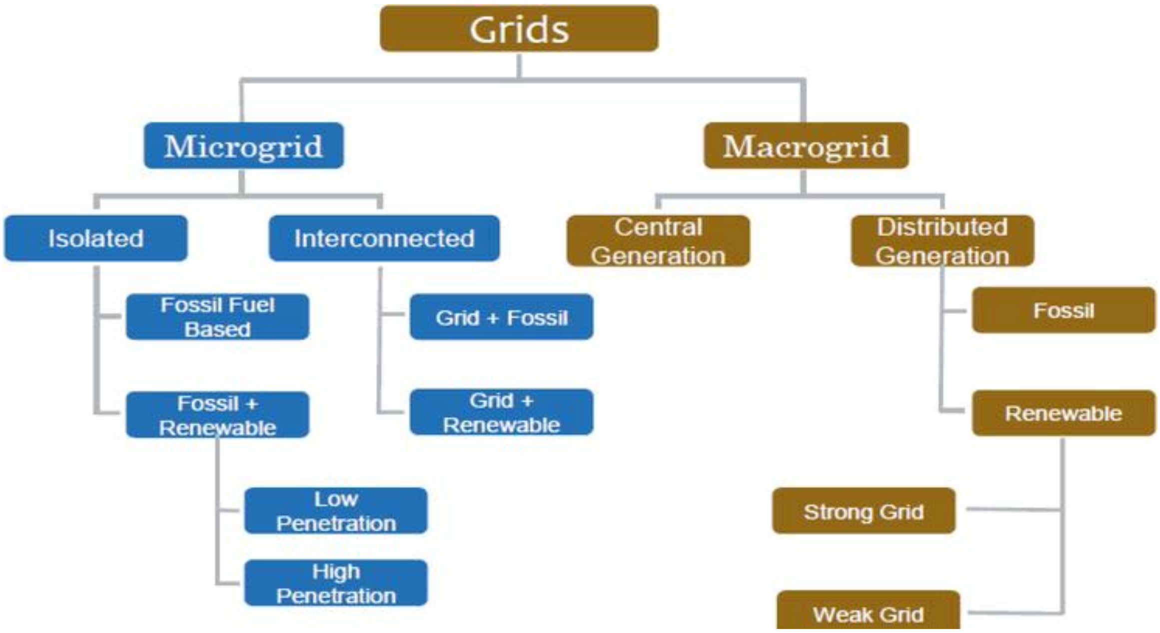

Figure 1 Grid classification

The DG's rising popularity may be attributed to its high efficiency, minimal emissions, and gentle operation. Using DG is as simple as plugging in a device. By using this route, the DG unit may be relocated wherever it is most convenient without requiring any adjustments to the distribution system's management infrastructure. DG, or diesel generator, is a secondary source of electricity used by many factories, malls, hospitals, universities, and other commercial establishments. Power from this device is used as a backup in the event that the main power source goes down. Fuel cells, microturbines, batteries, flywheels, and supercapacitors are some of the examples of distributed generators. The distributed generating system also includes “photovoltaic (PV) and wind turbine (WT) resources.” [5]

2. LITERATURE REVIEW

In this section, we will examine studies that focus on different power quality enhancement techniques. Here, we examine and contrast the strengths and weaknesses of several power quality enhancement methods, such as STATCOM and various controllers (such as PI and PID).

(Manikandan et al., 2023) [1] Whether or not the weather cooperates, renewable energy sources like solar photovoltaic panels and wind turbines can only provide so much power. Solar photovoltaic (PV) and wind-generated power are distinctive and very changeable. It is necessary to stabilize each of them independently in order to maintain a steady power output. Thus, some kind of regulating procedure is required. For this reason, fast energy adjustment is essential for power transmission and distribution networks. It is therefore necessary to use a STATCOM (Static Synchronous Compensator) for reactive power compensation, so that voltage variations during power production can be kept under control and a steady state operation may be achieved. Four genetic algorithm-based PI controllers are made available to STATCOM. A DFIG-based 2 MW wind turbine model, a PV energy system model producing 0.4 MW, and a 3 MVAR STATCOM are all used in this simulation. While traditional PI controllers based on GA can reduce voltage fluctuations at the end of the busbar by 8% and provide more stable operation, standard controllers are not able to match their performance.

(Khan, 2021) [2] Photovoltaic (PV) systems, which use the sun and wind to generate electricity, are very weather-dependent. Due to their erratic nature, their output is also unpredictable. This highlights the growing significance of fast compensation for systems that distribute and use energy. The "Static Synchronous Compensator (STATCOM)" may be used to smooth out voltage swings induced by the grid and renewable energy sources, thereby compensating for reactive power. Here, we demonstrate a Solar PV-Wind Hybrid Micro-lattice and investigate whether or not the inclusion of STATCOM raises the framework's stable operating limitation. The primary contribution of this paper is the optimization of the addition bounds of four PI regulators in STATCOM using genetic algorithms (GA) and the Particle Swarm Optimization (PSO) procedure, resulting in improved reactions and voltage solidness with respect to the nonlinear nature of the solar-powered breeze mixture miniature matrix. The design's Simulink models include a DFIG-based 2 MW wind turbine model, a 0.4 MW solar-based PV power framework model, and a 3 MVAR STATCOM. Using a regular PI regulator guarantees an 8% reduction in voltage variation at the bus bar's end. We compare the results obtained by a GA-based regulator to those obtained by a PSO-based streamlining of PI regulators and find that the latter yields superior results.

(Kharadi & Christian, 2021) [3] Sustainable energy sources are an integral aspect of our electrical infrastructure. Wind, solar, geothermal, ocean thermal, and biomass are just few of the renewable energy sources that may be used to create electricity. Because solar energy can be captured everywhere at no cost, it is the most practical source for power production. The solar photovoltaic modules can convert sunlight into electricity (PV). Wind and solar photovoltaic (PV) systems rely heavily on environmental conditions for electricity production. Its output is unstable due of their inconsistency. As a result, it's becoming more crucial that energy transmission and distribution networks have access to rapid correction. Reactive power compensation and voltage variations from the grid and renewables might be mitigated by installing a "Static Synchronous Compensator (STATCOM)." To such objective, this study modelled a Solar PV-Wind Hybrid Micro-grid and looked into whether or not adding STATCOM may raise the system's stable operating limit. In view of the nonlinear features of the solar-wind hybrid micro-grid, the primary contribution of this study is the application of genetic algorithms (GA) to optimise the gain parameters of four PI controllers in STATCOM, resulting in faster response times and more consistent voltage.

(Prasanna & Jyothi, 2021) [4] Photovoltaic (PV) systems, which use the sun and wind to generate electricity, are very weather-dependent. Due to their unpredictable nature, their output is also unpredictable. This highlights the growing significance of fast compensation for systems that distribute and use energy. The Static Synchronous Compensator (STATCOM) can smooth out voltage fluctuations and level down reactive power generated by the grid and renewable energy sources. This research presents a Solar PV-Wind Hybrid Micro-lattice and investigates whether or not the inclusion of STATCOM will boost the framework's stable operating limits. To improve reactions and voltage solidness with respect to the nonlinear nature of the solar-powered breeze mixing micro matrix, the authors of this study make a substantial contribution by simplifying the addition limits of four PI regulators in STATCOM using genetic calculations (GA). The design's Simulink models include a 3 MVAR STATCOM, a 0.4 MW model of a solar PV power framework, and a 2 MW model of a wind turbine dependent on a doubly taken care of acceptance generator (DFIG). Using a regular PI regulator guarantees an 8% reduction in voltage variation at the bus bar's terminus. We compare the results obtained by a GA-based regulator to those obtained by a PSO-based streamlining of PI regulators and find that the latter yields superior results.

(Deng et al., 2021) [5] Nowadays, distribution network power quality adjustment device setup algorithms may be quite involved. As a result, the algorithm is programmed with a simulation of the natural laws governing dominant genes. Weak coupling between loads and compensation devices is considered, leading to the establishment of an ideal configuration model for harmonic compensation devices. Fast convergence and great accuracy are achieved by the “Implicit genetic rule of adaptive discrete genetic algorithm (IGADGA),” and the method is verified by simulation.

(Elgammal & Ramlal, 2021) [6] It is possible to complement or even entirely replace the inefficient power systems that service remote locations with renewable energy facilities like hydro turbine generators. Using a small hydro turbine that is connected into the grid, the current and electrical load is shared. Due to the power quality issue, the voltage amplitude in the energy distribution system will shift, which will have an effect on the electric load. In this research, the unique smart inverter PV-STATCOM is presented, which may be used to regulate a solar inverter in the role of a “dynamic reactive power compensator (DRPC)”. The suggested solar STATCOM may be used to provide voltage regulation for critical building needs. For the duration of the night, all of the inverter's power is put into STATCOM activities. Throughout a major outage that occurs during the day, the smart inverter will stop its actual power producing function and make its full inverter capacity available for STATCOM operation.

(Ramakrishna et al., 2021) [7] When many forms of renewable energy are connected to the grid at once, the voltage often dips and fluctuates. Several FACTs devices wired to the PCC improve the voltage profile and lessen the severity of these issues. The "STATCOM module," which is built into the controller's grid and FIS, allows for improved performance. Both the PV array module and the PMSG wind farm are linked at PCC in parallel with the primary grid and STATCOM in the research distribution grid. MATLAB's Simulink block sets are used to analyse the proposed distribution test system under a variety of operating conditions. Every single comparison diagram is created using the 'powergui' toolkit's temporal domain analysis.

(Shahgholian, 2021) [8] To fully realise the potential of the smart grid, microgrids must be implemented. It is an energy network that serves a local area and makes use of decentralised power sources. Distributed generation can only reach its full potential if the accompanying loads and generation are treated as a separate system, or microgrid. This article presents a literature review on microgrids. The research done on microgrids may be divided into two categories control and optimization, and feasibility and cost studies. Microgrids and their uses and varieties are outlined, followed by a discussion of microgrid control and its purpose. Both centralised and decentralized methods of control may be used to microgrids. Stability under weak signals is examined, as are strategies for increasing it. Microgrids' load frequency management is evaluated.

- **Microgrid Control Strategy**

Several strategies are described below that may be used to manage a distribution system's components.[3]

- Control by a master and slave: The voltage and frequency are controlled by the master, while the current is managed by the slaves.
- Current and power flow control: this technology involves control signals to govern current and power distribution.
- Droop control: This approach is superior for merging with previous approaches due to the converters' ability to function as non-ideal voltage sources.

1.3 Centralized Control System

With a centralised control system, all the brains are in one place, which may be a switch, a server, or a controller. A centralised network is easy to manage since the operator has greater command over the whole setup. The manager may now construct comprehensive control strategies to meet all of the organization's power requirements owing to this new capability.

However, the centralised control system requires just a single control node to handle all of the data collection and analysis. This one control node has the potential to generate a wide variety of flaws and communication problems that might put the whole system to a standstill. [4]

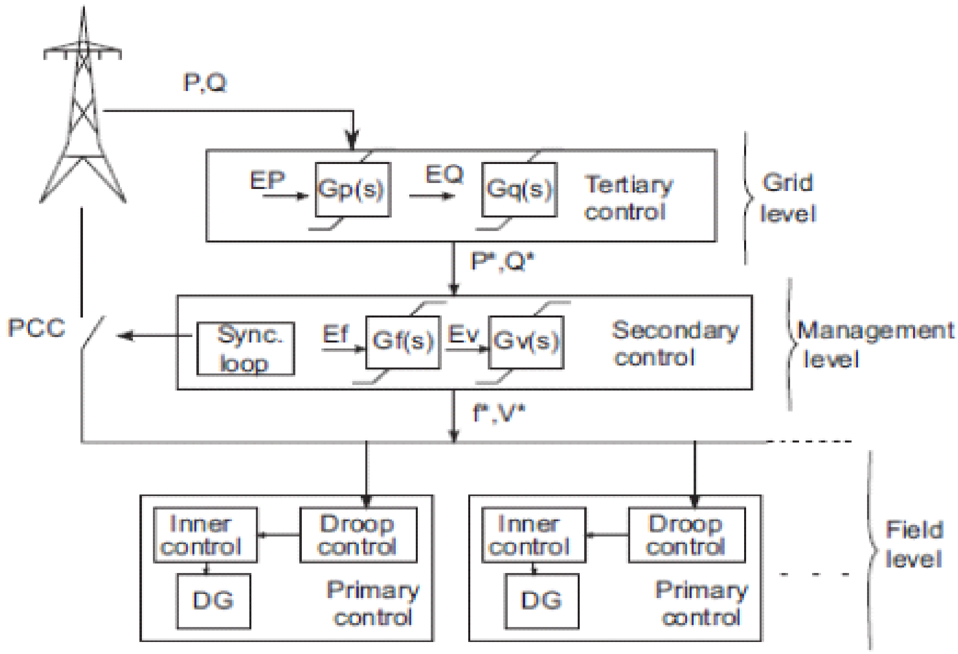

Figure 2 Centralized hierarchical control of micrograds

- **1.4 Total Harmonic Distortion**

The advancement of technology has resulted in a significant improvement in semiconductor devices. Semiconductor devices are important in the energy sector because they make system control easier. However, nonlinear semiconductor devices draw nonlinear current from the source. Harmonics and reactive power are generated when nonlinear loads are used. Harmonics are regarded as a serious power quality issue. As a result, it's critical to minimize harmonics in order to maintain power quality and keep THD below 5%, as defined by the IEEE 519 harmonics standard. [5]

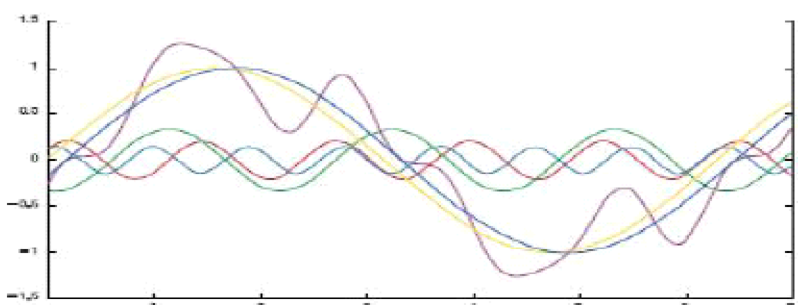

Figure 3 Harmonic distortion for electrical signals

When V is replaced for I in the foregoing equation, a similar expression for voltage THD emerges. Based on odd harmonics up to the 50th, the THDI for a single-phase converter is roughly 95 percent against 30 percent for a three-phase converter. [46] Because the average system impedance up to a harmonic source is low as well as the typical harmonic source is a tiny load, the resulting THDV (in percent) has been in the single digits up until now. For some devices, the harmonic content as well as THD can be determined at various load levels. For instance, a battery charger's harmonic content and total harmonic distortion (THD) vary with the load. The total harmonic distortion (THD) and the percent of individual harmonics (percent of harmonics) at rated load are usually sufficient measurements. The lower base current at lower loads often cancels out the higher percentages (of individual harmonics and THD) produced by the lower load. One that generates 20% THDI at 50% load is no worse than one that generates 10% THDI at 100% load, provided that both loads have the same base current. Equal ampere distortion is produced by each of them. Utilizing filters in the power system is one option for resolving the harmonics problem. The harmonic effect could be reduced by installing a filter for nonlinear loads linked to the power supply. Harmonic reduction is a common application for filters. [47]

4. METHODOLOGY

- **Essential Components of the System**

The purpose of this research was to include STATCOM for reactive power compensation into the current power system design to expand its dependable working limit. Moreover, it aims to mitigate voltage fluctuations brought on by the intermittent nature of renewable energy sources.

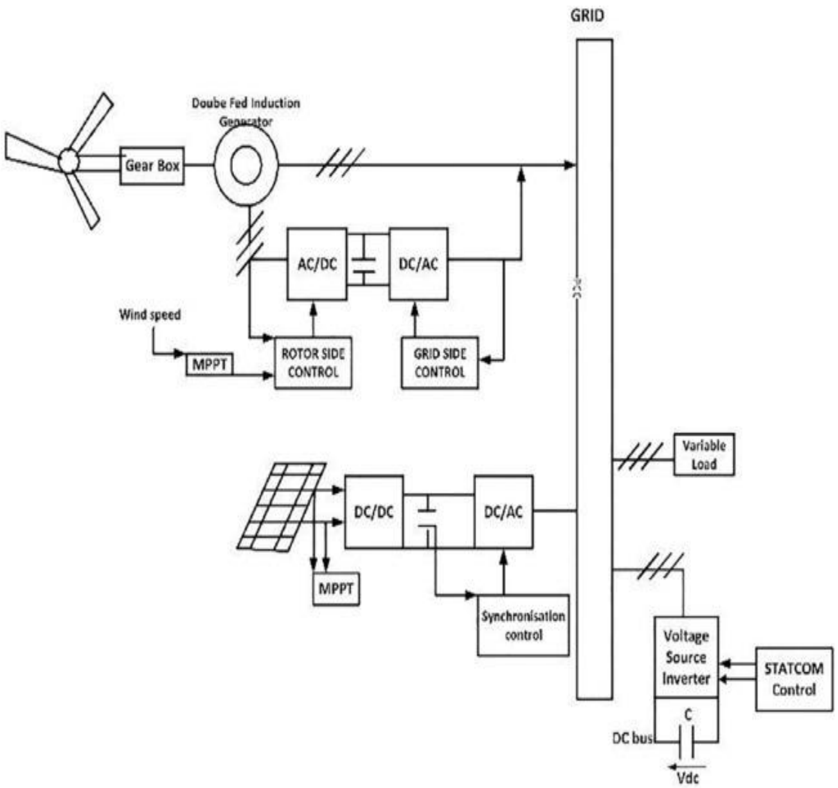

Figure 4 Solar-wind hybrid system including STATCOM [25]

Voltage Source Inverter: A voltage source inverter (VSI) is a device that inverts the polarity of a direct current (DC) voltage so that it may be used with alternating current (AC) devices. A efficient voltage source inverter maintains a stable voltage throughout the operation.

In most cases, a VSI will have one large DC link capacitor, one DC voltage source, one switching transistor, and one DC voltage source. Transistors used may be IGBTs, BJTs, MOSFETs, or GTOs, and DC voltage sources may come from batteries, generators, or solar cells. There are two main types of VSI topologies: single-phase and three-phase inverters, with further subcategorization into half-bridge and full-bridge inverters for each phase. The DFIG is made up of a series of voltage-induced converters that are linked in both directions to the rotor windings and directly coupled to the fixed frequency three-phase grid. Power factor and converter operation are both regulated by the grid-side inverter, which also regulates the DC link voltage.

- **WIND POWER SYSTEM MODELLING**

One of today's most popular wind generators nowadays is the Doubly Fed Induction Generator (DFIG) [13]. DFIGs have back-to-back voltage-based converters installed in the rotor windings and stator windings that are linked directly to a fixed frequency 3-phase network. The phrase "doubly-fed" refers to a power converter where the stator voltage is taken from the mains and the rotor voltage is induced by the converter itself.

The system supports a wide range of speeds, within a certain range (it can function with a speed differential of 40%). Transducers inject current at varying frequencies to the rotor, allowing both mechanical and electrical frequency control. Power converters or controllers govern generator behaviour during normal operation and fault circumstances.

- **STATCOM**

STATCOMs also have the ability to enhance power quality by performing tasks such as power factor correction, reactive power management, dampening low-frequency power oscillations (often through reactive power modulation), active harmonic filtering, flicker reduction, and more. Applications where voltage stability and power quality are of paramount significance include electric power transmission, electric power distribution, electrical networks of large industrial facilities, arc furnaces, high-speed rail systems, and other electric systems. [51]

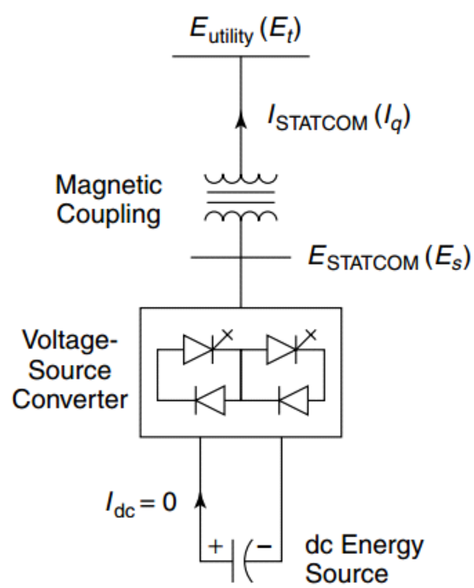

Figure 5 Principal Diagram of STATCOM

• **4.4 Fuzzy Logic Controller**

There are two inputs to fuzzy processing: an error and an error change. A fuzzy controller uses a set of language rules to regulate its actions. Since no mathematical model is necessary, it may be used with erroneous inputs. [3]

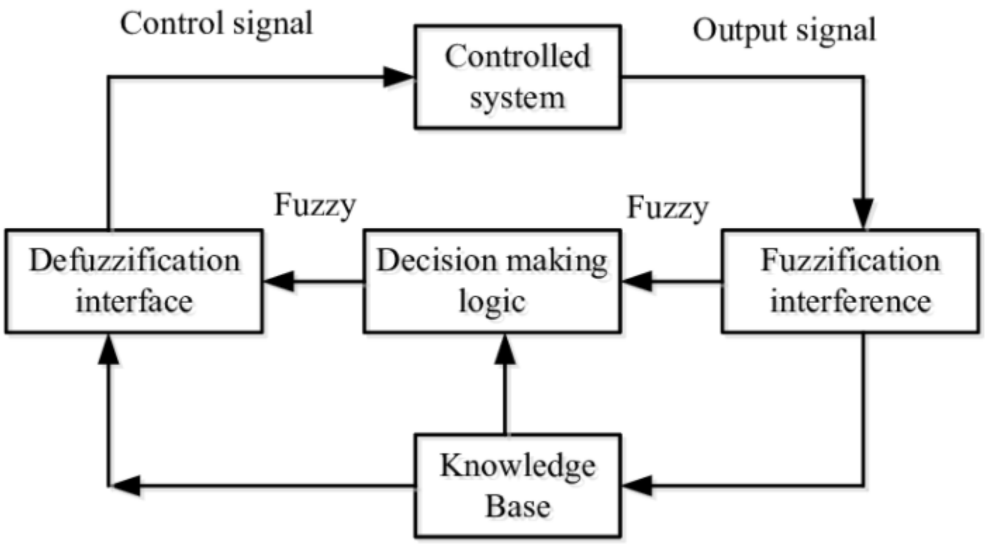

Fig.6 Block diagram of Fuzzy Logic Controller

A. Fuzzification:

In fuzzy logic control, instead of numerical variables, linguistic variables are employed. These mistakes may be classified as either positive, medium, large, negative, or zero when compared to the reference and output signals, with the exception of zero, which is always positive. Using a triangle membership function, fuzziness is being implemented. Numerical variables are transformed into linguistic variables using fuzzification. [34]

B. Rule Elevator:

As opposed to numerical variables, Fuzzy logic employs language variables. The fuzzy set rules used to regulate the system are as follows:

AND-Intersection:

OR-Union:

NOT-Complement:

C.Defuzzification:

According to fuzzy logic principles, linguistic variables are transformed into crisp values. Precision vs computational power are the two options. As a consequence, the output inferred from the fuzzy control method should be defuzzified, as should the fuzzy control action.

D. Rule Base:

The language control rules needed by rule elevator are stored in the rule base. The following table lists the controller's rules.

Table 1: Fuzzy Rules

$e/_{de}$	NB	NM	NS	ZE	PS	PM	PB
NB	ZE	ZE	NB	NM	NM	ZE	ZE
NM	ZE	ZE	NM	NM	NS	ZE	ZE
NS	ZE	ZE	NS	NS	ZE	ZE	ZE
ZE	ZE	ZE	NS	NM	PS	ZE	ZE
PS	ZE	ZE	ZE	PS	PS	ZE	ZE
PM	ZE	ZE	NS	PM	PB	ZE	ZE
PB	ZE	ZE	NS	PM	PB	ZE	ZE

Fig. 5Membership functions for input and output variables

4. 5 Advantages of Fuzzy Logic Controller

The following are the benefits of fuzzy control over PI control methods:

- System design can be improved since it does not need to know all the variables, allowing for more precision.
- The language, rather than the numerical, elements make the process resemble that of logical cognition.
- Due to their ability to handle a wide range of operating conditions, they are more robust than PI controllers.
- FLC is cost-effective.
- FLC is adaptable.
- FLC is a trustworthy company.
- FLC is more efficient.
- It improves stability.

5. CONCLUSION

This review comprehensively analyzed the integration of a Static Synchronous Compensator (STATCOM) in a solar-wind hybrid microgrid for improved voltage regulation and reactive power compensation. Simulation-based insights indicate that while conventional PI controllers offer a degree of voltage stability, their performance under dynamic conditions remains limited. In contrast, advanced control techniques like Fuzzy Logic controllers show remarkable improvement in transient response, power quality, and total harmonic distortion (THD) reduction. The STATCOM's ability to maintain voltage within permissible limits and support reactive power under variable loads makes it a critical element in modern microgrids. Going forward, incorporating real-time adaptive tuning algorithms, artificial intelligence-based control strategies, and hardware-in-the-loop (HIL) validation could further elevate the performance and scalability of hybrid renewable systems. This paper provides a strong foundation for future research and deployment of optimized STATCOM control in sustainable energy net

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