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Stability Improvement in Hybrid Renewable Microgrid Using Intelligent STATCOM Control

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Abstract: *The integration of solar photovoltaic (PV) and wind energy systems provides an eco-friendly solution for power generation, but their outputs are highly variable due to changing weather conditions. These fluctuations cause instability in voltage and reactive power in hybrid microgrids. To address these issues, this study proposes a Solar–Wind Hybrid Microgrid model incorporating a Static Synchronous Compensator (STATCOM) for dynamic reactive power compensation and voltage regulation. A Fuzzy Logic Controller (FLC) with 49 rules replaces the conventional Proportional–Integral (PI) controller to enhance the nonlinear control performance of STATCOM. The hybrid system consists of a 1.5 MW Doubly Fed Induction Generator (DFIG)-based wind turbine, a 0.1 MW solar PV system, and a 3 MVAR STATCOM connected at the point of common coupling (PCC). Simulation results in MATLAB/Simulink demonstrate that the fuzzy-controlled STATCOM significantly improves voltage stability and reduces bus voltage fluctuations by approximately 8% compared to the conventional PI-based control scheme. Hence, the proposed controller provides superior damping, faster response, and better system stability under varying load and source conditions.*

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 around the world to provide a long-term solution to the energy dilemma, and they include solar, wind, and hydro.

2. Doubly Fed Induction Generator (DFIG)

Wind turbines have come a long way since their inception in 1975, when they were first used to generate electricity. In the 1980s, the first modern turbine was wired into the grid. The widespread use of DFIG may be traced back to the rise in popularity of wind energy and wind power generation. The term "doubly fed induction generator" refers to the fact that the electrical power generated is sent in both directions (between the stator and the rotor). Since these generators can adapt to changing wind conditions, they have garnered a lot of interest. There are benefits to using variable-speed wind power plants rather than constant-speed wind power plants. [6]

Variable-speed wind farms cover a larger energy range than their constant-speed counterparts, and they do so with less mechanical stress and less noise than stationary wind farms. The advancement of power electronics has made it practical and inexpensive to regulate every speed. Working with varying wind speeds has unique challenges, and this research focuses on variable-speed DFIGs to address those needs. Wind power plants, as depicted in the figure, have a layout in which the stator's orbit of the DFIG is connected directly to the grid, while the rotor's orbit is connected to the grid through a back-to-back converter (generator side converter and grid-side converter) with slippery rings. A capacitor connected as a dc connection between the two converters acts as a ripple-smoothing energy saver and reduces the voltage rise that may occur between the two. [7]

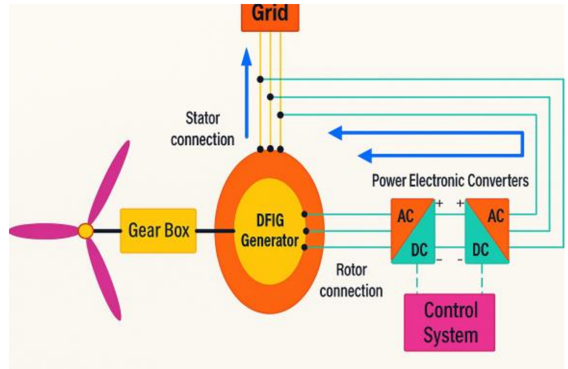

Figure 1: Schematic diagram of DFIG Generator

In its normal mode of operation, DFIG's grid-side converter allows for independent regulation of active and reactive power. In addition, the soft starter may be omitted during grid connection if the converter is installed on the rotor side. The DFIG's control plane may be subdivided into its two main subsystems, the mechanical and electrical systems. Although the control systems were developed with a variety of objectives in mind, regulating grid-injection power has always been a top priority. The rotor-side converter regulates the grid-exposed active power, while the stator- and rotor-side converters regulate the reactive power injection. [8]

3. Methodology

3.1 Essential Components of the System

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

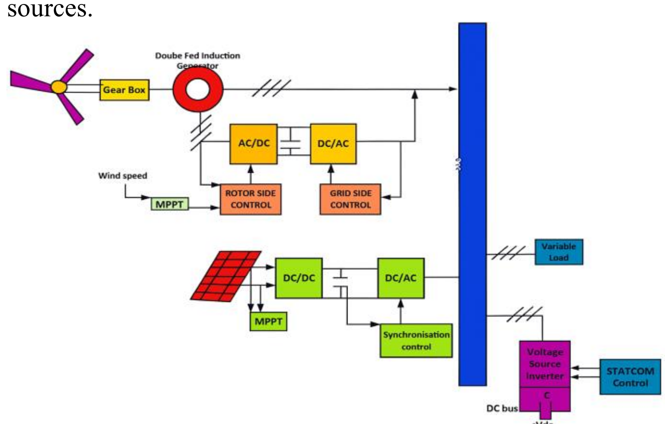

Figure 2 Solar-wind hybrid system including STATCOM.

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. An 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.
Variable Load: The needs of the users are taken into account while planning an electric power plant. A continuous, long-lasting load is desirable for a power plant since it allows for planning and regular maintenance.
Directly coupled to the fixed-frequency three-phase grid and bidirectionally connected to the rotor windings, the DFIG comprises of voltage-induced converters in sequential order. Within power converter unit, there have been two converters: “a rectifier on the rotor side and an inverter on the grid side.” The fundamental concept is to manage the active and reactive powers by regulating the rotor current components of the rectifier. The grid-side inverter regulates the DC link voltage and coordinates the converter's operation with the power factor.
The simulation software Simulink is used to build the control circuit. The mechanical torque is presented by the aerodynamic model as a function of air-flow on the blades, and hence represents the power of the rotor [15].
The average speed of the air across the region swept by the blades is what is meant by "wind speed" (Vw). The wind turbine power equation is derived from the following.

$\boldsymbol{P_w = \frac{1}{2} C_P \rho A V_w^3}$ …………..…… Equation 1

Torque due to aerodynamic forces is calculated in

$\boldsymbol{T_t = \frac{1}{2} \rho R^3 V_w^2 C_t}$ ……………….. Equation 3

An expression for the ratio of the velocities at the ends of wind turbines is

$\boldsymbol{\partial = R\Omega_t / V_w}$ ……………………Equation 4

The maximum power point of a wind turbine is calculated using the modelled indirect speed control based on the derived power and torque equations. The DFIG was modelled after the DFIM, which means that some data from the DFIM was used in the simulation.

3.2 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]

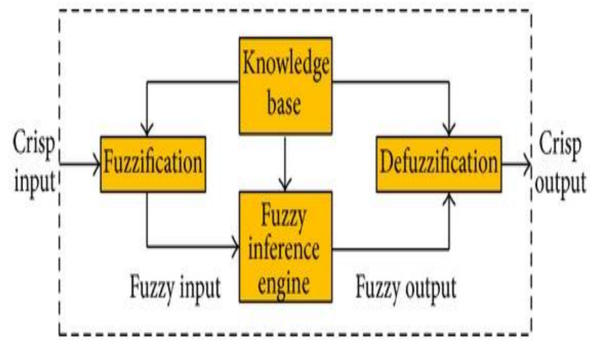

Fig.3 Block diagram of Fuzzy Logic Controller

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. [4]

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: $\mu A \cup B = min[\mu A(X), \mu B(x)]$
OR-Union: $\mu A \cup B = max[\mu A(X), \mu B(x)]$
NOT-Complement: $\mu A = 1 - \mu A(x)$

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.

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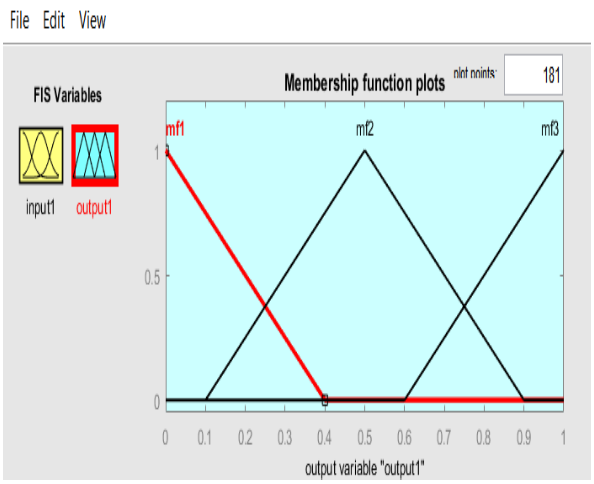

Fig. 4 Membership function for output variable

3.3 Advantages of using Fuzzy Logic Controller in STATCOM

- Solar and wind energy systems are highly nonlinear due to variations in sunlight and wind speed.
- Fuzzy controllers can handle these nonlinearities effectively without needing an exact system model.
- FLC offers faster response compared to conventional PI controllers, especially during disturbances like load changes or faults.
- It improves voltage recovery time and reduces instability
- Renewable sources are unpredictable. Fuzzy controllers are robust and can handle uncertainties and changing operating conditions better than PI controllers.
- FLC helps achieve smoother voltage control with less overshoot, minimal oscillations, and faster settling time.

4. Simulation Results and discussion

As per the given proposed system the modeling of grid with DFIG wind farm, PV source and STATCOM connected at PCC is given below in figure 5. STATCOM is based on a voltage source DC/AC converter. At the STATCOM output, balanced three-phase voltages are obtained at the mains frequency, with controllable amplitude and phase angle. In this embodiment, the steady-state power exchange between the AC system and the device is generally reactive. The reactive power exchange between the STATCOM and the AC system is controlled by regulating the magnitude and phase angle.

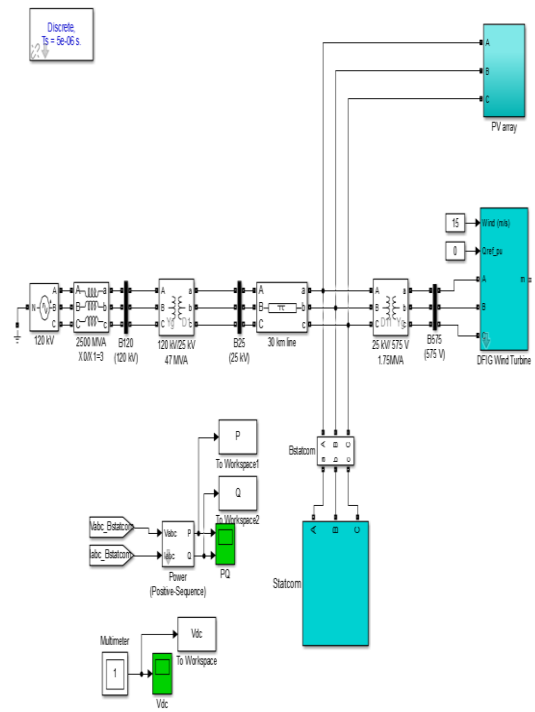

Figure 5 Simulation of Solar-wind Hybrid System Including STATCOM

The internal modeling of wind farm and PV source are shown below in Figure 6.

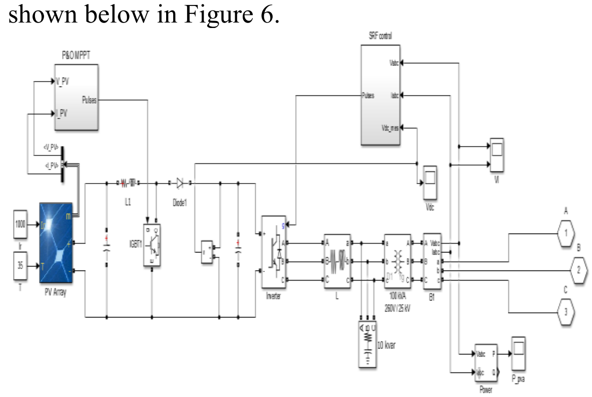

Figure 6: structure of PV Array

The wind farm and the PV source are operated optimally at maximum possible solar irradiation and wind speed with maximum power generation from the renewable sources.

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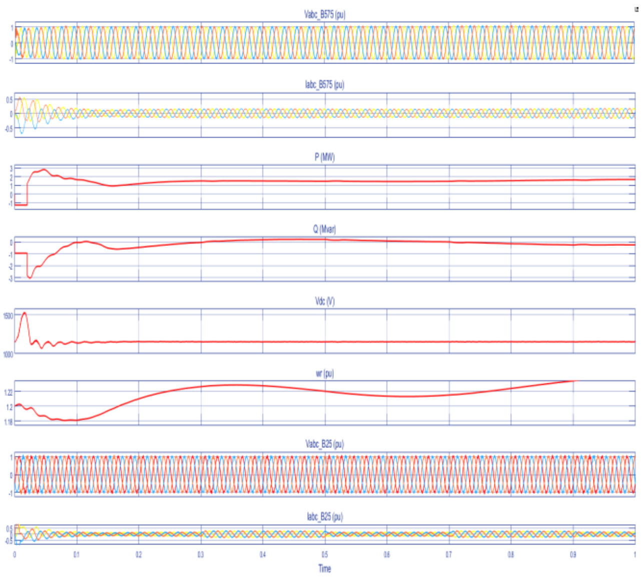
Figure 7 DFIG wind farm characteristics

With the updated DC voltage regulator the STATCOM characteristics with comparative analysis is shown in figure below.

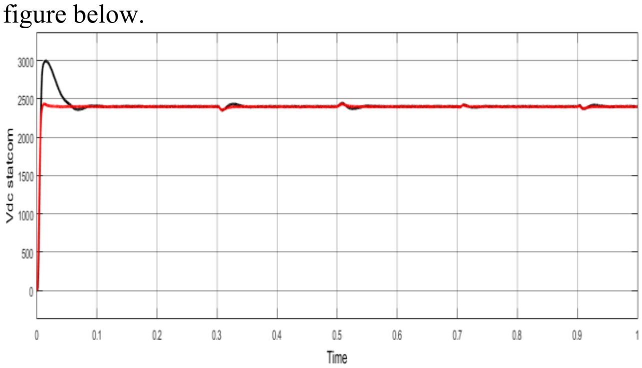

Fig. 8 Comparison of active and reactive powers of STATCOM with PI and Fuzzy Logic controllers

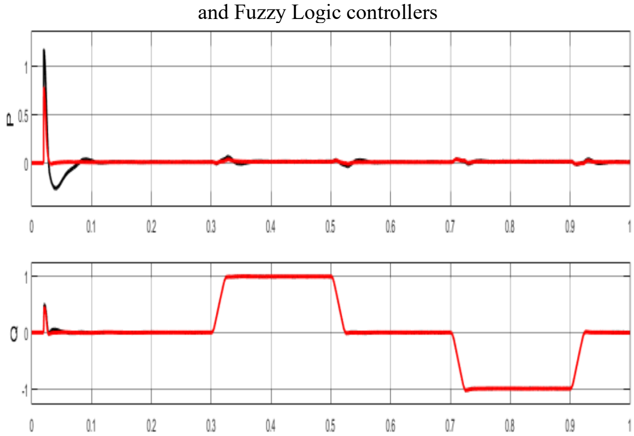

Fig.9 DC voltage of STATCOM with PI and Fuzzy Logic controller

As observed in the above graphs of active and reactive powers, DC voltage of STATCOM the damping is reduced during Qref changing conditions. The lower and upper peak value generation is reduced to greater extent and the system is more stable with Fuzzy Logic controller as compared to PI controller.

5. Conclusion

In this research, the performance improvement of a Solar–Wind Hybrid Microgrid system has been successfully demonstrated using a Fuzzy Logic Controller (FLC)-based STATCOM. The integration of the FLC in place of the conventional PI controller significantly enhances the nonlinear control characteristics of the STATCOM, enabling more accurate and faster voltage regulation under varying wind and solar conditions. Simulation results validate that the fuzzy-controlled STATCOM provides superior damping, minimized voltage fluctuations, and improved transient stability compared to the traditional control approach. The system achieves approximately 8% reduction in voltage deviation and exhibits better dynamic response, ensuring stable operation of the hybrid microgrid even under sudden load and irradiance variations.

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