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An Analytical Study of Active and Reactive Powers of STATCOM with PI and DSM-PI Controllers

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ABSTRACT Electricity generation from wind and solar photovoltaic (PV) systems relies heavily on prevailing weather conditions. Their intermittent output nature leads to fluctuations. As a result, there is an increasing need for swift compensation within energy transmission and distribution systems. One solution is the adoption of a Static Synchronous Compensator (STATCOM) for reactive power compensation, aiming to mitigate voltage fluctuation stemming from the system and renewable energy sources. This research delves into modelling a Solar PV-Wind Hybrid Micro-grid and explores how incorporating STATCOM can extend the stable operating limit of the system. A significant contribution of this study lies in implementing sliding control of Proportional Integral (PI) gains through DSM-PI (Dual Sliding Mode Proportional Integral) methodology. This approach yields improved responses and enhanced voltage stability, effectively addressing the nonlinear attributes of solar-wind hybrid microgrids. The Simulink models of the system architecture encompass a 1.5 MW wind turbine model utilising a doubly fed induction generator (DFIG), a 0.1 MW solar PV power system model, and a 3 MVAR-rated STATCOM. The results showcase an 8% reduction in voltage fluctuation at the bus bar's end using a conventional PI controller. A comparative analysis between the outcomes of the DSM-PI controller and the conventional counterpart demonstrates superior performance achieved through the DSM-PI approach.

Keywords: photovoltaic, Static Synchronous Compensator (STATCOM), PI controller; DSM-PI (Dual Sliding Mode Proportional Integral); Solar PV-Wind Hybrid Microgrid.

1. INTRODUCTION

Climate change and the responsible management of the world's depleting fossil fuel resources constitute the two greatest challenges currently faced by the planet. To ensure a safe environment for future generations, it is imperative that we reduce our reliance on fossil fuels and substantially decrease emissions of greenhouse gases. The growing investment in renewable energy reflects its increasing significance in mitigating global carbon emissions [1]. Centralised power plants suffer from several drawbacks. Firstly, most of these plants utilise fossil fuels, leading to higher CO2 emissions and wastage of rejected heat. Secondly, the need to transmit large quantities of power necessitates transformers and extensive transmission and distribution networks. Thirdly, the considerable length of transmission lines and the presence of transformers contribute to power losses and voltage drops. Lastly, this approach fails to offer a financially viable solution for supplying power to impoverished and remote communities. Transitioning to renewable energy sources such as wind and solar photovoltaic (PV) generation can reduce our reliance on fossil fuels and our environmental impact.

Microgrids represent compact power networks comprising renewable energy generators, battery storage, and end-use consumers. The utilisation of microgrids offers several advantages, including enhanced reliability, greater controllability, and superior electricity quality. Two microgrids exist those integrated with the main grid and those functioning independently. Coordinating a grid-connected microgrid with a stable electric power system mitigates concerns related to undesirable frequency fluctuations. Consequently, financially, grid-connected microgrids should emphasise augmenting electric power exchanges and profitability.

Conversely, isolated microgrids, lacking access to the larger electric grid, encounter difficulties maintaining voltage and frequency stability [2]. Distributed microgrids, leveraging renewable energy sources like solar, wind, and biogas, are crucial in satisfying the escalating global electricity demand. Simultaneously, they curb costs and reduce emissions of hazardous greenhouse gases from conventional central power plants reliant on fossil fuels. Using renewable energy sources remains the sole avenue to craft a cleaner, unpolluted planet. The feasibility of generating electricity through renewable resources is evident. Across the globe, conventional renewable sources such as solar, wind, and hydro are being efficiently harnessed to provide a sustainable resolution to the energy quandary.

1.1. Doubly Fed Induction Generator (DFIG)

Wind turbines have evolved significantly since their inception in 1975, marking the beginning of electricity generation through wind energy. By the 1980s, the first modern turbine was integrated into the grid. The widespread adoption of Doubly Fed Induction Generators (DFIG) can be traced back to the growing popularity of wind power generation. The term “doubly fed induction generator” indicates that the generated electrical power flows in both directions, between the stator and the rotor. The adaptability of these generators to changing wind conditions has captured significant attention. Choosing variable-speed wind power plants over constant-speed ones offers distinct advantages [6]. Variable-speed wind farms encompass a broader energy range compared to their constant-speed counterparts. Compared to stationary wind farms, they achieve this with reduced mechanical stress and noise levels. The progress in power electronics has made efficient speed regulation practical and cost-effective. Dealing with varying wind speeds poses unique challenges, and this study addresses these challenges using variable-speed DFIGs. The arrangement of wind power plants, as illustrated, involves a setup where the stator’s path of the DFIG connects directly to the grid. Simultaneously, the rotor’s path links to the grid via a back-to-back converter consisting of a generator-side converter and a grid-side converter facilitated by slip rings. A capacitor forms a DC connection between the two converters, acting as an energy buffer to smooth out fluctuations and mitigate potential voltage surges between them [7].

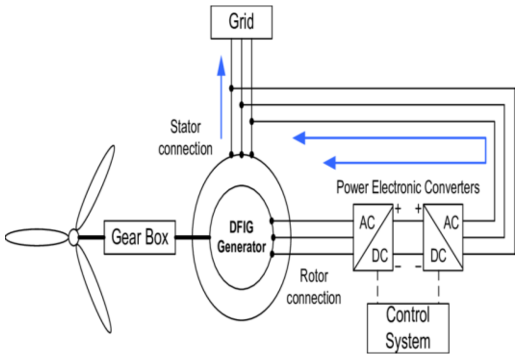

Figure 1 Schematic diagram of DFIG Generator

Under its standard operational mode, the grid-side converter of the DFIG enables independent control of active and reactive power. Furthermore, the need for a soft starter during grid connection can be eliminated if the converter is situated on the rotor side. The control architecture of the DFIG can be divided into two main subsystems: mechanical and electrical. While the control strategies were developed with diverse objectives, the primary focus has always been regulating grid-injected power. The rotor-side converter governs the active power injected into the grid, while both stator- and rotor-side converters manage reactive power injection [8].

1.2. Microgrid

The United States Department of Energy (DOE) defines a microgrid: “A microgrid is a local network of energy. It offers integration of Distributed Energy Resources (DER) with a local load that can be operated in islanding or grid mode, providing flexibility during grid disturbances and ensuring high reliability. This distribution system addresses the need for applications in areas with electrical supply and delivery constraints, particularly in remote locations, while economically supporting critical load protection and growth”. A microgrid is a compact electrical system that can function independently or in conjunction with the larger utility grid [9].

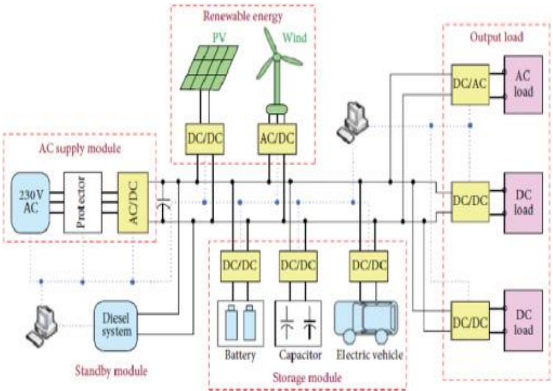

Figure 2 Microgrid architecture

The rapid expansion of microgrids is largely attributed to the integration of Distributed Generation (DG). While DG has resolved certain issues within the distribution network, it has also introduced new challenges. Particularly, when the distribution system lacks stability or reliability, DG becomes a significant concern. This situation has led to the emergence of microgrids. It’s important to note that a microgrid doesn’t automatically form when distributed generators are connected to the distribution grid; rather, its formation requires careful oversight. The concept of microgrids introduces the idea of decentralised power generation and delivery [10].

2. METHODOLOGY

2.1. Essential Components of the System

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The proposed model considers photovoltaic (PV) and wind power systems as modular entities, enabling the desired installed capacity to be achieved by adjusting the quantity of PV modules and wind turbines. The system's size can be effectively optimised by optimising the area covered by PV modules and the count of wind turbines. The versatility of the suggested Hybrid Renewable Energy System (HRES) cost-optimisation approach makes it applicable across various scenarios, owing to its adaptability to different types of renewable power subsystems. Users can modify input variables related to system size, such as installed capacities and efficiencies of biomass or wind subsystems, as well as location-specific factors like solar irradiation and wind speed data. The system is designed to prioritise renewable energy sources such as solar and wind over grid-based alternatives like biomass. In cases where renewable energy sources like solar panels or wind turbines are insufficient, the biomass engine operates at maximum capacity, with surplus electricity exported to the grid.

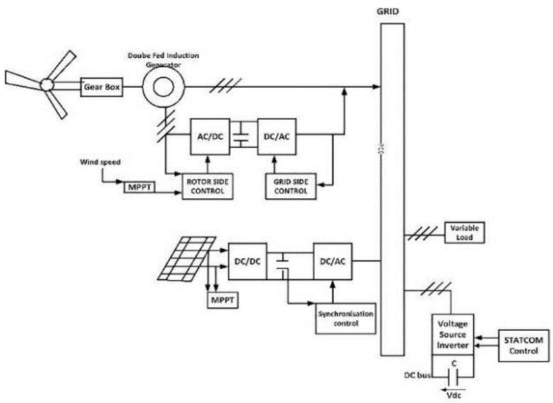

Figure 3 Proposed system

Conversely, during inadequate solar, wind, and biomass supply periods, the system resorts to drawing power from the grid as a backup. A review of existing literature highlights a dearth of studies on the impact of hybrid solar-wind microgrids on voltage fluctuations in the context of the STATCOM (Static Synchronous Compensator) system. As the demand for PV and wind power systems continues to rise, traditional Flexible Alternating Current Transmission System (FACTS) devices must undergo further controller refinements and comprehensive investigation across a broad spectrum of operational scenarios. The primary objective of this research was to incorporate STATCOM for reactive power compensation within the current power system design, thereby expanding its operational limits. Additionally, the research aims to mitigate voltage fluctuations stemming from the intermittent nature of renewable energy sources.

Voltage Source Inverter:
A Voltage Source Inverter (VSI) is a device that converts the polarity of direct current (DC) voltage, enabling its utilisation with alternating current (AC) devices. An efficient VSI ensures voltage stability throughout its operation. Typically, a VSI includes a large DC link capacitor, a DC voltage source, switching transistors (IGBTs, BJTs, MOSFETs, or GTOs), and a DC voltage source derived from batteries, generators, or solar cells. VSI configurations encompass two primary topologies: single-phase and three-phase inverters, further divided into half-bridge and full-bridge inverters for each phase. In the Doubly Fed Induction Generator (DFIG) context, voltage-induced converters establish bidirectional links with rotor windings and direct connections to the three-phase grid. The grid-side inverter governs power factor, converter operation, and DC link voltage.

Variable Load:
The design of electric power plants takes into consideration user requirements. A consistent, sustained load is advantageous for effective planning and routine maintenance. However, the impact of variable load on power plants is multifaceted, leading to several noteworthy consequences:

(i) Requirement for Additional Equipment: As the demand for electricity at a power plant fluctuates, the facility must possess adaptable power generation capabilities. For instance, envision a steam power plant utilising air, coal, and water as primary inputs. Variations in power demand necessitate corresponding adjustments in input resources. Supplementary machinery is necessary to accommodate increasing power demands, such as enhancing the supply of coal, air, and water to the boiler. In modern power plants, many components exist solely to regulate raw material input rates in response to fluctuations in power demand.

(ii) Increase in Production Costs: Fluctuations in a plant's load over the day escalate electricity generation expenses. An alternator performs most efficiently near its rated capacity. Under light loads, a single alternator's efficiency diminishes significantly. Multiple alternators of varying capacities are deployed to address this, allowing most of them to operate at or near maximum load capacity. However, adding producing units escalates the initial cost per kW of plant capacity and

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necessitates more floor space, contributing to an overall increase in energy production costs.

MPPT (Maximum Power Point Tracking):
In pursuit of optimal compatibility between a solar array (PV panels) and a battery bank or utility grid, a Maximum Power Point Tracker (MPPT) system is employed. MPPT optimises the DC output of solar panels (and occasionally wind turbines) to the level required for battery charging. The primary objective of MPPT is to maximise the output of a Photovoltaic (PV) system by operating each module at its optimal voltage, known as the maximum power point. In essence, the MPPT system assesses power generated by PV modules. It compares it to battery voltage to determine the optimal voltage for drawing maximum current from the PV modules for charging or powering DC loads. Furthermore, the MPPT system can directly power a DC load connected to the battery. Optimal MPPT performance is realised under specific conditions:

Cold Weather, Cloudy, or Hazy Days: MPPT is often employed to extract maximum power from PV modules, particularly when their performance is enhanced in colder temperatures.

Deep Battery Discharge: In cases of low battery charge, MPPT can extract higher current for quicker battery charging.

Doubly Fed Induction Generator (DFIG):

Wind turbines equipped with Doubly Fed Induction Generator converters (DFIG) have their generator stators directly connected to the power grid. A back-to-back power converter links the rotor to the mains. This variable-speed design is commonly applied for outputs ranging from 1.5 MW to 6 MW. Approximately one-third of the DFIG converter's energy is bidirectionally transmitted through power semiconductors. DFIG technology provides the advantage of cost-effective speed control with reduced power losses. This efficiency is attributed to the fact that power electronics solely process rotor power, which typically constitutes less than 25% of the total output power.

2.2 DSM-PI Controller

The "conventional PI controller" maintains fixed gains, while the "DSM-PI controller" erroneously adjusts the values continuously. In contrast, the "DSM-PI controller" enhances response time through ongoing monitoring and adjustment of proportional (Kp) and integral (Ki) gains. This approach offers a significant advantage by curtailing vibrations and tremors [2]. As a result, the "DSM-PI controller" expedites speed response, leading to diminished oscillations and disturbances [3]. This innovative control strategy continuously evaluates the proportional and integral gains (Kp and Ki), considerably reducing reaction time. The decrease in oscillations and disturbances accelerates the speed-time response, marking a major advantage of this design. A visual representation in Figure 4 portrays the block schematic of the contemplated DSM PI controller. The switching laws defined by sliding surface blocks C and S dictate the gains (kp and ki) of the DSM PI controller.

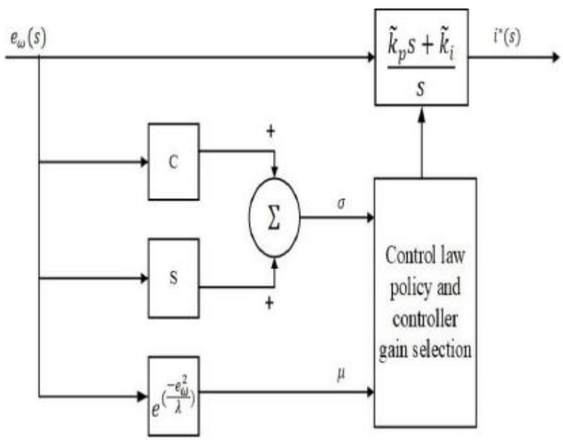

Figure 4 DSM-PI block diagram

4. Simulation model and Result Analysis

The provided test system includes the representation of the grid incorporating a DFIG wind farm, PV source, and STATCOM interconnected at the Point of Common Coupling (PCC), illustrated in Figure 5.

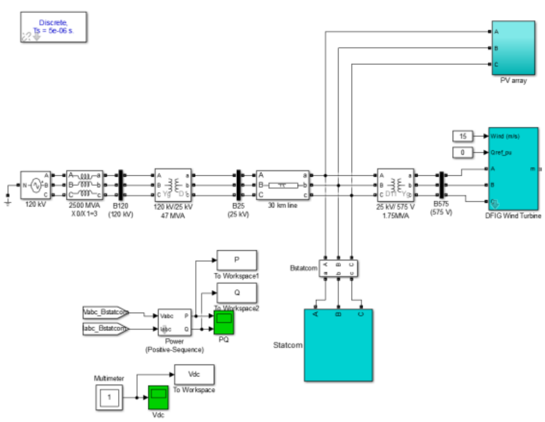
Figure 5 Simulation of Solar-wind Hybrid System Including STATCOM

Figure 6 depicts the internal models of the wind farm and PV source.

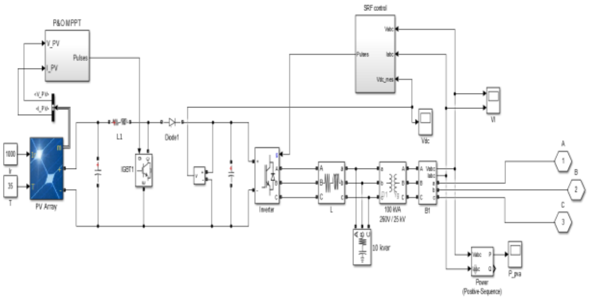

Figure 6 Structure of PV Array

The wind farm and PV source are operated optimally during peak solar irradiation and wind speed conditions, ensuring maximum power generation from these renewable sources.

The modelling of STATCOM for reactive power compensation is illustrated in Figure 7.

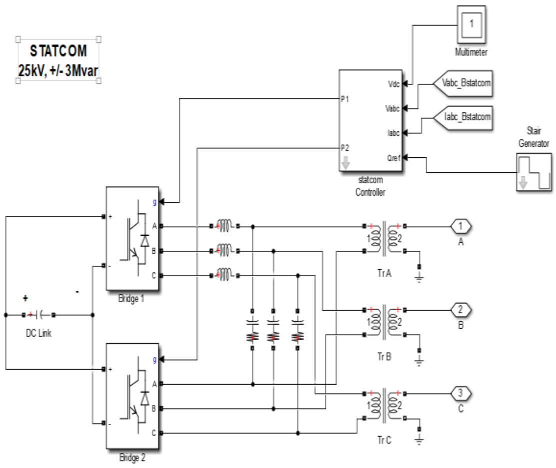

Figure 7 Internal Structure of STATCOM modeling

Between 0 and 0.3 seconds, there is no exchange of reactive power, denoted by Qref = 0. Shifting to the period from 0.3 to 0.5 seconds, the reactive power reference transitions to 1pu, signifying the absorption of 3MVAR from the grid. Subsequently, during the interval from 0.5 to 0.7 seconds, Qref returns to 0. This setting then shifts to -1pu between 0.7 and 0.9 seconds, representing the injection of 3MVAR reactive power into the grid.

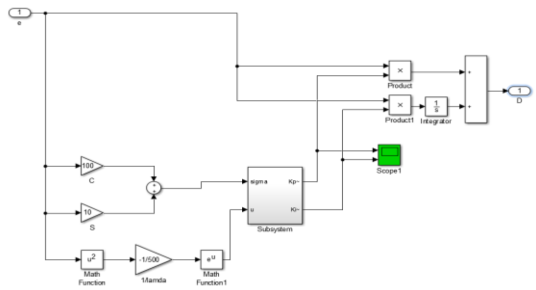

Figure 8 DSM-PI controller modeling

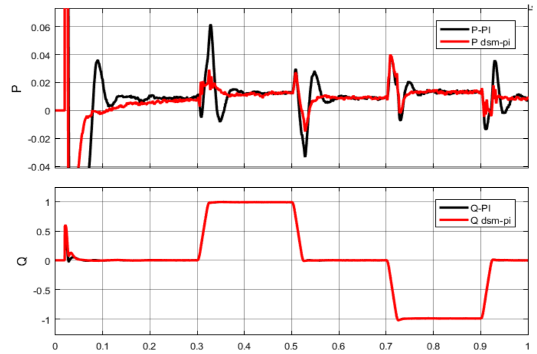

Figure 9 Comparison of active and reactive powers of STATCOM with PI and DSM-PI controllers

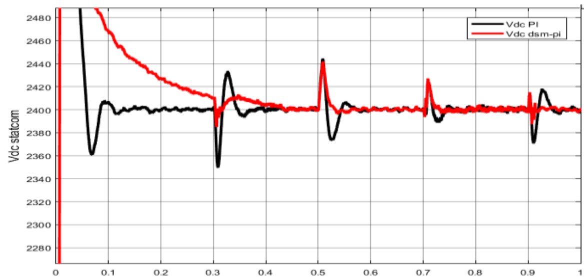

Figure 10 DC voltage of STATCOM with PI and DSM-PI controller

As evident from the graphs presented in Figure 10, depicting active and reactive powers alongside the DC voltage of the STATCOM, a reduction in damping is noticeable during transitions of Qref. This change in conditions has a noticeable impact. Specifically, the lower and upper peak values of power generation experience a significant decrease. Notably, the system exhibits enhanced stability when comparing the DSM-PI controller to the conventional PI controller.

5. CONCLUSION

This study investigated the impact of integrating a solar power generation system with a 0.1 MW capacity and a wind power generation system with a capacity of 1.5 MW on the current power grid. The potential utilisation of STATCOM for compensating reactive power in this hybrid system was explored. The analysis included a detailed examination of the output voltage profiles for the hybrid solar PV-wind power system.

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