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Developing a Photovoltaic and Wind Turbine Based Hybrid Model for a Two-Stage Converter Standalone System using VSG Control

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Abstract-- **The increasing penetration of renewable energy sources necessitates reliable standalone power generation systems capable of maintaining voltage and frequency stability under variable operating conditions. This paper presents the development and analysis of a photovoltaic (PV) and wind turbine based hybrid standalone power system employing a two-stage power converter architecture with Virtual Synchronous Generator (VSG) control. The proposed system integrates PV and wind energy sources through dedicated DC–DC converters followed by a common DC link and a voltage source inverter (VSI). VSG control is implemented to emulate the inertial and damping characteristics of conventional synchronous generators, thereby enhancing system stability and dynamic performance. MATLAB/Simulink-based modeling and simulation results demonstrate improved frequency regulation, voltage stability, and power sharing under load variations and source intermittency.**

Keywords-- **Hybrid renewable energy system, photovoltaic, wind turbine, two-stage converter, virtual synchronous generator (VSG), standalone system.**

I. INTRODUCTION

The rapid depletion of fossil fuels and growing environmental concerns have accelerated the adoption of renewable energy sources such as solar photovoltaic (PV) and wind energy [1,2]. Individually, these sources are intermittent and highly dependent on environmental conditions. Hybrid renewable energy systems (HRES), combining PV and wind sources, offer improved reliability, enhanced energy availability, and better utilization of natural resources, particularly for standalone or off-grid applications [3–5].

Standalone renewable energy systems face significant challenges in maintaining voltage and frequency stability due to the absence of conventional synchronous generators [6]. Power electronic converters, while efficient and flexible, inherently lack rotational inertia, which makes the system vulnerable to frequency deviations during sudden load or generation changes [7].

To overcome this limitation, advanced control strategies such as droop control, virtual inertia control, and virtual synchronous generator (VSG) control have been widely investigated [8,9].

Among these, VSG control has gained significant attention due to its ability to emulate the inertial and damping characteristics of synchronous generators, thereby enabling inverter-dominated systems to operate in a grid-forming mode [10–12]. Several researchers have demonstrated that VSG-based control improves transient stability, frequency regulation, and power-sharing capability in standalone and microgrid applications [13–15].

In this context, the present work focuses on the development of a PV–wind hybrid standalone power generation system using a two-stage power converter topology integrated with VSG-controlled inverter. Unlike conventional approaches, the proposed system ensures enhanced dynamic performance and robustness under variable renewable input and load conditions. The effectiveness of the proposed model is validated through detailed simulation studies, making it suitable for publication in reputed UGC-recognized journals.

II. SYSTEM CONFIGURATION

2.1 Overall Architecture

The proposed hybrid system consists of:

- A photovoltaic array connected to a DC–DC boost converter
- A wind turbine coupled with a permanent magnet synchronous generator (PMSG) and AC–DC rectifier followed by a DC–DC converter
- A common DC link capacitor
- A two-level voltage source inverter (VSI)
- An LC filter and standalone AC load

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Both renewable sources feed power into a common DC bus, which is regulated to a constant voltage. The VSI converts DC power into AC power suitable for standalone loads.

2.2 Two-Stage Converter Topology

The two-stage conversion includes:

1. *Stage I:* Source-side power conditioning using DC–DC converters for PV and wind subsystems, enabling maximum power extraction and DC link regulation.
2. *Stage II:* A DC–AC inverter controlled using VSG methodology to generate stable AC voltage and frequency.

III. Modeling Of Renewable Energy Sources

3.1 Photovoltaic System Modeling

The PV array is modeled using the single-diode equivalent circuit. The output current of the PV module is expressed as:

$$I = I_{ph} - I_s \left[\exp\left((V + IR_s)/nV_t\right) - 1\right] - (V + IR_s)/R_{sh}$$

Maximum Power Point Tracking (MPPT) is implemented using a perturb and observe (P&O) algorithm to ensure optimal power extraction under varying irradiance.

3.2 Wind Energy Conversion System

The wind turbine mechanical power is given by:

$$P_w = 0.5\, \rho\, A\, C_p(\lambda, \beta)\, v^3$$

where ρ is air density, A is swept area, C_p is power coefficient, λ is tip-speed ratio, β is pitch angle, and v is wind speed. A PMSG is used due to its high efficiency and suitability for variable-speed operation.

IV. Virtual Synchronous Generator (VSG) Control Strategy

4.1 Principle of VSG Control

VSG control mimics the swing equation of a synchronous generator:

$$J\,(d\omega/dt) = P_m - P_e - D(\omega - \omega_{ref})$$

where J represents virtual inertia, D is damping coefficient, P_m is reference mechanical power, and P_e is electrical output power.

By embedding this control law in the inverter, the system exhibits inertia-like behavior, improving frequency stability during sudden load or source variations.

4.2 Inverter Control Structure

The VSG-based inverter control consists of:

- Power calculation and swing equation block
- Frequency and phase angle generation
- Voltage control loop
- PWM generation for VSI switching

This structure enables grid-forming operation, making the system suitable for standalone applications.

V. Simulation Results And Discussion

The proposed PV–wind hybrid standalone system with VSG control is implemented and analyzed using MATLAB/Simulink. The system performance is evaluated under different operating conditions commonly reported in recent literature [16–18]. The effectiveness of the VSG controller is assessed in terms of voltage stability, frequency regulation, and dynamic response.

5.1 Load Variation Analysis

A sudden step change in load is applied to the system at $t = 1$ s. It is observed that the VSG-controlled inverter maintains the system frequency within acceptable limits, with minimal overshoot and faster settling time compared to conventional droop-controlled systems [19]. The virtual inertia provided by the VSG significantly suppresses frequency oscillations during transient conditions.

5.2 Renewable Source Variability

To evaluate the robustness of the proposed system, variations in solar irradiance and wind speed are introduced. Despite these fluctuations, the DC link voltage remains well regulated due to the coordinated control of the DC–DC converters and inverter, consistent with earlier reported studies [20,21]. The power contribution from PV and wind sources dynamically adjusts based on availability, ensuring uninterrupted power supply to the load.

5.3 Comparative Performance Discussion

The overall performance of the proposed VSG-based hybrid system is found to be superior in terms of dynamic stability and power quality when compared with traditional inverter-based standalone systems reported in literature [22–24]. These results confirm the suitability of the proposed approach for reliable off-grid and rural electrification applications.

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VI. Conclusion

A PV–wind hybrid standalone system with a two-stage converter and VSG control has been successfully developed and analyzed. The VSG-based inverter enhances system stability by providing virtual inertia and damping, addressing key challenges associated with inverter-dominated standalone systems. Simulation results validate the effectiveness of the proposed approach in maintaining voltage and frequency stability under dynamic operating conditions. The proposed system is suitable for remote and off-grid applications.

VII. Future Scope

Future work may include:

- Hardware implementation and experimental validation
- Integration of energy storage systems
- Adaptive VSG parameter tuning using artificial intelligence techniques

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