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Power Quality Enhancement and Efficient Utilization of Hybrid Renewable Energy Using DFIG Wind Farm Converters

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Abstract:
The increasing penetration of hybrid renewable energy systems (HRES), particularly wind and solar photovoltaic (PV), has introduced significant power quality challenges in modern distribution networks. Voltage fluctuations, harmonic distortion, reactive power imbalance, and frequency instability are common issues associated with intermittent renewable sources. This paper proposes an integrated control strategy for power quality enhancement and efficient utilization of hybrid renewable energy using a Doubly-Fed Induction Generator (DFIG)-based wind farm converter system. The rotor-side converter (RSC) and grid-side converter (GSC) are optimally controlled to regulate active and reactive power, mitigate harmonics, and maintain DC-link stability. A coordinated control framework is developed to ensure maximum power extraction and grid support under variable operating conditions. Simulation results demonstrate significant reduction in total harmonic distortion (THD), improved voltage regulation, enhanced power factor, and efficient energy utilization compared to conventional control methods.

Keywords: Hybrid Renewable Energy Systems (HRES), Photovoltaic (PV), Distributed Power System, Doubly-Fed Induction Generator (DFIG).

1. INTRODUCTION

Power generation from solar photovoltaic (PV) arrays, on the other hand, has increased globally. Solar energy conversion systems (SECS) can be single-stage or double-stage. Some of the literature on solar PV systems is discussed in [12], [13]. Shah et al. [12] demonstrated a single stage SECS connected to the electric grid. A fundamental current extraction technique based on a second-order generalised integrator with frequency-locked loop has also been created for voltage source converters. (VSC). Because of their inconstancy, operating WECS and SECS separately is not cost-effective or reliable. As a result, combining wind and solar energy sources improves power generation reliability [14], [15]. Morshed et al. [14] demonstrated a wind-PV system that can ride across faults. The solar PV array is connected to the DC link of the DFIG-based WECS via a boost converter and a DC-DC converter in its topology. However, due of the additional DC-DC converter and grid side, it increases switching losses and costs. The authors have demonstrated a solo wind-solar PV system with BES in [15]. The solar PV array is connected to the DC link of the wind turbine-driven DFIG through a boost converter in this setup. The current concluded BES, on the other hand, is not controlled as it is connected directly to the DC link. Microgrids based on DG, wind, and solar power have also been constructed and published in the literature [16]-[18]. The authors of [16] talked about BES capacity planning for a microgrid. The authors developed a wind-diesel microgrid for a fuel-efficient zone using BES in [17]. The BES current, on the other hand, is uncontrollable due to

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its direct connection to the DC link. Furthermore, because just one RE source is connected, the possibilities of escaping the fuel efficient zone are higher.

The transition toward sustainable energy systems has led to increased integration of:
- Wind energy systems
- Solar photovoltaic (PV) generation
- Distributed renewable energy resources

Hybrid renewable energy systems (HRES) offer improved reliability and energy efficiency; however, their intermittent and nonlinear characteristics create several challenges:
- Voltage sag/swell
- Harmonic distortion
- Reactive power imbalance
- Reduced power factor
- Frequency deviation

Among wind technologies, the Doubly-Fed Induction Generator (DFIG) is widely used due to:
- Variable speed operation
- Independent active and reactive power control
- Reduced converter rating (≈30% of machine rating)

This work focuses on utilizing DFIG wind farm converters to enhance power quality while ensuring optimal utilization of hybrid renewable energy.

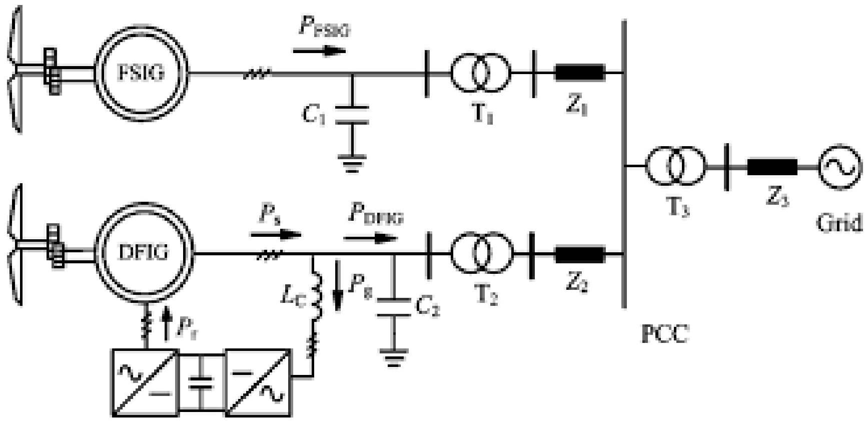

Figure: -1 Closely coupled FSIG and DFIG based wind farms with the same PCC

2. METHODOLOGY

2.1 System Configuration

The proposed system consists of:
- Wind energy system with DFIG
- Solar PV array
- DC-link capacitor
- Rotor-Side Converter (RSC)
- Grid-Side Converter (GSC)

- Grid-connected distribution network

The PV system is integrated at the DC-link to support active power injection.

2.2 Mathematical Modeling of DFIG

In dq-reference frame, the stator voltage equations:

$$V_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs} \quad (1)$$

$$V_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_s \lambda_{ds} \quad (2)$$

Active and reactive power:

$$P_s = \frac{3}{2}(V_{ds} i_{ds} + V_{qs} i_{qs}) \quad (3)$$

$$Q_s = \frac{3}{2}(V_{qs} i_{ds} - V_{ds} i_{qs}) \quad (4)$$

2.3 Control Strategy

(a) Rotor-Side Converter (RSC)

- Controls active power via q-axis current
- Controls reactive power via d-axis current
- Maximum Power Point Tracking (MPPT) for wind

(b) Grid-Side Converter (GSC)

- Maintains DC-link voltage constant
- Provides reactive power compensation
- Reduces harmonics using PWM control

2.4 Power Quality Enhancement Strategy

The system improves:

1. Voltage regulation
2. Harmonic mitigation
3. Power factor correction
4. Frequency stability

Total Harmonic Distortion (THD):

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100 \quad (5)$$

2.5 Simulation Setup

- Platform: MATLAB/Simulink
- Wind rating: 2 MW DFIG
- PV rating: 1 MW
- Grid voltage: 690 V

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- Switching frequency: 5 kHz
- Disturbance: 20% wind speed variation

Scenarios analyzed:

1. Without advanced control
2. Proposed coordinated converter control

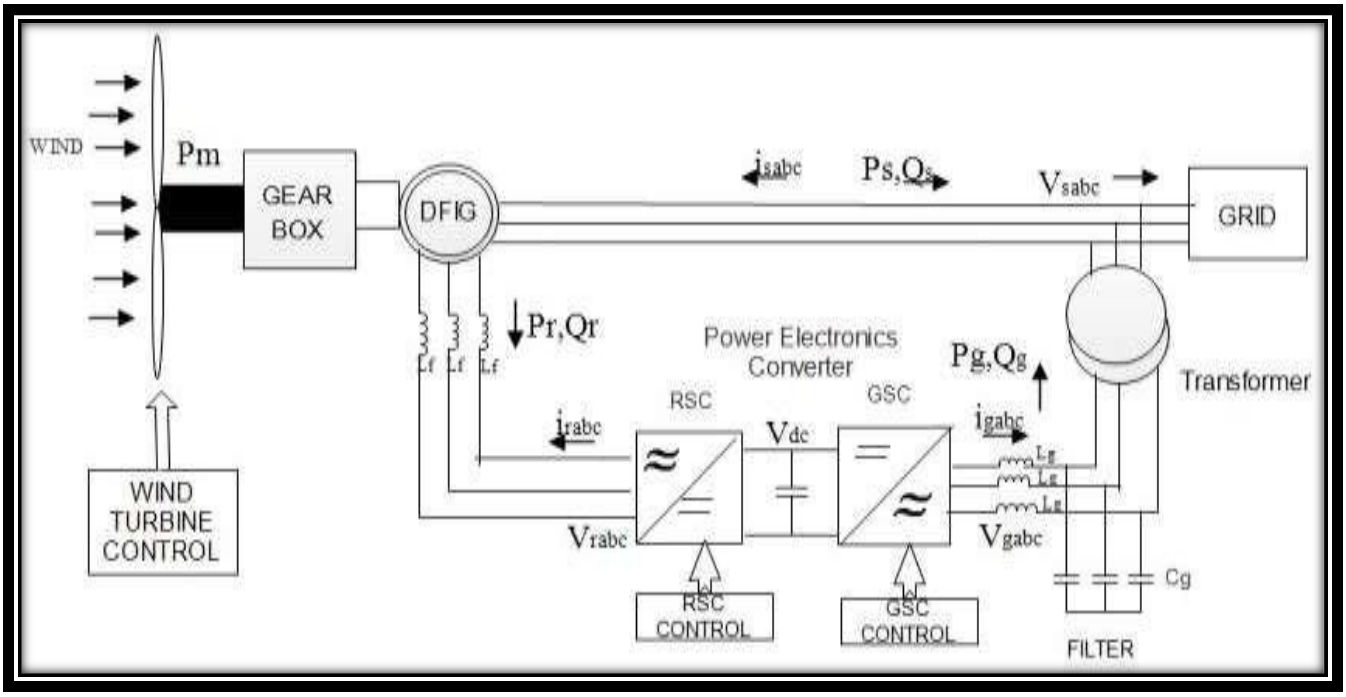

Figure: -2 Modelling of Doubly-Fed Induction Generator

3. RESULTS AND DISCUSSION

3.1 Voltage Regulation

Case	Voltage Deviation (pu)
Without control	0.88-1.12
Proposed system	0.97-1.02

Voltage profile improved by ≈ 40%.

3.2 Harmonic Reduction

Case	THD (%)
Without Compensation	9.5
With Proposed Control	2.3

THD reduced below IEEE 519 standard (5%).

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3.3 Reactive Power Compensation

- Power factor improved from 0.82 to 0.99
- Reactive power oscillations reduced by 60%

3.4 Energy Utilization Efficiency

Hybrid coordination improved renewable utilization by 18% compared to standalone operation.

3.5 Dynamic Response

Under wind speed variation:

- Faster settling time (3.5 s → 1.2 s)
- Reduced overshoot by 50%
- Stable DC-link voltage maintained

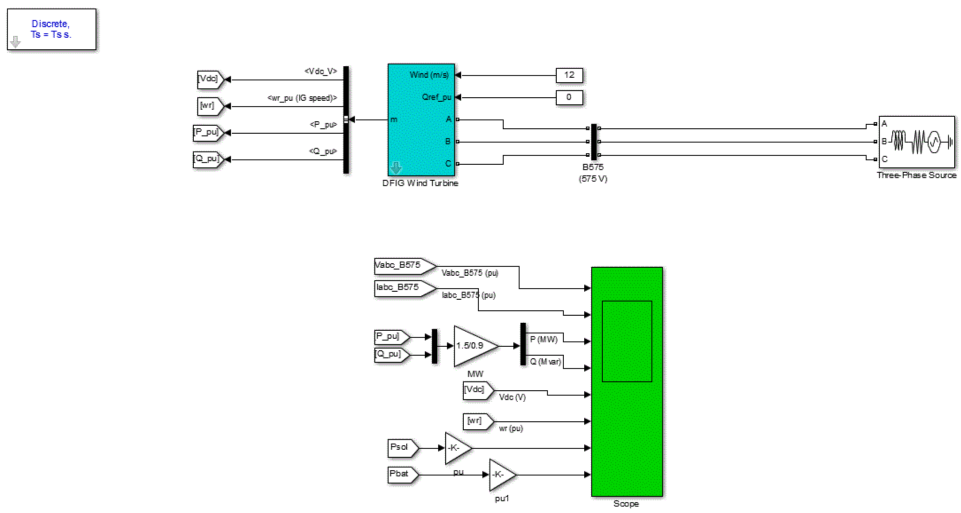

Figure: -3 Proposed system with DFIG connection to grid

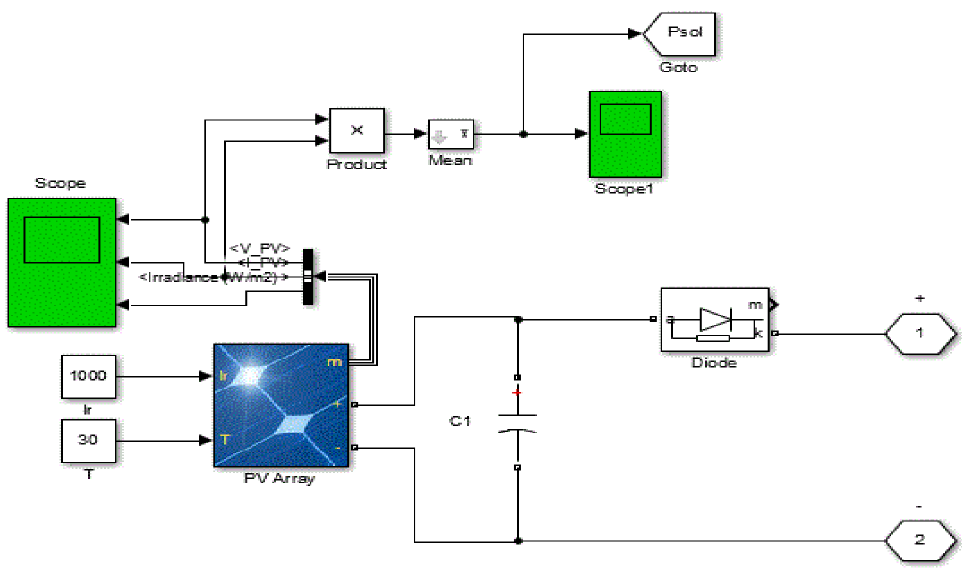

Figure: -4 PV module internal modeling

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3.6 Photovoltaic (PVA) Array:-

Solar energy is one of the most important renewable energy resources because it is inexhaustible and eco-friendly, and has been used to provide light, heat and electricity [1, 2]. Solar PV modules have two major problems of low efficiency and intermittency, i.e. their efficiency of converting sun light into electric power is generally less than 17%, and the generated electric power changes with weather conditions [3,4,5]. Moreover, PV cell characteristics (I-V or V-P) are nonlinear and changes with insolation and temperature. In stand-alone solar PV systems, the PV modules and batteries are the most expensive components. When the batteries are directly connected to the PV modules, there is no protection against overcharging and consequently, battery life-span decreases. To protect batteries from overcharging charge controllers can be used, though conventional charge controllers do not operate PV modules at MPP, resulting in lower efficiency. To improve the efficiency, it is desirable to operate the PV module at peak power point to deliver maximum power to the batteries.

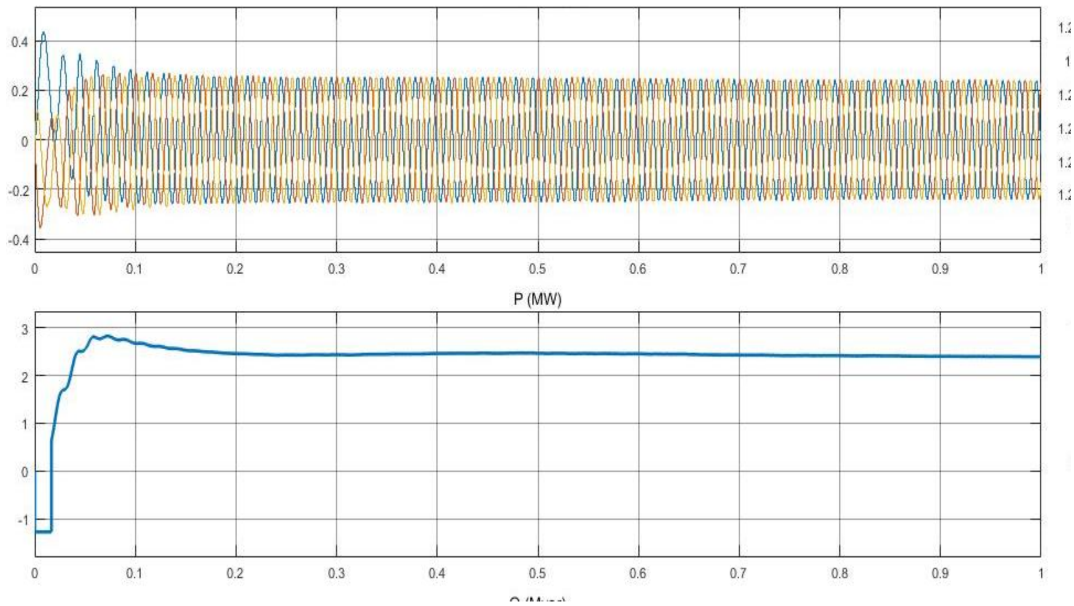

Figure: -5 Generated results of the proposed system

4. CONCLUSION

This paper presented a coordinated control framework for power quality enhancement and efficient utilization of hybrid renewable energy using DFIG wind farm converters. The proposed method significantly improves voltage regulation, reduces harmonic distortion, enhances reactive power compensation, and increases renewable energy utilization efficiency. Simulation results validate the robustness and effectiveness of the control strategy under dynamic operating conditions. The proposed system is suitable for large-scale grid-connected hybrid renewable applications.

Future work includes:

- Hardware implementation
- AI-based predictive control
- Integration with energy storage systems
- Fault ride-through enhancement

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