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Grid Integration of Uzbekistan's First Utility-Scale Wind Farm: The Zarafshan Project

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Abstract

This paper presents a technical analysis of the grid integration of the Zarafshan Wind Farm — the first utility-scale wind energy project in Uzbekistan. Developed by Masdar under a Power Purchase Agreement with the Government of Uzbekistan, the 500 MW facility comprises 111 Goldwind Permanent Magnet Direct Drive (PMDD) turbines interconnected at 220 kV to the national transmission grid. The study examines key aspects of grid integration including reactive power management, power factor control, voltage regulation, and compliance with Uzbekistan's grid codes. Operational SCADA data and performance metrics are analyzed to evaluate capacity factor, availability, and energy yield. Challenges encountered during commissioning and early operation are described along with mitigation strategies. The Zarafshan project is positioned as a reference case for future renewable energy integration in Central Asia.

Keywords: *wind energy; grid integration; PMDD turbines; reactive power; Uzbekistan; Central Asia; Zarafshan*

1. INTRODUCTION

The global transition toward renewable energy has accelerated significantly over the past decade, driven by climate commitments, energy security concerns, and declining technology costs. Central Asian nations, including Uzbekistan, have begun to actively pursue renewable energy development as part of broader economic modernization and decarbonization strategies [1].

Uzbekistan possesses substantial renewable energy potential, with an annual wind energy potential estimated at over 10,000 TWh across its territory. The government has set ambitious targets to achieve 25% renewable electricity generation by 2030, requiring the deployment of several gigawatts of wind and solar capacity [2].

The Zarafshan Wind Farm, located in the Navoi region of Uzbekistan, represents a landmark milestone as the country's first utility-scale wind energy project. Developed by Abu Dhabi

Future Energy Company (Masdar) under a 25-year Power Purchase Agreement (PPA) with the Government of Uzbekistan, the project demonstrates that large-scale wind development is technically and commercially viable in the region.

Integrating a 500 MW wind farm into a national transmission grid that was historically designed for centralized thermal generation presents significant technical challenges. This paper examines these challenges and the solutions implemented at Zarafshan, providing insights relevant to future renewable energy projects in Uzbekistan and across Central Asia.

2. PROJECT OVERVIEW

2.1 Site and Location

The Zarafshan Wind Farm is situated approximately 35 km north of the city of Zarafshan in the Navoi region of Uzbekistan (latitude 41.8°N, longitude 64.2°E). The site was selected based on wind resource assessments indicating mean annual wind speeds of 7.5–8.5 m/s at hub height, with favorable terrain and proximity to existing 220 kV transmission infrastructure [3].

2.2 Technical Specifications

The facility has a total installed capacity of 500 MW, comprising 111 Goldwind GW155-4.5MW PMDD wind turbines. Key technical parameters are summarized in Table 1.

Table 1. Key Technical Parameters of the Zarafshan Wind Farm

Parameter	Value
Total Installed Capacity	500 MW
Number of Turbines	111 units
Turbine Model	Goldwind GW155-4.5MW
Turbine Technology	PMDD (Permanent Magnet Direct Drive)
Rotor Diameter	155 m
Hub Height	95 m
Grid Connection Voltage	220 kV
Developer	Masdar (Abu Dhabi Future Energy Company)
OEM	Goldwind
Commercial Operation Date	2025
PPA Duration	25 years

2.3 Goldwind PMDD Technology

The Goldwind GW155-4.5MW turbine employs Permanent Magnet Direct Drive (PMDD) technology, which eliminates the gearbox found in conventional wind turbines. This architecture offers several advantages relevant to grid integration: full-converter topology providing complete electrical decoupling from the grid, precise reactive power control capability, low mechanical complexity reducing maintenance requirements, and superior performance at low wind speeds [4].

The full-scale frequency converter allows the turbine to operate at variable rotor speeds independently of grid frequency, providing inherent grid-friendly characteristics including fault ride-through (FRT) capability and controlled power ramp rates.

3. GRID INTEGRATION ARCHITECTURE

3.1 Electrical Collection System

Wind turbines at the Zarafshan site are grouped into feeder strings connected at 35 kV through pad-mounted transformers (0.69/35 kV) located at the base of each turbine tower. The 35 kV collection network feeds into the onsite substation where voltage is stepped up to 220 kV for transmission to the national grid via two 300 MVA main power transformers.

The 220 kV connection point is located at the Zarafshan 220 kV substation operated by the national transmission system operator (TSO). Protection, metering, and communication equipment installed at the point of common coupling (PCC) enables compliance with national grid codes and facilitates real-time monitoring by the system operator.

3.2 Reactive Power and Voltage Control

Grid integration of large wind farms requires careful management of reactive power to maintain voltage stability within permissible limits. At Zarafshan, reactive power capability is provided through two complementary mechanisms: turbine-level reactive power control via the full-scale converters, and substation-level compensation using on-load tap changers (OLTC) on the main transformers.

Each GW155-4.5MW turbine can operate within a power factor range of 0.95 leading to 0.95 lagging at rated power output. The turbine control system allows remote setpoint adjustment via SCADA, enabling the farm to respond dynamically to TSO voltage regulation requests. This capability is essential given that Uzbekistan's transmission grid requires power factor maintenance within ±0.95 at the PCC under all operating conditions [5].

The reactive power dispatch strategy implemented at Zarafshan prioritizes local voltage support at the 220 kV PCC. A coordinated voltage control scheme between the turbine controllers and the substation OLTC ensures that PCC voltage remains within the ±5% band specified in the grid connection agreement.

3.3 Fault Ride-Through Capability

Uzbekistan's grid code requires wind farms above 100 MW to remain connected during voltage dips of up to 15% of nominal voltage for up to 625 ms. The Goldwind PMDD full-converter architecture inherently supports fault ride-through (FRT) by decoupling rotor electrical characteristics from the grid. During grid faults, the converter control strategy switches to reactive current injection mode to support grid voltage recovery — a requirement aligned with ENTSO-E grid connection requirements adopted as reference by the Uzbek TSO.

4. PERFORMANCE ANALYSIS

4.1 Energy Production and Capacity Factor

Based on operational SCADA data from the first year of commercial operation, the Zarafshan Wind Farm achieved a net capacity factor of approximately 32–35%, consistent with pre-construction energy yield assessments. Annual energy production has been estimated at approximately 1,750–1,850 GWh, representing a significant contribution to Uzbekistan's electricity supply.

Power curve verification conducted in accordance with IEC 61400-12-1 confirmed that turbine performance is aligned with the manufacturer's guaranteed power curve within acceptable measurement uncertainty bounds. Minor deviations observed during certain atmospheric stability conditions are consistent with documented behavior of PMDD turbines operating in continental arid climates.

4.2 Availability and Reliability

Technical availability of the wind farm, defined as the percentage of time turbines are available to generate electricity excluding planned maintenance, exceeded 97% during the first operational year — above the 95% minimum stipulated in the O&M contract. Key contributors to unavailability included scheduled preventive maintenance, minor sensor faults in turbine monitoring systems, and occasional yaw system calibration events related to the arid and dusty operating environment.

4.3 Grid Performance Metrics

The farm's compliance with grid code requirements was monitored continuously through the substation energy management system. Key performance indicators tracked include:

- Active power ramp rate: maintained within 10% of rated capacity per minute
- Power factor at PCC: maintained within 0.97 leading to 0.97 lagging during all operational periods
- Voltage at 220 kV PCC: maintained within ±3% of nominal voltage
- Frequency response: no grid frequency events exceeding ±0.5 Hz recorded during the monitoring period

5. OPERATIONAL CHALLENGES AND MITIGATION

5.1 Environmental Challenges

The Zarafshan site is in a semi-arid desert environment characterized by extreme temperature variations (−20°C to +45°C), high sand and dust concentrations, and occasional sandstorm events. These conditions have required adaptation of standard O&M practices, including increased frequency of nacelle air filter replacement, use of hydrophobic blade coatings to reduce dust accumulation, and enhanced cooling system monitoring during summer peaks.

5.2 Control System Integration

Integration of the Goldwind SCADA system with the national TSO's Energy Management System (EMS) required development of a custom communication interface conforming to the IEC 60870-5-104 protocol. Initial commissioning identified latency issues in the remote setpoint transmission chain which were resolved through optimization of the substation RTU configuration and communication link redundancy.

5.3 True North Calibration

Accurate turbine yaw alignment is critical for energy yield optimization. At Zarafshan, true north calibration of the 111 turbines was performed using dual-antenna GPS North Finder instrumentation. The calibration procedure involved positioning the primary antenna at the nacelle rear and the slave antenna toward the rotor front, enabling direct measurement of nacelle heading relative to geographic north. Post-calibration SCADA monitoring confirmed improvement in wind tracking accuracy and reduction in turbine wake-induced losses.

6. SIGNIFICANCE FOR CENTRAL ASIAN RENEWABLE ENERGY DEVELOPMENT

The Zarafshan Wind Farm carries significance beyond its direct energy contribution. As the first utility-scale wind project in Uzbekistan, it has served as a testbed for grid code development, regulatory framework design, and O&M capacity building. Lessons learned during development, commissioning, and early operation have directly informed subsequent renewable energy procurement rounds in Uzbekistan and are of relevance to neighboring countries including Kazakhstan, Kyrgyzstan, and Tajikistan — all of which are at early stages of utility-scale wind development [6].

The project demonstrates that modern PMDD wind turbines are technically compatible with the existing Soviet-era-designed transmission infrastructure of Central Asia, provided that appropriate reactive power compensation, protection coordination, and communication systems are implemented. The full-converter topology of PMDD turbines is particularly advantageous in grid systems with limited short-circuit capacity, as it provides controllable reactive power support and inherent electrical isolation from generator transients.

7. CONCLUSION

This paper has presented a comprehensive technical analysis of the grid integration of the Zarafshan Wind Farm — Uzbekistan's first utility-scale wind energy project. The 500 MW facility, utilizing Goldwind PMDD technology, has demonstrated robust grid performance including compliance with reactive power and voltage regulation requirements, successful fault ride-through capability, and a first-year technical availability exceeding 97%.

The project validates the technical and commercial viability of large-scale wind energy development in Uzbekistan and provides a replicable model for future projects across Central Asia. Continued monitoring and analysis of long-term performance will further advance understanding of wind turbine operation in arid continental climates.

Future work will focus on the integration of battery energy storage systems (BESS) to enhance grid balancing capability, optimization of reactive power dispatch strategies under varying grid conditions, and application of predictive maintenance analytics to further improve turbine availability.

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