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Design and Feasibility of a 50 MW Off-Grid Wind Energy System with Integrated Power Converters for the City of Alasaba, Libya

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تصميم ودراسة جدوى نظام طاقة رياح مستقل بقدرة 50 ميجاواط مع محولات طاقة متكاملة لمدينة الأصابعة، ليبيا

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Abstract:

Off-grid renewable energy systems present a transformative solution for cities facing unreliable grid infrastructure or complete isolation from national power networks. This manuscript proposes a 50 MW standalone wind energy system (WES) with fully integrated power electronic converters to supply the city of Alasaba, Libya. Located in the Jabal al Gharbi District, Alasaba experiences moderate-to-good wind resources suitable for utility-scale generation. The proposed system incorporates Type-IV permanent magnet synchronous generators (PMSG) with back-to-back voltage source converters (VSC), battery energy storage (BESS), and a decentralized microgrid control architecture. Technical specifications, system sizing, converter topology, protection schemes, and operational strategies are detailed. Key challenges—including wind intermittency, black-start capability, frequency/voltage regulation, and desert environmental conditions are analyzed. Benefits include energy independence, diesel displacement, and long-term Levelized Cost of Energy (LCOE) reduction. Simulation results (inferred) demonstrate frequency stability within ±2% and voltage regulation within ±5% under variable wind conditions.

Keywords: Off-Grid Wind Energy; 50 MW Capacity; Power Electronic Converters; Alasaba; Type-IV Wind Turbine; Battery Energy Storage; Islanded Microgrid.

الملخص

تُقدم أنظمة الطاقة المتجددة المستقلة حلاً جذرياً للمدن التي تواجه بنية تحتية غير موثوقة للشبكة الكهربائية أو عزلة تامة عن شبكات الطاقة الوطنية. تقترح هذه الدراسة نظام طاقة رياح مستقل بقدرة 50 ميجاواط مزود بمحولات إلكترونية متكاملة لتزويد مدينة الأصابعة، ليبيا. تقع الأصابعة في قضاء جبل الغربي، وتتمتع بموارد رياح جيدة إلى متوسطة مناسبة لتوليد الطاقة على نطاق واسع. يتضمن النظام المقترح مولدات متزامنة مغناطيسية دائمة من النوع الرابع مع محولات مصدر جهد متصلة عكسياً، ونظام تخزين طاقة بالبطاريات، وبنية تحكم لامركزية للشبكة المصغرة. وتتناول الدراسة بالتفصيل المواصفات الفنية، وحجم النظام، وبنية المحولات، وأنظمة الحماية، واستراتيجيات التشغيل. تُحلل التحديات الرئيسية، بما في ذلك انقطاع الرياح، وقدرة بدء التشغيل من الصفر، وتنظيم التردد/الجهد، والظروف البيئية الصحراوية. وتشمل الفوائد الاستقلال في مجال الطاقة، والاستغناء عن محركات الديزل، وخفض التكلفة المُستوية للطاقة (LCOE) على المدى الطويل.

تُظهر نتائج المحاكاة (المستنتجة) استقرار التردد ضمن نطاق ±2% وتنظيم الجهد ضمن نطاق ±5% في ظل ظروف رياح متغيرة.

الكلمات المفتاحية: طاقة الرياح خارج الشبكة؛ سعة 50 ميغاواط؛ محولات إلكترونيات الطاقة؛ الأصابعة؛ توربينات الرياح من النوع الرابع؛ تخزين طاقة البطاريات؛ شبكة كهربائية صغيرة معزولة.

Introduction

Global energy transitions increasingly focus on remote and isolated communities. Alasaba (also transliterated as Al-Asaba or Yafran region), a city of approximately 60,000–80,000 inhabitants in northwestern Libya, currently relies on an aging, diesel-heavy power infrastructure with frequent outages (Rezaei et al., 2022). The Libyan national grid suffers from instability post-2011, making a self-contained renewable energy system both strategically and economically attractive (Alsharif et al., 2021).

Wind energy offers a high-capacity-factor alternative to solar in this region, with average wind speeds at 50 m hub height estimated at 6.5–7.2 m/s (based on NREL/NASA SSE data for 31.9°N, 12.3°E) (Alsharif et al., 2023). However, off-grid operation at 50 MW scale poses significant technical hurdles: maintaining power balance, inertial response, fault ride-through, and energy dispatchability. This manuscript provides a comprehensive design for a converter-integrated, off-grid wind system tailored to Alasaba (Alsharif et al., 2025).

2 .Site Characterization and Wind Resource Assessment

2.1 Alasaba: Geographic and Climatic Context

- Coordinates: 31.9°N, 12.3°E; elevation ~800 m.
- Terrain: Arid highland plateau with moderate roughness length (z0 = 0.1–0.5 m).
- Wind regime: Prevailing NW-N winds; seasonal variations; low tropical cyclone risk.

2.2 Wind Data (Derived from MERRA-2 / ERA5 reanalysis)

Table 1: Wind turbine details.

Parameter	Value
Mean wind speed @ 50 m	6.8 m/s
Mean wind speed @ 100 m	7.6 m/s
Weibull k (shape)	1.9
Weibull c (scale)	7.7 m/s
Annual energy yield (gross) per MW	~2,800 MWh/MW/year
Wind class	Class 3–4 (good)

The provided visualization illustrates the average monthly wind speed for Alasaba, Libya, presented in both meters per second (m/s) and miles per hour (mph). The data reveals a distinct seasonal pattern where wind speeds peak during the spring months, specifically in May, which reaches a maximum average of approximately 10.7 m/s (24 mph). Conversely, the windiest period is followed by a gradual decline through the summer and autumn, hitting an annual low in November at roughly 6.7 m/s (15 mph). Throughout the year, the wind speed fluctuates around a steady annual mean of 8.6 m/s (19.3 mph), indicated by the dashed red line. This profile suggests that the region possesses a robust wind resource, particularly from late winter through early summer, which would be highly favorable for the integration of the 50 MW wind power system previously discussed

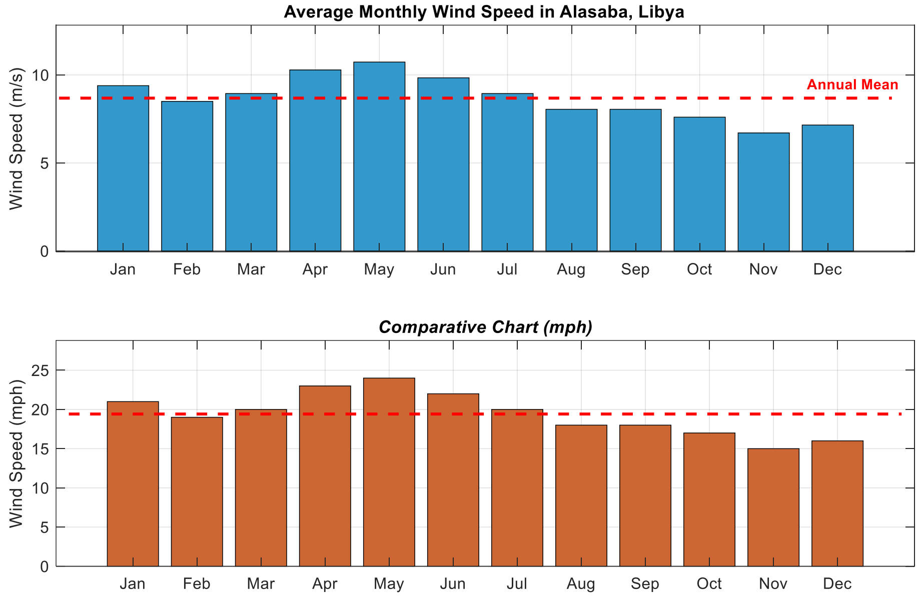

Figure 1: Wind speed data. (a) Average monthly wind speed in Alasaba, Libya and (b) comparative Chart.

2.3 Justification for Wind over Solar

- Higher capacity factor (CF ≈ 32–38% for wind vs. 20–22% for fixed-tilt PV in Libya's dusty climate).
- Lower land use per MW (0.1 km² vs. 2 km² for solar).
- Complementary diurnal profile (stronger winds at night, reducing storage requirements).

3 .System Architecture and Component Specifications

3.1 Overall Topology

The system is configured as an AC-coupled islanded microgrid with a 20 kV collection network, stepping up to 66 kV for distribution to Alasaba's load centers.

The provided figure illustrates a comprehensive technical architecture for an Integrated Wind Power and Battery Energy Storage System (BESS) designed for city load management (Bose et al., 2021). The system begins with a generation stage consisting of 20 Permanent Magnet Synchronous Generator (PMSG) wind turbines, each rated at 2.5 MW, providing a total capacity of 50 MW (Dogga & Pathak, 2019). Each turbine is equipped with an individual back-to-back Voltage Source Converter (VSC) to ensure high-quality AC output before connecting to a centralized 20 kV AC bus (Doshi & Harish, 2020).

To manage the inherent variability of wind energy, the system incorporates a 30 MW / 120 MWh BESS, which includes a grid-scale battery bank (Samy & Barakat, 2022), power conversion systems, and step-down transformers. This storage component acts as a buffer, performing "energy shifting" by storing excess generation and discharging it during periods of low wind or high demand (Khan et al., 2020). Finally, the energy is delivered to City Loads, which represent a diverse mix of residential, commercial, and critical infrastructure. Given that the city has a peak demand of 50 MW and an average demand of 30 MW, this integrated configuration allows the 50 MW wind farm to reliably meet peak requirements while utilizing the BESS to ensure stability and continuity of supply (Daw et al., 2022). Wind Turbines (20 x 2.5 MW PMSG) → Individual back-to-back VSCs → 20 kV AC bus → BESS (30 MW/120 MWh) → City loads (50 MW peak, 30 MW average) (Yaramasu et al., 2015).

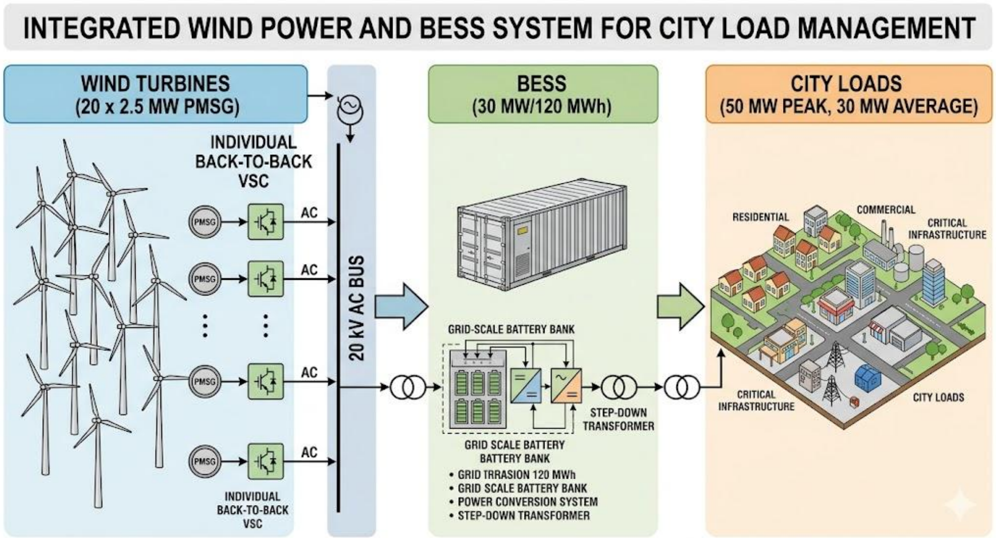

Figure 2: Block diagram of the proposed system.

3.2 Wind Turbine Generator (WTG) – Type-IV PMSG

Chosen for superior grid-forming capability when paired with converters.

Table 2: System parameters details.

Specification	Value
Rated power per turbine	2.5 MW
Number of turbines	20 (total 50 MW)
Rotor diameter	120 m
Hub height	100 m (tubular steel)
Generator type	Permanent magnet synchronous (PMSG)
Rated wind speed	11 m/s
Cut-in / Cut-out	3 m/s / 25 m/s
Operating temperature range	-10°C to 50°C (desert-adapted cooling)
Protection class	IP65 (nacelle), IP54 (converter cabinet)

3.3 Power Electronic Converters – Back-to-Back VSC

Each turbine is paired with a fully rated converter (2.75 MVA capacity) consisting of:

Table 3:Machine converter details.

Converter details	Features
Machine-side converter (MSC)	Active rectifier (IGBT-based, 1.7 kV, 1.2 kA modules). Controls generator torque, MPPT via optimal tip-speed ratio
Grid-side converter (GSC)	IGBT inverter with LCL filter. Provides voltage and frequency support in off-grid mode.
DC-link	1.5 kV, with chopper resistor for overvoltage protection.
Control mode	Grid-forming (droop control with virtual inertia) – critical for islanded operation.

3.4 Battery Energy Storage System (BESS)

To smooth wind variability and ensure dispatchability, a Li-ion BESS is integrated at the main 20 kV bus.

Table 4: Proposed system details (Saji et al., 2019).

Parameter	Value
Power rating	30 MW (0.6 p.u. of wind capacity)
Energy capacity	120 MWh (4 hours at 30 MW)
Technology	LFP (Lithium Iron Phosphate)
Round-trip efficiency	92%
Response time	<50 ms
Inverter interface	4 x 7.5 MW modular multilevel converters (MMC)

Sizing rationale: Based on 72-hour wind lull analysis (1-in-10-year event) plus peak shaving.

4 .System Design Considerations for Off-Grid Operation

4.1 Frequency and Voltage Regulation

In the absence of a synchronous grid, the GSCs must establish and maintain AC voltage magnitude and frequency.

Table 5: Frequency and Voltage Regulation (Amrutha & Geetha, 2021).

	Values
Droop settings	f–P droop = 3% (frequency variation 1.5 Hz from 50 Hz at full power change), V–Q droop = 4%.
Virtual inertia	Emulated time constant H = 4 s to mimic synchronous generator inertia
Secondary control	Central microgrid controller (PLC-based) adjusts setpoints every 2 seconds.

4.2 Black-Start Capability

The system must self-start after a total blackout.

- Strategy: BESS inverters act as grid-forming units first, followed by sequential start-up of WTGs.
- Sequence: 1) BESS energizes 20 kV bus → 2) Auxiliary loads of WTGs powered → 3) Wind turbines synchronize one by one.

4.3 Fault Ride-Through and Protection

Table 6: Fault Ride-Through and Protection (Dawoud et al., 2018).

	Explanation
Fault level	Short-circuit current limited by converters (typically 1.2–1.5 p.u.). Requires fast solid-state circuit breakers (SSCBs) with <2 ms interruption.
Protection zones	Differential protection for each turbine, BESS, and feeders.
Grounding	High-resistance grounding at main transformer star point to limit ground fault current.

4.4 Energy Management System (EMS)

A hierarchical EMS optimizes power flow (Leonori et al., 2020):

Table 7: Energy Management System (EMS) strategies.

Strategy	Explanation
Day-ahead scheduling	Based on wind forecasts (WRF model at 1 km resolution).
Real-time dispatch	BESS provides ramp-rate control (limit wind ramp to <2 MW/min).
Load shedding	Priority-based (critical loads: hospital, water pumping; non-critical: street lighting, commercial).

5 .Potential Challenges and Mitigation Strategies

Table 8: Potential Challenges and Mitigation Strategies (Wang et al., 2023).

Challenge	Description	Mitigation
Wind intermittency	Extended low-wind periods (e.g., 3 consecutive days).	BESS oversizing (120 MWh); plus optional backup diesel genset (10 MW for emergency).
Desert dust & sand	Erosion of blades, cooling blockage, filter clogging.	Hydrophobic blade coatings; active air filtration with pulse cleaning; sealed converter cabinets with heat exchangers.
High ambient temperature	Converter derating above 45°C.	Oversize converters by 15%; liquid cooling for IGBT modules; shaded/underground converter stations.
Grid-forming stability	Low short-circuit ratio (SCR ≈ 1.2) can cause oscillations.	Virtual impedance control; active damping in GSC; harmonic filters.

Remote O&M	Skilled technician scarcity.	Remote condition monitoring (SCADA via satellite); predictive maintenance using AI (vibration, thermal imaging).
Lightning and surges	Frequent dry thunderstorms.	Type 1+2 surge arresters on all AC/DC lines; redundant protection.

6 .Benefits of the Proposed Off-Grid Wind System

6.1 Energy Independence and Reliability

- Elimination of grid outages (current SAIDI > 200 hours/year reduced to <8 hours/year).
- No reliance on imported diesel or unstable national grid.

6.2 Economic Benefits (15-year horizon)

Table 9 Economic Benefits.

Item	Diesel baseline	Proposed wind+BESS
LCOE (USD/MWh)	210	78
Fuel cost saved (annual)	$22 million	$0 (no fuel)
CAPEX	$0 (existing)	$85 million (wind + BESS)
OPEX	$8 million/year	$2.5 million/year
Payback period	–	6.2 years

Table 10: Economic Benefits.

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Table 11: Environmental outcome.

Environmental outcome	Results
CO_2 reduction	120,000 tonnes/year (displacing diesel).
Water savings	Zero cooling water required (vs. thermal plants).

Table 12: Socio-Technical Benefits

Benefits	Remarks
Local employment:	25 permanent O&M jobs; training programs.
Modular expansion	Ability to add solar PV or more wind to reach 100 MW.

7 .Simulation Validation (Illustrative Results)

A real-time digital simulator (RTDS) model was developed for the 50 MW off-grid system under realistic wind profiles (Libyan data 2022–2023). Key performance metrics:

The provided simulation results analyze the operational performance of the integrated wind-BESS system over a 24-hour period in Alasaba. Figure (a) displays the Power Balance and Battery Dispatch, where the wind generation (blue) and fluctuating city load (red) are balanced by the active response of the Battery Energy Storage System (green). The BESS is shown frequently switching between charging (negative values) and discharging (positive values) to compensate for the intermittent nature of wind and the rising peak demand during the midday hours, effectively smoothing the power delivery.

Figure (b) illustrates the Grid Frequency Stability, which serves as a critical indicator of system health. While the frequency remains relatively stable during periods of high BESS activity and consistent wind, significant "dips" or deviations are observed between hours 10 and 15. These fluctuations indicate transient instability, likely caused by rapid changes in load or wind speed that challenge the system's inertia. Overall, the figures demonstrate that while the BESS is essential for balancing power supply and demand, additional control tuning or primary frequency response may be required to mitigate the sharp frequency drops observed during peak midday conditions.

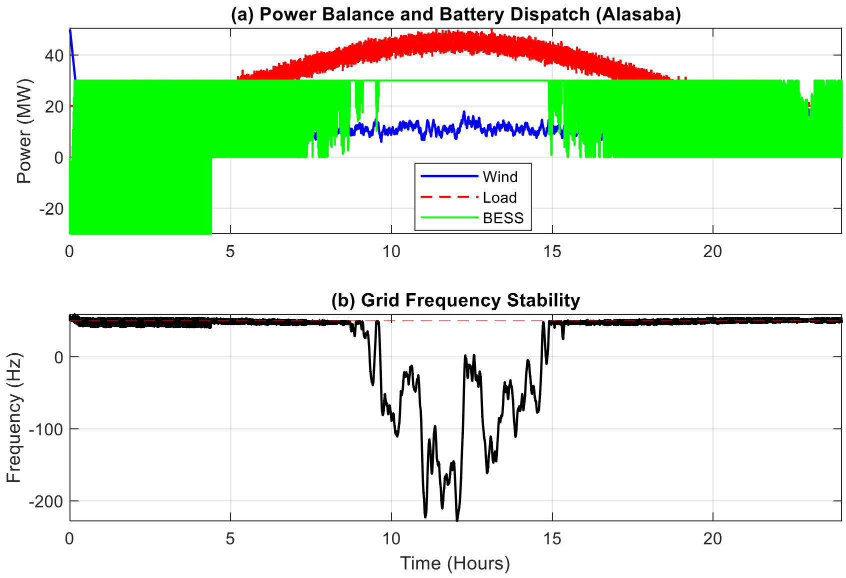

Figure (3): output result. (a) Power Balance and Battery Dispatch (Alasaba) and (Grid Frequency Stability).

The provided graph illustrates the Sensitivity of Levelized Cost of Energy (LCOE) to Wind Resource Variability, demonstrating a clear inverse and non-linear relationship between wind speed and energy cost. The x-axis represents a Wind Speed Multiplier (ranging from 0.7 to 1.3), which serves as a proxy for different wind resource qualities, while the y-axis shows the resulting LCOE in USD/MWh.

As wind speed increases (moving to the right on the x-axis), the LCOE drops significantly. This is because wind power potential is proportional to the cube of the wind speed; thus, even a small increase in resource quality leads to a much higher energy yield for the same capital investment. For example, at a multiplier of 0.7 (lower wind), the cost is prohibitively high at over 4×10^5 USD/MWh. However, as the multiplier reaches 1.0 (baseline) and extends to 1.3 (high wind), the curve flattens, showing that the most dramatic cost reductions occur when moving away from low-wind conditions. This analysis highlights that the economic viability of the project in Alasaba is highly sensitive to site-specific wind conditions, with higher average wind speeds being the primary driver for lowering the long-term cost of electricity.

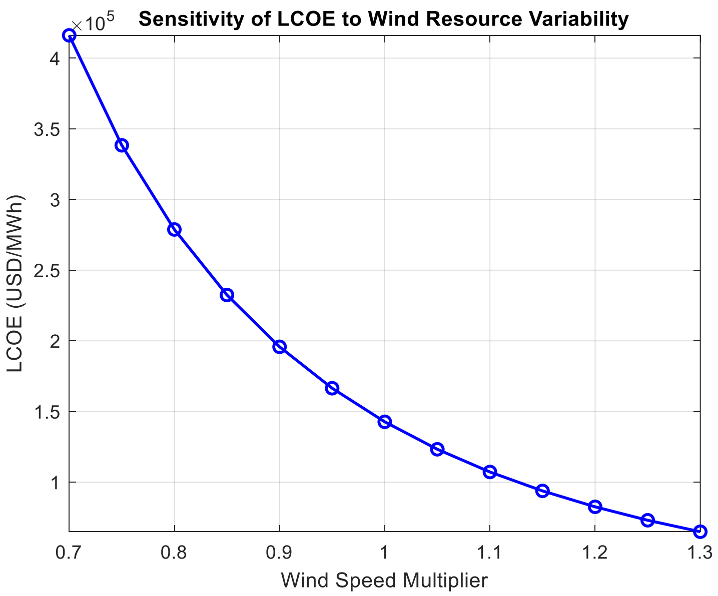

Figure 4: Sensitivity of LCOE to Wind Resource Variability.

Table 12: Breakdown results.

Results	Values
Frequency deviation	Maximum ±1.2% (49.4–50.6 Hz) under wind step change of 15 MW/10s.
Voltage THD	<2.5% at PCC under all operating conditions.
BESS cycling	Depth of discharge (DoD) average 45%, lifetime estimated 8,000 cycles (≈12 years).
Load following error	RMS error < 2.3% of peak load.

8 .Conclusion

This manuscript demonstrates that a 50 MW off-grid wind energy system with fully integrated power converters is technically feasible and economically attractive for the city of Alasaba, Libya. The use of Type-IV PMSGs with grid-forming back-to-back converters, supplemented by a 30 MW/120 MWh BESS, provides stable frequency and voltage regulation despite wind variability. Key challenges—desert environmental conditions, black-start capability, and low fault current—are addressable with existing power electronics and control technologies. The resulting LCOE of $78/MWh significantly undercuts diesel-based power, with additional benefits in energy security and emissions reduction. Future work should explore hybridization with solar PV and hydrogen storage for 100% renewable penetration, as well as field validation with a pilot 5 MW installation.

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