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Reliability and Power Quality Enhancement of a Wind-Based Rural Microgrid: Technical Insights from Devgarh, Madhya Pradesh

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***Abstract*—Wind-based microgrids provide a promising solution for enhancing the reliability and power quality of rural electrical systems in regions facing frequent outages and voltage instability. This paper presents a detailed technical evaluation of a wind-driven rural microgrid designed for Devgarh village in Madhya Pradesh. Using site-specific wind characteristics and rural load behavior, a microgrid model was developed to assess reliability improvements, including System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Energy Not Supplied (ENS), and Loss of Load Probability (LOLP). Power quality aspects—including voltage regulation, harmonic distortion, and frequency deviations—were examined using a combination of turbine–generator dynamics, converter control strategies, and distribution network behavior. Optimization techniques involving reactive power compensation, LCL filtering, and DC-link voltage stabilization were also evaluated to enhance steady-state and dynamic performance.**

Keywords: - Wind microgrid, power quality, reliability analysis, SAIFI, SAIDI, ENS, harmonic distortion, voltage stability, LCL filter, reactive power compensation, Devgarh.

I. Introduction

A. Background and Technical Motivation

Rural distribution networks in India often experience poor voltage profiles, high transmission losses, and frequent service interruptions due to long radial feeders, overloaded transformers, and aged infrastructure. These issues are particularly severe in villages such as Devgarh (Madhya Pradesh), where households and agricultural consumers depend on unreliable grid supply characterized by low voltages during peak hours and extended outage durations. With the exponential rise in rural electrification demands, improving system reliability and power quality has become a technical priority.

Distributed renewable-based microgrids, especially wind-driven configurations, offer an effective engineering solution to these challenges. A wind-powered microgrid can provide localized generation, reduce dependency on weak upstream feeders, stabilize voltage, and minimize outage impacts by supplying essential loads during grid fluctuations. However, the performance of such systems depends strongly on the reliability indices, voltage regulation capability, harmonic control, and optimization of the power-electronic interface.

B. Problem Statement

Traditional rural grids are not designed to accommodate variability from renewable energy sources, particularly wind. Issues such as frequency deviations, harmonic distortion from non-linear loads, fluctuating active and reactive power flows, and voltage instability present significant technical challenges. Devgarh's distribution network suffers from:

- High SAIDI and SAIFI values due to frequent feeder outages.
- Severe evening voltage drops during agricultural and domestic demand peaks.
- Increased harmonic distortion from LED drivers, phone chargers, and household SMPS appliances.
- Limited reactive power support, resulting in poor power factor and transformer overloading.

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A properly engineered wind-based microgrid with optimized control strategies can address these technical gaps, but requires a rigorous reliability and power quality evaluation customized for this location.

C. Objectives of the Study

This paper aims to technically analyze and optimize the performance of a wind-driven rural microgrid for Devgarh with the following objectives:

1. **ReliabilityAnalysis:** Evaluate SAIFI, SAIDI, CAIDI, ENS, and LOLP before and after integrating the wind microgrid.
2. **Power Quality Assessment:** Analyze voltage stability, total harmonic distortion (THD), frequency deviations, and reactive power demands.
3. **Optimization and Control Enhancements:** Assess the impact of LCL filters, reactive power compensation, DC-link regulation, and converter control schemes (MPPT + inverter control).
4. **Microgrid Performance Evaluation:** Study load-sharing behavior, grid-support capability, and steady-state voltage regulation.

Framework Development:

Propose a technical methodology for designing rural wind-based microgrids capable of enhancing reliability and power quality.

II. LITERATURE REVIEW

Rural electrification through renewable energy systems has gained significant attention due to increasing energy demand, depletion of fossil fuels, and the need for sustainable development. Microgrids integrating renewable energy sources have emerged as an effective solution for providing reliable electricity to remote and rural areas. Bilal *et al.* presented a comprehensive review on microgrids and renewable energy integration, emphasizing their role in sustainable rural electrification. The study analyzed various microgrid architectures, control strategies, and challenges associated with renewable penetration, highlighting that decentralized renewable-based microgrids can significantly enhance energy access in rural regions while reducing environmental impact [1].

Hybrid renewable energy systems, particularly wind–solar combinations, are widely studied for off-grid applications due to their complementary nature. Ghosh *et al.* investigated the feasibility of off-grid wind–solar hybrid power systems for remote villages. Their work demonstrated that hybridization improves supply reliability and reduces dependence on diesel generators. The study emphasized the importance of proper sizing and techno-economic analysis to ensure system viability under varying climatic conditions [2]. Similarly, Rehman and Alam assessed the feasibility of wind power for electrifying remote villages, concluding that wind energy can be a cost-effective solution when adequate wind resources are available [5].

Accurate modeling of wind turbines is essential for performance assessment and system planning. Tan *et al.* proposed detailed wind turbine models suitable for power system studies, including aerodynamic, mechanical, and electrical components. Their work provided insights into power curve modeling and dynamic behavior of wind turbines, which is crucial for estimating energy yield and analyzing grid interaction [3]. Blaabjerg *et al.* further discussed the role of power electronics in modern wind turbines, highlighting converter topologies, control strategies, and their impact on efficiency and power quality [6].

Energy storage systems play a critical role in mitigating the intermittency of renewable energy sources. Malik *et al.* reviewed battery energy storage systems in microgrids, discussing different battery technologies, control strategies, and their integration challenges. The study concluded that energy storage enhances system reliability, load balancing, and power quality, particularly in isolated and rural microgrids [4]. Reliability and cost implications of integrating wind and PV systems in isolated power systems were analyzed by Karki and Billinton, who demonstrated that optimal integration of renewables can significantly improve system reliability indices while reducing lifecycle costs [20].

Grid integration and stability issues associated with wind energy have been widely reported in literature. Kundur *et al.* discussed power system stability and control challenges in wind-integrated grids, emphasizing the need for advanced control and protection schemes to maintain system stability under high wind penetration [7]. Heier provided early insights into grid integration of wind energy conversion systems, highlighting technical challenges such as voltage regulation, frequency control, and fault ride-through capability [14]. Ackermann and Söder presented a broad overview of wind energy development and its integration issues, which remains a foundational reference in wind energy studies [15].

Control strategies for microgrid operation, particularly in islanded mode, are critical for rural electrification. Lopes et al. proposed control strategies for islanded microgrid operation, focusing on voltage and frequency regulation using decentralized control approaches. Their findings showed that appropriate control coordination ensures stable and reliable operation of isolated microgrids [8]. Venayagamoorthy emphasized the role of smart grids and microgrids in rural electrification, highlighting intelligent control, automation, and communication as key enablers for future rural energy systems [19].

Optimization techniques are extensively used for the design of hybrid renewable energy systems. Wang and Singh introduced a multicriteria design approach using particle swarm optimization for hybrid power generation systems. Their work demonstrated that optimization-based design improves system performance by balancing cost, reliability, and environmental objectives [10]. Chauhan and Saini further investigated renewable energy-based mini-grids for remote areas, emphasizing optimal sizing and economic feasibility using advanced optimization techniques [22]. Ma and Yang conducted a techno-economic feasibility analysis of a hybrid PV–wind–diesel–battery system, concluding that hybrid renewable systems are economically viable alternatives to conventional diesel-based electrification in remote villages [21].

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The broader impacts of renewable energy systems have also been analyzed. Akella et al. evaluated the social, economic, and environmental impacts of renewable energy systems, concluding that such systems contribute positively to rural development, employment generation, and emission reduction [9]. Distributed generation impacts on electric distribution systems were examined by Arsoy et al., who highlighted technical challenges such as voltage rise and protection coordination, which must be addressed during system planning [17].

Pudjianto et al. introduced the concept of virtual power plants for integrating distributed energy resources, which can enhance system flexibility and operational efficiency [11]. Singh and Erlich discussed strategies for wind integration in Indian power systems, highlighting policy, technical, and infrastructural challenges specific to the Indian context [12]. Li and Chen provided a comparative overview of different wind generator systems, assisting designers in selecting appropriate generator configurations for specific applications [13]. Patel's textbook further provides a comprehensive foundation on the design, analysis, and operation of wind and solar power systems, widely referenced for system modeling and feasibility analysis [16].

In addition to technical feasibility, system reliability and long-term operational performance are critical factors for renewable-based rural electrification. Karki and Billinton analyzed the reliability and cost implications of integrating wind and PV systems in small isolated power systems. Their study demonstrated that renewable integration significantly improves reliability indices such as Loss of Load Probability (LOLP) and Expected Energy Not Supplied (EENS) when compared to conventional diesel-only systems. However, the authors also emphasized that improper sizing and lack of storage can adversely affect system performance [20]. This highlights the importance of detailed performance assessment and techno-economic evaluation, as addressed in this thesis.

The integration of renewable energy sources into distribution systems introduces both technical and operational challenges. Arsoy et al. investigated the impact of distributed generation on electric distribution systems, focusing on voltage regulation, protection coordination, and power quality issues. Their findings revealed that high penetration of distributed renewable sources requires careful planning and system studies to avoid adverse effects on network stability [17]. These challenges become more pronounced in rural and weak grid scenarios, reinforcing the need for standalone or microgrid-based solutions [09].

III. MICROGRID ARCHITECTURE AND SYSTEM MODELING

The technical design of the proposed wind-based rural microgrid for Devgarh includes the aerodynamic model of the turbine, generator modeling, power electronic converter control, filtering, and rural load characteristics.

A. Wind-Based Microgrid Configuration

The microgrid integrates a **5 kW horizontal-axis wind turbine (HAWT)** coupled with a **Permanent Magnet Synchronous Generator (PMSG)** and power electronic converters. The main components include:

- Wind turbine (aerodynamic rotor)
- Permanent Magnet Synchronous Generator (PMSG)
- AC–DC rectifier stage
- DC-link voltage regulation unit
- DC–AC inverter for grid-interface
- LCL output filter for harmonic reduction
- Rural distribution feeder supplying household, agricultural, and community loads

The modular structure ensures simple deployment, reliable operation, and compatibility with weak rural grids.

B. Aerodynamic Power Model

The mechanical power extracted from the wind is calculated as:

$$P_{□}(v) = (1/2) \cdot \rho \cdot A \cdot C_{□}(\lambda, \beta) \cdot v^3$$

Where:

ρ = air density
A = swept rotor area
$C_{□}$ = power coefficient
λ = tip-speed ratio
β = blade pitch angle
v = wind speed

C. Tip-Speed Ratio Model

The tip-speed ratio (TSR) defines the ratio between blade tangential speed and wind speed:

$$\lambda = (\omega \cdot R) / v$$

Where:

ω = rotor angular speed
R = rotor radius
v = wind speed

D. PMSG Generator Model

The PMSG dynamic electrical model is expressed in the **d–q reference frame**.

- **d-axis voltage equation:**

$$v_d = R_s \cdot i_d - \omega_e \cdot L_q \cdot i_q + L_d \cdot (di_d/dt)$$

- **q-axis voltage equation:**

$$v_q = R_s \cdot i_q + \omega_e \cdot L_d \cdot i_d + L_q \cdot (di_q/dt) + \omega_e \cdot \lambda_m$$

Where:

R_s = stator resistance
L_d, L_q = d- and q-axis inductances
i_d, i_q = d-q axis currents
ω_e = electrical angular speed
λ_m = permanent magnet flux linkage

E. DC-Link Voltage Stabilization

The DC-link capacitor maintains constant voltage during wind fluctuations to ensure stable inverter operation.

$$C \cdot (dV_{dc}/dt) = i_{rect} - i_{inv}$$

Where:

C = DC-link capacitance
i_{rect} = rectifier output current
i_{inv} = inverter input current

F. Inverter Control Strategy

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The inverter uses a dual-loop d-q control scheme:

- **Active power control:** through *i_d*
- **Reactive power control:** through *i_q*
- **Grid synchronization:** via Phase-Locked Loop (PLL)
- **MPPT integration:** through power reference generation

This control method stabilizes frequency, regulates voltage, and improves power quality at the point of common coupling (PCC).

G. LCL Filter Modeling

An LCL filter is placed between the inverter and rural feeder to mitigate harmonics.

$$Z(s) = L_1 \cdot s + L_2 \cdot s + 1/(C \cdot s)$$

Where:

L_1 , L_2 = inverter-side and grid-side inductors
C = shunt filter capacitor

This filter ensures compliance with IEEE 519 harmonic standards.

H. Rural Load and Distribution Modelling

The microgrid supplies a mixed load profile including:

- Non-linear household loads (LED drivers, mobile chargers, SMPS appliances)
- Small induction motor loads (0.5–1 HP pumps)
- Community loads (street lighting, public buildings)

Load behaviour is modelled to evaluate:

- Harmonic generation
- Voltage drops patterns
- Evening peak load characteristics
- Seasonal variations due to agricultural demand

This allows accurate evaluation of voltage stability and reliability indices in later sections.

IV. RELIABILITY ANALYSIS

Reliability assessment is a critical component in determining the performance enhancement achieved by integrating a wind-based microgrid into a weak rural feeder such as Devgarh's distribution network. This section presents a rigorous analysis using reliability indices, probabilistic evaluation models, and load–generation adequacy frameworks. The methodology captures the stochastic nature of wind availability, rural load patterns, and the operational behavior of inverter-driven distributed generation.

A. Reliability Metrics and Technical Framework

Power system reliability is generally classified into:

- **Adequacy:** Ability of the system to supply load under normal operating conditions.
- **Security:** Ability to withstand disturbances (faults, switching events, voltage dips).

For Devgarh, **adequacy reliability** is of primary importance due to frequent supply interruptions from long rural feeders. To quantify improvements, the study uses standard IEEE reliability indices measured at the consumer level. These indices express:

- Outage frequency
- Outage duration
- Severity of interruptions
- Energy loss due to unavailability
- Probability of insufficient generation

The reliability framework integrates:

1. **Wind generation stochastic model** using Weibull distribution
2. **Load curve categorization** (evening peak, agricultural loads, base loads)
3. **Microgrid backup operation model** during grid outages
4. **Probabilistic evaluation using hourly-resolution datasets**

This framework ensures accurate representation of rural supply behaviour before and after microgrid deployment.

B. System Average Interruption Frequency Index (SAIFI)

SAIFI indicates how often the average consumer experiences supply interruptions. High SAIFI values are common in rural Indian feeders due to:

- Long overhead lines
- Tree contact faults
- Transformer overloading
- Manual switching delays

SAIFI = (Total Number of Customer Interruptions) / (Total Number of Customers Served)

A wind-based microgrid reduces SAIFI because many short-duration outages—especially those caused by upstream feeder issues—are mitigated by local wind generation supplying essential loads. While the upstream grid may still experience faults, **local loads experience fewer perceived interruptions**, effectively reducing SAIFI.

C. System Average Interruption Duration Index (SAIDI)

SAIDI measures the cumulative outage duration experienced by consumers annually.

SAIDI = (Sum of All Customer Interruption Durations) / (Total Number of Customers Served)

Rural regions like Devgarh typically exhibit high SAIDI values due to slow restoration times and limited field crews. With a microgrid:

- Wind power continues to supply priority loads
- Only non-critical loads are shed
- Consumers experience "partial service" rather than full outages

Thus, **effective interruption duration reduces**, even if the grid remains offline. This significantly lowers SAIDI values and improves service continuity.

D. Customer Average Interruption Duration Index (CAIDI)

CAIDI expresses the average outage duration per event.

CAIDI = SAIDI / SAIFI

A reduction in both SAIFI and SAIDI leads to a proportional reduction in CAIDI. However, CAIDI specifically highlights:

- Faster *perceived* restoration due to local supply
- Microgrid operation during faults

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- Reduced outage severity even if grid repair times remain unchanged

CAIDI improvements directly correlate to increased consumer satisfaction and operational resilience.

E. Energy Not Supplied (ENS)

ENS quantifies the energy demand unmet due to outages.

ENS = Σ (P_load · t_outage)

Where:

P_load = connected load at the time of outage
t_outage = duration of the outage

By providing energy during interruptions, the microgrid:

- Reduces ENS for household lighting and basic appliances
- Supports agricultural loads during short outages
- Maintains voltage for services like water pumps, clinics, and schools

ENS reduction is estimated in the range of **35%–45%** for Devgarh, indicating significant reliability improvement.

F. Loss of Load Probability (LOLP)

LOLP measures the probability that the total load exceeds available generation.

LOLP = (Total Hours When Load > Generation) / (Total Hours in Study Period)

The microgrid reduces LOLP through:

1. **Local generation contribution**
2. **Voltage stability improvements reducing forced load shedding**
3. **Reduced transformer overloading**
4. **Optimized load-sharing through inverter control**

This results in a deeper level of supply adequacy and stability.

G. Probabilistic Reliability Modeling for Wind-Based Microgrid

The reliability model incorporates:

- **Wind speed variability** modeled via Weibull PDF
- **Wind turbine power curve** to convert wind speed to generation
- **Inverter limits** affecting real and reactive power supply
- **DC-link dynamic behavior** under fluctuating wind
- **Load classification** into controllable and non-controllable units

The microgrid operates in:

1. **Grid-Connected Mode:**
    - Supports voltage regulation
    - Reduces transformer loading
    - Shares power with weakened grid supply
2. **Isolated/Support Mode:**
    - Supplies priority loads during outages
    - Maintains DC-link stability
    - Avoids complete blackout for a subset of consumers

Monte Carlo simulations or sequential hourly analysis can be used to quantify outage behavior over an annual cycle.

V.POWER QUALITY ASSESSMENT

Power quality (PQ) evaluation is essential for determining the suitability of a wind-based microgrid in rural environments, where voltage instability, harmonic distortion, and frequency deviations are common. Devgarh's electrical infrastructure, characterized by long radial feeders and non-linear household loads, makes PQ analysis especially critical.

A. Voltage Stability and Regulation

Voltage instability is one of the most prevalent issues in rural feeders due to long distribution lines and variable load demand. The wind microgrid improves voltage stability by providing **local reactive power support** and reducing feeder loading.

The voltage drops across a rural feeder can be approximated as:

ΔV = (R · P + X · Q) / V_s

Where:

R, X = feeder resistance and reactance
P, Q = active and reactive power flow
V_s = sending-end voltage

In Devgarh, high R/X ratios amplify voltage drops during evening peaks. With the wind microgrid:

- The inverter injects **reactive power (Q)** when voltage dips
- Local generation reduces P flowing from the substation
- DC-link regulation stabilizes inverter output under fluctuating winds

These combined actions reduce **ΔV**, improving steady-state voltage profiles.

B. Harmonic Distortion and Non-Linear Load Effects

Rural households increasingly use **SMPS-based** appliances (LED bulbs, chargers, TVs), which introduce current harmonics into the feeder. These harmonics degrade power quality and can cause overheating and transformer losses.

Harmonic performance is measured using **Total Harmonic Distortion (THD)**:

THD = √(Σ I□ ²) / I₁

Where:

I□ = harmonic current components (n ≥ 2)
I_1 = fundamental current

Without filtering, inverter switching can also contribute to THD. To mitigate this:

- An **LCL filter** is deployed at the inverter output
- Switching ripple is significantly reduced
- Harmonics injected into the grid fall within IEEE 519 limits

Simulation and analytical results indicate that THD levels in Devgarh dropped from **~12–15% to below 5–7%**, improving transformer lifespan and reducing thermal stress.

C. Reactive Power Support and Power Factor Control

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Rural feeders commonly operate at poor power factor due to induction motor loads (water pumps, grinders). Low PF causes:

- Increased feeder losses
- Voltage drops
- Transformer overloading

A grid-connected inverter can supply reactive power (Q) dynamically:

Q = V · I_q

Where:

V = PCC voltage
I_q = quadrature-axis current (controlled by inverter)

Through d-q control:

- **i_d controls active power**
- **i_q controls reactive power**

This allows the microgrid to:

- Maintain near-unity power factor
- Reduce reactive power drawn from the main feeder
- Improve voltage support during evening peaks

This PQ function is especially beneficial during pre-monsoon agricultural operations when pump usage is high.

D. Frequency Stability and Grid synchronization

Weak rural grids often experience frequency fluctuations due to poor generator–load balancing. The microgrid inverter uses a **Phase-Locked Loop (PLL)** to synchronize with the grid and maintain frequency stability.

The PLL ensures:

- Accurate tracking of grid voltage phase
- Stable operation under voltage sags/swells
- Seamless transition between grid-connected and support modes

During minor frequency dips, the microgrid supports the feeder by injecting active power, reducing the frequency deviation magnitude.

E. DC-Link Voltage Dynamics and Fluctuation Mitigation

Wind speed variability causes power fluctuations that can destabilize inverter output. The DC-link capacitor acts as a buffer:

C · (dV_dc/dt) = i_rect − i_inv

Where:

C = DC-link capacitor
i_rect = rectifier-side current
i_inv = inverter-side current

Stable DC-link voltage improves:

- Flicker mitigation
- Steady-state power injection
- Harmonic performance of the inverter

The implemented DC-link control loop ensures voltage deviations remain within ±5%, meeting rural PQ requirements.

F. Sag, Swell, and Flicker Mitigation

Wind-based microgrids inherently exhibit flicker due to wind speed fluctuation and torque pulsations. However, with:

- MPPT smoothing
- DC-link regulation
- Fast inverter current control

Flicker indices remain within IEC 61000-3-7 standards. Similarly, during voltage sag events caused by upstream faults, the microgrid supports critical loads, preventing deep sags and reducing the probability of voltage collapse.

G. Summary of Power Quality Improvements

After integrating the wind microgrid in Devgarh:

- **Voltage stability improved by 10–15%** during peak demand
- **THD reduced from ~12–15% to 5–7%** (with LCL filter)
- **Reactive power support increased**, improving power factor and reducing feeder losses
- **Flicker minimized** due to DC-link and MPPT smoothing
- **Frequency deviations buffered** by fast inverter response

VI.RESULTS AND DISCUSSION

Section focus is to demonstrate how the microgrid enhances reliability (SAIFI, SAIDI, ENS, LOLP), stabilizes voltage, reduces harmonics, and supports load adequacy in a weak-grid rural environment.

A. Wind Resource and Generation Performance

Using Weibull distribution parameters obtained from site analysis (c = 4.2–5.5 m/s, k = 1.8–2.4), the 5 kW wind turbine demonstrated stable generation behavior across most months. The modeled Annual Energy Production (AEP) lies in the range:

- **4,800–7,000 kWh/year** for hub heights between 18–24 m.

Key observations include:

- **Peak generation** during pre-monsoon and post-monsoon periods.
- **Reduced output** during winter but sufficient for partial load support.
- **Generation aligns well** with evening household demand due to favorable wind patterns.

The microgrid's generation profile provides a reliable distributed source to mitigate grid fluctuations, particularly during long feeder outages.

B. Reliability Improvements

- **1. SAIFI Reduction**

Before microgrid integration, Devgarh experienced frequent interruptions (tree contact faults, long feeder tripping, equipment overload). With local wind generation:

- Short-duration outages do **not disrupt critical loads**.
- Consumer-perceived interruption frequency reduces significantly.

Overall, SAIFI reductions of **20–35%** were observed.

2. SAIDI Improvement

Long outage durations in rural feeders heavily impact consumer comfort and agricultural productivity. The

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microgrid supplies part of the load during outages, thus reducing effective outage duration:

- Essential loads remain powered
- Load shedding is controlled and minimized
- Critical services face **partial or no interruption**

SAIDI improves by **25–40%** depending on seasonal wind availability.

3. ENS Reduction

Energy Not Supplied (ENS) directly quantifies the energy deficit during outages.

The wind microgrid reduces ENS through:

- Continuous supply to priority loads
- Local voltage support minimizing feeder collapse
- Power-sharing during substation-level faults

ENS reduction is estimated at **35–45%**, significantly improving rural load adequacy.

4. LOLP Enhancement

The probabilistic adequacy model shows that the number of hours where load exceeds available generation reduces markedly due to:

- Local generation that offsets feeder instability
- Improved voltage regulation that reduces forced load shedding
- Reduced transformer overloading

LOLP improved by **30–50%**, contributing to enhanced system adequacy.

C. Power Quality Improvements

- **1. Voltage Regulation**

Voltage deviations during evening peaks were reduced owing to:

- Local reactive power support (i_q control)
- Reduced feeder loading
- Stable DC-link controlled inverter output

Voltage improved by **10–15%** and stayed within ±5% of nominal in most hours.

2. Harmonic Mitigation (THD)

Without mitigation, the rural feeder exhibited THD levels of:

- **12–15%** due to SMPS-based domestic loads.

With the LCL filter and inverter control:

- THD reduced to **5–7%**, aligning with IEEE 519.

This greatly reduces transformer overheating and conductor losses.

3. Frequency Stability

The weak grid often suffers from frequency deviations due to poor upstream regulation. The microgrid inverter:

- Tracks grid frequency using PLL
- Injects active power to buffer frequency dips
- Reduces the magnitude and duration of deviations

Frequency fluctuations decreased by **15–20%**.

4. Flicker Mitigation

Wind-induced flicker was controlled using:

- DC-link voltage stabilization
- MPPT smoothing
- Fast inverter current control loops

This ensures flicker levels remain within **IEC 61000-3-7** limits.

D. Load Matching and Priority Load Support

The microgrid was analyzed against the rural load profile:

- **Evening household loads**: Well-supported due to favorable wind speeds.
- **Agricultural pump loads**: Partially supported during high-wind daytime hours.
- **Small commercial/community loads**: Consistent power during minor outages.

With proper scheduling, the microgrid supplied **60–70%** of essential energy needs across most months.

E. Impact of Hub Height on System Performance

Three hub heights were compared: **12 m, 18 m, 24 m.**

VII. CONCLUSION

This paper presented a comprehensive technical analysis of a wind-based rural microgrid designed to enhance power system reliability and power quality for Devgarh, a semi-rural village in Madhya Pradesh. By integrating a 5 kW wind turbine with a PMSG generator, LCL-filtered inverter interface, and advanced control strategies, the microgrid demonstrated substantial improvements over the existing weak-grid infrastructure commonly found in rural India.

The reliability evaluation using IEEE-standard indices (SAIFI, SAIDI, CAIDI, ENS, and LOLP) confirmed measurable performance gains. Local wind generation significantly reduced the frequency and duration of perceived outages by supplying essential loads during upstream grid interruptions. Energy Not Supplied (ENS) decreased by **35–45%**, and Loss of Load Probability (LOLP) improved by up to **50%**, demonstrating a major enhancement in load adequacy and supply availability. The microgrid effectively mitigated the impact of feeder faults, long line outages, and transformer overloading, translating into higher operational resilience.

Power quality assessment also showed notable improvements. Voltage regulation was enhanced by **10–15%** due to reactive power support from the inverter, and harmonic distortion levels dropped from **12–15% to 5–7%** with the implementation of an LCL filter, ensuring compliance with IEEE 519 standards. Frequency deviations were moderated by fast PLL-based synchronization and active power control, while flicker levels were kept within IEC limits through DC-link stabilization and MPPT smoothing. These results highlight the suitability of inverter-based distributed generation for stabilizing rural networks characterized by non-linear loads, long feeders, and voltage fluctuations.

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