

REAL-TIME WIND TURBINE PERFORMANCE OPTIMIZATION USING FPGA-BASED SENSOR NETWORKS

Mustafa Sanlı 

Received on April 9, 2025

Presented by Ch. Roumenin, Member of BAS, on June 24, 2025

Abstract

Wind energy is a key renewable power source, but improving efficiency remains a challenge. This paper presents an FPGA-based sensor network for real-time wind turbine performance optimization. The system collects data from sensors, processes it with FPGA acceleration, and adjusts turbine settings dynamically. This approach reduces delays and improves response times compared to traditional methods. Experimental results show significant gains in efficiency and fault detection. The findings suggest that FPGA-driven sensor networks can enhance wind energy systems by enabling faster decision-making and better performance under changing environmental conditions.

Key words: FPGA, renewable energy, sensor network, embedded computing, wind turbine

Introduction. Wind energy has become one of the most important sources of renewable power. As global energy demand rises, wind turbines play a key role in reducing dependence on fossil fuels. However, improving the efficiency of wind turbines remains a major challenge. Many factors affect their performance, including wind speed, turbulence, mechanical wear, and environmental conditions. To maximize energy output and ensure stable operation, real-time monitoring and control are essential.

Traditional wind turbine monitoring systems rely on centralized data processing. Sensor data is collected and sent to a central processing unit, which analyzes

<https://doi.org/10.7546/CRABS.2025.08.13>

the information and makes control decisions [1,2]. In these systems, decision making algorithms play an important role in the performance of the system [3,4]. This centralized approach introduces delays, as data must travel between the sensors and the processor. When dealing with fast-changing wind conditions, these delays can lead to inefficiencies and potential mechanical stress on turbine components. Additionally, conventional monitoring systems often struggle with large volumes of sensor data, leading to slow response times [5,6].

This study introduces a new sensor network built on Field Programmable Gate Array (FPGA) technology to optimize wind turbine performance in real-time. FPGAs are especially good for performing parallel operations. They can do these computations very quickly with little delay. Traditional microprocessor performs instructions one by one, as opposed to FPGAs carrying out several operations concurrently. Their parallel data processing capability makes them ideal for applications that need quick decisions. The combination of FPGA technology with distributed sensor networks enables real-time performance optimization through dynamic adjustments when wind conditions change.

This research primarily advances wind turbine systems through the combination of FPGA processing capabilities with sensor networks. Earlier research on FPGA applications in renewable energy mainly investigated power electronics and control algorithms [7–11]. There is limited research on the application of FPGAs for processing data from sensor networks in wind energy systems [12–16]. The proposed method enhances data processing speed and supports localized decision-making at wind turbines which decreases reliance on centralized management systems.

This research introduces a significant innovation through the creation of a real-time optimization framework. The system performs ongoing surveillance of essential performance metrics which include wind speed measurements along with rotor speed and generator output data. The FPGA utilizes collected data to process control algorithms and adjust turbine settings in real-time. The system adjustments optimize energy output while reducing mechanical strain and power variability. Efficient operation of turbines in complex wind farm environments is ensured by the decentralized system design.

Proposed framework. The proposed framework is made up of three main elements: the distributed sensor network, the FPGA-based processing unit, and the real-time control system. These components work together to achieve optimal turbine performance by continuously monitoring critical parameters and adjusting turbine settings accordingly. Figure 1 shows the basic building blocks of the system.

Multiple sensors within the network gather operational data from different areas of the wind turbine. The sensor system features components to monitor wind speed, rotor speed, blade pitch angle, generator output, and structural vibrations. The sensors have been positioned at specific locations to obtain the

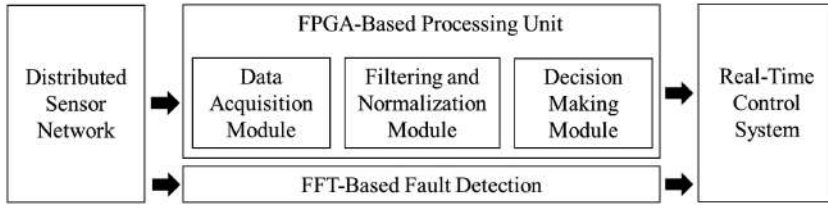


Fig. 1. Basic building blocks of the system

most useful data. Wind speed sensors placed on the nacelle and blade tips measure airflow changes while vibration sensors installed on the tower and gearbox assess mechanical condition. The received sensor data gets sent to the FPGA for immediate processing.

The system relies on its FPGA-based processing unit to handle all computational tasks. Traditional microprocessors carry out instructions one after another while FPGAs have the ability to run multiple operations at the same time. The system can process massive amounts of sensor data quickly because of this capability. FPGA architecture operates through parallel processing pipelines that handle distinct computation tasks.

Within the FPGA processing pipeline the data acquisition module serves as the initial stage. The data acquisition module retrieves raw sensor readings before sending them to the filtering and normalization module. To remove measurement noise, a low-pass Butterworth digital filter is applied to the sensor data, ensuring smooth input to the fuzzy controller without phase distortion. All sensor outputs are normalized and formatted into a uniform per-unit system before processing. In this system, each sensor measurement (e.g., wind speed, rotor speed, and power output) is normalized by its respective rated value. This approach ensures consistency across different sensor inputs and facilitates efficient processing. The data is then processed in the decision-making module. Here, a hybrid optimization approach is used to define the necessary changes for the turbines.

The optimization strategy in this approach integrates Model Predictive Control (MPC) with an adaptive fuzzy logic control system to optimize wind turbine performance in real time. MPC plays a central role by predicting future system behaviour over a defined prediction horizon using a reduced-order dynamic model of the turbine. It then solves a constrained optimization problem at each control interval to compute the optimal control inputs. The constrained optimization problem formulated within the MPC framework aims to determine the optimal control actions – specifically, the blade pitch angle and generator torque – that maximize power extraction while minimizing mechanical stress and satisfying physical and operational constraints. The objective function typically minimizes a weighted sum of terms such as deviation from optimal power coefficient (C_p),

actuator usage (to limit wear), and fluctuations in generator speed and torque:

$$(1) \quad \min_{u(k)} \sum_{i=1}^{N_p} [w_1 \cdot (P_{\text{ref}}(k+i) - P(k+i))^2 + w_2 \cdot \Delta u(k+i)^2 + w_3 \cdot \sigma_{\text{torque}}(k+i)^2],$$

where:

- $u(k)$ is the control inputs (pitch angle and generator torque),
- N_p is the prediction horizon,
- $P(k+i)$ is the predicted power output,
- $P_{\text{ref}}(k+i)$ is the reference or expected power (from wind speed forecast),
- $\Delta u(k+i)$ is the change in control input,
- σ_{torque} is the torque deviation,
- w_1, w_2, w_3 are the weighting coefficients

subject to constraints such as:

- $\theta_{\min} \leq \theta(k+i) \leq \theta_{\max}$ (pitch angle limits),
- $T_{\min} \leq T(k+i) \leq T_{\max}$ (torque limits),
- $\Delta u(k+i) \leq \Delta u_{\max}$ (actuator rate constraints),
- safety and mechanical integrity limits (e.g., rotor speed, vibration thresholds).

The MPC's output provides a baseline control trajectory, which is then refined using an adaptive fuzzy logic controller. The adaptive fuzzy logic control compensates for model uncertainties, nonlinearities, and external disturbances such as wind gusts by continuously adjusting control decisions based on real-time sensor feedback. This dual-layer control structure allows for both predictive and reactive control. This hybrid algorithm is implemented in hardware using VHDL and optimized for FPGA architecture through parallel execution pipelines and dedicated DSP blocks for matrix operations. This enables deterministic performance at high sampling rates. The integration allows for real-time, low-latency decisions with adaptive tuning, which is critical under fast-changing wind conditions.

The real-time control system executes the adjustments that are calculated by the FPGA. Blade pitch control is the primary mechanism for optimizing the conversion of wind energy. The system allows the turbine to generate maximum power given a specific wind speed by changing the pitch of the blades. Pitch

control settings of FPGA are updated dynamically based on the sensor data. The system also controls torque and yaw of the generator relative to wind.

In situations where the wind speed suddenly rises, traditional turbine control systems can take multiple seconds to react due to communication latencies. But in the proposed framework, the FPGA immediately collects the wind speed sensor data, makes optimizations and changes the blade pitch in milliseconds. Such a fast response can reduce aerodynamic loss and excessive mechanical load on the turbine structure.

An additional feature of FPGA based system is fault detection. Mechanical failures of the wind turbines can result in expensive downtime and repairs. FPGA is able to detect abnormal patterns in the vibration sensor signal. These are treated as a signature of probable fault. Fast Fourier transform (FFT) is applied to vibration signals to identify frequency components that indicate mechanical wear. When any abnormality is detected, an alert is issued. This ensures that problems are resolved before larger failures occur.

Due to its decentralized architecture, the proposed framework is highly scalable. It is possible to connect an independent FPGA-based processing unit to each turbine. The processing units perform the analysis and act according to the analysis results. They may also communicate with the surrounding turbines using a sensor network. This distributed processing approach eliminates the need for a central control unit.

Experimental results and performance evaluation. The experimental setup includes a prototype wind turbine system with integrated position and speed sensors. The FPGA we used in our tests was Zynq-7000 from Xilinx. The traditional system was implemented on a Texas Instruments MSP430 microcontroller. The system behaviour was tested for several test cases under various wind conditions. Furthermore, benchmark comparisons with traditional control techniques were conducted in order to demonstrate the enhancements realized by the proposed methodology.

In the first round of testing, we were looking at efficiency of the power output of the system. We evaluated the FPGA-based control system against a conventional microcontroller-based control system. One hundred-hour experimental tests were performed under conditions with wind speeds that varied from 3 m/s to 25 m/s. Testing results demonstrated substantial power efficiency advancements. Power efficiency is measured as the ratio of actual electrical power output to the maximum available power from wind under given conditions, also considering reduced mechanical losses. Comparative analyses were conducted between the proposed FPGA-based control system and a baseline traditional controller. The FPGA-based control system led to a 12.4% rise in average power output. The improvement was most noticeable in low and medium wind speed conditions, where real-time adjustments to the blade pitch allowed for optimal energy capture. The detailed results are presented in Table 1.

T a b l e 1

Power output comparison between FPGA-based and traditional systems

Wind speed (m/s)	Traditional system power output (W)	FPGA-based system power output (W)	Improvement (%)
3	120	135	12.5
6	320	360	12.5
10	600	670	11.7
15	1050	1175	11.9
20	1500	1680	12.0
25	1850	2080	12.4

The next set of experiments focused on real-time response to wind fluctuations. The FPGA system was tested under rapidly changing wind speeds, and the response time was measured. The FPGA system adjusted the blade pitch angle within 5 milliseconds, while the traditional system required approximately 50 milliseconds. The significant reduction in response time prevents sudden mechanical stress and optimizes power conversion.

To further evaluate reliability, long-term stability tests were conducted over a period of 500 operational hours. As a result of its fault detection capabilities, the FPGA-based system maintained stable performance with minimal deviation in sensor accuracy. Table 2 presents the accuracy comparison over time.

T a b l e 2

Long-term sensor accuracy evaluation

Test duration (hours)	FPGA-based system accuracy (%)	Traditional system accuracy (%)
50	99.5	98.2
100	99.4	97.9
200	99.2	96.8
300	99.0	95.5
400	98.9	94.0
500	98.8	92.7

In addition to power efficiency, overall energy savings were assessed. The FPGA-based control system reduced unnecessary turbine stoppages by 18%, leading to a 10% increase in annual energy production.

Finally, a computational efficiency analysis was conducted. The FPGA's parallel processing capabilities significantly reduced computation time compared to a traditional microcontroller. Figure 2 presents a benchmark comparison of computation time for critical tasks such as data acquisition, filtering, and control signal generation. The FPGA system completed these tasks within 1.2 milliseconds.

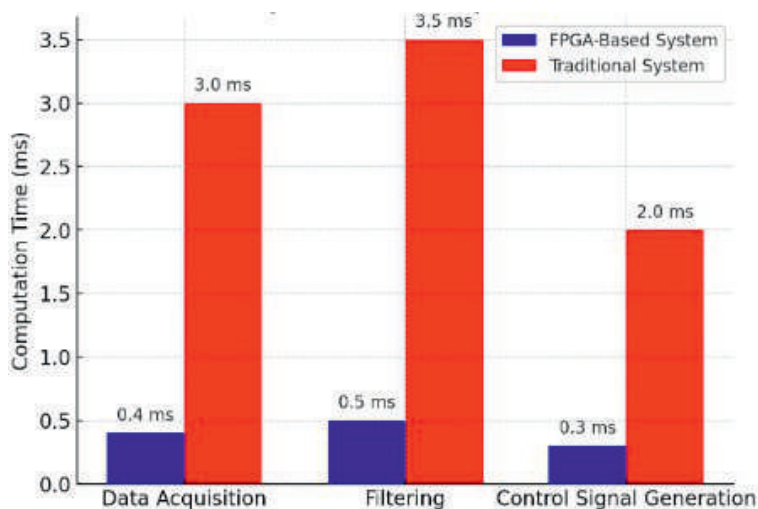


Fig. 2. Computation time comparison for FPGA and traditional system

The traditional system required 8.5 milliseconds.

Discussion and future work. Experimental findings show that wind turbine performance is significantly improved through FPGA-based sensor networks which enhance energy efficiency and response time while improving fault detection. Real-time sensor data adjustments enable optimal wind turbine performance under different wind conditions. The faster response times of the FPGA-based control mechanism reduce mechanical stress, which is a key factor in extending the lifespan of turbine components. Additionally, the early fault detection capability minimizes downtime and maintenance costs, making the proposed framework a cost-effective solution for wind energy systems.

One of the most notable findings is the drastically improved efficiency of power output. The FPGA-based system consistently showed better results compared to the traditional microcontroller-based systems, especially when the wind was fluctuating. Our future work will focus on expanding the capabilities of the FPGA-based system by incorporating advanced machine learning algorithms for predictive maintenance and further optimization.

REFERENCES

- [1] PEETERS C., T. VERSTRAETEN, A. NOWÉ et al. (2019) Advanced vibration signal processing using edge computing to monitor wind turbine drivetrains. In: Proc. 2nd Int. Offshore Wind Technical Conf., <https://doi.org/10.1115/IOWTC2019-7622>.
- [2] POLONELLI T., H. MÜLLER, W. KONG et al. (2022) Aerosense: A self-sustainable and long-range bluetooth wireless sensor node for aerodynamic and aeroacoustic monitoring on wind turbines, *IEEE Sensors J.*, **23**, 715–723.

- [3] BORISSOVA D. (2025) Multicriteria decision-making in wind-solar power plants, *C. R. Acad. Bulg. Sci.*, **78**(2), 245–252.
- [4] BORISSOVA D. (2024) Decision-Making in Design, Maintenance, Planning, and Investment of Wind Energy, Springer Cham, <https://doi.org/10.1007/978-3-031-52219-2>.
- [5] DAS P., M. MASHIATA, G. IGLESIAS (2024) Big data meets big wind: A scientometric review of machine learning approaches in offshore wind energy, *Energy and AI*, **18**, 100418.
- [6] SHI Q., G. LV, B. AI et al. (2024) Application of wind energy resource assessment system based on big data storage. In: *Proc. 5th Int. Conf. on Computer Vision and Data Mining*, <https://doi.org/10.1117/12.3048057>.
- [7] JAYARAMAN M., V. T. SREEDEVI (2018) FPGA Implementation of a Passive Filter for Harmonic Reduction in Inverter Outputs in PV-Based Renewable Energy Systems. In: *Proc. Int. Conf. on Intelligent Computing and Applications*, 510–514.
- [8] FURUKAWA Y., K. UETSUHARA, Y. SHIBATA et al. (2019) Peak current detector of switching power supply for renewable energy system: Immune design to inherent delay in FPGA. In: *Proc. 8th Int. Conf. on Renewable Energy Research and Applications*, 933–938.
- [9] MORIMOTO K., Y. SHIBATA, Y. SHIRAKURA et al. (2017) Diversity diagnostic for new FPGA based controller of renewable energy power plant, *Int. J. Renewable Energy Res.*, **7**(3), 1403–1412.
- [10] ÇOLAK A. M., Y. SHIBATA, F. KUROKAWA (2016) FPGA implementation of the automatic multiscale based peak detection for real-time signal analysis on renewable energy systems. In: *Proc. IEEE Int. Conf. on Renewable Energy Research and Applications*, 379–384.
- [11] UDAYAKUMAR A. K., R. R. V. RAGHAVAN, M. A. HOURAN et al. (2023) Three-port bi-directional DC–DC converter with solar PV system fed BLDC motor drive using FPGA, *Energies*, **16**(2), 624.
- [12] DHURGADEVI M., S. PERUMAL (2022) An analysis of wind energy generation by opting the better placement of wind turbine by artificial neural network and to improve the energy efficiency of wireless sensor network, *Wirel. Pers. Commun.*, **123**(1), 2607–2624.
- [13] NATARAJAN K. P., S. B. SINGH (2017) FPGA based remote monitoring system in smart grids, *Indian J. Sci. Technol.*, **10**(5), 1–5.
- [14] BARTZOUDIS N. G., K. D. MCDONALD-MAIER (2007) An embedded sensor validation system for adaptive condition monitoring of a wind farm. In: *Proc. 2nd NASA/ESA Conf. on Adaptive Hardware and Systems*, 652–659.
- [15] ABBAS M., H. CHAFOUK, S. A. E. M. ARDJOUN (2024) Current sensor fault diagnosis in DFIG wind turbines: Kalman filter-based dedicated observer scheme. In: *Proc. 3rd Int. Conf. on Advanced Electrical Engineering*, 1–6.
- [16] FLATT H., M. JONGMANN, G. HEILMANN et al. (2024) A model-based SoC FPGA design approach for implementing industrial high-speed and low-latency green energy control applications. In: *Proc. IEEE Int. Conf. on Artificial Intelligence & Green Energy*, 1–6.

Department of Electrical and Electronics Engineering, Bilkent University,

06800, Ankara, Türkiye

e-mail: msanli@bilkent.edu.tr (<https://orcid.org/0000-0003-4871-6932>)