Chapter 6

Artificial Intelligence and Digital Twin Synergy for Predictive Maintenance and Fault Detection in Wind Turbines

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ABSTRACT

This chapter explores the integration of Artificial Intelligence (AI) and Digital Twin (DT) technologies for intelligent condition monitoring and fault detection in wind energy systems. It highlights the limitations of traditional approaches and presents AI-based models for fault prediction, anomaly detection, and remaining useful life estimation. The layered architecture of DTs, their real-time synchronization, and hybrid AI-DT frameworks for predictive maintenance are discussed. The chapter

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also examines challenges such as data integrity, scalability, and cybersecurity while outlining emerging trends like federated learning and quantum digital twins for resilient and sustainable wind farm operations.

INTRODUCTION

The global pursuit of decarbonization and sustainable energy has positioned wind power as one of the most critical pillars of modern electricity generation. As nations accelerate their commitments to carbon neutrality, the deployment of large-scale wind farms—both onshore and offshore—has expanded dramatically over the past decade. However, this rapid growth brings forth substantial challenges related to reliability, maintenance, and operational efficiency. Wind turbines are complex electromechanical systems that operate under fluctuating wind speeds, variable loads, and harsh environmental conditions. These operational stresses can induce gradual degradation and unexpected faults in key components such as blades, gearboxes, bearings, generators, and power converters (Sasinthiran et al., 2024; Astolfi et al., 2023). Addressing these challenges through advanced condition monitoring and fault detection techniques is essential for ensuring high availability, reducing maintenance costs, and extending the lifespan of assets in modern wind energy systems.

Need for Condition Monitoring in Wind Turbines

Condition monitoring systems (CMS) form the foundation of predictive maintenance strategies by providing continuous health assessment of turbine components. Traditional CMS approaches typically rely on rule-based thresholds, vibration analysis, and model-based estimations. While these techniques have been useful for early fault detection, they often struggle with the inherent complexity and nonlinear behavior of wind turbines. For instance, threshold-based detection methods may fail to capture subtle changes in system dynamics or differentiate between operational fluctuations and actual fault signatures. As a result, conventional approaches frequently lead to false alarms or missed detections, ultimately increasing downtime and maintenance costs (Ng & Lim, 2022; Tang et al., 2021).

Moreover, the modern wind energy ecosystem is characterized by large-scale data acquisition through sensors and supervisory control and data acquisition (SCADA) systems. These sensors collect data on vibration, torque, temperature, current, wind speed, and acoustic emissions, creating an enormous volume of time-series data. Managing and interpreting this high-dimensional, multimodal data requires more sophisticated analytical techniques. The limitations of traditional methods have therefore catalyzed the integration of Artificial Intelligence (AI) and data-

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