

Chapter 2

Integrating AI and Digital Twins for Real-Time Fault Identification in Wind Turbines

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ABSTRACT

The integration of artificial intelligence (AI) and digital twin technologies has revolutionized condition monitoring and fault detection in industrial systems, particularly in wind energy applications. This chapter explores the synergistic relationship between AI algorithms and digital twin frameworks for enhanced predictive maintenance strategies. Digital twins create virtual replicas of physical systems, enabling real-time monitoring, simulation, and analysis of operational conditions.

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When combined with AI techniques such as machine learning, deep learning, and neural networks, these systems can predict failures, optimize maintenance schedules, and reduce operational costs. The chapter examines current methodologies, implementation challenges, and future prospects of AI-enhanced digital twins in condition monitoring. Case studies from wind turbine applications demonstrate the practical benefits of this integrated approach, showing improvements in fault detection accuracy, reduced downtime, and enhanced system reliability.

1. INTRODUCTION

The Fourth Industrial Revolution has ushered in an era of unprecedented technological integration, where physical and digital systems converge to create intelligent manufacturing and operational environments. At the forefront of this transformation lies the convergence of artificial intelligence (AI) and digital twin technologies, which together form a powerful paradigm for condition monitoring and fault detection across various industrial sectors.

Digital twin technology, first conceptualized by NASA for space missions, has evolved into a cornerstone of modern industrial digitalization. A digital twin represents a virtual replica of a physical asset, process, or system that enables real-time monitoring, simulation, and optimization (Jeong et al., 2022). When augmented with AI capabilities, digital twins transcend traditional monitoring approaches by incorporating predictive analytics, adaptive learning, and autonomous decision-making capabilities.

The significance of this technological convergence becomes particularly apparent in critical infrastructure systems such as wind energy installations, where unplanned downtime can result in substantial economic losses and grid instability. Traditional condition monitoring approaches, while effective to some extent, often rely on reactive maintenance strategies or fixed scheduling protocols that fail to optimize operational efficiency and resource utilization.

AI-enhanced digital twins address these limitations by providing a comprehensive framework that combines real-time data acquisition, advanced analytics, and predictive modeling. This integration enables organizations to transition from reactive to proactive and ultimately to predictive maintenance strategies, resulting in improved system reliability, reduced operational costs, and enhanced safety performance.

The evolution of sensor technologies, edge computing capabilities, and cloud-based analytics platforms has further accelerated the adoption of AI-driven digital twin solutions. Modern industrial systems generate vast amounts of operational data through IoT sensors, SCADA systems, and embedded monitoring devices. This data wealth, when processed through sophisticated AI algorithms within digital twin

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