Chapter 3
Artificial Intelligence and Digital Twin Applications in Wind Turbine Monitoring, Control, and Maintenance

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ABSTRACT

This chapter explores how digital twins (DT), machine learning (ML), and artificial intelligence (AI) enhance monitoring, control, and maintenance of modern wind turbines. These technologies enable predictive, data-driven solutions using real-time SCADA and high-resolution sensor data, reducing reliance on reactive, schedule-based maintenance. AI and ML improve resource allocation, fault detection, and performance optimization through continuous learning, while DTs synchronize virtual and physical turbines for advanced diagnostics, planning, and simulation. The chapter also outlines implementation challenges, including model drift, data delays, security risks, and integration within existing infrastructure. It aims to guide researchers and engineers in deploying AI-based tools to improve turbine reliability, efficiency, and lifecycle management.

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1. INTRODUCTION

With tremendous growth in the number of wind turbines, the area of wind farms, and the technical complexity of wind farms worldwide, wind farm clusters have grown larger, become more geographically distributed, and become more technically complex. The circa-end-2023 global installed wind capacity broke the 1,100-GW barrier, a milestone that symbolizes widespread deployment across diverse geographical and weather conditions. (IEA, 2024). Also, the Global Wind Energy Council (GWEC, 2024) Writes that new installations are increasingly scattered across emerging markets, making it difficult to operate them. These trends and emerging issues may make conventional monitoring, control, and maintenance schemes, whether scheduled or reactive, insufficient for handling the complexity and variability of large-scale wind farms. Therefore, there is a growing demand for new digital tools capable of overcoming this high level of complexity.

Conventional wind turbine maintenance is based on regular preventative maintenance and corrective actions upon failures. Planned preventive maintenance is applied periodically regardless of the components' actual condition, resulting in inefficient resource utilization and unnecessary downtime. (Yu, Patriksson, & Sagitov, 2021). Reactive maintenance generally results in unplanned outages and higher operation and maintenance (O&M) costs due to unforeseen malfunctions and delayed fault detection. (Pérez, 2022). These techniques have limited fault-detection capability and poor forecasting, leading to low turbine availability and reliability. So much so that, driven by real-time data and advanced analytics, these RUL systems can predict Remaining Useful Life (RUL) and promptly take maintenance actions to minimize downtime and cost while maximizing maintenance schedules (Shah, Daoliang, & Kumar, 2024).

The oil and gas industry is in the midst of a digital revolution, with SCADA systems and IoT sensors converging with cloud analytics. Such equipment allows for real-time monitoring and the automatic transmission of wind speed, vibration, or power output data from the wind turbines at any given moment, providing them with quicker reaction times and improved performance. (Alves, Mendonça, Mostafa, & Morgado-Dias, 2024). Scanned data enables timely control and early error detection, filling the gap left by intermittent manual monitoring. Furthermore, digital twinning models – integrating real-time sensor data with predictive models allow maintenance and performance optimization decisions to be made in real-time using data as a basis. (Abdullahi, Longo, & Samie, 2024).

Digital twin, machine learning (ML), and artificial intelligence (AI) are becoming part of modern wind turbine systems to increase operational efficiency and reliability. AI is a broad term that encompasses a range of computer systems capable of performing tasks that require human intelligence. Meanwhile, machine learning

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