Abstract

The variation in production and higher intermittency of wind power generation makes it difficult to fit into conventional procedures of power system operations, planning, and scheduling. The latest advancements in energy storage technology provide an opportunity for utilizing energy storage systems to address the intermittency of wind energy. Recent studies suggest that the Battery Energy Storage System (BESS) can play a significant role in handling risks associated with wind power generation uncertainties and maximizing wind power producers' revenue (WPP). This thesis mainly focuses on two aspects of the grid integration of wind energy: (i) the active power management of wind farms and (ii) the wind energy trading in short-term electricity markets, both incorporating BESS.

A grid operator must foresee the day-ahead generation and demand, such that a proper dispatch schedule is prepared, and hence, wind power forecasting is essential. It further assists the WPP to participate in futuristic energy markets with optimal decision-making. Several wind power forecasting modules based on machine learning and deep learning algorithms are developed as preliminary work in this thesis. First, a Wavelet Neural Network (WNN) based forecasting model is created, which utilizes a multi-level discrete wavelet decomposition technique to analyze the nonlinearity present in the historical wind power profiles. Based on a similar WNN model, an electricity price forecasting model is also developed, which is instrumental in wind energy trading in electricity markets. Further, an ensemble forecast model is proposed that takes the benefits of four machine learning algorithms, which include Convolutional Neural Network (CNN), Long Short-Term Memory (LSTM), Light Gradient Boosting Machine (LightGBM), and eXtreme Gradient Boosting (XGBoost). It is found that the performance of the ensemble model reasonably performs well throughout the year as compared to the other models.

The next part of the thesis addresses the dispatchability problem of wind power plants. A two-layer Coordinated Model Predictive Control (CMPC) algorithm is devised that coordinates the operation of a wind-BESS hybrid system (WBHS). The optimized reference signals are then sent to the BESS subsystem controller at the lower level. The lower-level controller drives its subsystem subjected to the system constraints to track the reference signal and provides optimal charging/discharging

instructions to the BESS. Thus, the combined WBHS power output is brought to the desired dispatch level. It also helps in smoothening the wind farm power output. Simulation results verify the efficiency of the presented MPC controller.

The following segment of the thesis focuses on a risk-constrained stochastic bidding strategy for a WPP to play in the short-term electricity market. The strategy is formulated considering the uncertainties present in wind power generation and electricity market prices, aiming to minimize the power deviation during real-time delivery utilizing BESS. CVaR as a risk-measure is incorporated, and a two-stage stochastic optimization problem is formulated where the first stage decides the day-ahead (DA) offering while the second stage deals with the real-time (RT) operation. The stochastic problem is further reformulated using Extended Mathematical Programming (EMP), which reduces the problem's mathematical complexity. The wind power generation profile from an actual wind farm located in Gujarat, India, is taken as a test study. Various potential case studies are presented to illustrate the effectiveness of the proposed bidding strategy.

In conclusion, this thesis presents effective wind power forecasting and electricity price-forecasting models, which are much robust to predict throughout the year accurately. A coordinated model predictive controller is proposed to improve the dispatchability of the wind power plants by optimally scheduling the BESS. After that, an optimal bidding strategy is devised for WPP to participate in short-term electricity markets and maximize their revenue. This work can be further extended to incorporate the grid operator’s perspective, where the algorithm can be developed considering the network constraints and grid disturbances. Wind energy and BESS roles can be explored in the ancillary services markets for frequency regulation and demand response. This energy trading in the electricity market could also incorporate multiple players with distributed generators and electric vehicles. The stochastic optimization problem developed in Chapter 5 may be solved for numerous participants by employing distributed algorithms like ADMM, Bender’s decomposition, etc. This would further reduce the problem's computational complexity and protect data privacy among the market participants.