A Forecast-Embedded Digital Twin for MPC-Aware Battery Sizing and Multi-Objective Energy Management in PV-Based Microgrids

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Abstract

Digital twin (DT) applications in microgrids are frequently restricted to offline analysis or monitoring, treating energy management, battery sizing, and forecasting as separate issues. For a PV-battery microgrid, this study suggests a decision-oriented Digital Twin framework that combines real-time energy management, battery capacity optimization, and hybrid PV power forecasting into a single operational loop. For short-term PV power forecasting, a BiLSTM–GPR hybrid model is employed, and the predicted outputs are immediately incorporated into the DT control layer. utilizing the same economic Model Predictive Control (MPC) formulation used for energy management, candidate battery sizes are assessed based on their operational performance in order to optimize battery capacity utilizing an MPC-aware sizing approach. This takes dynamic electricity tariffs into account and guarantees consistency between planning and control. Across 100 Monte Carlo trials with independently sampled load realizations, the proposed MPC-based EMS achieves a mean cost reduction of 19.22% (95% CI: [18.69%, 19.76%]) and a mean peak grid power reduction of 35.66% relative to a naïve rule-based EMS, with both improvements statistically significant (Wilcoxon signed-rank test, $p < 0.001$) and favoring the proposed EMS in all 100 of 100 trials (rank-biserial effect size $r = 1.0$).

Keywords

Battery sizing, Digital Twin, Energy management, Microgrid, Model Predictive Control (MPC), PV power hybrid.