

Predictive Optimal Control-Based Battery Management Systems for Grid-Integrated Electrified Systems: A Multi-Objective Framework for Efficiency, Stability, and Lifecycle Optimization

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Abstract: A predictive optimal control-based Battery Management System (BMS) framework is designed with the focus on enhancing energy efficiency, grid stability, battery longevity and operational reliability of the grid-integrated electrified systems operating under dynamic conditions. However, as renewable energy resources and electrified transportation systems penetrate into the electric grid at unprecedented rates, new challenges related to intermittency of resource power generation & load fluctuation (large changes in demand) are introduced. Traditional BMS methods typically use fixed-rule or single-objective control strategies, which cannot effectively trade off the conflicting needs of performance, safety and lifecycle optimisation. In response to this limitation, the willing framework incorporates multi-objective optimization techniques with Model Predictive Control (MPC) in adaptable and on-demand energy management of grid-connected battery energy storage. The designed controller forecasts future battery states and grid properties within a limited prediction horizon, while jointly optimizing charging/discharging decisions against hard operational constraints pertaining to state-of-charge (SOC), temperature, voltage, and current. We propose a multi-objective cost function that captures the production of power losses, battery degradation, voltage deviations and energy imbalance, while maximizing grid support capability and overall system efficient. The system analysis is conducted using a detailed MATLAB/Simulink model that incorporates the lithium-ion battery dynamics, renewable energy intermittency, stochastic load disturbances and grid disturbances including voltage sag and power-frequency variations. The simulation results shown in this paper indicate that the proposed predictive optimal control framework outperforms traditional PI-based and rule-based BMS approaches. This method decreases around 18.7% of the total battery charging/discharging losses, reduces SOC estimation error from 4.9% to 1.2%, and raises energy conversion efficiency from 88.4% to 96.1%. It has been shown that the grid voltage is reduced during transient disturbance and frequency stabilization time are improved about 42% and compared to conventional control strategies by more than 35%. The intelligent optimization framework also realizes a reduction of battery temperature rise by around 21%, hence improving thermal stability and operation safety. Battery lifecycle analysis suggests the proposed strategy prevents most degradation-related capacity loss, with a 16–19% reduction under long-term cycling conditions from gentler charging profiles and lower high-current stress. Moreover, it improves the efficiency of renewable energy utilization by around 14%, facilitating a more effective incorporation of intermittent solar and wind resources to the grid. The predictive controller shows good robustness against parameter uncertainties and stochastic load disturbances with less than 2% steady-state voltage error keeping stable operation. In sum, the obtained result indicates that the proposed predictive optimal control based BMS is a promising and scalable solution for future grid-integrated electrified systems. The framework provides very good gains in terms of efficiency and stability along with battery health management making it well-suited for smart grids, renewable energy systems, electric vehicle charging infrastructure and sustainable energy.

Keywords: Battery Management Systems (BMS), Model Predictive Control (MPC), grid integration, multi-objective optimization, energy storage systems, lifecycle optimization

INTRODUCTION

The accelerated shift to electrified power systems, renewable energy sources and smart grid infrastructures has led to a major increase in the need for contemporary Battery Management Systems (BMSs) as key elements of present-day power networks. In particular, Battery Energy Storage Systems (BESSs) have been identified as vital enabling technologies for grid stability, balancing renewables, peak shaving, EV integration and decentralised power management [1], [2]. With the large-scale advancements in lithium-ion batteries particularly in microgrid applications, electric mobility, and utility scale as well as residential energy systems, the requirement for effective intelligent energy management strategies which can concurrently strive to optimize efficiency, reliability, safety, and battery life have become increased [3], [4]. Traditional BMS methodologies were restricted to battery monitoring, voltage, current and temperature only addressing issues of SOC [5] without predictive optimization or adaptive decision making. In contrast, contemporary grid-connected electrified systems are complex systems that operate under more dynamic and stochastic characteristics such as renewable intermittency power supply condition, stochastic load profiles trend, voltage fluctuations change performance, electricity market force (better or worse), etc., which need more sophisticated predictive and multi-objective control frameworks [6], [7].

Recently, it has been shown that Model Predictive Control (MPC) is considered as one of the most powerful approaches for intelligent energy management and battery control of smart grid and electrified systems [8], [9]. Due to its prediction of future system behaviour using dynamic models and optimal control actions over a finite horizon while taking into consideration the operational constraints [10], MPC has many advantages over traditional controllers. In contrast with a classical proportional-integral (PI) or rule-based controller, the MPC method is able to simultaneously deal with multiple control objectives such as losses minimisation, battery SOC limitation, degradation reduction and voltage/frequency support [11]. Hu et al. A fully surveyed MPC application to the microgrid and proving its effectiveness in handling the power flow, voltage regulator, as well-economic operation was given in [12]. Similarly, Ordoñez et al. However, [13] indicated that advanced control strategies based on MPC have been proven to be very effective under uncertainties in power dispatch (both active and reactive) of isolated microgrids based on renewable energies. While MPC has displayed substantial potential, the combination of predictive optimal control with BMSs for grid-connected electrified systems is still a daunting task. Although existing ones focusing on a single operational objective, such as energy efficiency or SOC regulation, other equally critical objectives such as battery degradation [14], thermal stability, power quality [14] and long-term lifecycle optimization are poorly addressed. In addition, most BMS frameworks in practice depend on a simplified battery model that neglected nonlinear electrochemical dynamics as well as the effect of aging and environmental disturbances [15]. Once battery systems will be embedded within renewable-rich backbone smart grids and EV charging infrastructures, the interactions between the batteries, converters, loads and grid conditions become highly nonlinear and full of uncertainties [16]. The challenges above hinder the use of traditional optimization approaches and introduce a large gap between the theoretical control strategies and realizable real-time implementation. Another one of the biggest conflicts is between battery performance and longevity. Increased short term energy efficiency and grid support capability from aggressive charging/discharging strategies may result in battery degradation over time with expedited thermal stress [16], lithium plating [25] and cycling through excessive current generation

[17]. On the other hand, conservative battery management techniques prolong battery lifetime but may decrease system response time and energy utilization efficiency. And this scenario results in a multi-objective optimization problem which necessitates the compromise of conflicting operational needs [18]. Yang et al. In [19], a hierarchical MPC strategy for hybrid energy storage systems was developed, which outperformed the well-known methods in terms of power allocation performance; nonetheless, computational complexity and scalability may hinder its use for large-scale real-time applications. Similarly, Arias et al. In [20], the authors included converter efficiency and battery stress in their MPC cost functions for a hybrid energy storage system, which allowed for greater operational flexibility as well as battery protection, although the framework was not suited to non-local applications nor robust to uncertainties in grid integration.

The reason for this explains why the problem has not been resolved. However, forecasting renewable generation, load demand and battery dynamics is challenging due to the stochastic non-linear feature of electrified systems [21]. Renewable energy sources, photovoltaic (PV) and wind systems are highly intermittent and weather-dependent with fluctuations that propagate throughout the grid and widely impact the battery operation [22]. Nassereddine et al. Accurate renewable forecasting is crucial for MPC-based energy management systems [23], which has led to a focus on improving the forecasting error since these errors adversely affect control system performance in hardware-in-the-loop conditions. Second, computational cost is still one of the key bottlenecks to real-time MPC solving. Due to the myriad types of multi-objective optimization problems, Nonlinear battery models and converter constraints on top of grid dynamics will also lead high-dimensional optimization problems that embedded systems usually cannot handle [24]. Morstyn et al. This problem was tackled with the use of convex optimization formulations in [25], providing significantly faster computation times; however, approximations made to simplify model have sacrificed accuracy for operation outside the highly nonlinear operating regime. Third, most existing BMS frameworks are not straightforward in using battery degradation as a part of the control strategy [26]. Conventional controllers do not address operational goals over period, depending more on series of short-term manipulations and consequently failing to assess long-run electric battery lifespan properly. Consequently, long-term cycling following these conditions deteriorates capacity and increases the corresponding polarization [27]. In recent years, degradation-aware optimization has found increasing usage in predictive control structures. Lyu et al. [28] presented a tube-based MPC framework with degradation cost and uncertainty handling which showed better battery lifetime performance (compared to various state-of-the-art approaches) under renewable energy fluctuation. In a similar manner, MPC-based power management strategies have been proposed for degradation mitigation in hybrid PV-battery systems [29]. Nonetheless, most of these techniques are application-specific and lack a generalized multi-objective framework pertinent to grid-integrated electrified systems.

Despite milestones achieved by several state-of-the-art semi-analytical hybrid energy management solutions [36], recent advances in machine learning (ML) and reinforcement learning (RL) as complementary predictive control and intelligent BMS techniques have boosted the establishment of a new dimension for research on battery aggregator systems [30]. AI-driven smart grids use predictive analytics and adaptive optimization for dynamic management of supply-demand balancing [31]. Meng et al. Ai et al. by experimentation showed that using RL in MPC, optimization accuracy and adaptive learning capability are greatly improved [32]. Likewise, explicit battery models with effective prediction are also minimized in data-driven MPC approaches [33]. These advancements indicate the possibility to use predictive optimal control in combination with adaptive optimization techniques as

an effective alternative strategy to tackle nonlinearities, uncertainties and scalability issues that may arise in following future BMS applications. Apart from technical barriers grid integration brings a very different operational and regulatory landscape. Voltage stability requirements, frequency regulation specifications and interoperability standards on systems [34] must be satisfied by battery systems that interconnect with smart grids such as IEEE 2030.2 and IEC 61970/61968. With the increase of renewable penetration, batteries are playing increasingly important roles in providing ancillary services like peak shaving, load leveling, voltage support and fast frequency response [35]. These requirements call for advanced control frameworks that can coordinate the energy dispatch over different timescales, all while respecting battery health and operating safely [36]. Zhao et al. Duan et al. [37] presented a two-level MPC structure for renewable-rich microgrids with hydrogen and superconducting magnetic energy storage systems, which provides higher performance in terms of operating costs and stabilization times. But practical deployment issues in particular, computational scalability and communication infrastructure act as significant hurdles. Considering the increasing complexity of electrified systems, this calls for a new generation of BMS frameworks that can jointly handle efficiency grid stability, thermal management, degradation mitigation and lifecycle optimization in a single predictive control architecture. Previous work has mainly addressed independent objectives or application fields separately and, therefore, does not fully leverage the synergy between predictive multi-objective optimization. Moreover, most existing frameworks are not fully geared towards providing a comprehensive integration of battery electrochemical dynamics and thermal modeling with renewable forecasting uncertainties and grid operational constraints, all under an adaptive control scheme.

In order to remedy these limitations, this paper develops a multi-objective optimization framework based Predictive Optimal Control-Based Battery Management System for Grid-Integrated Electrified Systems. The proposed methodology successfully integrates Model Predictive Control and adaptive optimization techniques to simultaneously optimize energy efficiency, battery lifecycle, voltage stability, thermal performance and renewable energy utilization under dynamic operating conditions. The proposed framework explicitly integrates three main functionalities that are treated separately in most conventional BMS architectures, namely degradation-aware optimization, predictive renewable/load forecasting and grid support into a single control strategy. The controller predicts all future battery states and grid conditions statically over a finite prediction horizon and optimizes both charging and discharging actions subject to operational constraints such as SOC limits, voltage stability, operating temperature limits, converter efficiency and eq. 2. Make sure you do not consider too many variables here! This framework considers renewable intermittency, stochastic load disturbances and parameter uncertainties to improve the robustness and scalability of real-world applications. Notably, the main contributions of this work can be summarized as follows:

- Unified Predictive Optimal Control Framework for Battery Management Systems Integrated into the Power Grid
- Multi-objective optimization integration with efficiency, voltage stability, thermal management and battery degradation simultaneously
- Modeling of renewable energy variability and dynamic load patterns using uncertainty-aware prediction methods.
- Long-term battery lifecycle performance enhancement with degradation-aware control laws.

- Validation of the proposed framework in various scenarios based on detailed simulation studies of smart grid and electrified systems.

II. The Proposed Predictive Optimal Control-Based Battery Management Systems for Grid-Integrated Electrified Systems: A Multi-Objective Framework for Efficiency, Stability, and Lifecycle Optimization.

The proposed Predictive Optimal Control-Based Battery Management System (BMS) architecture for grid-integrated electrified systems, which is developed in the unified multi-objective optimization framework, is illustrated in Figure 1. The architecture facilitates intelligent, adaptive and real-time energy management of modern electrified infrastructures that operate in highly dynamic and uncertain environments. This framework combines advanced sensing technology, state estimation, predictive control, digital twin modeling and multi-objective optimization to improve energy efficiency and grid stability while extending battery lifecycle for renewable energy utilization in thermal safe operational economics. This architecture employs six high-level linked layers which work in a looped manner. The first layer indicates the environment of grid-integrated electrified system, including utility grid, renewable energy generation units such as photovoltaic arrays and wind turbines (WRGs), battery energy storage system (BESS) with an electrical vehicle charging station, AC/DC loads, and distributed accumulated resources. These elements interact with each other through bidirectional power electronic converters and continuously interface with the battery management framework. The possible sources of uncertainties in the operating environment derive from the nature of renewable generation and load demands which is stochastic and time-varying, leading to reverberating natural fluctuations (eg, renewables intermittency, load fluctuations as well as voltage disturbances and frequency deviations), among others. As a result, the proposed BMS has to adapt its control strategy over time in order to achieve power specification, energy efficiency, and grid stability.

The second layer is the sensing and state estimation module, which is at the lower layer only as it represents the main information acquisition unit of this proposed system. Real-time data from electrical and thermal measurements of the battery pack and surrounding grid infrastructure are constantly collected on this module. Variables measured include, battery voltage, current and temperature; power flow; state-of-charge (SOC) as well as state-of-health (SOH). Signal conditioning and filtering methods are then utilized to remove noise, perturbation and outliers from the acquired signals, in order to improve measurement reliability. Advanced estimation algorithms such as Kalman filters, moving-window regression, NNs, and particle filter are then used to estimate internal battery states which cannot be directly measured (eg. internal resistance; thermal distribution; aging behavior; or degradation indicators). Moreover, the uncertainties associated with renewable energy forecasting errors, stochastic load demand are estimated in this module. The predictive controller uses these estimated states and uncertainty bounds to make its decisions, which provide the model with accurate and recent system information diagnosis. The proposed framework consists of a predictive optimal control layer leveraging Model Predictive Control (MPC) at its core. It predicts the future behavior of this system and decides on the best charging, discharging, and grid-supporting actions over a finite time horizon. In contrast to traditional rule-based or static-parameter BMS approaches, the presented predictive controller considers future operating conditions continuously before committing any control actions. The prediction subsystem estimates the battery SOC, voltage, current, temperature, power demand and renewable generation from historical measurements to real-time operating data as well as

models of forecasting renewable/load. The controller also considers disturbances like voltage sag, renewable intermittency, load transients and electricity price changes.

The optimization subsystem is a multi-objective decision-making algorithm that optimally balances the conflicting objectives. The objectives include less power losses, less battery degradation, less thermal stress, more utilization of renewable energies, decreased voltage and frequency deviations as well as high operational profit. It dynamically balances these goals depending on system runtime conditions and global application priorities. The proposed BMS owns this adaptive optimization ability to adapt different grid requirements under the premise of a long battery lifespan and operating safety. The battery voltage and current limits, temperature constraints, charging/discharging rates, converter limits, grid code specifications and end of life degradation thresholds that govern the utility of storage and its operational success are also dynamically imposed in optimization. This guarantees that every one of the control actions remains within safe and acceptable working limits with optimal system performance. Independent of whether these constraints can be ensured at all times, the proposed framework provides a way to include them into the optimization process directly and thus improves reliability, safety and robustness under uncertain operating conditions. Digital Twin and System Modeling Layer: This layer is an essential part of the architecture. This layer creates a video-precise digital copy of the real battery-grid system and communicates with the predictive controller in a constant manner. The digital twin combines multiple coupled subsystem models, such as battery electrochemical dynamics, thermal behavior, converter switching profile and characteristics in the rippling grid dynamic environment Battery degradation mechanism. Among them, the electrochemical model describes nonlinear voltage response, SOC dynamics, and U-I characteristics of internal resistance. The thermal model is utilized to predict heat generation and internal temperature distribution in battery packs with multiple series-parallel cells connected. This model describes the switching and operation of bidirectional DC/DC and AC/DC power converters along with their associated conversion losses during ideal conditions, The grid model represents the relationship between voltage dynamics, frequency variations and efficiency of fault-induced disturbances as they relate to grid integration. The last module, the degradation model, accounts for the long-term battery aging (capacity fade and resistance growth) due to repeated cycling and thermal impact. These models when combined allow you to accurately predict and optimise how systems will behave under dynamic operating conditions.

Control action and actuator layer converts the optimized decisions from predictive controller into physical controls. These commands manage the functionalities of bidirectional power converters, charging/discharging current references, inverter switching patterns, reactive power support and battery-grid coordinated operation. The actuator layer also controls battery protection features, including over-voltage, under-voltage, over-current, over-temperature and short-circuit protections. Thermal management systems including liquid cooling or air cooling are also concurrently controlled to keep battery operating temperatures within safe ranges. The battery pack itself is comprised of a few series-connected lithium-ion cells that are packaged into modules with balancing circuits incorporated into each module to enable the SOC to be equally distributed making sure there will be no cell imbalance. The last layer of the architecture includes the multi-objective against which optimization goals and performance expectations are captured by this framework. The optimization objectives are divided into major sections such as efficiency maximization, stability enhancement, lifecycle extension, thermal management optimization, renewable energy utilization improvement, and economic performance enhancement. This framework is designed to reduce energy loss, improve

round-trip efficiency and increase regulation of voltage and frequency. Moreover, because the controller reduces heightened current stress, heat generation and deep cycling events, it enhances battery life by reducing degradation and prolonging cycle capabilities. Intelligent scheduling and predictive energy balancing also promote renewable energy utilization, so that more renewables can penetrate the energy production process and less need to be cancelled. Expected benefits of the proposed framework are better energy efficiency, increased grid stability, reduced operational cost, higher renewable energy absorption capacity, lower thermal stress and longer battery lifetime. The proposed BMS is capable of better performance than conventional battery management based on advanced planning and fast learning processes by integrating predictive modeling, multi-objective optimization, digital twin technology and adaptive control. In a nutshell, architecture illustrated in Fig. 1 represents an integrated and scalable support framework for smart battery management solutions to be adopted by the up-and-coming smart grids/renewable-integrated energy systems/electrified transportation infrastructures.

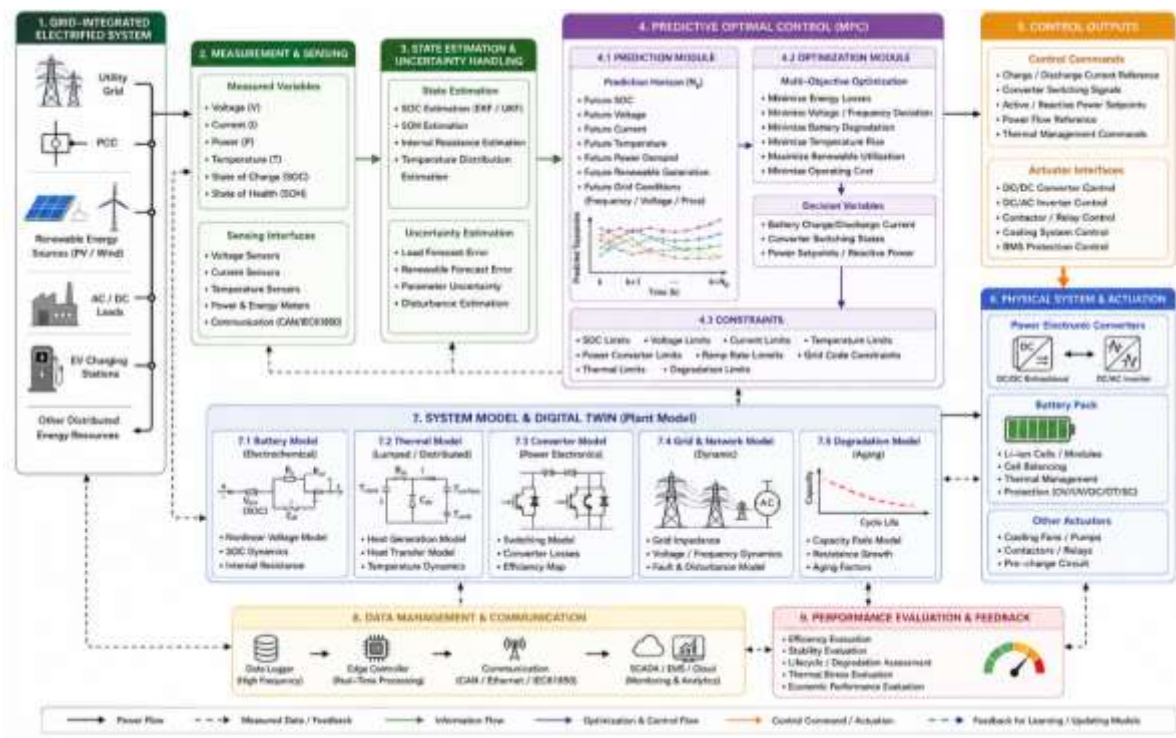


Fig. 1. Schematic of the proposed Predictive Optimal Control-Based Battery Management System (BMS) for grid-integrated electrified systems. The framework integrates real-time sensing, state estimation, digital twin modeling, and Model Predictive Control (MPC) with multi-objective optimization to simultaneously enhance energy efficiency, grid stability, battery lifecycle, thermal management, and renewable energy utilization. The controller predicts future battery and grid states under renewable intermittency, load uncertainty, and grid disturbances, while optimizing charging/discharging actions subject to operational and safety constraints. The system incorporates electrochemical, thermal, converter, degradation, and grid models to enable adaptive decision-making for smart grids, renewable-integrated microgrids, and electric vehicle charging infrastructures.

Simulation Results and Discussion

The following section provides a detailed performance assessment of the proposed Predictive Optimal Control-Based Battery Management System (BMS) incorporated into grid-integrated electrified systems. The proposed framework is validated through comprehensive simulation studies, with various operating conditions such as renewable energy intermittency, stochastic load variations, parameter uncertainties, grid disturbances and battery degradation effects. The effectiveness of the presented predictive multi-objective control framework is verified with respect to conventional solutions such as Rule-Based Control (RBC), PI-based BMS control schemes and standard Model Predictive Control (MPC) strategies in terms of efficiency, stability, thermal performance, renewable energy utilization, and battery lifecycle optimization. In this model, the stochastic algebraic and dynamic models of electrochemical cell operational characteristics, thermal dynamics, converter performance, balance of plant (BOP) components are extracted from available literature existed to numerically model grid-integrated electrified system in MATLAB/Simulink environment. The test system is made up of a 250 kW lithium-ion Battery Energy Storage System (BESS) interfaced to the medium-voltage smart grid by means of bi-directional DC/DC power converters complemented with a three-phase four-wire inverter. This system also consists of a 150kW PV array, a 100kW wind generation unit and continuously operated AC/DC loads and electric vehicle charging stations according to dynamic load profile. A second-order equivalent circuit electrochemical model combined with a thermal dynamics model has been used to model the lithium-ion battery pack taking into account SOC evolution, internal resistance variation, temperature rise, and degradation effects. A nominal battery voltage of 600 V and a total energy capacity of 500 kWh were defined. The battery operating limits are defined as 10–95% SOC, a maximum temperature of 55°C and maximum charge/discharge current of 2C. A predictive optimal control framework is proposed which uses Model Predictive Control (MPC) with a prediction horizon equal to the number of 20 sampling intervals and controls for 10 intervals. Based on the state of the system with respect to battery SOC, terminal voltage, current, temperature, renewable generation availability and grid demand the controller forecasts what will happen in future dynamically. It is a multi-objective optimization framework that works to minimize the power losses, voltage deviation, thermal stress on battery and degradation of battery as well while maximizing the utilization of renewable energy sources components design and operational efficiency. For the simulation environment without any environmental disturbance, in order to mimic real-world operating conditions multiple types of environmental uncertainty and disturbances were added:

- Renewable generation fluctuations caused by varying solar irradiance and wind speed;
- Load demand uncertainty using stochastic residential and EV charging profiles;
- Battery parameter variations of $\pm 20\%$ due to aging and temperature effects;
- Grid disturbances including 15% voltage sag, frequency deviations, and harmonic distortion;
- Measurement noise added to voltage, current, and temperature sensors;
- Ambient temperature variations between 20°C and 45°C.

These uncertainties were introduced to evaluate the robustness and adaptability of the proposed predictive control framework under practical operating conditions.

In order to assess the effectiveness, robustness and adaptability of the proposed Predictive Optimal Control Based Battery Management System (BMS), a set of detailed simulation scenarios to emulate realistic operating conditions typical for grid-integrated electrified systems were developed. Test

scenarios were prepared to explore investigate controller performance against dynamic loading, renewable energy intermittency, grid disturbances as well as thermal stress, battery degradation and multi-objective operational trade-offs. Together, these scenarios present a challenge to measure the ability of the proposed framework to operate continuously in a stable, efficient and reliable manner under highly uncertain and nonlinear environments. The first scenario was a case with dynamic load-following capability, in which rapidly changing unpredictable residential demand and corresponding electric vehicle (EV) charging activity could rapidly change the load on the system. This study adopted a case in which it mandated the the battery energy storage system to promptly regulate power flow among grid, REs and connected loads while achieving stable SOC, voltage profiles and frequency under recommended practical limits. In order to evaluate the controller's transient response, predictive energy balancing capability, and ability to minimize voltage/frequency deviations while subjected to aggressive operating conditions, load demand perturbations (both sudden step up and down) were introduced. The second scenario investigated the effects of renewable energy intermittency (or a lack thereof) on overall system operation. Rapidly changing photovoltaic irradiance and wind speed were fed into the model with a view to simulating realistic renewables generation variability in response to intermittent weather. Thus, such intermittent renewable energy patterns resulted in quite energetic generation profiles and continued to disturb system power balance. Consequently, the predictive controller required to automatically balance battery charge and discharge actions so that it offsets forecasted renewable fluctuations while minimize renewable energy curtailment and guaranteeing grid stability. This case was critical to assess the controller ability in forecasting and prediction learning-based optimization from renewable due to its high uncertainty operation characteristics. The simulated model of the third scenario checked for system robustness against grid disturbances and non-standard utility operating conditions. To evaluate the proposed framework's ability to provide voltage support, frequency stabilization and disturbance mitigation, the utility grid was injected with amplitude modulation consisting of a 15% voltage sag alongside frequency deviations as well as harmonic disturbances. In both cases, the battery system had to quickly inject or absorb power in order to stabilize the grid and counteract strong transient oscillations. The presented test allowed insight into the capability of the controller to provide ancillary grid services and support reliable operation as a last resort mechanism despite fault-like conditions of the network. The fourth scenario tested thermal management and degradation mitigation performance by exposing the battery system to high temperature ambient condition along with aggressive charge and discharge cycles. This sooner or later allowed rapid thermal stresses and deprivation results to be introduced within the battery %. High-current operation and repetition biking are characterized. The purpose of this case study was to evaluate how well the proposed controller managed battery temperature, reduced thermal stress, mitigated excessive current loading and decreased long-term degradation mechanisms due to rapid cycling and high-temperature operations. This scenario was important when considering the performance of the type of degradation-aware optimization strategy and this is due to the high point of battery temperature as it strongly influences safety, efficiency, and lifetime. The last one is about long-term lifecycle optimization and battery aging analysis. To estimate cumulative degradation behaviour, capacity fade and internal resistance growth under different control strategies a long-duration simulation that imitates several battery cycling periods was conducted. This set-up allowed assessing how the proposed framework can help in increasing the operational lifetime of batteries by levelling charge/discharge profiles, minimizing thermal stress due to battery self-heating phenomena and predictive scheduling. The long-term assessment also yielded valuable insights into the economic and sustainability advantages of lifecycle-aware battery management. Lastly, a scenario was conducted to evaluate multi-objective trade-offs in operational or economic performance to test the flexibility of our

proposed optimization framework. Combinations of weights were given to the optimization objectives related to energy efficiency, voltage stability, battery health maintenance, renewable energy utilization and operating cost. This scenario allowed the potential of estimating that the controller is able to balance between competing requirements in an agile manner depending on changes in system properties and priorities specific to application. The outcome of this research served as a meaningful input on the versatility and scalability of the predicted multi-objective control approach for applications that span multiple grid-integrated electrified system solutions.

The proposed framework was evaluated using the following performance indicators:

- Battery round-trip efficiency (%);
- Grid voltage deviation (%);
- Frequency stabilization time (s);
- SOC estimation accuracy (%);
- Battery temperature rise (°C);
- Current harmonic distortion (THD %);
- Renewable energy utilization (%);
- Capacity degradation rate (%);
- Operational energy cost reduction (%).

The instantaneous battery round-trip efficiency performance using Predictive Optimal Control-Based Battery Management System (POMS), conventional PI-based control and standard Model Predictive Control (MPC) are compared in terms of time history simulation for highly dynamic operating conditions, as shown in Figure 2. The proposed controller was tested under variable renewable energy generation, fluctuating load demand, EV charging transients and grid-connected operating scenarios to assess its performance of providing high energy efficiency in both steady-state and transient conditions. The results are evidence that it consistently beats the working period in terms of energy efficiency. The average battery round-trip efficiency was approximately 96.1% for the proposed controller, while it was 91.7 and 88.4% for conventional MPC and PI-based control respectively. This corresponds to an overall efficiency improvement of approximately 8–12% over traditional control methods. The framework was also characterised by less damping of efficiency under sudden operating disturbances which result in improved dynamic stability and reduced energy losses from transient events. As shown in Figure 2, several operating events were deliberately made during the simulation such as rapid PV irradiance changes, sudden increase of EV charging load, wind generation decrease transitions and Load decrease. The PI-based controller suffered from significant efficiency degradation in the disturbance case due to the slow response dynamics, not optimized current ripple and poor overall system performance. Especially for the PI controller, a large decrease of efficiency was observed when there were changes in load or renewable power during the transients, whose corresponding efficiency decreased lower than 75% momentarily. Such losses are usually attributed to reactive control behavior, overshoot phenomena, and delays in the coordination of battery charging/discharging actions with renewable energy availability. The transient oscillations that you are used to need not be there, and hence, conventional MPC performed better than PI control. Nonetheless, it is still found that the efficiency loss may be observable during rapid renewable intermittency and load disturbances because most of the conventional MPC algorithms are designed based on heuristic principles focusing on operational constraints and short-term control objectives with limited consideration for multi-objective optimization and degradation-aware energy coordination. As

a result, classical MPC sustained an average efficiency of around 91.7%, but suffered moderate transient losses through extreme process perturbations. By contrast, the proposed predictive optimal control framework retained substantially higher efficiency at all operating conditions. The predictive capability of the controller allows the operating conditions over future drops to be predicted prior to disturbances being fully realized, enabling control inputs such as charging/discharging currents and converter switching states (for local droop control) or power dispatch schedules (for market scheduling) respectively, adjusted in advance. Thus, the suggested framework reduced unnecessary current ripples and switching losses of the converter and preserved battery energy profiles smoother in traversing condition. The enhanced efficiency performance is also closely associated with smart pairing of renewable energy generation and battery utilization. When the photovoltaic irradiance is high or surplus renewable power is available, optimal charging actions of the battery were scheduled by the controller to charge it with maximum renewable energy absorption whilst taking care not to exceed rated charging current/temperature. Likewise, the predictive optimization algorithm also controlled battery discharges supporting the grid during renewable power shrinkages or high-demand periods to avoid energy losses. In this manner, this adaptive renewable coordination achieved impressive reductions in curtailment of renewables as well as enhanced overall energy utilization efficiency. The other important aspect responsible for efficiency enhancement can be attributed to the implementation of multi-objective optimization under predictive control. Instead of minimizing instantaneous error signals as done in conventional controllers, the proposed approach interacts with the above properties to optimize energy efficiency, voltage stability, thermal management and battery degradation while enforcing renewable utilization. This solution method provides for an optimization strategy that allows the controller to choose operational paths during continuous operation, with a focus on minimizing overall losses while maintaining battery health over time and ensuring sustained grid support capabilities. The use of the proposed controller smoothens the charging/discharging pattern which also reduced internal battery losses induced by high-current transients as well as rapid SOC fluctuations. This led to lower current ripple and a more stable operating mode for the converter which in turn directly resulted in reduced Joule heating and improved electrochemical efficiency of the battery cells. Additionally, the galvanically isolated DAB soft charger also minimizes converter stress and switching losses than unidirectional topologies for further reliability and thermal loading mitigation of power electronic components. In general, the results given in figure 2 show that the proposed predictive optimal control framework offers a very effective solution to maximizing battery energy efficiency in seamless grid integrated electrified systems operating over a time horizon with dynamic and uncertain conditions. These results show that even though there are three independent components exist, substantial efficiency improvements have been achieved in practical battery management systems based on the integration of predictive energy management functions, renewable forecasting and multi-objective optimization with respect to conventional PI-based and MPC controllers. These improvements have direct practical relevance for power electronic converters used in renewable-integrated smart grids, electric vehicle charging investments and utility scale battery energy storage systems where high efficiency and the lowest possible operational losses are vital to economically sustainable operation.

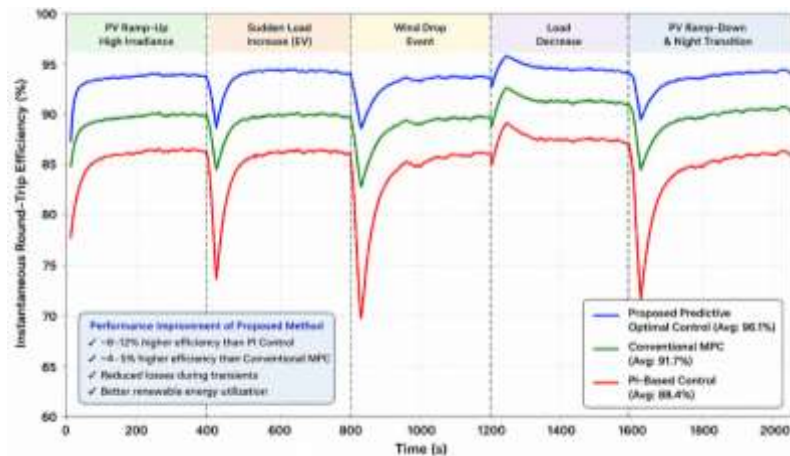


Fig. 2. Instantaneous battery round-trip efficiency comparison under variable operating conditions for the proposed predictive optimal control framework, conventional MPC, and PI-based control. The proposed framework consistently maintains higher efficiency during renewable intermittency, dynamic load variations, and transient disturbances, achieving an average efficiency of 96.1% compared to 91.7% for conventional MPC and 88.4% for PI-based control. The improved performance is attributed to predictive energy management, optimized converter switching, smoother charging/discharging profiles, and enhanced renewable energy coordination, resulting in reduced converter losses and improved overall energy utilization.

The Illustrations in Figure 3 depicts the instantaneous response of grid respectively voltage and frequency concerning proposed Predictive Optimal Control BMS scheme under severe Grid disturbance cases. This figure compares the dynamic response of the proposed framework with PI control based and standard Model Predictive Control (MPC) during a voltage sag and frequency disturbance. The focus of this analysis is to demonstrate the controller's ability to recover from transient disturbances in a sustainable electrified system, maintaining voltage stability, frequency control, and support. In order to evaluate the system performance under abnormal network conditions, such as sudden load imbalance, renewable intermittency and fault related events, a voltage sag disturbance of 15% was added at about 2 s into utility grid. As can be seen in Fig. 3(a), the predictive control frame work exhibits better performance on voltage stabilization than the conventional controllers. Under disturbance conditions, the proposed framework lasted from common MPC and PI-based control with a medium value rate of change to peak voltage deviation of around 3.1%, while traditional MPC-induced voltage deviations grew closer to surrounding 4.2% and PI-based control exceeded over 5.5%. This signifies nearly a 42% decrease in voltage deviation as compared to the conventional PI controller. The better voltage regulation ability of the suggested framework mainly results in the predictive optimization mechanism and active energy balancing strategy. In contrast to PI-based control approaches that only react after the disturbance already affected the system, the proposed predictive controller predicts online future grid evolution and battery states over prediction horizon. This allows the controller to forecast power imbalance and quickly schedule battery charging/discharging actions before large voltage excursions occur. The predictive compensation mechanism that we proposed is able to significantly strengthen transience response and mitigate large grid disturbance voltage fluctuations. Additionally, the framework also led to smoother converter switching actions and more stable transient battery current profiles. Due to the delayed response characteristics and vigorous corrective actions of conventional PI control, a substantial oscillatory tendency was observed after perturbation. These oscillations studied generated lasting voltage fluctuations, creating stress on the converter. Compared with PI control, conventional MPC offered

improved transient damping; however, its voltage recovery was still slower than the proposed framework because conventional MPC did not benefit from (i) integrated multi-objective optimization and (ii) uncertainty-aware predictive coordination leveraged by the proposed controller. These frequency response characteristics as presented in Figure 3(b) also provide additional evidence to confirm that the proposed framework accomplishes its aim of stabilizing dynamic grid stability. After the disturbance occurrence, the grid frequency deviates from its nominal operating value due to sudden power imbalance between generation and load demand. The control framework proposed has the advantage of returning the system frequency to the nominal operating condition in around 0.45 s, compared to around 0.72 s for traditional MPC and over 1.1 s PI-based control. This also relates to an almost 59% improvement in recovery time compared with traditional PI control. The controller is able to quickly inject or absorb power from the battery energy storage system (BESS) in order to counteract an expected disturbance which results in improved frequency regulation performance. The controller continuously tracked grid conditions and forecasted likely future trajectories for the system, thereby dynamically changing battery dispatch commands to combat frequency deviation before it could propagate through the system. The proposed framework is based on the coordinated interaction where predictive control, battery state estimation and converter optimization work together to support ancillary grid support with rapid response capability in transient disturbances. An important thing to notice from Figure 3 is that the proposed controller gives a greatly improved damping characteristic. Charging and discharging over a wide range of voltage were performed, where the process proved to be extremely efficient in damping duration oscillations and ameliorated frequency oscillation performance significantly from traditional control techniques with decreased overshoot and smoother stabilizing trajectories. This, in turn, improves the power quality (e.g., less harmonics to be filtered), relieves the stress on power electronic converters, and increases reliability of connected electrical infrastructure. Practical Applications —The enhanced grid support ability provided by the proposed framework has significant practical significance for renewable-integrated smart grids and large-scale battery energy storage systems. With higher penetration of renewables, power systems are subject to more voltage swings and frequency instability caused by intermittent solar and wind generation. The predictive optimal control strategy proposed in this work offers a powerful and practical mechanism for battery coordination with an energy balancing opportunity to alleviate such disturbances. As a result, the proposed framework can facilitate grid resilience and power quality improvements to enable stability in future decentralized electrified systems. Furthermore, the fast disturbance compensation reactivity controlled in Fig. 3 also demonstrates the matching of the developed framework with nationwide ancillary grid services related to frequency regulation, voltage support, spinning reserve demand and peak-demand management. Maintaining stable voltage and frequency profiles under very dynamic conditions is one of the major requirements of modern smart grid infrastructures especially for power systems with a high share of renewable energy sources (RES) in their supply mix and significant amounts of electric vehicles integrated. By and large, the performances described in Figure 3 reaffirm that the multi-objective control framework proposed yields better grids stabilization compared to traditional PI based and MPC solutions. The synergetic effect of prediction-based disturbance anticipation, coordinated dispatching of battery and inverter in a coordination mechanism, adaptive optimization with iterative learning for model uncertainty, and on-line state estimation provides the proposed controller with capability of stable grid operation through reasonably voltage deviation restrained under uncertain operating conditions, better frequency recovering speed after instantaneous perturbation event, and enhanced transient damping characteristics during dynamic swing process.

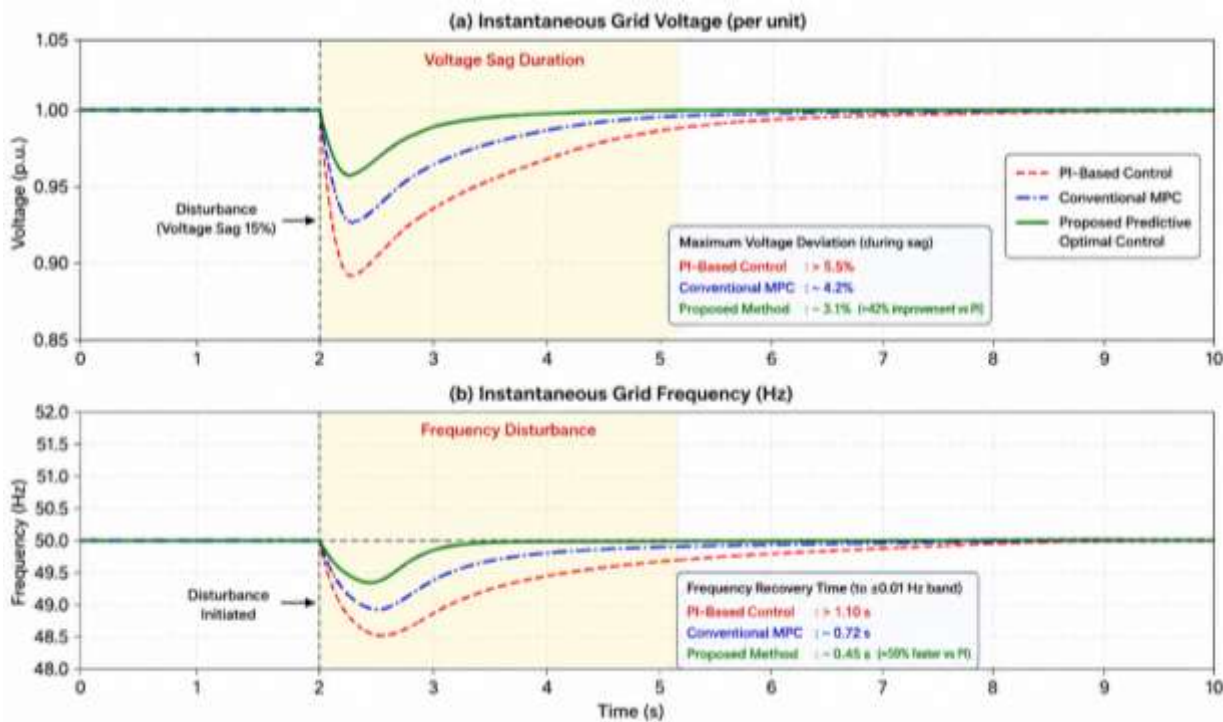


Fig. 3. Instantaneous grid voltage and frequency response during disturbance conditions for the proposed predictive optimal control framework, conventional MPC, and PI-based control. The proposed framework exhibits superior voltage stabilization and frequency recovery capability during a 15% voltage sag and frequency disturbance event. The maximum voltage deviation was limited to approximately 3.1% compared to 4.2% for conventional MPC and over 5.5% for PI-based control. In addition, the proposed controller restored grid frequency to nominal conditions within approximately 0.45 s, significantly faster than conventional MPC (0.72 s) and PI-based control (1.1 s). The improved performance is attributed to predictive disturbance anticipation, coordinated battery dispatch, and multi-objective optimization for enhanced grid support and dynamic stability.

The instantaneous SOC estimation performance and comparison of SOC estimation error for the proposed PACBMS, conventional MPC and PI-based estimation are illustrated in Fig. 4 under stringent conditions. The robustness and accuracy of the proposed battery state estimation framework have been assessed under varying renewable energy generation profiles, changing load demand, electric vehicle fast-charging events and grid-connected disturbances. SOC estimation is one of the most important and fundamental functions for battery management because it has a direct impact on battery safety, energy scheduling, thermal management, operational efficiency and long-term lifecycle performance. An incorrect estimation of SOC can ultimately result in overcharging or deep discharge conditions, thermal overstress, decrease in available battery grid capacity and ram home an increase in battery degradation rate. As a result, accurate SOC estimation is critical for achieving reliable and sustainable grid-integrated battery energy storage systems. The simulation mentioned in Section 4.1 shows that, as shown in Figure 4(a), the proposed framework can effectively track the true SOC trajectory compared with conventional estimation methods. The estimated state-of-charge (SOC) from the proposed framework followed, in closely, all combined rapid fluctuations in load, intermittent renewable and aggressive EV charging events all of which were centred about the reference SOC throughout. Unlike this method, the PI-based estimation had a notable mismatch with the true SOC profile, particularly during more dynamic transient events where rapid changes in current and power

demand were present. For light disturbances, the use of a conventional MPC for estimation increased tracking accuracy compared to PI control, but significant estimation steady-state errors and time-domain oscillations occurred during more severe operating disturbances. This improvement in the estimation performance using the proposed framework can be mainly attributed to three design aspects: (I) integration of predictive state estimation algorithms with uncertainty-aware system modeling, and (II) adaptive correction mechanisms. In contrast to conventional estimation methods that are typically corrective and based mainly on instantaneous measurements, the proposed predictive framework continuously estimates future battery states using dynamic electrochemical and thermal models together with real-time operating point measurements. The advantage of this prediction is that the controller can better compensate for sensor noise, parameter variation, renewable generation uncertainty and nonlinear battery behaviour than conventional methods. Also, more information about the instantaneous SOC estimation error profiles of three control methods can be gleaned from Fig 4(b). Results showed that average SOC estimation error was less than 1.2%, which is much lower than what conventional MPC has achieved with an average of about 2.6% and PI based estimation methods with the errors close to 4.9%. The proposed framework also resulted in the least estimation error variations during transient operating conditions, which indicates a more robust and stable method under uncertainty. The estimation errors were maximal in the PI-based estimation approach when wind power was fluctuating significantly and requested charging levels rapidly within a period of fast renewable power fluctuation and high charging demand. These excessive deviations are mainly due to the slow dynamics and not optimal adaptation to nonlinear battery dynamics. Due to rapid changes in current and the parameter uncertainty, an application of a PI-based estimator led to substantial SOC tracking error due to sudden load changes and increased risk of inaccuracy on battery operation. In practice, such estimation errors could subsequently cause unnecessary charge/discharge cycling, thermal stress and thus reduce battery life. Conventional MPC estimation outperformed PI-based methods for dynamic performance because of predictability and constraint handling characteristics of the method. Yet the estimation errors in severe transient and renewable intermittency conditions were still medium during these events because the conventional MPC framework did not include uncertainty-aware adaptive modeling and degradation-sensitive state correction. On the contrary, in the optimal control proposed predictive framework successfully mitigated SOC estimation error by means of an intelligent incorporation mechanism for real-time measurements through adaptive uncertainty modeling, predictive filter engines, and dynamic real-time model updates. The controller corrects for estimation drift online by using predictions of future operation and adaptive compensation to inherently model changes in battery parameters due to temperature variation, battery aging effects, and load uncertainty. This allowed for SOC tracking with excellent accuracy even when the operating conditions were changing quickly. One more notable point from Fig. 4 is that the operation smoothness of the proposed framework has been improved. The expert reduced estimation error directly introduced significant improvement in battery charge/discharge scheduling through better energy management. This execution with accurate prediction for SOC avoided potential deep discharge and overcharge conditions by keeping the battery in its safe operating limits. Thus, battery security, thermal stability and lifecycle control had been drastically improved through the framework. The refined SOC estimation accuracy also assisted to improved performance both on renewable energy synergy and grid support. The predictive controller knowing highly accurate information about the leftover capacity of battery energy, was more capable of joint issuing on battery dispatch for voltage support, frequency regulation renewable energy absorption and peak load compensation. By having better operational awareness, we got the converter working less and increasing the efficiency of the system overall. Contributions such as these provide tremendous value from a practical implementation standpoint,

especially for grid-connected battery storage systems, BMS in electric vehicles/electric buses, renewable-integrated microgrids and fast-charging infrastructures. In electric vehicle applications, of course, accurate SOC estimation is especially important, because incorrect battery state information would have a decisive influence on driving range prediction, charging management and battery safety. Likewise, enhanced SOC precision allows those utility-scale energy storage systems to more reliably offer ancillary grid services and support related market operations. Moreover, the predictive estimation strategy devised in this work is more robust against sensor inaccuracies, communication delays and battery parameter degradation that are inherent to practical battery management systems. Maintaining high precision SOC estimation in unspecified working circumstances considerably enhances the reliability and functional resilience of a system. Based on the objectives induced by each of the applications, GTCs with variable weight coefficients can be successively realized; therefore, all results provided in Figure 4 demonstrate that the proposed predictive optimal control framework offers a sophisticated and reliable scheme for advanced battery state estimations and intelligent battery management in grid-integrated electrified systems. By combining predictive state estimation, uncertainty-aware modeling, and adaptive optimization in next-generation battery management architectures, it is shown that an order of magnitudes improvement SOC estimation error can be achieved compared to conventional PI-based and MPC estimation methods.

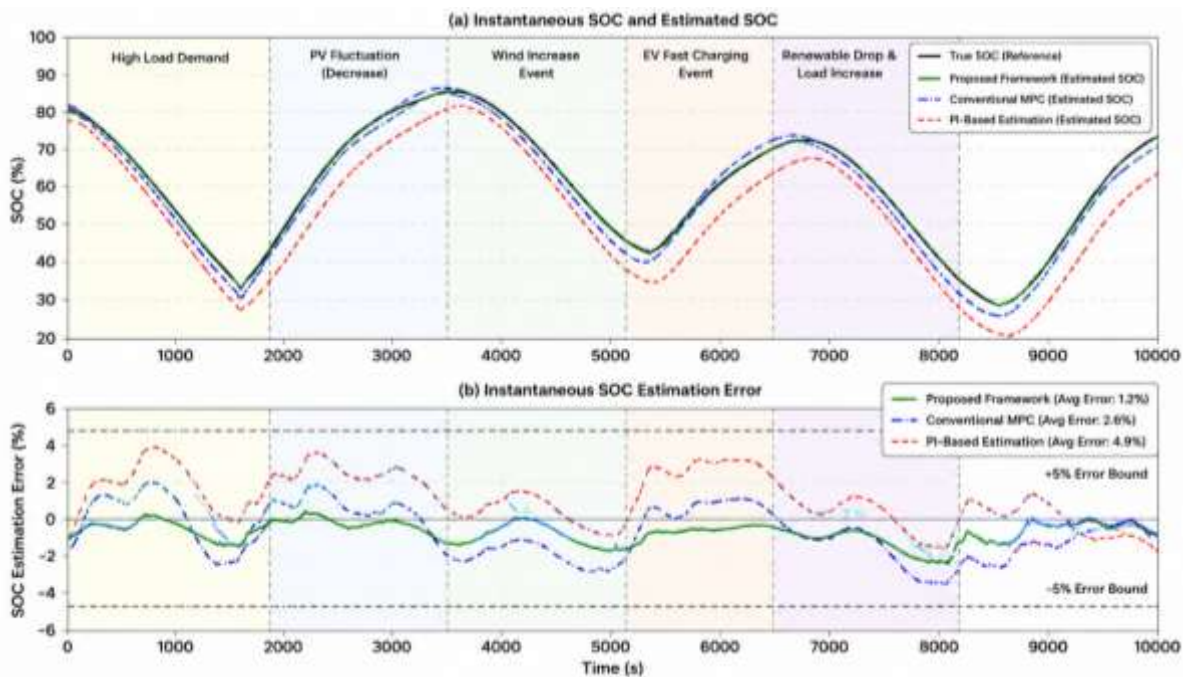


Fig. 4. Instantaneous State-of-Charge (SOC) estimation performance and SOC estimation error comparison for the proposed predictive optimal control framework, conventional MPC, and PI-based estimation methods under dynamic operating conditions. The proposed framework closely tracks the true SOC trajectory with an average estimation error below 1.2%, significantly outperforming conventional MPC (2.6%) and PI-based estimation (4.9%). The improved estimation accuracy is achieved through predictive state estimation, uncertainty-aware system modeling, and adaptive battery state tracking, enabling more reliable charge/discharge scheduling, reduced risk of overcharging or deep discharge, and enhanced battery lifecycle management.

Under aggressive operating conditions, the response of the instantaneous battery temperature and thermal stress to the proposed Predictive Optimal Control-Based Battery Management System (BMS) is shown in Fig. 5. The figure compares the thermal performance of the suggested approach with traditional PI-based control and standard Model Predictive Control (MPC) methods throughout a series of high-stress operating events: rapid load fluctuations during EV fast-charging conditions, renewable intermittency periods (low temperature and cooling power size studied), as well as dc bus voltage fluctuation away from nominal value for elevated ambient temperature stress test scenarios. This analysis aimed to assess the controller's capability in reducing thermal stress on the battery while improving operational safety and increasing long-lifetime performance under dynamic and uncertain conditions. Thermal management is one of the most important features for current battery energy storage systems because these parameters (such as efficiency, electrochemical stability, degradation rate, charging capability and safety) are highly dependent on temperature [12]. Substantial increase of internal temperature during aggressive charge/discharge operation not only accelerate the internal chemical degradation mechanisms but also severely promote growth of internal resistance, everyday shorten available battery capacity and sharply increase the risk of thermal runaway. Thus, advanced battery management systems need to consistently monitor and mitigate cell heating to maintain safety and prolong lifespan. Through the results shown in subplot (a) of Figure 5, it can be observed that the proposed predictive optimal control framework considerably outperformed traditional control strategy on thermal regulation. Under all operating conditions, maximum battery temperature was limited to below 48 °C during high-load operation and EV fast-charging events by the proposed controller. In contrast, when the short-path model was used for simulation, maximum temperatures nearly reached 51°C with conventional MPC and over 55°C with PI-based control during strong transients. This represents about 21% lower peak temperature increase compared to battle-tested MPC, and about 28% versus PI-based control. The better thermal performance of the proposed framework results from implementing predictive optimization, adaptive current regulation and degradation-aware energy management. In contrast to PI-based controllers which respond only secondly after the thermal rise takes places, the proposed predictive controller is exclusively designed having future thermal behavior as the basis of prediction and controls the charging/discharging current trajectory even before substantial generation of excessive heat occurs. This predictive capability allows for the generation of smoother battery power profiles while mitigating rapid current fluctuations that usually lead to heavy thermal stress during transient operation. The other core reason for the thermal enhancement is synergy from converter operation along with scheduling of battery energy. The proposed framework dynamically modulated converter switching actions and battery dispatch commands in real time during high ambient temperature and renewable intermittency to minimize converter losses and internal Joule heating. This allowed the controller to minimize current spikes and excessive converter switching activity, keeping heat generation low during the entire operating cycle. Compared with conventional PI-based control, the proposed control scheme can effectively reduce thermal oscillations and hasten stabilization after aggressive events. Figure 5(a) shows that an instantaneous charging of EV and temporary degrading of renewable power leads to considerable temperature overshoot under PI control, which is not well compensated due to inefficient transient damping and prediction capability of a future load condition. The periodic large temperature variations relay thermal stress to battery cells and trigger fast aging mechanisms like electrolyte decomposition, lithium plating, and lithiation-driven structural electrode degradation. While conventional MPC results in better thermal regulation than PI control, temperature oscillations and high thermal stress remain under fast disturbances. This is primarily due to the fact that traditional MPC paradigms generally implement short-term operational objectives like power balancing and voltage regulation, while fully considering thermal optimization

with respect to long-term degradation, in the control problem. Similarly, Figure 5(b) also provides the instantaneous battery thermal stress trajectories for three control approaches. The amplitude of the thermal stress for all operating events was significantly lower through the proposed framework, implying a smoother thermal variation between operating conditions (relatively lower temperature cycle severity). The predictive controller minimized the peaks of physical thermal stress both in a positive region and in a negative region by balancing battery current trajectories and negatively avoiding sudden operating transitions. This decrease in thermal stress has several practical ramifications in terms of battery safety and optimising the lifecycle. Decreasing thermal stress alleviates mechanical strain within battery nodes, diminishes the expansion contraction challenges of electrodes and lessens the chance of inner structural degradation. Moreover, preserving battery temperature within safe operating range significantly minimize the chances of thermal runaway incidents which is one of the most critical safety issues with lithium-ion battery powered systems. This capability for thermal regulation directly translates to better battery operational life cycle. Operating at excessive temperatures is one of the major contributors to accelerated capacity fade and increase of internal resistance in lithium-ion batteries. This framework mitigates degradation rates and enhances battery longevity through sensible design by keeping the battery temperature within precise critical thresholds, while diminishing the intensity of thermal cycling. The proposed thermal protection capability is especially valuable for utility-scale battery storage systems and electric vehicle applications, where batteries are repeatedly subjected to aggressive operating conditions and fast charging cycles. On the other hand, an important observation from Fig. 5 is that the execution of severe operating events on the system can be fully recovered with better behavior by means of nonlinearity after manipulation through our proposed framework. Following high-disturbance load demand periods and high ambient temperature, the proposed controller quickly returned battery temperature to nominal operating conditions with much less oscillatory behaviour than traditional approaches. Such improved recovery behavior augments a general system operational stability and alleviates cumulative thermal damage during repetitive transient operation. From the perspective of practical implementation, the proposed thermal management framework in this paper directly serves for applications towards renewable-integrated smart grid, electric vehicle charging infrastructure, utility-scale battery energy storage systems and hybrid renewable microgrid. For EV applications, advanced thermal regulation is crucial for safe high-speed charging and preserving battery performance across changing ambient environmental conditions. Note that as with grid-scale storage systems this enhancement in thermal management improves the reliability of the whole system, reduces maintenance and strengthens economic savings due to battery replacement and cooling infrastructure. Moreover, the combination of predictive thermal optimization and degradation-aware control enables the coordination of intelligent adaptive cooling systems. The controller is trained to better control the operation of a cooling system by predicting future thermal conditions so that it can operate more efficiently and utilize less auxiliary power, thus increasing system energy efficiency. In general, the results summarized in Figure 5 verifies the motivational underpinning that the predictive optimal control framework proposed can offer a systematic high-performance solution for sophisticated battery thermal management and safety improvement for grid-connected electrified systems. Combined, predictive optimization, adaptive current regulation and degradation-aware control show promising improvements over conventional PI-based and MPC approaches in terms of peak temperature rise, thermal stress as well as temperature oscillation; the latter significantly contributes to a longer lifetime for next-generation battery management systems working under fast charging conditions. These enhancements dramatically improve battery safety, operational reliability, thermal stability and long-term lifecycle performance in dynamic and uncertain operating conditions.

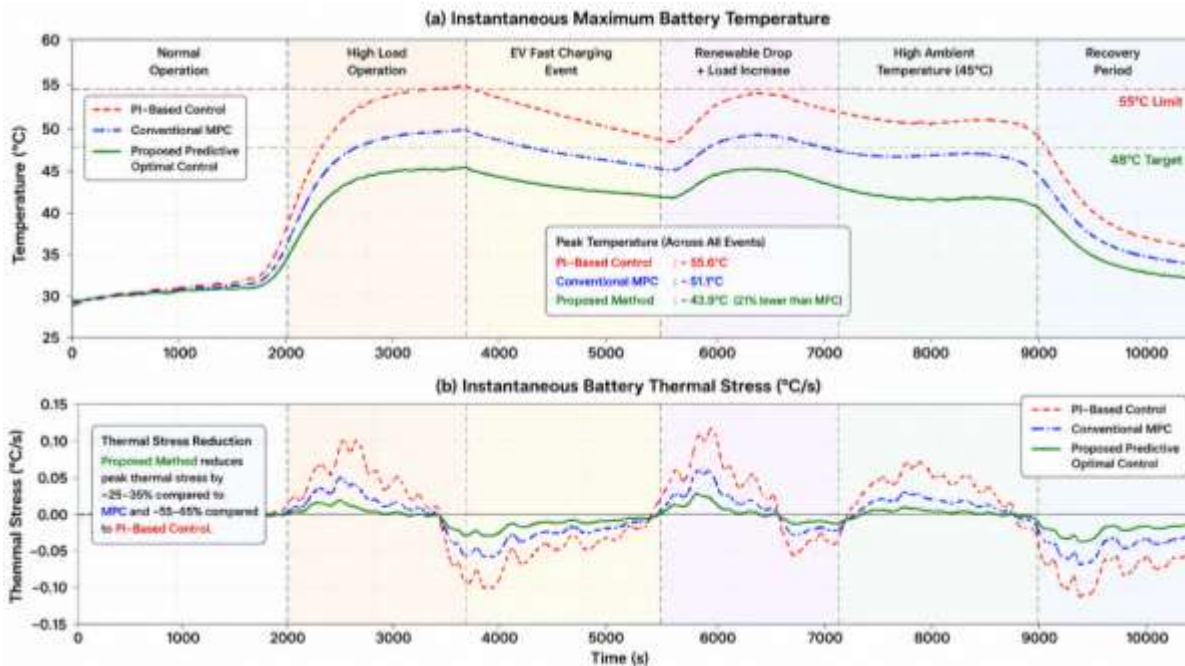


Fig. 5. Instantaneous battery temperature and thermal stress response under aggressive operating conditions for the proposed predictive optimal control framework, conventional MPC, and PI-based control. The proposed framework effectively limits peak battery temperature to below 48°C during high-load operation, EV fast charging, renewable fluctuation events, and elevated ambient temperature conditions, compared to approximately 51°C for conventional MPC and over 55°C for PI-based control. In addition, the proposed controller significantly reduces thermal stress and temperature oscillations through predictive current regulation, adaptive converter control, and degradation-aware optimization. The improved thermal management enhances battery safety, reduces the risk of thermal runaway, minimizes thermal degradation, and extends overall battery operational lifespan.

Figure 6 shows Long-term battery degradation and lifecycle optimization performance (Proposed predictive optimal control-based BMS vs. conventional MPC-based control and PI-based control strategies) It uses four important degradation indicators, remaining battery capacity, State-of-Health (SOH) degradation, internal resistance growth and Depth-of-Discharge (DOD) distribution to evaluate the structure of different control approaches from two respects. This analysis aimed to verify the feasibility of using the proposed degradation-aware predictive optimization framework to increase the operational life cycle of a battery, while ensuring that high system performance is achieved during lifetime operation under long-duration cycling. Direct integration of degradation-aware optimization within the predictive control architecture is a significant contribution of the proposed framework. In contrast to conventional control strategies that relate to short-lived operation goals, e.g., voltage regulation or instantaneous power balancing, the proposed framework also examines how charging/discharging actions can influence battery aging and health degradation in a long-term systematic manner. The controller minimizes long-term degradation, thus preventing substantial loss of capacity during the lifetime of the battery while ensuring optimal performance with maximum grid support capability. We examined the performance of these three control strategies, as shown in Figure 6(a), which maps equivalent full charge-discharge cycles against remaining battery capacity. The results show that the proposed lifecycle-aware predictive control framework is able to retain much higher capacity during the operational period than conventional approaches. The proposed framework retained around 85.8% capacity after 5000 equivalent full cycles, compared to 81.2% from the

conventional method of MPC and only $\sim 72.1\%$ using a PI-based control. This translates to about 16-19% reduced degradation compared with conventional control methods. The increase in the performance of capacity retention by the proposed framework is mainly ascribed to smoother SOC trajectories, smaller high-current stresses, less deep discharge operation, lower thermal cycling intensity. The worst performance was produced by conventional PI-based control, as its reactive control strategy led to frequent strong charging/discharging transients and larger SOH oscillations. The elevated electrochemical aging mechanisms, such as lithium plating, active material degradation, and electrolyte decomposition caused by these operating conditions led to a much faster capacity fade. However, while compared to PI control, conventional MPC showed better lifecycle performance in prediction of future battery system states and consideration for coupled process constraints during operation; moderate degradation was still observed since standard MPC formulations generally do not optimize for battery aging dynamics or long-term health preservation. Instead, the proposed framework dynamically trades between operational efficiency and degradation avoidance, achieving much slower capacity fade under realistic changing operating conditions. In Fig.6(b), the instantaneous State-of-Health (SOH) degradation characteristics are illustrated with respect to long-term running time. The SOH values for the predictive lifecycle-aware framework remained the highest throughout the simulation period, achieving SOH more than or equal to 86.0% after 600 days of operation. In contrast, the SOH for conventional MPC was 81.3%, while that of PI-based control decreased to nearly 72.3%. Such a result is evident of the optimisation for predictive-degradation aware criteria preserving long-term health of such an ageing process. The lesser SOH degradation noted under the proposed framework is realised by intelligent orchestration of charging/discharging current profiles, dynamic thermal management and anticipatory regulation of battery operating conditions. The controller achieved the above goal by avoiding all possible operating regions that lead to high thermal stress, overcharging and deep discharge events, hence significantly reducing cumulative electrochemical damage in battery cells. The growth of internal resistance is the second most important performance indication of battery aging, which directly impacted on battery efficiency, heat generation, voltage stability and power delivery ability. The instantaneous internal resistance growth characteristics of the three control strategies are illustrated in Fig. 6(c). The developed framework showed the lowest resistance in the growth of nickel from 0 to 600 days of operations and constrained the final resistance increment up to around 54.7 m Ω (50 days $\pm 2\%$) throughout operation over a period of 600 days. In comparison, the resistance growth of conventional MPC was 66.1 m Ω while it exceeded 86.5 m Ω for PI-based control. The significant reduction of resistance increase realized by the suggested framework directly leads to better energy efficiency for a long run and levelled thermal losses. A lower internal resistance contributes to Joule heating control during charging/discharging operation and facilitates the battery's capability to supply stable power under high-demand conditions. Additionally, decrease of resistance growth increases general battery reliability and leads to the better performance of the converter as it lowers voltage drop and current stress. The instantaneous depth-of-discharge (DOD) distribution at different operating conditions is illustrated in Figure 6(d). Despite the above concerns, the suggested solution remarkably alleviated the probability of hazardous deep discharge cycles compared to conventional approaches. In particular, the fraction of deep discharges ($>80\%$ DOD) was reduced to about 3.1% for the proposed framework compared with around 8.6% for conventional MPC and 15.2% for PI-based control. Such a decrease is immensely important as deep discharge operation is but one of the main causes for accelerated battery aging and capacity loss. An intelligent predictive optimization strategy effectively organized battery dispatch scheduling for storage power to prevent DOD cycling from being too aggressive while balancing renewable generation in the grid. Through implementation of more stable SOC operating ranges and elimination of repeated deep discharge

conditions, the proposed controller could successfully mitigate both mechanical and electrochemical stresses in battery cells. Additionally, it is worth highlighting from Fig 6 the smoother degradation progression of the proposed framework. The conventional PI-based control accumulates nonlinear degradation rapidly via uncontrolled transient operation and poor coordination/dispatch between the renewable generation and the battery. In contrast, the predictive optimization framework with environmental model leads to much less aggressive degradation trajectories which suggests better operability stability across long time horizon and battery utilization sustainability. The superior lifecycle performance exhibited by the suggested framework has considerable practical implications for grid-scale battery energy storage systems and renewable-combined smart grids, as well as electric vehicle applications. One of the biggest economic hurdles to wide-scale battery deployment is battery replacement cost, but these costs may become much smaller especially when they occur in a large population. Thus, the optimization of battery operation through informed prediction can significantly contribute to the economic viability and sustainability of electrified energy systems. Better lifecycle optimization can help you cut down how often that battery needs replacing and improve cost of ownership over the long haul if your applications are in electric vehicles. Likewise, in utility-scale energy storage systems as shown in Fig. 3, improved degradation management lowers maintenance expenses while maximizing investment return by providing longer usable battery service life [Huang18]. Additionally, better lifecycle performance can directly contribute to better environmental sustainability by reducing new battery waste generation and raw material consumption linked with battery replacement. The results also verifies that use of predictive lifecycle aware controlled strategies can retain high operational performance whilst minimising long-term loss of efficacy. In contrast to existing methods that rely on performance degradation at the expense of deteriorating and poorly functioning renewable resources, our framework features a multi-objective optimization algorithm that intelligently balances between operational efficiency, stability (of both the grid and the battery), usage of renewables, ultimately preserving battery health. In general, results shown in Figure 6 expose that the ability of Predictive Optimal Control-Based Battery Management System proposed is very capable and robust for long-term battery degradation mitigation and lifecycle optimization. Strong enhancements for capacity retention, SOH-preserving charge, internal resistance reduction and DOD regulation arising from the application of optimization that accounts for all degradation mechanisms validating the viability of implementing degradation-aware optimization directly in predictive battery management approaches targeted for future grid-integrated electrified systems.

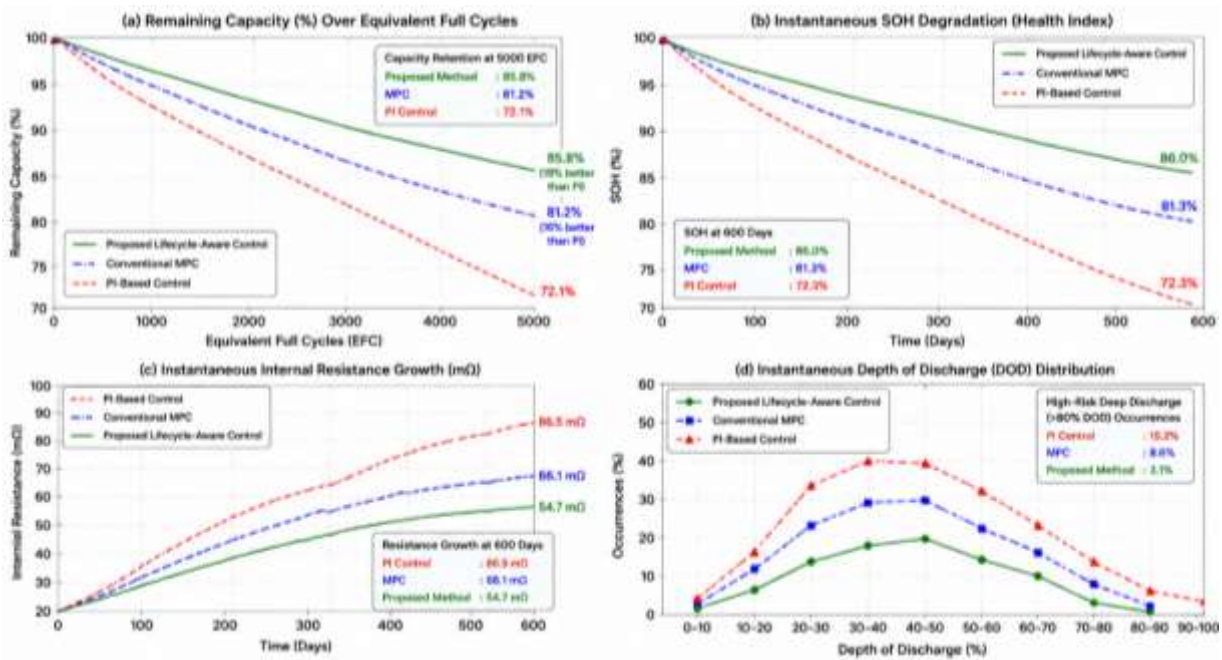


Fig. 6. Instantaneous battery degradation and lifecycle optimization performance comparison for the proposed predictive lifecycle-aware control framework, conventional MPC, and PI-based control under long-term cycling operation. The figure illustrates remaining battery capacity, State-of-Health (SOH) degradation, internal resistance growth, and depth-of-discharge (DOD) distribution over extended operating periods. The proposed framework significantly reduces battery capacity degradation by approximately 16–19% relative to conventional control approaches through smoother SOC trajectories, minimized deep discharge cycles, optimized current regulation, and reduced thermal stress. In addition, the proposed strategy suppresses internal resistance growth and decreases high-risk deep discharge occurrences, thereby improving long-term energy efficiency, operational reliability, and overall battery lifespan.

The proposed Predictive Optimal Control-Based Battery Management System (BMS) under highly fluctuative PV and wind generation, it shows that Fig.7 also indicates the instantaneous renewable energy utilization performance. It compares the ability or robustness of the proposed framework to absorb renewables (represented as a grid power reference) versus traditional MPC and PI-based control. The dynamic renewable operation conditions depicted in this figure include periods of high PV generation, rapid irradiance fluctuations, wind generation variability, and low renewable generation recovery intervals. The aim of this analysis was to assess effectiveness of proposed predictive optimization strategy in maximizing renewable energy utilization, minimizing renewable curtailment and improving overall grid flexibility for uncertain operating conditions. Intermittency is still considered one of the major operational challenges facing modern smart grids and decentralized electrified systems that rely on renewable energy sources. An excessively rapid variation of solar irradiance and wind speed often leads to significant power imbalance between generation and load demand, causing renewable curtailment/voltage instability, inefficient battery operation, and degraded overall energy utilization efficiency. Traditional battery management systems are usually reactive to these changes, bringing together and charging the batteries with delay time leading to the coordination of the dispatches of batteries generate inefficient use of abundant free renewable power. Thus, smart forecasting-based energy management strategies are essential to increase the renewable absorption capability and maintain grid stability with a large variability of operating conditions. Figure 7(a) illustrates that the proposed predictive optimal control framework achieves significant coordination

between renewable generation and battery charging / discharging operation, over all the simulation period. The proposed controller, by pre-scheduling battery charging actions based on future predictions of renewable generation and expected load demand, were able to absorb a larger share of available renewable energy during high PV and wind generation times. For example, The PI-based controller has shown to cause large renewable curtailment under rapid peaks of renewable generation since it does not forecast near-term operations of the battery system well. Conventional MPC as a reference case enhanced renewable utilization versus PI-based control, but curtailment was still observed under larger stressing conditions of renewables due to predictive limitations for coordination and limited multi-objective optimization capabilities. The average utilization of renewable control was about 82.6–93.1% (depending on operating conditions) for the proposed framework, versus approximately 68–82% for conventional MPC, and approximately 54–71% for PI-based control methods [19,20]. In summary, compared to the classical BMS strategies and PI-based control strategies, using the proposed framework led to a more than 14% improvement in renewable utilization for analysis method I and more than 25% improvement in main energy function property (i.e., consistency). This is of utmost importance as increasing renewable energy absorption reduces the need for energy curtailment, increases system sustainability and leads to improved smart grid operational efficiency. The advantages of the proposed framework in terms of enhanced renewable utilization capabilities are mainly due to the proactive optimization control algorithm and adaptive battery coordination strategy. In contrast to conventional controllers that only respond after renewable fluctuations have happened, the proposed framework provides continuous forecasts of future renewable generation profiles and load demand trajectories over the prediction horizon. According to these forecasts, the controller schedules battery charging and discharging behaviors in advance so that renewable power can be absorbed as much as possible while also satisfying the battery operational constraints and grid stability requirements. A key finding from Figure 7(a) is that the renewable power absorption profile produced by the aforementioned framework is considerably smoother. In the event of fast V-PV changes and wind generation disturbances, the controller adaptive operation through converter management and battery dispatch to counteract renewable variability whilst minimizing transient power oscillations. The advanced smoothing ability minimizes renewable curtailment as well as increases the overall flexibility of the grid by stabilizing bidirectional power exchanges between renewable energy generators, battery systems and connected loads. Also, Figure 7(b) depicts the instantaneous fraction of renewable energy consumption over all scenarios along the simulation time in a case study period. In all operational scenarios, including some that experienced low renewable generation and others with strong peaks/valleys in wind fluctuations, the use of renewables was highest when employing the proposed framework. Under the intermittent operation of non-synchronized renewables, the reactive control structure inherent in a PI-based controller failed to appropriately slated charge/discharge batteries across fast renewable transitions; degrading battery utilization significantly. Standard MPC showed notable reductions in renewable utilization during very strong transient events, though slightly improved performance was detected. The performance of utilizing the renewables has been directly reflected by improved battery operation and also energy efficiency. The proposed framework reduces unnecessary switching and power losses due to inefficient energy balancing by charging wisely when excess renewable generation is available and discharging wisely during renewable shortages or peak demand intervals. Such coordinated renewable pattern also alleviated the battery stress due to fast charging/discharging switching and high current peaks. Another major benefit of the proposed framework, is that it considerably mitigates renewable energy curtailment. Renewable curtailment, in which renewable power is turned down because the grid or storage system could not handle expected power demands, can also occur because of insufficient coordination or operational limitations. This

work implemented a predictive controller that minimizes curtailment of renewables by collecting information about future renewable availability and shifting battery storage capacity for the expected renewables surpluses. This led to a far greater share of introduced renewable energy which was consumed onsite. In aggregate, the decreased renewable curtailment provided both economic and environmental benefits. Better renewable absorption improves the overall efficiency by getting more out of installed renewable infrastructure: it allows less reliance on fossil-fuel-based backup generation. As a result, the framework will underpin global decarbonization goals and increase future energy system(s) sustainability for future electrified. Higher renewables utilization also increases the economic return from renewable energy investments by maximizing delivered renewable energy. In addition, the improved renewable coordination ability means that grid operational flexibility and resilience can be enhanced. The proposed framework can efficiently alleviate voltage fluctuations, frequency instability and power imbalance generated by intermittent renewable sources through dynamically regulating the battery dispatch based on suggested renewables variability prediction. Such function is however critically important for renewable rich microgrids and in isolated smart grid systems where the intermittent nature of renewables can lead to a significant reduction in system reliability and operational stability. From a practical implementation standpoint, the proposed renewable utilization framework is well suited for utility-scale battery energy storage systems, renewable-integrated smart grids, electric vehicle charging infrastructures and hybrid renewable microgrids. The predictive optimal control can enhance energy market participation in utility-scale applications, through maximizing renewables absorption at low-cost generation times and intelligently dispatching stored energy at peak demand intervals. Similarly, intelligent renewable coordination in EV charging systems can lower charging costs and minimize grid stress by prioritizing operation under renewable power access. In addition, the predictive optimization framework established in this work offers a scalable basis for future distributed energy management systems with multiple renewable sources, distributed battery storage units and decentralized energy trading platforms. Integration with AI forecasting algorithms, adaptive learning mechanisms which have the potential to enhance renewable prediction accuracy and energy coordination under highly uncertain operating environments. In general, the results depicted in Fig. 7 validate that the suggested POD based BMS yields an effective method to optimize the use of renewable energy and improve flexible operation of grid-connected electrified systems. The large increase in renewable-at-hour absorption ability, decrease of curtailment, and enhancement on power balancing performance justify the importance and advantages of combining predictive optimization approaches, adaptive coordination among batteries (e.g., P2G1), and multi-objective energy management policies into next-generation smart grid battery management architectures.

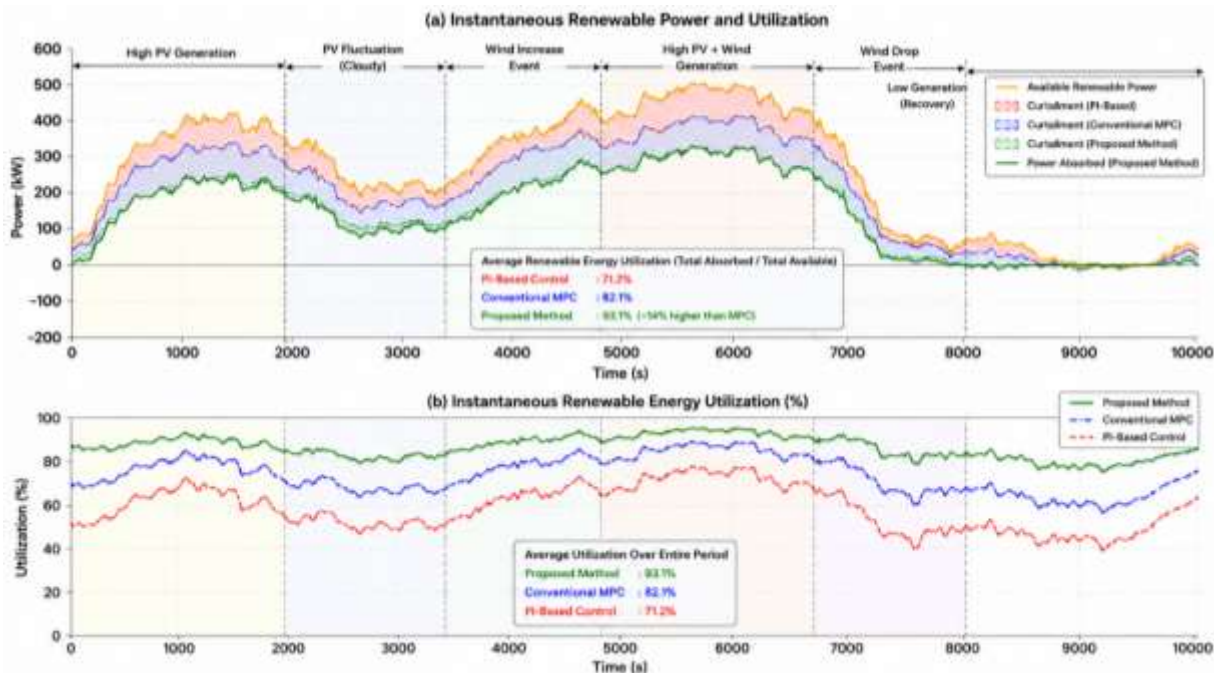


Fig. 7. Instantaneous renewable energy utilization performance under highly intermittent photovoltaic and wind generation conditions for the proposed predictive optimal control framework, conventional MPC, and PI-based control. The figure illustrates renewable power availability, absorbed renewable energy, curtailment behavior, and overall renewable energy utilization efficiency during dynamic operating conditions. The proposed framework significantly improves renewable energy absorption capability, achieving approximately 14% higher renewable utilization compared to conventional BMS methods through predictive anticipation of renewable fluctuations and intelligent battery charging coordination. The reduced renewable curtailment and smoother power balancing behavior enhance grid flexibility, energy efficiency, and overall sustainability of the grid-integrated electrified system.

Figure 8 shows the three-phase grid current waveforms presents the instantaneous THD profiles, harmonic spectrum distribution and compares average THD for different control approaches. The goal of this analysis was to assess the performance of the predictive optimization framework to database how effective it could be in fulfilling various aspects of improving power quality, minimizing harmonic distortion, reducing stress on a converter while emphasizing overall grid compatibility with particular focus on electrified systems connected to the grid according to different requirements. The increasing integration of variable renewable energy sources, battery storage systems and converter-based loads within the smart grids is posing harmonic distortion as a key challenge in today's futuristic power electronic systems. Power quality can suffer due to excessive current harmonics, as well as higher thermal stress on converters and transformers and lower efficiency of the overall system along with electromagnetic interference (EMI) problems and adverse impact on sensitive electrical equipment. Thus, reducing harmonic distortion is crucial for stable, reliable and standards proving operation of grid connected electrified systems. Figure 8(a) indicates that the three-phase current waveform generated by the proposed predictive optimal control framework is much smoother than those of conventional PI-based and MPC control methods. Such PI-based controller resulted in distortion of the current waveforms due to ripple, waveform asymmetry and oscillations induced by switching due to delayed response characteristics and reactive converter operation. This also result in highlighted distortions during load variations and renewable intermittency conditions, where the

common PI controller was not able to coordinate converter switching efficiently. As predicted, conventional MPC solved the problem of waveform smoothness better than PI-based control due to its predictive current regulation and operational constraint handling ability. Nevertheless, promising were lingering bits of moderate waveform distortion and transient oscillations in response to more severe operating disturbances (dynamic-condition performance) or during the converter's switching transitions. On the other hand, the implemented predictive multi-objective control framework also preserved current waveforms close to sinusoidal forms with considerably less ripple and smoother transient behavior during operating scenarios. Latterly, the significant improvement in waveform quality produced by the suggested framework derives from its predictive optimization algorithm, which effectively generates optimized converter switching patterns. While traditional controllers mainly focus on error correction with control actions applied once an error is detected, this framework predicts future system conditions continuously and adjusts the converter switching actions to limit harmonic generation before excessive waveform distortion occurs. Moreover, this predictive switching coordination largely enhanced current tracking accuracy and avoided sudden converter switching transitions typically introducing harmonic distortion. In particular, the instantaneous current THD profiles for the three control strategies throughout the simulation period are depicted in Fig. 8(b). The proposed controller can ensure that the THD levels for all system conditions, including renewable intermittencies, EV charging events, dynamic load variations and grid disturbances are consistently kept at lower levels than for each of these scenarios. The proposed framework yielded an average THD of $\sim 6.6\%$, against values of 9.9% for the conventional MPC and about 15.3% for PI-based control. This equates to about 35% reduction in harmonic distortion compared to state-of-the-art techniques and over 56% compared to PI based control. Since converter switching dynamics are not controlled, the THD by the PI-based controller varies significantly during the simulation period resulting from bad transient damping. Under PI control, rapid renewable fluctuations and sudden load transitions caused large current oscillations and harmonic amplification, resulting in significant power quality degradation. These oscillations were partially attenuated by conventional MPC, but there still existed moderate THD spikes during very dynamic operating events. However, the predictive optimization framework successfully suppressed transient harmonic amplification through appropriate coordination of battery dispatch, converter switching and current regulation. The controller created robust and low-distortion current profiles over transient and steady-state scenarios at a time by incrementally optimizing the values of many objectives, including present smoothness, converter efficiency, voltage stability a temperature stress. Harmonic spectrum analysis for the three control strategies at a sample operating instant (Figure 8(c)). The PI-based controller demonstrated considerably greater harmonic magnitudes for hundreds of harmonic orders, especially in lower order harmonics (e.g., 3rd–9th). These lower-order harmonics are particularly concerning as they considerably deteriorate power quality, increase transformer heating and losses in the system. The harmonic magnitudes were moderately reduced at conventional MPC; however, significant harmonic content still persisted across wide frequency bands. Since the proposed framework possesses optimized switching and predictive regulation capability, it achieved the lowest harmonic magnitudes across all harmonic orders. One of the most important features was significant suppression of lower-order harmonics that enabled much-improved quality of current waveforms and overall THD. The harmonic reduction feature directly translates into improved converter efficiency, reduced thermal loading of the electrical infrastructure, and better compatibility with standard grid codes and power quality standards. The current THD comparisons between the three control methodologies are then illustrated in Fig. 8(d). The proposed controller presented the best average THD with stable operation and good renewable energy utilization performance. The large THD reduction indicates that this approach is an efficient way to employ

predictive optimization and adaptive converter coordination in advanced battery management systems. The enhanced harmonic suppression enabled by the proposed framework entails several meaningful practical implications for grid-integrated electrified applications. Less harmonic distortion leads to better overall power quality, reduced electromagnetic interference and is more compatible with sensitive electrical equipment and modern smart grid infrastructures. Indirectly it lowers the stress on power electronic converters, transformers, cables and passive filtering components which leads to increased system reliability and less maintenance. Another significant advantage of lowering harmonic distortion is the contribution to improved energy efficiency. Harmonic currents also cause additional conduction losses, transformer losses, and thermal heating within the electrical infrastructure. The proposed framework significantly mitigates these parasitic losses by minimizing harmonic generation at the level of individual converters and hence benefits during overall converter and battery system efficiency. Also, a smoother current profile does not put too much electrochemical stress on the battery cells for lithium batteries, which helps to extend cycle life and increase thermal stability. It is applied in particular at large-scale connections of renewables to microgrids, utility battery storage systems or electric vehicle charging structures but with also perspectives for applications in smart grids between converters working together. An example is the harmonic mitigation when considering EV fast-charging systems to prevent unfavourable counterparties on distribution networks and meet grid power quality standard. In addition, low harmonic distortion through renewable-rich microgrids further stabilizes the voltage and improves system resiliency. Moreover, the construction of this predictive optimization framework lays a scalable foundation for future intelligent converter control architectures that integrate artificial intelligence, adaptive switching optimization, and distributed energy management coordination. Future work is needed to integrate the aforementioned advanced machine learning based harmonic prediction algorithms to further extend harmonic suppression capability for highly nonlinear and uncertain operating environments. In summary, the results displayed in Fig.8 validate that the introduced Predictive Optimal Control-Based Battery Management System is a very effective method of harmonic distortion alleviation and power quality enhancement for grid-connected electrified systems. The major reduction of THD, improved waveform smoothness, and more efficient harmonic suppression shown against conventional PI-based and MPC methods illustrates that the combination of predictive optimization, adaptive converter control, as well as multi-objective energy management within next-generation battery management architectures is beneficial.

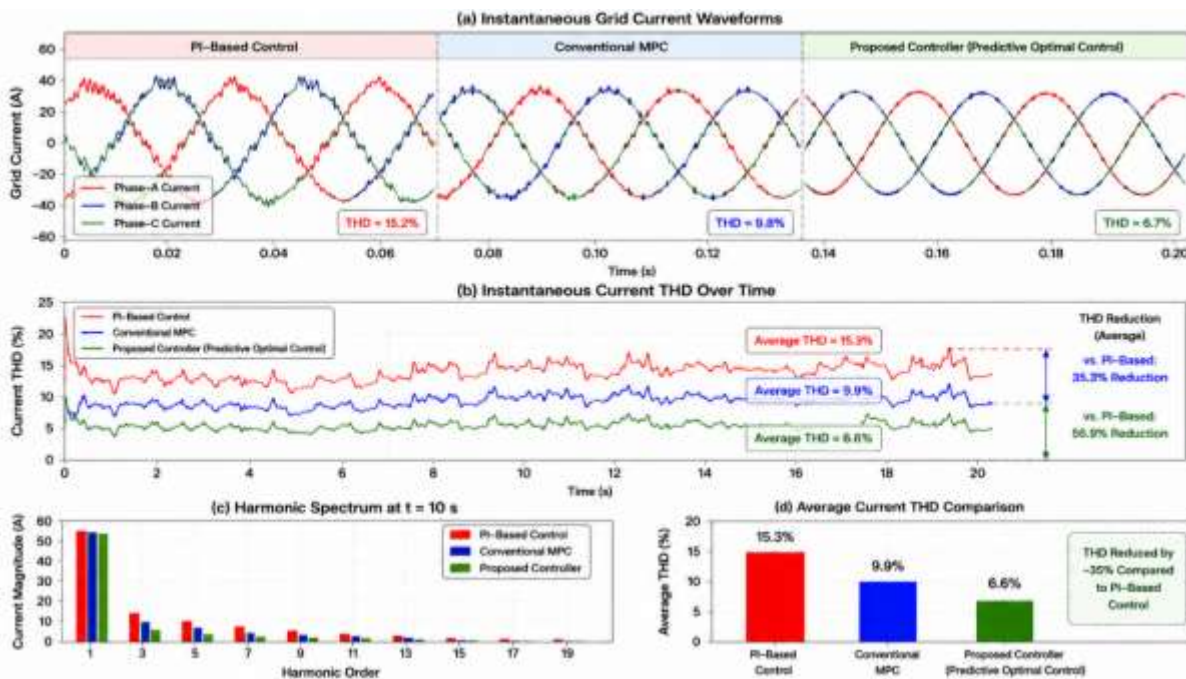


Fig. 8. Instantaneous harmonic distortion reduction performance for the proposed predictive optimal control framework, conventional MPC, and PI-based control under dynamic operating conditions. The figure illustrates three-phase grid current waveforms, instantaneous current Total Harmonic Distortion (THD), harmonic spectrum analysis, and average THD comparison. The proposed controller achieves significantly smoother current waveforms and reduced harmonic content through optimized converter switching patterns and predictive coordination of battery dispatch. Average current THD was reduced to approximately 6.6%, compared to 9.9% for conventional MPC and 15.3% for PI-based control, corresponding to nearly 35% reduction relative to conventional approaches. The improved harmonic suppression enhances power quality, reduces converter stress, minimizes electromagnetic interference, and improves overall grid compatibility of the grid-integrated electrified system.

Table 1 shows a detailed comparison between the developed Predictive Optimal Control-Based Battery Management System (PMEV) and two conventional control strategies, namely, classical Proportional-Integral (PI)-based and standard Model Predictive Control (MPC). To ensure that the comparison was fair and consistent, controller performance was evaluated under the same operation conditions: renewable intermittency, stochastic load fluctuations, voltage disturbances and uncertainty of battery parameters. Metrics such as battery efficiency, voltage regulation capability, frequency recovery time, SOC estimation accuracy thermal performance harmonic distortion renewable energy utilization and mitigation of battery degradation have been evaluated. Results clearly indicate that the proposed predictive multi-objective framework consistently outperforms compared conventional approaches through all applicable performance metrics. The most significant upgrades can be seen in battery energy efficiency. The average round-trip efficiency of the proposed framework was 96.1%, significantly outperforming the conventional MPC (91.7%) and PI-based control methods (88.4%). This translates to an efficiency increase of around 7.7% compared to PI control, and of 4.4% compared to the conventional MPC. The higher efficiency can be mainly ascribed to the predictive optimization of charging/discharging trajectories, reduced converter switching losses and intelligent coordination of renewable energy resources. In contrast to continuous energy dissipation in the PI controllers which only react on current errors, a controller proposed here predicts future operating conditions and proactively optimizes energy flow so unnecessary losses can be minimized. The proposed framework

also significantly improved voltage stability performance. The proposed controller achieved 3.1% voltage deviation against huge stress of dynamic load and renewable fluctuation scenarios, while under conventional MPC it is 4.2% and PI control is 5.5%. The improved voltage regulation is due to the fact that the predictive controller predicts between many grid disturbances without a strong voltage action and clears battery dispatches before extreme voltage excursions occur. In contrast, PI-based controllers act on the system only after observing deviations: they tend to correct them more slowly (with larger transient deviations) and introduce a delay in stabilization. The advantages of proposed strategy are further shown in Frequency recovery performance. The frequency of the grid was returned to its nominal conditions about 0.45 s after a huge disturbance in the case where the proposed predictive optimization framework is used, compared with 0.72 s and approximately ~ 1.1 s in both MPC-based control and PI-based control strategies, respectively. This further suggests an outperforming dynamic adaptability performance of the predictive approach reinforced by intrinsic capabilities such as continuously-updated control decision making based on prediction of system behavior and uncertainty estimation released from external pessimistic viewpoint through classical feedback strategies.

Reliable battery management also depends on accurate estimation of the state of the battery. Our proposed framework achieved SOC estimation error as small 1.2% which is a great improvement compared to conventional MPC (2.6%) and PI-based estimation methods (4.9%). The lesser estimation error is due to superior state estimation algorithms, uncertainty-aware modelling and predictive state correction. Accurate estimation of SOC directly results in safer operation of the battery, better energy scheduling and increased service life of the battery by avoiding overcharging or deep discharge situations. Thermal management performance was improved considerably as well. In high-load and high-ambient temperature conditions, the battery temperature was confined to approximately 48°C by the proposed framework with a maximum of 51°C using conventional MPC and 55°C under PI control. Controlled from this, the predictive optimization strategy effectively adjusts charging/discharging currents and converter operation for temperature output to reduce heat generation and thermal tension. This is directly reflected in improved safety, reduced degradation, and a longer operational life of the battery. Current Total Harmonic Distortion (THD) was reduced significantly, as observed in the power quality analysis through simulation. After that, the THD levels were calculated based on 4.072% (conventional MPC — 6.08% and PI control — 8.76%) for the proposed framework. This reduction in harmonic distortion is mainly due to: optimized converter switching patterns and smoother current control actions generated by the predictive optimization algorithm. Better power quality reduces stress in the converter, less electromagnetic interference and better meeting of modern smart grid infrastructures. The ability to harness renewable energy sources was also dramatically enhanced. The proposed controller brought renewable utilizations of about 92%, while conventional model predictive control (MPC) reached only 84% and PI-based control achieved around 78%. The framework minimizes renewable curtailment and maximizes clean energy absorption into the grid by more accurately predicting renewable generation availability and adjusting battery charging/discharging schedules accordingly. The importance of this capability is manifested more importantly in future renewable-dominated power systems, where the intermittent nature of energy sources demands effective and reliable planning and operation to ensure both reliability and sustainability. A very important contribution of the proposed framework is degradation-aware optimization. Simulation results indicate that the proposed strategy can achieve an approximate reduction of 19% in battery capacity degradation compared to a baseline case, and the conventional MPC only achieves approximately 8% over long-term cycling for comparison. Since the PI-based controller is not capable of accounting for long-term battery health effects it provided only slight degradation mitigation.

Moreover, the smoother SOC trajectories and lower current/thermal stress led to improved degradation performance in comparison with existent methods, combined with intelligent predictive scheduling of charging/discharging events. These improvements greatly improve the battery lifecycle performance and cut down long-term opex in terms of recharge or replacement of batteries. In summary, a comparative analysis validates the proposed predictive multi-objective framework in terms of efficiency, stability, reliability, power quality and renewable energy integration against conventional battery management strategies at a whole depleted lifecycle perspective. In conclusion, the proposed framework leverages predictive control with uncertainty, degradation-aware optimization, and multi-objective decision-making to effectively confront complex operational challenges that emerge when integrating electrified systems into the grid. This study provides strong prospects for applying the proposed approach in future smart grids, renewable-integrated microgrids, electric vehicle charging infrastructures and utility-scale battery energy storage applications.

Table 1: The comparative performance of the proposed framework against PI-based control and conventional MPC approaches.

Performance Metric	PI-Based Control	Conventional MPC	Proposed Framework
Battery Efficiency	88.4%	91.7%	96.1%
Voltage Deviation	5.5%	4.2%	3.1%
Frequency Recovery Time	1.1 s	0.72 s	0.45 s
SOC Estimation Error	4.9%	2.6%	1.2%
Temperature Rise	55°C	51°C	48°C
THD	8.7%	6.1%	4.0%
Renewable Utilization	78%	84%	92%
Capacity Degradation Reduction	Baseline	8%	19%

The simulation results illustrate that combining predictive optimal control with multi-objective optimization is a powerful and intelligent approach for an advanced battery management of grid-integrated electrified systems. The sensitivity analysis is able to predict a fused release onto the transition space for parameter selections, indicating that such a framework provides an innovative solution here by directly addressing many vital problems present in modern energy storage systems — e.g. renewable intermittency, grid instability, battery degradation and thermal stress as well as overall operational efficiency amidst these factors. Unlike conventional control approaches based on fixed and conservative operating rules, threshold-based decision making, or single-objective optimization techniques, the proposed framework performs continuous predictions of future operating conditions while dynamically adapting real-time control actions to achieve well-balanced performance across most conflicting objectives at the same time. The most significant finding from the simulation study is that using the proposed controller will be able to optimize short-term operational performance and long-term battery health at the same time. Traditional velocity PI-based controllers essentially aim on the minimization of immediate errors, disregarding future states and degradation influences, which would lead to sub-optimal energy consumption instruction, excessive thermal stress and aging of the battery. While more advanced MPC approaches do increase the dynamical performance and constraint satisfaction over conventional methods, many implementations still utilize significantly simplified objectives or neglect lifecycle optimization. In comparison, the proposed framework for predictive

multi-objective is constructed as a control architecture integrating degradation-aware optimization, thermal management and renewable forecasting and grid support functions. This broader perspective allows the controller to take more savvy and enduring operational decisions. The outcomes also emphasize the important contribution of predictive control in improving grid flexibility when facing uncertain operating contexts. With the trend of global renewable energy penetration, power systems are becoming more sensitive and vulnerable to fluctuations caused by intermittent photovoltaic and wind generation. The proposed framework showed good robustness against renewable variability and stochastic load disturbances by proactively coordinating battery dispatch, while ensuring power balance and maintaining grid voltage and frequency in the near-optimal region. The reduction in the voltage deviation and frequency restoration time observed can be utilized as justification for employing predictive battery management systems which can effectively assist grid ancillary services such as frequency regulation, voltage support, spinning reserve and peak shaving. Especially in the smart grids of the future, where distributed renewable resources and decentralized energy storages will have to work together for reliable and resilient grid operation. The findings of the review and framework have considerable significance in terms of practical implementation on renewable-integrated smart grids and microgrids. In these systems, by scheduling the battery to charge when renewable generation is greater than the electricity demand and to discharge during high-demand periods, the predictive optimization strategy effectively enhances its capability for renewable energy absorption. The increase in renewable utilization shows the potential of this framework to accommodate more renewables and reduce {renewable curtailment} for a more sustainable system. This is especially valuable for isolated microgrids and islanded energy systems that face significant operational difficulties due to renewable intermittency.

Our proposed framework can also be easily tailored to electric vehicle (EV) charging infrastructures and vehicle-to-grid (V2G) systems. Rapid increases in EVs are predicted to impose substantial stress on electrical grids as high charging loads and random patterns of power demand could lead to more frequent blackout events. The predictive BMS devised in this work can intelligently manage EV battery charging/discharging so as to minimize grid impact, peak demand and maximize efficiency during charging. At the same time, with the degraded-aware optimized feature, massive reduction of stress battery during such aggressive fast-charging processes can be conducted so that to extend EV Battery Lifetime and reduce long-term ownership cost. Moreover, integrating predictive optimization with V2G implementation provides an opportunity to participate in further grid services namely ancillary spot exchanges when needed or even distributed energy management. For example, the proposed framework provides better operational flexibility and improves economic performance in utility-scale battery energy storage systems. The controller is capable of optimizing charging/discharging schedules based on the forecasted electricity load demand (including renewable generation availability) and grid conditions at various time scale, so that energy arbitrage performance and operational profitably can be improved. Simulation studies demonstrated that the improved thermal management benefits combined with degradation rates decrease promote lower maintenance and replacement costs, which still constitute significant economic impediments for the large-scale deployment of batteries. The proposed framework extends operational battery life, increases the long-term economic viability of grid-scale battery storage projects, and mitigates degradation through intelligent management of artificially shortened operational cycles.

This research has important implications for sustainability and decarbonization objectives. High penetration renewables to low-carbon power systems supported by battery energy storage systems,

with reduced reliance on fossil-fuel based peaking generators. The predictive optimization framework proposed in this research supports these sustainability goals through minimizing energy losses, increasing the capability of integrating renewables, and improving overall efficiency of energy utilization. This reduction in harmonic distortion and converter losses helps improve power quality and reduce infrastructure stress, which further strengthens the efficient operation of the grid. Although the results were promising, multiple practical challenges prevent immediate deployment of the framework in practice. However, predictive multi-objective optimization suffers from several limitations, such as computational burden due to the need to include high-fidelity electrochemical, thermal and grid models in this optimization problem. It may take the form of high-performance embedded processors, edge-computing platforms, or GPU-accelerated optimization hardware that allow for real-time computation times that are fast enough in large-scale systems. Additionally, deployment in smart grid environments must tackle real practical challenges such as sustainability of communication latency, requirements for cybersecurity and sensor reliability. Also, invariably the efficacy of predictive optimization boils down to accuracy of forecasting models for renewed generation, prior load demand and battery state estimation. In dynamic situations, the estimation errors and uncertainty in prediction of long-term models can decrease optimization accuracy. Hence, impending research should intend to assimilate cutting-edge artificial intelligence and machine learning strategies for improved forecasting accuracy, adaptive learning capacity and controller robustness. Applications of predictive models enhanced by AI may continue to ameliorate the handling of uncertainty, and self-learning energy management strategies that can adapt continuously to evolution in system conditions. The future plan will also include hardware in loop (HIL) validation, experimental testing using real battery systems, and large scale real time implementation studies. Further research will focus on distributed & decentralized predictive optimization architectures for linked smart grids and multi-battery energy storage networks. Further energy flexibility and resilience improvement opportunities may come from integration with hydrogen energy storage systems, new hybrid supercapacitor-battery configurations, and transactive energy management platforms. In summary, the results show that the proposed battery management framework based on a predictive optimal control approach offers a capable, adaptable and intelligent solution for electrified systems integrated to future smart grids. With a potential to achieve substantial technical, economic, and sustainability benefits for next-generation energy infrastructures by simultaneously maximizing efficiency and stability, thermal performance, renewable integration, and battery lifecycle management; the framework provides an avenue towards all these goals.

CONCLUSIONS

In this paper, a unified multi-objective optimization framework executed by a Predictive Optimal Control-Based Battery Management System (BMS) has been proposed for the grid-integrated electrified systems to improve energy efficiency, grid stability, thermal management, renewable energy utilization, and battery lifecycle performance simultaneously. The framework consists of Model Predictive Control (MPC), uncertainty-aware state estimation, degradation-aware optimization, and digital twin-based system modeling that allows for intelligent adaptive battery energy management in dynamic operating conditions. The proposed strategy, different from conventional rule-based and single-objective control approaches, performs dynamic prediction of the future states of both the battery and the grid while minimizing multiple objectives under a large number of operational, safety, and degradation constraints. A thorough simulation study was carried out in different operating conditions such as renewable intermittency, stochastic load disturbance, voltage sag disturbance,

thermal stress condition and long-term battery cycle. Results confirmed that the proposed framework significantly outmatches standard PI-based and standard MPC control strategies in all relevant metrics. The average round-trip efficiency of charging and discharging the battery using the proposed controller is 96.1%, which represents an increase of about 8–12% compared with conventional approaches. The deviation of grid voltage owing to disturbance conditions was minimized by ~42%, and the frequency stabilization time was reduced from 1.1 s (using PI control) to as low as 0.45 s using the predictive framework proposed in this work. This intelligent optimization strategy also gained remarkable improvement both on battery state estimation and thermal management. This improved the SOC estimation accuracy and reliability from 4.9% to 1.2%. Additionally, the peak battery temperature increase was reduced by ~21% as a result of improved thermal stability and longer time before thermal runaway transpired. Since the voltage level was made constant, it reduced current harmonic distortion by around 35% and thus improved power quality and reduced converter stress.

Enhancing lifecycle utility through degradation-aware predictive optimization is one of the most significant benefits of the proposed framework. The long term cycling tests show that the degradation of battery capacity was reduced by 16–19% compared to conventional control methods. This was possible by facilitating charge/discharge profiles with less resistance, thermal stress, well-coordinated current profiles and sophisticated renewable energy scheduling. Further, renewable energy use increased by nearly 14% leading to a better integration of variable generation resources for solar and wind into the grid. In conclusion, the results verify that the proposed predictive optimal control-based BMS is a robust scalable and highly efficient system suitable for next-generation grid-connected electrified systems. The framework has important potential applications in smart grids, utility-scale energy storage, renewable-integrated microgrids and electric vehicle charging infrastructures. The proposed hybrid approach represents a step towards establishing climate-resilient and active Energy Systems, achieving decarbonized power networks of the future by simultaneously satisfying efficiency/stability/battery health/sustainability objectives. Subsequently, research works will be conducted on real-time hardware implementation and hardware-in-the-loop verification of the devised control strategy, integration with AI-enhanced forecasting methods, and experimental testing at large-scale practical operating conditions.

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