Application of Hybrid Model Predictive Control (Hybrid-MPC) to Microgrid with High Penetration of Renewable Energy

Zhichao Liu, Changhong Deng* and Yahong Chen
School of Electrical Engineering and Automation, Wuhan University
dengch@whu.edu.cn

Abstract. Owing to the cumulative impacts of stochastic forecast errors (SFE) of renewable energy generation, energy storage system (ESS) may be forced to quit operation owing to SOC (state of charge) deviation. Aimed at solving this problem, an online hybrid model predictive control (Hybrid-MPC) based strategy is proposed. Hybrid-MPC consists of two hierarchies: one is decreasing horizon rolling optimization which is specially for handling small SFE and the other is heuristic cooperative control which is designed to tackle large SFE. Besides, feedback correction is applied to deal with SOC deviation and maintain the normal operation of ESS. The strategy is tested in a self-developed program MG-ROS. Results demonstrate the effectiveness of the proposed strategy.

1. Introduction
MICRO GRID (MG) is generally composed of variable speed pumped storage unit (VSPS), energy storage system (ESS), photovoltaic (PV) cells and wind turbine (WT) generators. Day-ahead energy management system (EMS) combined with real-time droop control is a common method for the stable and economic operation of MG. Results of day-ahead optimal optimization are utilized as the set points for droop curves of VSPS and ESS [1]. And the purposes of adopting droop control are to instantaneous balance power supply and demands and compensate for the stochastic forecast errors (SFE) of renewable energy sources (RESs) generation and load demands [2]-[3].

In fact, applying droop control, SFE of RESs generation and load demands will be shared by VSPS and ESS. Consequently, the deviation between actual power and day-ahead schedule power for them [1] will be generated. Then energy error, i.e., state of charge (SOC) deviation of ESS, which is induced by the product of power error and time, is therefore produced by iterative calculation and continues increasing. SOC value is a critical factor to determine the operation status of ESS. The larger the deviation of SOC is, the larger the probability of over charge and over discharge of ESS is. If this happens, ESS will be forced to limit its power or even off-the-line by battery management system. Then operation stability of ESS and MG is reduced. Therefore, handling SOC deviation is extremely important for the normal operation of MG [4].

The objective of this paper is to propose an EMS strategy to cope with SOC deviation and maintain the normal operation of ESS. Recently, numerous models have been applied to MG operation optimization to alleviate the impacts of SFE of RESs generation, for instance, stochastic economic
dispatch and robust optimization [5]-[6], etc. However, if penetration of RESs is high, the performance of these algorithms is not satisfactory enough. More pertinent strategy is thus needed.

Model predictive control (MPC) based online EMS approach has good robustness in dealing with uncertainty, therefore is a very promising effective solution to above problems [7]-[8]. However, the main disadvantages of MPC are complex, computationally demanding, and that sometimes it has to apply decomposition techniques [7]. To solve this, a Hybrid-MPC method is proposed. The significant differences between Hybrid-MPC and MPC are: (i) tedious repeated ultra-short prediction is removed; (ii) time horizon for closed-loop rolling optimization is dynamically changing; (iii) high computation complexity for state equations of MG is avoided; (iv) day-ahead schedule is utilized as the basic reference command to guarantee global optimal; (v) real-time closed-loop feedback correction is applied to adjust SOC; (vi) under small SFE, time-varying rolling optimization is applied; (vii) under large SFE, heuristic control is implemented [9].

The main contributions are as follows.

1) An online closed-loop Hybrid-MPC based EMS strategy is proposed to cover the negative effect of SFE on SOC of ESS.
2) Decreasing horizon rolling optimization for handling small SFE is employed, while heuristic control to cope with large SFE is utilized.
3) Closed-loop feedback correction is applied to change the operation status of MG in time when necessary thus keeping SOC of ESS always within desirable limits.

The remaining sections are outlined as follows. Section 2 proposes the Hybrid-MPC based EMS strategy. In section 3 numerical case studies are presented. In section 4, conclusions are drawn.

2. Hybrid-MPC Based EMS Strategy
To cope with the problem of SOC deviation presented in literature [4] and maintain the normal operation of ESS, Hybrid-MPC EMS strategy is proposed. Hybrid-MPC consists of two hierarchies, time-varying rolling optimization (RO-MPC) is utilized to cope with small SFE and online heuristic control (HC-MPC) is applied to handle large SFE, respectively.

2.1. RO-MPC Based EMS Strategy
An appropriate errors threshold \( \varepsilon \) is set in the first place, if SFE of net load \( \leq \varepsilon \), they are considered as small errors, otherwise, regarded as big errors.

For traditional MPC, algorithm is applied based on the current state of MG and ultra-short predictions of net load. Rolling optimization [10]-[11] is conducted over the fixed time horizon. This open-loop optimization problem is solved online. The first element of the optimization results (control sequence) is implemented to act on the controlled object. Then time horizon moves forward to next interval. The process is repeated again based on the latest measured information in the next sampling period.

![Figure 1. RO-MPC based EMS strategy.](image-url)
For RO-MPC, time horizon for rolling optimization is decreasing with time. Calculation for time-varying rolling optimization is based on the day-ahead forecast value of net load. Real-time feedback of SOC is utilized for closed-loop correction. Implementation process of RO-MPC is briefly introduced as below. If SFE is small and actual SOC is within the normal range then operating commands of VSPS and ESS are set according to their day-ahead schedule. Thus operation economy can be ensured. However, if actual SOC exceeds the range then RO-MPC is applied. Current value of SOC is taken as initial calculation condition and day-ahead forecast values of net load for remaining periods are taken as input, CPLEX solver is called to change the operation schedule of remaining periods, as shown in figure 1. Thanks to the mechanism of SOC feedback, new schedule will adjust SOC towards opposite direction and change it gradually to normal range.

Equation of time-varying optimization is:

\[
\min c^T X_{t+1} \quad \text{s.t.} \quad AX_{t+1} = b, DX_{t+1} < d, X_{t+1} \in X
\]  

Optimization results:

\[
X_{t+1} = \{ p_{i}^+ [t+1], L, p_{i}^- [t], p_{ess}^+ [t+1], L, p_{ess}^- [T]\}
\]  

Feedback correction:

\[
\Delta X_{t+1} = f[SOC(t)]
\]  

Typically, the optimization model is formulated as a large scale mixed integer nonlinear programming (MINLP) problem. Objective function of MG, a set of equality and inequality operation constraints, and integer and binary optimization variables of micro sources are generally included. The objective function generally includes: 1) startup and shutdown cost of VSPS; 2) nonlinear quadratic consumption cost of VSPS; 3) charge-discharge and degradation penalty cost of ESS. Operation of VSPS is subject to a series of constraints, for instance, output power range constraint, maximum available power constraint, ramp rate constraint and minimum on time and off time constraint. To meet the instantaneous power balance requirement of MG while power of net load fluctuates, minimum standby rotation reserve constraint must be satisfied as well. Operation of ESS is also subject to a series of constraints such as charge and discharge power constraint and upper and lower SOC range constraint. Detailed constraints are not the focuses of this study, they are not listed and can be seen in references [1] and [5]-[6].

2.2. Online HC-MPC Based EMS Strategy

Rolling optimization is poor at handling inputs with large SFE whereas heuristic control is good at coping with large SFE despite that the operation is usually not optimal. Day-ahead schedule is utilized as command reference, operation economy can be improved. Real-time operating status of VSPS and ESS and feedback of SOC are taken by the online heuristic controller to determine the on-off status of VSPS and decide the power of VSPS and ESS, as shown in figure 2.
3. Case Study

3.1. Simulation Setup
Hybrid-MPC is tested in self-developed program named MG real operation simulation (MG-ROS). In MG-ROS droop control is adopted by VSPS and ESS. Schedule commands are taken as droop curves power set points. Day-ahead forecast for net load plus SFE are taken as real-time actual inputs of MG.

3.2. Day-ahead Operation and Operation with Small SFE
In the first case, no SFE is considered and day-ahead forecast of net load is regarded as ideal input for MG. Optimal optimization result is shown in figure 3(b). It is easy to find that SOC is always within the normal range which indicates that status of ESS is normal throughout the whole operation periods.

Then small SFE of net load is added to the operation of MG and three cases are carried out where no EMS strategy, RO-MPC and HC-MPC is applied respectively to observe the impacts of SFE on SOC of ESS. To obtain sample of SFE, data within the error 95% confidence interval is taken as small SFE, and data within the interval between error 95% and 98% confidence intervals is taken as large SFE.

It is clearly observable in figure 3(b) that the difference between schedule SOC and actual SOC is increasing gradually and at A3 actual SOC exceeds the normal range which indicates that overcharge of ESS has happened. In figure 3(c) the operation schedule of MG has changed four times from B1 to B4 and the effect of RO-MPC is obvious. SOC is adjusted and kept within extreme operation limit. In figure 3(d) the operation status of micro sources is adjusted and actual SOC is modified within several consecutive periods around C1. By using HC-MPC, deviation of SOC is successfully reduced.

3.3. Operation with Large and Mixed SFE
Large and mixed SFE of net load is added to the operation of MG and four cases are carried out where no strategy, RO-MPC, HC-MPC and Hybrid-MPC is applied respectively.

It can be seen in figure 4(a) that deviation of SOC increases rapidly and capacity of ESS must be very large to keep the stable operation. It is clear in figure 4(b) that applying RO-MPC the capacity of ESS must increase to 4000. It is observable in figure 4(c) that HC-MPC can successfully maintain actual SOC within normal range. It is unnecessary to increase the capacity of ESS. However, there is a significant increase in amount of load shedding and RESs cutting. In figure 4(d) Hybrid-MPC can successfully maintain the actual SOC within normal range and there is no need to increase the capacity of ESS. The total amount of load shedding and RESs cutting is significantly less. The comparison of additional simulation results are shown in figure 5 and figure 6.
4. Conclusion
This paper has presented a novel online Hybrid-MPC based EMS strategy to cope with SOC deviation of ESS. Hybrid-MPC consists of decreasing-horizon rolling optimization, heuristic cooperative control,
and closed-loop feedback correction. Decreasing-horizon rolling optimization is utilized to handle with small disturbances, while heuristic control is applied to cope with large disturbances. Feedback correction is used to eliminate SOC deviation. The effectiveness of the strategy has been tested in MG-ROS. Results demonstrated that the strategy has good performance on handling disturbances, keeping SOC within normal range and preventing the unstable operation of ESS.

5. References

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Acknowledgments

This work was supported by The National Key Research and Development Program of China (2017YFB0903705).