A Hierarchical Energy Management Strategy for Grid-connected Microgrid

Xingpeng Li, *Student* Member, IEEE, Guangchao Geng, *Student Member, IEEE*,
Quanyuan Jiang, *Member, IEEE*

***Abstract*—A novel hierarchical energy management strategy for grid-connected microgird is proposed in this paper. The proposed concept follows the idea of multiple time-scale coordination and consists of day-ahead layer, adjustment layer, and real-time layer. The day-ahead layer is based on look-ahead multi-step optimization techniques and the predicted availability of renewable energy sources. Future operational states of the controllable units in the microgrid could be determined ahead of time. The adjustment layer adjusts power output of online units by using the data at the dispatch time. Then, real-time layer is utilized to maintain the exchange power between the external macrogrid and the microgrid constant. In addition, energy storage plays a critical role in three dispatch and control layers. A typical microgrid system is simulated to demonstrate the performance and effectiveness of the proposed hierarchical energy management strategy.**

***Index Terms*— Microgrid, Energy Management, Hierarchical Optimization, Multiple Time-scale, Renewable Energy Sources.**

I. INTRODUCTION

WITH the increasing demand of energy, renewable energy sources (RES) develop very rapidly nowadays. Deployment of RESs is able to potentially reduce the need for traditional transmission system expansion [1]. Uncertainty has been identified as one of the biggest challenges in modern power systems. This challenge can be partially addressed by microgrids, which are entities that coordinate RESs in a consistently more autonomous and decentralized way, thereby reducing the control burden on the grid and permitting them to provide their full benefits [1]. Moreover, featured by its flexible and reliable operation, microgrid has a great prospect for utilizing RESs [2].

Microgrid energy management strategy is a very complex problem since it depends on not only the load level, but also the weather conditions, electricity price and gas tariff. Multi-time-scale coordination is a key issue due to high intermittency of some renewable energy sources. It is responsible to coordinate the RESs and operate the microgrid economically [3].

A combined heat and electricity dispatching model was proposed in [4] in which operational constraints, network loss and physical limits are addressed. But only a typical winter day is analyzed. [5] went further based on [4]. Combined heat and power unit (CHP), electric heater, boiler and heat storage are included in the model. It analyzed the relationship between heat to power ratio (HPR) of demand and the optimal operation schedule with an extra typical summer day. The volatile nature of wind is reduced using scenario reduction technique [6]. Two-layer multi-step microgrid energy management strategy was proposed in [7]. The top-layer and the component-layer are both based on look-ahead multi-step optimization techniques. However, the model did not consider the startup cost and the assumption that each intermittent source contains a built-in storage is not practical.

The operation strategies in [4-7] are mainly based on look-ahead optimization. They, however, do not consider the real-time situation, and the forecast error will be alleviated by the external macrogrid. This would definitely result in some negative effects on the stable operation of the external macrogrid. This will be more severe when more intermittent sources of large capacity exist in the microgrid and/or when a large number of microgrids exist in the macrogrid.

To resolve this problem, a hierarchical energy management strategy, consisting of day-ahead layer, adjustment layer, and real-time layer, was proposed for grid-connected microgrid. The purpose of the proposed strategy is to minimize the cost while keeping the tie-line power constant. By keeping the tie-line power constant, it will not cause negative effects on the macrogrid, and, then, the macrogrid operators do not need to worry about the fluctuation of the renewable energy resources inside the microgrid. This will absolutely decrease the complexity of schedule and dispatch of the macrogrid. With the proposed energy management strategy, microgrid will be operating as a grid-friendly and grid-responding controllable load in the eyes of macrogrid.

II. STRATEGY TO SOLVE THE MICROGRID ENERGY MANAGEMENT PROBLEM

In the day-ahead layer, unit commitment problem is solved, giving the on-off state of each unit and charge-discharge state of storage in each period. Certain margins for adjustment layer and real-time layer are reserved in the day-ahead layer. In the adjustment layer, economic dispatch is performed using the wind/solar/load data at the

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X. Li is with School of Electrical, Computer and Energy Engineering, Arizona State University, Tempe, 85281, AZ, USA (email: xingpeng.li@asu.edu).

G. Geng and Q. Jiang are with College of Electrical Engineering, Zhejiang University, Hangzhou, 3100027, China. (email: ggc@zju.edu.cn, jqy@zju.edu.cn).

dispatch time. Adjustment layer is also required to reserve the margin for real-time layer. In the real-time layer, only the storage is allowed to be adjusted to alleviate the fluctuation of wind/solar/load and it maintains the exchange power between the macrogrid and microgrid unchanged.

The three-layer strategy is implemented in following steps.

Step 1: According to the characteristics of the controllable generations, the nonlinear cost-output curves are linearized by using piecewise linear approximation, shown in Fig. 1.

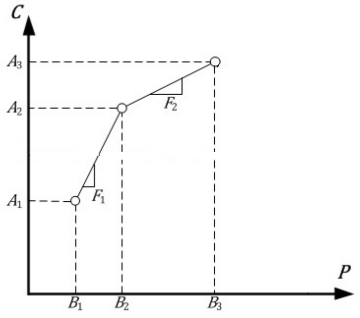


Fig. 1 Linearized cost function curve for controllable units

Step 2: Forecast the wind/solar/load in the microgrid for the next 24 hours.

Step 3: Mixed integer linear programming (MILP) was formulated for the unit commitment problem in the day-ahead layer instead of mixed integer nonlinear programming (MINLP) which is much complicated to solve [8]. The storage is forced on in all periods since it is the only source that could provide a reserve and adjust its output in the real-time layer. By solving MILP problem, the on-off state of controllable generators and the charge-discharge state of storage are given for all periods.

Step 4: In the adjustment layer, use the updated wind/solar/load data at the dispatch time to dispatch the power of each online unit, and then determine the exchange power between macrogrid and microgrid, which will be kept constant through real-time layer control.

Step 5: By updating the real-time wind/solar/load data, the net-load will be calculated, and the storage then will adjust its charging/discharging power to alleviate the fluctuation of net-load. Net-load denotes the difference between real load and non-controllable units output.

Step 6: Go back to step 4.

The flowchart of the proposed strategy is shown in Fig. 2.

III. MATHEMATICAL MODEL OF THREE-LAYER OPERATION STRATEGY

A. *Day-ahead Layer*

The goal of day-ahead layer is to minimize the cost over a given time horizon (24 hours in this paper) by finding the best possible control sequence of controllable units, taking into account power trading price, forecasting power of non-dispatchable units, and load level [9]. To alleviate the effect of forecast error, reserve power must be guaranteed for adjustment layer and real-time layer in the day-ahead layer. Thus, the range of charge/discharge schedule rate and state of charge (SOC) of storage, and thermal constraints of tie-line (the line connecting macrogrid and microgrid) should decrease/relax as shown in Fig. 3.

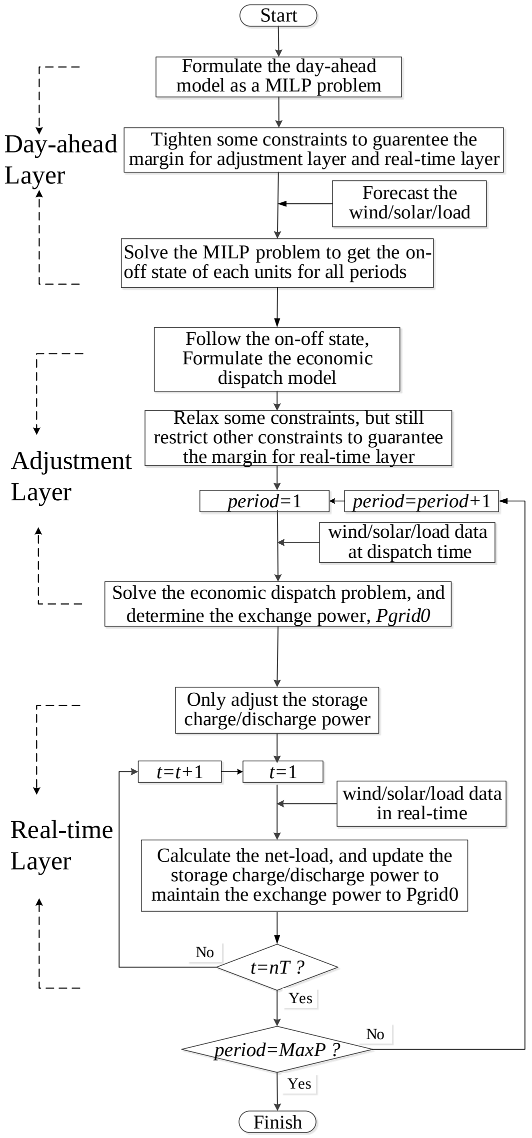


Fig. 2 Flowchart of the three-layer operation strategy

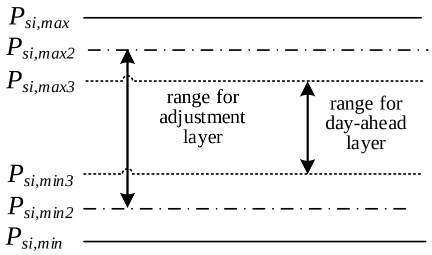
The day-ahead model is formulated as a MILP problem, as shown below:

$$\min \; f(\boldsymbol{x},\boldsymbol{u})$$
$$s.t \begin{cases} \boldsymbol{h}(\boldsymbol{x},\boldsymbol{u})=0 \\ \underline{\boldsymbol{g}} \le \boldsymbol{g}(\boldsymbol{x},\boldsymbol{u}) \le \overline{\boldsymbol{g}} \end{cases} \qquad \boldsymbol{x}\in \mathrm{R}, \boldsymbol{u}\in\{0,1\}$$

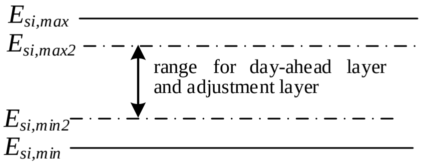
where the objective function is minimizing the cost, and the constraints include the power balance equations, the power limitation of controllable units, thermal limitation of tie-line, power reserve requirement, and the state of charge (SOC) and charge/discharge power limitation of storage. The details are disclosed in our previous work [9]. The differences are that the upper limitations and lower limitations of some constraints are tightened here.

B. *Adjustment Layer*

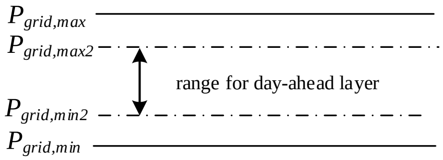
At any given interval of adjustment layer, the on-off state of controllable units and charge-discharge state of storage are



(a) constraint for charge/discharge rate of storage



(b) constraint for state of charge (SOC) of storage



(c) constraint for thermal limitation of tie-line

Fig. 3 constraints for charge/discharge rate and state of charge (SOC) of storage, and constraint for thermal limitation of tie-line

determined by day-ahead layer. Their dispatch power of online units controlled in adjustment layer's economic dispatch will eliminate the forecast error at the dispatch time.

The objective of adjustment layer is to minimize the cost in this single interval. As for the constraints, the storage charge/discharge power limitation is relaxed, and the thermal constraint of the tie-line restores to its physical constraint while the constraint for SOC of storage is the same as that in the day-ahead layer.

C. Real-time Layer

The core part of the proposed energy management strategy for grid-connected microgrid is the third layer, real-time layer. The objective of real-time layer is to maintain exchange power on the tie-line unchanged. To achieve this, constraints of the storage restore to its physical limitation, which would ensure that the storage has the capacity to alleviate the power fluctuation. The wind turbines, PV systems, and loads are monitored in real time. The net-load is calculated every 10 seconds (assume the net-load does not change in this interval). The fluctuation of net-load is alleviated by the storage. Thus, the exchange power on the tie-line will be kept the same value given by the adjustment layer, and, hence, it will cause little impact on the macrogrid.

In real-time layer, the output power of controllable units keep unchanged from upper layer, and the storage is the only one element that is the allowed to adjust. It alleviates the power fluctuation by adjusting its charge/discharge power. However, the charge-discharge state is prohibited to switch since frequent state switching will reduce the lifespan of storage devices dramatically. The control strategy flowchart of storage in real-time layer is shown in Fig. 4.

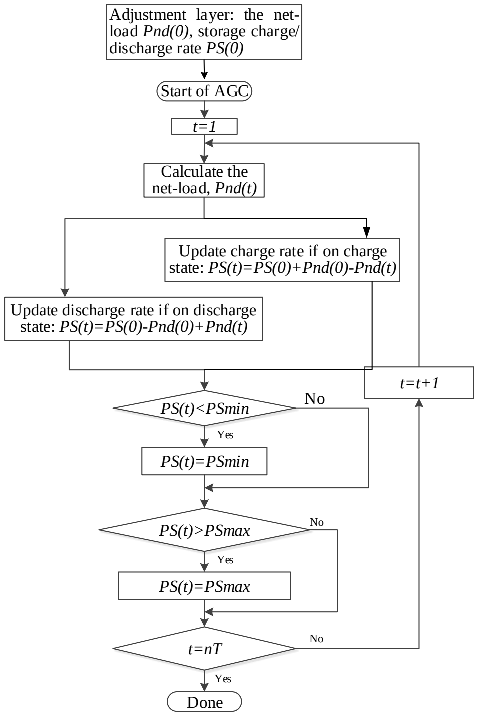


Fig. 4 Flowchart of storage control strategy in the real-time layer

IV. CASE STUDIES

The system setup used for the simulation is shown in Fig. 5, a modified system of [9]. The controllable units include a fuel cell (FC), a micro turbine (MT), a diesel engine (DE) while non-controllable units consist of a photovoltaic (PV) unit and a wind turbine (WT) unit. In addition, the energy storage system (ESS) contains a battery storage (BS).

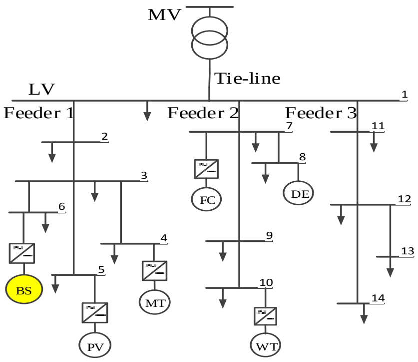


Fig. 5 A typical microgrid

TABLE I Controllable Units Information

Type		DE	MT	FC
Output limit (kW)	lower	11.11	12.74	14
	upper	60	75	80
Maintenance cost (￥/ kW)		0.0859	0.0401	0.0286
Startup cost (￥)		20	25	30
Ramping limit (kW/h)	lower	-240	-280	-170
	upper	240	280	170

The rating of PV unit and WT unit is 200kW, and 250kW respectively. Detail information of the controllable units is listed in Table I. For BS: the energy capacity is 300kWh, and the maximum charge/discharge power is 90kW.

In this paper, the time horizon for day-ahead layer is 24 hours while each adjustment period is 30 minutes. The real-time control works every 10 seconds. We assume that wind/solar/load is constant during one interval, i.e. 10s.

A sequence of random noise is used to simulate the forecast errors of wind/solar/load. The forecast net-load and real-time net-load curves are shown in Fig. 6. In this case, the maximum forecast error of wind unit and PV unit are both set to 12%; the maximum forecast error of load is set to 6%. The market prices reflect peak and valley loads of the macrogrid. Prices are high at peak load and low at valley load. The price of import/export power from external grid is shown in Fig. 7.

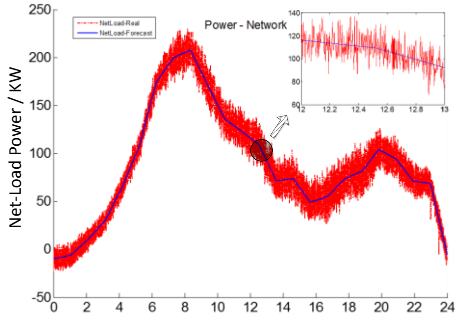


Fig. 6 The net-load power

Fig. 7 The market price

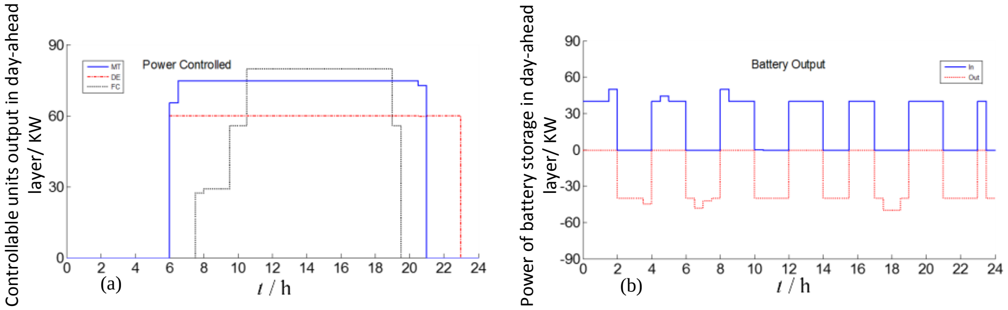


Fig. 8 State and power of controllable units and battery storage in the day-ahead layer.

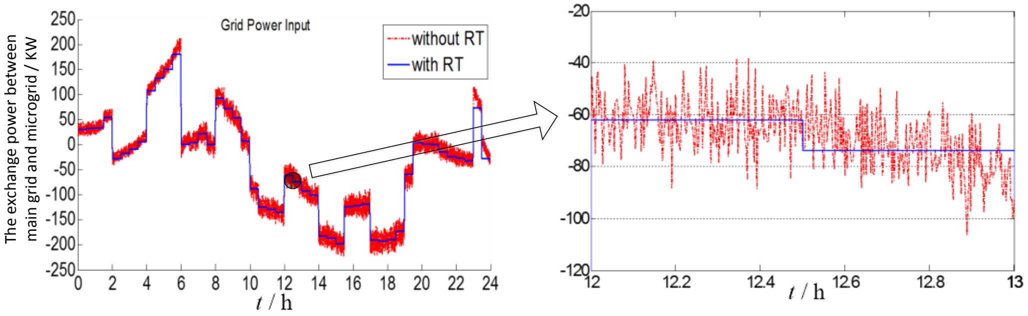


Fig. 9 The exchange power between macrogrid and microgrid

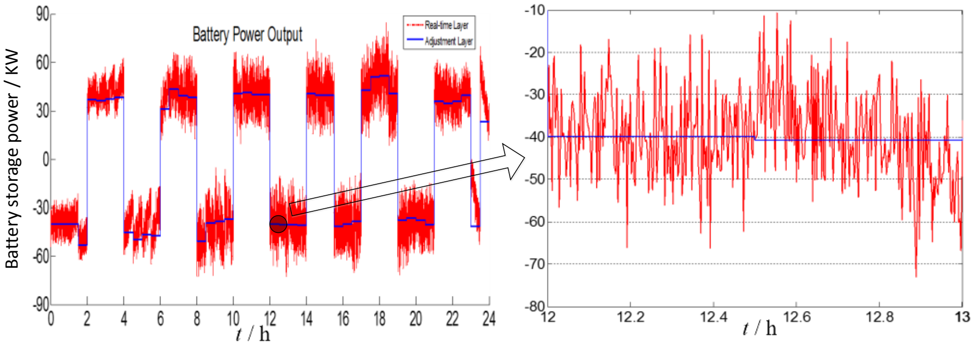


Fig. 10 The charge/discharge power of battery storage

The MILP day-ahead problem is solved by Cplex [10]. The schedule of controllable units and battery storage is shown in Fig. 8. It can be concluded that the controllable units reach their upper limitation when prices are high and stay off when prices are low. The charge/discharge power of battery storage lies in the range from 40kW to 50kW instead of range from 0 to 90kW. This is because the day-ahead layer should guarantee the margin for adjustment layer and real-time layer. In the adjustment layer, economic dispatch is performed to adjust the output of online controllable units. In the real-time layer, the exchange power is maintained unchanged by adjusting the storage charge/discharge power.

By using the proposed hierarchical energy management strategy, the exchange power between the macrogrid and microgrid is kept constant during each adjustment period, which will ensure that it would not introduce fluctuation to the macrogrid, shown in Fig. 9. The charge/discharge power of battery storage with real-time control and without real-time control is shown in Fig. 10. The red dotted curves in Fig. 9 and in Fig. 10 denote the exchange power and the battery power without the real-time layer, respectively. Without the real-time control, the macrogrid will be responsible for the fluctuation of wind/solar/load. This would produce negative impacts on the macrogrid especially when penetration of intermittent energy is high.

The proposed three-layer hierarchical strategy ensures that the electrical impact of microgrid on external world at least qualifies it as a good citizen; that is, it complies with grid rules and does no harm beyond what would be acceptable from an existing customer [11]. The microgrid is then treated as a controllable load though there are intermittent sources in it. The proposed strategy will be more meaningful when more intermittent sources of large capacity exist in the microgrid and/or when a large sum of microgrids exist in the macrogrid.

V. FUTURE WORK

One important potential benefit of microgrid lies in the high efficient cogeneration of electricity and thermal [11]. The possible future research work will consider the thermal load as well as network physical constraint.

Since microgrid contains energy sources, it could provide electricity to its nearby blocks. A new issue comes out that how to determine the price to make it more competitive than local distribution network utility. The price of local utility and the prices of microgrids will interact with each other. Game theory may be chosen as a method to determine which strategy a microgrid should take to maximize its revenue.

VI. CONCLUSIONS

A novel hierarchical energy management strategy for grid-connected microgrid was proposed in this paper. The on-off state of controllable units and charge-discharge state of storage are determined in day-ahead layer. In the adjustment layer, economic dispatch is performed to eliminate the forecast error. Margins for real-time control are guaranteed in day-ahead layer and adjustment layer. Real-time layer alleviates the fluctuation of net-load, and, hence, maintains the exchange power between the macrogrid and the microgrid constant. This strategy can decrease the impact of power fluctuation of intermittent sources and load. Storage plays a critical function in the real-time layer. Case studies validate the performance and effectiveness of the proposed hierarchical energy management strategy.

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Xingpeng Li (S'12) received his B.E. and M.S. degree in 2010 and 2013 from Shandong University and Zhejiang University, China, respectively. He is currently pursuing the Ph.D. degree in electrical engineering and pursuing the M.S. degree in industrial engineering concurrently, Arizona State University, Tempe, AZ, USA.

His research interest includes renewable energy sources into power system, microgrid energy management strategy, and power system optimization.

Guangchao Geng (S'10) received his B.E. degree in 2009 from the College of Electrical Engineering, Zhejiang University, Hangzhou, China, where he is pursuing the Ph.D. degree in electrical engineering.

From 2012 to 2013, he was a visiting student at the Department of Electrical and Computer Engineering, Iowa State University, Ames, USA. His research focuses on power system stability and control, numerical analysis and optimization, and high performance computing.

Quanyuan Jiang (M'10) received his B.S., M.S., and Ph.D. degrees in electrical engineering from Huazhong University of Science & Technology (HUST), Wuhan, China in 1997, 2000, and 2003, respectively.

He is currently a professor at the College of Electrical Engineering, Zhejiang University, Hangzhou, China. He was a visiting professor at the School of Electrical and Computer Engineering, Cornell University, Ithaca, USA, from 2006 to 2008. His research interest includes power system stability and control, power system optimization and parallel computing, and applications of energy storage systems in power systems.