Optimal Day-ahead Scheduling for Microgrid Participation in Frequency Regulation Markets

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***Abstract*—As microgrid installations are steadily growing in the United States and around the world, widespread adoption of commercial microgrids would rely upon the economic benefit to the owners and operators. With the introduction of new market mechanisms and growing penetration of non-traditional generation assets, there is an increasing need and interest in allowing distributed assets to participate in traditional grid services such as frequency regulation. This paper considers the problem of determining the optimal balance of energy and ancillary services for individual microgrid generation assets to participate in such markets. An optimization framework that maximizes the predicted performance of the microgrid over a day-ahead time horizon while accounting for individual asset constraints is proposed. Simulation results on a realistic test system with practical considerations are presented.**

***Index Terms*—Frequency control, Microgrids, Optimization, Power system control.**

I. INTRODUCTION

The concept of microgrid has been widely researched for decades [1]. Previous research and development efforts were focused on developing optimization algorithms and implementing model predictive control approaches for economic dispatch of the assets within microgrids [2]-[3]. The key objectives were economic efficiency during the grid connected mode and continuity of service to critical loads during islanded mode. The technology to achieve these objectives is fairly mature and many vendors are providing microgrid control and dispatch optimization solutions.

Despite considerable effort, the commercial acceptance of microgrids is still at the infancy stage. Most of the installations to date are military bases, university campuses and research facilities [4]. In the United Sates, it is estimated that more than 80 microgrid projects, with total installed capacity of one gigawatt, is currently under operation [4]. The adoption of microgrids will soon increase with increasing interest from state governments and the DoE especially for the purpose of increasing storm resiliency. New York has already announced a $40 million competition to create community microgrids [5]. Similar initiatives are being also planned in New Jersey [6].

The widespread commercial adoption of microgrids hinges on the clear demonstration of benefit to the owner and operator. In this context, this paper provides a formulation for microgrids to participate in ancillary services to the grid operators as an additional value stream. This concept will allow microgrid operators to take part in ancillary services in addition to offsetting energy costs. While the results presented in the paper considers frequency regulation services, the concept can be expanded to other services like capacity, spinning reserve, non-spinning reserve and demand response.

The concept of a microgrid providing various ancillary services was presented in recent work [7]-[10]. The technical feasibility, profitability and difficulty of microgrids providing ancillary services were investigated in [7]. The concept of controlling assets in multiple microgrids to meet the minimum ancillary services requirement was proposed in [7]. A model to enable the participation of microgrid agents in providing reactive power, active loss balancing and demand interruption ancillary services were discussed in [8]. A comprehensive central demand response algorithm is described in [9] which provides the frequency regulation ancillary service while minimizing the amount of load control in a microgrid setting. In a recent work, an optimal power scheduling framework for a microgrid with renewable energy was proposed, where the renewable power was coordinated with the building thermal dynamics to increase the microgrid profit and reduce the renewable curtailment [10]. In the proposed work here, an optimization approach considering model predictive control is proposed where the microgrid acts like an aggregator to optimize the day-ahead energy schedule and frequency regulation ancillary service schedule to maximize the profit. The formulation also considers the practical limitation imposed by independent system operators (ISO), which requires the asset to be of a certain minimum size to take part in the ISO's ancillary service market.

II. PROBLEM FORMULATION

In this section, a mathematical formulation is presented for a microgrid control algorithm and the optimization problem to determine the day-ahead schedule for participation in frequency regulation markets.

A. Microgrid Model and Constraints

A microgrid is a collection of distributed energy generation assets, storage devices, and loads, interconnected

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together. Energy generated at one point may be used in another within the microgrid; there may or may not be a bulk grid which is, for practical purposes, an infinite source or sink of energy. In general, a microgrid can comprise electrical assets such as diesel generators, combined heat/power (CHP) generators, battery energy storage, fuel cells, electrolyzers, renewable sources, loads and a connection to the macro grid. Solving the microgrid mathematical model at intervals of time involves:

- Obtaining the predicted values of non-dispatchable signals of interest in the microgrid, such as loads, renewables or prices. Historical measurement data or models coupled with current measurements can be used for such a prediction.
- Predicting, using a high-level model, the behavior of the microgrid as far into the future as practical. The time interval up to which the prediction is carried out is called the prediction horizon.
- Optimizing the predicted performance of the system (e.g., cost of operation) while respecting operational constraints. Operational constraints include the microgrid physics (e.g., energy balance or export constraints must be respected), and other asset considerations (e.g., generator ramp rate limits).

Each generating asset in the microgrid can be modeled in terms of its ability to provide power, and the rate at which the power can be altered. Supposing there are N_g electrical generators in the microgrid. If $P_{g,min}$ and $P_{g,max}$ are the minimum and maximum power outputs, and RD and RU are the down and up ramp rate limits for each generator i, the following constraints would apply:

$$P_{g,min} \le P_{g,i}^{k} \le P_{g,min},\ i = 1, \dots, N_g \quad (1)$$

$$RD\Delta t \le P_{g,i}^{k+1} - P_{g,i}^{k} \le RU\Delta t,\ i = 1, \dots, N_g \quad (2)$$

For an energy storage asset in the microgrid, the following constraints would apply:

$$P_{chg,\,min} \le P_{chg,i}^{k} \le P_{chg,\,max},\ i = 1, \dots, N_{es} \quad (3)$$

$$P_{dis,\,min} \le P_{dis,i}^{k} \le P_{dis,\,max},\ i = 1, \dots, N_{es} \quad (4)$$

$$Q_i^{k+1} = Q_i^{k} + P_{chg,i}^{k} * \Delta t * \eta_{chg} - P_{dis,i}^{k} * \Delta t * \eta_{dis}^{-1},\ i = 1, \dots, N_{es} \quad (5)$$

$$Q_{min} \le Q_i^{k} \le Q_{max},\ i = 1, \dots, N_{es} \quad (6)$$

where, N_{es} is the number of energy storage devices, $P_{chg,\,min}$ and $P_{chg,\,max}$ are the minimum and maximum power charging limits, $P_{dis,\,min}$ and $P_{dis,\,max}$ are the minimum and maximum power discharging limits, Q_{min} and Q_{max} are the minimum and maximum state-of-charge limits, η_{chg} and η_{dis} are the charge and discharge efficiencies.

The bulk grid is used to balance generation and load through the following constraint:

$$P_{grid} = \sum_{i=1}^{N_g} P_{g,i} + \sum_{i=1}^{N_{es}} P_{dis,i} + \sum_{i=1}^{N_r} P_{r,i} - \sum_{i=1}^{N_{es}} P_{chg,i} - \sum_{i=1}^{N_l} P_{l,i} \quad (7)$$

where, N_r is the number of renewable generators, N_l is the number of loads, P_r is the renewable generation power output, P_l is the load power consumption, P_{grid} is the power bought from (shortage of generation) or sold to (excess of generation) the grid. As mentioned earlier, it is assumed that predictions are available for P_r and P_l.

The objective of the optimization problem is to minimize the total cost of providing energy to the microgrid loads over the prediction horizon. That is, the cost function is given by:

$$min \sum_{k=0}^{T} C_g^k + C_{es}^k + C_{grid}^k \quad (8)$$

where, C_g, C_{es}, C_{grid} are the cost of providing power from generators, energy storage devices and importing power from the grid. These costs are functions of the power outputs P_g, P_{es}, P_{grid} respectively. The above problem solves for the optimal generation mix in order to meet the microgrid forecasted load for a given time horizon, within the individual asset constraints.

B. Day-ahead scheduling algorithm for regulation markets

The framework discussed above can be used to determine the day-ahead schedule for the microgrid's participation in regulation markets. In order to solve such a problem, two additional variables are introduced for each asset: P_{up} and P_{down}. These variables represent the asset's power that will be utilized in meeting the up and down regulation signal. For simplicity of notation, consider a case where only fuel-based (e.g., diesel) generators provide regulation. Then, the cost function (8) is modified to include the net cost of providing regulation in conjunction with energy as,

$$min \sum_{k=0}^{T} C_g^k + C_{es}^k + C_{grid}^k + C_{up}^k - R_{up}^k - R_{down}^k \quad (9)$$

where, C_{up}^k, R_{up}^k, R_{down}^k are the cost and revenue of providing up and down regulation from the individual assets. The cost and revenue are functions of the regulation power outputs P_{up} and P_{down}. The revenue from providing regulation can be obtained using a prediction of regulation price based on historical prices multiplied by P_{up} and P_{down}. The constraints (1) and (2) are modified as

$$\left.\begin{matrix} P_{g,min} \le P_{g,i}^{k} + P_{up,i}^{k} + P_{down,i}^{k} \le P_{g,min} \\ P_{down,i}^{k} \le 0 \\ 0 \le P_{up,i}^{k} \end{matrix}\right\} \quad (10)$$

$$RD\Delta t \le P_{g,i}^{k+1} - P_{g,i}^{k} + P_{up,i}^{k+1} - P_{up,i}^{k} + P_{down,i}^{k+1} - P_{down,i}^{k} \le RU\Delta t \quad (11)$$

The above optimization problem solves for the schedule for individual microgrid assets to simultaneously meet the energy demand of the microgrid as well as provide power output for frequency regulation. The optimization objective is to minimize the microgrid's net financial outlay (or maximize profit) over a certain time duration (typically 24 hours) while staying within the asset constraints. All the constraints and objective can be written as linear functions of the power variables, and so, the problem can be solved using a linear programming solution.

III. Simulation Results

Results are presented in this section of the algorithm described in section II applied to a test microgrid system. The test system consists of one 2.1 MW run-of-river hydro generator, 6.2 MW diesel generators, 520kW/3.3MWh energy storage, and a peak load of 4.7 MW. The test system also has a grid connection with potential for time-of-day energy prices.

A. Results Without Participation in Regulation

First, a case is considered where the microgrid is not participating in the frequency regulation market. The optimization problem is solved for a predicted load and renewable profile over a 24-hour time horizon. The test case assumes that the microgrid is grid connected, thereby allowing the possibility of importing a portion of the power demand from the grid. The amount of power that would be imported from the grid is a function of the grid buy price, as the overall optimization objective is to determine the least cost solution. The resulting power outputs of the dispatchable units (diesel generators) for three different grid buy price scenarios are as shown in Figure 1. As expected, it can be seen from the figure that as the grid buy price decreases, the proportion of net load (load – renewable) being met by the grid increases and the proportion of net load served using diesel generators decreases.

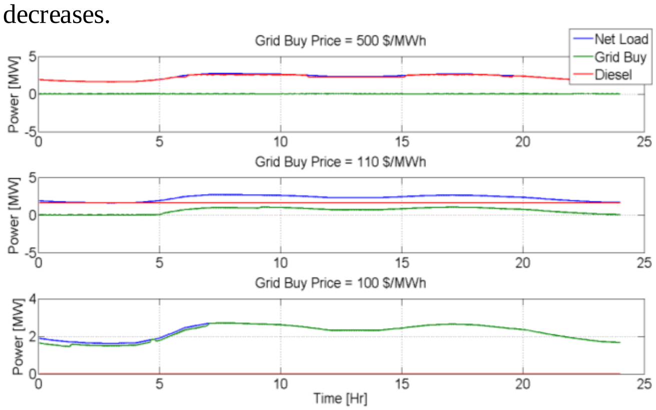

Figure 1. Dispatch results for different grid prices – no regulation.

B. Results With Participation in Up-Regulation

Next, the study considers a case where the microgrid is participating in an Up-regulation market. In such a case, the constraints (10) and (11) described in section II get modified as:

$$\left.\begin{array}{r} P_{g,min} \le P_{g,i}^{k} + P_{up,i}^{k} \le P_{g,min} \\ 0 \le P_{up,i}^{k} \end{array}\right\} \qquad (12)$$

$$RD\Delta t \le P_{g,i}^{k+1} - P_{g,i}^{k} + P_{up,i}^{k+1} - P_{up,i}^{k} \le RU\Delta t \qquad (13)$$

The expected regulation price based on historical trends is shown in Figure 2. The resulting up-regulation power outputs P_{up} for the three grid buy price scenarios are as shown in Figure 3. The power outputs P_g corresponding to meeting the load demand are shown in Figure 4.

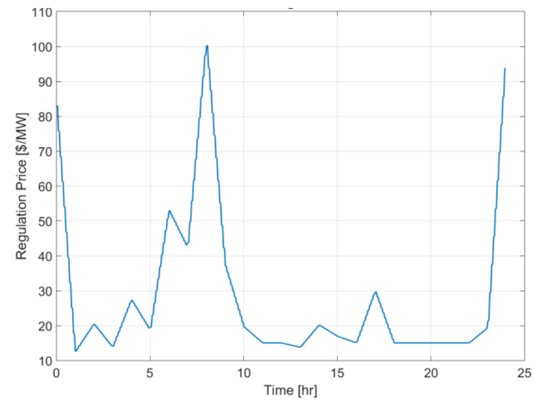

Figure 2. Expected regulation price for a 24-hour time horizon.

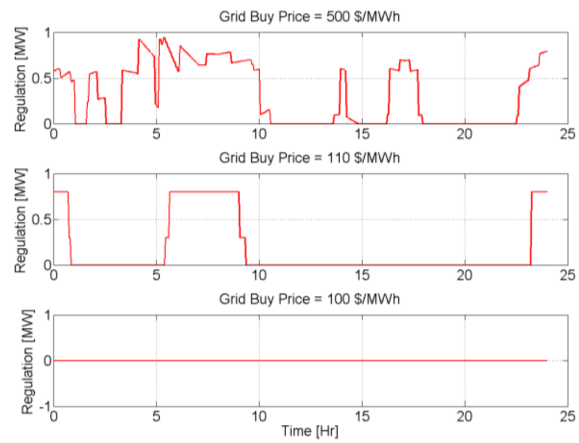

Figure 3. Day-ahead regulation schedule for Up-regulation.

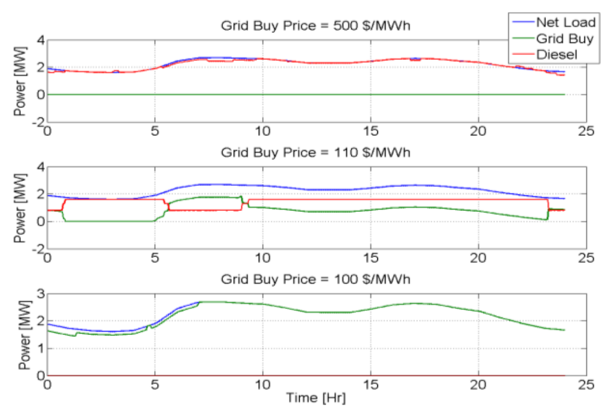

Figure 4. Dispatch results for different grid prices – with Up-regulation.

Figures 3 and 4 show that when the grid buy price is high, the load demand is almost entirely met by diesel generators. In such a scenario when diesel generators are ON, it can be seen that it is also incentivizing to participate in the Up-regulation market. However, as the grid price reduces, a larger proportion of the load is met from grid imports and therefore the participation of diesel generators in regulation is also reduced.

The optimization result in Figure 3 shows the profile of regulation power over a 24-hour time horizon for every few minutes. This needs to be post-processed in order to obtain a power bid for each hourly time slot. This final step can be done as simply as just determining the average value across all the samples within the given hourly time slot. In practice, there are no penalties for deviation of real-time regulation from the day-ahead cleared bid as long as the deviation is within a certain percentage value. Therefore, if B is the desired hourly bid for a given hourly time slot, and there is no penalty as long as the deviation is within say 95% availability, B can be obtained by solving

$$0.95B \geq \sum_{j=1}^{N} P_{up} \tag{14}$$

where N is the number of time samples in the given hourly time slot. From (14), it can be seen that as the availability criteria increases, the hourly bid decreases. This is also reflected in the result in Figure 5.

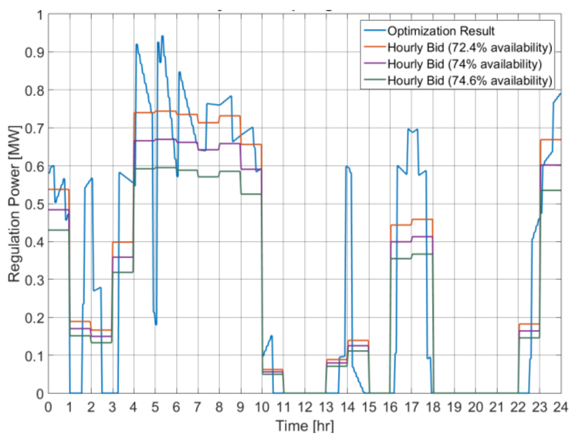

Figure 5. Post-processing of optimization result to obtain hourly bid.

Typically, there is a difference between the amount of power that is bid in the day-ahead market and the real-time regulation command requested by the system operator. To account for this difference, a scaling factor γ is introduced in the optimization formulation's cost function (9) as:

$$min \sum_{k=0}^{T} C_g^k + C_{es}^k + C_{grid}^k + \gamma C_{up}^k - R_{up}^k \tag{15}$$

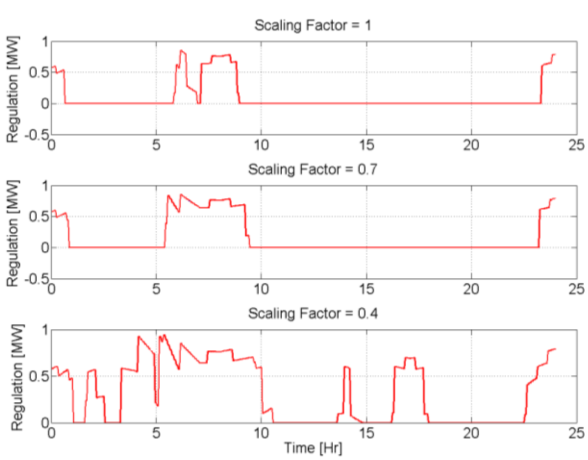

Figure 6. Day-ahead regulation schedule for different cost scaling factors.

The scaling factor is only multiplied with the cost and not the revenue because irrespective of what the real-time regulation signal, the revenue is based on the cleared bid and not the actual signal. Figure 6 shows the resulting up-regulation power outputs for three different scaling factors. As can be seen from Figure 6, as the scaling factor decreases, the regulation power output increases. This is because a lower scaling factor implies a lower cost for the same revenue, and therefore it is more beneficial to participate in regulation for a smaller scaling factor.

C. *Results With Participation in Up and Down Regulation*

Next, a scenario is considered where there is an independent Up and Down regulation market. The formulation given in (10) is used to determine the P_{up} and P_{down}. Unlike Up regulation (where there is a cost associated with providing the additional power from the diesel generators), there is a reduction in cost associated with providing down regulation. The resulting regulation power outputs are as shown in Figure 7. As can be seen from the figure, the Up and Down regulation power outputs are non-symmetrical and these depend on the profitably of participating in the respective market for the given time slot.

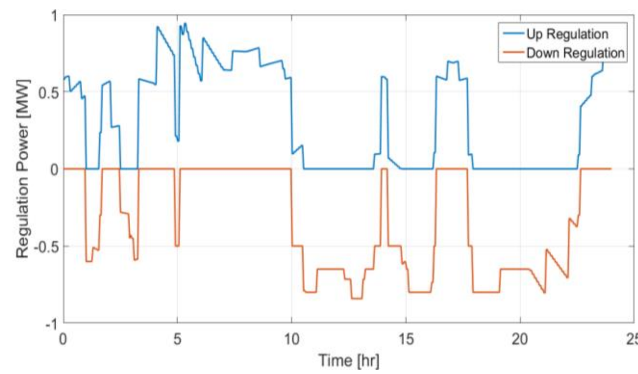

Figure 7. Day-ahead regulation schedule for Up and Down regulation.

Finally, recognizing that even with the emerging rules around participation of non-traditional assets in grid services, there is a minimum capacity requirement. By enforcing the following linear constraint,

$$\sum P_{Up,\ i}^{k} \geq MW_{threshold} \tag{16}$$

the optimization framework can explicitly account for such a requirement.

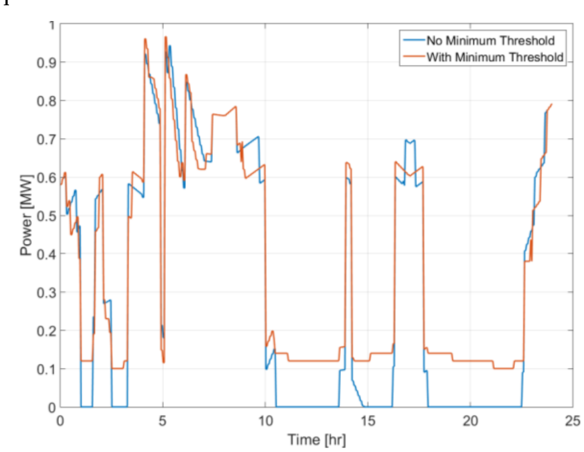

Figure 8. Resulting regulation power with capacity requirement = 100 kW.

Figure 8 shows the resulting Up-only regulation power output with such a constraint accounted for. As can be seen from the figure, the regulation power output is greater for the case when there is a minimum capacity threshold. Figure 9 shows the resulting regulation power output when the resource constraint is changed to 250 kW.

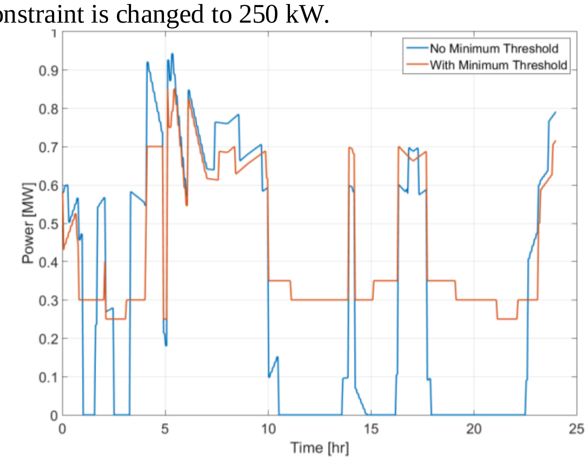

Figure 9. Resulting regulation power with capacity requirement = 250 kW.

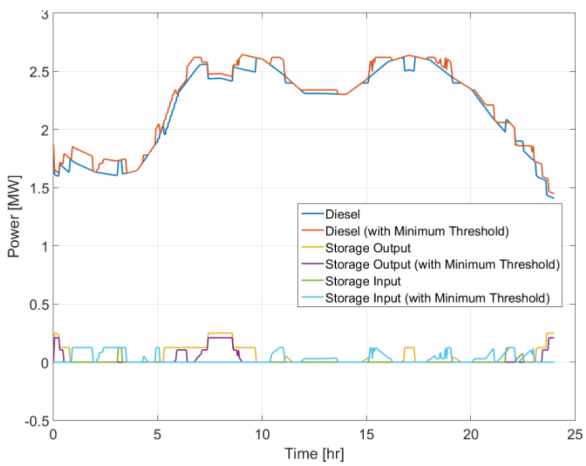

Figure 10. Resulting asset power with capacity requirement = 100 kW.

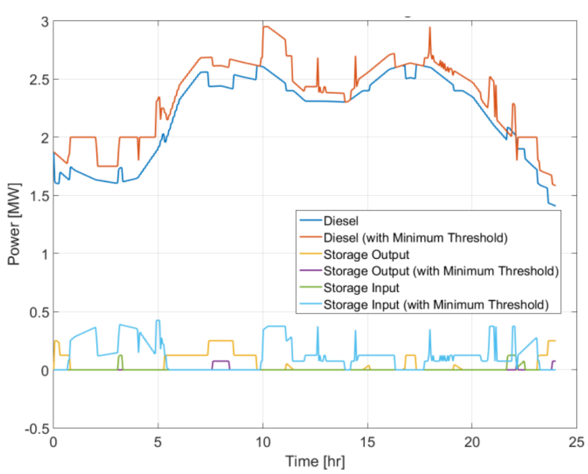

Figure 11. Resulting asset power with capacity requirement = 250 kW.

Comparing Figures 8 and 9, it can be seen that as the minimum capacity constraint increases, there is greater participation in regulation. However, this has an impact on the energy dispatch profile of the microgrid assets, as shown in Figures 10 and 11. The results show when there is no minimum threshold, most of the load is served by diesel generators, and at certain times by energy storage devices. As the threshold increases from 0 to 100 kW and then to 250 kW, we can see that a greater proportion of the load is being met by diesel generators, and the amount of energy storage being used to provide the load is decreasing. The reason for this is that due to the minimum capacity constraint being imposed on the diesel generators, they are being forced to operate even during time periods where it would be more economical to use energy storage. The capacity constraint forces the solution to be less optimal as compared to a situation when there is no constraint.

IV. Conclusion

This paper has considered the problem of how the controllable assets within a microgrid can be committed and dispatched to participate effectively in ancillary services. Furthermore this study is appropriate and timely as new regulations are being introduced to encourage participation from non-traditional generation assets in power grid functions, including creation of new market incentives. Specifically, this paper has considered the problem of day-ahead scheduling of microgrid assets for participation in frequency regulation. The algorithm proposed in this paper accounts for day-ahead forecasts of loads and renewables, forecast of regulation clearing price, individual asset capabilities and constraints in order to determine the optimal balance of energy and regulation participation for individual assets in the microgrid.

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