Robust Microgrid Operation Considering Renewable Power Uncertainties

R. A. Gupta
Department of Electrical Engineering
Malaviya National Institute of Technology
Jaipur, India

Nandkishor Gupta
Department of Electrical Engineering
Malaviya National Institute of Technology
Jaipur, India
nkgupta1987@gmail.com

Abstract—Micro Grids (MGs) are clusters of the Distributed Energy Resource (DER) units and loads. MGs are self-sustainable and generally operated in two modes: 1) grid connected 2) grid isolated. This paper focuses on optimal MG operation for these modes in deregulated environment considering wind uncertainty. Wind uncertainty can be modeled by interval forecasting using time series based Autoregressive Integrated Moving Average (ARIMA) model. Other uncertainties like Photo-Voltaic (PV) generation demand and grid prices are modeled in deterministic manner. Considering the various uncertainties this paper proposes robust optimization based approach for optimal scheduling of MG in deregulated environment. Proposed approach is illustrated by practical case study considering different test cases. Comparative analysis between obtained results and existing approaches shows strength of proposed approach.

Keywords-Microgrid Operation, Generation Scheduling, Uncertainties, Robust Optimization.

NOMENCLATURE

The main notations that are used throughout in this paper are listed below and others are defended as required.

A. Sets or Indices

\( j \) Index of conventional dispatchable units running from 1 to \( N_j \).
\( t \) Index of time period running from 1 to \( N_t \).
\( w \) Index of wind power units running from 1 to \( N_w \).
\( k \) Index of robustness running from 1 to \( N_k \).

B. Variables

\( P_{j,t} \) Power generated by dispatchable unit \( j \) at time \( t \) (\( kW \)).
\( P_{grid,t} \) Power imported/exported from/to the grid at time \( t \) (\( kW \)).
\( P_{shd,t} \) Demand shedding at time \( t \) (\( kW \)).
\( r_{u,j,t} \) Scheduled upward reserve of unit \( j \) at time \( t \) (\( kW \)).
\( r_{d,j,t} \) Scheduled downward reserve of unit \( j \) at time \( t \) (\( kW \)).
\( \Delta P_{w,t} \) Expected wind power deviation at time \( t \) (\( kW \)).
\( \Delta PV_{v,t} \) Expected PV power deviation at time \( t \) (\( kW \)).

C. Parameters

\( N_j \) Number of dispatchable units.
\( N_t \) Number of time periods.
\( \lambda_{grid,t} \) Grid power price at time \( t \) (\$/\( kWh \)).
\( \lambda_{shed} \) Load shedding price (\$/\( kWh \)).
\( P_{d,t} \) Forecasted system’s demand at time \( t \) (\( kW \)).
\( P_{f,w,t} \) Forecasted wind power generation at time \( t \) (\( kW \)).
\( P_{f,t} \) Forecasted solar power generation at time \( t \) (\( kW \)).
\( p_{max} \) Total installed capacity of wind units (\( kW \)).
\( p_{min} \) Minimum output power of unit \( j \) (\( kW \)).
\( P_{max} \) Maximum output power of unit \( j \) (\( kW \)).
\( p_{max} \) Capacity of the line linking the upstream grid and the MG (\( kW \)).
\( r_{u,j}^{\text{grid}} \) Maximum upward reserve capacity of conventional generating units.
\( r_{d,j}^{\text{grid}} \) Maximum downward reserve capacity of conventional generating units.

I. INTRODUCTION

A microgrid is a small-scale power supply network that is designed to provide power for a small community. MG can be operated into two modes: grid connected and grid isolated. In grid-connected mode, MG can export its excess power to the grid and can import its deficit power from grid. On other hand, MG can manage its demand independently in grid-isolated mode. Due to uncontrollable nature of demand and generators’ technical limitations, efficient and economic management of these generators is highly desirable. With increasing penetration of renewable sources like wind and solar in the distribution power system MG management system may become complex. The complexity of MGs’ energy
management is further enhanced by the deregulation of power systems because of volatility of grid prices [1]-[2]. Several approaches has been proposed in the recent literatures for MG’s energy management considering renewable resources. A simple optimization based approach has been used for MG” operation considering different market policies [3]. However, renewable power and market price uncertainties are modelled deterministically. A Lagrangian Relaxation along with genetic algorithm approach can optimally schedule generators of isolated MG [4]. However, uncertainty in renewable generation still modelled deterministically. Stochastic programming based approach suggested for optimal MG operation considering wind and solar power uncertainties [5]. In [5] the impact of network losses and network constraints also investigated. Renewable power uncertainties have been modelled through different scenarios. An artificial intelligence based methodology has been proposed for optimal MG operation with an objective of minimization of operation and emission cost considering renewable power and demand uncertainties [6]. These uncertainties are modelled using artificial neural network.

Recent studies are focused on optimizing the generators cost in MG, however scheduling in both modes i.e. grid connected and grid isolated is not considered and complexity of optimization problem in both deterministic and stochastic approach is not justified. The two main difficulties with such an approach are: (i) knowing the exact distribution for data, and thus enumerating scenarios that capture this distribution is rarely satisfied in practice, and (ii) the size of the resulting optimization model increases drastically as a function of the number of scenarios, which poses substantial computational challenges [13]. Therefore, there is a need to develop an approach that will able to overcome these issues.

This paper aims to develop a new approach for optimal MG operation in both grid-connected and grid-isolated modes considering renewable power uncertainties. Considering the various uncertainties this paper proposes a new approach for optimal MG operation in deregulated environment. Proposed approach can model MG generation scheduling problem in robust optimization framework. Wind uncertainty can be modeled by interval forecasting using time series based Autoregressive Integrated Moving Average (ARIMA) model. Other uncertainties like PV generation demand and grid prices are modeled using deterministic or point forecasting. Proposed approach is illustrated by practical case study considering different test cases. Comparative analysis between obtained results and existing approaches shows strength of proposed approach.

The rest of paper is organized as follows: Section II, describe the nature of problem and basic problem formulation microgrid energy scheduling model. Section III, proposes the formulation of the robust microgrid energy-scheduling model considering renewable power generation uncertainties. Section IV, introduces the test platform and provides a detailed case study of proposed algorithm and compares the simulation results with those obtained using a traditional deterministic approach under various operational conditions. Section V concludes the paper.

II. PROBLEM DISRUPTION

Mircogrid energy controller manages MGs with an objective of operation cost minimization subject to different constraints. Parameters in both grid-connected and isolated mode are slightly different. The detailed formulation of MG energy management formulation is described below:

A. Grid connected mode

In grid connected mode, the upstream grid is connected to the microgrid and power exchange is allowed. The upstream grid can participate in providing power and spinning reserve to the microgrid [3]. The day-ahead unit commitment problem should minimize the total expenses of operating the microgrid in grid-connected mode for a scheduling horizon of 24 hours. The total expenses consist of the local generators operating cost, the cost of the power imported from the upstream grid. In grid-connected mode, the basic objective function is formulated in deterministic approach as:

$$\min \sum_{j} \sum_{t} \left( C_j \left( P_{j,t} \right) + r_{j,t}^m - r_{j,t}^d \right) + P_{grid,j} \lambda_{grid,j}$$  \hspace{1cm} (1)

Subject to

$$\sum_{j} \sum_{w} P_{w,j,t} + \sum_{w} PV_{w,t} = P_{d,t}^f, \forall t$$  \hspace{1cm} (2)

$$\sum_{j} \left( r_{j,t}^m - r_{j,t}^d \right) + \sum_{w} \left( \Delta P_{w,j} \right)$$  \hspace{1cm} (3)

$$+ \sum_{w} \Delta PV_{w,t} + P_{grid,t} - \Delta P_{d,t} = 0, \forall t$$

$$\Delta P_{a,d} = P_{a,d}^f - P_{a,d}^v, \forall a, \forall t$$  \hspace{1cm} (4)

$$\Delta PV_{v,t} = PV_{v,t}^a - PV_{v,t}^f, \forall v, \forall t$$  \hspace{1cm} (5)

$$\Delta P_{d,t} = P_{d,t}^a - P_{d,t}^f, \forall d, \forall t$$  \hspace{1cm} (6)

$$P_{min} \leq P_{j,t} \leq P_{max}$$  \hspace{1cm} (7)

$$r_{j,t}^m \leq R_{j,t}^d, \forall j, \forall t$$  \hspace{1cm} (8)

$$r_{j,t}^d \leq R_{j,t}^d, \forall j, \forall t$$  \hspace{1cm} (9)

$$P_{j,t} + r_{j,t}^m - r_{j,t}^d \geq 0, \forall j, \forall t$$  \hspace{1cm} (10)

$$P_{j,t} + r_{j,t}^m - r_{j,t}^d \leq P_{j,t}^d, \forall j, \forall t$$  \hspace{1cm} (11)

$$P_{grid,t} \leq P_{grid,t}^d, \forall t$$  \hspace{1cm} (12)

Objective function (1) states that operating cost of conventional generating units’ power, reserves and cost of power imported/exported from/to grid should be minimized. Constraint (2) states that sum of scheduled power of conventional generating units, wind power units and PV generation must be equal to day-ahead forecasted demand. Constraint (3) shows that at actual time sum of wind, PV and demand deviation must be balanced by scheduling
A robust approach to solving an optimization problem with uncertain data has been proposed in the early 1970s and has recently been extensively studied and extended. Robust optimization refers to the modeling of optimization problem with data uncertainty to obtain a solution that is guaranteed to be “good” for all or most possible realization of the uncertain parameter. There are three types of robustness in optimization problem (i) constraint robustness (ii) objective robustness (iii) combinational robustness [12], [13]. If uncertainty is present in only constraint parameter than problem is of constrained robustness and if uncertainty is present in only objective function parameter than problem is of objective robustness, and if uncertainty is present in both constraint parameter and objective function parameter than problem is of combinational robustness. In proposed work, wind is considered as uncertain parameter and for modeling uncertainties in wind power here scenarios are not generated. Here first wind power is forecasted on the basis of historical data than its lower and upper limits are generated at 95% confidence interval [14].

### A. Grid Connected Mode:

$$
\text{min } \sum_{t=1}^{N_t} \left( C_j \left( P_{j,t} \right) + \delta_{j,t}^u - \delta_{j,t}^l \right) + P_{d,t}^\text{shed} \cdot A_{d,t}^\text{shed} \\
\text{Subject to}
\sum_{j=1}^{N_j} \left( \delta_{j,t}^u - \delta_{j,t}^l \right) + \sum_{w=1}^{N_w} \left( \Delta P_{w,t} \right) \\
+ \sum_{v=1}^{N_v} \Delta P_{v,t} + P_{d,t}^\text{shed} - \Delta P_{d,t} = 0, \quad \forall t
$$

### B. Grid Isolated Mode:

$$
\text{min } \sum_{t=1}^{N_t} \sum_{j=1}^{N_j} \left( C_j \left( P_{j,t} \right) + \delta_{j,t}^u - \delta_{j,t}^l \right) + P_{d,t}^\text{shed} \cdot A_{d,t}^\text{shed} \\
\text{Subject to}
\sum_{j=1}^{N_j} \left( \delta_{j,t}^u - \delta_{j,t}^l \right) + \sum_{w=1}^{N_w} \left( \Delta P_{w,t} \right) \\
+ \sum_{v=1}^{N_v} \Delta P_{v,t} + P_{d,t}^\text{shed} - \Delta P_{d,t} = 0, \quad \forall t
$$

The remaining constraints and equations are the same as mentioned already by equations (2), (4)- (11). Objective function (13) states that operating cost of conventional generating units’ power, reserves, and cost of demand shedding should be minimized. Constraint (14) states that at actual time total system deviation must be balanced by scheduling conventional generating units’ upward/downward reserves and demand shedding power. Other constraints are same as in grid connected mode; however one more constraint (16) states that shedding demand power is always less than the demand.

### III. PROPOSED FORMULATION

A robust approach to solving an optimization problem with uncertain data has been proposed in the early 1970s and has recently been extensively studied and extended. Robust optimization refers to the modeling of optimization problem with data uncertainty to obtain a solution that is guaranteed to be “good” for all or most possible realization of the uncertain parameter. There are three types of robustness in optimization problem (i) constraint robustness (ii) objective robustness (iii) combinational robustness [12], [13]. If uncertainty is present in only constraint parameter than problem is of constrained robustness and if uncertainty is present in only objective function parameter than problem is of objective robustness, and if uncertainty is present in both constraint parameter and objective function parameter than problem is of combinational robustness. In proposed work, wind is considered as uncertain parameter and for modeling uncertainties in wind power here scenarios are not generated. Here first wind power is forecasted on the basis of historical data than its lower and upper limits are generated at 95% confidence interval [14]. Than robust optimization formulation is used as follows:

#### A. Grid Connected Mode:

$$
\text{min } \sum_{t=1}^{N_t} \sum_{j=1}^{N_j} \left( C_j \left( P_{j,t} \right) + \delta_{j,t}^u - \delta_{j,t}^l \right) + P_{d,t}^\text{shed} \cdot A_{d,t}^\text{shed} \\
\text{Subject to}
\sum_{j=1}^{N_j} \left( \delta_{j,t}^u - \delta_{j,t}^l \right) + \sum_{w=1}^{N_w} \left( \Delta P_{w,t} \right) \\
+ \sum_{v=1}^{N_v} \Delta P_{v,t} + P_{d,t}^\text{shed} - \Delta P_{d,t} = 0, \quad \forall t
$$

#### B. Grid Isolated Mode:

In the isolated mode, it is also required to minimize the expenses of the MG; however, more attention is given to meeting the demand with stable operation. The objective function (16) similar to (1) however auxiliary variable used to obtain the corresponding linear expressions. Objective function (16) states that if uncertainty is present in both constraint parameter and objective function parameter than problem is of combinational robustness. In proposed work, wind is considered as uncertain parameter and for modeling uncertainties in wind power here scenarios are not generated. Here first wind power is forecasted on the basis of historical data than its lower and upper limits are generated at 95% confidence interval [14]. Than robust optimization formulation is used as follows:

$$
\text{min } \sum_{t=1}^{N_t} \sum_{j=1}^{N_j} \left( C_j \left( P_{j,t} \right) + \delta_{j,t}^u - \delta_{j,t}^l \right) + P_{d,t}^\text{shed} \cdot A_{d,t}^\text{shed} \\
\text{Subject to}
\sum_{j=1}^{N_j} \left( \delta_{j,t}^u - \delta_{j,t}^l \right) + \sum_{w=1}^{N_w} \left( \Delta P_{w,t} \right) \\
+ \sum_{v=1}^{N_v} \Delta P_{v,t} + P_{d,t}^\text{shed} - \Delta P_{d,t} = 0, \quad \forall t
$$

The remaining constraints and equations are the same as mentioned already by equations (2), (4)- (11). Where, $\Gamma_k$ is the degree of robustness which controls the robustness of problem, while variable $z_k$ and $q_k$ are dual variables used to take into account the known bounds of wind power while $\bar{y}_k$ is an auxiliary variable used to obtain the corresponding linear expressions. Objective function (16) states that dual variables used in robust wind power scheduling must balance the difference of lower and upper bounds of wind power. Constraints (19), (20), and (22) show that dual variables used in robust approach must be positive. Other constraints are same as in grid connected mode in basic formulation of MG generation scheduling problem.
function in the isolated mode is stated as
\[ \min \sum_{t=1}^{N_t} \left[ \sum_{j=1}^{N_j} \left( C_j (P_{f,j}^u - P_{f,j}^d) + P_{d,j}^\text{Shed} \right) \right] \] (23)
\[ \sum_{j=1}^{N_j} \left( P_{f,j}^u - P_{f,j}^d \right) + \sum_{v=1}^{N_v} \Delta P_{v,j} + P_{d,j}^\text{Shed} - \Delta P_{d,j} = 0, \forall t \] (24)

The remaining constraints and equations are the same as mentioned already by equations (2), (4) - (11), (17), (19) - (22)
Objective function (23) states that operating cost of conventional generating units' power, reserves and cost of demand shedding should be minimized with robust optimization way wind power scheduling. Constraint (24) states that at real time wind spillage must be balanced by scheduling conventional generating units’ upward/downward reserves and demand shedding power. Other constraints are same as in grid-connected mode in proposed approach.

C. Proposed Algorithm
The following algorithm is used to build the hourly wind power offering:
Step 1: Parameter Initialization. Set initial output of wind unit is \( W_t = W_t^{\max} \), degree of robustness is \( \Gamma_k = N_k \), and incremental factor \( G^k \) that takes increasing values in the interval [0, 1].
Step 2: Iteration Counter Initialization. Define total number of iteration \( N_k \). Counter start with \( k = 1 \).
Step 3: Wind Uncertainty Characterization. Get upper and lower limits of wind power using ARIMA model. Then set wind power in the iteration as \( W_{t,k} = G^k \left( W_t^{\max} - W_t^{\min} \right) \). Value of wind power is limited in the interval \( [W_t^{\max}, W_t^{\min} - W_{t,k}] \).
Step 4: Problem Solution. Formulated MG scheduling problem for both modes is solved considering wind uncertainty.
Step 5: Check Iteration Counter. If iteration \( k \leq N_k \), update range of incremental factor \( G^k \) by step \( \delta \) and repeat Step 3 and 4. Otherwise, go to next step.
Step 6: Published results. Show obtained optimal cost of MG along with optimal value of scheduled dispatchable unit generation and reserves.
Step 7: End.

IV. CASE STUDY
A. Data
In this study, installed capacity of PV unit and wind units is considered as 200 kW and 1.34 MW respectively. Wind units consists ENERCON turbines model which parameters are detailed in manufacturer database [15]. The historical wind speed data used in this study taken form publically available database at Illinois Institute of Rural Affair, USA. [16]. Along with renewable units, 10 dispatchable units are considered, there parameters are shown in Table I. Hourly grid price, demand profile and PV generation profile is shown in Table II. The capacity of line linking grid and MG is considered to 3000 kW. Historical grid price obtained for PJM electricity market.

<table>
<thead>
<tr>
<th>Dispatchable unit</th>
<th>Installed capacity (kW)</th>
<th>Upward reserve (kW)</th>
<th>Downward reserve (kW)</th>
<th>Marginal cost ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>600</td>
<td>240</td>
<td>240</td>
<td>0.0141</td>
</tr>
<tr>
<td>2</td>
<td>600</td>
<td>240</td>
<td>240</td>
<td>0.0222</td>
</tr>
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<td>3</td>
<td>400</td>
<td>160</td>
<td>160</td>
<td>0.02775</td>
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<tr>
<td>4</td>
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<tr>
<td>9</td>
<td>100</td>
<td>40</td>
<td>40</td>
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<tr>
<td>10</td>
<td>100</td>
<td>40</td>
<td>40</td>
<td>0.05154</td>
</tr>
</tbody>
</table>

B. Simulation Results
Using above discussed data, proposed approach is
illustrated by considering two cases. In Case I, grid connected operation simulated while in Case II, grid isolated operation of MG is simulated. Both test cases are coded in GAMS platform using CPLEX solver [17].

Fig. 1 shows the forecasted wind power with upper and lower level using ARIMA model.

For Case I, obtained scheduled power, upward and downward reserve of dispatchable units using proposed approach are shown in Fig. 2, 3 and 4 respectively. Fig. 5 shows power imported/exported to/from grid in Case I. From these figures, it is observed that when grid price is higher MG can export their reserve capacity to grid and vice-versa to reduce its operating cost.

Fig. 2: Scheduled power of dispatchable units in Case I

Fig. 3: Scheduled upward reserve in Case I

Fig. 4: Scheduled downward reserve in Case I

Fig. 5: Power imported/exported to/from grid in Case I

Similar to previous Case, Fig 6, 7, and 8 shows scheduled dispatchable unit power, upward and downward reserve using proposed approach for Case II, respectively.

Fig. 6: Dispatchable unit scheduled power in Case II

Fig. 7: Scheduled upward reserve in Case II
Fig. 8: Scheduled downward reserve in Case II

Fig. 9: Demand shedding in Case II

Demand shedding in Case II is shown in Fig. 9. From these figures, it is visualized that MG can utilize its upward reserve capacity during peak demand to reduce demand shedding events. The cost of 1kW demand shedding is $1000.

C. Discussion

A comparative analysis is performed to illustrate proposed approach on daily MG operation. Obtained daily MG operation cost using proposed robust optimization approach is compared with deterministic and stochastic approach as shown in Table III. From the table it is observed that reduction in daily cost using proposed approach in Case II is higher as compare to Case I. Because in Case II, small reduction in demand shedding event results large reduction is operation cost.

Table III
Comparative Analysis of MG Daily Operation Cost

<table>
<thead>
<tr>
<th>Approaches</th>
<th>Case I</th>
<th>Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deterministic</td>
<td>857.9346</td>
<td>636642.230</td>
</tr>
<tr>
<td>Stochastic</td>
<td>830.6901 (-3.07 %)</td>
<td>568712.504 (-10.67 %)</td>
</tr>
<tr>
<td>Proposed</td>
<td>814.8662 (-5.02 %)</td>
<td>526375.796 (-17.32 %)</td>
</tr>
</tbody>
</table>

V. CONCLUSION

A robust optimization based approach has been proposed in this paper for optimal generation scheduling of MG in both grid-connected and -isolated modes. Wind power uncertainty has been modeled through interval forecasting using ARIMA model. A comparative study on daily MG operation cost using proposed approach with deterministic and stochastic approach has been done. A significant reduction in operation cost clearly shows strength of proposed approach in MG generation scheduling. Proposed approach can be enhanced by incorporating various uncertainties and technical constraints in future.

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