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Generation Scheduling in Microgrids under Uncertainties in Power Generation

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***Abstract*—This paper studies the scheduling of power generation in a Microgrid (MG) that has a group of dispatchable and non-dispatchable generators. In order to maximize the benefits of the resources available in a MG, an optimal scheduling of the power generation is required. Renewable resources have an intermittent nature that causes uncertainties in the system. These added uncertainties must be taken into consideration when solving the generation scheduling problem in order to obtain reliable solutions. The operation of a MG in grid-connected mode and isolated mode is analyzed in this paper for different demand profiles. Two mixed integer linear programming (MILP) models for the day-ahead unit commitment problem in a MG are proposed. Each model corresponds to one mode of operation. Uncertainty handling techniques are integrated in both models. The models are solved using the General Algebraic Modeling System (GAMS). Two study cases are examined to study the operation of a MG, and to evaluate the effects of uncertainties on the day-ahead unit commitment problem.**

***Index*—Distributed Generation (DG), Microgrid (MG), optimization, unit commitment, spinning reserve.**

NOMENCLATURE

A. Indices

j	Index of dispatchable units, $j \in \{1, \dots, J\}$
k	Index of time period, $k \in \{1, \dots, K\}$
s	Index of scenarios, $s \in \{1, \dots, S\}$

B. Variables

Z	Total expenses ($)
U_{jk}	Status of unit j at time k (0/1)
P_{jks}	Power generated by unit j at time k scenario s (kW)
$P_{GIn,ks}$	Power imported from the upstream grid at time k scenario s (kW)
$P_{GOut,ks}$	Power exported to the upstream grid at time k scenario s (kW)
$P_{shed,ks}$	Load shedding at time k scenario s (kW)
$P_{Curt,ks}$	Power curtailment at time k scenario s (kW)
$U_{shed,ks}$	Load shedding decision variable at time k scenario s (0/1)
$U_{curt,ks}$	Power curtailment decision variable at time k scenario s (0/1)
SRu_{jks}	Reserve provided by unit j at time k scenario s (kW)
$SRgrid_{ks}$	Reserve provided by the upstream grid at time k scenario s (kW)
$SRall_{ks}$	Available spinning reserve in the system at time k scenario s (kW)

C. Constants

J	Number of dispatchable units
K	Number of time periods
S	Number of scenarios
ρ_s	Probability of scenario s
C_r	Reserve price ($/kWh)
C_{grid}	Upstream grid power price ($/kWh)
C_{DSM}	Load shedding and power curtailment price ($/kWh)
D_{ks}	Forecasted system's demand at time k scenario s (kW)
W_{ks}	Forecasted wind power generation at time k scenario s (kW)
PV_{ks}	Forecasted solar power generation at time k scenario s (kW)
SR_{ks}	System's spinning reserve requirement at time k scenario s (kW)
P_j^{min}	Minimum output power of unit j (kW)
P_j^{max}	Maximum output power of unit j (kW)
P_{grid}^{max}	Capacity of the line linking the upstream grid and the MG (kW)
$\alpha_D, \alpha_W, \alpha_{PV}$	Load, wind, and solar forecasting error factors
μ	Upper bound for if-condition linearization

I. INTRODUCTION

THE electricity grid is being restructured to allow for higher penetration levels of Distributed Generators (DGs) in order to maximize their utilization. Microgrids (MG) have been introduced recently in distribution networks and are defined as small power systems that consist of various distributed micro generators which are capable of supplying a significant portion of the local demand. MGs provide multiple benefits to the system including reducing customers' interruption costs, reducing system losses, and accommodating higher penetration levels of renewable resources [1], [2]. MGs can operate in grid-connected mode, in which they are allowed to exchange power with the upstream grid, or in isolated mode, where they are isolated from the upstream grid and their local generators are the only source of power supply. Optimizing the operation of a

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MG is essential to reduce fuel costs, energy not served, power losses, and gas emissions.

The generation scheduling problem consists of two sub problems: Unit Commitment (UC), and Economic Dispatch (ED). The UC problem defines the on/off status of the dispatchable generation units over a daily or weekly time horizon, while the ED problem finds the optimal operating power levels of the units committed by the UC problem over a shorter time horizons: i.e., hourly or in real time. Both problems search for an optimal solution that satisfies the generators and network constraints.

The optimal scheduling of power resources in a MG has been discussed recently in many research articles. Basu et al. [3] presented a planned scheduling model for the economic dispatch problem in a combined heat and power (CHP) based MG. Optimal locations, sizes, and types of distributed energy resources (DERs) were first selected considering minimum power losses as the objective function. Economic power sharing between a mix of DERs was then performed using differential evolution while satisfying all the constraints. However, the work presented in [3] did not consider any type of renewable resources, and studied the system only during grid-connected mode. Furthermore, the applied optimization technique, i.e. differential evolution, cannot guarantee an optimal solution.

Tsikalakis and Hatziargyriou [4] studied the operation of a MG during grid-connected mode. Two market policies were analyzed: minimizing operating cost, and maximizing revenue. The UC problem was solved using priority list, and economic dispatch was performed using sequential quadratic programming. However, authors considered only the case of grid-connected mode, and did not study the MG in the isolated mode. Furthermore, the effects of uncertainties due to forecasting errors were not tackled.

Chen et al. [5] proposed a new method to size energy storage systems (ESS) in MGs. The day-ahead UC problem was used to facilitate the proposed method in grid-connected and isolated mode. Load and renewable power forecasting errors were taken into consideration by increasing the required amount of spinning reserve. Nevertheless, the proposed UC formulation remained deterministic. The authors did not consider multi-scenario stochastic models that could have covered a wider spectrum of uncertainties.

This paper studies the scheduling of power generators in a MG that has a group of dispatchable and non-dispatchable generators. Two mathematical models will be proposed to optimally solve the day-ahead UC problem. One model is for a MG operating in grid-connected mode and the other is for a MG operating in isolated mode. The proposed models will handle uncertainties in load and renewable power generation forecast by allocating proper amounts of spinning reserve and by using a multi-scenario stochastic model instead of the classical deterministic model.

The paper will first introduce the uncertainty handling techniques in Section II. Section III will discuss the operation of the MG. The formulation of the day-ahead UC problem will be presented in details in Section IV. Section V will cover analysis and case studies using the proposed models. Finally, conclusions are given in Section VI.

II. Handling Uncertainties

In the classical UC problem, there are two main sources of uncertainties: load forecasting errors, and unit outage events. The integration of renewable sources adds more uncertainties to the UC problem due to the power forecasting errors. For example, practical wind power forecasting tools still suffer from a mean absolute error of 10% on average for day-ahead forecast [6]. There are two main approaches in the literature to handle uncertainties: additional reserve requirement [5], [7], and multi-scenario stochastic models [8], [9], [10]. While uncertainties are modeled implicitly in the first approach, the second approach considers multiple scenarios for the load and renewable power generation, and therefore the uncertainties are explicitly represented. This paper will integrate both approaches in the UC formulation for a better representation of the uncertainties.

A. Additional reserve requirement

Spinning reserve is essential in any power system to respond to sudden outages in generation units and to maintain power supply to all the loads in the system. Classically, the amount of spinning reserve is selected deterministically to be equal to the largest committed unit in the system, or to a certain percentage of the demand. However, increasing the penetration level of renewable generators in the system can cause possible shortages due to sudden decreases in renewable power generation. Increasing the amount of spinning reserve can help in accommodating the volatility of renewable power generators, and reduce the effects of forecasting errors. The additional reserve amounts are determined by the errors of the forecasting tools [5], and are represented as a percentage of the demand and the generated renewable power. In MGs, the spinning reserve can be provided by the dispatchable generators inside the MG, the upstream grid in case of the grid-connected mode, or using load shedding in the isolated mode.

B. Multi-scenario stochastic models

Several methods were introduced in the literature to generate the load and renewable power scenarios [7], [9], [10]. One common method is to discretize the probability distribution function (PDF) of the forecasting error. Load and wind power forecasting errors are usually represented using normal PDFs [8], [11]. Similarly, solar power forecasting error can be modeled as a normal PDF [9]. Each continuous PDF is discretized to create a set of finite states such that a probability is assigned to each state according to its PDF. The discrete sets of the load δ_D, wind power δ_w, and solar power δ_{pv} forecasting errors are described as follows [9]:

$$\delta_D = \{(e_D^1, \rho_D^1), (e_D^2, \rho_D^2), .. (e_D^n, \rho_D^n)\} \tag{1}$$

$$\delta_w = \{(e_w^1, \rho_w^1), (e_w^2, \rho_w^2), .. (e_w^m, \rho_w^m)\} \tag{2}$$

$$\delta_{pv} = \{(e_{pv}^1, \rho_{pv}^1), (e_{pv}^2, \rho_{pv}^2), .. (e_{pv}^q, \rho_{pv}^q)\} \tag{3}$$

where e_D^i is the error of the i^{th} state in the load forecasting error PDF, ρ_D^i is the corresponding probability of that state, and n is the number of states in the discrete set. The discrete sets of wind and solar power forecasting errors are defined similarly. The states' probabilities are subject to

$$\sum_{i=1}^{n}\rho_D^i = \sum_{i=1}^{m}\rho_W^i = \sum_{i=1}^{q}\rho_{pv}^i = 1 \tag{4}$$

The discrete sets in (1), (2), and (3) can be used to create a set of scenarios that represent the possible deviations from the load, wind power, and solar power forecasted values. The total number of scenarios created equals to the product of the number of states in each discrete set. Each scenario has a probability ρ_S^i that is equal to the product of the probabilities of the states' corresponding to that scenario such that

$$\sum_{i=1}^{S}\rho_S^i = \sum_{i=1}^{S}\rho_D^i\rho_W^i\rho_{pv}^i = 1 \tag{5}$$

$$S = n \times m \times q \tag{6}$$

where S is the total number of scenarios. The created scenarios and their corresponding probabilities are used to formulate the UC problem as a multi-scenario stochastic model. The UC problem should find an optimal solution that satisfies all the constraints under any scenario.

III. Microgrid Operation

There are different policies and objectives considered in the literature to optimize the operation of MGs [4]. The objective of the optimization problem presented in this paper is to minimize the MG expenses during both modes of operation. It is also considered that the MG has to accommodate all the renewable power generation. Nevertheless, power curtailment might be indispensable in the case of security risks. The MG contains critical loads that should be provided with adequate reserve at all times in order to maintain their power supply.

A. Grid-connected mode

In this mode, power exchange with the upstream grid is allowed. The upstream grid can be considered as a virtual generator that is committed to the MG as long as it is operating in the grid-connected mode [3]. The virtual generator has a minimum power supply limit of zero and a maximum limit equal to the capacity of the line linking the upstream grid and the MG. The virtual generator is assumed to generate power at a higher cost compared to the other dispatchable units inside the MG. Furthermore, the upstream grid provides a significant portion if not the entire required spinning reserve. The operation of a MG in grid-connected mode can be summarized in the following cases:

1) Normal operation: The demand is first supplied by the available renewable power, and then by the dispatchable units. The upstream grid is connected but neither supplying nor receiving any power. However, its capacity is enough to supply the entire spinning reserve.

2) Excess demand: In this case, the demand exceeds the capacity of renewable and dispatchable generators. Therefore, the upstream grid supplies the excess demand. Spinning reserve is provided by the remaining capacity of the upstream grid line.

3) Excess renewable generation: In this case, the entire demand can be supplied by the renewable generators and any excess power is supplied to the upstream grid. The spinning reserve can be provided by the upstream grid.

B. Isolated mode

In this mode, the only sources of power supply available to the MG are the local dispatchable and renewable generators. Spinning reserve can be provided only by the dispatchable generators. Load shedding and power curtailment are allowed to maintain the power balance in the system. However, those two measures are performed only if it is necessary to do so. The operation of a MG in the isolated mode can be summarized in the following cases:

1) Normal operation: The demand is first supplied by the available renewable power. Dispatchable units are then dispatched to supply the remaining demand. The unused capacity of the committed dispatchable units provides the spinning reserve.

2) Excess demand: In this case, the demand exceeds the capacity of both renewable and dispatchable generators. Therefore, excess demand must be shed to preserve the power balance. Furthermore, extra load shedding should take place in order to free a portion of the dispatchable units' capacity to provide the required reserve for the critical loads. Load shedding decision variable is described as

$$U_{shed,ks} = \begin{cases} 1, & D_{ks} > W_{ks} + PV_{ks} + \sum_{j=1}^{J} P_j^{max} - SR_{ks} \\ 0, & otherwise \end{cases} \tag{7}$$

3) Excess renewable generation: In this case, the entire demand can be supplied by the renewable generators and any excess renewable power is curtailed. However, providing spinning reserve for the critical loads requires committing at least one dispatchable unit with enough capacity. It is worth mentioning that once a dispatchable units is committed, it has to generate a minimum power P_{min}. Therefore, additional renewable power curtailment that is equal to P_{min} will take place in order to maintain the power balance in the system. Power curtailment decision variable is described as

$$U_{curt,ks} = \begin{cases} 1, & W_{ks} + PV_{ks} > D_{ks} - \sum_{j=1}^{J}\left(P_j^{min} \times U_{jk}\right) \\ 0, & otherwise \end{cases} \tag{8}$$

IV. Problem Formulation

This section presents the formulation of the day-ahead UC problem in a MG. The formulation presented builds on the UC formulation introduced in [9] and [12]. The uncertainty handling techniques presented in Section II, and the MG operation policies discussed in Section III are considered in this formulation. Two different models are presented; one for a MG operating in grid-connected mode, and the other in isolated mode. Both models are represented using Mixed Integer Linear Programming (MILP).

A. Grid-connected mode

In the grid-connected mode, the objective function is to minimize the expenses of the MG. It is stated as

$$\min \quad Z=\sum_{s=1}^{S}\rho_s\left[\sum_{k=1}^{K}\sum_{j=1}^{J}\left(C_j(P_{jks})+SU_{jk}\right)+\sum_{k=1}^{K}(SRall_{ks}\times C_r)+\sum_{k=1}^{K}\left(P_{GIn,ks}\times C_{grid}\right)\right] \tag{9}$$

where $C_j(P_{jks})$ and SU_{jk} are the linearized fuel cost function and the start-up cost function of unit j. The problem is subject to a set of constraints given by

- System power balance

$$\sum_{j=1}^{J}P_{jks}+W_{ks}+PV_{ks}+P_{GIn,ks}-P_{GOut,ks}=D_{ks} \tag{10}$$

- Dispatchable units output limit and spinning reserve

$$P_j^{min}\le P_{jks}\le P_j^{max} \tag{11}$$

$$SRu_{jks}=\left(U_{jk}\times P_j^{max}\right)-P_{jks} \tag{12}$$

- Upstream grid power limits and spinning reserve

$$0\le P_{GIn,ks}\le P_{grid}^{max} \tag{13}$$

$$0\le P_{GOut,ks}\le P_{grid}^{max} \tag{14}$$

$$SRgrid_{ks}=P_{grid}^{max}-P_{GIn,ks} \tag{15}$$

- Total available spinning reserve

$$SRall_{ks}=\sum_{j=1}^{J}SRu_{jks}+SRgrid_{ks} \tag{16}$$

- Microgrid's spinning reserve requirement

$$SRall_{ks}\ge SR_{ks}+\alpha_D.D_{ks}+\alpha_W.W_{ks}+\alpha_{PV}.PV_{ks} \tag{17}$$

The last three terms in the right hand side of (17) are the extra reserve added to mitigate the effects of uncertainties in the load, wind power, and solar power forecast. In addition to the constraints shown in (10)-(17), dispatchable units are subject to ramp-up and ramp-down constraints, minimum up-time and minimum down-time constraints, in addition to logical constraints [12].

B. 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 in the isolated mode is stated as

$$\min \quad Z=\sum_{s=1}^{S}\rho_s\left[\sum_{k=1}^{K}\sum_{j=1}^{J}\left(C_j(P_{jks})+SU_{jk}\right)+\sum_{k=1}^{K}(SRall_{ks}\times C_r)+\sum_{k=1}^{K}\left(\left(P_{shed,ks}+P_{Curt,ks}\right)\times C_{DSM}\right)\right] \tag{18}$$

The problem is subject to a set of constraints given by

- System power balance

$$\sum_{j=1}^{J}P_{jks}+W_{ks}+PV_{ks}+P_{shed,ks}-P_{Curt,ks}=D_{ks} \tag{19}$$

- Total available spinning reserve

$$SRall_{ks}=\sum_{j=1}^{J}SRu_{jks} \tag{20}$$

The remaining constraints are exactly similar to the grid-connected mode except for the upstream grid constraints (13)-(15) which are not applied in this mode.

To limit load shedding and power curtailment actions only to the cases when security risks are present, conditions (7) and (8) were added. However, the two conditions are nonlinear and must be linearized to preserve the MILP formulation. Condition (7) can be linearized as follows

$$-D_{ks}+W_{ks}+PV_{ks}+\sum_{j=1}^{J}P_j^{max}-SR_{ks}\le\mu(1-U_{shed,ks}) \tag{21}$$

$$D_{ks}-W_{ks}-PV_{ks}-\sum_{j=1}^{J}P_j^{max}+SR_{ks}\le\mu.U_{shed,ks} \tag{22}$$

$$P_{shed,ks}\le\mu.U_{shed,ks} \tag{23}$$

where μ is a sufficiently large upper bound. Condition (8) can be linearized in a similar way. The price of load shedding and power curtailment C_{DSM} in the objective function (18) is assigned to a high value. This is to insure that, when conditions (7) and (8) are satisfied, renewable and dispatchable generators has higher priority over load shedding and power curtailment.

V. Simulations and Results

A MG that has 8 dispatchable units, one wind turbine, and one PV system is considered in this study. The total installed capacity of the dispatchable units is equal to 2.6MW. The parameters of the dispatchable units are as given in [13]. The capacity of the wind turbine is equal to 1.1MW. The turbine's parameters and the wind speed profile are taken from [14]. The PV system capacity is 200kW, where the system parameters, the insolation profile, and the temperature profile are obtained from [13]. The capacity of the line linking the upstream grid and the MG is assumed to be equal to 1000kW. A 24 hour demand profile of a MG is adapted from [4]. Two linearly modified versions of the demand profile are created to simulate the cases of excess demand and excess renewable generation. One third of the demand is assumed to be critical.

The PDFs of load, wind power, and solar power forecasting errors are extracted from [9]. The load and wind power PDFs are discretized into 5 states and the solar power PDF into 3 states as shown in Fig. 1. A total of 75 scenarios are generated.

The two models presented in Section IV were modeled using the General Algebraic Modeling System (GAMS), and solved using CPLEX solver. The time horizon of both models is 24 hours. The price of the grid power is set at 100\$/kWh, and the price of load shedding and power curtailment equals to 200\$/kWh. Both prices were selected such that they are more expensive than the fuel cost of any of the dispatchable units. The price of the reserve equals to 0.01\$/kWh [5]. The spinning reserve requirement in the grid-connected mode is equal to 10% of the entire load.

During the isolated mode, the reserve requirement is equal to 10% of the critical load only. The forecasting error factors are adapted from [5] as follows: α_D = 0.03, α_W = 0.13, and α_{PV} = 0.09. The value of the constant μ used in (21)-(23) equals to 5000.

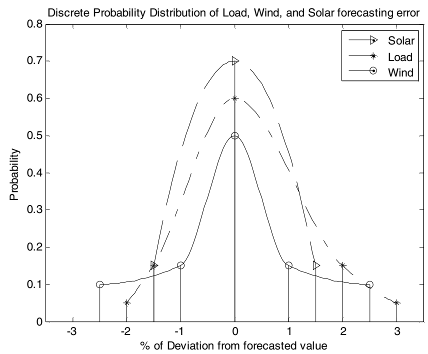

Fig. 1. Discretized probability distribution functions of the load, wind power, and solar power forecasting error.

A. Microgrid operation

To study the operation of a MG in the isolated and grid-connected mode, two demand profiles are applied to each of the optimization models presented in Section IV. Fig. 2 shows the solution of the day-ahead UC problem for the four cases under study.

In the case of an excess demand profile, Fig. 2a and Fig. 2b, the power imported from the upstream grid in the grid-connected mode is lower than the amount of load shedding in the isolated mode. This is because load shedding is performed in the isolated mode not only to supply the excess demand, but also to free a portion of the dispatchable units' capacity to supply the required spinning reserve.

For an excess renewable power generation profile, Fig. 2c and Fig. 2d, the excess renewable power is curtailed in the isolated mode. It is noticed that at time periods when power curtailment is performed, at least one dispatchable unit is committed and operating at P_{min}. This is because the spinning reserve has to be supplied by the dispatchable units. In the grid-connected mode, the excess renewable power is supplied to the upstream grid instead of being curtailed. It is noticed that during time periods when power is supplied to the upstream grid, few dispatchable units are still committed and operated at minimum power. At these time periods, the available renewable power is capable of supplying the whole demand. However, it is more economical to operate an already committed unit at minimum power instead of shutting all the units off and then turning them on again. This is mainly due to the expensive start-up cost of the dispatchable generators.

B. Effects of uncertainties

To study the effects of uncertainties on the day-ahead UC problem in MGs, four cases are considered.

Case 1) No renewables: This case assumes that there are no uncertainties in the system. It replaces the renewable generators that has a total capacity of 1.3MW with three dispatchable units of capacitates 600kW, 400kW, and 300kW. The dispatchable units' parameters are similar to the ones presented in [13]. It is assumed that the load forecast is perfect, and thus there is only one scenario to examine.

Case 2) With renewables + no uncertainties: This case uses the same system that was presented earlier in this section with 8 dispatchable units, one wind turbine, and one PV system. However, it assumes that all the forecasts are perfect. Thus, only one scenario is considered.

Case 3) With renewables + uncertainties: This case is similar to case 2; however, uncertainties are considered. Uncertainties are represented using the 75 scenarios that were generated earlier.

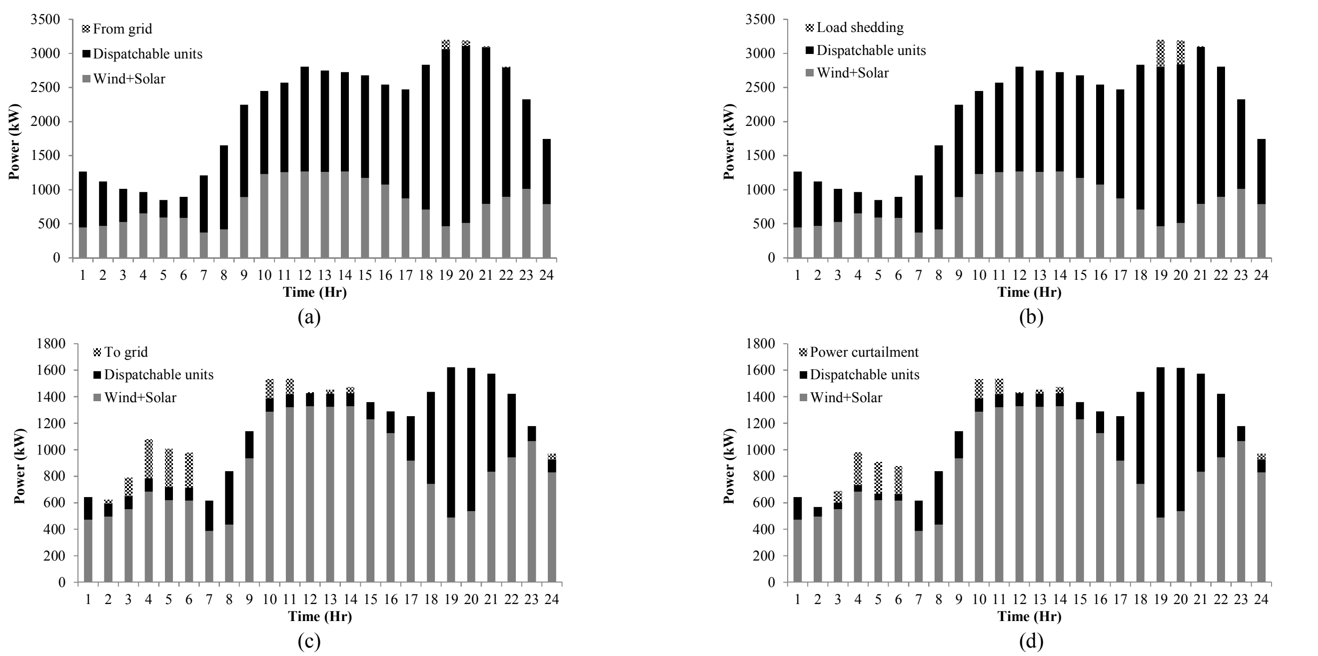

Fig. 2. Microgrid operation: a) Grid-connected mode: Excess demand, b) Isolated mode: Excess demand, c) Grid-connected mode: Excess renewable generation, d) Isolated mode: Excess renewable generation.

Case 4) With renewables + higher uncertainties: This case is similar to case 3; however, higher uncertainties are assumed. The added uncertainties are obtained by assigning a larger standard deviation to the PDFs of the forecasting errors. The new distribution functions are extracted from [9]. The number of scenarios considered remains at 75 scenarios.

The four cases are applied to a MG operating under an excess demand profile during both isolated and grid-connected modes. Table I and Table II show the MG expenses for each of the four cases in both modes of operation. The MG expenses are equal to the addition of the dispatchable units' operating cost, reserve cost, the cost of supplying power from the upstream grid in the grid-connected mode, and the cost of load shedding in the isolated mode.

TABLE I
EFFECTS OF UNCERTAINTIES ON A MG OPERATING IN GRID-CONNECTED MODE

Case	MG expenses ($)	Dispatchable units' operating cost ($)	Upstream grid power cost ($)	Reserve cost ($)
1	310782	310451	0	331
2	193866	190743	2800	324
3	196237	191466	4442	328
4	197821	191627	5865	329

TABLE II
EFFECTS OF UNCERTAINTIES ON A MG OPERATING IN ISOLATED MODE

Case	MG expenses ($)	Dispatchable units' operating cost ($)	Load Shedding cost ($)	Reserve cost ($)
1	312098	312001	0	97
2	229998	188363	41543	92
3	233592	190297	43181	114
4	235342	190590	44638	114

For both modes of operation, cases 2-4 have lower expenses compared to case 1 due to the presence of renewable generators that are supplying power at no cost. It can be also noticed that the load shedding cost in cases 2-4 in the isolated mode are higher than the upstream grid cost for the same cases in the grid-connected mode. This is because the amount of load shedding during the isolated mode includes the spinning reserve requirement in addition to the excess demand. The reason behind no load shedding cost or upstream grid cost in case 1 is that the renewable generators were replaced with dispatchable generators that can reliably supply power whenever it is needed.

Cases 2-4 show the effects of using a multi-scenario stochastic model to solve the day-ahead UC problem. In both modes of operation, increasing the number of scenarios from one scenario (case 2) to 75 scenarios (case 3) increases all the costs in the problem. In the same manner, considering higher forecasting errors, as in case 4 compared to case 3, increases all the costs in the problem. This is because increasing the uncertainties in the problem requires committing additional or larger dispatchable units in order to mitigate the possible deviations in the demand and renewable power supply.

It is important to mention that energy storage systems can provide an alternative source of spinning reserve [5]. Therefore, they can reduce load shedding and power curtailment, and thus the MG's operating cost during the isolated mode.

VI. CONCLUSION

Two optimization models to solve the day-ahead UC problem in a MG operating in grid-connected mode and isolated mode were presented in this paper. Both models handled forecast uncertainties by assigning an additional spinning reserve requirement and by applying a multi-scenario stochastic model. Several study cases were examined to investigate the operation of a MG. It was concluded that additional load shedding is needed in the isolated mode in order to supply the required spinning reserve. On the other hand, the upstream grid provides all the required spinning reserve in the grid-connected mode. It was also found that when higher uncertainties are present, it is required to commit more dispatchable units in the system to cater the possible deviations from the forecasted values, and therefore resulting in higher expenses. Future work includes the integration of energy storage systems in MGs to supply the required reserve during the isolated mode, and to help in mitigating the effects of uncertainties.

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