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Microgrid optimal scheduling considering normal and emergency operation

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ABSTRACT

This paper deals with the optimal scheduling of a microgrid (MG) equipped with dispatchable distributed generators (DGs), renewable generators and electrical storages (batteries). A chance-constrained model is developed to handle normal operation and emergency conditions of MG including DG outage and unwanted islanding. Purchasing reserve from the upstream grid is also considered. Moreover, the uncertainties of loads and renewable resources are incorporated into the model. Furthermore, a novel probabilistic formulation is presented to determine the amount of required reserve in different conditions of MG by introducing separate probability distribution functions (PDFs) for each condition. Accordingly, an index named as the probability of reserve sufficiency (PRS) is introduced. The presented model keeps a given value of PRS in normal and emergency conditions of MG operation. In addition, some controllable variables are added to the chance constraints as an innovative technique to reduce the complexity of the model. Finally, a test microgrid is studied in different case studies and the results are evaluated.

Article Info

Keywords:
Microgrid, Renewable generation, probability distribution function (PDF), Unwanted Islanding, DG outage

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Nomenclature

b, bb: Index of battery storage devices, running from 1 to N_b

d: Index of demands, running from 1 to N_d

g, gg: Index of dispatchable generators, running from 1 to N_g

m: Index of energy blocks offered by generators, running from 1 to N_m

t: Index of time periods, running from 1 to N_t

$\mathbf{u_{gt}}$: 1 if unit is scheduled on during period t and 0 otherwise

$\mathbf{u_{bt}^{C}}$: 1 if battery b is scheduled charging at period t and 0 otherwise

$\mathbf{u_{bt}^{D}}$: 1 if battery b is scheduled discharging at period t and 0 otherwise

$\mathbf{u_{mt}^{B}}$: 1 if microgrid is scheduled buying power from main grid at period t and 0 otherwise

$\mathbf{u_{mt}^{S}}$: 1 if microgrid is scheduled selling power to main grid at period t and 0 otherwise

$\mathbf{A_g}$: Operating cost of dispatchable unit g at the point of minimum output of unit g

$\mathbf{C_{gt}(m)}$: Marginal cost of the m[th] block of energy offered by dispatchable DG g in period t.

$\mathbf{C_{mt}^{S}, C_{mt}^{B}}$: Selling /buying price of energy to/from main grid in period t

$\mathbf{C_{bt}}$: Degradation cost of battery b during period t

$\mathbf{P_{gt}(m)}$: Power output scheduled from the m[th] block of energy, offered by dispatchable unit g during period t.

$\mathbf{P_{g}^{min}, P_{g}^{max}}$: Max./min. output of DG g.

$\mathbf{P_{gt}}$: Power output scheduled from unit g in period t.

$\mathbf{P_{mt}}$: Exchange power with upstream grid during period t.

$\mathbf{P_{m}^{max}}$: Maximum of exchange power with upstream grid.

$\mathbf{P_{mt}^{S}, P_{mt}^{B}}$: Selling/ buying power to/from main grid during period t.

$\mathbf{P_{bt}}$: Output power of battery b in period t

$\mathbf{P_{b}^{C,max}, P_{b}^{D,max}}$: Maximum charging/discharging power of battery b.

$\mathbf{P_{bt}^{C}, P_{bt}^{D}}$: Charging/discharging power of battery b in period t.

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$\mathbf{p_{dt}}$: Power consumption scheduled for demand d in period t.

Penalty: Penalty factor (a constant parameter)

$\mathbf{PRS_{Dt}}$: Probability of reserve sufficiency during period t, in the normal operation

$\mathbf{PRS_{it}}$: Probability of reserve sufficiency during period t, when unwanted islanding occurs

$\widetilde{\mathbf{P_{WTt}}}, \widetilde{\mathbf{P_{PVt}}}$: Wind turbine and Photo Voltaic power output during period t

$\mathbf{Q_{gt}^{U}, Q_{gt}^{D}}$ **:** Cost of up- and down-spinning reserve of unit g in period t

$\mathbf{Q_{bt}^{U}, Q_{bt}^{D}}$ **:** Cost of up- and down-spinning reserve of battery b in period t

$\mathbf{Q_{mt}^{UB}, Q_{mt}^{DB}}$ **:** Cost of up- and down-spinning reserve of the main grid in period t

$\mathbf{R_{gt}^{U}, R_{gt}^{D}}$: Up- and down- reserve of unit g in period t

$\mathbf{R_{bt}^{U}, R_{bt}^{D}}$: Up- and down-reserve of battery b in period t

$\mathbf{R_{mt}^{UB}, R_{mt}^{DB}}$ **:** Up- and down-reserve purchased from the main grid in period t.

$\mathbf{R_{g}^{U,max}}, \mathbf{R_{g}^{D,\mathit{max}}}$: Maximum up/down ramp rate of DGs.

$\mathbf{SU_{gt}}$: Startup cost of unit g in period t.

$\mathbf{SOC_{bt}^{min}}, \mathbf{SOC_{bt}^{max}}$: Maximum/minimum state of charge of battery b.

$\mathbf{SOC_{bt}}$: State of charge of battery b in period t.

URNS: Required Up-Reserve Not Supplied

DRNS: Required Down-Reserve Not Supplied

$\mathbf{\Delta P_{Wt}}, \mathbf{\Delta P_{PVt}}$: Forecasting error of Wind turbine and Photo Voltaic power output.

$\mathbf{\Delta P_{\mathit{d}}}$ **:** Forecasting error of demand d.

$\mathbf{\Delta t}$ **:** Time duration of each period.

$\boldsymbol{\tau}$ **:** Amount of time available of DGs and batteries to ramp up/down their output to deliver the reserve

η_b^C, η_b^D **:** Battery charging/discharging efficiency factor.

I.Introduction

One of the most important challenges in microgrids (MGs) optimal scheduling is maintaining the power balance under both normal and emergency conditions [1-3]**.** Some valuable pieces of research have been done in this respect, which fit into three general categories in terms of the type of factors that affect the power balance of MGs.

1- Uncertainties of the demand and renewable resources

Some researchers have dealt with deterministic power and reserve scheduling in which the total amount of required reserve is determined before the scheduling process while the uncertainties of renewable resources and demand is neglected [4-6]. On the other hand, in the stochastic method, reserve scheduling is carried out regarding the uncertainties of renewable resources and demand which are modeled by probabilistic scenarios [7-10].

2- Outages in microgrid

Many studies about large scale power systems have noted the sudden outage of generating units [11, 12]. However, this event has recently been noticed in MG studies. In [13], a probabilistic method is proposed to determine the amount of required reserve for MGs considering the sudden outage of DGs inside the MG. However, purchasing reserve from the upstream grid (UG) is not considered.

It should be mentioned that the special features of MGs, such as islanding, are not considered in the two above-mentioned groups.

3- Unwanted islanding

In the grid-connected mode, the UG is seen as an infinite bus, so that when MG is encountered with DG outages or renewable variants, the UG can instantly balance the power in the MG, but incur additional costs for the MG [14]. However, when unwanted islanding occurs, the power balance is disturbed in the MG. To prevent the complete collapse of the electrical system of the MG, the power balance should be immediately rebuilt only by relying on internal resources of the MG. Hence, MG scheduling has recently been considered along with considering unwanted islanding [15-17]. In [15], an MG optimal scheduling model is proposed to minimize the operating costs during grid-connected mode by considering the reserve for unwanted islanding and renewable uncertainties. However, DGs are assumed to be able to satisfy the constraints of unwanted islanding, to provide 100% of the required reserve (RR) of MG, and to supply all local loads in the islanded mode. An MG optimal scheduling model is presented in [16] to minimize the operating costs during the grid-connected mode while multi-period islanding constraints are considered. In the model, the generation adequacy of the MG in the islanded mode operation is guaranteed for certain specified durations in case of any unwanted islanding. However, the uncertainty of renewable resources is neglected. In [17], a chance-constrained scheduling strategy is proposed to consider the unwanted islanding. A new concept, i.e. probability of successful islanding (PSI), is propounded to evaluate the probability of keeping enough reserve required to meet the local demand and also to compensate the fluctuations of demand and renewable resources after sudden unwanted islanding. In the model, although the reserve constraints are well-formulated for unwanted islanding, but the reserve constraints are not considered for the normal operation of MGs. In addition, in [15-17], the outage of DGs and the purchasing reserve from the UG are not considered.

Regarding the different nature of the three above-mentioned factors, simultaneous consideration of all these aspects complicates the scheduling problem. Therefore, it is necessary to find a suitable way to handle this complexity. In this respect, this study develops a chance-constrained model for the optimal scheduling of an MG which can handle simultaneously the DG outage, the unwanted islanding, and the forecasting error of demand and renewable resources. A simple and innovative technique is applied to reduce the complexity of the scheduling model, by adding controllable variables to the chance constraints. Moreover, separate probability distribution functions (PDFs) are formulated to determine the required reserve (RR) of the MG in different operational conditions (i.e., normal operation, when DG outage occurs and when unwanted islanding is occurs). Based on these PDFs, a probabilistic index, i.e. probability of reserve sufficiency (PRS) is defined to evaluate the reserve sufficiency for different conditions of MG operation. For example, when the outage of a certain DG (g) occurs at a given time (t), PRS_{gt} indicates the probability of the sufficiency of the existing reserve in such a way that the existing reserve compensates both the output power of the failed DG and the uncertainty of demand and renewable resources.

A similar concept is defined for other operational conditions. The proposed model maintains a certain amount of PRS in different conditions of MG operation. In summary, the main contributions of the paper can be highlighted as follows:

- A chance-constrained model for microgrid scheduling is proposed.
- The model considers islanding and DG outage.
- The model considers uncertainty of renewable and demand.
- An innovative technique is applied to reduce the complexity of the scheduling model.
- A novel index is proposed to evaluate the sufficiency of the reserve.

II. Mathematical modeling and problem formulation

A. Objective function

The objective function illustrated in Eq. (1) is to minimize the total operating cost (TOC) of the MG. The first term indicates the cost function of DGs. The second term represents the battery degradation cost. The third and the fourth terms are the costs of up- and down-spinning reserve from both the DGs and the batteries. The fifth term refers to the cost/benefit of buying/selling energy from/to UG and the sixth term is the cost of up- and down-spinning reserve from the UG.

The seventh to ninth terms are the penalty terms that are used in the present paper to solve the proposed chance-constrained optimization problem. Detailed descriptions about these terms are explained in 2.4.

$$TOC = \sum_{t=1}^{N_t}\sum_{g=1}^{N_g}\left[\sum_{m=1}^{N_m} C_{gt}(m)P_{gt}(m) + A_g u_{gt} + SU_{gt}\left(u_{gt}, u_{g,t-1}\right)\right] + \sum_{t=1}^{N_t}\sum_{b=1}^{N_b} C_{bt}(P_{bt}^C + P_{bt}^D) + \sum_{t=1}^{N_t}\sum_{g=1}^{N_g}\left(Q_{gt}^U R_{gt}^U + Q_{gt}^D R_{gt}^D\right) + \sum_{t=1}^{N_t}\sum_{b=1}^{N_b}(Q_{bt}^U R_{bt}^U + Q_{bt}^D R_{bt}^D) + \sum_{t=1}^{N_t}(C_{mt}^B P_{mt}^B - C_{mt}^S P_{mt}^S) + \sum_{t=1}^{N_t}(Q_{mt}^{UB} R_{mt}^{UB} + Q_{mt}^{DB} R_{mt}^{DB}) + \left[\sum_{t=1}^{N_t}\sum_{g=1}^{N_g} Penalty_g * \left(URNS_{gt} + DRNS_{gt}\right)\right] + \left[\sum_{t=1}^{N_t} Penalty_i * (URNS_{it} + DRNS_{it})\right] + \left[\sum_{t=1}^{N_t} Penalty_D * (URNS_{Dt} + DRNS_{Dt})\right] \quad (1)$$

Since the cost function of DGs has an increasing curve, $C_{gt}(1)$ has the lowest value and $C_{gt}(m)$ has the highest value. Therefore, the blocks of energy of unit g will be scheduled in order of 1 to Nm.

B. Common operational constraints

<u>Power balance:</u> The power balance constraint is represented in (2), and the forecasted net demand is represented in (3). $\widetilde{N_t^D}$ represents the net demand and the upper symbol "~" on some parameters indicates the existence of prediction error of those parameters.

$$\sum_{g=1}^{N_g} P_{gt} + \sum_{b=1}^{N_b} P_{bt}^D - \sum_{b=1}^{N_b} P_{bt}^C + P_{mt} = \widetilde{N_t^D} \quad (2)$$

$$\widetilde{N_t^D} = \sum_{l=1}^{N_d} \widetilde{P_{dt}} - \widetilde{P_{WTt}} - \widetilde{P_{PVt}} \quad (3)$$

<u>Operational constraints of DG units:</u> The production costs of DGs are approximated in constraints (4) and (5) by blocks of energy [18], and the output of DGs is forced by constraint (6) to be zero if it is not committed.

$$P_{gt} = \sum_{m=1}^{N_m} P_{gt}(m) + u_{gt}P_g^{min} \quad \forall g, \forall t \quad (4)$$

$$0 \le P_{gt}(m) \le P_{gt}^{max}(m) \quad \forall g, \forall t \quad (5)$$

$$P_{gt}^{min}u_{gt} \le P_{gt} \le P_{gt}^{max}u_{gt} \quad \forall g, \forall t \quad (6)$$

<u>Operational constraints of batteries:</u> The maximum charging/discharging power of a battery is represented by constraints (7) and (8). These two mutually exclusive states are ensured by (9). In (10), the battery state of charge (SOC) is represented and the SOC's limit is enforced by (11).

Since the scheduling of the microgrid has been considered for 24 hour, equation (12) states that the primary stored energy at the time interval 1 is taken equal to the stored energy at the time interval 24 [19, 20]. Further, (13) represents the output power of a battery.

$$0 \le P_{bt}^C \le P_b^{C,max}u_{bt}^C \quad \forall b, \forall t \quad (7)$$

$$0 \le P_{bt}^D \le P_b^{D,max}u_{bt}^D \quad \forall b, \forall t \quad (8)$$

$$u_{bt}^D + u_{bt}^C \le 1 \quad \forall b, \forall t \quad (9)$$

$$SOC_{bt} = SOC_{b,t-\Delta t} + P_{bt}^C.\eta_b^C.\Delta t - P_{bt}^D.\frac{1}{\eta_b^D}.\Delta t \quad \forall b, \forall t \quad (10)$$

$$SOC_b^{min} \le SOC_{bt} \le SOC_b^{max} \quad \forall b, \forall t \quad (11)$$

$$\sum_{t=1}^{N_t} P_{bt}^D = \sum_{t=1}^{N_t} P_{bt}^C \quad \forall b \quad (12)$$

$$P_{bt} = P_{bt}^{D} - P_{bt}^{C} \quad \forall b, \forall \tag{13}$$

Up and down spinning reserve constraints of DGs: The DG's up-spinning reserve is constrained by the difference between its maximum capacity and current output in (14) and its ramping rate in (15). Likewise, (16) and (17) include the down-spinning reserve constraints.

$$R_{gt}^{U} \le P_{g}^{max} u_{gt} - P_{gt} \qquad \forall g, \forall t \tag{14}$$

$$R_{gt}^{U} \le R_{g}^{U,max}.\tau.u_{gt} \quad \forall g, \forall t \tag{15}$$

$$R_{gt}^{D} \le P_{gt} - P_{g}^{min} u_{gt} \qquad \forall g, \forall t \tag{16}$$

$$R_{gt}^{D} \le R_{g}^{D,max}.\tau.u_{gt} \quad \forall g, \forall t \tag{17}$$

Up and down reserve constraints of batteries: The up-spinning reserve of a battery is limited by the difference between its maximum discharging power and current output in (18) and the difference between its current SOC and minimum SOC in (19). Similarly, (20) and (21) include the down-spinning reserve constraints of a battery.

$$R_{bt}^{U} \le P_{b}^{D,max} u_{bt} - P_{bt} \qquad \forall b, \forall t \tag{18}$$

$$R_{bt}^{U} \le \eta_{b}^{D}.(SOC_{bt} - SOC_{bt}^{min})/\tau \qquad \forall b, \forall t \tag{19}$$

$$R_{bt}^{D} \le P_{b}^{C,max} u_{bt} + P_{bt} \quad \forall b, \forall t \tag{20}$$

$$R_{bt}^{D} \le (1/\eta_{b}^{C}).(SOC_{bt}^{max} - SOC_{bt})/\tau \qquad \forall b, \forall t \tag{21}$$

For more detail about common operational constraints see [17]. To considering interaction between MG and UG, the PXFC market is used which consists of two submarkets: an energy market for trading reference power, and a band market for preparing reserve capacity. All the contracts are agreed on a daily basis, and they should satisfy two quantities as a function of time: the anticipated power and the reserve capacity[14].

C. PDF formulation of required reserve

In this section, to determine the required reserve (RR) for various conditions of MG operation, the individual PDFs are formulated. The PV and wind generation prediction errors are both modeled as independent normally distributed random variables [17]. It is assumed that the load forecast error follows a normal distribution and is independent of the renewable power prediction [17, 21]. The sum of the forecasting error of demand, wind and PV resources is given in (22), where, ΔN_t^D represents the forecasting error of net demand, which can be expressed as a normal PDF ($\Delta N_t^D \sim N(\mu_t, \delta_t^2)$) [17]. At normal operation of the MG, the reserve in the MG should be capable of compensating the forecasting error of net demand. Therefore, the PDF of required reserve must be equal to the PDF of ΔN_t^D ($RR_t^D(\mathrm{r}) = \Delta N_t^D$). In (23), the mathematical formulation of the normal PDF of $RR_t^D(\mathrm{r})$ is shown, Where, r is the required reserve and $RR_t^D(r)$ denotes the PDF of the required reserve by the MG to compensate the forecasting error of net demand. μ_t and σ_t represent mean and standard deviation of ΔN_t^D, respectively.

$$\Delta N_t^D = -\Delta P_{Wt} - \Delta P_{PVt} + \sum_{d=1}^{N_d} \Delta P_{dt} \qquad \forall t \tag{22}$$

$$RR_t^D(\mathrm{r}) = N(\mu_t, \delta_t^2) = \frac{1}{\sqrt{2\pi\,\delta_t^2}} * e^{\left(\frac{-1}{2\,\delta_t^2}\right)(r-(\mu_t))} \tag{23}$$

At the moment of the sudden outage of a DG, the reserve must be adequate to compensate both the output power of failed DG and the forecasted error of net demand. Required reserve for compensating the power of failed DG is equal to its output power in normal operation before the sudden outage. Each DG is assumed as a dispatchable unit for which the output power of DG has a certain value, i.e. its mean is equal to P_{gt} and its variance is equal to 0.

Therefore, the variance of sum of DG power and $RR_t^D(\mathrm{r})$ is equal to the variance of $RR_t^D(\mathrm{r})$. Hence, the PDF of the RR at the time of the sudden outage of a DG can be written as (24). For considering unwanted islanding, equation (25) can be written with the same reasoning. $RR_t^D(r)$, $RR_t^g(r)$, and $RR_t^i(r)$ are shown in Figs. 1 (a), 1(b), and 1(c). μ_t is considered to be zero.

$$RR_t^g(r) = N\left(\left(P_{gt} + \mu_t\right), \delta_t^2\right) = \frac{1}{\sqrt{2\pi\,\delta_t^2}} * e^{\left(\frac{-1}{2\delta_t^2}\right)(r-(\mu_t+P_{gt}))} \tag{24}$$

$$RR_t^i(r) = N\left(\left(P_{mt} + \mu_t\right), \delta_t^2\right) = \frac{1}{\sqrt{2\pi\,\delta_t^2}} * e^{\left(\frac{-1}{2\delta_t^2}\right)(r-(\mu_t+P_{mt}))} \tag{25}$$

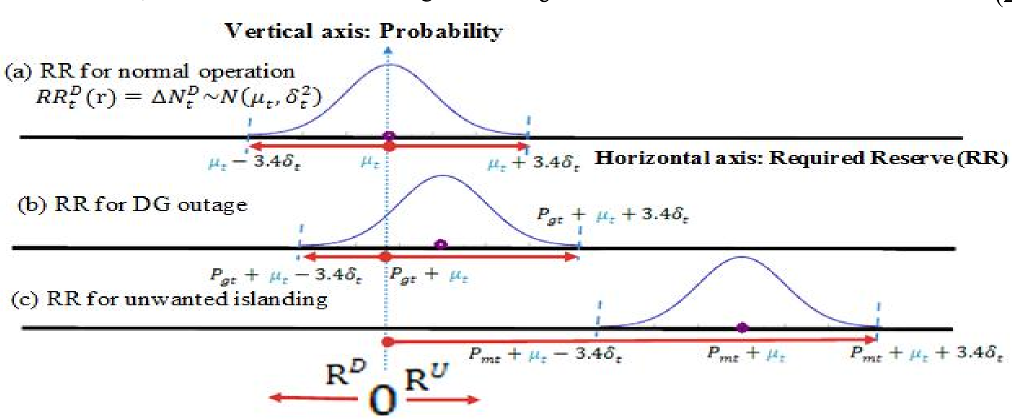

Fig 1: PDFs of required reserve for normal operation, DG outage, and unwanted islanding

D. Formulation of the chance constraints of the required reserve

D.1. Required reserve for net demand forecasting error

All DGs, batteries and the UG can contribute to supplying the reserve. The total up and down reserve available in the MG should be able to compensate the prediction error of net demand, so, the constraint (26) should be satisfied. Given the property of normal PDF, the area under the RR_t^D graph within the negative and positive infinity is equal to 1. However within $(+3.4\delta_t)$ and $(-3.4\delta_t)$, it is equal to 0.9994. Therefore, the constraint (26) can be replaced by (29) and (30) with a 99.94% probability of reserve sufficiency.

$$-(D) \leq RR_t^D \leq \text{U} \quad \forall t \qquad (26)$$

$$U = \sum_{g=1}^{N_g} R_{gt}^U + \sum_{b=1}^{N_b} R_{bt}^U + (R_{mt}^{UB}) \qquad (27)$$

$$\text{D} = \sum_{g=1}^{N_g} R_{gt}^D + \sum_{b=1}^{N_b} R_{bt}^D + (R_{mt}^{DB}) \qquad (28)$$

$$\mu_t + 3.4\delta_t \leq \text{U} \quad \forall t \qquad (29)$$

$$-(\text{D}) \leq \mu_t - 3.4\delta_t \quad \forall t \qquad (30)$$

In some cases, it is likely that the MG operator decides to consider a lower value, instead of %99.94, with the aim of reducing the cost or any other reason. To this end, the parameter L^{req} is used instead of the constant number of 3.4. The parameter L^{req} has a direct but nonlinear relationship with the area under the RR_t^D graph in the range between $(\mu_t + L^{req}\delta_t)$ and $(\mu_t - L^{req}\delta_t)$. Theoretically, the parameter L^{req} can range between zero and positive infinity. However, for values larger than 3.4, the variation of the area is negligible. In Fig. 2, the area under the RR_t^D graph in the range between $(\mu_t + L^{req}\delta_t)$ and $(\mu_t - L^{req}\delta_t)$ is shown for different values of L^{req} ($0<L^{req}<3.4$). This area represents the required probability of reserve sufficiency (PRS^{req}). With the addition of L^{req}, constraints (29) and (30) are rewritten as (31) and (32).

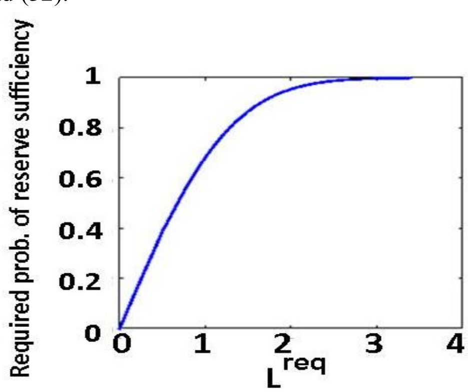

Fig2: The relation between L^{req} and the required probability of the reserve sufficiency (PRS^{req})

$$\mu_t + L^{req} * \delta_t \leq \text{U} \quad \forall t \qquad (31)$$

$$-(\text{D}) \leq \mu_t - L^{req} * \delta_t \quad \forall t \qquad (32)$$

Given that the UG is considered as an infinite bus and the variables R_{mt}^{UB} and R_{mt}^{DB} are almost unlimited. Thus, the above-mentioned constraints are always satisfied. In many cases, the MG operator is not likely to want or cannot purchase reserve from the UG [13]. In these cases, constraints (31) and (32) may not be satisfied and the problem becomes infeasible. In such cases, smaller values should be considered for $(\mu_t - L^{req}\delta_t)$ and $(\mu_t + L^{req}\delta_t)$, and the problem should be solved with new constraints. This process should be repeated as many times as the problem becomes feasible.

In order to eliminate the repetitive loop and therefore reducing the solving time, the positive variables of $URNS_{Dt}$ and $DRNS_{Dt}$ are defined, and Eqs. (31) and (32) are rewritten as Eqs. (33) and (34). Instead of reducing $(\mu_t - L^{req} * \delta_t)$ and $(\mu_t + L^{req} * \delta_t)$, the values of positive variables $URNS_{Dt}$ and $DRNS_{Dt}$ are increased. Given that these variables are added to the objective function (Eq. 1) with a large penalty coefficient, the smallest positive values are obtained for $URNS_{Dt}$ and $DRNS_{Dt}$, which satisfy constraints (33) and (34). Therefore, it is no longer necessary to solve the problem in a repetitive loop. It should be noted that URNS and DRNS are not real parameters of the power system operation.

$$\mu_t + L^{req} * \delta_t - URNS_{Dt} \leq \text{U} \quad \forall t \qquad (33)$$

$$-(\text{D}) \leq \mu_t - L^{req} * \delta_t + DRNS_{Dt} \quad \forall t \qquad (34)$$

D.2. Required reserve for DG outage and unwanted islanding

When sudden outage of a DG occurs, constraint (35) should be satisfied. Based on previous discussions, the constraint (35) can be replaced by (36) and (37). When unwanted islanding occurs, all batteries and DGs are contributing factors in supplying reserve. Therefore, due to considering unwanted islanding, constraints (38) and (39) can be put forward. $URNS_{gt}$ and $DRNS_{gt}$ in equations (36) and (37) work the same as $URNS_{Dt}$ and $DRNS_{Dt}$ in equations (33) and (34). Also, the same description is true for $URNS_{it}$ and $DRNS_{it}$ in equations (38) and (39).

$$-\left(\text{D} - R_{gt}^D\right) \leq RR_t^g \leq \text{U} - R_{gt}^U \quad \forall g\, \forall t \qquad (35)$$

$$P_{gt} + \mu_t + L^{req} * \delta_t - URNS_{gt} \leq \text{U} - R_{gt}^U \quad \forall g \forall t \qquad (36)$$

$$-\left(\text{D} - R_{gt}^D\right) \leq P_{gt} + \mu_t - L^{req} * \delta_t + DRNS_{gt} \quad \forall g\, \forall t \qquad (37)$$

$$P_{mt} + \mu_t + L^{req} * \delta_t - URNS_{i,t} \leq \sum_{g=1}^{N_g} R_{gt}^U + \sum_{b=1}^{N_b} R_{bt}^U \quad \forall t \qquad (38)$$

$$-\left(\sum_{g=1}^{N_g} R_{gt}^D + \sum_{b=1}^{N_b} R_{bt}^D\right) \leq P_{mt} + \mu_t - L^{req} * \delta_t + DRNS_{i,t} \quad \forall t \qquad (39)$$

E. Probability of the reserve sufficiency (PRS)

In Fig. 3, the function RR_t^g for a sample DG is shown. The area under the graph RR_t^g in the range between the two dotted lines was introduced as PRS_{gt} in the present article. The concept of PRS_{gt} denotes the probability that the reserve will be sufficient in the MG in the event of sudden DG outage at period t, so that the reserve can compensate both the power of the failed DG and the forecasting error of net demand. To calculate PRS_{gt} the $\psi_g(z)$ function is used (see Eq. 40). This function calculates the area under the RR_t^g curve from negative infinity to the point of z. Therefore, Eq. (41) can be employed to calculate PRS_{gt}.

$$\psi_g(z) = \int_{-\infty}^{z} RR_t^g(r)(dr) \tag{40}$$

$$PRS_{gt} = \psi_g\left(\mathrm{U} - R_{gt}^U\right) - \psi_g\left(-\left(\mathrm{D} - R_{gt}^D\right)\right) \quad \forall g \forall t \tag{41}$$

Using the same reasoning, PRS_{Dt} and PRS_{it} can be calculated as follows:

$$\psi_D(z) = \int_{-\infty}^{z} RR_t^D(r)(dr) \tag{42}$$

$$PRS_{Dt} = \psi_D(\mathrm{U}) - \psi_D(-(\mathrm{D})) \quad \forall t \tag{43}$$

$$\psi_i(z) = \int_{-\infty}^{z} RR_t^i(r)(dr) \tag{44}$$

$$PRS_{it} = \psi_i\left(\sum_{g=1}^{N_g} R_{gt}^U + \sum_{b=1}^{N_b} R_{bt}^U\right) - \psi_i\left(-\left(\sum_{g=1}^{N_g} R_{gt}^D + \sum_{b=1}^{N_b} R_{bt}^D\right)\right) \quad \forall t \tag{45}$$

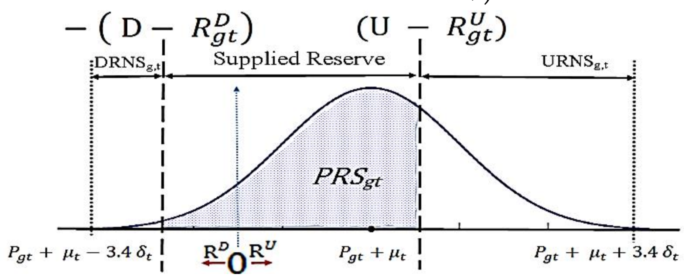

Fig3: Probability of reserve sufficiency (PRS) in the event of a DG outage

F. *Scheduling strategy*

In Figure 4, the flowchart of the proposed strategy is presented. It should be noted that, PRS^{req} is an input parameter of the problem. If PRS^{req} is applied into the problem formulation directly, the problem is become non-linear. To make the problem linear the parameter L^{req} is defined. The relation of PRS^{req} and L^{req} is shown in Fig. 2. Based on the flowchart, first, L^{req} is calculated through Fig. 2. Then, L^{req} is used in the formulation.

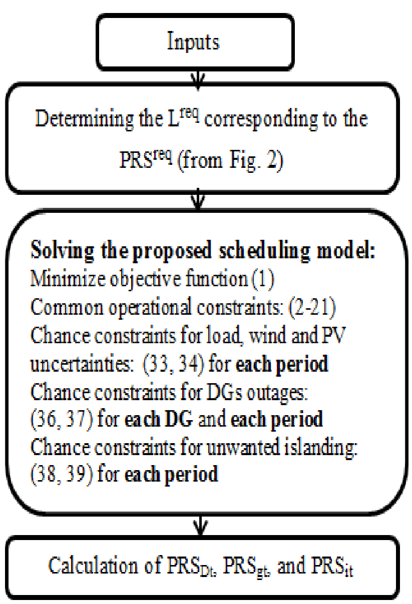

Fig4. Flowchart of proposed scheduling strategy

III. Numerical studies and discussions

A. Case study

The efficiency of the proposed scheduling strategy is evaluated by several case studies implemented on the modified ORNL DECC MG test system (see Fig. 5). The test system and the required input data are taken from [17]. The Mixed Integer Linear Programming model is implemented in GAMS optimization software and solved using the CPLEX solver. In order to evaluate and demonstrate the efficacy of the proposed strategy, various cases have been considered.

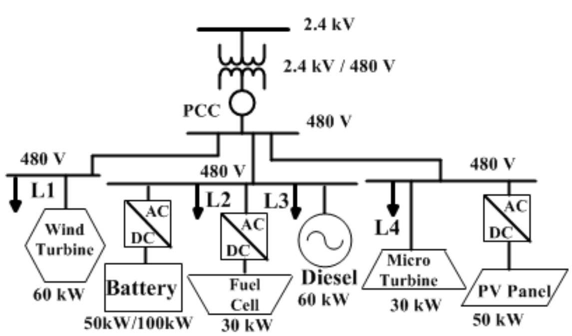

Fig5. Test system

B. *Case 0: Considering reserve just for net demand forecasting error*

In case 0, the MG scheduling was performed according to the proposed strategy, but only the chance constraints of the RR to compensate the prediction error of net demand (Eqs. 33 & 34) have been taken into account. It should be noted that purchasing reserve from the UG, unwanted islanding, and outage of DGs have been neglected, and PRS^{req} has been set at 99.94%. The results are presented in Fig. 6. As it is clear in Fig. 6, due to the low-cost output power of DG2 and DG3, in comparison with other sources and the UG, the second and third DGs operate at maximum power at all hours. Given that the reserve constraints for normal operation have been considered in this case, as expected, all available capacity has been used to reach the maximum possible value for PRS_{Dt} (i.e. 99.94%). while PRS_{gt} and PRS_{it} are not in a good condition. It is worth noting that the daily cost in this case is $ 235.01.

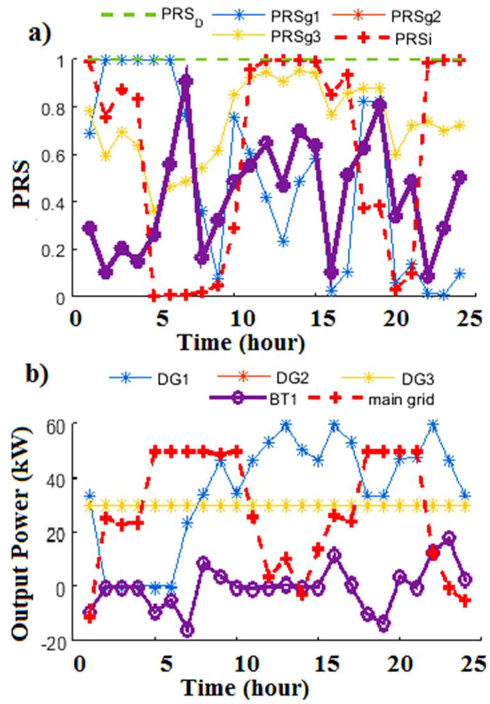

Fig 6: **a)** PRS **b)** output power (for case 0)

C. Case 1: Case 0 + considering reserve for DG outage

In Case 1, the reserve constraints for the sudden outage of DGs (36) and (37) have been added to Case 0. In Fig. 7, the results of this case are shown. As it is clear in fig. 7, in this case, DG1 and DG2 productions are considerably reduced. The reduced production of these DGs was compensated by the UG. In fact, the model requires that more expensive energy be purchased from the UG towards increasing PRS for DGs as much as possible. The PRS almost obtained 99.94% for DG3 and DG2 in all hours, but not for DG1, because its output power was so high that in some hours the internal resources of the MG did not have the necessary capacity to provide the required reserve, and PRS for DG1 outage obtained less than 60% in many hours.

In addition, the production of DG2 and DG3 was considerably reduced. The reduced production was compensated by the UG. In fact, the model requires that more expensive energy be purchased from the UG towards increasing PRS for DGs as much as possible. Therefore, daily cost increased as much as $42 compared to Case 0 and measured $277.44.

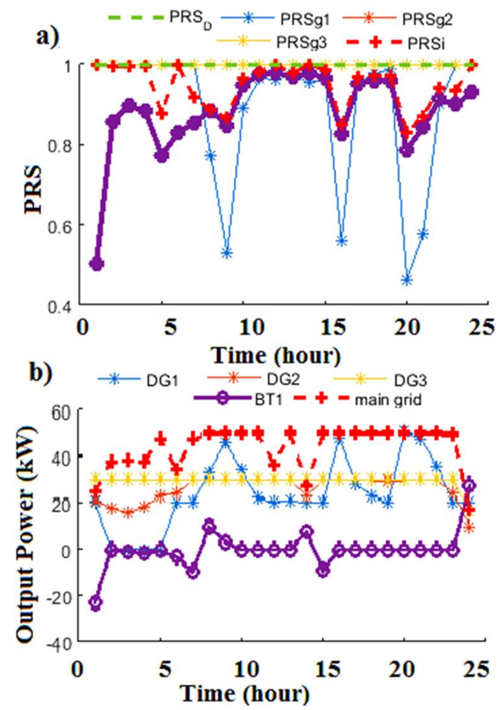

Fig 7: **a)** PRS **b)** output power (for case 1)

D. Case 2: Case 1+ considering reserve for unwanted islanding

In Case 2, the reserve constraints for the unwanted islanding (38) and (39) have been added to Case 1. In fact, all constraints have been included in this case and the results are shown in Fig. 8. The noteworthy point in this case is that in spite of considering reserve constraints for all MG conditions, PRS still had low values for some conditions and hours. For example, if unwanted islanding occurred in 16, 20 and 21 hours, the probability of the reserve sufficiency was less than 90%. In addition, in the event of DG1 outage in the said hours, the probability of the reserve sufficiency was less than 60%. The only way to increase PRS for DGs is to purchase reserve from the UG, which is addressed in Case 3.

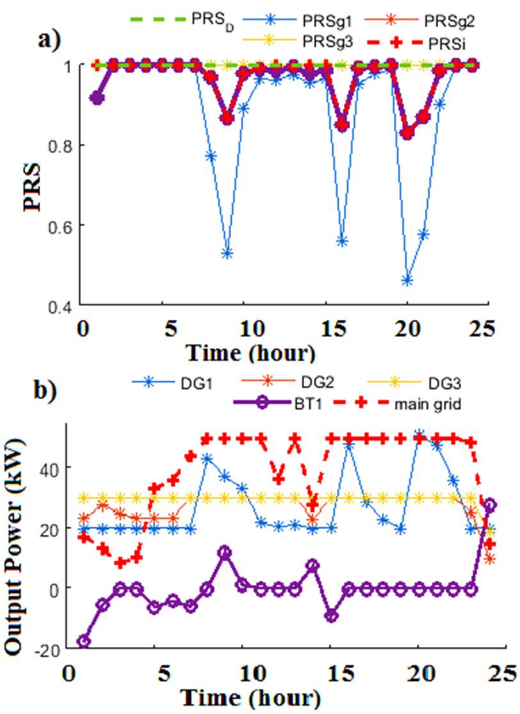

Fig 8: **a)** PRS **b)** output power (for case 2)

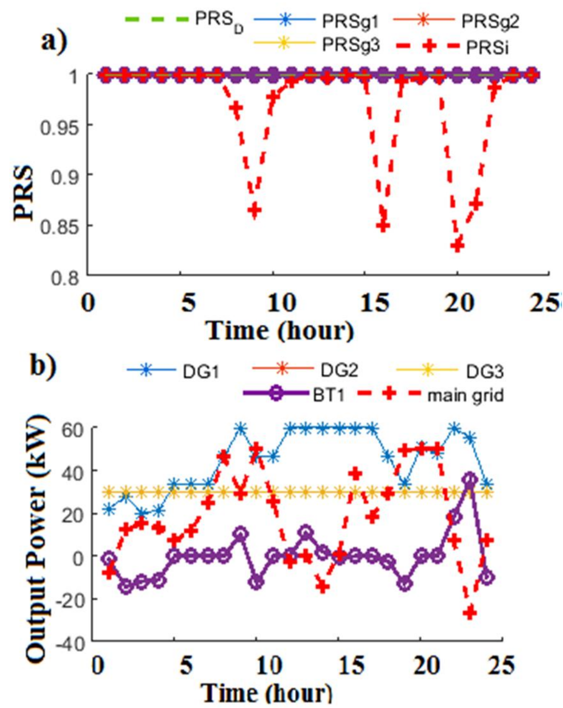

Fig 9: **a)** PRS **b)** output power (for case 3)

E. Case 3: Case 2+ Buying reserve from the UG

In this case, the effects of purchasing reserve from the UG on MG scheduling and PRS are addressed. The price of purchasing reserve from the UG is considered 10% of the price of purchasing power from the UG.

E.1. Comparing with Case 2

In Fig. 9, the results of this case are shown. As expected, because of purchasing reserve from the upstream grid, the PRS_{Dt}, and PRS_{gt} measured 99.94% during all periods. The operating cost witnessed a significant 34-dollar drop reaching $253.31 because the required reserve was purchased from the UG when it was cost-effective, thereby changing the MG scheduling. For example, in comparison with the case 2, the production power of the DG1 was increased, and the share of this DG in providing the up reserve was reduced. However, a significant amount of up reserve was purchased from the UG instead. Because the price of the reserve of the UG is competitive with the reserve of internal resources, the UG was the main provider of down reserve.

E.2. Sensitivity analysis with different values of PRS^{req} and reserve prices of the UG

In all previous examinations, PRS^{req} was considered 99.94%. In Fig. 10, the total operating cost (TOC) of the MG for different amounts of PRS^{req} and several different reserve prices of the UG are compared. The price of purchasing reserve from the UG is considered a submultiple of the price of purchasing power from the UG, which is represented by ‘q’ (i.e. $Q_{mt}^{UB} = q * C_{mt}^{B}$). As can be seen, the larger the value of PRS^{req}, the higher the TOC will be, but in a completely non-linear way. When q=0.05, and there is a rise in PRS^{req} from 0.1 to 0.8, there will be a 4.76% rise in the TOC. However, as PRS^{req} increases from 0.8 to 0.9994, there will be a 13.63% rise in the TOC, which is indicative of the fact that a large increase of reliability requires a small rise of cost when the system reliability is already low. In contrast, a small increase of reliability requires a large rise of TOC when the system reliability is already high. Moreover, whatever larger q becomes, this issue will be intensified. For example, when q=0.05, and there is a rise in PRS^{req} from 0.8 to 0.9994, there will be a 13.63% rise in the TOC. However, as q=0.3, there will be a 19.59% rise in the TOC.

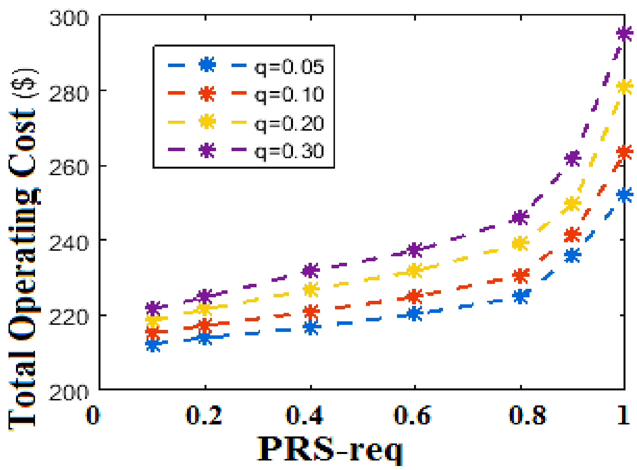

Fig 10: Comparison of total operating cost with different PRS^{req} and different q values

IV. Discussion

In order to analyze PRS of an emergency condition, PRS for DG1 outage for all case studies is shown in Fig. 11. As it is obvious, PRS index in case 0 is very low in various hours and even reached to zero in hours 9, 15, 22, and 23. In case 1, as expected, PRS is increased due to reserve consideration for DGs outages. In case 2, reserve is also considered for unwanted islanding, which has no effect on PRS for DG1. Since the ability of purchasing reserve from UG is considered in case 3, Maximum possible value of PRS for DG1 is reached in all hours.

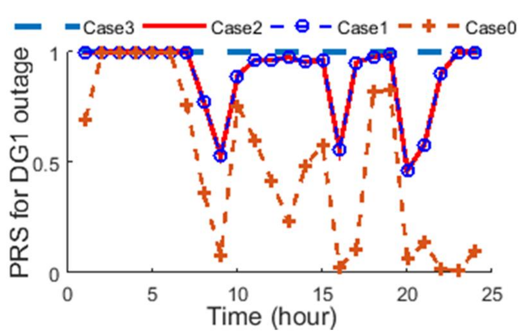

Fig 11: Comparison of PRS of DG1 in different cases

In Table 1, TOC of different case-studies are shown to be compared. According to TOCs in Table 1, the case 0 has the least operating cost, as expected, since no reserve is considered for emergency conditions. In case 1, the reserve is considered for compensation of DG outage. Therefore, the operation cost is increased about 42$ compared to case 0. In case 2, the reserve is considered for compensation of unwanted islanding conditions besides DG outage. Consequently, the operating cost is increased about 10$ compared to case 1. In case 3, also the reserve is considered for both DG outage and unwanted islanding, but, the operating cost is reduced. In this case, the ability of purchasing reserve from UG is considered. Therefore, the degree of freedom in decision-making is increased, which leads to optimal operating cost.

Table 1 : The comparisons of TOCs($)

Case 0	Case 1	Case 2	Case 3
235.01	**277.44**	**287.29**	**253.31**

V. Conclusions

In this paper, the most important factors that affect the power balance of the MG such as unwanted islanding, DG outage, and the uncertainty of demand and renewable resources were considered. Different probability distribution functions (PDFs) were formulated to determine the required reserve in different conditions of MGs. Based on these PDFs a probabilistic index entitled PRS was formulated for different conditions of the MG. finally, to achieve a certain amount of PRS a novel chance-constrained model was proposed. Moreover, to reduce the complexity of the model, the chance constraints were formulated innovatively by adding controllable variables to the chance constraints. Numerical examinations were performed on a sample microgrid with several case studies which investigate different conditions of MG operation, different values of the required PRS and different prices of purchasing reserve from the UG. The results of examining different case studies were indicative of the efficiency of the proposed strategy.

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