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Abstract—This paper aims to investigate the optimal scheduling of stochastic reconfigurable hybrid AC-DC microgrid (MG) in the present of renewable energies and also considering Dynamic Line Rating (DLR) constraint. DLR is a practical limitation that can potentially affect the ampacity of lines, particularly in the islanded mode when the lines reach their maximum capacity in lack of main generation source at the point of interconnection with the utility. In order to prevent overloading of the lines, the reconfiguration technique is developed to change the topology of the network by some prelocated switches. A linearization technique is adapted to address the nonlinearity of both nodal AC power flow and the DLR constraints. The Unscented Transform (UT) technique is utilized to model uncertainties including renewable energy generations, hourly load demands, and hourly market prices along with the DLR uncertainties such as solar radiation, wind speed, and ambient temperature. Finally, a sensitivity analysis is performed to see the effect of wind speed and solar radiation on the energy management of hybrid AC-DC MG. The performance of the proposed methodology is examined on a modified IEEE-33 bus test system, which demonstrates the high efficiency and importance of the proposed techniques in minimizing the hybrid AC-DC MG operation cost while all of the constraints of the network are satisfied.

Index Terms—Dynamic Line Rating, Hybrid AC-DC Microgrid, Reconfiguration Technique, Uncertainty.
I. INTRODUCTION

MICROGRID (MG) is a small self-supplied electric network that can operate in both grid-connected and islanded modes [1]. MGs have been proposed to the conventional AC power grids due to their technical and economic aspects such as lower operation cost, higher reliability, higher resiliency, and self-healing capability [2-5]. In spite of the benefits associated with the integration of the MGs, there are still challenges regarding MGs operation and planning such as stability, maintenance scheduling, and efficient power/energy management [6-9]. Overall, MGs can be classified into three main categories based on the voltage types: AC, DC, and hybrid AC-DC. In [10], the optimal scheduling of AC MG was studied where the authors used the matrix real-coded genetic algorithm to address the problem. In [11], a linear programming (LP)-based optimization method is utilized to minimize the operation cost of an AC MG. The optimal operation of a multi-period islanding AC MG was discussed in [12] by addressing the complexities of the network and using the bender decomposition approach. The optimal scheduling of distributed DC MGs was addressed in [15] based on a primal-dual decomposition technique. In [16] the efficient operation of battery storage systems along with electric vehicles was investigated within a DC MG with high renewable energy penetration.

The benefits associated with both AC and DC MGs can be reflected in an interconnected configuration of MGs known as a hybrid AC/DC MG. The economic dispatch problem of the hybrid MG was addressed in [17] by considering multiple energy storage systems to modify the power dispatch. In [18] the power flow control and management for AC and DC sources were investigated by using a decentralized power sharing method. In [19] an efficient interconnection of DGs within the power grid for both AC and DC busses was proposed for hybrid MGs. In [20] the optimal energy management in a hybrid AC-DC MG was studied. However, the optimization problem was solved using the crow search algorithm (CSA) which is a heuristic method and does not guarantee the global optimum. A two-stage robust optimal dispatch for hybrid AC/DC MGs considering the uncertainties associated with generation sources and loads was investigated in [21]. Effective planning for hybrid AC/DC MGs was explored in [22] where the main objective is to guarantee reliable power flow with minimum distribution. A modified Newton-Raphson method for optimal power flow of hybrid AC/DC MGs was presented in [23]. Efficient energy management of a hybrid AC/DC MG was studied in [24] where a mixed-integer linear programing method was used to balance the generation and load.

Although energy management in MG is widely discussed in different research studies, the impact of the DLR constraint on the optimal scheduling of hybrid MGs has not been yet well addressed. The DLR is a practical limitation that can potentially affect distribution feeders regarding lines ampacity, particularly in summer when the power lines approach their maximum capacity due to the high temperature. In the MG operation, the DLR constraint can be a more serious concern, especially in the islanded MG where the distribution lines approach their maximum thermal capacity. It should be noted the DLR constraint has been proposed for the operation of the conventional bulk power systems by Nick et al. [25], where the DLR impacts on both the generation and transmission levels were investigated. However, because of the greater size of the conductor as well as the symmetrical loads in the transmission network, the DLR constraint is less restrictive in transmission network than in the distribution network. This
reveals the importance of considering the DLR constraint in the low-voltage grids such as MGs [26], [27]. In [26], the effect of DLR on the reliability of the network was investigated. In [27], the DLR constraint was considered for a single MG operation. Since the operation of a AC-DC MG is more complicated than that of a single MG due to power exchanging among the DC and AC parts, any changes in any parts can significantly influence the entire network. Thus, the influence of DLR in the AC power flow can affect both the AC and DC parts. In addition, a single MG’s operation in [27] was solved by utilizing a heuristic method in which the optimal solution is not guaranteed. Hence in this study, to address the nonlinearity and non-convexity challenges of the problem, a new linearization technique is developed, which seeks to obtain the optimal solution. Furthermore, to the best of authors’ knowledge, this research is the first work that investigates the impact of renewable energy on the stochastic energy management of a reconfigurable hybrid AC-DC MG under DLR security constraint.

Based on the IEEE standard 738, the DLR depends on the weather condition and conductor characteristics such as current, resistance, and size [28]. In this paper, the impact of DLR on the hybrid AC-DC MG operation is investigated in both grid-connected and islanded modes. Opposed to large power distribution systems, power lines in islanded MGs are more prone to become overloaded in the presence of renewable energy sources. Furthermore, voltage fluctuations are more significant due to the lower Thevenin impedances in the islanded MG. It should be noted that the DLR constraint can potentially affect both active and reactive power flow limit of feeders due to the imposed current constraint. The AC part can be directly influenced by the DLR constraint, since the existence of reactive power causes higher currents when compared to unity power factor scenario and thus line thermal limits may occur sooner than in their dc counterpart. In the hybrid AC-DC MGs, since AC and DC parts are coupled, any change in the power flow (either AC or DC part) impacts the power dispatch of the entire network. That is, any change in the DC power flow results in a change in the AC active power flow, which in turn affects the reactive power flow. Conversely, a change in the AC power flow results in a different active power flow, which in turn affects the DC power flow. In order to reduce such a two-sided effect on the optimal operation of the hybrid MGs, this paper proposes a reconfiguration strategy in which reconfiguring the AC or DC circuits can be effectively used to reduce thermal stress on the other side. Better understanding the impact of DLR on MGs would help prevent critical failures or other issues in the network. As mentioned, in order to improve the MG performance and also prevent any contingency within the network, a feeder reconfiguration method is developed for an AC-DC hybrid MG. Reconfiguration is a process of changing the topology of the network by using prelocated sectionalizing and ties switches, which can significantly improve the emission control [29], line losses [30], voltage profile [31], load balance [32], and grid reliability [33]. In addition to feeder reconfiguration, an energy storage system is employed to guarantee the satisfactory operation [34].

The DLR constraint adds a set of nonlinear equations into the reconfigurable hybrid AC-DC MG (RHMG) analysis. Therefore, a piecewise linearization technique is employed to deal with nonlinear constraints associated with the proposed problem such as DLR and AC power flow. To model the problem more accurately, a stochastic framework based on the unscented transform (UT) [27] is utilized to characterize uncertainties in different sources such as renewable energy sources (RESs), hourly market price, hourly load demand, solar radiation, wind speed, and ambient temperature. Briefly, the main contributions of this paper are summarized as follows:

- Model the DLR limitation on hybrid AC/DC microgrids operation, which considers the heat balance of conductors to incorporate the most effective weather parameters such as temperature, irradiance, etc.
- Develop a flexible structure for hybrid AC/DC microgrids based on optimal reconfiguration, based on which the hybrid microgrid can be remotely controlled by using tie and sectionalizing switches to reduce power losses, avoid feeder congestion, and provide optimal power dispatch.
- Develop an effective stochastic hybrid AC/DC microgrids operation framework based on the UT method, which is capable of characterizing and handling uncertainties in the correlated environment of hybrid MGs (e.g., the bidirectional effect of loads or wind turbines).

II. DYNAMIC LINE RATING CONSTRAINT

DLR is a security constraint which can dynamically affect the ampacity of distribution lines in harsh and hot ambient temperature. According to IEEE standard 738, the dynamic ampacity of the conductor depends on the conductor current, ambient conditions, conductor size, and conductor resistance [28]. The total conductor temperature, which is known as the heat balance equation (HBE), is the summation of the heat losses (convective and radiative heats) and heat gains (resistive and solar heats). Hence, the HEB equation of the conductor for any time interval is calculated as [28]

$$q_{c,\text{nm,t}} + q_{r,\text{nm,t}} + mCp \frac{dT_{\text{ave}}}{dt} = q_{s,\text{nm,t}} + (I_L)^2 R(T_{\text{ave}}) \quad (1)$$

$$\frac{dT_{\text{ave}}}{dt} = \frac{1}{mCp} ((I_L)^2 R(T_{\text{ave}}) + q_{s,\text{nm,t}} - q_{c,\text{nm,t}} - q_{r,\text{nm,t}}) \quad (2)$$

The convective and radiative heat losses can be calculated as (3)-(9). IEEE 738 standard defines two scenarios for the convective heat loss based on the wind speed conditions as follows:

1) Natural Convection

The natural convection is specified in a way that the surrounding air, in the absence of wind, cools the conductor and can be taken into account as (3) [28].
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\[ q_{cm,t}^1 = (3.645) f_t^0.5 D_0^0.75 (T_a - T_{ma})^{1.25} \ (w / m) \]  
(3)

2) Forced Convection

For forced convection, the conductor is cooled down by a cylinder that moves around it. Equations (4), and (5) are related to the low and high wind speeds, respectively [28].

\[ q_{cm,t}^2 = K_{angle} (1.01 + (1.35) N_{Re}^{0.52} K_f (T_a - T_{ma})) \ (w / m) \]  
(4)

\[ q_{cm,t}^3 = K_{angle} (0.754) N_{Re}^{0.66} K_f (T_a - T_{ma}) \ (w / m) \]  
(5)

where \( N_{Re} \) is the Reynolds number and is defined as follows,

\[ N_{Re} = \frac{D_u P_f V_w}{\mu_f} \]  
(6)

Moreover, \( K_{angle} \) is the wind direction that can be calculated as (7).

\[ K_{angle} = (1.94) - \cos( \beta ) + (0.194) \cos( 2 \beta ) + (0.3) \sin( 2 \beta ) \]  
(7)

According to the IEEE standard 738, the largest value among the convective heat scenarios should be taken into consideration as shown in (8) [28].

\[ q_{cm,t} = \max( q_{cm,t}^1, q_{cm,t}^2, q_{cm,t}^3 ) \]  
(8)

The radiative heat loss expresses that the conductor with a temperature greater than ambient can emit thermal radiation. Conductive heat transfer by radiation can be calculated as (9).

\[ qr_{cm,t} = e (17.8) D_0 \left[ \frac{T_a + 273}{100} \right] - \left[ \frac{T_a - 273}{100} \right] \ (w / m) \]  
(9)

The solar and resistive heat gains are considered as the heat gains and can be taken into account based on (10)-(12). The rate of solar heat that can be delivered by the conductor is calculated as (10).

\[qs_{nm,t} = \alpha Q_{sc} \sin(\Phi) \hat{A} \ (w / m)\]  
(10)

where,

\[\Phi = \arccos[\cos(He) \cdot \cos(Zc - Zl)]\]  
(11)

Furthermore, as shown in (12), the resistive heat energy is generated due to the line currents that heat up the distribution line.

\[ q_{R,nm,t} = (I_{nm,t})^2 R (T_{mw}) \]  
(12)

Based on (2), an approximate relationship to the average line temperature can be taken as (13).

\[ T_{nm,t+1} - T_{nm,t} = \frac{\Delta t}{m C_p} \left[ I_{nm,t}^2 R_{T_{nm,t}} + qs_{nm,t} - q_{cm,t} - qr_{nm,t} \right] \]  
(13)

where \( \Delta t \) is considered an hour (3600 s).

The DLR constrain has been originally designed to consider the thermal rating effects in the transmission lines. Nevertheless, the main motivation for authors to bring DLR in the distribution level is its significance in the MG islanded mode. In a normal distribution system, the feeders may be loaded more than 60% of their maximum capacity. The same rule applied to the MG at the grid-connected mode. Having this in the mind, the DLR constraint has been ignored in all distribution systems for the simplicity. Nevertheless, when it comes to the islanded mode in the MGs, some feeders may be loaded at their maximum capacity to avoid load interruption as much as possible. In this situation, even a small change in the power capacity of feeders caused by weather risk factors can affect the whole MG scheduling and may lead to unexpected load shedding. In order to avoid such a circumstance, one needs to consider DLR to make sure that the MG can reveal an appropriate performance in the islanded mode as well. For sure, in the very small size MGs, this may not be a big deal, but in the middle size and the bigger MGs, it is a recommended constraint for secure operation.

III. RECONFIGURABLE HYBRID AC-DC MG SCHEDULING FORMULATION

In this section, a mathematical formulation is developed for the reconfigurable hybrid AC-DC MGs energy management including the objective function and necessary constraints.

A. Objective Function

The objective function includes costs of reconfigurable switching, power generation by distributed generations (DGs), purchasing power from the main grid, and generated power by energy storage system shown by:

\[ \text{Cost} = C_{SW} + C_{DG} + C_{sub} \]  
(14)

where,

\[ C_{SW} = \sum_{k \in SW} N_{RCS,k} \lambda_{RCS} \]  
(15)

\[ C_{DG} = \sum_{i \in DG} \sum_{t \in \mathcal{T}^{DG}} C_{it} (P_{it}^{G} U_{it} + S U_{it} + S D_{it}) \]  
(16)

\[ C_{sub} = \sum_{i \in \mathcal{I}} C_{it} (P_{it}^{L} + P_{loss,i}) \]  
(17)

The first term of the objective function is the switching cost of the reconfiguration that is calculated based on (15). It is worth mentioning that each remotely controlled switch (RCS) can be either 0 (when the switch is opened) or 1 (when the switch is closed). The second term is the power generation cost of DGs that can be calculated according to (16). Equation (17) is related to the third term in the objective function and represents the purchasing power cost from the main grid. This includes the cost of exchanging power and power losses.

B. Problem Constraints

The proposed optimization problem includes some constraints for both AC and DC parts of the hybrid MG as follows:

**Power balance constraint**: A set of recursive equations, called DistFlow branch equations, is used to represent the AC power flow model in a radial distribution network as shown in (18)-(21). Hence, equations (18) and (19) guarantee active and reactive power balances at the buses of the system, respectively. Furthermore, equations (20) and (21) apply the KVL to the distribution/tie lines. It is worth noting that \( \Delta V_{nm,t} \)
is an auxiliary variable which can be zero if the line \(mn\) is switched on at time \(t\), otherwise, it will be positive/negative based on the difference between the voltages of the sending and receiving ends of line \(mn\).

\[
\sum_{mn \in \Omega^{AC} \cup \Omega^{DC}} \left[ p_{L,mn}^L - R_m (i_{mn,m}^L)^2 \right] - \sum_{mn \in \Omega^{AC} \cup \Omega^{DC}} P_{L,mn}^L + P_{i,m}^L + P_{D}^L = 0 \quad \forall i \in \Omega^{AG}, \forall i \in \Omega^{DG}, \forall t
\]

\[
\sum_{mn \in \Omega^{AC}} Q_{L,mn}^L - X_m (i_{mn,m}^L)^2 - \sum_{mn \in \Omega^{AC}} Q_{L,mn}^L + Q_{i,m}^L = 0 \quad \forall i \in \Omega^{AG}, \forall t
\]

\[
0 \leq Q_{i,m}^L \leq Q_{i,m}^{max} \quad \forall t, \forall i \in \Omega^{AG}
\]

**Bus voltage limit:** The steady-state voltage and angle of each bus should be within the limits as described in (24) and (25).

\[
V_{min} \leq V_{mn} \leq V_{max} \quad \forall t, \forall n \in \Omega^{HA} \cup \Omega^{HD}
\]

\[
-\pi \leq \theta_{mn} \leq \pi \quad \forall t, \forall n \in \Omega^{HA} \cup \Omega^{HD}
\]

**Power flow constraint:** Equation (26) assures that the power flow in any feeder will not violate its maximum allowed value.

\[
S_{mn}^L \leq S_{mn}^{max} \quad \forall t, \forall n \in \Omega^{HA} \cup \Omega^{HD}
\]

**Exchanging power with the main grid:** Equations (27) and (28) guarantee that exchanging energy with the main grid will not be more than its allowable limit.

\[
-P_{max}^M \leq P_i^L \leq P_{max}^M \quad \forall t
\]

\[
-Q_{max}^M \leq Q_{i}^L \leq Q_{max}^M \quad \forall t
\]

**Reconfiguration constraints:** Number of reconfirmation switching has a limitation per day. This limitation is guaranteed by (29). Also, equation (30) confirms the radial structure of the main closed loop network.

\[
N_{RCS,k} \leq N_{RCS,k}^{max} \quad \forall k \in Sw
\]

\[
N_{loop} = N_{branch} - N_{max} + 1
\]

**DLR constraint:** Equations (31) and (32) prevent the line overload and also assure that the temperature of each distribution line is bounded.

\[
|Q_{mn,m}^{L}|^2 + |P_{mn,m}^{L}|^2 = |i_{mn,m}^{L}|^2 \quad \forall t, \forall mn \in \Omega^{AC}
\]

\[
T_{mn,m} \leq T_{max} \quad \forall mn \in \Omega^{AC}, \forall t
\]

The above formulations are developed for both AC and DC parts. Also, an AC-DC power flow coordinator is considered to connect the AC and DC parts of the grid as well as the capability of the network to exchange the power between the AC and DC parts. Furthermore, the proposed formulation is valid for the grid-connected mode. In the case we are going to use it for the islanded mode, only the variables \(P^M\) and \(Q^M\) in constraints (19)-(32) as the active and reactive powers of utility grid will be set to zero. This will automatically disconnect the hybrid MG from the main grid, revealing an islanded mode operation. Hence, the main differences between the proposed reconfigurable hybrid AC-DC MG and other existing models can be summarized as: 1) Incorporating the DLR constraint for the first time in hybrid AC-DC MG operations. The DLR constraint has consequences in both the active and reactive power capacity of feeders and thus affects the MG operations. Compared with conventional hybrid AC-DC MG models, the DLR constraint is modeled in the optimal operation formulation which makes the energy management of the entire network more challenging. 2) Developing a flexible structure for hybrid AC-DC MGs via network reconfiguration. The reconfiguration enables automatic control of hybrid MGs through remotely switching schemes such as tie and sectionalizing switches, to reduce power losses, avoid feeder congestion, provide optimal power dispatch, and prevent line thermal stress. 3) Developing a new linearization approach for the optimal operation and management of reconfigurable AC-DC hybrid MGs by considering DLR as explained in the next section.

**IV. CONSTRAINTS LINEARIZATION**

The presented optimization problem is a Mixed-Integer Nonlinear Programming (MINLP) that is hard to solve; however, it can be numerically intractable. Furthermore, the solution optimality of MINLP models may trap in a locally optimal solution and never reach the optimal global solution. To overcome these drawbacks, the proposed problem is converted to a Mixed-Integer Linear Programming (MILP) model by linearizing the nonlinear constraints. The first nonlinearity arises from equations (18)-(21). Hence, the following variables are defined to linearize them.

\[
f_{L,mn,t} = (i_{mn,m}^{L})^2 \quad \forall mn \in \Omega^{AC}, \forall t
\]

\[
u_{m,t} = (V_{m,t})^2 \quad \forall m \in \Omega^{HA}, \forall t
\]

\[
u_{m,t} = (V_{m,t})^2 \quad \forall m \in \Omega^{HA}, \forall t
\]

\[
u_{mn,t} = \left[ (V_{min})^2 - (V_{mn,t})^2 \right] / (w_{mn,t}^L) \quad \forall mn \in \Omega^{AC}, \forall t
\]

By considering (33)-(34), constraints (18)-(21) have been linearized. However, equation (35) is still nonlinear and also should be linearized. The left-hand side of (35) can be rewritten as follow:
Accordingly, (35) can be rewritten as mentioned in (40),
\[
\left( \omega_{mn,t}^+ \right)^2 - \left( \omega_{mn,t}^- \right)^2 = \left( p_{mn,t}^L \right)^2 + \left( Q_{mn,t}^L \right)^2 \quad \forall mn \in \Omega^{AC}, \forall t \tag{40}
\]
where the variables \( \omega_{mn,t}^+ \) and \( \omega_{mn,t}^- \) are defined as written below:
\[
\omega_{mn,t}^+ = \left( u_{mn,t} + f_{mn,t}^L \right) / 2 \quad \omega_{mn,t}^- = \left( u_{mn,t} - f_{mn,t}^L \right) / 2 \tag{41}
\]

Now, by using the piecewise-based linearization technique, (40) can be linearized as follows:
\[
\sum_{\lambda=1}^{\Lambda} \left( \delta_{\lambda,mn,t,\lambda} + b_{\lambda,mn,t,\lambda} \right) = \sum_{\lambda=1}^{\Lambda} \delta_{\lambda,mn,t,\lambda} \tag{43}
\]
\[
\sum_{\lambda=1}^{\Lambda} \left( a_{\lambda,mn,t,\lambda} + b_{\lambda,mn,t,\lambda} \right) \leq \sum_{\lambda=1}^{\Lambda} \delta_{\lambda,mn,t,\lambda} \tag{44}
\]

It can be inferred from the piecewise linearization technique that, first, the feasible range of each of the variables \( \omega_{mn,t}^+ \), \( \omega_{mn,t}^- \), \( p_{mn,t}^L \), and \( Q_{mn,t}^L \) are partitioned into \( \Lambda \) segments. Afterwards, a line with the slope of \( a_2 \) and intercept of \( b_2 \) is considered for each segment \( \lambda \). Consequently, only one line is chosen to represent each quadratic term by using the binary variables \( \Delta_{\lambda} \). By using the mentioned linearization technique, the proposed problem can be considered as an MILP model in which the global optimal solution is guaranteed and computational time is reduced considerably. It should be noted that the DLR nonlinearity is addressed in the same manner as AC power flow.

V. STOCHASTIC OPTIMIZATION FRAMEWORK

A. Stochastic Framework Based on UT

Unscented transformed (UT) is an efficient uncertainty modeling technique that is more effective than other techniques, such as analytical methods (that are not suitable for nonlinear problems), and Monte Carlo method (that needs a greater number of runs to converge [29]). In this paper, the UT method is employed for modeling the uncertain parameters associated with the proposed problem such as hourly load demand, hourly market price, the output power of non-dispatchable DGs as well as the DLR uncertain parameters such as wind speed, solar radiation, and ambient temperature. UT is based on the following assumption.

Assumed the nonlinear problem \( y = f(x) \) with \( h \) random input variables where the input means is \( \mu \) and input covariance is \( \sigma \). Therefore, the output mean \( \mu_y \) and output convenience \( \sigma_y \) can obtain as follows [35]:

A) Take \( 2h+1 \) samples from the uncertain input data:

\[
x_0 = \mu \tag{62}
\]

\[
x_e = \mu + \left( \frac{h}{1-W_0} \right) \sigma_e, e = 1, 2, ..., h \tag{63}
\]

\[
x_e = \mu - \left( \frac{h}{1-W_0} \right) \sigma_e, e = 1, 2, ..., h \tag{64}
\]

where \( W_0 \) is the weight of the mean value \( \mu \).
B) Calculate the weight factors \( W \) for sample points:

\[
W^0 = W^0
\]

\[
W_e = \frac{1 - W^0}{2h}; \quad e = 1,...,h
\]

\[
W_{e+h} = \frac{1 - W^0}{2h}; \quad e + h = h + 1,...,2h
\]

\[
\sum_{e=0}^{2h} W_e = 1
\]

C) Give the sample points to the nonlinear function:

\[
y_e = f(X_e)
\]

D) Calculate the output covariance \( \sigma_y \) and the output mean \( \mu_y \) of the output variable \( \theta \) as follows:

\[
\mu_y = \sum_{e=0}^{2h} W_e \theta_e
\]

\[
\sigma_y = \sum_{e=0}^{2h} W_e (\theta_e - \mu_y)^T (\theta_e - \mu_y)^T + \sigma^2
\]

B. Solution Procedure

In this sub-section, a solution procedure is defined to explain how the proposed stochastic framework is used to solve the hybrid MG operation problem.

1. Initialize the problem: input system data (bus data, branch data, and voltage level), distributed generations (MT, FC, WT, PV), and setting parameters of the optimization algorithm.

2. Define the uncertain parameters including the WT power forecasting error and PV power forecasting error, as well as AC and DC load forecasting error. Assuming a normal distribution to characterize forecasting errors, the mean and standard deviation of the distribution are estimated.

3. Run the proposed stochastic framework based on UT to generate \( 2h+1 \) concentration points using (62)-(64). Each concentration point creates a deterministic framework with a specific probability to be solved individually.

4. Run the proposed MILP optimization for each deterministic framework to obtain solutions using (14)-(61).

5. Check to see whether the problem is solved for all \( 2h+1 \) deterministic framework. If not, return to step 4, otherwise go to step 6.

6. Consider the weighting factors of each concentration point in (65)-(68), and calculate the expected cost function for the problem.

7. Demonstrate the expected values of the variables including MT, FC, AC-DC inverter, main grid, etc.

VI. SIMULATION RESULTS

To validate the effectiveness of the proposed model, a reconfigurable hybrid AC-DC MG network based on the modified IEEE 33-bus test system is investigated as the case study. The network is made up of one fuel cell (FC), two microturbines (MTs), two wind turbines (WTs), and five tie switches as the reconfigurable normally open switches. The RCSs lifetime is 30 years with average 150,000 complete switching operations where the maximum switching per day is 14, including 12 operations that are designed for the reconstructions strategy and 2 operations that are designed for the fault detections, maintenance outages or isolation duty. Furthermore, the operation cost is 1($) per switching [29]. It is also assumed that; there is an AC-DC power flow coordinator is considered to connect the AC and DC parts of the grid as well as the capability of the network to exchange the power between AC and DC parts. Fig.1 presents the proposed reconfigurable AC-DC hybrid MG diagram. Also, Table I summarizes the characteristics of generation units.

![Fig. 1. Single line diagram of reconfigurable hybrid AC-DC MG.](image)

<table>
<thead>
<tr>
<th>Type</th>
<th>Min/Max Power (kW)</th>
<th>Cost ($/kWh)</th>
<th>SU/SD cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT1</td>
<td>100-1500</td>
<td>0.215</td>
<td>1.65</td>
</tr>
<tr>
<td>MT2</td>
<td>100-2000</td>
<td>0.275</td>
<td>1.65</td>
</tr>
<tr>
<td>FC</td>
<td>80-1000</td>
<td>0.294</td>
<td>1.65</td>
</tr>
<tr>
<td>AC-DC Converter</td>
<td>(-80)-80</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 2 demonstrates the forecasted values of WTs, where they have similar patterns to simplify the problem. Moreover, the forecasted values of hourly load demands and market prices are presented in Fig. 3. The forecasted values of solar radiation are presented in Fig. 4.

![Fig. 2. Input data values for WTs](image)
To demonstrate the effectiveness of the proposed problem, four cases are defined as follows:

**Case 1 – Grid Connected mode:** In this case, the hybrid MG is in the grid-connected mode, that is, it can exchange energy with the main utility. This case is investigated under the original overload limits along with the DLR constraint. Fig. 5 presents the DGs output powers within the MG while wind turbines operate. Based on the results, the cheapest units (MT1 and MT2) are more committed to satisfying the load demand (see Table I and Fig. 5). The results demonstrate that the optimal solution of the hybrid MG is only based on economic consideration. For instance, by increasing the market price at 8 AM, the output power of DGs within the MG is increased (see Figs. 3 and 5) to purchase less power from the utility. Furthermore, the MG purchases energy from the main grid when electricity is cheaper than DGs power. Moreover, the low-cost unit (MT 1) always participates more than the others. The total operating cost of this case is $52,981.

**Case 2 – Islanded mode, and ignoring (without considering) the DLR constraint:** This case presents the optimal operation of an MG in the islanded mode; that is, the MG is disconnected from the utility. In this case, the DLR limitation, as well as the reconfiguration technique, are ignored while the common overload (line capacity) constraints are considered. The optimal output power of DGs in the conventional islanded mode is demonstrated in Fig. 7. Based on the simulation results, same as case 1, the cheapest unit (MT1) is committed with its maximum capacity in the entire horizon. However, unlike the previous case, DG2 is more committed to compensating the shortage power of the main grid; that means the commitment of the units only depend on their operational cost and economic consideration. The total operating cost of this case is $57,645. The operational cost of the second case is $4664 (8%) more than case 1. This difference is known as the islanded cost.

**Case 3 – Islanded, Considering the DLR constraint and reconfiguration technique:** In this case, the effect of the
DLR constraint is considered into the optimal energy management of the hybrid MG. According to the results, by applying the DLR constraint, it is seen that lines 8, and 6 are congested during the peak hours. That means by considering the DLR constraint, the power flow capacity of these lines does not allow the system to operate at a feasible solution. Therefore, there is no feasible solution due to constraint violations. Hence, the reconfiguration technique is utilized to change the topology of the network so that the reconfigured MG can reach a feasible solution. Table II demonstrates the reconfiguration switches of this case. The optimal output power of the FC and MTs under the DLR constraint and reconfiguration technique is presented in Fig. 8. According to Fig. 8, the FC is the most expensive unit is more committed than previous case. For instance, in comparison with the previous cases, FC generates more power at 8:00 AM by increasing the solar radiation and decreasing the wind speed simultaneously. In fact, the optimal output powers of generation units are revised due to the DLR effect and reconfiguration switches to reach a feasible solution. Based on Fig. 9, by utilizing the reconfiguration process in case 3, the capacities of the violated lines 6 and 8 have been released to 97% and 99% of their maximum allowable ampacity respectively. It should be noted that the optimal operation cost of this case is $58,260.

Fig. 8. The output power of case 3

Fig. 9. Violated lines of case 3 before and after reconfiguration.

Case 4 – Islanded, considering the DLR constraint by shifting the solar radiation and reconfiguration technique:
In this case, the solar radiation is shifted; however, other assumptions are the same as case 3. Based on the results, by considering the DLR constraint based on the shifting the solar radiation, lines 6, 8 and 10 are congested at peak hours, that means constraint violation within the networked. Same as the previous case, the reconfiguration technique is employed to find a feasible solution. Table II demonstrates the reconfiguration switches of this case. According to the Fig.10, by employing the reconfiguration technique, the capacity of the violated lines has been released to 96%, 98% and 96% (for lines 6, 8 and 10) of their maximum allowable ampacity respectively. Therefore, the MG is operated at a feasible operating point.

The optimal output power of the units, after the reconfiguration switching, is demonstrated in Fig.11. As shown, by shifting the solar radiation, the output powers of generation units are revised; that means units are affected by the DLR constraint. It is worth noting that most changes are

Table II

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started since solar radiation is increased. The optimal operation cost of this case is $59,850.

![Fig. 11. The output power of case 4](image)

According to the results, the optimal output powers of the committed units are different from the solution that ignoring DLR. Moreover, the impact of the DLR and the location of the generation unit is more important than its power generation cost, to provide a secure network. For instance, at 16:00 PM, in cases 3 and 4, FC (which is the most expensive DG) is committed with its maximum capacity while in cases 1 and 2 the FC is committed with almost 75% of its capacity.

The optimal output power of the inverter in all cases are shown in Fig. 12, in which the negative value means the power transferred from AC to DC, a positive value means DC to AC, and zero value means the power is not transferred. As can be seen, the performance of the inverter significantly depends on the MT 2 which is close to it. For example, in case 4, by increasing the MT 2 at 10:00 AM, the power is transferred from AC to DC.

The comparative plot of the objective functions in both the deterministic and stochastic frameworks for different cases shows in Fig. 13, where considering the uncertainty effects has resulted in incremental cost values in all cases. In fact, this additional value in the objective function is the cost of having more realistic results compatible with the realities of the system. This has been achieved by modeling the uncertainty of forecast error of solar irradiation, wind speed, ambient temperature, market price forecast error, and load demand forecast error, in the problem. Also, the different cost of the first and second cases is $4664 (8%) which is known as the islanded cost. As can be seen, by considering the DLR as a new constraint, the expected cost is increased. However, this increase is less than 1% due to reconfiguration technique, that can lead to reducing in lower losses. It is worth noting that in comparison with the cost, grid security is the priority of the problem.

The conventional operation of hybrid AC-DC MGs does not consider practical constraints to reflect weather effects. By considering DLR, it is seen that the optimal operating point of the MG becomes infeasible, which will force the grid to trigger the alarm mode of operation (i.e., beyond voltage limits or maximum power flow of feeders). For instance, in case 3, it is seen that after considering the DLR effects, lines 6 and 8 are congested (or overloaded). Similarly, in case 4, lines 6, 8, and 10 are overloaded after modeling DLR in the system.

To address this issue and find the new optimal operation point of the MG, we have developed a feeder reconfiguration strategy. Figures 9 and 10 demonstrate the current magnitude in the congested lines before and after the reconfiguration process for case 3 and case 4, respectively. As can be seen in Figs. 9 and 10, there is no violation with the lines’ maximum power flow after considering the reconfiguration. From the perspective of DGs, it is seen that the optimal reconfiguration affects the optimal output power generation of DGs such that they may reduce or increase their power depending on the new MG topology, which is illustrated in Figs. 7, 8, and 11. Thus, it is critically important to consider DLR in the hybrid AC/DC MGs operation as an independent constraint.

![Fig. 12. Inverter out power for all cases.](image)

![Fig. 13. Deterministic and stochastic costs for all cases.](image)

**VII. CONCLUSION**

This paper considers and examines the effects of DLR on the hybrid AC-DC MG which is caused by ambient conditions, on the optimal load dispatching solutions in multi-period islanded MGs. It is shown that, by considering DLR constraints to protect power lines, an optimal dispatching solution can be very different from solutions by conventional assumptions that neglect them. This is mainly because the ampacity of lines is affected due to the DLR constraint, especially when the lines approach their maximum capacity in the MG islanded mode. The feeder reconfiguration is used to obtain the optimal solution and has a better dispatch as well as the power loss minimization. It is worth noting that the
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contribution of DGs, battery storage, and loads depend on the network reconfiguration that is an outcome of the optimal solution.

REFERENCES


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