Impact of the Weather on the Combined Economic and Emission Optimization Problem of MG

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Abstract: The high integration of renewable energy resources and utilizing of storage devices with possible exchange power with the utility grid make the optimization problem of microgrid (MG) significantly difficult comparing with the conventional systems. This paper quantifies the impact of weather conditions on the combined economic and emission optimal operation of the MG. The optimization problem is formulated as mixed integer quadratic program (MIQP), where the unit commitment (UC) is taken into consideration in the optimization problem. In addition, realistic constraints are taken into account to make the problem close to the real scenario. The proposed optimization approach is applied to the low voltage MG, which includes distributed generators (DGs), renewable energy sources (wind, solar) and storage battery. The results reveal that the abundant of wind and solar energies leads to reduce the operation and emission cost.

1. Introduction
Decreasing of fossil fuel, increasing of load demands, environmental pollution, and global warming lead to draw more attention to use renewable and clean energy sources in the generation of electricity. The MG is an enabling technology to integrate these energy sources with distribution system. The MG is a small system comprises of renewable energy sources which are uncontrollable, such as wind and solar energy resources. The MG also has DGs such as diesel generators, micro turbine and fuel cell which are controllable sources. Besides, it involves storage devices. In addition, it has different types of loads which can be managed to make sure the system work safely and economically. The MG operates either autonomously in an isolated mode without any connection with the utility grid or operates in a connected mode and can exchange power with main grid. In both operation modes, the MG has to maintain power supply to its load. The penetration of the renewable energy sources, DGs, and storage devices with distribution networks creates many challenges in different aspects especially for optimal management of power flow in the MGs. Accordingly, new intelligent methods have been proposed to solve the optimal scheduling of the MG.

The optimization problem includes both continuous decision variables such as battery (charging / discharging) and discrete variables, such as UC. The UC, charging and discharging operations of battery, and trading energy with the main grid make the optimization problem significantly complex and a nonlinear. The outcome of the optimization of the MG result in enormous economic benefits for humans and environment. This urges researchers to develop approaches and algorithms to formulate and solve the optimization problem of MGs efficiently. So, many sophisticated algorithms have been presented to solve these complicated problems.
Many researchers have reported the optimization problem in MG in their studies. Authors in [1] proposed an optimal management approach to optimize the operation of low voltage MG with integration of renewable energy resources. Authors in [2] presented a method combining the UC and scheduling of generation into a single optimization approach. This method applied on Texas (ERCOT) power system which includes mix of conventional generation and wind generation. Reference [3] addressed economic dispatch problem with unit commitment in MGs. Lambda Iteration algorithm has been modified to use in this context and a genetic algorithm with some novel specific operator has been used to tackle the UC problem with different constraints and scenarios. In reference [4] a novel energy management system for MG with UC based on rolling horizon strategy was suggested. The optimization problem formulated as (MIP) and for each decision step the optimization problem was solved. The Benders decomposition technique has been used to solve the Multi-objective optimization approach with UC of a MG includes 33-bus. References [6, 7] proposed a model predictive control (MPC) approach to formulate optimization problem in MG with UC. The proposed method applied on connected MG consists of distributed generators, storage device and controlled. The aim of paper is to minimize the operating cost and satisfying the constraints.

In this paper, the impacts of weather conditions on the optimal operation of the MG are analyzed and the optimization problem is solved for the system for four different scenarios. Different renewable and low emission generation technologies with storage battery are considered in this study. Constraints are inserted in the formulation of problem to make the prosed system close to real one.

2. System modelling

It is necessary to model the distributed generators, storage battery, and constraints to formulate the optimization problem in the MG.

2.1. Operation cost of the distributed generators

The fuel cost of DGs is formulated as a function of output real power at interval \( t \) and it is modelled by quadratic function as follows [8, 9]:

\[
C_{DGi}(P_{DGi}) = \sum_{i=1}^{N} \left( a_i + b_i P_{DGi}(t) + c_i P_{DGi}^2(t) \right)
\]

where \( a_i (\text{€/h}), b_i (\text{€/kWh}), \) and \( c_i (\text{€/kW}^2\text{h}) \) are the fuel cost function coefficient, \( N \) is the number of distributed generators.

2.2. Cost of operating and maintenance of the distributed generators

This cost is assumed to be proportional with the produced power and it is calculated by the following equation [10]:

\[
C_{OMi}(P_i) = \sum_{l=1}^{N} K_{OMi} P_{DGi}(t)
\]

where \( K_{OMi} \) is the coefficient of operating and maintenance cost of \( i \)th distributed generators.
2.3. Model of storage battery

Storage battery has been modelled in several different ways. Criteria that have been used for choosing the model of battery depend on the details and the field of the study. Accordingly, the following equation is used in the field of optimal operation of MG [7]:

\[
E_{bat}(t) = E_{bat}(t-1) - \left( \frac{P_{bat-ch}(t)}{\eta_{ch}} \right) \Delta t + \left( \frac{P_{bat-dis}(t)}{\eta_{dis}} \right) \cdot \Delta t
\]

where \( E_{bat}(t) \), \( E_{bat}(t-1) \) are the charge of battery at current and previous state. \( P_{bat-ch}(t) \), \( P_{bat-dis}(t) \) are the battery charging and discharging power respectively. \( \eta_{ch}, \eta_{dis} \) are charging and discharging efficiencies, \( \Delta t \) is the sampling time.

The battery is deteriorated due to charge and discharge operations. This degradation is converted to monetary concept using the following equation:

\[
C_{bat} = C_{Degradation} \cdot E_{bat}(t)
\]

where \( C_{Degradation} \) is the degradation cost of battery (€/kWh), \( E_{bat}(t) \) is the charging or discharging energies of the battery (-) for charging (+) discharging.

2.4. Interaction with the utility grid

MG can exchange power with the utility grid when it works in connecting mode. The trading power cost with the upstream grid is calculated using the following equation [8]:

\[
C_g(P, t) = C_g(t) \cdot P_g(t)
\]

where \( C_g(t) \) is the trading power price with the main grid, \( P_g(t) \) is the trading power with the main grid (+) when buying power and (-) when selling power to the utility grid.

2.5. Model of emission of the greenhouse gases

The emission of carbon dioxides CO2, Sulphur dioxides SO2, nitrogen oxides NOx, and particle matter are caused by burning the fossil fuel which leads to environmental pollution. This emission depends on the power generated by the unit. The cost of emission at interval \( t \) for each greenhouse gases is calculated by the following equations [11]:

The emission cost of the CO2 from \( i^{th} \) distributed generators

\[
E_{CO2,i}(t) = \sum_{i=1}^{N} E_{CO2,i} \cdot C_{CO2,i} \cdot P_{DG,i}(t)
\]

where \( C_{CO2} \) (€/kW) is a cost of CO2 emission, \( E_{CO2} \) (kg/kWh) is the emission rate of CO2 from \( i^{th} \) generators.

The emission cost of the NOx from \( i^{th} \) generators

\[
E_{NOX,i}(t) = \sum_{i=1}^{N} E_{NOX,i} \cdot C_{NOX,i} \cdot P_{DG,i}(t)
\]

where \( C_{NOX} \) (€/kW) is the emission cost of NOX, \( E_{NOX} \) is the emission rate of NOX from \( i^{th} \) generators.
The emission cost of SO₂ from \( i \)th generators

\[
E_{SO₂,i}(t) = \sum_{i=1}^{N} E_{SO₂,i} \cdot C_{SO₂,i} \cdot P_{DG,i}(t)
\]

where \( C_{SO₂}(€/kW) \) is a cost of SO₂ emission, \( E_{SO₂} \) is the emission rate of SO₂ from \( i \)th generators.

The emission cost of particle matters from \( i \)th generators

\[
E_{PM,i}(t) = \sum_{i=1}^{N} E_{PM,i} \cdot C_{PM,i} \cdot P_{DG,i}(t)
\]

where \( C_{PM}(€/kW) \) is a cost of emission of particulate matter, \( E \) (kg/kWh) is the emission rate of particulate matter from \( i \)th generators.

3. Objective function

The UC in the optimization problem is a mixed integer and its aim is to determine which generators are turned on or off, otherwise all generators are working through the entire scheduling time. The objective function of operation of the MG with is formulated with considering the UC as follows:

\[
F = \min \sum_{t=1}^{T} \sum_{i=1}^{N} U_{DG,i} \left[ (C_i(P_{DG,i}(t)) + OM_i(P_{DG,i}(t)) + SU_{DG,i}(t) + SD_{DG,i}(t) + E_{SO₂,i}(t) + E_{NOX,i}(t) + E_{SO₂}(t) + E_{PM,i}(t) + C_{bat}(P_{bat}(t)) + C_{grid}(t) \right]
\]

where \( SU_{DG,i} \) and \( SD_{DG,i} \) are startup and shut down cost of the DGs and they are calculated as follows [5, 12]:

\[
SU_{DG,i}(t) = S_{ci} \cdot (U_{DG,i}(t) - U_{DG,i}(t) \cdot U_{DG,i}(t - 1))
\]

\[
SU_{DG,i}(t) \geq 0
\]

\[
SD_{DG,i}(t) = S_{di} \cdot (U_{DG,i}(t - 1) - U_{DG,i}(t) \cdot U_{DG,i}(t - 1))
\]

\[
SD_{DG,i}(t) \geq 0
\]

where \( S_{ci} \) and \( S_{di} \) are the startup and shut down cost of the \( i \)th generators (€).

4. Modelling of constraints

The following constraints are taken into consideration when formulation of the optimization problem:

4.1. Generating capacity constraint

\[
U_{DG,i}(t) \cdot P_{DG,i-min} \leq P_{DG,i}(t) \leq U_{DG,i}(t) \cdot P_{DG,i-max}
\]

4.2. Minimum up/minimum down constraints

Each generator has a minimum up/down time constraint. The generator has to operate for a specific period of time after it switches on (minimum up) before it switches off. It also has to be off for a period (minimum down) before it switches again. These constraints can be formulated as following [6, 13]:

\[
U_{DG,i}(t) - U_{DG,i}(t - 1) \leq U_{DG,i}(t)\quad \text{(Off-on switch)}
\]
\[ U_{DG,i}(t - 1) - U_{DG,i}(t) \leq 1 - U_{DG,i}(\tau) \quad \text{(On-off switch)} \]  

where \[ \tau = t+1, \ldots, \min (t + T^{up} - 1, T) \] in case of the minimum up time and \[ \tau = t+1, \ldots, \min (t + T^{down} - 1, T) \] for the minimum down constraint.

### 4.3. Spinning reserve constrain

\[ \sum_{i=1}^{N} U_{DG,i} \cdot P_{DG,i}^{max}(t) = P_D(t) + R(t) \]  

### 4.4. Power balance constrain

The summation of output power of each generation source, purchased and sold energy from the utility grid, and the charging/discharging of batteries should satisfy the total load demand at each sampling time.

\[ \sum_{t=1}^{T} \left( \sum_{i=1}^{N} P_{DG,i}(t) \right) + P_{w}(t) + P_{pv}(t) + P_{bat}(t) + P_{grid}(t) = P_D(t) \]  

where \( P_{bat}(t) \) is (+) for discharging and (-) for charging, \( P_{grid}(t) \) is (+) for purchasing and (-) for selling.

### 4.5. Ramp rate limits constraint

It is inconvenient to increase the generated power of any \( i^{th} \) generators in a certain interval more than a specific value up–ramp limit (UR\(_i\)) compare to the previous generated level and neither deceases less than certain value down-ramp limit (DR\(_i\)) compare to previous generated power. This constraint should be met when solving the optimal problem of the MG and it is formulated as follows [14]:

\[ -DR_i \cdot \Delta T \leq P_{DG,i}(t + 1) - P_{DG,i}(t) \leq UR_i \cdot \Delta T \]  

### 4.6. Exchange power with the main grid constraints

The limitation of power exchanges with the upstream grid should be satisfied for each time interval. The exchange power with utility grid at each period either purchasing power from the utility, selling power to the utility or neither of them. Therefore, two binary variables \( u_{g-pur}(t) \), \( u_{g-sell}(t) \in [0,1] \) are assigned to represent these operations and to prevent purchasing and selling power in the same time. This operation is formulated as follows:

\[ u_{g-pur}(t) \cdot P_{g-min} \leq P_{g-pur}(t) \leq u_{g-pur}(t) \cdot P_{g-max} \]  

\[ u_{g-sell}(t) \cdot P_{g-min} \leq P_{g-sell}(t) \leq u_{g-sell}(t) \cdot P_{g-max} \]  

\[ u_{g-pur}(t) + u_{g-sell}(t) \leq 1 \]  

### 4.7. Constraints of the Storage Battery

The storage devices have many constraints should be met and they are formulated as in the following.

A. Battery state charge constraint:

\[ E_{bat-min} \leq E_{bat}(t) \leq E_{bat-max} \]  

B. Charging and Discharging Power Constraints:
The exchange power with storage battery at each sampling period: charging, discharging or no exchange power. Two binary variable $u_{\text{bat-ch}}(t), u_{\text{bat-dis}} \in \{0,1\}$ are assigned to formulate the status of battery operation and to prevent charging and discharging power simultaneously.

$$u_{\text{bat-ch}}(t).P_{\text{bat-ch,min}} \leq P_{\text{bat-ch}}(t) \leq u_{\text{bat-ch}}(t).P_{\text{bat-ch,max}}$$  \hspace{1cm} (25)

$$u_{\text{bat-dis}}(t).P_{\text{bat-dis,min}} \leq P_{\text{bat-dis}}(t) \leq u_{\text{bat-dis}}(t).P_{\text{bat-dis,max}}$$  \hspace{1cm} (26)

$$u_{\text{bat-ch}}(t) + u_{\text{bat-dis}}(t) \leq 1$$  \hspace{1cm} (27)

4.8. Emission constraints

The constraints of emission of greenhouse gas from DGs are formulated as follows:

$$\sum_{i=1}^{N} \beta_{\text{CO2},i}.(P_{DGi}(t)) \leq L_{\text{CO2}}$$  \hspace{1cm} (28)

$$\sum_{i=1}^{N} \beta_{\text{NOX},i}.(P_{DGi}(t)) \leq L_{\text{NOX}}$$  \hspace{1cm} (29)

$$\sum_{i=1}^{N} \beta_{\text{SO2},i}.(P_{DGi}(t)) \leq L_{\text{SO2}}$$  \hspace{1cm} (30)

$$\sum_{i=1}^{N} \beta_{\text{PM},i}.(P_{DGi}(t)) \leq L_{\text{PM}}$$  \hspace{1cm} (31)

where $L_{\text{CO2}}$, $L_{\text{NOX}}$, $L_{\text{SO2}}$, $L_{\text{PM}}$ are the limitations of CO$_2$, NO$_X$, SO$_2$, PM in area of the MG.

5. Case study

Fig.1 shows the MG that is considered in this paper. It is a modified grid of the MG which has been presented in [15]. It consists of nineteen bus bars and three feeders: residential feeder supply residential loads, the industrial feeder supplies the workshops and Commercial feeder supplies commercial loads. The Load for each feeder and the total load are shown in Fig.2. This grid includes two diesel generators (DG), two micro turbines (MT), a fuel cell (FC), a wind turbine (WT), photovoltaic panels (PV) and a storage battery. ILOG CPLEX version 12.6 is used to solve (MIQP) optimization problem [16, 17]. In this paper, four scenarios are considered for weather as shown in Table 1. In all cases, the storage device should be fully charged at the beginning and end of control horizon.

| Table 1 Scenarios of weather effect on optimal operation of MG |
|---------------------------------------------------------------|
| LC | Low wind and cloudy day                                  |
| LS | Low wind sunny day                                       |
| HS | Windy and sunny                                          |
| HC | Windy but cloudy day                                     |
Fig. 1. MG under study

Fig. 2. Typical load curves for the feeders of the MG
6. Results and discussion

Figs. 3 to 6 show the optimal scheduling of DGs and interaction power with storage battery and the main grid. It can be noticed from Fig. 3 that the MG purchases the lowest power from the utility grid at hour 10 because the price has the highest value. It also can be seen from Fig. 5 that the MG sells energy to the main grid at hour 10 because the renewable energy abundant and the price at this hour has the highest value. In addition, it can be observed from these figures that the storage battery charges at hours 23 to 24 to fully charge to satisfy the constraint of fully charging at the end of the scheduling day.

Figs. 7 and 8 show the operating and emission cost of the four scenarios. It can be seen from these figures that the highest value of the operation cost is at hour 13 when renewables energy is low at low wind and cloudy weather. It also can be observed that the highest value of the emission cost is at hour 10 for all cases because at this hour the generation from the DGs is the highest value among other hours because the price has the highest value and the renewable energy has low value. Further, it can be seen that the UC makes micro turbines that they have the lowest fuel and emission cost provide higher energy than fuel cell and diesel generators. Furthermore, the UC also makes micro turbines work more operating hours than fuel cell and diesel generators. This leads to reduce the operating and emission cost.

Table 2 summarizes the obtained results from applying aforementioned analysis on four scenarios. It can be seen from the data in this table the lowest operating cost obtains in case of windy and sunny day because the energy from renewable sources is regarded as free operating cost.

![Fig. 3. Generation schedule for low wind and cloudy day](image1)

![Fig. 4. Generation schedule for low wind and sunny day](image2)
Fig. 5. Generation schedule for high wind and sunny day

Fig. 6. Generation schedule for high wind and cloudy day

Fig. 7. Operating cost of four scenarios

Fig. 8. Emission cost of four scenarios
7. Conclusions

The impacts of weather conditions on the combined economic and emission optimization of the MG with consideration of the UC and constraints are analyzed. Comparison between different scenarios is carried out to quantify the effect of weather on the optimal operation of MG. The whole optimization problem is formulated as (MIQP). It can be concluded from the results that the implementing of the UC in the simulation leads to reduce the total operating and emission cost. In addition, it can be concluded that the weather has significant effect on the operating and emission cost and the optimal scheduling of DGs and exchanging power with the main grid and storage device. Further, the lowest operating and emission cost occurs when the renewable energies are abundant.

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