Effects of Dynamic Topology Reconfiguration for Optimal Operation in Multi-Microgrid System

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Abstract. Multiple microgrids (MMG) system can reconfigure its topology by adjusting statuses of static switches and tie switches to improve reliability and economics of individual MGs. In this paper, a day-ahead optimal operation approach of MMG system in parallel model with topology reconfiguration is proposed, and a co-evolution algorithm (CEA) based approach is studied to manage multiple MGs more economically. In addition, proper feasible regions are set to ensure feasibility of the solution in CEA. Effectiveness of MMG system reconfiguration as well as cooperative operations of reconfiguration, energy storage systems (ESSs), and dispatchable distributed generations (DGs) are studied via numerical simulations. Specifically, simulation results indicate that MMG system reconfiguration in parallel mode can improve economic operation of MMGs and enhance efficient utilization of dispatchable DGs and ESSs.

1. Introduction

Distributed generations (DGs), renewable DGs in particular, are being rapidly deployed in recent years due to their advantages in the aspects of economy, environmental protection, and flexibility. However, a high penetration of DGs with intermittent renewable energy brings challenges to the security of distribution network operation [1]. Microgrid (MG) is a small-scale self-government power system containing loads, DGs, energy storage systems (ESSs), and a control system, which provides an effective way to make use of renewable DGs effectively and securely [2].

With the increasing number and capacity of MGs, multi-MG (MMG) system emerges as a technology to manage multiple MGs more reliably and economically [3]. Specifically, an MG is usually connected to the distribution network through point of common coupling (PCC) which is normally a closed static switch. While in an MMG system, MGs in close proximity can be connected to each other through tie switches [4]. Under this setting, an MMG system can be reconfigured by changing statuses of static switches and tie switches in parallel mode, which makes it possible to optimally adjust topology of the MMG system and effectively manage power exchange among MGs.

The study on MMGs focused on the cooperative operation of multiple MGs to enhance reliability, economics and resiliency of MMG system. In [5], a decentralized energy management system for the cooperative operation of networked MGs in both parallel and islanded modes is presented. In [6], a
multi-agent based demand response energy management system is proposed to facilitate power trading among MGs. In [7], a decentralized partially-observable Markov decision process is adopted to explore the optimal control of multiple MGs. In [8], adjustable power and demand response of each MG are applied in the energy management strategy. In [9], household appliance scheduling is considered in energy management of MMG system.

In the survey of the optimal operation of MMGs, DGs, ESS and other different kinds of adjustable resources are studied for improving economics of MMG system. However, adjustment of the statuses of static switches and tie switches have not been fully considered in the existing studies of optimal operation of networked MMG system.

In this paper, day-ahead optimal operation of an MMG system with topology reconfiguration is proposed and solved via co-evolution algorithm (CEA). Effectiveness of the MMG system reconfiguration in parallel mode as well as the cooperative operations of reconfiguration, ESSs, and DGs is illustrated via simulations. Compared with existing work, the main contributions of this paper are listed as follows: (i) Proposing a day-ahead optimal operation model of MMG system in parallel mode with dynamic topology reconfiguration and solving the day-ahead optimal operation model via CEA. (ii) Illustrating that MMG system reconfiguration in parallel mode can improve economic operation of MMGs and enhance efficient utilization of dispatchable DGs and ESSs.

2. Topology of an MMG System
An MG is usually connected to the distribution network through normally closed static switch. Meanwhile, in an MMG system, MGs in close proximity can be connected to each other through tie switches. Dynamic MMG system topology reconfiguration is realized by changing statuses of static switches and tie switches for enhancing reliable and economic operation of the MMG system.

Taking an MMG system in Fig. 1 for example, the MMG system contains MG1, MG2, and MG3. They are connected to distribution network through static switches S1, S2, and S3, respectively. When static switch S1 is open and tie switch S4 is closed, MG1 and MG2 can be connected to each other to alter power exchange. That is, statuses of these static switches and tie switches can be adjusted to change topology of the MMG system. Reconfiguring topology of the MMG system could alter power exchange among MGs, which will influence economical and reliable operation of the MMG system.

![Fig. 1. Diagram of an illustrative MMG](image)

3. Problem Formulation of MMG system reconfiguration
In the proposed day-ahead optimal operation model of MMG system in parallel mode with topology reconfiguration, the objective (1) is to minimize total operation cost of the MMG system.

$$ F = \sum_{i=1}^{N_{dg}} \left( \sum_{j=1}^{N_{mg}} C_{i,j}^{dg} + \sum_{j=1}^{N_{mg}} C_{i,j}^{ext} + \sum_{k=1}^{N_{ess}} C_{i,j}^{ele} \right) $$

where \( t \) is the length of each time slot and it is supposed to be an hour in this paper. In each hour, the operation state such as outputs of DGs and statuses of switches is unchanged. \( N_{dg}, N_{ess} \) and \( N_{mg} \) are respectively the number of DGs, ESSes and MGs in MMG system. \( C_{i,j}^{ele} \) is power purchase cost of the
kth MG from the distribution network at time $t$. $C_{\text{dg},i}^{d}$ and $C_{\text{ess},j}^{e}$ are respectively operation costs of the ith DG and the jth ESS at time $t$, which are calculated as in $(2)-(4)$.

$$C_{\text{dg},i}^{d} = c_{\text{dg},i}^{d} P_{\text{dg},i}^{d} + c_{\text{dg},i}^{c} (P_{\text{dg},i}^{d})^2 \tag{2}$$

$$C_{\text{ess},j}^{e} = \begin{cases} \beta_{\text{ess},j}^{\text{pur}} P_{\text{ess},j}^{\text{pur}} & P_{\text{ess},j}^{\text{pur}} > 0 \\ \beta_{\text{ess},j}^{\text{sel}} P_{\text{ess},j}^{\text{sel}} & P_{\text{ess},j}^{\text{sel}} < 0 \end{cases} \tag{3}$$

$$C_{\text{ess},j}^{\text{cd}} = \begin{cases} c_{\text{ess},j}^{\text{cd},\text{dis}} P_{\text{ess},j}^{\text{dis}} & P_{\text{ess},j}^{\text{dis}} > 0 \\ c_{\text{ess},j}^{\text{cd},\text{cha}} (-P_{\text{ess},j}^{\text{dis}}) & P_{\text{ess},j}^{\text{dis}} < 0 \end{cases} \tag{4}$$

where $c_{\text{dg},i}^{d}$ and $c_{\text{dg},i}^{c}$ are operation cost factors of the ith DG, $c_{\text{ess},j}^{\text{cd}}$ are charging and discharging cost factors of the jth ESS, $P_{\text{dg},i}^{d}$ and $P_{\text{ess},j}^{e}$ are respectively active outputs of the ith DG and the jth ESS at time $t$. When $P_{\text{ess},j}^{e}$ is positive, it means that the ESS is discharging, and a negative $P_{\text{ess},j}^{e}$ means that the ESS is charging. $\beta_{\text{pur}}$ and $\beta_{\text{sel}}$ are electricity price and feed-in tariffs at time $t$. $P_{\text{ess},j}^{e}$ is the net electricity that the kth MG exchanges with the distribution network, which can be calculated as in $(5)$.

$$P_{\text{ess},j}^{e} = P_{\text{ess},j}^{\text{load}} + P_{\text{ess},j}^{\text{loss}} - \sum_{i,k} P_{\text{dg},i}^{\text{load},k} - \sum_{j,s} P_{\text{ess},j}^{\text{load},s} \tag{5}$$

where $P_{\text{ess},j}^{\text{load}}$ is the active load at time $t$ in the kth MG, $P_{\text{ess},j}^{\text{loss}}$ is the active loss at time $t$ in the kth MG, which can be described as:

$$P_{\text{ess},j}^{\text{loss}} = \sum_{i} r_{i} \frac{S_{i,j}^{2}}{U_{i,j}^{2}} \tag{6}$$

where $S_{i,j}$ is the apparent power of the ith line at time $t$, $U_{i,j}$ is the end terminal voltage of the ith line at time $t$, $r_{i}$ is the resistance of the ith line, and $T_{i}$ represents the set of all lines in the kth MG.

It is worth mentioning that considering topology reconfiguration capability of MMG system, number of MGs as well as assets contained in each MG are not fixed. For example, the MMG system shown in Fig. 1 originally contains three MGs. However, when switches of line1 and line3 are open while switches of line2, line4, and line5 are closed, the MMG system after reconfiguration is consisted of only one MG which contains all DGs and ESSs.

The following constraints are to be satisfied in the day-ahead optimal operation of the MMG system:

2) Power injection Constraints: The total power injection to the distribution network through PCC should not exceed limit.

$$S_{t}^{\text{PCC}} \leq S_{t}^{\text{PCC},\text{max}} \tag{7}$$

where $S_{t}^{\text{PCC}}$ is power injection at the ith connection node at time $t$, and $S_{t}^{\text{PCC},\text{max}}$ is its capacity limit.

3) Branch power Constraints: The magnitude of apparent power of each branch must lie within their permission ranges:

$$S_{i,j} \leq S_{i,j}^{\text{max}} \tag{8}$$

where $S_{i,j}$ is the permitted maximum power transmission of the ith line, and $S_{i,j}^{\text{max}}$ is the apparent power of the ith line at time $t$.

4) Dispatchable DG Operation Constraints: Operation constraints of dispatchable DGs include power output limits and ramping up/down limits as shown in $(9)$.

$$\begin{align*}
R_{i}^{d}_{\text{min}} & \leq P_{i,j}^{d} \leq R_{i}^{d}_{\text{max}} \\
R_{i}^{d}_{\text{up}} - P_{i,j}^{d} & \leq R_{i}^{d}_{\text{up},\text{max}} \\
P_{i,j}^{d} - R_{i}^{d}_{\text{down},\text{max}} & \leq R_{i}^{d}_{\text{down}}
\end{align*} \tag{9}$$

where $R_{i}^{d}_{\text{max}}$ and $R_{i}^{d}_{\text{min}}$ are upper and low limits on active power output of the ith DG, $R_{i}^{d}_{\text{up},\text{max}}$ and $R_{i}^{d}_{\text{down},\text{max}}$ are the maximal ramp-up and ramp-down rates of the ith DG.
5) ESS Operation Constraints: Operation constraints of an ESS include state of charge (SOC) limits and charging/discharging power limits as shown in (10).

\[
\begin{align*}
SOC_{j,\text{min}}^{\text{ess}} & \leq SOC_{j,t}^{\text{ess}} \leq SOC_{j,\text{max}}^{\text{ess}} \\
0 & \leq P_{j,t}^{\text{cha}} \leq P_{j,\text{max}}^{\text{cha}} \\
0 & \leq P_{j,t}^{\text{dis}} \leq P_{j,\text{max}}^{\text{dis}} \\
SOC_{j,\text{fin}}^{\text{ess}} & = SOC_{j,\text{ini}}^{\text{ess}}
\end{align*}
\]

where \(SOC_{j,t}^{\text{ess}}\) is the SOC of the jth ESS at time t, \(SOC_{j,\text{min}}^{\text{ess}}\) and \(SOC_{j,\text{max}}^{\text{ess}}\) are the lower and upper SOC limits of the jth ESS, \(P_{j,t}^{\text{cha}}\) and \(P_{j,t}^{\text{dis}}\) are charging and discharging power of the jth ESS at time t, \(P_{j,\text{max}}^{\text{cha}}\) and \(P_{j,\text{max}}^{\text{dis}}\) are maximum charging and discharging power limits of the ith ESS, \(SOC_{j,\text{ini}}^{\text{ess}}\) and \(SOC_{j,\text{fin}}^{\text{ess}}\) are initial and final SOC levels of the jth ESS in daily operation schedule. For ensuring that the ESS will be available in the next schedule, the final SOC levels of ESS in daily operation schedule should be equal to the initial SOC levels of the ESS.

4. Day-Ahead Optimal Dispatching of MMGs with Dynamic Reconfiguration Based on Co-evolution algorithm

4.1 Co-evolution algorithm
If the reactive power of the MMG system is sufficient and the nodal voltage is supposed to be rated, the presented optimization problem can be formulated as a mixed integer linear programming model with quadratic constraints. The CEA, which has been successfully used to solve complex optimization problems, especially those with a large number of variables [10], is applied to solve the optimization problem. In this paper, one day is divided into 24 periods and values of variables in each hour are unchanged. Solution sets of daily outputs of controllable DGs, daily outputs of the ESSs, and daily operation modes of switches represent different populations in the co-evolution algorithm.

4.2 Encoding and decoding
Decimal integer encoding is applied in CEA, and decision variables include daily reconfiguration schedule, daily output power of dispatchable DGs, and daily charging/discharging power of ESSs.

Because of the topology constraints, the number of feasible reconfiguration schemes is limited, and in turn decimal numbers can be used to express topology of the MMG system. Taking MMG system in Fig. 1 as an example, 1 and 0 are used to represent close and open status of a switch. According to radial constraint, feasible statuses of the five switches include 11100, 01011, 01110, 10011, 10101, 10110, 11001, and 00111.

4.3 Initial population generation
In order to ensure that solutions are satisfied with constrains, the initial populations should be in feasible regions.

Dispatchable DGs are constrained by the maximum output and ramping up/down limits, the lower bound \(P_{i,t}^{\text{low}}\) and upper bound \(P_{i,t}^{\text{upp}}\) of their feasible region of output power for the ith DG in time period \(t\) can be described as:

\[
P_{i,t}^{\text{low}} = \max \left(0, P_{i,t-1}^{\text{low}} - R_{i,\text{max}}^{\text{th}} \cdot \Delta t\right) \quad (11)
\]

\[
P_{i,t}^{\text{upp}} = \min \left(P_{i,t-1}^{\text{upp}} + R_{i,\text{max}}^{\text{th}} \cdot \Delta t, P_{i,\text{max}}^{\text{th}}\right) \quad (12)
\]

In order to ensure that the initial and final SOC of ESSs in daily operation schedule keep the same, the optimal schedule of ESSs is divided into two phases and the minimum period number \(N_{\text{ess}}\) of the first section is set as:
\[
N_{i}^{\text{ess}} = \max \left\{ \left( \text{ceil} \left( \frac{S_{i}^{\text{ess}} \cdot \text{SOC}_{i,\text{max}}^{\text{ess}} - S_{i}^{\text{ess}} \cdot \text{SOC}_{i,\text{fin}}^{\text{ess}}}{P_{i,\text{max}}} \right) \right) \right. \\
\left. \left( \text{ceil} \left( \frac{S_{i}^{\text{ess}} \cdot \text{SOC}_{i,\text{fin}}^{\text{ess}} - S_{i}^{\text{ess}} \cdot \text{SOC}_{i,\text{max}}^{\text{ess}}}{P_{i,\text{max}}} \right) \right) \right\} 
\]  
(13)

Where, \( \text{ceil}(x) \) expresses to get the minimum inter that is bigger than \( x \). \( S_{i}^{\text{ess}} \) is the capacity of the \( i \)th ESS.

In first phase, the lower bound \( P_{\text{ess-low},i,t} \) and upper bound \( P_{\text{ess-upp},i,t} \) of the feasible region of the output of the \( i \)th ESS in time period \( t \) can be described as:
\[
P_{\text{ess-low},i,t} = \max \left( S_{i}^{\text{ess}} \cdot \text{SOC}_{i,\text{min}}^{\text{ess}} , S_{i}^{\text{ess}} \cdot \text{SOC}_{i-1}^{\text{ess}} - P_{i,\text{max}}^{\text{dis}} \cdot \Delta t \right) 
\]  
(14)
\[
P_{\text{ess-upp},i,t} = \min \left( S_{i}^{\text{ess}} \cdot \text{SOC}_{i,\text{max}}^{\text{ess}} , S_{i}^{\text{ess}} \cdot \text{SOC}_{i-1}^{\text{ess}} + P_{i,\text{max}}^{\text{cha}} \cdot \Delta t \right) 
\]  
(15)

In second phase, the lower bound \( P_{\text{ess-low},i,t} \) and upper bound \( P_{\text{ess-upp},i,t} \) of the output of the \( i \)th ESS in time period \( t \) can be described as:
\[
P_{\text{ess-low},i,t} = \max \left( S_{i}^{\text{ess}} \cdot \text{SOC}_{i,\text{min}}^{\text{ess}} , S_{i}^{\text{ess}} \cdot \text{SOC}_{i+1}^{\text{ess}} + P_{i,\text{max}}^{\text{dis}} \cdot \Delta t \right) 
\]  
(16)
\[
P_{\text{ess-upp},i,t} = \min \left( S_{i}^{\text{ess}} \cdot \text{SOC}_{i,\text{max}}^{\text{ess}} , S_{i}^{\text{ess}} \cdot \text{SOC}_{i+1}^{\text{ess}} - P_{i,\text{max}}^{\text{cha}} \cdot \Delta t \right) 
\]  
(17)

In order to avoid generating large numbers of infeasible reconfiguration solutions in population initialization, the reconfiguration plan that all static switches are closed and all tie switches are open is regarded as initial chromosome.

4.4 Selection operation
The tournament algorithm is used in the selection operation. That is, successively choosing two individuals from all chromosomes and the one with a smaller objective is selected.

4.5 Crossover operation
The order-based crossover method is applied in the crossover operation. That is, we (i) randomly choose two points of one chromosome to cut off, (ii) take position of the first point as starting point and put genes between the two points into another chromosome, and (iii) check if the inserted genes are in the feasible regions, if not, create new genes in the feasible regions and replace the old one.

4.6 Mutation operation
Multiple points of the chromosome are randomly chosen, and new values in the feasible regions are created to replace the corresponding old genes.

5. Case Study
The MMG system with three MGs in Tianjin, shown in Fig. 2, is used to illustrate the proposed approach. The feed-in tariff is set as 0.029$/kWh. Fig. 3 shows the parameters of wind speed and light intensity. Fig. 4 shows the daily load profiles and day-ahead electricity purchasing prices. The rated output of WT is 200kW. The cut-in wind speed, wind speed and cut-out wind speed are 3m/s, 14m/s and 25m/s respectively. The area of the photovoltaic panel is 2.16m2. The conversion efficiency is 13.4%. The numbers of WTs in MG1, MG2 and MG3 are 2, 4 and 5, respectively. The numbers of photovoltaic panels in MG1, MG2 and MG3 are 2000, 2000 and 2400, respectively. The ESS capacity in MG1, MG2 and MG3 are 400kWh, 500kWh and 400kWh, respectively. The charging/discharging cost of ESS is 0.004$/kWh. The power limit of ESS is 200kW. The lower and upper limit of SOC are 0.1 and 0.9, respectively. The other parameters of MMG system is shown in Table 1 and Table 2. In this test system, feasible statuses of the five switches S1-S5 include the following eight states: 11100, 01011, 01110, 10011, 10101, 10110, 11001, and 00111, here 0 denotes the switch-off status, 1 denotes the switch-on status, which are defined as state 1-8 respectively. The switch action cost and switch action time
constraint are temporarily ignored when analysing the cooperation relationship among reconfiguration, dispatchable DGs and ESSs. What’s more, supposing that the reactive power of the MMG system is sufficient and the nodal voltage hold rated. The population size and the evolutionary generation are set as 50 and 200, respectively. The cross rate and mutation rate are 0.1 and 0.05. In order to study the effectiveness of reconfiguration on the optimal operation of MMG system, four scenarios with respect to different controllable resources are analyzed and the corresponding day-ahead optimal operation results are shown in Table 3.

![Diagram of the illustrative MMG in Tianjin](image)

**TABLE 1. Technical data of lines**

| Line  | Line1 | Line2 | Line3 | Line4 | Line5 |
|-------|-------|-------|-------|-------|-------|
| Resistance (Ω) | 0.194 | 0.235 | 0.194 | 0.209 | 0.209 |
| Reactance (Ω) | 0.662 | 0.484 | 0.662 | 0.430 | 0.430 |
| Maximum Power (kVA) | 1000 | 2000 | 1000 | 1500 | 1500 |

**TABLE 2. Technical data of dispatchable DGs**

| Cost coefficient 1 | Cost coefficient2 | Lower Limit | Upper Limit | Ramp-up rate | Ramp-down rate |
|--------------------|-------------------|--------------|-------------|--------------|----------------|
| 0.09$/kWh          | 0.0017$/kWh       | 0kW          | 400kW       | 400kW/h      | 400kW/h        |

![Parameters of wind speed and light intensity](image)
TABLE 3. Results of different scenarios under study

| Scen. | Controllable resources | Total cost ($) | Electricity cost ($) | ESS cost ($) | DG cost ($) | Loss Electricity (kWh) |
|-------|------------------------|----------------|---------------------|-------------|-------------|------------------------|
| 1     | No                     | 2581.4         | 2581.4              | 0           | 0           | 45.7                   |
| 2     | Reconfiguration        | 2404.4         | 2404.4              | 0           | 0           | 46.5                   |
| 3     | ESS and DG             | 2261.7         | 1245.5              | 15.4        | 1000.8      | 26.7                   |
| 4     | DG, ESS and reconfiguration | 2069.1 | 1084.4              | 17.2        | 967.5       | 30.1                   |

5.1 Impact of Reconfiguration

Scenario 1 and scenario 2 are used to explore that reconfiguration has the potential to exchange power among MGs. Fig. 5 shows the reconfiguration schedule of MMGs in scenario 2. Fig. 6 shows the power exchange through lines in scenario 1 and scenario 2. Specifically, power flows through line 1, line 2, and line 3 reflect power exchanges between individual MGs and the distribution network, while positive/negative value means that the MG withdraws/injects power from/into the distribution network. Furthermore, real power flows through line 4 and line 5 respectively reflect power exchanges between MG1 and MG2 as well as MG2 and MG3.

By comparing the power exchange in Fig. 6, it can be learned that power exchange among the MGs through tie lines and power injection from MGs to the distribution network substantially decrease after reconfiguration. In addition, operation results of scenario 1 and scenario 2 in Table 3 show that electricity purchase from the distribution network also reduces after reconfiguration.
5.2 **Cooperative Operation of ESSs and Dispatchable DGs in Reconfiguration**

Figs. 7 shows the reconfiguration schedule in scenario 4. Figs. 8, 9, and 10 respectively show power outputs of dispatchable DGs, charging/discharging power of ESSs, and power exchange through lines in scenario 3 and 4. Specifically, during the periods of 10:00-15:00, the dashed zones interval1 of Figs. 7-10 illustrate the potential that reconfiguration has on reducing operation cost of dispatchable DGs and improving utilization efficiency of ESSs. In addition, during the periods of 22:00-24:00, the dashed zones interval2 of Figs. 7 demonstrate the potential that reconfiguration has on improving utilization efficiency of dispatchable DGs.

In summary, it can be concluded that dynamic reconfiguration of the MMG system makes it possible to: (i) effectively exchange power among MGs, (ii) greatly reduce electricity that dispatchable DGs/ESSs need to generate/store, (iii) significantly enhance utilization efficiency of dispatchable DGs and ESSs, and finally (iv) improve economic operation of the MMG system.
Fig. 8. Active power outputs of dispatchable DGs in scenario 7 and scenario 8

Fig. 9. Charging/discharging power of ESSs in scenario 7 and scenario 8

Fig. 10. Power exchange through PCC in scenario 7 and scenario 8
6. Conclusion
In the paper, the MMG system reconfiguration for day ahead optimal operation in parallel mode is proposed based on CEA. The feasible regions are set to ensure the feasibility of the population in CEA. The case of a MMG with multiple scenarios is used to validate the effectiveness of MMG system reconfiguration in parallel mode. The simulation results indicate that MMG system reconfiguration in parallel mode can improve the economy of MMGs and the utilization efficiency of dispatchable DGs and ESSs, which proves the importance of MMG system in the operation of MMG system.

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