Resilience-Oriented Microgrids: A Comprehensive Literature Review

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Abstract—The salient features of microgrid (MG), such as operational flexibility, self-adequacy, and coordinated energy management, make it a promising candidate for facilitating the restoration of distribution power system after “low-frequency, high impact” events. In the literature, various methods have been proposed for improving the resilience of the system using MG or networked-MGs (NMGs). This paper conducts a comprehensive review of the state-of-the-art methods reported in the literature, aiming to provide more valuable insights into this area and help the system operator/planner to design more effective restoration strategies based on microgrids. At first, the principle of MG for resilience is described, and the formulation of the resilience problem is revisited. Subsequently, restoration strategies are classified into several categories and reviewed respectively. Finally, conclusion and outlook for future research are discussed.

Index Terms—microgrid, networked-microgrids, resilience.

I. INTRODUCTION

Power system resilience refers to the ability of the power system to withstand and recover from “low-frequency, high impact” events such as deliberate attacks, accidents, or naturally occurring incidents, while minimize the negative impacts, both short-term and long-term, of these events on the power system [1]-[3]. Recent years have witnessed many large area power outages due to extreme weather such as the 2005 Hurricane Katrina, 2011 Japan Earthquake, and 2012 Hurricane Sandy. Given that the severity and frequency of such uncertain events are expected to increase in the future as consequences of climate change [4], it is well-advised to attach sufficient importance to the exploration of power system resilience through the help of alternative approaches, instead of simply pouring investment into facility and network reinforcements. MG is a self-autonomic power distribution system, consisting of distributed generators (DGs), energy storage system (ESS) and controllable loads [5], [6]. With its inherent characteristics such as flexible operation modes (grid-connected and islanded mode), more interactions with customers and self-adequacy, MG is a promising, reliable and efficient solution for boosting the resilience of distribution power system. Furthermore, a networked-MGs, constructed by connecting multiple MGs with various generation and load profiles or dividing a distribution network into several MGs [7], can further improve the reliability and performance of the system with its salient features like critical loads support, coordinated energy management, decreased feeder losses, and increased power quality [8-11].

In the literature, various MG-based restoration strategies have been proposed [12]-[23]. However, there are still many pending questions to be solved, including but not limited to:

1) Flexible Objectives
Different goals in normal mode and in post-contingency stage should be well coordinated.

2) Privacy Dilemmas
Since forming networked-MGs does not necessarily mean acquiescent data sharing among the MGs and DG owners, each entity can reserve the options to share their information or not. However, restricted local observation and information might impair the performance as well as the economic benefits.

3) Uncertainty Concerns.
considering the obscure interactions between generation profiles, MGs, and perplexing load patterns during extreme events, conventional prevalent probabilistic distribution for weather forecast and load prediction needs further scrutinization when applied in networked-MGs.

4) Real-world Constraints and Limitations.
It is too conservative to apply the strict thermal limits of power lines adopted in normal mode for emergent scenarios. And ramp capability is crucial in terms of dynamic response, but often excluded from recent studies.

5) Incentives for Demand Response (DR)
Successful incentive for DR consist not only of mutual beneficial price itself but also of human factors associated with them, such as customer experience and potential leverage of large consumers. Negotiating with entities in MGs with the presumption that they all follow the motivation and penalty rules accurately is a desirable ideal rather than an achievable reality.

In the literature, there has not been a systematical review of the resilience-oriented microgrid research. This paper aims to fill this gap through a comprehensive literature study of the problem formulation, methodologies, and limitation of the state-of-the-art works, and envision the future research direction. The value of this paper is to provide a deep insight.
into this research area and help the system operator and planner to better design the restoration strategies based on microgrids.

II. PRINCIPLES OF MG FOR RESILIENCE

3 original MGs (MG1, MG2 and MG3) are formed for the normal operation in Fig. 1. They consist of local load, ESS, dispatchable/non-dispatchable DGs/renewable energy sources (RESs). They will be disconnected and all entities within this region will operate in a post contingency mode when large disturbance occurs. Resilient microgrids (RMG) are formed based on the geographical features of original MGs, fault area, and the damaged facilities. Connecting lines, between different MGs or MG and individual load scattered around the distribution network, will be used for network reconfiguration. For instance, RMG1 is formed by MG1 of which dispatchable DGs are insufficient and MG3 with redundant dispatchable capacity. Other load outside of any MG will be reallocated to a nearby MG2 according to a certain restoration strategy.

Figure 1. a schematic diagram of the distribution network and microgrid

A conceptual resilience curve is introduced in [18] where the resilience level is defined as a function of time with respect to a disturbance event. In this paper, we extended the idea with the presence of MGs in Fig. 2 where upper sub-figure stands for a scenario without MGs and lower one illustrates alleviations brought by MGs as flexible energy sources and potential preventive measures, such as securing critical loads with early-warning for extreme incidents, active/defensive islanding [24]-[25], and isolating vulnerable infrastructures. In general, the resilience can be classified into 2 groups: 1) operational resilience ($t_0-t_a$), consisting of normal/pre-contingency state, adaptive self-organization, response/recovery, and robust/resistance; and 2) infrastructure resilience ($t_p-t_n$) for the preparation of reconnecting to main grid. Adaptive self-organization stage represents the capability of the MGs to withstand the initial shock and the resilience level ($R_p$) of the system. The time $t_p$ to $t_1$ is for the preparation of restoration stage, including data collection, strategy modification, and rudimental computations, which aims to impede further cascading events and improve the feasibility of restoration in next stage. Thanks to the active islanding and the salient features of MGs to recovery the network and critical load, duration of this stage is shortened as showed in Fig. 2(b). Preventive measures and the focuses on critical load and power facilities will effectively improve the resilience level $R_p$ in Fig. 2(b) compared with the scenario without MGs. Similarly, MGs will facilitate and accelerate the restoration process without compromises in terms of the recovery rate of critical load on the one hand, and flexibility and stability of the system on the other.

Figure 2. resilience curve

Once the all the restoration measures are implemented, the system is starting to enter a stage of post-restoration ($t_{pr}-t_{ir}$) where resilience level might be lower than normal operation because of the damaged power infrastructures. Again, MG serves as a stabilizer in this stage by sharing power among area with extra energy sources and regions experiencing power deficiency. A full recovery from the incident can be expected after the infrastructure recovery ($t_{ir}-t_n$) is over.

III. MATHEMATICAL FORMULATION

Considering the substantial power balance fluctuation before/after incidents, and the potential reconfigurations in the recovery process, operational objectives of MGs are diversified in different stages. This section reviews objective functions and their corresponding constraints in the normal/pre-contingency stage and restoration stage respectively ($t_0-t_e$ and $t_r-t_{ir}$).

A. Formulation of the Normal Operation Problem

1) Objective Function

A common objective of the MGs in the normal operation is to minimize the operation cost. The operation cost generally consists of three components [17]-[19]: 1) base generation cost based on prediction of loads and RESs, 2) adjustment cost, including generation cost of dispatchable DGs and power exchange cost between MGs or MG and main grid, and 3) penalty cost due to scheduling adjustable loads outside the time intervals pre-specified by consumers. So, the normal operation problem can be formulated compactly as follows, with subscript $t$, $s$ and $t$ stand for node, scenario and time.

$$\min \sum_t (F_{t,s} + \Delta F_{t,s} + K_{pen})$$ (1)
2) Technical Constraints
The constraints can be grouped into 4 categories: power balance, ESS operation, system operation, and DG operation. Mathematical details are available in [12]-[20].

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power balance constraints</td>
<td>power exchange balance, active power and reactive power flow constraint</td>
</tr>
<tr>
<td>ESS constraints</td>
<td>state of charge (SOC), ramp constraint, exclusive operational state at any given time, the charging/discharging</td>
</tr>
<tr>
<td>System operational constraints</td>
<td>voltage deviation constraints, thermal limits of transmission lines, overall generation and load balance, topological limit (no loop and exclusive power source)</td>
</tr>
<tr>
<td>DG operational constraints</td>
<td>output constraint, ramp constraint, fuel constraint for dispatchable DGs</td>
</tr>
</tbody>
</table>

**B. Formulation of the Resilient Operation Problem**

During the restoration process, either by maintaining planned MGs or sectionalizing the on-outage area into new self-adequate MGs, the islanded area is facilitated to recovery from incidents to a best possible state without violating any operational constraints and facility constraints.

1) Objective Function
For the affected area, the objective is to minimize the unserved load instead of maximizing the profits [15]-[18]. There are several methods (for recovered loads, cost of load shedding, etc.) to address this issue, which will be discussed in subsequent sections. As an example, the objective can be expressed as follows (minimize the cost of load shedding):

$$
\min \sum_{t} \sum_{L} P_{L}^c \cdot r_{t}^c + r_{t}^h \cdot P_{L}^h
$$

2) Technical Constraints
The constraints in Tab. I can be applied to (2) with updates and modifications about the affected nodes correspondingly. However, due to the absence of main grid there should be one extra constraint for the reactive power regulation.

**IV. LITERATURE STUDY**

A. General Review of State-of-the-Arts
Table II gives a general review of the representative state-of-the-art works in the literature within recent 4 years, focusing on their objective and constraints in the system restoration stage. Detailed discussions are given in the sequel.

B. Realistic Concerns of the Constraints
Some realistic concerns of the constraints which have not been (or partially) addressed in the literature are discussed here.

1) Thermal Limit of the Power Line
A high pressure is imposed on the connecting lines between MGs due to the surging power flows from MG with abundant generation capacity to MG with energy deficiency. But considering their relatively short and predictable lasting time, as well as an adequate margin of the thermal limit itself, it is too conservative to apply the same constraint used in normal grid-connected operation mode. These constraints can be adopted in a more flexible way according to different priorities in different stages, which will assist the system to recover more loads and find a balance between robustness and conservativeness.

2) Topological Constraints
If the original network is well established according to the local regulations, the topological constraint [21], [22], of which purpose is to prevent loop scenarios, is not so imperative as it seems to be. On the other hand, given the relatively short and the expected duration of the initial stage of the restoration, the loop or multi-source scenario will eventually transfer to a radial structure. However, in the less severe situation, these structure constraints are necessary for preventing isolated load nodes or loop structure [26].

3) Ramping Constraints
Ramp constraints of RESs are much difficult to describe since there is always a dynamic balance between the prediction errors of the generation and load variation. Ref. [27] and [28] discuss this problem but they focus on a normal operation and dispatch cost rather than an emergency with harsh requirements for forecast accuracy. As for resilience problem, the stability of the system should be attached more importance when a sudden change in wind occurs, or a cloud blocks the sunshine entirely. A well-designed “ramp coefficient” can be incorporated to represent the collaboration between ESSs and RESs in a more precisely way and subjectively narrow down the fluctuations caused by the forecast errors.

C. Reactive Power Deficiency
After disconnected from main grid, MGs are inevitably exposed to the reactive power deficiency. An efficient but costly way to maintain reactive power balance is the installation of distributed reactive sources [29]. A counterintuitive experimental result shows that the reactive power margins of some load buses under the generation re-dispatch are higher than those under load shedding [30]. This information reminds us to review the differentiation of our alternatives in voltage regulation, where electric distance and geographical location should be incorporated as weighting factors.

D. Effective Price Strategy
Since we are no longer living in a world where people pay their exclusive attention to electric prices, a successful incentive strategy that convinces customers to participate in DR during post-contingency should consist not only of mutual beneficial price strategy itself, but also of human factors associated with them, such as customer experience and potential leverage of large consumers. Although a decentralized energy management strategy values the autonomous behavior of single end-user and often tries to incorporate the dynamic interaction between the users and the generators [31], [32], some determinants are still missing. As for resilience problem, time varied penalties or incentive prices based on different restoration stages are essential because blackout or load shedding in the initial stage is usually more acceptable than lasting outage in later stages. The priority can also be integrated into the penalties or incentives to represent the significance of certain loads under varied scenarios.
1) **Opportunity Cost**

The opportunity cost [33], [34] of precious dispatchable DGs and ESSs are often ignored. By adding this into the price function, the state of the reservoirs of dispatchable power resources can be described realistically in terms of the expected service time and varying energy cost, to other constraints in different restoration stages. It will impress the customers by the mounting price during emergency and encourage them to participate in DR actively and to pursue a longer service time.

2) **Reactive Power Support**

DGs owned by entities (other than MG owners) are usually not responsible for the voltage regulation during emergency. In fact, they are reluctant to use their limited DGs to generate reactive power to support voltage profile for possibilities of active power generation capacity reduction, which is not desirable from the owners' perspective. However, more entities should be encouraged to participate in this matter. Compared with expensive distributed static compensators, incorporating the reactive power support into the incentive strategy, either by exchange with modified electricity price or by direct purchase, is a viable solution for a better voltage profile.

### TABLE II. REVIEW OF STATE-OF-THE-ARTS

<table>
<thead>
<tr>
<th>Objective</th>
<th>Ref.</th>
<th>Single/Multi-MGs</th>
<th>Highlights and Fociuses</th>
<th>Demerits and Limitations</th>
<th>Mathematical Model/Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimization of Operational Cost</td>
<td>[12]</td>
<td>single</td>
<td>relaxed constraints on power line limits and power losses</td>
<td>high dependence on the accuracy of load forecast</td>
<td>MINLP</td>
</tr>
<tr>
<td></td>
<td>[13]</td>
<td>single</td>
<td>EV as load and power resource in different scenarios</td>
<td>cost of battery life is not considered</td>
<td>SLP</td>
</tr>
<tr>
<td></td>
<td>[14]</td>
<td>multi-MGs</td>
<td>privacy-preserving, nested structure</td>
<td>-cost of battery life is not considered</td>
<td>MILP</td>
</tr>
<tr>
<td>Maximization of Restored Load</td>
<td>[15]</td>
<td>multi-MGs</td>
<td>different priorities of load</td>
<td>arbitrary assumption of consensus from different MGs or DGs owners</td>
<td>MILP</td>
</tr>
<tr>
<td></td>
<td>[16]</td>
<td>multi-MGs</td>
<td>investigation of interaction between MGs and operators</td>
<td>-RES and load stochasticity is not fully addressed</td>
<td>MILP</td>
</tr>
<tr>
<td></td>
<td>[17]</td>
<td>multi-MGs</td>
<td>information is only exchange with neighboring MGs</td>
<td>oversimplification of generation of RESs</td>
<td>MILP</td>
</tr>
<tr>
<td>Minimization of Load Shedding</td>
<td>[18]</td>
<td>multi-MGs</td>
<td>Continuous Operating Time (COT) for a better resilience evaluation</td>
<td>inflexibility of restoration paths</td>
<td>ILP</td>
</tr>
<tr>
<td>Minimization of Switch Operation (restoration path)</td>
<td>[21]</td>
<td>multi-MGs</td>
<td>shortest switch operation time</td>
<td>lack of dynamic investigation</td>
<td>Modified Viterbi</td>
</tr>
<tr>
<td></td>
<td>[22]</td>
<td>multi-MGs</td>
<td>unbalanced three-phase power flow model for topology verification</td>
<td>-lack of consideration of reactive power</td>
<td>Spanning Tree Search</td>
</tr>
</tbody>
</table>

E. **Ownership and Privacy Dilemma**

1) **Issues with Ownerships of MG, DG, and ESS**

For the operator of the distribution system (or MG), the objective in the post-contingency is system-oriented: either pursuing higher recovery rate of critical load or setting minimization of total cost of the system as objective. But in NMGs where MGs are usually managed and operated under different ownership, to restrict the autonomy of MGs is not realistic since the diversified owner-ships will have a substantial impact on restoration strategies [35]. For instance, if the operator is not the owner of MG, DG, and ESS, the objective functions should be modified to include energy exchange cost within same MG. Thus, it is sensible to categorize MGs or DGs into several groups from totally rejecting the participation of DR to enthusiastically embracing it according to their inherent desires, because taking the monetary incentive as the sole driving force is arbitrary and unrealistic. This issue is partially addressed in [15] by describing the optimization problem with an additional objective function, which maximizes profits and minimizes the operational cost of DGs. Besides, realizing the phenomenon is also helpful to design a more profitable and efficient incentive and penalty strategy.
2) Privacy Concerns
Since the sole owner is just an ideal it is reasonable to form a flexible objectives and constraints with diversified focuses: higher autonomy for events with less influence and expected islanded time, and lower autonomy for extreme scenarios with unpredictable islanded time causing severe damage to network structure and generation sites. Thus, we should shed some light on the customer privacy [14], namely the reluctance of customers to share their information, especially in situations that are less imperative. In MGs adopting decentralized control strategies with coupled autonomous and cooperative units [16], [19], the conundrum of protecting privacy is how to make dependable decisions based on local observations, which in most cases cannot reflect the system state comprehensively and leads to sub-optimal solutions. Although certain algorithms can get around this issue by taking advantage of aggregative data and statistical analysis [36] under specific scenarios, and some privacy protection strategies are proposed [14], [17], generally there is no universal solution. Again, the flexibility is valued here since different stages, along with the severity of unfavorable events, should be considered to find an equilibrium between individual privacy and benefits of the whole system.

F. Modeling of Uncertainty
Uncertainties can be classified according to the sources and features as showed in Fig. 3, where inter-category correlations are also presented.

Simplifying the uncertainty modelling is necessary for efficient analysis. Generally, considering the variety of the sources of uncertainty, forming a system level strategy for minimization of the impacts of errors is difficult [12], [21], but granting more autonomy to individuals for modifications of dispatch orders can be a potential solution.

G. Solution Algorithms
For the description of stochasticity of RESs and the load consumption, scenario-based stochastic programming is prevalent in RES-based MGs [37]-[39]. Since it is based on the reproductions of deterministic models in scenarios generated by Monte Carlo simulations, overwhelming scenarios used to present the uncertainties increase the computation burden [40]. So, it is necessary, particularly for MGs with shorter dispatch horizon, to adopt appropriate techniques to reduce the scenarios for the computation alleviation without sacrificing their accuracy and with considering the "low-probability, high-impact scenarios". Scenario reduction techniques are proposed to pack similar scenarios into one based on certain probabilistic metrics [41], [42], but their feasibility in NMGs needs more investigation, like the possibility of suboptimal solutions, and capability to deal with continuous/discrete uncertainties. A probabilistic power balance constraint is a potential solution for this [43]. Although designed for UC problem, the idea of replacing many scenarios with inclusive possibilities of loads and RES generation is also viable here. Ref. [13] modifies the methods in [44] to be well incorporated into a single MG case. An alternative method is, instead of de-composing the problem based on scenarios, to decompose it based on entities [15]. And each entity is granted certain autonomy to pursue its own optimal decision. However, this will impair the capability to maximize recovered loads. Besides, load priority can be utilized to reduce the computation burden further since the scenario range will be obviously narrowed and some load-oriented strategies can be prepared in the initial stage [18].

V. SUMMARY AND OUTLOOK

Flexibility objectives in different stages, balance between privacy concerns and efficient robust performance, effective methods to minimize the uncertainty impacts, real-world constraints, compelling incentives for DR, and feasible strategies for load shedding are the principal challenges in this area. Further researches can be extended based on these concerns according to diversified and changeable priorities in various scenarios. Besides, there are still some unexplored area for resilient MGs, which can be described as follows:

1) Defensive Islanding Scheme
Defensive islanding is a preventive operational action and is intentionally deployed to avoid larger losses or damages in extreme condition. With advanced monitoring capabilities and real-time operational and predictive data, the power system adopting defensive islanding will operate in a less versatile, but more robust abnormal state [24], [25]. As for the resilient problem, defensive islanding can be utilized by either isolating the vulnerable power infrastructures or securing the critical loads in advance with early-warning for extreme incidents. The merits are threefold: 1) splitting the system into stable, controllable self-adequate MGs to prevent cascading events and to prepare for restoration; 2) avoiding protection relay errors due to uncontrollable passive islanding; 3) minimizing load shedding due to losses of power facilities when generation is sufficient. Ref. [45] implements the defensive islanding algorithm into the service restoration problem. However, they fail to incorporate the stochasticity features of RESs, and need more investigation regarding voltage stability and power balance.

2) Elastic Autonomy
A flexible autonomy is beneficial to every entity in 3 ways: 1) dispatch with a certain range of decision sets are favorable because of its adaptability against uncertainties; 2) encouraging more active participation in DR and promoting efficient and profitable price strategy; 3) addressing the privacy issues objectively according to scenarios in terms of severity of unfavorable events and stages of the restoration process.

3) Operative Assessment Criterion.
The absence of a feasible and impartial evaluation criteria impedes us from scheming preventive plan and comparing performances of potential strategies. Additionally, a comprehensive evaluation scheme is a cornerstone to propose practical and pertinent ameliorations afterward.

REFERENCES


