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A resilient microgrid formation strategy for load restoration considering master-slave distributed generators and topology reconfiguration

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HIGHLIGHTS

- A resilient microgrid-forming model is set up considering master-slave DG operation.
- The topology reconfiguration and microgrid-forming are coordinated in the model.
- A mixed-integer second-order cone programming is employed to solve the model.

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ABSTRACT

Recent severe power outages caused by extreme weather hazards have highlighted the importance and urgency of improving the resilience of electric distribution grids. Microgrids with various types of distributed generators (DGs) have the potential to enhance the electricity supply continuity and thus facilitate resilient distribution grids under natural disasters. In this paper, a novel load restoration optimization model is proposed to coordinate topology reconfiguration and microgrid formation while satisfying a variety of operational constraints. The proposed method exploits benefits of operational flexibility provided by grid modernization to enable more critical load pickup. Specifically, a mixed-integer second order cone programming is employed to reduce the computational complexity of the proposed optimization with optimality guaranteed. Finally, the effectiveness of the proposed method has been verified on an IEEE 33-bus test case and a modified 615-bus test system.

1. Introduction

Electrical power production is the large-scale conversion process of transforming different types of primary energy into easily transportable electrical energy. In particular, the distribution system is at the end of the whole power system, and directly affects the power supply quality and reliability seen by customers. Statistics from electric power companies show that more than 80% of power outages are caused by faults in the distribution network level [1]. Hence, load restoration from outages for resilient operation is the core function of the distribution network, and it has great significance for serving customer demand and improving the reliability of the power supply [2]. With the development of information technology and distribution automation, remote control enables fast switch operations, allowing the distribution system topology to adapt quickly to isolate faults and achieve optimal operation. Reconfiguration has become a common feature in urban distribution systems, and has contributed greatly to enhancing power system reliability by redirecting faulted areas to alternative supply sources through sectionalizing switches within a feeder or tie switches between feeders [3–13].

In recent years, the world has witnessed several natural disasters and resulting severe power outages and blackout. For example, a hurricane hit Zhanjiang, China in October 2015, causing a loss of 4.24 million kW h of energy. In this scenario, the substations may be at fault so that the distribution system cannot be supplied by the main grids, or the damages to the distribution facilities may lead to several isolated areas without power. Thus, the traditional load restoration approaches (e.g., [3–13]), which rely entirely on reconfiguration, may not guarantee supply continuity of energy after natural disasters, and thus customers may experience extended outages [14].

Today's power system is transiting from a centralized bulk system to smart grid, with the distribution system being smarter and more active by the integration of distributed generators (DGs) [15].

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Nomenclature

Indices and sets

i, j, s, k	index of buses
ij	index of branch from bus i to bus j
$\mathscr{E}$	set of lines in the network
Π	set of DGs
$\mathscr{E}_o$	set of lines in the open state
$\mathscr{V}$	set of nodes in the network
Θ	set of master DGs
$\delta(j)$	set of all children of bus j
$\pi(j)$	set of all parents of bus j
$\lvert\mathscr{E}\rvert$	the numbers of lines
$\lvert\mathscr{V}\rvert$	the numbers of nodes
$\lvert\Pi\rvert$	the number of DGs
$\lvert\Theta\rvert$	the number of master DGs
r_{ij}	the resistance of branch ij
x_{ij}	the reactance of branch ij
$b_{s,j}$	the charging capacitance connected to bus j
P_L^0	the active load demand under normal condition
Q_L^0	the reactive load demand under normal condition
$P_{DG,j}^0$	the j-th DG output under normal condition
U_j^0	the given voltage magnitude on master DG bus j
$S_{DG,j}{}^{\max}$	the maximum capacity of the DG j
θ_j	the maximum power factor angle of the j-th DG
$S_{ij}{}^{\max}$	the maximum capacity of the branch ij
$I_{ij}{}^{\max}$	the maximum branch current of the branch ij
N	the number of substations
R	the number of load islands
w	weight of load
M	a big number
α_j	the power factor angle of the j-th load demand

Decision variables

y_{ij}	binary variable for line ij. If the line is open, $y_{ij} = 0$; otherwise, $y_{ij} = 1$
H_{ij}	the active power flow on distribution line ij
G_{ij}	the reactive power flow on distribution line ij
$P_{DG,j}$	the active power output of DG j
$Q_{DG,j}$	the reactive power output of DG j
P_L	the active load demand under faulted condition
Q_L	the reactive load demand under faulted condition
l_{ij}	the square of branch current on line ij
u_i	the voltage magnitude square on bus i
F_{ij}	the fictional flow on the distribution line ij
W_j	the power supplied by the "source" buses in the fictitious network

DGs can make the distribution system more diverse, flexible, and secure. DGs are increasingly integrated in the distribution network due to their benefits such as loss reduction, voltage stability, system reliability enhancement and lowered global warming [16–19]. In addition to their ability to satisfy the increasing energy demand, DG intentional islanding is gradually recognized as an essential capability in providing the load in contingency, which is further validated by IEEE 1547.4 [20]. It is found in many studies DGs can be used to enhance load restoration, providing an alternative way to improve distribution network resilience [14]. The efficient way to manage a power system with significant level of DGs is to break the distribution system into small clusters or microgrids [21–23]. Thanks to the microgrids powered by the DGs, the supply to the customers can still be guaranteed, even for isolated areas [24–30].

On the basis of this idea, the concept of "resilience" in distribution network was proposed in [31–35] to restore the system after natural disasters by use of microgrids. Ref. [31] built a model suitable for re-configuration of a distribution system with microgrids. Once a fault occurs in a distribution system, some DG-based islands will be formed to guarantee the power supply of important customers. Ref. [32] studied multi-agent coordination for distributed information discovery, but the restoration process did not consider the topology of the distribution network. Ref. [33] discussed a spanning tree method for distribution network restoration with embedded microgrids to enhance the self-healing capability. However, this method only considered a single fault in the distribution network. When natural disasters occur, multiple faults could lead to several unsupplied, isolated islands. An operational approach to restore loads after natural disasters was given in [14], where multiple microgrids were dynamically formed to continue supplying critical loads. Ref. [34] reviewed the contribution of reconfiguration in reducing load shedding. Ref. [35] presented the reconfiguration scheme for minimal load shedding considering soft-open points.

The above references presented sound results and investigated the basic framework of resilience in distribution networks, but there are still two points that haven't been addressed:

(i) Different types of control strategies for DGs may lead to different operation rules for system restoration. Originally, droop-control-based methods were widely adopted for DGs in microgrid, which does not require communication among DGs for effective grid control. However, droop control faces the problem of circulating current among DGs because it uses a voltage loop at each DG node [36]. Subsequently, the master-slave control technique was deployed to solve the above problem; in this technique, the voltage and frequency of the system are controlled by only one generation unit, which serves as the master unit, and the rest of the DGs work in current control mode and serve as the slave units. The master unit can be a diesel generator, storage device or DG with large capacity, etc. In contrast, DG units based on renewable energy, such as solar and wind, are usually chosen as the slave units. However, the existing studies on service restoration haven't considered the DG control strategies.

(ii) The network reconfiguration and the control strategy of the microgrids haven't been coordinated in the previous works. The existing studies are based on either reconfiguration [1–8] or microgrids [31–35]. To our best knowledge, how to coordinate the reconfiguration and microgrids should be investigated.

To address the above two shortcomings identified in the previous research, this paper proposes a new resilient microgrid formation strategy for load restoration with both topology reconfiguration and master-slave DG control framework. The main contributions can be summarized as follows:

(i) A resilient microgrid-forming model is formulated considering master-slave DG operation, where there is only one master DG in each island to guarantee a self-adequate system.

(ii) The topology of the whole system can be reconfigured by sectionalizing and using tie switches, such that the load at one feeder can be transferred to another feeder in the microgrid-forming model to pick up more loads.