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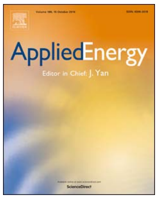

A linear two-stage method for resiliency analysis in distribution systems considering renewable energy and demand response resources

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HIGHLIGHTS

- The concept of the resiliency in distribution networks is addressed.
- A linear path-based approach is proposed to model the topological characteristics of the network.
- A two-stage stochastic programming approach is applied to characterize the uncertainty of the renewables.
- Impacts of the demand side programs and renewable energies on system resiliency are investigated.

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ABSTRACT

Due to the unique structure and special characteristics of electric distribution networks, along with the increase in the number and severity of the natural disasters in recent years, presenting a proper framework and procedure for evaluating the resiliency of these systems is more essential. In addition, it is obligatory to model the different capabilities and features of the smart grids components in order to provide a better knowledge about their expected performance in such circumstances. In response to these challenges, this paper addresses the concept of resiliency and its dimensions in distribution networks. A new model based on mixed-integer linear programming is proposed to properly model and evaluate the resiliency of smart distribution systems. In the proposed model, optimal formation of dynamic microgrids (MGs), their service areas, and the optimal management of different technologies such as energy storage (ES) units, demand side management programs and distributed generations (DGs) units are investigated. In addition, employing a two-stage framework based on stochastic programming, the impact of increasing penetration level of the renewable energy resources and their related uncertainties on system resiliency is examined. The efficiency and applicability of the proposed integrated model is verified by performing multiple simulations on the modified 118-bus test system and a real distribution network.

1. Introduction

Due to the climatic changes, the number and intensity of the natural disasters such as hurricanes, floods, droughts, etc. have increased significantly in many countries in recent years [1–3]. Enlargement of the destructive effects of such phenomena on electric power system implies that the utilization of the existing methods and common strategies for the operation and planning of power systems which have been developed based on the familiar concepts such as the risk, reliability, stability, security, etc. will be faced with serious challenges in the near future [4,5]. In such incidents, even systems with high reliability and appropriate status in terms of risk and equipment vulnerability may encounter significant problems and experience extensive blackouts. Hence, in recent years, the concept of resiliency as a complement to the previous concepts is introduced to ensure the optimal functionality of the power system in these circumstances [6,7]. A resilient system will be able to efficiently implement the necessary actions to reduce the effects of the catastrophic events [8].

Up until now, the issue of power system resiliency has been examined in several papers, and some indices have been developed for this purpose [9–11]. However, owing to the higher vulnerability of the distribution network against these events, and its special structure and distinct characteristics, providing suitable frameworks to evaluate and enhance the system behavior in such situations will be of great importance. Despite the large body of research in this field, less attention has been paid to resiliency concept and its dimension in distribution networks.

Nevertheless, in recent researches, utilization of smart grid

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Nomenclature

Indices and sets

N	set of the nodes in the network
Λ	set of the lines in the network
$\overline{\mathrm{N}}$	set of the loads with control capabilities
Ω	set of the wind power uncertainties
K	set of the formable microgrids
M	set of the all distributed generations
E	set of the energy storages
$\mathrm{N_{ADG}}$	set of the nodes connected to all DGs
$\mathrm{N_{CDG}}$	set of the nodes connected to master DGs
Ψ_ℓ	set of the nodes belongs to the line ℓ
$\Lambda_{i-\zeta}^{x}$	set of the lines belongs to the path x between node i and node ζ
$\Lambda_{i-\mu}^{z'}$	set of the lines belongs to the path z' between node i and node μ
$\Lambda_{i-\mu}^{z}$	set of the lines belongs to the path z between node i and node μ
$\mathrm{AllPath}_{i-\zeta}$	set of the paths between node i and node ζ
WTur	set of the wind turbines
$\mathrm{N_{WTur}}$	set of the nodes connected to wind turbines
$\mathrm{N_{ES}}$	set of the nodes connected to storages
n	index of the wind turbines
i	index of the buses
k	index of the microgrids
m	index of the distributed generations
e	index of the energy storages
$\theta L(i)$	set of the connected lines to the node i

Variables and parameters

N_{CDGs}	number of the master DGs
N_{MGs}	maximum number of formable MGs
$P_{i,d,t}^{b}$	blocks of the load control
$\mathrm{PLoad}_{i,t}$	predicted load i at the period t
η_e^{ES}	efficiency of the storage
r_ℓ	the resistance of the line ℓ
$V_{i,k,t,\omega}$	voltage magnitude of the nodes
BigM	a big number
$SOC_e^{ES,initial}$	initial SOC of storage
ζ	lowest common ancestors of the parents of the node i
$\alpha_{i,k}$	the binary variable indicating whether node i belongs to MG k
β_ℓ	the binary variable indicating whether the line ℓ is active
HL_ℓ	the binary variable indicating the health of the line ℓ after the event
HB_i	the binary variable indicating the health of the bus i after the event
Sec_ℓ	the binary variable indicating the existence of switch on the line ℓ
$\mathrm{Path}_{i-\zeta}^{x}$	the binary variable indicating whether the path x between node i and node ζ is active
$\mathrm{NumPath}_{i-\zeta}$	number of the paths between node i and node ζ
$P_m^{DG,Max}$,$Q_m^{DG,Max}$,$Q_m^{DG,Min}$	the active and reactive power limits of DGs
$P_{m,k,t}^{DG,s}$,$P_{m,k,t,\omega}^{DG,dep}$,$Q_{m,k,t,\omega}^{DG,dep}$	scheduled and generated active and reactive power of DGs
$SOC_e^{ES,Max}$,$SOC_e^{ES,Min}$	maximum and minimum SOC limits of the storages
$Rate_e^{ch,Max}$,$Rate_e^{dch,Max}$	maximum charge and discharge rate of the storages
$P_{i,k,t}^{L,s}$,$P_{i,k,t,\omega}^{L,dep}$,$Q_{i,k,t,\omega}^{L,dep}$	scheduled and supplied active and reactive power of the loads
$P_{i,k,t}^{LC,s}$,$P_{i,k,t,\omega}^{LC,dep}$	scheduled and deployed active load control of the loads
$\sigma_{i,d,t}^{L,s}$,$\sigma_{i,d,t,\omega}^{L,dep}$	scheduled and deployed block for the load controls
$PES_{e,k,t}^{dch,s}$,$PES_{e,k,t,\omega}^{dch,dep}$	scheduled and deployed discharging power of the storage
$PES_{e,k,t}^{ch,s}$,$PES_{e,k,t,\omega}^{ch,dep}$	scheduled and deployed charging power of the storage
$SOC_{e,k,t}^{ES,s}$,$SOC_{e,k,t,\omega}^{ES,dep}$	scheduled and realized SOC of the storage
$\gamma_{e,k,t}^{ES,s}$,$\gamma_{e,k,t,\omega}^{ES,dep}$	scheduled and realized status of the storages
$\gamma_{n,k,t,\omega}^{Wnd,dep}$	binary variable indicating whether wind turbine n is connected to MG k
$\mathrm{Prod}_{n,t,\omega}^{Wnd}$,$P_{n,t}^{Wnd,Max}$	predicted and maximum output power of the wind turbines
$P_{n,k,t,\omega}^{Wnd,dep}$,$P_{n,k,t}^{Wnd,s}$	scheduled and realized active power generation of the wind turbines
$\Delta P_{i,k,t,\omega}^{LC}$	difference in the scheduled and deployed load control programs
$\Delta P_{m,k,t,\omega}^{DG}$	difference in the scheduled and generated active power of DGs
$flow_{\ell,t,\omega}^{P}$,$flow_{\ell,t,\omega}^{Q}$	the active and reactive power flows of the line ℓ
$flow_\ell^{P,Max}$,$flow_\ell^{Q,Max}$	maximum active and reactive power flow limits of the line ℓ
$V_m^{DG,set}$	given voltage magnitude of the nodes connected to master DGs
$P_{i,t}^{LC,Max}$	maximum limit of the load control options
$Zflow_{\ell,t,\omega}^{P}$,$Zflow_{\ell,t,\omega}^{Q}$	slack variables to make the power equality constraints valid
$\mathrm{F1}_\ell$,$\mathrm{F2}_\ell$	indicating electrical characteristic of the line ℓ
$NLine_{i-\mu}^{z}$	number of the lines in the path $\Lambda_{i-\mu}^{z}$
$NLine_{i-\mu}^{z'}$	number of the lines in the path $\Lambda_{i-\mu}^{z'}$
$NLine_{i-\zeta}^{x}$	number of the lines in the $\mathrm{Path}_{i-\zeta}^{x}$
D	number of the load control blocks
Cap_e^{ES}	capacity of the storage
x_ℓ	the reactance of the line ℓ
$\delta_{i,k,t,\omega}$	voltage angles of the nodes
δ^{Max}	maximum limit of the voltage angles

technologies has been propounded as an effective tool to improve the resiliency of distribution networks [12,13]. In [14] the plan development process and the R&D areas requirement in this field has been investigated. In [15] a conceptual approach for the transition process to achieve a resilient distribution system through the implementation of microgrids (MGs) has been proposed. Ref. [16] focuses on the role of networked MGs as distributed systems for enhancing the system resiliency against extreme events. In [17] hardening strategies and smart grid technologies as tools to increase the system resiliency are discussed. In [18], a decision framework is developed for grid modernization and the system performance improvement in restoration process under extreme weather conditions.

In addition, recent studies address the issue of quantifying the resiliency of distribution network [19,20]. In [19] a new method have been presented for measuring the resiliency of a distribution system; the objective of this paper is to enable resiliency by comparing some possible existing reconfiguration schemes and choosing the one, which increases the resiliency most. In [20], resiliency evaluation of distribution system has been modeled as a multi-criteria decision making problem and calculated using graph theoretic methods.

However, the methods presented in the aforementioned references mainly discuss the topological characteristics of the distribution networks and cannot adequately represent electrical features, existing capabilities, and the nature of the events in this part of the power grid.

Ref. [21] proposes a service restoration process that uses MGs with inadequate generation capacity to serve critical loads on distribution