Electrical Power and Energy Systems 62 (2014) 679–688

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Vulnerability assessment and reconfiguration of microgrid through search vector artificial physics optimization algorithm

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ARTICLE INFO

Article history:
Received 4 July 2013
Received in revised form 21 April 2014
Accepted 13 May 2014
Available online 11 June 2014

Keywords:
Microgrid
Structure vulnerability
Comprehensive sensitivity
Vulnerability assessment system
Reconfiguration
SVAPO

ABSTRACT

Taking the mathematical model and reliability parameters of the microgrid into account, this paper has proposed two vulnerability assessment indices (VAI) – weighted complex network structure parameters and comprehensive operational sensitivity to set up a vulnerability assessment system. The microgrid reconfiguration (MR) model is built with consideration of the grid-connected/island mode and the VAI. A novel artificial physics optimization algorithm with a searching vector (SVAPO) is presented and applied to minimize the system vulnerability. The technique has been successfully implemented on CERTS and 38-bus microgrids to demonstrate the performance and effectiveness of the proposed method. The results obtained are encouraging.

Introduction

Microgrid reconfiguration (MR) is aimed at optimizing the network operation on the premise of meeting the basic requirement of the bus voltage, feeder current as well as configuration of radial network [1]. This paper addresses the purpose of achieving high power quality of sensitive loads, improving the bus voltage profile, and eliminating the overloads by adjusting the loads (including interruptible loads and adjustable loads) and changing the open/close status of sectionalizing switches, tie switches and the PCC switch in the system.

A microgrid can be regarded as a supplement to the large power grid, which is capable of improving the reliability and quality of power supply. Because of its inherent vulnerability [2], the vulnerability assessment of microgrid aims at finding out the weak points to enhance the system security and stability in order to guide the MR later in terms of reducing loss, load balancing and power restoration.

Microgrids are governed by droop control algorithms so they can operate in an autonomous fashion. Conventionally, Lasseter et al. [3] have suggested the real power–frequency droop control and the reactive power–voltage magnitude droop as the control strategies. In [4], a $Q - \dot{V}$ droop control method with $\dot{V}$ restoration mechanism is proposed to improve reactive power sharing. Rowe et al. [5] have introduced the concept of utilizing an arctan function for the power–frequency droop profile in a microgrid. Babazadeh and Karimi [6] have presented a new robust control strategy characterized by a two-degree-of-freedom feedback–feedforward controller for an islanded microgrid.

Most researches about vulnerability assessment only focus on the transmission network. In [7], a transmission vulnerability assessment method based on the fault chain theory of security science is proposed. The technique describes the cascading failure process and its generic features according to a fault chain. In [8], Ten et al. have presented a vulnerability assessment framework to systematically evaluate the vulnerabilities of SCADA systems. The proposed method is based on cyber systems embedded with the firewall and password models. Carrión et al. [9] have suggested network planners to select the new lines accounting for the vulnerability of the transmission network. The vulnerability of the transmission network is measured in terms of the expected load shed. In [10] Yu et al. have used adequacy indices, the security index probability of stability and integrated system vulnerability as VAI. Overbye and DeMarco [11] defined a security measure to indicate vulnerability based on an energy function for system models. In [12], Fouad et al. have presented the transient energy as a tool of analysis. Chen et al. [13] proposed a novel method using the line betweenness as the vulnerability index according to the complex network theory. In [14], Ying Shao and Jilai Yu have presented another new method for vulnerability assessment based on electrical dissection information.

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http://dx.doi.org/10.1016/j.ijepes.2014.05.024
0142-0615/© 2014 Published by Elsevier Ltd.

Notations

PCC	point of common coupling	p_{li}	real power flow at line i
V^*	nominal voltage set point	$p_{li}^{\lim}$	capacity of the line
m_{pi}, n_{qi}	active and reactive power static gain of ith DG	$sevf_i$	frequency deviation judgment index
P_{Gi}, Q_{Gi}	three-phase injected active power of ith DG	X_i	feeder switch at line i
ω_i	output voltage frequency of ith DG	X_{PCC}	PCC switch
ω^*	nominal frequency set point	A	incidence matrix of node-line
P_{Oi}, Q_{Oi}	nominal active and reactive power of load i	P	vector of power flow
α, β	active and reactive power exponents	V_o^{sp}	nominal deviation set of operation indices
P_{Li}, Q_{Li}	active and reactive power of load i	D	vector of load demand
P_i^a, Q_i^a	a phase active and reactive power at bus i	g_k	set of current configuration
R_i	resistance at line i	G_k	set of radial configuration
γ_{os}	failure time probability of network topology	N	operation numbers of switch
V_s	vulnerability value of structure indices	$N_{\max}$	maximum switching numbers allowed
V_o	vulnerability value of operation indices	x_{best}, x_{worst}	the position of best and worst adaptive value
w_1, w_2, w_3	weighted value of each operation index	$v_{i,k}$	speed vector of individual i in kth dimension
ISV_i	vulnerability value of element i	$x_{i,k}$	position vector of individual i in kth dimension
ISV	vulnerability value of the whole microgrid	G	gravitational constant
NB	number of buses	w	inertia weight factor
V_i	voltage magnitude at bus i	λ	random number between 0 and 1
V_i^{sp}	specified voltage magnitude at bus$i$	x_k^u	upper limit of position vector in kth dimension
$\Delta V_i^{\lim}$	voltage deviation limit	x_k^l	lower limit of position vector in kth dimension
NL	number of lines		

Traditionally, the main objective of reconfiguration is dedicated to minimize the total power loss. Due to the uniqueness of microgrids, the conventional distribution system reconfiguration is not totally suitable for the MR. In addition, much research are only conducted on distribution system. Gonzáleza et al. [15] proposed a method for computing the sensitivities of the state variables with respect to switching operations and obtaining estimations of voltages and power flow in the network. In [16], Srinivasa Rao et al. have presented a new method to solve the network reconfiguration problem in the presence of DG with an objective of minimizing real power loss and improving voltage profile in distribution system. A meta heuristic Harmony Search Algorithm (HSA) is used to simultaneously reconfigure. Zin et al. [17] have put forward a new heuristic method to optimize the network based on minimum branch current in the system. Malekpour et al. [18] made a significant contribution to interactive fuzzy satisfying optimization algorithm based on adaptive particle swarm optimization (APSO) for the optimal reconfiguration plan. In [19], Zin et al. have developed two hybrid heuristic methods for reconfiguration of the radial electrical distribution system. A circular minimum branch-current updating mechanism is proposed to pass the local optimum points. Then, the best known configuration is obtained according to a circular neighbor-chain updating technique.

This paper analyzes the network characteristics with the complex network theory on the basis of the mathematical model and power flow calculation of microgrid. Considering the reliability and operational sensitivity of the bus and feeder, the vulnerability assessment system of microgrid is proposed on the purpose of the energy demand management and power quality for users. The reconfiguration model aiming at minimum the total vulnerability value is built. The algorithm is tested on CERTS and 38-bus microgrids system and results obtained are compared with other methods.

The reminder of this paper is organized as follows. 'Microgrid and VAI modeling' below provides the overviews of the microgrid and VAI modeling. 'Problem formulation' describes the mathematical formulation of MR problem. The introduction of SVAPO and its application in MR problem are explained in 'Overviews of SVAPO algorithm'. 'Case study and results' presents the test results and 'Conclusions' outlines the conclusion.

Microgrid and VAI modeling

A microgrid which contains a number of DGs of multiple energy forms can provide heat or cool energy for users. It operates under the islanded or grid-connected mode through the PCC switch. The traditional researches have concentrated on the model of transmission network, in which the line resistance is much smaller than the line reactance because of the high voltage level. However, the voltage level is low in distributed network, especially in a microgrid, which is only several hundred volt. So the line characteristic in a microgrid is different. Due to the high R/X ratio in a microgrid, the traditional mathematical model proposed is not available under this condition of $X \gg R$ used in the transmission network. So it is necessary to establish a novel model considering the characteristics of the microgrid, in which the line resistance cannot be ignored now.

DG Modeling

Different from traditional generators, the DG units with power electronic converters and filtering devices connect into the microgrid with some control strategies [20]. Fig. 1 depicts the equivalent circuit.

$$P = (EV/Z\cos\phi - V^2/Z)\cos\theta + EV/Z\sin\phi\sin\theta \tag{1}$$

$$Q = (EV/Z\cos\phi - V^2/Z)\sin\theta - EV/Z\sin\phi\cos\theta \tag{2}$$

Because the system impedance is resistive and ϕ is always so small, this paper assumes $Z = R$, $\theta = 0°$, $\cos\phi = 1$, $\sin\phi = \phi$. So the active and reactive powers can be decoupled. Fig. 2 illustrates the behaviors of P/Q in the polar plot [21].

From Fig. 2, the delivered active and reactive powers increase with E. But the reactive power increase with ϕ in the polar plot, whereas the active power remains constant.

Under the grid-connected mode, the large power grid can be treated as the slack bus, DGs can be equivalent to PQ, PV, and PI bus. Under the islanded mode, there is no slack bus now, each DG operates by droop strategies. Here the DGs' model under the