Electrical Power and Energy Systems 63 (2014) 1030–1038

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A power restoration strategy for the distribution network based on the weighted ideal point method

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ARTICLE INFO

Article history:
Received 17 August 2013
Received in revised form 13 June 2014
Accepted 6 July 2014
Available online 30 July 2014

Keywords:
Power recovery
Multi-objective optimization
Rough set theory
Ideal point method

ABSTRACT

A power restoration strategy for the distribution network based on the weighted ideal point method is proposed in this paper. First, with the power loss, voltage quality and load balancing as the reconfiguration goal, the comprehensive evaluation function is established. And then, the rough set theory is used to calculate the weight coefficients of the sub-objective functions. Finally, the optimal solution of the comprehensive evaluation function is obtained by applying the ideal point method. Simulation tests on the 33-bus and 69-bus radial distribution networks verify that, the proposed method of using multi-objective function instead of single objective function to gain the optimal solution is more comprehensive in different considerations and more in line with the requirement of the actual distribution network power restoration. Furthermore, the uncertainty problem in traditional weight setting due to dependence on experience can be avoided.

Introduction

Power restoration in the distribution network refers to the restoring of power supply to the lost load in the non-fault area by means of network reconfiguration after a fault occurs. Power restoration should meet the constraints of the node voltage and line current, as well as taking into account the economic and reliable operation of the distribution network after the fault recovery. Therefore, power restoration is a multi-objective optimization problem with multiple constraints [1–3].

Currently there are many methods to establish and solve the power restoration objective function and these methods can be sorted into three major categories. (1) Mathematical optimization methods [4–7]. This category of methods is based on a complete mathematical theory, and is not dependent on the initial structure of the distribution network. However, these methods have the 'dimension calamity' problem, thus are only applicable to power restoration of systems with relatively small scale and complexity. (2) Heuristic search methods [8–10]. This category of methods is widely used for fault restoration in the distribution network, and is mainly based on switch operation, according to the search mode guided by the heuristic rules. These methods are real-time, and have good versatility and practicability. However, the search result is easily affected by the initial state, thus the algorithm stability is not favorable. (3) Artificial intelligence methods [11–16]. This category of methods is effective in solving specific power restoration problems. However, parameters such as the penalty coefficient, the initial particle swarm, and the mutation probability are needed. These parameters will directly affect the calculation speed and convergence of the algorithm. And currently there is no clear theoretical basis as to what values the parameters should apply. Continuous grope is needed concerning the specific problem.

The advantage of the above methods is that the power restoration problem can be expressed accurately in the form of objective function with constraints However, since power restoration is a complicated optimization problem with multiple objectives, and the sub-objectives are conflictingly inter-connected, it is difficult to describe the comprehensive objective function. Besides, the weight setting is often reliant on subjective experience, which makes the solving process complicated. In view of the above problems, a power restoration strategy for the distribution network based on the weighted ideal point method is proposed in this paper. First, with the power loss, voltage quality and load balancing as the reconfiguration goal, the comprehensive evaluation function is established. And then, the rough set theory is used to determine the weight coefficients of the sub-objective functions. Finally, the optimal solution of the comprehensive evaluation function is obtained by applying the ideal point method. Simulation tests on the 33-bus and 69-bus radial distribution networks verify

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http://dx.doi.org/10.1016/j.ijepes.2014.07.017
0142-0615/

Nomenclature

U_j^{min}	lower bound of the RMS value of the voltage at node *j*.
U_j^{max}	upper bound of the RMS value of the voltage at node *j*.
$\mathbf{I}^{max}$	line current constraint matrix
I_i^{max}	the maximum current allowed in line *i*
I_i	the current on line *i*
D_1	node voltage constraint
D_2	line current constraint
C_1	power loss function
C_2	voltage quality function
C_3	load balancing function
m	number of lines
P_i	active power on the end of line *i*
Q_i	reactive power on the end of line *i*
U_i	voltage of the end node of line *i*
r_i	resistance of line *i*
k_i	state variable of line *i*
P_{imax}	maximum capacity of line *i*
$\boldsymbol{U_m}$	measured voltage vector of the system
$\boldsymbol{U_e}$	rated voltage vector of the system
$\boldsymbol{S}$	knowledge representation system
U	universe of discourse
A	finite set of properties
V	value range of *A*
f	decision function
$\boldsymbol{C}$	condition property set
$\boldsymbol{D}$	decision property set
$pos_Q(P)$	the set of elements in *U* that can be accurately divided to *U*/*P* through *Q*
$\varphi(C_i)$	importance degree of property C_i
$\gamma_C(D)$	dependence degree of the decision property set *D* on the condition property set *C*
$\gamma_{C-C_i}(D)$	dependence degree of the decision property set ***D*** on the condition property set C–C_i
Y	comprehensive evaluation function
w_i	weight coefficient of the sub-objective function
$H_i(+)$	ideal point vector of the *i*th index of object *H*
$H_i(-)$	anti-ideal point vector of the *i*th index of object *H*
$C_i(x)$	value of the *i*th index
$g_j(+)$	positive evaluation function
$g_j(+)$	negative evaluation function
$L_i(+)$	the distance from the evaluation function to the ideal point
$L_i(-)$	the distance from the evaluation function to the anti-ideal point
T_i	the weighed ideal point close degree

that, the proposed method of using multi-objective function instead of single objective function to gain the optimal solution is more comprehensive in different considerations and more in line with the requirement of the actual distribution network power restoration. Furthermore, the uncertainty problem in traditional weight setting due to dependence on experience can be avoided.

Constraints and objective functions

After the fault is located and separated accurately, there will be lost load in the downstream of the fault area. First, all the contact switches in the original network that may help to restore power to the lost load are virtually closed. It should be noted that, this operation may cause branches to interconnect and form loops (the route between two different sources is also equivalent to a loop). On this basis, all the breakable branches in the loops constitute of an operable switch set. And then, virtual breaking of the switches in the operable switch set is done separately, and power flow of the resulting network is calculated to determine whether each virtual breaking meets the constraints of the node voltage and line current. With all the constraints met, the optimal breaking scheme can then be determined by the optimization of the multi-objective function of power loss, voltage quality and load balancing.

Constraints of node voltage and line current

The node voltage amplitude constraint is as follows:

$$U_j^{min} \le U_j \le U_j^{max} \tag{1}$$

where U_j^{min} and U_j^{max} are the lower bound and upper bound of the RMS value of the voltage at node *j*.

In order to meet the thermal stability constraint of the distribution network lines, the line current constraint matrix $\mathbf{I}^{max}$ is defined according to the maximum current allowed in each line:

$$\mathbf{I}^{max} = [I_1^{max}, \cdots, I_i^{max}, \cdots, I_m^{max}]^T \tag{2}$$

where I_i^{max} represents the maximum current allowed in line *I*; *m* is the number of lines.

The line current constraint is as follows:

$$I_i \le I_i^{max} \tag{3}$$

where I_i is the current of line *i*.

Power loss function

The objective function of the distributed system power loss is:

$$C_1 = \sum_{i=1}^{m} \left(\frac{P_i^2 + Q_i^2}{U_i^2} \right) r_i k_i \tag{4}$$

where *m* is the number of lines; P_i and Q_i are the active and reactive power of line *i*; U_i is the voltage of line *i*; r_i is the resistance of line *i*; k_i is the state variable of line *i*, with $k_i = 0$ representing that line *i* is open and $k_i = 1$ representing that line *i* is closed. The smaller the power loss function C_1 is, the higher the power utilization rate is, and the more energy saving and economic the distribution network proves to be.

Voltage quality function

The objective function of the power quality is:

$$C_2 = \|\boldsymbol{U}_m - \boldsymbol{U}_e\| \tag{5}$$

where $\boldsymbol{U_m}$ and $\boldsymbol{U}_e$ are the measured voltage vector and rated voltage vector of the system. The smaller the voltage quality function C_2 is, the closer the bus voltage is to the rated value, and the better the voltage quality is.

Load balancing function

Load balancing refers to the ability of the distribution system to match the load distribution with the power supply capacity of each line. It aims to improve operational efficiency of the lines and power supply capability of the distributed system, at the same time reducing power loss and lowering the risk of overloading.