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Dynamic reconfiguration of three-phase unbalanced distribution networks

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ABSTRACT

The increasing penetration of distributed generations (DGs) and variable loads introduces significant power fluctuations to distribution networks, rendering conventional reconfiguration strategies ineffective. In the context of an active distribution network (ADN), remote control switches can be operated in real time through a centralized control scheme. Therein the distribution network topology can be configured in a flexible and dynamic manner capable of adapting to time-varying load demand and DG output. This paper presents a dynamic reconfiguration approach for a three-phase unbalanced distribution network. The ADN topology is optimized for the look-ahead time periods and is adaptive to the time-varying load demand and DG output while minimizing the daily power loss costs. To improve the calculation efficiency, several linearization methods are introduced to formulate the dynamic reconfiguration as a mixed-integer linear programming problem, which can be effectively solved using off-the-shelf solvers. The effectiveness of the proposed approach is verified by the test results obtained on a modified IEEE 34 node test feeder.

1. Introduction

Distribution network reconfiguration (DNR) is performed by altering the topological structure of distribution networks by opening and closing sectionalizing switches and tie switches and is used to improve the performance of a network, such as reducing power losses, balancing load demand, increasing distributed generation (DG) penetration, and mitigating operational constraint violations [1–4]. With the increasing penetration of renewable generations, the topologies of distribution networks are expected to become more flexible to respond to varying system operation conditions. As such, the dynamic DNR is attracting increasing attention from both the academic and industrial communities [5].

DNR is a typical combinatorial optimization problem, which is NP-hard [1]. Considerable work has been performed to solve the DNR problem over the last few decades. Many algorithms have been proposed in the literature and can be categorized into three categories: heuristic-, metaheuristic- and mathematical programming-based approaches [3]. Heuristic-based approaches are widely adopted because they can consistently produce fast and reliable reconfiguration results. The branch-exchange method is a classical method that is widely used in DNR studies [6–8]. In this method, the distribution network is assumed to be radial, and thus, the opening of a switch will correspond to the closing of another switch to retain the radial network structure. An alternative approach is the sequential switch opening method [9]. In this method, all switches are initially closed to form a meshed system, and then, certain sectionalizing switches are opened sequentially and strategically to regain the radial configuration. Metaheuristic DNR methods are typically based on intelligent search algorithms, such as genetic algorithms (GAs) [10], artificial neural networks [11], and particle swarm optimization [12]. Such methods are typically complex and require more computational resources to find near-optimal solutions. Furthermore, such methods cannot always guarantee that the solutions are the global optimums. In mathematical optimization methods, the DNR models are typically formulated as linear programming [1,13], quadratic programming [1] or nonlinear programming [14] problems. The global optimal solution can be obtained when the model is convex.

Although major achievements have been made in solving DNR problems, the majority of existing approaches assume that the studied distribution systems are three-phase balanced. In practice, distribution systems are typically operated with an observable degree of imbalance among three phases due to (1) the uneven allocation of loads across the three phases; (2) asymmetrical network structures, e.g., single-phase and double-phase laterals; and (3) the emergence of low-carbon-generation technologies with random behaviors, e.g., single phase connected wind turbines. To address this issue, Wang et al. [15] proposed an efficient real-time network reconfiguration algorithm for large-scale unbalanced distribution systems with the goal of minimizing power losses. The backward-forward sweep method and branch-exchange

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Nomenclature

Sets

N	set of all buses
L	set of buses connected to loads
G	set of buses connected to distributed generations (DGs)
B	set of all branches
T	set of look-ahead time periods (e.g., 24 h)
F	set of substation buses
N/F	set of buses that are not substations
Φ	set of three phases (e.g., {a, b, c})

Branch variables and parameters

$z_{ij,t}$	binary variable that represents the on/off status of a branch switch (*i, j*) in period *t*
$\alpha_{ij,t}$	auxiliary binary variable that represents the opening action of switch (*i, j*) in period *t*
$\beta_{ij,t}$	auxiliary binary variable that represents the closing action of switch (*i, j*) in period *t*
$\boldsymbol{P}_{ij,t}^{\phi} \in \mathbb{R}^{3\times1}$	vector of three-phase active power flow from bus *i* to bus *j* through branch (*i, j*) in period *t*
$\boldsymbol{Q}_{ij,t}^{\phi} \in \mathbb{R}^{3\times1}$	vector of three-phase reactive power flow from bus *i* to bus *j* through branch (*i, j*) in period *t*
$\boldsymbol{w}_{ij,t}^{\phi,r} \in \mathbb{R}^{3\times1}$	vector of weight associated with the *r*th point on the piecewise linear approximation curve for $\boldsymbol{P}_{ij,t}^{\phi,r}$
$\boldsymbol{v}_{ij,t}^{\phi,r} \in \mathbb{R}^{3\times1}$	vector of weight associated with the *r*th point on the piecewise linear approximation curve for $\boldsymbol{Q}_{ij,t}^{\phi,r}$
$\boldsymbol{S}_{ij}^{\max} \in \mathbb{R}^{3\times1}$	three-phase apparent power capacity of branch (*i, j*)
$\boldsymbol{r}_{ij}$, $\boldsymbol{x}_{ij} \in \mathbb{R}^{3\times1}$	resistance and reactance matrices of branch (*i, j*)
$S_{\max}$	maximum number of switching actions over all periods T

Bus variables and parameters

$\boldsymbol{P}_{f,t}^{\phi}$,$\boldsymbol{Q}_{f,t}^{\phi} \in \mathbb{R}^{3\times1}$	vector of three-phase active, reactive power provided by the substation at bus *f* in period *t*
$\boldsymbol{P}_{g,t}^{\phi}$,$\boldsymbol{Q}_{g,t}^{\phi} \in \mathbb{R}^{3\times1}$	vector of three-phase active, reactive DG output at bus *g* in period *t*
$\boldsymbol{P}_{g}^{\max,\phi} \in \mathbb{R}^{3\times1}$	vector of upper limit of three-phase active DG output at bus *g*
$\boldsymbol{Q}_{g}^{\max,\phi} \in \mathbb{R}^{3\times1}$	vector of upper limit of three-phase reactive DG output at bus *g*
$\boldsymbol{P}_{l,t}^{\phi}$,$\boldsymbol{Q}_{l,t}^{\phi} \in \mathbb{R}^{3\times1}$	vector of three-phase active, reactive load demand at bus *l* in period *t*
$\boldsymbol{V}_{i,t}^{\phi} \in \mathbb{C}^{3\times1}$	vector of three-phase voltage at bus *i* in period *t*
$\boldsymbol{U}_{i,t}^{\phi} \in \mathbb{R}^{3\times1}$	vector of squared three-phase voltage magnitude at bus *i* in period *t*
$V_i^{\min}$,$V_i^{\max}$	lower, upper limit of three-phase voltage magnitude at bus *i*

Other notations and vectors

$\phi \in \Phi$	specific phases of branch or bus
N_n, N_f	number of buses and substations
R	number of points on a power loss curve selected to perform the linear interpolation
M	a large number used in the big-M formulation
C_{dis}, C_{con}	cost of opening and closing a switch
$\boldsymbol{C}_{loss} \in \mathbb{R}^{3\times1}$	cost vector of three-phase power loss per kWh

Abbreviations

DG	distributed generation
ADN	active distribution network
DNR	distribution network reconfiguration
GA	genetic algorithm
PF	power flow
LPF	linear power flow
MILP	mixed-integer linear programming
DMS	distribution management system
MIQCQP	mixed integer quadratically constrained quadratic programming
MIQP	mixed integer quadratic program

method were used to efficiently compute the power flow (PF) and select exchangeable switch pairs, respectively. A heuristic method that is applicable for both balanced and unbalanced distribution networks was proposed in [16] to minimize power losses. This method is suitable for balanced networks. However, for unbalanced networks, the effectiveness of the method depends on the degree of system imbalance. A two-stage reconfiguration algorithm for both balanced and unbalanced distribution systems was presented in [17]. In the first stage, all candidate switches are initially closed, and the branch current information obtained from PF solutions is used to determine which switch should be opened in a sequential manner. In the second stage, the branch-exchange operation is executed for further loss reduction.

The aforementioned methods all fall into the static reconfiguration category, which assumes that the load demand is constant throughout the reconfiguration process. However, in practice, the load demand and DG output change continuously. In some cases, varying load demand and DG output may cause the system condition outside of permitted operating conditions [2], hence necessitating the dynamic reconfiguration. Dynamic reconfiguration means that the distribution system operators can change the topological structure of distribution networks in real time by changing the status of remotely controlled switches [4]. Capitanescu et al. [4] used the dynamic reconfiguration method to improve the DG hosting capacity of active distribution networks (ADNs) by effectively countering the effects of time-varying demand and DG output. Furthermore, as discussed in [18], the energy loss can be reduced by dynamically reconfiguring the distribution system on a time-of-day basis. In [19], static DNR is performed for each hour of a day to consider the load variation, and the results are compared with the daily reconfiguration only considering the maximum or average demand of the day. However, the time-coupling constraints are not considered in the study, which may cause unfeasible or uneconomical decision results. Ding et al. [2] recently proposed a multi-period DNR model for unbalanced distribution systems with DG to consider the dynamic behaviors of load demand. In that paper, the day-ahead reconfiguration problem was solved to minimize the total energy losses over the next 24 h. The optimal DG output during each hour could be scheduled as well. Both the hierarchical decentralized approach and GA were used to solve the DNR problem to ensure efficiency and accuracy.

In this paper, a novel one-day period reconfiguration optimization model is proposed for unbalanced distribution networks considering the time-varying nature of load demand and DG output. The advantages of the proposed approach are as follows:

1. The model considers the time-varying nature of loads and generates a control sequence to fully coordinate the operation of switches to minimize the cost of power losses over specified look-ahead time periods rather than simply reducing losses for a fixed operation condition.
2. The model considers several practical concerns, such as the three-phase voltage imbalance and three-phase power imbalance, when solving the dynamic reconfiguration and DG output dispatch problems.