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Multi-objective operation optimization of an electrical distribution network with soft open point

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HIGHLIGHTS

- The SOP's capability of bringing benefits on multiple objectives simultaneously was investigated.
- A multi-objective framework was developed to improve distribution network operation with SOP.
- An optimization method integrating both global and local search techniques was proposed.
- The optimization method is capable of obtaining diverse Pareto optimal solutions.

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Soft open point (SOP)
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ABSTRACT

With the increasing amount of distributed generation (DG) integrated into electrical distribution networks, various operational problems, such as excessive power losses, over-voltage and thermal overloading issues become gradually remarkable. Innovative approaches for power flow and voltage controls are required to ensure the power quality, as well as to accommodate large DG penetrations. Using power electronic devices is one of the approaches. In this paper, a multi-objective optimization framework was proposed to improve the operation of a distribution network with distributed generation and a soft open point (SOP). An SOP is a distribution-level power electronic device with the capability of real-time and accurate active and reactive power flow control. A novel optimization method that integrates a Multi-Objective Particle Swarm Optimization (MOPSO) algorithm and a local search technique – the Taxi-cab method, was proposed to determine the optimal set-points of the SOP, where power loss reduction, feeder load balancing and voltage profile improvement were taken as objectives. The local search technique is integrated to fine tune the non-dominated solutions obtained by the global search technique, overcoming the drawback of MOPSO in local optima trapping. Therefore, the search capability of the integrated method is enhanced compared to the conventional MOPSO algorithm. The proposed methodology was applied to a 69-bus distribution network. Results demonstrated that the integrated method effectively solves the multi-objective optimization problem, and obtains better and more diverse solutions than the conventional MOPSO method. With the DG penetration increasing from 0 to 200%, on average, an SOP reduces power losses by 58.4%, reduces the load balance index by 68.3% and reduces the voltage profile index by 62.1%, all compared to the case without an SOP. Comparisons between SOP and network reconfiguration showed the outperformance of SOP in operation optimization.

1. Introduction

Growing awareness of energy and environment, and the demand for a reliable, secure, and sustainable power grid lead to the continuously expanding deployments of Distributed Generators (DG). However, high penetrations of DG significantly affect the operation of electrical distribution networks, where the technical challenges are mainly power loss increments, line and transformer overloads, and voltage violations [1–5].

The use of power electronic devices provides alternative solutions to overcome these challenges. The application of power electronics to High Voltage Direct Current (HVDC) transmission systems has gained increasingly importance in the bulk power transfer. The extensive growing demand for power electronic devices and their continuous developments offer significant reductions in converter costs [6], which provide a chance for their further applications in medium voltage (MV) and low voltage (LV) distribution networks.

Power electronic devices were applied in distribution networks for

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Nomenclature

Network parameters

I_k current flow through branch k
$I_{k,rated}$ rated current of branch k
I_k^{max} maximum current limit of branch k
LBI load balance index
N_{bus} total number of buses
N_{branch} total number of branches
P_i, Q_i active and reactive power flowing from bus i to bus $i+1$
$P_{load\,(i)}$, $Q_{load\,(i)}$ active and reactive power demand at bus i
$P_{loss\,(i,i+1)}$, $Q_{loss\,(i,i+1)}$ active and reactive power loss of the branch connecting buses i and $i+1$
P_{C1}, Q_{C1} active and reactive power provided by VSC1
P_{C2}, Q_{C2} active and reactive power provided by VSC2
P_{loss} total active power loss of a network
$P_{SOP\,loss}$ power loss within an SOP
S_{C1} rated capacity of VSC1
S_{C2} rated capacity of VSC2
V_i voltage at bus i
V_k voltage drop through branch k
V_{C1} voltage at VSC1
V_{C2} voltage at VSC2
$V_{i,ref}$ nominal voltage of bus i
V^{min}, V^{max} minimum and maximum bus voltage limits
VPI voltage profile index
x_k, r_k reactance and resistance of branch k

Optimization parameters

A archive that stores Pareto optimal solutions in each iteration
c_1, c_2 cognitive learning and social learning factors
e_m set of standard base vectors
F_n value of the n^{th} objective function
g_{best} global best position
g_m optimal step size generated by the golden section search technique
M total number of decision variables
m the m^{th} decision variable
N_{obj} total number of objective functions
OBJ set of objective functions
obj_n the n^{th} objective function
p_{best} individual/personal best position
r_1, r_2 random numbers $\in [0,1]$
v_i velocity vector of the i^{th} particle
ω inertia weight
x_i position vector of the i^{th} particle
X position of a particle selected from the archive and used in the local search process

different purposes [7–16]. A power electronic grid interconnector was introduced to decouple the frequency and voltage from the upstream grid [7]. A loop power flow controller and a loop balance controller implemented with back-to-back converters to form an active meshed distribution system were proposed in [8] and [9]. Voltage source converter-based smart power router was proposed for minimizing load shedding [10]. Specifically, the use of soft open point (SOP) in distribution networks was investigated in [11–16]. SOP is a power electronic device that can be installed in place of a normally open/closed point in distribution networks, with the capability to accurately control active and reactive power flows between the feeders that it is connected to. Moreover, it has the advantages of fast response, frequent actions and continuous control. In [11], the capability of SOP was quantified for voltage regulation in order to increase DG penetration, and the network with SOP showed better performance compared with other voltage control options. A combination of SOP with energy storage was investigated to mitigate the transient effects caused by photovoltaic systems [12]. Two control modes for the SOP operation were developed in [13] for the power flow control and supply restoration. The operational benefits of SOPs installed in a distribution network were quantified in [14], in which an improved Powell's Direct Set method was used to determine the optimal SOP operation. In [15], a Jacobian matrix-based sensitivity method was proposed to define the operating region of SOP considering different objectives separately. The results illustrated a confliction between the objectives of voltage profile improvement and energy loss minimization. Optimal siting and sizing of SOPs was investigated in [16] to minimize the annual expense of the overall distribution system under study.

Previous research on SOP has mainly focused on the following attributes: (1) development of control strategies for SOP; (2) minimization of network energy losses considering the influence and increase of DG; (3) analysis and quantification of benefits of SOP considering different objectives separately. However, in order to achieve the potential benefits and wider applications of SOP, it is important to investigate the device's capability of bringing advantages on multiple objectives simultaneously, which makes the problem of distribution network operation with SOP a multi-objective optimization problem.

Over the past few decades, multi-objective optimization problems have attracted considerable interests from researchers motivated by the real-world engineering problems [17]. Many multi-objective optimization problems are solved under the concept of *a priori* method, in which the decision maker defines the importance amongst objectives before the search performs, and the multi-objective optimization problem is transformed into a single objective one. Afterwards, a classical single objective optimization algorithm is used to find the optimum. The key drawback of the *a priori* method is the arbitrarily imposed limitation of the search space, which does not allow findings of all solutions in a feasible set [18]. In addition, since it is common that real-world objectives are incommensurable in nature and can be conflicting with each other, aggregating multiple objectives into one may result in losing significance. Pareto optimality, on the contrary, is based on a simultaneous optimization of multiple objective functions. It provides a set of non-dominated solutions named Pareto optimal solutions, illustrating the nature of trade-offs among conflicting objectives. Evolutionary algorithms, e.g., the widely recognized SPEA2 [19] and NSGA-II [20], are suitable to solve multi-objective optimization problems using the concept of Pareto optimality, since these techniques deal with a set of possible solutions simultaneously, which allow obtaining an entire set of Pareto optimal solutions in a single run. Particle Swarm Optimization is one of the most recently used evolutionary algorithms. It is a global search technique with the most attractive features of simple concept, easy implementation, fast computation and robust search ability. Compared with other evolutionary algorithms, Particle Swarm Optimization shows incomparable advantages in searching speed and precision [21]. There are different Pareto-based multi-objective Particle Swarm Optimization variants, and a state-of-the-art review was given in [22].

Despite the global exploration capability, evolutionary algorithms are comparatively inefficient in fine tuning solutions (the exploitation) [23]. To overcome this deficiency and to enhance the search capability of evolutionary algorithms, appropriate integrations of global and local search techniques to maintain the balance between exploration and exploitation have been proposed. In [24] an adaptive local search method for hybrid evolutionary multi-objective algorithms was