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Multi-objective reactive power optimization strategy for distribution system with penetration of distributed generation

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ABSTRACT

The study investigates multi-objective reactive power optimization (MORPO) of distribution system penetrated with distributed generation (DG). Integrating the reactive power of DG as one type of decision variables, a multi-objective model for RPO has been established to decrease the system active power loss, reduce voltage deviation and minimize the total capacity of reactive power compensation (RPC) devices (or minimize investments on RPC devices). Instead of converting the multiple objectives into a single one, a dynamically adaptive multi-objective particle swarm optimization (DAMOPSO) algorithm with introduction of special adaptive techniques has been proposed and validated and then applied to the MORPO problem with continuous and discrete variables. In order to the proposed MORPO model and the application of DAMOPSO, and to obtain a deep insight into MORPO with different objectives, a series of simulations on IEEE 33-bus system along with analysis and discussion are carried out. The results verified the feasibility and effectiveness of the proposed strategy.

Introduction

With energy and environmental challenges, distributed generation (DG, such as fuel-cells, biomass, micro-turbines, small hydroelectric and other forms of renewable energy technologies [1,2]) has attracted special attention all over the world, and its estimated share will increase significantly in electric power systems in the near future. In general, DG can be installed within distribution systems or on the customer side of the network [3]. However, the traditional distribution systems have been constructed without considering DG's penetration. The impact of DG on the distribution of the reactive power is significant in a distribution system with radial configuration and small X/R ratio [4–8]. Thus, RPO of the distribution system with DG is fundamental to ensure the economic operation of the system without violating technical and operational limits and to provide consumers with sufficient power of high quality.

RPO of the distribution system with integrated DG has been investigated, and a large number of optimization models and methods for this problem have been proposed. Firstly, different kinds of single-objective optimization model have been studied and various single-objective optimization algorithms have been applied [8,9]. Afterwards, researchers advocated that a wide range of objective functions should be considered and a multi-objective formulation should be formed to effectively replicate different perspectives of RPO problem. The commonality of such researches is that a multi-objective problem (MOP) is converted to a single-objective one using a weighted aggregation approach [4,5,10] or fuzzy optimization method [6,7]. It have to be pointed that fuzzy method and weighted aggregation approach are inherently single-objective optimization techniques, and the only one best solution fails to provide the designer with alternative options [11,12], though they simplify the optimization process of MORPO problem. Then, single-objective optimization cannot accurately reflect the relationship between the various objectives, especially when the involved objectives are conflict with each other. Furthermore, fuzzy optimization turns out to be weighted aggregation approach with a set of stationary weights (preference factors [13]). If such a relative preference factor among the objectives is known for a specific problem, weighted aggregation approach is a simple and adequate method to deal with the MOPs. While, it's important to realize that the solution obtained by this strategy is largely sensitive to the relative vector used in forming the composite function [13,14].

Therefore, some multi-objective optimization (MOO) techniques, which have been proved to be efficient in solving MOPs

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by tackling multiple competing objectives simultaneously, should be applied to the MORPO problem. The objectives involved in MORPO are usually non-commensurable or even conflict with each other, and it is always impossible to find a solution which can optimize all the objectives at the same time. Instead of a single optimal solution, the solution to a MOP is a set of different solutions (so-called Pareto optimal set [13]). Via MOO algorithms, we aim to find Pareto solutions that represent the best possible compromises among the objectives. Deb [13] argued that the MOO technique can provide flexibility with a variety of diverse choices and it is more methodical, more practical and less subjective, compared with the method converting the multi-objective into a single objective. Such MOO technique has been applied to the MORPO problem, which made the MORPO come into true. Especially, the MOO technique has been applied to MORPO of distribution system with DG. Considering the voltage stability of the grid-connected wind farm, Zhao and Lv [15] addressed the MORPO model for power system with wind farms and indicated that the identified Pareto solutions can provide decision maker with alternative choices. To maintain the diversity of Pareto solutions, the niching technique was adopted, while one of its drawbacks is difficult to define the involved parameters.

This study aims to investigate the MORPO strategy for distribution system penetrated with DG. Integrate the reactive power of the DG to be the decision variables together with the traditional RPO decision variables and establish the MOO model, in which the objective functions include minimization of the system active power loss, voltage deviation and total capacity of the RPC devices (or investments on the RPC devices). To provide the decision maker with alternatives and to allow to analyze correlations between optimization objectives, a dynamically adaptive multi-objective optimization (DAMOPSO) algorithm has been presented to deal with the non-linear MORPO problem with continuous and discrete variables. For demonstrating advantages of the proposed model and effectiveness of the application of DAMOPSO, comparison and discussion have been carried out along with a series of simulations on modified IEEE 33-bus system.

Multi-objective reactive power optimization model

Objective function

Economic and safe operation of the electric power system is paramount to all others, which also results in great benefits to the society. Even though power loss cannot be completely removed, it can be brought down to an acceptable value. Moreover, reducing the power loss has a positive impact on relieving the feeders, decreasing the voltage drop and possessing other environmental and economical benefits [16]. Hence, power loss is a key and greatly concerned index regarding RPO.

Besides, stability of the system and quality of power supply become more and more important with the development of the society. Failure of power supply and lower power quality would produce faults to the terminal system even paralysis, the resulting effect is devastating and the disrupted productivity would cost billions of dollars in damages. Voltage deviation is one of indices to evaluate the stability of the system and the quality of power supply [17], and minimization of voltage deviation has been selected as one of the multiple objectives in [6,7,10].

Furthermore, the utmost aim of RPO is to reducing active power loss, improving voltage profile and promoting voltage stability with acceptable investment on RPC devices. Since the investment is related to the total capacity of the installed RPC devices, less investment means less total capacity of RPC devices while meeting reactive power demand. Under electric power market environment with separation of power plant and power grid, researchers realized the importance and necessity of pricing the reactive power, and have investigated the RPO problem considering the cost of reactive power, such as decreasing investment of RPC equipments [4,5], minimizing reactive power injection costs [18].

Based on these considerations, this study propose MOO model for RPO of the distribution system penetrated with DG, in which the multiple objectives consist of minimizing the active power loss, the total voltage deviation and the total capacity of RPC devices (or investments on RPC devices). The mathematical formulations of the objectives can be expressed as follows:

$$min \quad f_{loss} = \sum_{k=1}^{N_{bra}} G_k[V_i^2 + V_j^2 - V_iV_j cos\theta_{ij}] \tag{1}$$

$$min \quad f_{\Delta V} = \sum_{i=1}^{N_{bus}} (V_i - V_i^*)^2 \tag{2}$$

$$min \quad f_{cost/Q} = \sum_{s=1}^{N_Q} C_{CAPs}|Q_{qs}| \tag{3}$$

where f_{loss}, $f_{\Delta V}$ and $f_{cost/Q}$ represent the total active power loss, the total voltage deviation and the investments on RPC devices (or total capacity of RPC devices), respectively. C_{CAP} indicates the investment for RPC devices per unit. If $C_{CAP} = 1$, Eq. (3) becomes a function of total capacity of RPC devices. N_{bra}, N_{bus} and N_Q denote the total number of branches, buses and RPC devices in the system, respectively. G_k is the conductance of branch k which connects bus i and bus j. V and θ are voltage magnitude and voltage angle, respectively. $\theta_{ij} = \theta_i - \theta_j$. Q_q represents the actual capacity of RPC device installed.

Constraints

The conventional decision variables of RPO include generator terminal voltage magnitude V_G, reactive power of capacitors Q_C and tap of transformers T, while the state variables consist of reactive power of generator(s) Q_G and voltage magnitude of each load bus in the system. Considering the reactive power capability of DG, the decision variables also include the reactive power of the DG, Q_{DG}. Decision variables and state variables must keep within the pre-defined ranges to ensure the quality of power supply, economic and safe operation of the power system. According to the regulations of power system operation and technical and physical limits, constraints are defined as follows:

Power balance constraints

The equality constraints are the power balance constraints with DG, which include two nonlinear recursive power flow equations. For bus i, it can be formulated as Eq. (4).

$$\begin{cases} P_{Gi} + P_{DGi} - P_{Li} = V_i \sum_{j=1}^{N_{bus}} V_j (G_k cos\theta_{ij} + B_k sin\theta_{ij}) \\ Q_{Gi} + Q_{DGi} + Q_{Ci} - Q_{Li} = V_i \sum_{j=1}^{N_{bus}} V_j (G_k sin\theta_{ij} + B_k cos\theta_{ij}) \end{cases} \tag{4}$$

where P_G, P_{DG} and P_L represent active power of generator, DG and load at bus i, respectively. Q_G, Q_{DG}, Q_C and Q_L represent reactive power of generator, DG, RPC and load, respectively. B_k represent the susceptance of the branch k.

While, inequality constraints mainly include the following ones: