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Optimal allocation of distributed generation with reconfiguration in electric distribution systems

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ABSTRACT

This work presents a methodology for the optimal distributed generation allocation associated with the optimal reconfiguration in radial distribution networks to minimize energy losses. The proposed methodology comprises a step by step heuristic algorithm based on sensitivity indexes. The index for the distributed generation allocation is calculated from the conventional power flow solution. The proposed algorithm considers the demand variation through the system load curves as well as the options to build a new branch for connecting a distributed generator to a busbar of the network. This algorithm is applied to three systems of the literature, including a practical distribution network. The results show that the optimal distributed generation allocation with the reconfiguration provides lower energy losses proving the effectiveness of this approach.

1. Introduction

Power loss reduction in electric distribution systems (EDS) is a relevant concern in power system operations. Power loss minimization is a fundamental way for economic operation and energy cost reduction. Technical losses are associated with the power flow through distribution lines, which is a significant part of the total losses in EDS.

An attractive alternative for the reduction of technical losses in EDS is the distributed generation (DG) allocation. Suitably sized distributed generators placed in appropriate locations can provide many benefits for the system operation, including energy loss reduction [1].

Different approaches for DG allocation based on heuristic methods [2–5] and meta-heuristics can be found in the literature, such as Genetic Algorithms [6], Particle Swarm Optimization [7], Ant Colony Optimization [8] and Tabu Search [9]. In Refs. [10,11], hybrid methods are proposed for solving the DG allocation problem.

Network reconfiguration is another option for loss reduction in EDS [12–18]. Considering the sizes of medium- and large-scale EDS, the search for optimal solutions for the DG allocation with network reconfiguration is a very complex problem. Approaches for both the DG allocation and the optimal reconfiguration are addressed in [19,20].

This paper presents a constructive heuristic algorithm for solving the problem of DG allocation with reconfiguration in EDS. Given that the objective is to minimize the energy losses, determining the optimal DG allocation is important because different power injection points would affect the flow distribution and, consequently, the losses. The proposed methodology considers the addition of a new busbar with a new branch to connect a DG unit to the system. The power dispatch of the DG unit is pre-specified, as are the characteristics of the new branch, such as its length and impedance. At each step of the proposed methodology, a new solution is obtained toward the minimum-loss point. Simulations using certain well-known distribution systems are presented to evaluate the proposed methodology.

2. Problem formulation

The optimal distributed generation allocation combined with the problem of EDS reconfiguration for energy loss minimization is formulated as follows:

$$\text{Min}\quad \text{losses} = \sum_{\mu=1}^{NT}\left[\sum_{km=1}^{NB} t_\mu \cdot L_{km,\mu} \cdot CH_{km} + \sum_{i=1}^{NDG}\sum_{k=1}^{NC} t_\mu \cdot L_{ik,\mu} \cdot DG_{ik}\right] \tag{1}$$

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$$Pg_{k,u} - Pl_{k,u} - \sum_{m \in \Omega_k} CH_{km} \cdot P_{km,u} - \sum_{i \in \Omega_k} DG_{ik} \cdot P_{ik,u} = 0 \tag{1.1}$$

$$Qg_{k,u} - Ql_{k,u} - \sum_{m \in \Omega_k} CH_{km} \cdot Q_{km,u} - \sum_{i \in \Omega_k} DG_{ik} \cdot Q_{ik,u} = 0 \tag{1.2}$$

$$DG_{ik} \cdot PDG_{ik} - \sum_{k \in \Omega_i} P_{ik,\mu} = 0 \tag{1.3}$$

$$DG_{ik} \cdot QDG_{ik} - \sum_{k \in \Omega_i} Q_{ik,\mu} = 0 \tag{1.4}$$

$$L_{km,u} = g_{km} \cdot (V_{k,u}^2 + V_{m,u}^2 - 2 \cdot V_{k,u} \cdot V_{m,u} \cdot \cos\theta_{km,u}) \tag{1.5}$$

$$L_{ik,u} = g_{ik} \cdot (V_{i,u}^2 + V_{k,u}^2 - 2 \cdot V_{i,u} \cdot V_{k,u} \cdot \cos\theta_{ik,u}) \tag{1.6}$$

$$\overline{Z}^{\min} \leq \overline{Z}_{\mu} \leq \overline{Z}^{\max} \tag{1.7}$$

Radiallity and connectivity constraints (1.8)

where

NT	total number of load levels,
NB	total number of existing branches,
NDG	total number of distributed generator,
NC	total number of candidate branches to connect the distributed generator,
t_{μ}	time interval the EDS operating at load level u (hours),
$L_{km,u}$	active power loss of existing branch km at load level u (kW),
$L_{ik,u}$	active power loss of candidate branch ik at load level u (kW),
CH_{km}	discrete variable associated with the position of the maneuverable switch of branch km,
DG_{ik}	discrete variable associated with the distributed generator at busbar i connected to the system through busbar k,
$P_{ik,u}$	active power flow through connection branch ik at load level u (kW),
$Pg_{k,u}$	existing active power generation at busbar k at load level u (kW),
$Pl_{k,u}$	active power load at busbar k at load level u (kW),
$P_{km,u}$	active power flow through existing branch km at load level u (kW),
Ω_k	set of busbars directly connected to busbar k,
$Q_{ik,u}$	reactive power flow through connection branch ik at load level u (kVAr),
$Qg_{k,u}$	existing reactive power generation at busbar k at load level u (kVAr),
$Ql_{k,u}$	reactive power load at busbar k at load level u (kVAr),
$Q_{km,u}$	reactive power flow through branch km at load level u (kVAr),
PDG_{ik}	active power from distributed generator i connected to the system through branch ik (kW),
QDG_{ik}	reactive power from distributed generator i connected to the system through branch ik (kVAr),
g_{km}	conductance of branch km (pu),
$V_{k,u}, V_{m,u}, V_{i,u}$	voltage magnitude at busbars k, m and i at load level u (pu),
$\theta_{km,u}$	phase angle between busbars k and m at load level u (rad),
$\theta_{ik,u}$	phase angle between busbars k and i at load level u (rad),
$\overline{Z_u}$	set of variables that have lower and upper limits on the load level u, and
$\overline{Z}^{\min}, \overline{Z}^{\max}$	sets of lower and upper limits of variables $\overline{Z_u}$, respectively.

Eq. (1) denotes the objective function that minimizes the energy losses in EDS, including the original branches and the new branches that are added to connect DG units to EDS. If branch *km* has no maneuverable switch, CH_{km} is fixed at a value of 1, as shown in reference [13]. Moreover, open branches do not contribute to the loss calculation because $CH_{km} = 0$ for these branches. If there is a DG unit connected to busbar *k* ($DG_{ik} = 1$), then the DG unit is allocated to the new busbar *i*, which is connected to the system through the new branch *i*–*k*. Otherwise, DG_{ik} is equal to zero.

Eqs. (1.1) and (1.2) correspond to the constraints of the real and reactive power balances at bus *k*, respectively, where the busbar *i* is a distributed generation bus.

Eqs. (1.3) and (1.4) establish the active and reactive power balances at the new busbar *i*, which is included in the system for a DG unit allocation. The active and reactive power dispatches of the distributed generator (PDG_{ik} and QDG_{ik}) are fixed according to its pre-specified capacity.

The active power losses of branches *k*–*m* and *i*–*k* at load level *u* are given by Eqs. (1.5) and (1.6), respectively. Expressions (1.7) define the limits of variables, such as the busbar voltage magnitudes and power generation. Constraints (1.8) represent the radiality and the connectivity operation of the radial EDS. These constraints are handled implicitly, as described in the following section.

It should be stressed that the variables CH_{km} and DG_{ik} have integer values that represent the discrete status of the maneuverable switches and the DG connection, respectively. Therefore, these variables are set to values of 0 or 1 based on the solutions of problem (1). The modeled problem is complex, non-convex and combinatorial and includes features of a mixed-integer nonlinear programming (MINLP) problem. To solve the proposed and complex problem (1), we can use the nonlinear integer toolbox in many optimization packages. However, these packages are not adequate to solve problem (1) because they require too much time. Therefore, the present work proposes an efficient strategy based on a Combined Heuristic Constructive Algorithm (CHCA) that considers the network radiality and connectivity constraints.

3. Proposed methodology – (CHCA)

The proposed (CHCA) aims to combine the advantages of the distributed generation allocation with the network reconfiguration options for technical loss reduction in EDS. A flowchart of the CHCA is depicted in Fig. 1.

The following comments help to explain the CHCA:

In **Step-1**, the losses of the original system topology are stored as the Base Case, and the *ig*-Case is equal to *ig* = 1 for the first iteration.

In **Step-2**, the variables (DG_{ik}) are considered to be equal to 0.01 for all *i* and *k* to evaluate the system sensitivity. However, if one of the DG units was allocated in the previous iteration, then the variable (DG_{ik}) is fixed at 0.99 for this DG unit. It is therefore possible to obtain the sensitivity between the system losses and an incremental dispatch at each candidate DG unit from these reduced power generation injections.

In **Step-3**, a conventional nonlinear power flow simulation is performed with the modifications described in **Step-2**. This power flow is solved through the Newton–Raphson method as used in reference [21] for radial electrical networks. Using these results, the active power losses, incremental costs [22] and the sensitivity index, ID_{ik}, are determined. The ID_{ik} values are calculated for each candidate DG unit, *i*, to be connected to the system through candidate branches *i*–*k*. The sensitivity index will be discussed in Section 3.1.

In **Step-4**, a new DG unit, DG_{ik}, is selected to be connected to the system based on its sensitivity index, ID_{ik}. A positive value for ID_{ik} indicates that the DG_{ik} allocation increases the system losses. On the other hand, a negative value for ID_{ik} indicates a system loss reduction for the allocation of DG_{ik}. Therefore, only DG units with negative sensitivity indexes may be connected to the system. The sensitivity indexes ID_{ik} for these DG units are ranked in descending order, and the DG unit with the largest absolute value of its index is selected to correspond to $DG_{ik} = 1$, and the others are set equal to zero.

Step-5 consists of the calculation of system losses considering the allocation of the DG unit selected in **Step-4**. The system losses associated only with the allocation of the DG unit selected at the current iteration (*ig*) must be evaluated. These results are stored as