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A novel adequate bi-level reactive power planning strategy

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ABSTRACT

Planning of reactive power sources is a serious issue for secure and economic operation of power systems. In this paper, a bi-level strategy is proposed to optimize the Reactive Power Planning (RPP) problem. In the first level, the weakest buses are selected to be the optimal placements to install the additional VAR sources and its corresponding suitable sizes are determined using a proposed Refined Heuristic Process (RHP). In the second level, two modified versions of Differential Evolution Algorithm (DEA) are proposed for optimizing the RPP control variables which able to minimize both the allocation costs of additional VAR sources throughout the system, and the system operational costs of real power losses. To validate the effectiveness of proposed strategy, several applications are carried out on three power systems networks namely IEEE 14-bus, IEEE 30-bus test systems and the West Delta region system as a part of the Egyptian Unified network. The proposed strategy is evaluated compared with other optimization methods as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and the commonly used Differential Evolution (DE) version (DE/rand/1). The robustness of the proposed versions of DEA is proven compared to other optimization techniques. Added to that, the control parameters of the proposed DEA are optimally identified. Numerical results show that the proposed version of DEA achieves highest reduction in the operation and investment costs compared to other optimizing algorithms in the literature which denotes that the proposed version of DEA can be efficiently applied to the RPP problem.

Introduction

Reactive Power Planning (RPP) is generally defined as optimal siting and sizing of new VAR sources like shunt capacitors in a power system at a minimum cost which guarantees adequate voltage levels of the buses throughout the network. Usually the RPP problem is concerned with investment and operational planning aspects. In the investment side, new VAR sources are optimally allocated at a minimal investment costs. In the operational side, the shunt VAR sources (existing and additional), generator voltages, and tap setting of transformers are optimally controlled to minimize the system operational costs of power losses and achieve a satisfactory voltage profile [1].

RPP is a nonlinear multi-objective constrained combinatorial optimization problem which has been handled using various solution algorithms. Arithmetic programming algorithms have been still applied to the RPP problem such as Linear Programming (LP) based Interior Point (IP) method [1], Non-Linear Programming (NLP) [2], Mixed Integer Non-Linear Programming (MINLP) [3], IP methods [4,5], and Dual Projected Pseudo Quasi-Newton (DPPQN) procedure [6], but they are very weak in handling multi-objective nonlinear problems and they may also converge to a local optimum since they are usually based on some simplifications.

On the other hand, Meta-heuristic Optimization Algorithms (MOAs) is very suitable in solving the RPP problem since they are robust, effective and it can find multiple optimal solutions in single simulation run. They have been widely applied to solve this problem such as Simple Genetic Algorithm (SGA) [7–9], Real Coded GA (RGA) [10,11], Modified Non-dominated Sorting Genetic Algorithm II (MNSGA-II) [12], Covariance Matrix Adaptation Evolution Strategy (CMAES) [13], Multi-objective Fuzzy Linear Programming (MFLP) [14,15], Particle Swarm Optimization (PSO) [16–19], and evolutionary programming [20].

Nonetheless, DEA has been used in [11,21] to solve the RPP problem to minimize both the VAR and energy loss costs. In [22], DEA has been performed for solving the contingency constrained optimal RPP problem. In [23], Fast Voltage Stability Index (FVSI) has been used to identify the weak buses for the RPP problem which has been solved using DEA. In [24,25], DEA has been applied to solve the RPP problem after identifying the candidate buses using L-index. DE/randSF/1/bin scheme has been implemented in

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Nomenclature

F	total costs of both operation and investment costs of reactive power supplies
I_C	investment cost of new reactive power supplies
O_C	operational costs of power losses
e_i	fixed cost at bus i
$C_{c_i}\lvert Q_{c_i}\rvert$	variable purchase cost of capacitive or inductive source at bus i
N_c	number of reactive compensator buses
h	the per unit energy cost
d_L	duration of load level (h)
N_L	number of load level duration
P^L_{Loss}	real power loss during the period of load level L
g_{ij}	conductance of branch between buses i and j
θ_{ij}	voltage angle difference between bus i and bus j
V_i and V_j	voltage magnitude at buses i and j, respectively
G_{ij} and B_{ij}	mutual conductance and susceptance between buses i and j, respectively
N_{PQ}	number of load buses
P_{g_i}	active power generated at bus i
P_{L_i}	active power demand at bus i
Q_{g_i}	reactive power generated at bus i
Q_{L_i}	reactive power demand at bus i
Q_{c_e}	capacitive or inductive power of existing VAR source installed at bus i
$Q^n_{C_i}$	capacitive or inductive power of new VAR source installed at bus i
N_{pv}	total number of voltage-controlled buses
T_k	tapping change of a transformer k
N_t	total number of on-load tap changing transformers
S^{flow}	apparent power flow
$S^{\max}$	maximum MVA rating of the transmission lines and transformers
N_L	number of transmission lines in the system
$Q^{\max}_c$	maximum capacity of the VAR sources
P_s	active power at slack bus
$P^{\min}_s$	minimum limit of the active power generated at slack bus
$P^{\max}_s$	maximum limit of the active power generated at slack bus
Std	standard deviation
Ste	standard error

[23–25] which modified the commonly used strategy (DE/rand/1/bin) of DE with a self-tuned mutation parameter. Although the most references executed the DEA [11,21–25], the only applied DE strategy is DE/rand/1/bin.

In this paper, a bi-level strategy is presented to solve the RPP problem. In the first level, the optimal placements to install the additional VAR sources are determined using a proposed RHP. In the second level, two versions of DEA are proposed for handling the RPP problem to minimize both the allocation costs of additional VAR sources, and the system operational costs of real power losses. Likewise, the optimal control parameters of the proposed DE version are analyzed to extract the optimal range of both mutation and crossover constants as application guide to solve the RPP problem for any power system. The robustness of the proposed versions DEA is checked compared to other optimization techniques.

Rest of this paper is organized as follows: section 'General formulation of RPP problem' presents the formulation of the RPP problem. Section 'Differential evolution algorithm variants' introduces the DEA and its different strategies. The proposed procedure for optimizing the RPP problem is described in section 'Proposed strategy for reactive power planning problem'. Section 'Simulation results' presents the application results of case studies. The outcome of the current work is concluded in the last section.

General formulation of RPP problem

There are various objective functions that have been utilized in the RPP problem such as minimization of VAR investment cost and system operation cost of real power losses, improvement of voltage profile, and enhancement of voltage stability. However, the modeling of each objective has different shapes. Conventionally, the classical objective of the RPP problem is to achieve the minimum investment cost of additional reactive power supplies and minimize the system operation costs [9–13,16,21,22] as:

$$\text{Min } F = \text{Min } (O_C + I_C) \tag{1}$$

The investment costs of VAR sources can be generally modeled as Eq. (2) with two components, a fixed cost which covers the physical installation and additional equipment costs (such as switchgear and breakers) and a variable purchase cost of capacitive or inductive source which is the procurement cost that depends on the amount of nominal installed VAR source [7–13,16,21,22], while, the annual cost of energy losses has been traditionally used as a direct measure to the operational costs as Eq. (3) [9–13,16,21,22]:

$$I_C = \sum_{i=1}^{N_c} (e_i + C_{c_i} |Q_{c_i}|) \tag{2}$$

$$O_C = h \sum_{i=1}^{N_L} d_L P^L_{\text{loss}} \tag{3}$$

The real power loss during the period of load level L is modeled as:

$$P_{\text{loss}} = \sum_{i,j \in N_b} g_{ij} (V_i^2 + V_j^2 - 2V_i V_j \cos\theta_{ij}) \tag{4}$$

Equality constraints

The equality constraints are usually represented by the load flow balance equations which could be formulated as:

$$Q_{g_i} - Q_{L_i} + Q^n_{C_i} + Q_{C_e} - V_i \sum_{j=1}^{N_b} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0, \quad i = 1, 2, \ldots N_{PQ} \tag{5}$$

$$P_{g_i} - P_{L_i} - V_i \sum_{j=1}^{N_b} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) = 0, \quad i = 1, 2, \ldots N_b - \text{slack} \tag{6}$$

Inequality constraints

Moreover, the power system has to satisfy inequality constraints corresponding to the operational variables as: