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Security constrained multi-period optimal power flow by a new enhanced artificial bee colony

Saber Armaghani, Nima Amjady*, Oveis Abedinia

Department of Electrical Engineering, Semnan University, Semnan, Iran

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ABSTRACT

Security constrained optimal power flow (SCOPF) is an important operation function for dispatching centers of current power systems. It optimizes operating conditions of the system, while saves its security. However, SCOPF in its present form focuses on a single time interval, which is known as static SCOPF. A multi-period SCOPF model, referred to as dynamic SCOPF (DSCOPF) in this paper, is presented. It extends static SCOPF to multi-period frameworks considering the inter-temporal constraints. The proposed DSCOPF is a more practical operation function and can optimize operating conditions of the system more realistically compared to traditional SCOPF. Moreover, to solve this DSCOPF model, considering its nonlinear and non-convex behavior, a new stochastic search method is presented, which is an enhanced version of artificial bee colony (ABC) algorithm. The proposed enhanced ABC (EABC) has high exploration capability and can discover different areas of the solution space. Also, it is a robust algorithm and has low sensitivity with respect to the initial population. Effectiveness of the proposed EABC is extensively illustrated on various test cases.

1. Introduction

Economic dispatch (ED) is one of the most important nonlinear optimization problems in the operation of power systems. In this problem, to meet the system load with the lowest possible cost, the optimal output of electricity generation facilities is determined. For this purpose, the operational constraints of the system and available resources should be considered. Optimal power flow (OPF) is an extension of the conventional ED problem. OPF determines the optimum operating state of power system considering the other control variables, such as voltage set-point of generators and settings of tap-changing transformers, phase shifters and shunt compensators in addition to active power output of generators. OPF includes nodal balance constraints in addition to ED limits. A review of different ED and OPF models and their solution methods can be found in [1,2].

Taking into account the importance of security for power system operation, security constraints, such as branch flow and voltage magnitude limits, are incorporated into ED and OPF operation functions leading to security constrained ED (SCED) [3] and security constrained OPF (SCOPF) [4,5], respectively. SCED is usually considered as a sub-problem of security constrained unit commitment (SCUC) [6,7] and SCOPF is extensively used in today power system dispatching centers. Different SCOPF formulations, including the objective functions and constraints, as well as their solution methods have been reviewed in [8,9].

ED and OPF models usually focus on a single time period also called static ED [10,11] and static OPF [12,13]. In another extension for ED and OPF, recently introduced in the literature, these operation functions have been extended to multi-period frameworks known as dynamic ED (DED) [10,11] and dynamic OPF (DOPF) [12,13]. Combination of the both enhancements, i.e. considering security constraints and multi-period operation framework, for ED is suggested in [14] leading to DSCED model. In this paper, the more complete operation function of DSCOPF is proposed. Compared to DSCED only including the control variables of generator outputs, the proposed DSCOPF can optimize operating state of the power system taking into account all control variables of OPF. Moreover, by including security constraints, not considered in ED, OPF, DED and DOPF, the proposed DSCOPF can provide both secure and economic operating conditions for the system. Finally, by modeling multi-period operation and inter-temporal ramping limits, DSCOPF can provide a more realistic power system operation model compared to ED, OPF, SCED and SCOPF. Thus, DSCOPF can more accurately and comprehensively model the operating state of power system in comparison with the previous operation functions, presented in the industrial software packages or academic literatures, including ED, OPF, SCED, SCOPF, DED, DOPF and DSCED.

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* Corresponding author. Tel.: +98 21 88889096; fax: +98 21 88880098.
E-mail address: amjady@semnan.ac.ir (N. Amjady).

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Nomenclature

a_i, b_i, c_i, d_i and e_i	generation cost coefficients of *i*th unit with valve loading effects
DR_i	down ramp rate limit of *i*th unit
$F_i(.)$	generation cost function of *i*th unit
G_{ij} and B_{ij}	conductance and susceptance of the branch connected between *i*th and *j*th buses, respectively
L	number of branches
N_B, N_{B-S} and N_{PQ}	number of buses, number of buses excluding the slack buses and number of PQ buses, respectively
NC	number of shunt compensators
NF_i	number of fuel options of *i*th unit
NG	number of units of the power system
NP_i	number of POZs for *i*th unit
NPS	number of phase shifters
NPZ_i	number of prohibited operating zones of *i*th unit
NT	number of tap-changing transformers
$P^{LB}_{G,i,k}$, $P^{UB}_{G,i,k}$	lower and upper bound for *k*th prohibited operating zone (POZ) of *i*th unit
$P^{\min}_{G,i}$, $P^{\max}_{G,i}$	minimum and maximum active power generation limits for *i*th unit
$P_{G,i,t}$ and $P_{D,i,t}$	active power generation and demand of *i*th bus in hour *t*, respectively
P_G	a vector including all $P_{G,i,t}$ variables
$PS_{i,t}$	phase shifter setting for *i*th phase shifter in hour *t*
$PS^{\min}_i$, $PS^{\max}_i$	minimum and maximum limits for *i*th phase shifter setting
$Q_{C,i,t}$	reactive power injection of *ith* shunt compensator in hour *t*
$Q^{\min}_{c,i}$, $Q^{\max}_{c,i}$	minimum and maximum limits for reactive power injection of *i*th shunt compensator
$Q^{\min}_{G,i}$, $Q^{\max}_{G,i}$	minimum and maximum reactive power generation limits for *i*th unit
$Q_{G,i,t}$ and $Q_{D,i,t}$	reactive power generation and demand of *i*th bus in hour *t*, respectively
T	number of hours of the operation horizon
$TP_{i,t}$	tap-changer setting for *i*th transformer in hour *t*
$TP^{\min}_i$, $TP^{\max}_i$	minimum and maximum limits for *i*th tap-changer setting
UR_i	up ramp rate limit of *i*th unit
$V_{i,t}$	voltage magnitude of *i*th bus in hour *t*
$V^{\min}_i$, $V^{\max}_i$	minimum and maximum limits for voltage magnitude of *i*th bus
$S_{k,t}$	apparent power flow of *k*th branch in hour *t*
$S^{\max}_k$	apparent power flow limit for *k*th branch
SRR_t	system reserve required in time interval *t*
$\theta_{ij,t}$	phase angle difference between buses *i* and *j* in hour *t*

To the best of the authors' knowledge, DSCOPF has not been presented in the previous research works in the area and is specific to this paper.

Another main contribution of the paper is presenting a new solution approach for solving DSCOPF. In the following, the recent solution methods presented for SCOPF and DOPF, which are more relevant problems to DSCOPF, are briefly reviewed. Then, the outline of the proposed solution approach is introduced.

An improved version of bacterial foraging algorithm including a differential evolution-based mutation operation, aiming to enhance the exploration capability of the algorithm, is presented for solving SCOPF problem in [9]. Multi-constraint optimal power flow problem including valve point effect and security constraints is solved by biogeography based optimization (BBO) in [15]. A hybrid algorithm composed of sequential quadratic programming and differential evolution is presented for solving SCOPF problem including two objective functions of fuel cost with valve point effects and transmission line losses [16]. A robust differential evolution algorithm is proposed for solving SCOPF considering valve point effects, multi-fuel option and prohibited operating zone constraints of units in [4]. Two objective functions of generation cost and voltage stability margin are taken into account in [4]. Multi-agent differential evolution is proposed for solving SCOPF including unit generations (except slack bus), unit voltages and transformer tap settings as the control variables in [17]. In [18], a bi-level optimization approach is presented in which ED is first solved in the lower level and using its results as the initial solution, SCOPF is solved in the upper level. Both the levels of the bi-level approach use an enhanced version of gravitational search algorithm as the optimization method.

In [12], an algorithm based on nonlinear primal dual interior point method (PDIPM) is presented for solving DOPF problem. Also, a three-stage solution procedure to implement the PDIPM algorithm is proposed in [12]. Another solution approach, based on decomposed predictor-corrector interior point method (DPCIPM), to solve DOPF problem is presented in [13]. As DOPF is a large-scale and nonlinear optimization problem, the Karush–Kuhn–Tucker (KKT) system in DPCIPM is decomposed into subsystems, such that the size of each subsystem only depends on the size of the network.

DSCOPF is a more complex optimization problem than SCOPF and DOPF as it includes more nonlinear, mixed-integer and inter-temporal constraints and variables. In this paper, a new stochastic search method, i.e. EABC, is presented to solve DSCOPF. EABC is composed of ABC, harmony search (HS), improved particle swarm optimization and chaotic search techniques. Search abilities of these methods are combined in the proposed EABC to enhance its exploration capability, which is the key issue for solving DSCOPF problem considering its complex high-dimensional solution space. Also, a new hybrid constraint handling method is suggested to process the large number of DSCOPF constraints and generate feasible solutions for it.

1.1. Main contributions of the study

The new contributions of this paper can be summarized as follows:

1. A new operation function for power systems, i.e. DSCOPF, is presented. Compared to the previous operation functions of ED, OPF, SCED, SCOPF, DED, DOP and DSCED, the proposed DSCOPF can more comprehensively model the operating conditions of a power system as described previously.
2. A new stochastic search method, named EABC, is proposed. Although ABC is a simple basic evolutionary algorithm, it presents a flexible framework for hybridizing with other evolutionary operators and algorithms. This is due to different bees (i.e. individuals) with different characteristics used in the structure of ABC. Using the flexible structure of ABC, EABC incorporates the positive features of harmony search (HS) and particle swarm optimization (PSO), chaotic tent map, Deb's rule based on tournament selection, new probability assignment, and opposition-based learning into ABC. These features give high search ability to EABC, which makes it an effective solution approach for solving the complex optimization problem of DSCOPF.