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# Voltage stability constrained multi-objective optimal reactive power dispatch under load and wind power uncertainties: A stochastic approach

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## ABSTRACT

Optimal reactive power dispatch (ORPD) problem is an important problem in the operation of power systems. It is a nonlinear and mixed integer programming problem, which determines optimal values for control parameters of reactive power producers to optimize specific objective functions while satisfying several technical constraints. In this paper, stochastic multi-objective ORPD (SMO-ORPD) problem is studied in a wind integrated power system considering the loads and wind power generation uncertainties. The proposed multi objective optimization problem is solved using ε-constraint method, and fuzzy satisfying approach is employed to select the best compromise solution. Two different objective functions are considered as follow: 1) minimization of the active power losses and 2) minimization of the voltage stability index (named L-index). In this paper VAR compensation devices are modeled as discrete variables. Moreover, to evaluate the performance of the proposed method for solution of multi-objective problem, the obtained results for deterministic case (DMO-ORPD), are compared with the available methods in literature. The proposed method is examined on the IEEE-57 bus system. The proposed models are implemented in GAMS environment. The numerical results substantiate the capability of the proposed SMO-ORPD problem to deal with uncertainties and to determine the best settings of control variables.

## 1. Introduction

From the viewpoint of operation cost, environmental concerns and system security, optimal reactive power dispatch (ORPD) is important for power utilities operators. The ORPD is a specific subcategory of OPF problem, which optimizes objective functions such as transmission losses or voltage stability enhancement by adjusting the generators voltages set-points, allocating reactive power compensation in weak buses, adjusting transformers tap ratios, etc.

### 1.1. Literature review

ORPD can be divided into two categories considering the number of target objective functions. These two categories are single objective function (mostly minimizing power losses) or multi objective (with considering two or three objectives) ORPD.

In the single objective ORPD, intelligent search based optimization algorithms like seeker optimization algorithm (SOA) [1], harmony search algorithm [2], differential evolutionary-based method [3,4], and gravitational search algorithm (GSA) [5] have been developed to deal with the ORPD problem. In this category voltage stability enhancement index or system real power loss are minimizing separately. In Refs. [6], a method for coordinated optimal allocation of reactive power sources in AC–DC power systems using unified power flow controller (UPFC) is presented for minimization of the sum of the squares of the voltage deviations of all load buses. Management and scheduling of VAR generation to enhance the voltage stability margin (VSM) in the framework of optimal reactive power dispatch (ORPD) problem is proposed in Ref. [7]. A reformed particle swarm optimization (PSO) strategy for the ORPD in the presence of wind farms has been proposed in Refs. [8], where PSO merged with a feasible solution search (FSSPSO). Optimal active–reactive power dispatch (OARPD)

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## Nomenclature

*Sets*

| | |
|---|---|
| $N_B$ | set of buses |
| $N_L$ | set of branches |
| $N_G$ | set of generating units |
| $N_W$ | set of wind farms |
| $N_s$ | set of all possible scenarios |
| $N_T$ | set of tap changing transformers |
| $N_C$ | set of VAR compensators |
| $N_{PQ}$ | set of system PQ buses |
| $N_{PV}$ | set of system PV buses |

*Indices*

| | |
|---|---|
| $k$ | index of objective functions |
| $m$ | index of tap changing transformers |
| $i/j$ | index of bus numbers |
| S | index of scenario numbers |
| $\ell$ | index of transmission lines |
| $sl$ | index of slack bus |

*Parameters*

| | |
|---|---|
| $\pi_s$ | probability of scenario *s* |
| $\pi_d$ | probability of demand scenario *d* |
| $\pi_w$ | probability of wind power generation scenario *w* |
| $Y_{ij}\angle\gamma_{ij}$ | magnitude/angle of *ij-th* element of $Y_{BUS}$ matrix (pu/radian) |
| $P_{G_i,s}$ | active power production of generator at bus *i* in scenario *s* |
| $P_{G_i}^{\min}/P_{G_i}^{\max}$ | minimum/maximum value for active power |
| $Q_{C_i}^{\min}/Q_{C_i}^{\max}$ | minimum/maximum value for reactive power compensation at bus *i* in scenario *s* |
| $T_m^{\min}/T_m^{\max}$ | minimum/maximum value for *m*-th tap changer settings |
| $P_{D_d}^{\min}/P_{D_d}^{\max}$ | minimum/maximum value of real power demand at *d*-th load scenario |
| $P_{D_i,s}$ | expected real power of the *i*-th bus in scenario *s* |
| $Q_{D_i,s}$ | expected reactive power of the *i*-th bus in scenario *s* |
| $Q_{G_i}^{\min}/Q_{G_i}^{\max}$ | minimum/maximum value for reactive power of generator at bus *i* |
| $V_i^{\min}/V_i^{\max}$ | minimum/maximum value for voltage magnitude of the *i*-th bus |
| $S_\ell^{\max}$ | maximum transfer capacity of line $\ell$ |
| $v$ | wind speed in m/s |
| $v_{in}^c/v_{out}^c$ | cut-in/out speed of wind turbine in m/s |
| $v_{rated}$ | rated speed of wind turbine in m/s |
| $P_W^{avl}$ | available wind power generation |
| $Q_{C_i}^b$ | VAR compensation capacity in each step at bus *i* |
| $I_{C_i}^{\min}/I_{C_i}^{\max}$ | minimum/maximum Reactive power compensation step at bus *i* |
| $cos(\varphi_{lag,i})/cos(\varphi_{lead,i})$ | lag/lead power factor limits of the wind farms located at node *i* |
| $\zeta_{W_{i,s}}$ | percentage of wind power rated capacity realized at scenario *s*in bus *i* |
| $P_{W_i}^r$ | wind farm rated capacity installed in bus *i* |

*Variables*

| | |
|---|---|
| $\overline{x}_s$ | vector of dependent variables in scenario *s* |
| $\overline{u}_s$ | vector of control variables in scenario *s* |
| $T_m$ | value of *m*-th tap changer setting (which connects buses *i* and *j*) |
| $V_{i,s}$ | voltage magnitude of bus *i* in scenario *s* |
| $\theta_{i,s}$ | voltage angle at bus *i* in scenario s |
| $S_{\ell,s}$ | power flow of $\ell$-th branch in scenario *s* |
| $P_{G_{sl},s}$ | active power production of slack bus in scenario *s* |
| $P_{W_i,s}/Q_{W_i,s}$ | active/reactive power produced by wind farm at scenario s |
| $Q_{W_i}^{\min}/Q_{W_i}^{\max}$ | minimum/maximum value of reactive power produced by wind farm |
| $Q_{G_i,s}$ | reactive power production of generator at bus *i* in scenario *s* |
| $I_{C_i,s}$ | reactive power compensation step at bus *i* in scenario *s* |
| $Q_{C_i,s}$ | reactive power compensation at bus *i* in scenario *s* |
| $\phi_k$ | individual value of *k-th* conflicting objective function |
| $\widehat{\phi}_k$ | normalized value of *k-th* objective function |

*Functions*

| | |
|---|---|
| $PL_s$ | active power losses in scenario *s* |
| $EPL$ | expected active power losses |
| $EPL^L/EPL^U$ | minimum/maximum value for expected real power loss |
| $L_{max,s}$ | $L_{\max}$ value in scenario *s* |
| $EL_{max}$ | expected value of voltage stability enhancement index ($L_{max}$) |
| $EL_{\max}^L/EL_{\max}^U$ | minimum/maximum value of $EL_{max}$ |

problem resolved one-by-one with evolutionary calculation methods like as evolutionary programming (EP), PSO, differential evolution (DE) and hybrid differential evolution (HDE) in Ref. [9]. An enhanced load flow Jacobian is presented in Ref. [10] to redispatch the reactive power. The proposed approximation used tangent vector approach to decrease operational loss in a vital area considering the voltage collapse possibility. In Ref. [11] a new objective function is proposed for the ORPD problem based on a local voltage stability index called DSY, which has a strong correlation with VSM. Hybridized multiple heuristic algorithms are widely used for solution of ORPD problem. For example, hybrid shuffled frog leaping algorithm (SFLA) and regional seek algorithm known as Nelder–Mead (NM-SFLA) [12], hybrid modified teaching–learning algorithm (MTLA) and double differential evolution (DDE) [13], hybrid modified imperialist competitive algorithm (MICA) and invasive weed optimization (IWO) [14], firefly algorithm (FA) and Nelder Mead (NM) simplex method [15] are used for ORPD solution. The most significant advantage of hybrid algorithms is higher speed of convergence to the optimal solution. A penalty function based method presented in Ref. [16] to convert discrete ORPD model to the continuous and differentiable one. In a recent study [17], to consider uncertainties in ORPD problem, the researchers used chance constrained programming to solve ORPD problem for minimizing active power losses. Nodal power injections and random branch outages are considered as uncertainty sources in this paper.

Voltage stability control is one of present-day challenges in power systems operation and control. In Ref. [18] a multi-period ORPD model is proposed which uses the concept of model predictive voltage control. In Ref. [19], the settings of reactive power compensation devices are determine based on new improved voltage stability index (IVSI) by using hybrid differential evolution (HDE) algorithm. Voltage stability constrained optimal power flow (VSC-OPF) problem with considering $L_{\text{Max}}$ index is proposed by