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Optimal power flow solution of power system incorporating stochastic wind power using Gbest guided artificial bee colony algorithm

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ABSTRACT

This paper focuses primarily on implementation of optimal power flow (OPF) problem considering wind power. The stochastic nature of wind speed is modeled using two parameter Weibull probability density function. The economic aspect is examined in view of the system wide social cost, which includes additional costs like expected penalty cost and expected reserves cost to account for wind power generation imbalance. The optimization problem is solved using Gbest guided artificial bee colony optimization algorithm (GABC) and tested on IEEE 30 bus system. The simulation results obtained using proposed method are compared with other methods available in the literature for a case of conventional OPF as well as OPF incorporating stochastic wind. Subsequently an extensive simulation study is conducted to investigate the effect of wind power and different cost components on optimal dispatch and emission. Numerical simulations indicate that the operation cost of system and emission depends upon the transmission system bottlenecks and the intermittency of wind power generation.

Introduction

The majority of the world's power plants produce electricity with natural gas, coal or oil as primary resource to drive electrical generators. The human induced greenhouse gas emissions particularly carbon dioxide is the main cause of global warming. With availability of economic incentives and other policy mechanisms, there is a growing trend towards wind energy installations all around the world. The electrical power systems throughout the world are undergoing significant changes due to increased penetration level of wind power creating new challenges to system planning and operation. As a result of this an optimal power flow (OPF) is becoming an important tool for power system operators both in planning and operating stage. The main aim of an OPF is to determine the optimal values of control variables of power systems for economic operation under steady state, while satisfying set of equality and inequality constraints. The conventional OPF problem, considering fossil fuel based power plants in system has been extensively studied in the past [1–21]. Moreover, the previous studies associated with the wind–thermal coordination and economics are mostly based on deterministic approach assuming perfect forecast [22–27].

However, since, in contrast to conventional fossil fuel based power generation, the wind power has random nature, it is necessary to suitably include the wind power uncertainty in optimization problem to determine optimal values of decision variables. Miranda and Hang in [28] proposes a cost model to include wind-powered generators as independent sources, using concepts from the fuzzy set theory. The authors of [28] added a penalty cost in classical economic dispatch problem representing compensation payment to private owners of wind farms for not using the available wind power capacity. In another similar work, an additional cost term for overestimation of the available wind power has been included in dispatch problem along with use probability functions to characterize the wind speed profiles in [29]. To account for wind power uncertainty, a model similar to [28] is analyzed using particle swarm optimization algorithm in [30]. The pioneering work by Hetzer [29], which includes over-estimation and under-estimation of available wind power in classical economic dispatch model, has been studied extensively during recent years in [31–41]. In all these studies the uncertainty of wind power is modeled by Weibull probability distribution function. Although all these studies provides valuable insight into the economic dispatch strategies for wind integrated power systems, none of them except [29] addresses the effect of change in wind speed profile and wind power cost coefficients on optimal dispatch schedule of power plants. Moreover, though the impact of different wind speed profile and cost coefficients corresponding to overestimation and

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underestimation of available wind power is presented in [29], the reactive power capability of the wind farms, transmission line thermal loading limits and bus voltage constraints are not included in the study.

This paper solves an optimal power flow (OPF) problem of wind–thermal of power system for network operating conditions similar to those reported in [42–45] with the wind speed profile characterized by Weibull probability function [46]. In [42] the OPF model, which accounts for the additional costs of managing wind intermittency, is based on probability/relative frequency histograms of forecasting error. However, the study in [42] considers induction generator based wind farm and hence the reactive power capability of variable speed wind turbine is not included in OPF formulation. The reactive power supply capability of variable speed wind turbines e.g. doubly fed induction generator (DFIG) [47] has been utilized for bus voltage improvement in [43–45] with other operating conditions assumed same as given in [42]. In [43,45] wind–thermal optimal power flow (WTOPF) problem is implemented on IEEE 30 bus test system by applying Bacterial Foraging and Modified Bacteria Foraging algorithms respectively. While authors of [44] have implemented wind–thermal OPF on IEEE 39 bus test system by applying self adaptive evolutionary programming technique. Although the work in [42–45] which is based on cost model suggested in [29] appears to be more practical, none of these papers compares the results with published literature to validate the performance of different techniques employed. Moreover, the effect of change in wind speed profile and wind power cost coefficients on optimal dispatch schedule of power plants is not examined in [42–45]. The proposed work assumes that the power network is integrated with wind a farm which consists of variable speed wind turbines capable of supplying reactive power to grid.

The unique contributions of this work are given:

- The conventional OPF problem is implemented for standard IEEE 30 bus test system by GABC algorithm.
- The OPF formulation considering stochastic wind power, reactive power capability of wind turbines and emission constraint is developed and implemented by GABC algorithm.
- The OPF framework developed for wind–thermal system is analyzed considering $N - 1$ contingency criteria.
- The effect of different wind speed profiles, wind power cost coefficients and emission constraint on optimal dispatch is examined for OPF framework developed for wind–thermal system.

The simulation results obtained for conventional OPF problem as well as OPF incorporating stochastic wind power are compared with other methods available in literature.

The rest of the paper is organized as follows. Section 'OPF problem formulation' gives the mathematical formulation of the OPF problem considering wind power; Section 'Optimization algorithms' provides overview of Gbest guided artificial bee colony algorithm and its implementation for wind thermal optimal power flow; Section 'Numerical results and discussion' contains simulation results and discussion of different test cases and scenarios. Conclusions are summarized in Section 'Conclusion'.

OPF problem formulation

The primary objective of OPF is to optimize the settings of control variables to meet certain objectives while satisfying set of equality and inequality constraints. In general, the OPF problem can be mathematically expressed as follows:

$$\mathit{Minimize}\ f(x,u) \tag{1}$$

subject to,

$$g(x,u) = 0 \tag{2}$$

$$h(x,u) \leqslant 0 \tag{3}$$

where f is the objective function to be minimized, g is set of equality constraints representing nodal power injections, and h is set of inequality constraints. The vector u consists of independent variables or control variables and vector x consists of dependent variables or state variables.

Control variables

The control variables, u of wind–thermal OPF problem are set of variables which are determined by optimization algorithm. These variables are listed below and defined in Eq. (4).

(i) p_G, real power generation of thermal units at PV buses except slack bus (ii) w, real power generation of wind farms (iii) T, tap settings of transformer (iv) Q_C, shunt VAR compensation.

$$u^T = [p_{G_2} \ldots p_{G_{NG}}, w_1 \ldots w_{NW}, V_{G_1} \ldots V_{G_{NG}}, Q_{C_1} \ldots Q_{C_{NC}}, T_1 \ldots T_{NT}] \tag{4}$$

where NG, NW, NC and NT are the number of thermal units, the number of wind farms, number of VAR compensators and the number of regulating transformers, respectively.

State variables

These are the set of variables describing the mathematical state of system. The set of state variables for the OPF problem formulation are given below and defined in Eq. (5).

(i) p_{G_1}, slack bus real power (ii) V_L, load (PQ) bus voltage magnitude (iii) Q_G, generator reactive (iv) Q_w, wind farm reactive power (v) S_l, transmission line loading (in MVA)

$$x^T = [p_{G_1}, V_{L_1} \ldots V_{L_{NL}}, Q_{G_1} \ldots Q_{G_{NG}}, Q_{w_1} \ldots Q_{w_{Nw}}, S_{l_1} \ldots S_{l_{nl}}] \tag{5}$$

where NL, and nl indicates number of load buses, and number of transmission lines, respectively.

Technical constraints

The wind thermal optimal power flow problem which minimizes the objective function given by Eq. (1) should satisfy set of equality and inequality constraints described in the following sections:

Equality constraints

The equality constraints are typically defined by active and reactive power balance equations at each load as given in Eq. (6).

$$\left.\begin{aligned} \sum P_k &= 0 \\ \sum Q_k &= 0 \end{aligned}\right\} \text{at each node}, k \,(\text{net power injections}) \tag{6}$$

where P_k and Q_k are net active and reactive power injections at kth node.

Inequality constraints

These constraints consists of active and reactive power outputs of thermal units, active power outputs of wind farms, voltage at generator and load buses, transformer taps, shunt injections, reactive power output limits of wind farms and transmission line loading limits as defined in Eqs. (7)–(14),