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Optimal power flow with environmental constraint using a fast successive linear programming algorithm: Application to the algerian power system

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ABSTRACT

Harmful ecological effects caused by the emission of gaseous pollutants like sulfur dioxide (SO_2) and nitrogen oxides (NO_x), can be reduced by load adequate distribution between power plants. However, this leads to a noticeable increase in their operating cost. In order to eliminate this conflict, and to study the trade-off relation between fuel cost and emissions, an approach to solve this multiobjective environmental/economic load dispatch problem, based on an efficient successive linear programming technique is proposed. Simulation results on the Algerian 59-bus power system prove the efficiency of this method thus confirming its capacity to solve the environmental/economic power dispatch problem.

1. Introduction

The economic load dispatch (ELD) problem is to determine the optimal combination of power outputs of all thermal generating units which minimizes the total fuel cost while satisfying load demand and operational constraints [1]. However, due to strict governmental regulations on environmental protection, the conventional operation at absolute minimum fuel cost can not be the only basis for dispatching electric power. Therefore, it is mandatory for electric utilities to reduce pollution from power plants either by design or by operational strategies. The most important emissions considered in the power generation industry due to their effects on the environment are sulfur dioxide (SO_2) and nitrogen oxides (NO_x). The emission of these pollutants affects not only human beings, but harms other life forms as well causing damage to materials and global warming.

Many researchers have studied the environmental/economic dispatch (EED) problem by considering the emission in the objective function or treating them as additional constraints [2–5]. Traditionally, different solution approaches have been developed to solve the EED problem. These methods are nonlinear programming techniques with very high accuracy, but their execution time is very long and they can not be applied to real-time power system operations.

Since the introduction of the sequential or successive programming techniques, it has become widely accepted that successive linear programming (SLP) algorithms can be effectively used to solve nonlinear optimization problems [6]. In SLP, the original problem is solved by successively approximating the original problem using Taylor series expansion at the current operating point and then moving in an optimal direction until the solution converges.

In this paper, a method based on an efficient successive linear programming technique is presented and tested on the Algerian 59-bus power system. Simulation results confirm the advantage of computation rapidity and solution accuracy of the proposed method. These results show great promise for on-line application.

2. Problem statement

The goal is to minimize two conflicting objectives, which are the fuel cost and pollutants emission, while satisfying operating and loading constraints. Generally the problem is formulated as follows:

2.1. Problem objectives

2.1.1. Minimization of fuel cost

The generators cost curves are represented by quadratic functions [1]. The total \$/h fuel cost $F(P_g)$ can be expressed as:

$$F(P_g) = \sum_{i=1}^{ng} a_i + b_i P_{gi} + c_i P_{gi}^2 \tag{1}$$

2.1.2. Minimization of emission

The atmospheric pollutants caused by fossil-fueled thermal units can be modeled separately. However, in this work, only

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Nomenclature

P_g active power generation vector
$F(P_g)$ total fuel cost function
$E(P_g)$ total emission function
$F_t(P_g)$ total objective function
y set of state and control variables
$g(y)$ set of equality constraints
$h(y)$ set of inequality constraints
n number of buses
ng number of thermal units
nl number of load buses
a_i, b_i, c_i cost coefficients of generator i
α_i, β_i, γ_i, ω_i, μ_i emission coefficients of generator i
h weighting factor
λ price associated with gaseous pollutants
P_i, Q_i injected active and reactive powers at bus i
P_{gi}, Q_{gi} active and reactive power generations at unit i
P_{di}, Q_{di} active and reactive power demands at bus i
V_i, θ_i bus voltage magnitude and angle at bus i
B' susceptance matrix
G_{ij}, conductance of ijth element in the bus admittance matrix
B_{ij} susceptance of ijth element in the bus admittance matrix
$P_{gi\ min}$, $P_{gi\ max}$ lower and upper active power generation limits at bus i
$Q_{gi\ min}$, $Q_{gi\ max}$ lower and upper reactive power generation limits at bus i
$V_{i\ min}$, $V_{i\ max}$ lower and upper voltage magnitudes at bus i
P_{ij} transmission line active loading of line i–j
$P_{ij\ max}$ upper limit of transmission line active loading of line i–j
$\left[P_g^{(k)}\right]$ active power generation vector at iteration k
$[V^{(k)}]$ voltage magnitude vector at iteration k
$[\theta^{(k)}]$ voltage angle vector at iteration k
$[P_d]$ active power demand vector
$[P^{(k)}]$ injected power vector at iteration k
ΔF_t incremental change of total objective function
$[\Delta P_g]$ incremental changes vector of active power generations
$[\Delta\theta]$ incremental changes vector of bus voltage angles
$[\Delta V]$ incremental changes vector of bus voltage magnitudes
$[P_B]$ vector of transmission line active loadings
$\left[P_B^{(k)}\right]$ vector of transmission line active loadings at iteration k
$\left[J_h^{(k)}\right]$ Jacobian matrix of $F_t(x)$ at iteration k.
$\left[J_{h\theta}^{(k)}\right]$ Jacobian submatrix of $h(y)$ with respect to θ at iteration k
$\left[J_{hv}^{(k)}\right]$ Jacobian submatrix of $h(y)$ with respect to V at iteration k
$\left[J_{h\theta.mi}^{(k)}\right]$ mith element in the Jacobian submatrix $\left[J_{h\theta}^{(k)}\right]$

NO_x emission reduction is considered, since it is more harmful than other pollutants. The total ton/h emission $E(P_g)$ of these pollutants can be expressed as [4]:

$$E(P_g) = \sum_{i=1}^{ng} 10^{-2}(\alpha_i + \beta_i P_{gi} + \gamma_i P_{gi}^2) + \omega_i \exp(\mu_i P_{gi}) \quad (2)$$

2.1.3. Total objective function

Economic objective and emission objective are combined with different weightings in a single function. For a specified demand a trade-off curve may then be obtained. The total objective function F_t is then described by:

$$F_t(P_g) = hF(P_g) + (1-h)\lambda E(P_g) \quad (3)$$

where h is the weighting factor that can be varied between 0 and 1. λ is the price associated with gaseous pollutants.

The values of h indicate the relative significance between the two objectives. By varying the value of h, the trade-off between the fuel cost and the environmental degradation cost can be determined over the range of h. If $h = 1.0$, the solution is that of minimum cost, and if $h = 0.0$ the solution is minimum emissions.

The price associated with pollutants represents the degree of harmfulness of the emission type. Assigning a price to emissions depends on its biological and ecological effects. In this paper only one type of emissions is considered (NO_x) with a relative price of 1 [3].

2.2. Objective constraints

Power balance constraints: The total power generation must cover the total power demand and the power loss. This implies solving the power flow problem, which has equality constraints on active and reactive power at each bus as follows [7]:

$$P_i = P_{gi} - P_{di} = \sum_{j=1}^{n} V_i V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij})$$
$$Q_i = Q_{gi} - Q_{di} = \sum_{j=1}^{n} V_i V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \quad (4)$$

where $i = 1, 2, \ldots, n$ and $\theta_{ij} = \theta_i - \theta_j$.

Generation capacity constraints: For stable operation, real and reactive power output of each generator is restricted by lower and upper limits as follows:

$$\begin{matrix} P_{gi\,min} \leqslant P_{gi} \leqslant P_{gi\,max} \\ Q_{gi\,min} \leqslant Q_{gi} \leqslant Q_{gi\,max} \end{matrix} \quad , i = 1, 2, \ldots, ng \quad (5)$$

Security constraints: For secure operation, transmission line active loading P_{ij} is restricted by its upper limit. Load buses voltage magnitude is also limited between lower and upper limits:

$$|P_{ij}| \leqslant P_{ij\,max} \quad (6)$$
$$V_{i\,min} \leqslant V_i \leqslant V_{i\,max}, \quad i = 1, 2, \ldots, nl \quad (7)$$

The transmission line active loading P_{ij} is given by [8]:

$$P_{ij} = -G_{ij}V_i^2 + G_{ij}V_iV_j\cos(\theta_i - \theta_j) + B_{ij}V_iV_j\sin(\theta_i - \theta_j) \quad (8)$$

2.3. Problem formulation

Aggregating the objectives and constraints, the EED problem can be mathematically formulated as a nonlinear constrained optimization problem as follows [4]:

$$\text{Minimize} \quad F_t(P_g) \quad (9)$$
$$\text{Subject to:} \quad g(y) = 0 \quad (10)$$
$$h(y) \leqslant 0 \quad (11)$$