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An emission-constrained approach to power system expansion planning

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ABSTRACT

In view of recent regulations concerning emission reduction, electric utility industries have been required to reduce, monitor and control emissions from fossil fuelled generating units. This paper presents a method of power system expansion planning based on sensitivity analysis, considering the constraints of CO_2 emissions. The method presented here uses a linearised power flow representation in the form of a linear programming (LP) model similar to those frequently used in power system studies to minimise the total operation cost and is applied to both generation and transmission expansion planning. The cost of the fuel, the cost/benefit of purchasing/selling emission allowances are combined to develop a piecewise linear objective function. This objective function is used to calculate the sensitivity of the operation cost with respect to emission limits. This work also utilises the concept of shadow price to perform sensitivity analysis of the objective function value with respect to the operation constraints to identify the most cost effective generation and transmission expansion plan. The dual solution of the LP provides the shadow prices that are used for determining the sensitivity of the minimum cost with respect to power generation. Also, an explicit development of linearised power flow is provided. The method is demonstrated on the IEEE Reliability Test System (IEEE-RTS).

Introduction

Due to global warming and climate change, several acts, protocols and regulations have been introduced to reduce emissions. These acts and protocols limit the amount of the Carbon Oxides (CO_x), Sulfur Oxides (SO_x) and Nitrogen Oxides (NO_x), impose emission reduction laws and allow emission allowances trading (the action of buying or selling the authorised amount of a pollutant on the open market). For instance, one of the main outcomes of these acts and protocols is emission trading in the free market. This trading makes the exchange of emission allowances more flexible and minimises the overall operational costs [1].

In view of these acts and protocols, there is an evolving body of research on minimum cost and minimum emission methods that are cognisant of these emerging factors. Several emission reduction auctions have been taking place. For instance, the first auction and trading on greenhouse emission allowances of California was on November 14, 2012 [2]. More than 8% reduction in greenhouse gas emissions between 2008 and 2012 was achieved in the European Union Emissions Trading System and it is expected to reduce greenhouse gas emissions below 20% of the 1990 levels by 2020, starting from 2013 [3].

While electric utility industries have been focusing on the potential use of the clean energy sources such as wind and solar, in most industrialised countries the bulk of electric generation comes from fossil fuelled power plants. According to the Environmental Protection Agency (EPA), in 2012, the CO_2 emissions from combustion of fossil fuels account for about 38% of total CO_2 emissions in the U.S.A. [4]. In the UE-27 (the European Union (EU) of 27 Member States from January 1, 2007–June 30, 2013), 40% of energy resources are used in generating electricity [5]. In 2008, 601.32 GW was generated from coal in China which is about 75.87% of the total electric energy generated [6].

Several methods have been proposed to reduce emissions from power generating units such as installing post-combustion cleaning equipment and carbon capturing [7,8], switching to fuels with lower emissions [9], increasing the penetration of the renewable energy [10,11], and modifying existing dispatch strategies to include emissions.

A considerable amount of research has been conducted on economic-emission dispatching strategies. Solving economic-emission load dispatch with line capacity constraints was proposed in [12]. Subsequently, considerable research were reported on variations and extensions of these methods [13–20]. These variations use different means of accommodating emissions within the optimisation problem. Considering the effect of emission constraints on the reliability of composite power systems were introduced in [21,22]. A considerable amount of research has focused on evolutionary

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Nomenclature

HR_i	heat rate of the generating unit i
$k_i,\ \ell_i,\ m_i$	coefficients of the heat rate of unit i
$P_i(t)$	real output power of the generating unit i at time t
$Ea_i,\ Eb_i,\ Ec_i$	coefficients of CO_2 emission rates of unit i
$a_i,\ b_i,\ c_i$	CO_2 emission-cost coefficients of generating unit i
$A_i,\ B_i,\ C_i$	fuel-cost coefficients of generating unit i
$\alpha_i,\ \beta_i,\ \gamma_i$	coefficients of the combined cost function of generating unit i
$P_k,\ Q_k$	real and reactive power injected at bus k
V_k	voltage magnitude at bus k
G_{km}	conductance between buses k and m
B_{km}	susceptance between buses k and m
δ_{km}	angle difference between voltages of buses k and m
N_g	number of generators
N_a	number of buses
N_t	number of transmission lines
B, G	susceptance and conductance sub matrices of $Y_{bus},\ (N_a \times N_a)$
b_{kk}	total susceptances of the shunt elements connected at bus k
g_{kk}	total conductances of the shunt elements connected at bus k
δ	vector of bus voltage angles, $(N_a \times 1)$
V	vector of bus voltage magnitudes, $(N_a \times 1)$
$P_G,\ Q_G$	vectors of real and reactive power of generation, $(N_g \times 1)$
$P_D,\ Q_D$	vectors of real and reactive power load, $(N_a \times 1)$
$P_{loss},\ Q_{loss}$	vectors of real and reactive power losses, $(N_g \times 1)$
P_G^{max}	vector of maximum available real power generation, $(N_g \times 1)$
P_G^{min}	vector of minimum available real power generation, $(N_g \times 1)$
Q_G^{max}	vector of maximum available reactive power generation, $(N_a \times 1)$
Q_G^{min}	vector of minimum available reactive power generation, $(N_a \times 1)$
V^{max}	vector of maximum allowable voltages, $(N_a \times 1)$
V^{min}	vector of minimum allowable voltages, $(N_a \times 1)$
b	a diagonal matrix of the transmission line admittances, $(N_t \times N_t)$
$F_f^{max},\ F_r^{max}$	vectors of forward and reverse flow capacities of the lines, $(N_t \times 1)$
A	element-node incidence matrix, $(N_t \times N_a)$
ECO_{2j}	total emission of CO_2 in tonne/t at the power plant j
ECO_{2j}^{max}	cap on the CO_2 emission at the power plant j
OC	operation cost
C_i	the capacity of component i
$F(x)$	total generation cost when the system is at state x
X	set of all possible states
E_i	emission from generating unit i
$B',\ G'$	susceptance and conductance sub matrices of Y_{bus} without including the susceptances and conductances of the lines, $(N_a \times N_a)$
$\partial F(x)/\partial C_i$	shadow price of the objective function with respect to the capacity limits of the generating unit i, (π_{pgi})
$\partial F(x)/\partial E_i$	shadow price of the objective function with respect to the emission limits of the generating units i, (π_{Ei})

techniques and multi-objective minimisation functions to minimise emissions and generation costs in generation expansion planning [14–17,23]. Some of the proposed formulations also take into account the different emission reduction methods described above, and thereby provide for strategies that may allow utilities to forgo, defer, or minimise additional capital costs. For example, [24] shows how a utility may avoid installation of new emission equipment by changing its commitment and dispatch schedules, or by switching to fuels with low emission (and high cost), or both. Planning decisions may comprise a trade-off between the cost of buying extra emission allowances or switching to fuels with low emission (and high cost), or both. Therefore, there is an emerging need to include emission considerations in operation and planning procedures. The work reported in [25] introduced a hybrid generation and transmission expansion planning method that considers the emission and reliability of power systems.

The work reported in this paper responds to the need of reducing emissions from power generating units including emission caps in the power system expansion planning. This paper proposes a method based on combining the economic-emission dispatch considering emission constraints and the cost of emission caps to perform sensitivity analysis that can be used in both planning and operation studies. The results of the sensitivity analysis can be used to determine marginal prices of the addition of new components. This work uses the shadow price concept to determine the sensitivity of the combined cost function with respect to the operation limits. Two sensitivity indices are proposed to provide a measure for the change of the objective function value with respect to the operation and emission limits. The uncertainty of the emission prices is also accommodated in performing the sensitivity analyses. Also, this paper uses a linearised load flow model that closely depicts the properties of the full AC load flow without iterations which was developed by the authors. This load flow model is incorporated with the linear programming optimisation problem to find the minimum operating cost. In addition to power balance and flow constraints normally used, this work introduces a suitably formulated set of emission constraints to initiate the action of selling or buying emission allowances. If the emission limit is reached, the planner should choose between buying emission allowances and investing in another power station that has available emission allowances. The proposed method is intended to identify the most suitable options to minimise the total operating cost. The method is applicable to any source that produces undesirable by-products that are capped by regulatory and other policies, as long as these by-products are a function of the output power. Also, this method can be extended to accommodate other limits such as limits on fuel sources which has been introduced in [25].

The remainder of this paper is organised as follows: Section "Modelling of fuel cost and emission functions" shows the modelling of the fuel cost and emission functions, Section "Network modelling – linearised load flow" presents the modelling of the power grid, Section "Minimum operating cost" presents the formulation of the optimisation problem, Section "Uncertainties in the emission prices" explains the inclusion of the uncertainties in the emission prices, Section "Sensitivity analysis and the concept of the shadow price" shows the sensitivity analysis of the cost function with respect to the emission allowances, Section "Case studies" presents case studies and Section "Conclusion" provides concluding remarks.

Modelling of fuel cost and emission functions

This section presents a method to combine the fuel cost and the emission cost-benefit functions and to linearise this combined function by a series of linear segments with different slopes for use in the