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Optimal power flow solutions incorporating stochastic wind and solar power

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ABSTRACT

Generations from several sources in an electrical network are to be optimally scheduled for economical and efficient operation of the network. Optimal power flow problem is formulated with all relevant system parameters including generator outputs and solved subsequently to obtain the optimal settings. The network may consist of conventional fossil fuel generators as well as renewable sources like wind power generators and solar photovoltaic. Classical optimal power flow itself is a highly non-linear complex problem with non-linear constraints. Incorporating intermittent nature of solar and wind energy escalates the complexity of the problem. This paper proposes an approach to solve optimal power flow combining stochastic wind and solar power with conventional thermal power generators in the system. Weibull and lognormal probability distribution functions are used for forecasting wind and solar photovoltaic power output respectively. The objective function considers reserve cost for overestimation and penalty cost for underestimation of intermittent renewable sources. Besides, emission factor is also included in objectives of selected case studies. Success history based adaptation technique of differential evolution algorithm is adopted for the optimization problem. To handle various constraints in the problem, superiority of feasible solutions constraint handling technique is integrated with success history based adaptive differential evolution algorithm. The algorithm thus combined and constructed gives optimum results satisfying all network constraints.

1. Introduction

Optimal power flow (OPF) remains a widely-cultivated topic within power system research community since its inception about half-a-century ago. The prime objective of OPF is minimization of generation cost with optimal settings of control variables which are the generated real power and generator bus voltages of the network. While optimizing the generation cost, system constraints on generator capability, line capacity, bus voltage and power flow balance are to be satisfied. Scheduled generator power, complex power flow in the lines and voltage vector of buses determined during the process of optimization represent the optimal operating state of the system. Classical OPF problem considers thermal power generators run on fossil fuels. With increasing penetration of wind power and solar PV in the network, the study of OPF becomes necessary incorporating uncertainties of these renewable sources.

OPF with only thermal power generators has extensively been studied by researchers across the globe. A recent literature described application of state-of-the-art evolutionary algorithm (EA) is differential search algorithm (DSA) [1] where a few standard objectives in OPF are optimized for IEEE bus systems with thermal generators. Standard group search optimization algorithm is improved with adaptive group search optimization (AGSO) [2] to perform similar study on OPF. Ref. [3] performs OPF calculation with more complex objectives of multi-fuel options and considers valve-point effect in thermal generators in applying backtracking search optimization algorithm (BSA). Improved colliding bodies optimization (ICBO) algorithm is proposed in [4] where number of colliding bodies are increased in each iteration to enhance performance of the algorithm when applied to the problem of OPF. A most recent literature [5] applied moth swarm algorithm (MSA) on numerous objectives of OPF for various bus systems to show effectiveness of the algorithm in terms of fast execution time and quick convergence. While abovementioned references deal with conventional generators only, a system consisting of thermal and wind power generators has recently been studied in pursuit of minimum generation cost in a few literatures. Gbest guided

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Nomenclature

Abbreviations
OPF optimal power flow
SHADE success history based adaptive differential evolution
SF superiority of feasible solutions
TG thermal power generator
WG wind generator
PV photovoltaic
ISO independent system operator
PDF probability density function

Symbol
P_{TGi} power output of i -th thermal generator
$P_{ws,j}$ scheduled power from j -th wind power plant
$P_{ss,k}$ scheduled power from k -th solar PV plant
$P_{wav,j}$ actual available power from j -th wind power plant
$P_{sav,k}$ actual available power from k -th solar PV plant
g_j direct cost coefficient for j -th wind power plant
h_k direct cost coefficient for k -th solar PV plant
$K_{Rw,j}$ reserve cost coefficient for over-estimation of wind power from j -th plant
$K_{Pw,j}$ penalty cost coefficient for under-estimation of wind power from j -th plant
$K_{Rs,k}$ reserve cost coefficient for over-estimation of solar power from k -th plant
$K_{Ps,k}$ penalty cost coefficient for under-estimation of solar power from k -th plant
C_{tax} carbon tax in $/tonne
G solar irradiance in W/m^2
$f_v(v)$ probability of wind speed v m/s
$f_G(G)$ probability of solar irradiance G W/m^2
p_{wr} rated output power of a wind turbine
P_{sr} rated output power of the solar PV plant
c, k Weibull PDF scale and shape parameters respectively
μ, σ lognormal PDF mean and standard deviation respectively
P_{loss} real power loss in the network
VD cumulative voltage deviation in the network

artificial bee colony (GABC) is applied in [6] to improve OPF results recorded in past literatures with similar experimental set up. Ref. [7] proposed modified bacteria foraging algorithm (MBFA) and introduced doubly fed induction generator (DFIG) model in OPF framework to define limits on reactive power generation capability. Additional reactive power supporting devices, static synchronous compensator (STATCOM) is incorporated in [8] for system with wind and thermal power generators and the OPF problem is solved using ant colony optimization (ACO) and also MBFA. Authors in [9] proposed a paradigm for modelling the cost of wind-generated electricity. The problem on scheduling of generators for economic dispatch is more commonplace for system with thermal power and wind generators. In an OPF dispatching program, Ref. [10] presented a stochastic model of wind generation. In attempting the same problem, authors in [11] included DFIG model of wind turbine. Literature [12] proposed dynamic economic dispatch (DED) model with penetration of large scale wind power considering risk reserve constraints. Ref. [13] incorporated emission, valve-point loading effect of generator in DED problem. OPF management for an isolated hybrid system with solar PV, diesel generator and battery is presented in [14]. Pumped hydro storage is introduced in [15] as an alternate form of storage for a similar standalone hybrid system consisting of a solar PV, a wind turbine and a diesel generator. Integration of wind and solar PV power into the grid is studied in a few literatures. However, these literatures focus primarily on real-time scheduling of generators for economical operation considering various pricing strategies between the utility operator and the independent system operator (ISO). Economic dispatch being main objective, Ref. [16] considered minute-to-minute variation of renewable energy sources. Hybrid system in [17] included diesel generator with optimization platform being basic MATLAB functions. In economic dispatch (ED) problem, system constraints especially limitations on network parameters may have often been ignored; however, complying with network constraints is a must in OPF. Literature [18] mentioned of system constraints, but details on satisfying those constraints have not explicitly been addressed. Furthermore, voltage profile throughout the network, emission aspects are generally not addressed in ED problem, but in OPF problem. In summary, optimal power flow in a network consisting of thermal, wind power generators and solar PV needs further attention. The present study is dedicated to optimal power flow problem with detailed uncertainty modelling of wind and solar power.

The biggest challenge in incorporating wind and solar PV power in grid integration is their intermittent nature. Normally wind or solar PV farms are owned by private operators. Grid/independent system operator (ISO) signs an agreement of purchasing scheduled power from these private operators. But as generations from these renewable sources are uncertain, sometimes the power output may be more than the scheduled power leading to underestimation of the available amount. ISO is to bear the penalty cost as surplus power goes wasted if not utilized. On contrary, overestimation is the scenario when the generated power is less than the scheduled power. To mitigate power demand, ISO needs to keep spinning reserve which adds up to the operating cost of the system. The objective function formulated in this paper considers direct cost, penalty and reserve cost of renewable sources in addition to generation cost of thermal power units. Wind distribution is modelled using Weibull probability density function (PDF), solar irradiance is modelled with lognormal PDF. IEEE-30 bus system is modified to accommodate wind generators and solar PV with reactive power capabilities. Generation cost is optimized and effect of change in reserve and penalty costs on optimal scheduling is studied. On the aspect of emission, fossil fuel driven thermal generators emit harmful gases into the environment, while renewable sources do not. Carbon tax [19] is imposed in some countries in proportion to the emitted greenhouse gases. In selected case studies, carbon tax amount is entwined with the objective function to study the effect on generator scheduling.

Success history based parameter adaptation technique of differential evolution (SHADE) is employed for the optimization problem. SHADE, an advanced variant of differential evolution (DE), uses a historical memory of successful control parameter settings to guide the selection of future control parameter values [20]. This ensures accurate and fast convergence to the global optima of a constrained, multimodal, non-linear optimization problem. SHADE is combined with an effective constraint handling technique called superiority of feasible solutions (SF) [21]. In almost all the literatures of OPF, penalty function approach is adopted to check violation of constraints. This approach is sensitive to selection of penalty coefficient. Small penalty coefficient over-explores the infeasible region, delaying the process of finding feasible solutions,