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A probabilistic multi-objective approach for power flow optimization in hybrid wind-PV-PEV systems

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HIGHLIGHTS

- Suggest a novel probabilistic optimal power flow (POPF).
- Study the uncertainties of plug-in electric vehicles, photovoltaic and wind energy.
- Consider load uncertainty by a Monte Carlo Simulation-Antithetic Variates method.
- Propose a parallel epsilon variable multi objective genetic algorithm (eV-MOGA)
- Present Message Passing Interface (MPI) to parallel the eV-MOGA.

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ABSTRACT

This paper formulates and solves a probabilistic optimal power flow approach (POPF) for a hybrid power system that includes plug-in electric vehicles (PEV), photovoltaic (PV) and wind energy (WE) sources. In the proposed approach, the Monte Carlo Simulation (MCS) was combined with the antithetic variates method (AVM) to determine the probability distribution function (PDF) of the power generated by the hybrid system. To reduce the computational cost of the optimal power flow calculations, we solved the POPF problem using a master–slave parallel epsilon variable multi objective genetic algorithm (Pev-MOGA). The performance of the proposed approach was assessed using the IEEE 30-bus, 57-bus and 118-bus power systems. Various scenarios incorporating several configurations of WEs, PVs and PEVs sources were considered in the evaluation. Sensitivity analysis was also performed for further assessment. The obtained results along with a comparison analysis with other optimization algorithms confirmed the effectiveness of the proposed approach in accurately providing a set of optimal solutions for the hybrid power system.

1. Introduction

In recent years, we have witnessed an increase in the penetration of renewable energy sources such as wind and photovoltaic systems into the grid [1–2]. However, though renewable energy sources have advantages such as reducing pollution and conserving resources, the resulting increase in load uncertainties and subsequent fluctuations in power production has led to new challenges in power systems' operation and distribution. Proper management of those sources is key to their successful implementation to the grid and to a safe and profitable power market [1–5]. Hence, the stochastic nature of wind energy (WE) and photovoltaic (PV) units, along with the uncertainties associated with the plug-in electric vehicles (PEV) charge/discharge dynamics must be taken into consideration when integrating these intermittent energy sources to the grid.

Optimal Power Flow (OPF) is one of the main tools used to offer high quality electrical energy at a minimum cost. This multi-dimensional, large-scale, and nonlinear approach attains these objectives by optimizing the generation and transmission of electrical power without violating network power flow, system constraints or operating limits [6]. However, the added uncertainties to the power generation forecast resulting from the large integration of renewables, along with the increased size and complexity of the network have drastically complicated the task of solving the OPF problem. Further, solving the OPF requires the completion of many simulation runs to encompass for the majority of possible operating conditions, thus making it a computationally demanding and impractical task. Deterministic optimization methods OPF (DOPF) have traditionally been considered to solve the

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Nomenclature

$C_{d,i}$	direct cost of i^{th} WE, PV and PEV ($/h)
$C_{ue,i}$	underestimating penalty cost of i^{th} WE, PV and PEV ($/h)
$C_{oe,i}$	overestimating penalty cost of i^{th} WE, PV and PEV ($/h)
$COST_i$	total cost of i^{th} WE, PV and PEV ($/h)
$d_{w,i}$	direct cost coefficient of WE, PV and PEV ($/MW)
$K_{ue,i}$	underestimating coefficient cost of i^{th} WE, PV and PEV ($/MW)
$K_{oe,i}$	overestimating coefficients cost of i^{th} WE, PV and PEV ($/MW)
$P_{w,i}$	power of the i^{th} WE (MW)
$P_{pv,i}$	power of the i^{th} PV (MW)
$P_{pev,i}$	available power of the i^{th} PEV's fleet (MW)
$P_{w,r,i}$	rated power of the i^{th} WE (MW)
$P_{pv,r,i}$	rated power of the i^{th} PV (MW)
$P_{pev,r,i}$	rated power of the i^{th} PEV's fleet (MW)
n_w	number of WEs
n_v	number of PVs
n_p	number of PEV fleets

OPF problem and determine power systems' state of operation in terms of power, voltage, and current injected to the grid [7–8]. Intelligence-based approaches such as genetic algorithms (GA) [9], particle swarm optimization (PSO) [10], harmony search [11], and bacterial foraging algorithms [12] were considered in solving the D-OPF problem.

Probabilistic approaches can provide better solutions and acceptable accuracy in the presence of uncertainties [6–7,13]. Several probabilistic methods were proposed to solve the OPF problem in power systems with large number of WE and PV units. The two point estimation approach (2PEM), which is based on the method of moments, was considered in [14] to obtain the PDF of the output power of a PV system. However the method of moments typically generates estimates that are outside of the parameter space and that are not necessarily sufficient statistics, thus making the solution unreliable. In [15], the Cornish Fisher expansion was implemented to deal with the uncertainty from PV. However, this approach does not provide a good estimation for problems with complex structure and non-continuous return functions [16]. A POPF approach was proposed in [17] for a wind power system and its PDF was calculated using the heuristic approach. However, accurate calculation of the PDF requires access to real data. A POPF problem exploring the impacts of high dimensional dependences of wind speed on POPF was proposed in [18]. In that approach, the Kernel density estimate method was considered in estimating the probability distribution of the wind speed. However, the fact that the density estimate depends on the starting position of the bins, and the number of bins grows exponentially with the number of dimensions, make this approach unpractical. A Multi-objective mean-variance-skewness model for non-convex and stochastic OPF including wind power was considered in [19] based on the Latin hypercube sampling (LHS). However, this approach suffers from the loss of statistical independence of sample points and does not seem to be significantly superior to the random sampling for computational sensitivity analysis in practice. The Monte Carlo Simulation (MCS) and its variants [20–23] were used to find the probability of the density function (PDF) of the output power generated by a WE system. Self-adaptive evolutionary programming [22]; ninth-order polynomial normal transformation [23]; Taguchi's orthogonal array testing (TOAT) [6], biogeography-based optimization (BBO) algorithm [24] were adopted to solve the OPF problem. An Optimal power flow problem was formulated in [25] based on the MCS approach for a power system that incorporates WE and PV units.

PEVs are among the newest additions to the distribution network. They owe their deployment to their decreased operational cost and emissions [26]. However, the extreme uncertainties associated with their state of charge/discharge further complicates the power operation problem [27]. A POPF analysis of a combined PV and PEV system was proposed in [28] based on the MCS approach. The POPF problem was formulated in [29] for a power system integrating wind energy and electric vehicles. The optimal dispatch of aggregated PEVs have been solved in [30] by an improved PSO, which uses MCS to obtain the available vehicle to grid (V2G) power. The hourly coordination of aggregated PEVs operation in the security-constrained unit commitment (SCUC) with the wind power generator have been proposed in [31]. A fuzzy logic approach was considered in [32] to model the charge/discharge dynamics of PEVs, and the multi-objective OPF problem was solved using the improved black hole algorithm. However, Refs. [31–32] did not propose a mathematical formulation to model the uncertain behavior of PEVs. A discrete-event simulation model that emulates the interactions between the power grid and PEVs was proposed in [33]. The simulated annealing have been used to jointly handle generation, storage, and V2G in [34]. It is worth noting that real-world statistical transportation data was used in Refs. [33–34] to model the uncertain behavior of PEVs. However, collecting real data is a complicated task and acceptable models are required.

This paper formulates and solves the probabilistic optimal power flow approach (POPF) for a hybrid power system which includes plug-in electric vehicles (PEV), photovoltaic (PV) and wind energy (WE) sources. The main contributions of this paper are:

(1) Formulating and solving the POPF problem for a hybrid power system which integrates plug-in electric vehicles with wind and solar energy sources. Contrary to existing approaches [8,17,24,27,29–30,35–38] which only considered one or two of these sources for simplicity.
(2) Using an accurate model for the PEV which takes into consideration its state of charge (SOC), contrary to existing approaches [27,29–30] which only rely on a simplistic model of the electric vehicle.
(3) Combining the Monte Carlo Simulation (MSC) with the antithetic variates method (AVM) to accurately model load uncertainties, contrary to existing approaches [8,17,24,29], which omitted load uncertainties, thus leading to non-optimum solutions.
(4) Solving the multi-objective POPF problem using a master-slave parallel epsilon variable multi objective genetic algorithm (Pεv-MOGA), thus reducing the computational cost of the optimal power flow calculations.

The rest of the paper is organized as follows. Section 2 provides the respective models for the considered renewable energy sources. The optimization problem and the associated Monte Carlo Simulation are formulated in Section 3. The parallel epsilon variable-multi objective genetic algorithm is detailed in Section 4. Section 5 provides some computer simulation results pertaining to the implementation of the proposed optimization approach to the IEEE 30, 57 and 118-bus power systems along with a comparison analysis with other optimization algorithms. Some concluding remarks are finally given in Section 6.

2. Modeling of energy sources

In this paper, WE, PV and PEV have been considered as sources of energy in the power system. The associated cost of each of these sources consists of three terms. The first term accounts for the direct cost of the power generated by these sources. The existence and size of this term depends on the respective owner of each source. If the sources are