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A Simple and Reliable Algorithm for Computing Boundaries of Power Flow Solutions due to System Uncertainties

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***Abstract*–Power flow studies are typically used to determine the steady state or operating conditions of power systems for specified sets of load and generation values, and is one of the most intensely used tools in power engineering. When the input conditions are uncertain, numerous scenarios need to be analyzed to cover the required range of uncertainty, and hence reliable solution algorithms that incorporate the effect of data uncertainty into the power flow analysis are needed. To address this problem, this paper proposes a new solution methodology based on the use of optimization techniques and worst-case scenario analysis. The application of these techniques to the power flow problem with uncertainties is explained in detail, and several numerical results are presented and discussed, demonstrating the effectiveness of the proposed methodology**

***Index Terms*–Power flow analysis, reliable computing, uncertain systems.**

I. Introduction

A robust and reliable power flow analysis is an essential requirement of many Energy Management System (EMS) applications, such as network optimization, voltage control, state estimation and others [1], [2]. In this context, there is a wide variety of power flow solution algorithms that have been proposed in the literature (e.g. [1]-[5]). However, their application is often complicated by the presence of system uncertainties [6], which are due in particular to:

- the increasing number of smaller geographically dispersed generators [7];
- the increasing penetration of renewable power generation [8];
- and the difficulties arising from the prediction and modeling of competitive market behaviors, governed mainly by unpredictable economic dynamics [9].

Since these uncertainties could affect the power flow solutions to a considerable extent, more reliable solution algorithms that incorporate the effect of data uncertainties into the power flow analysis are therefore required [6], [10], [11].

Reliable power flow algorithms allow system operators to estimate both the data (uncertainty characterization) and the solution tolerance (uncertainty propagation assessment), thus allowing to evaluate the level of confidence of power flow studies. These algorithms should also effectively support sensitivity analyses aimed at estimating the rate of change in the power flow solution with respect to changes in input data, since this information is important for system analysts and operators to, for example, ensure efficient and secure grid operation, minimize losses, and coordinate protective relaying against contingencies.

Conventional methodologies proposed in the literature address reliable power flow analysis by means of detailed probabilistic methods [12], and sampling-based approaches [13], which account for the variability and stochastic nature of the input data. In particular, uncertainty propagation studies based on sampling-based methods, such as Monte Carlo's, require several model runs that sample various combinations of input values. Since the number of required model runs may be rather large, the needed computational resources for these types of studies could be prohibitively expensive.

Probabilistic methods are useful tools, especially for planning studies. However, as discussed in [10] and [11], these present various shortcomings due mainly to non-normal probability distributions and the statistical dependence of the input data, as well as the problems associated with accurately identifying probability distributions for some input data, as in the case for example of the power generated by wind or solar generators. These could lead to complex computations that may limit the use of these methods in practical applications, especially in the study of large networks.

In order to overcome some of the aforementioned limitations of sampling- and statistical-based methods, the application of self-validated computing, as defined in [14], for uncertainty representation in power flow studies has been proposed in the literature. The simplest and most popular of these models is Interval Mathematics (IM), which is basically a numerical computation technique where each quantity is represented by an interval of floating point numbers without the need to assume a probability structure [15]. The application of IM to power flow analysis has been investigated by various authors [9], [16], [17]. However, the adoption of

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this solution technique present many drawbacks derived mainly by the so called “dependency problem” of IM [14]. In particular, the use of the Interval Gauss elimination in the power flow solution process leads to realistic solution bounds only for certain special classes of matrices (e.g. M-matrices, H-matrices, diagonally dominant matrices, tridiagonal matrices) [18]. The problem of excessive conservatism in interval linear equation solving could be overcome by using Krawczyk’s method or the Interval Gauss Seidel iteration procedure; nevertheless, in these cases, the linearized power flow equations should be preconditioned by an M-matrix in order to guarantee convergence. These drawbacks make the application of IM to power flow studies rather complex and time consuming.

In this paper, simple, robust and computationally efficient methods for power flow analysis with uncertainties are proposed. Thus, it is first shown that the hull boundary of the power flow solutions can be reliably assessed by solving a set of non-linear optimization problems. As a result of this analysis, useful approximations of the solution bounds are proposed based on straightforward assessments of a set of optimization and deterministic power flow solutions. A comparison between the power flow solution bounds obtained by using a Monte Carlo based approach and the proposed methods for several IEEE benchmark systems is presented and discussed in order to assess the effectiveness of the proposed methodologies.

The rest of the paper is organized as follows: Section II review briefly the power flow problem and the sources of uncertainties. In Section III, an analysis of the solution boundaries of the power flow problem is presented, and reliable and simple method to estimate these boundaries are proposed. Section IV discusses the application and validation of the proposed methodologies for several IEEE bus benchmark system. Finally, the main conclusions and contributions of the paper are highlighted in Section V.

II. Problem Formulation

Power flow analysis deals mainly with the calculation of the steady-state voltage-phasor angles and magnitudes of the network buses, for a given set of parameters such as load demand and real power generation, and under certain assumptions such as balanced system operation. Based on these voltages, the network operating conditions, which are typically reflected in the real and reactive power flows on each branch, power losses and generator reactive power outputs, can be determined. Thus, the input (output) variables of the power flow problem are typically: the real and reactive power (voltage magnitude and angle) at each load bus (a.k.a. PQ buses); the real power generated and the voltage magnitude (reactive power generated and voltage angle) at each generator bus (a.k.a. PV buses); and the voltage magnitude and angle (the real and reactive power generated) at the slack bus.

A. *Power Flow Equations*

The basic equations typically used to solve the power flow problem are the real power balance equations at the PV and PQ buses, and the reactive power balance at the PQ buses. These equations can be written as:

$$\begin{aligned} P_i^{SP} &= V_i \sum_{k=1}^{N} V_j Y_{ik} \cos(\delta_i - \delta_k - \theta_{ik}) \quad i \in nP \\ Q_j^{SP} &= V_j \sum_{k=1}^{N} V_k Y_{jk} \sin(\delta_j - \delta_k - \theta_{jk}) \quad j \in nQ \end{aligned} \tag{1}$$

where:

N is the total bus number;

nQ is the set of the buses in which the reactive power is specified;

nP is the set of the buses in which the active power is specified;

P_i^{SP} and Q_j^{SP} are the real and reactive power injections specified at i-th and *j*-th bus;

$\vec{V}_i = V_i \angle \delta_i$ is the *i*-th bus voltage (in polar coordinates);

$\bar{Y}_{ik} = Y_{ik} \angle \theta_{ik}$ is the *ik*-th element of the bus admittance matrix.

Due to the nonlinear nature of the power flow equations (1), numerical methods are employed to obtain a solution that is within an acceptable tolerance. Furthermore, limits on variables such as the reactive powers at PV buses, are typically considered by computing these powers, which is trivial, and “switching” buses from PV to PQ and vice versa, depending on the values of the reactive powers or voltage magnitudes at these buses.

B. *Source of Uncertainty in Power Flow Analysis*

Uncertainties in power flow analysis stem from several sources both internal and external to the power system. Many uncertainties are the result of the complex dynamics of the generator and load active and reactive powers that can vary due to, for example, the:

- overall economic activities and population in the analyzed area (long term);
- weather conditions (short term);
- price of electricity in relation to prices of other goods as well as competing energy sources (short and medium term);
- technological improvements on the energy end-use (long term).

A further source of uncertainty derives from the increasing number of wind- and solar-power sources and smaller geographically-dispersed generators connected to the grid. The significant growth of the number of these generators would sensible affect power dispatch and transactions due to their unpredictability and increased control, protection and maintenance complexities. Furthermore, in the case of intermittent/nonprogrammable energy sources such as wind and solar, the power profiles may vary widely with the natural fluctuations of the energy sources associated with location and time, due to weather changes such as clouds and wind patterns, which may be hard to predict [19].

The difficulties arising from prediction and modelling of the electricity market behaviour, governed mainly by unpredictable economic dynamics, represent another relevant source of uncertainty in power flow analysis. Furthermore, uncertainties may be induced by model errors, due to the approximations in the values of the resistances, reactances and shunts in the models used to represent transmission lines and transformers [20]; these types of uncertainties are not as significant as those associated with input active and reactive power variations, and are hence not considered in the proposed methodology discussed next.

III. Proposed Solution Approach

Since data uncertainties could affect the deterministic power flow solution to a considerable extent, reliable solution algorithms that incorporate the effect of data uncertainties into the power flow analysis are therefore required. These algorithms should allow the analyst to reliably estimate the hull boundary of the power flow solutions. In this way, the uncertainty propagation effect is explicitly represented and the level of confidence of power flow studies can be assessed.

Power flow solution bounds can be computed rigorously by solving the following optimization problems:

$$\begin{aligned} &\max_{\delta_l P_i P_j Q_j}/\min \; V_k \quad \forall j\in n\widehat{L}, i\in n\widehat{G}, k\in nQ, l\in nP \\ &\text{s.t.} \quad g(p,V_k,\delta_l,P_i,P_j,Q_j)=0 \\ &\qquad P_{j\min}\le P_j\le P_{j\max} \\ &\qquad P_{i\min}\le P_i\le P_{i\max} \\ &\qquad Q_{j\min}\le Q_j\le Q_{j\max} \end{aligned} \tag{2}$$

$$\begin{aligned} &\max_{V_k P_i P_j Q_j}/\min \; \delta_l \quad \forall j\in n\widehat{L}, i\in n\widehat{G}, k\in nQ, l\in nP \\ &\text{s.t.} \quad g(p,V_k,\delta_l,P_i,P_j,Q_j)=0 \\ &\qquad P_{j\min}\le P_j\le P_{j\max} \\ &\qquad P_{i\min}\le P_i\le P_{i\max} \\ &\qquad Q_{j\min}\le Q_j\le Q_{j\max} \end{aligned} \tag{3}$$

where:

p is the vector of fixed power flow parameters such as the voltage magnitudes at the PV buses and the slack bus voltage angle;

$n\widehat{L}$ is the set of the PQ buses in which the specified active and reactive power are uncertain;

$n\widehat{G}$ is the set of the PV buses in which the specified active power is uncertain;

$g(\cdot)$ is a vector function representing the power flow equations (1);

V_k is the voltage magnitude at the k-th bus;

δ_k is the voltage angle at the k-th bus.

The solution of these ($nP + nQ$) nonlinear programming (NLP) problems is not trivial and hence could require intensive computational resources, especially for large-scale power networks.

In order to reduce the complexity of these computations, a simplified solution approach could be used by introducing reasonable assumptions justified by operational experience. In particular, since the lowest (highest) bus voltage magnitudes are expected when the power network is more (less) loaded, in (2) it is possible to fix the load demand to its maximum (minimum) value to obtain the minimum (maximum) voltage magnitudes. For the voltage angles, exactly the opposite applies. Consequently, the bus voltage magnitude/angle bounds can be estimated by solving the following optimization problems:

$$\begin{aligned} &\max_{\delta_l P_i P_j Q_j} \; V_k \quad \forall j\in n\widehat{L}, i\in n\widehat{G}, k\in nQ, l\in nP \\ &\text{s.t.} \quad g(p,V_k,\delta_l,P_i,P_j,Q_j)=0 \\ &\qquad P_j = P_{j\min} \\ &\qquad P_{i\min}\le P_i\le P_{i\max} \\ &\qquad Q_j = Q_{j\min} \end{aligned} \tag{4}$$

$$\begin{aligned} &\min_{V_k P_i P_j Q_j} \; \delta_l \quad \forall j\in n\widehat{L}, i\in n\widehat{G}, k\in nQ, l\in nP \\ &\text{s.t.} \quad g(p,V_k,\delta_l,P_i,P_j,Q_j)=0 \\ &\qquad P_j = P_{j\min} \\ &\qquad P_{i\min}\le P_i\le P_{i\max} \\ &\qquad Q_j = Q_{j\min} \end{aligned} \tag{5}$$

$$\begin{aligned} &\min_{\delta_l P_i P_j Q_j} \; V_k \quad \forall j\in n\widehat{L}, i\in n\widehat{G}, k\in nQ, l\in nP \\ &\text{s.t.} \quad g(p,V_k,\delta_l,P_i,P_j,Q_j)=0 \\ &\qquad P_j = P_{j\max} \\ &\qquad P_{i\min}\le P_i\le P_{i\max} \\ &\qquad Q_j = Q_{j\max} \end{aligned} \tag{6}$$

$$\begin{aligned} &\max_{V_k P_i P_j Q_j} \; \delta_l \quad \forall j\in n\widehat{L}, i\in n\widehat{G}, k\in nQ, l\in nP \\ &\text{s.t.} \quad g(p,V_k,\delta_l,P_i,P_j,Q_j)=0 \\ &\qquad P_j = P_{j\max} \\ &\qquad P_{i\min}\le P_i\le P_{i\max} \\ &\qquad Q_j = Q_{j\max} \end{aligned} \tag{7}$$

The solution of these optimization problems yield a reliable estimation of the power flow solutions bounds at a reduced computational cost compared to the rigorous approach (2)-(3). This is mainly due to the reduced number of optimization variables involved in (4)-(7). It should be mentioned that in the optimization problems (2)-(7), the effect of reactive power limits can be introduced by means of the optimization models discussed in detail in [21].

The problem can be even further simplified through a "worst case" analysis of the load/generation scenarios. Thus, based on the operational knowledge of powers systems, the idea is simply to obtain the solution to the following 4 power flow problems:

1. Minimum load and maximum generation.
2. Minimum load and minimum generation.

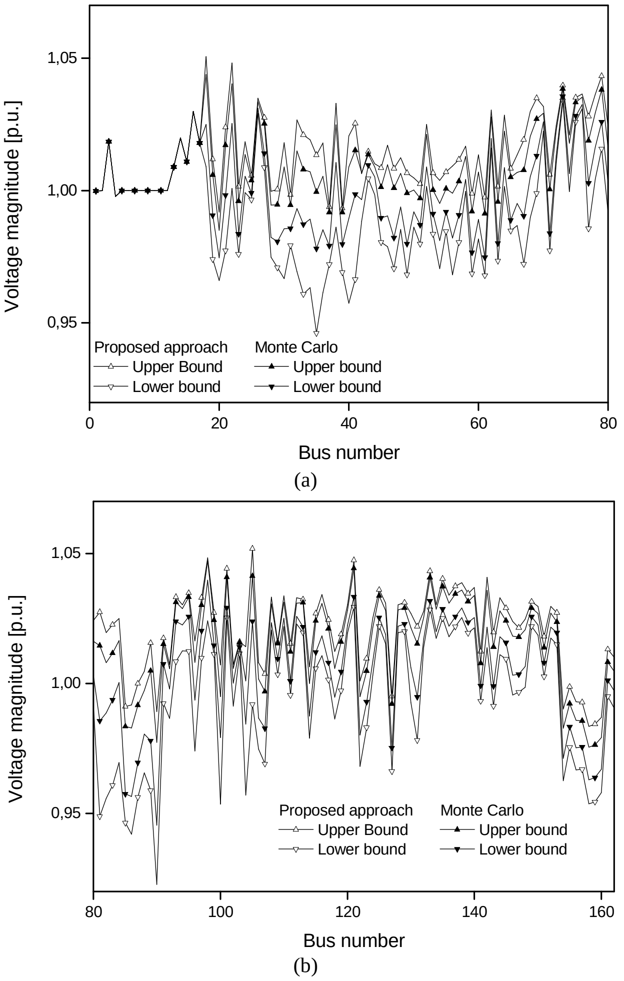

Fig. 1: Bus voltage magnitude bounds: (a) Buses 1-80; (b) Buses 81-162.

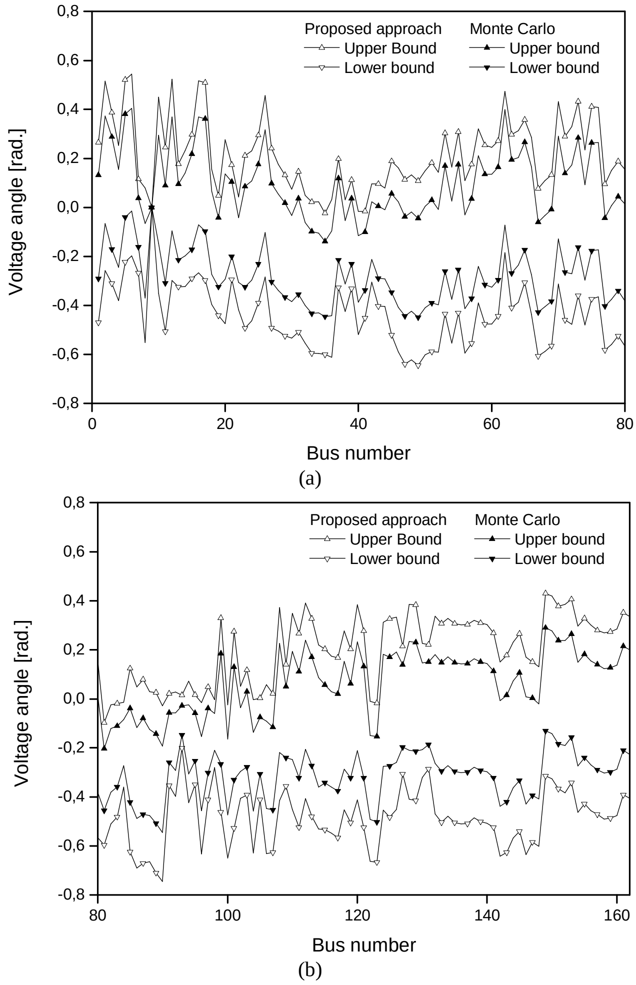

Fig. 2: Bus voltage angles bounds: (a) Buses 1-80; (b) Buses 81-162.

3. Maximum load and maximum generation.
4. Maximum load and minimum generation.

These deterministic power flow solutions can then combined to approximate the corresponding bounds. Although this method yields only a rough approximation of the hull boundary of the power flow solutions, it should be useful in practice, as demonstrated by the results obtained for realistic power networks in the next section.

IV. Simulation Results

This section first discusses the application of the proposed methodology to the power flow analysis with uncertainties of the IEEE 162-bus test system [22]. The power flow solution bounds obtained by the proposed technique are compared to those calculated using a Monte Carlo simulation with a uniform distribution, which is typically assumed to yield the "correct" solution intervals. For the latter, 5000 different values of the input variables within the assumed input bounds were randomly selected, and a conventional power flow solution was obtained for each one; this procedure yielded the desired interval solutions defined by the largest and the smallest values of the bus voltage magnitudes and angles. It should be noted that increasing the number of Monte Carlo simulations beyond 5000 did not yield any significant changes to the solution intervals.

Without loss of generality, a ± 10% tolerance on all load powers was assumed. For power generations, 5 generators were assumed to vary their input within a ± 10% tolerance. Observe that this defines an interval wide enough to properly evaluate the proposed method. With these load and generator power bounds that represent input data uncertainty, the optimization problems (4)-(7) were solved to estimate the bounds of the power flow solutions.

The voltage magnitude and angle bounds obtained with the proposed optimization approach are depicted in Figs. 1 and 2, respectively. Observe that the proposed methodology gives fairly good approximations of the power flow solution bounds when compared to the benchmark intervals obtained with the Monte Carlo approach. Notice also that the solution bounds are slightly conservative, which is due to the fact that the proposed technique yields "worst case" bounds. This is to be expected, since, as stated in [23], the random, uniformly distributed variation of parameters (with mean equal zero) assumed in the Monte Carlo approach tends to underestimate the worst case variations. This can be considered an advantage of the proposed approach, since no assumptions regarding the probability distribution of load and generator power variations are required.

The solution bounds obtained by applying the proposed optimization-based methodology were then compared to those obtained by solving the 4 worst-case power flows. The corresponding estimation errors obtained with this simple approach are less than 1%.

Further studies carried out by the authors on the IEEE 57- and IEEE 118-bus test systems confirm these results. From these studies, it was observed that:

- The employment of the proposed optimization based methodology allows the analyst to obtain a reliable estimation of the power flow solution bounds compared to those computed by the Monte Carlo approach. This estimation is slightly conservative compared to the solution bounds computed by the Monte Carlo method. Only in a limited number of cases a slightly underestimation of the voltage angle upper bounds in the order of 2-3 deg. for some buses was observed.
- The simple worst-case power flow studies allow the analyst to obtain a rough but fast estimation of the power flow solution bounds. This approximation was characterized by estimation errors in the order of 1-2% compared to the bounds computed with the proposed optimization-based methodology.

V. Conclusions

This paper discussed and experimentally compared two proposed alternatives to sampling-based approaches for the computation of power flow solutions bounds in the presence of data uncertainty. The proposed solution strategies are based on optimization models that allow a reliable assessment of the solution bounds, and a worst-case scenario analysis that yields a rough but fast approximate solution. The proposed techniques were assessed on realistic power systems.

The obtained results demonstrate that the proposed approaches are well suited for the assessment of uncertainty propagation in power flow solution, with the optimization-based methodology yielding better approximations at higher computational costs than the worst-case power flow studies. The presented studies should allow analysts to choose between the two proposed methods, depending on whether their interests are computational costs or precision.

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VII. Biographies

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