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A probabilistic security assessment approach to power systems with integrated wind resources

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ABSTRACT

Renewable energy sources, such as wind and photovoltaic solar, have added additional uncertainty to power systems. These sources, further to the conventional sources of uncertainty due to stochastic nature of both the load and the availability of generation resources and transmission assets, make clear the limitations of the conventional deterministic power flow in power system analysis and security assessment applications. In order to manage uncertainties, probabilistic approaches can provide a valuable contribution.

In this paper, we propose a new scheme for probabilistic security assessment. The model can deal with various types of probability distributions modeling power injections and can explicitly represent the effects on system security of correlation among nodal power injections (such as wind power) and of contingencies due to branch and generating unit outages. In addition, the steady-state behavior of the frequency regulation is explicitly included in the model. A new approach to deal with current limits is also proposed.

Extensive testing on both the modified IEEE-14 bus test system and the Sicilian power system indicates good performance of the proposed approach in comparison with the result obtained by the computationally more demanding Monte Carlo approach.

1. Introduction

The conventional deterministic Power Flow (PF) plays a very important role in various research areas of power systems. Deterministic PF uses the specified values of power generation and load, and the parameters of the network topology to compute system steady-state operating conditions without taking into account any sources of uncertainty affecting the power system. However, in modern power systems, it is necessary to take into account many sources of uncertainty in security assessment computations [1–3], such as loads and network configuration uncertainties in addition to sources from Renewable Energy Sources (RES), e.g., wind and photovoltaic solar. To manage uncertainties, Probabilistic Power Flow (PPF) has been introduced and can serve as an effective tool for power system planning, operation, and security assessment under uncertainty. PPF is gaining wider application in power systems as long as RES penetration increases.

The first contribution in the PPF area was the scheme published in 1974 [4]. Since then, PPF has been developed and applied to many different areas in power systems research where uncertainties need to be managed. PPF can be solved numerically, i.e., typically using a Monte Carlo Simulation (MCS), or approximately, e.g., point estimate method, or analytically, such as using convolution techniques or cumulant techniques.

MCS is a systematic methodology for the simulation of events under uncertainty. The MCS for PF studies under uncertainty [5–7] uses multiple deterministic PF solutions for the sampled values of the realizations of the random variables (*r.v.* s) that are used to represent the various sources of uncertainty. For MCS, different types of probability distributions as well as their relations within a considered model can be easily and flexibly modeled. In MCS, the non-linear PF equations can be directly used. It can provide a very good result whose accuracy mostly depends on the number of samples [8,9]; however, it is usually computationally very intensive. On the contrary, point estimate methods [10–12] are based on an approximation technique: input variables are decomposed into a series of values and corresponding weights, and then the moments of the output variables of interest are computed as a function of the inputs. The basic idea of analytical approaches is to apply a defined algorithm, i.e., convolution techniques [13] or cumulant techniques

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[14–17], with probability density functions (*p.d.f.s*) and/or cumulative distribution functions (*c.d.f.* s) of *r.v.* s of inputs so that *p.d.f.* s and *c.d.f.* s of *r.v.* s of system states and line flows can be obtained. According to these methods, some types of input distributions can be difficult to be modeled, and some output variables may be impossible to determine. Among analytical methods, while convolution methods convolve all *r.v.* s, so requiring a large amount of storage and computation time, the cumulant methods adopt the properties of cumulants, based on the probability distributions of input *r.v.* s and linearized PF equations. Cumulant-based approach is less computationally intensive process, compared to other methods especially MCS, while maintaining an appropriate level of accuracy, suitable for large power systems: this is why cumulant method is chosen in this paper to develop a probabilistic security assessment [18–20].

For cumulant-based PPF, series expansions, such as Gram–-Charlier, Edgeworth, Cornish–Fisher, are widely used to obtain the *p.d.f.* and *c.d.f.* of desired *r.v.* s from their cumulants or moments [15–17,21–23]. The advantages and disadvantages of these expansions can be found in Refs. [24–26]. Generally, these expansions give an approximation of a *p.d.f.* and *c.d.f.* of a *r.v.* around the Gaussian distribution [15,24]: they are expected to give a good approximation if the considered distribution is Gaussian or nearly Gaussian. However, if contingencies (e.g., due to random outages of branches and generating units) are taken into account in PPF, such input *r.v.* s will make output distributions far from Gaussian distribution, so that the accuracy of these approximations will be significantly affected. In these cases, Von Mises method should be adopted that gives a good performance, as indicated in Refs. [14,27]. In particular, in Refs. [27], the authors treat continuous and discrete distributions separately: while discrete distributions are related to random branch outages, to simplify the problem, all input continuous distributions are assumed to have Gaussian distribution. However, in PPF applications to a real power system, various types of probability distributions which are related to stochastic nature of load, RES, their forecast uncertainties, and random outages of power system components, etc., need to be modeled: therefore, cumulant-based PPF needs to be enhanced to take these distributions into account.

In this paper, a new framework for assessing security of power systems under uncertainty is proposed with following main advantages:

(1) It can provide the same results as a MCS, but less time, suitable for large-scale power systems.
(2) It can deal with various types of probability distributions to represent different sources of uncertainty in power systems: Gaussian distribution typically representing uncertainty of loads, non-Gaussian distribution such as uncertainties from wind generation, and discrete distribution, e.g., from branch and generating unit contingencies, by effectively combining Von Mises method and Gram–Charlier expansion. The Von Mises – Gram-Charlier combination helps cumulant-based PPF overcome the above-mentioned limitations. This makes the proposed approach very interesting from the practical point of view.
(3) It provides a way to determine branch current distributions to identify overloads of transmission lines and of other components possibly caused by contingencies. This is very helpful to enhance security assessment by analytical methods, since so far analytical techniques have provided probability distributions for real and reactive power flows only, but not for currents.
(4) It explicitly includes the steady-state behavior of the frequency regulation in the model by making use of Distributed Slack Bus (DSB) formulation; hence, in addition to probability of line overloading and of over-/under-voltage (as it is possible to do with existing methods), it also allows to evaluate the probability of not meeting ramping requirements and probability of violation of over-/under-regulation limits of conventional generators.
(5) It can explicitly represent the effects on power system security of contingencies and of correlation among nodal power injections such as among loads/RES.

In Section 2, we describe the method for modeling contingencies due to random outages of branches and generating units so that they can be integrated into the proposed PPF scheme. We discuss probabilistic modeling of power injections and the approximation technique to *p.d.f.* and *c.d.f.* of *r.v.* s in Section 3. We present the proposed probabilistic model for currents in Section 4. In Section 5, we describe the proposed PPF solution methodology and security assessment in detail, while in Section 6 we show results obtained by the proposed methodology on both the modified IEEE-14 bus test system and a real Sicilian power system model and present a comparison with the result obtained by MCS. Section 7 concludes.

2. Contingency modeling for probabilistic power flow

Contingencies [1] in power systems, e.g., outages of components such as a branch, a generating unit, etc., are random events that can affect security; therefore, they must be studied to keep system operation within security boundaries. From a computational point of view, adding contingencies makes PPF computation more challenging. However, with the probabilistic models given in the following, the proposed methodology presented in Section 5 can suitably take these contingencies into account.

In power system planning, a basic parameter used for modeling outages is the Forced Outage Rate (*FOR*) [28] that estimates the probability of a component being forced out of service in the future within a given time frame. However, *FOR* is the "steady-state" probability of being in the down state: *FOR* is not capable of estimating the probability of failure for a component in a short or very short time frame. In the latter framework, another parameter to represent the time-dependent unavailability of a component should be adopted: the Outage Replacement Rate (*ORR*) is used analogously to the *FOR*. While *FOR* is a fixed quantity associated with a component, *ORR* is a time-dependent quantity, depending on the lead time considered [28].

From the value of either *FOR* for planning or *ORR* for operation, the contingencies (random branch and generating unit outages) can be modeled.

- *Generating unit outage:* for a power plant or a group with multiple units, either *FOR* or *ORR* as the probability of failure will be used. If a power plant is made of units with different characteristics, a combination of 0–1 distributions ("0" denotes outage state; "1" denotes operating state) should be adopted and will result in a discrete distribution. If all units of the plant are identical, the combination of the 0–1 distributions will result in a binomial distribution.

Fig. 1 presents an example of the probabilistic modeling for the power injection from a power plant including 10 identical units with rated power 5 MW each (assume all units operating at the rated power) and $FOR = 0.03$. In this case, the power injection from the power plant is modeled by a binomial *r.v.* $\tilde{P}$ with the probability mass function as in Fig. 1.