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Risk-based optimal power flow with probabilistic guarantees

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ABSTRACT

Higher penetration of renewable energy sources and market liberalization increase both the need for transmission capacity and the uncertainty in power system operation. New methods for power system operational planning are needed to allow for efficient use of the grid, while maintaining security against disturbances. In this paper, we propose a risk model for risks related to outages, accounting for available remedial measures and the impact of cascading events. The new risk model is used to formulate risk-based constraints for the post-contingency line flows, which are included in an optimal power flow (OPF) formulation. Forecast uncertainty is accounted for by formulating the relevant constraints as a joint chance constraint, and the problem is solved using a sampling-based technique. In a case study of the IEEE 30 bus system, we demonstrate how the proposed risk-based, probabilistic OPF allows us to control the risk level, even in presence of uncertainty. We investigate the trade-off between generation cost and risk level in the system, and show how accounting for uncertainty leads to a more expensive, but more secure dispatch.

Introduction

Market liberalization and increasing penetration of renewable energy sources (RES) lead to a situation where power is not necessarily produced close to where it is consumed, but rather where production is cheap, the wind is blowing or the sun is shining. This trend increases the need for transmission capacity, and forces the transmission system operators to operate the system closer to the operational limits. At the same time, fluctuations in RES in-feed and short-term trading lead to larger deviations from the planned schedule, and thus increase uncertainty in power system operation. The combination of a highly loaded system and significant uncertainty increases operational risk. There is a need for methods which allow for efficient use of transmission capacity, while maintaining security and robustness against disturbances.

There are two types of disturbances in the system, *random outages* and *forecast uncertainty*, which have inherently different characteristics. Whereas outages can be characterized as discrete events with a (usually) low probability, forecast uncertainty (deviations in power in-feeds arising from load, RES or short-term trading) is characterized by a continuous probability distribution. The method proposed in this paper addresses both types of disturbances. The random outages are handled by a risk-based extension to the N-1 criterion that utilizes additional information about the probability of outages, the extent of post-contingency violations and the cost and availability of remedial actions to provide a more quantitative measure of power system security. The risk-based criterion is implemented in an optimal power flow (OPF). By formulating the OPF as a chance constrained optimization problem, we are able to account for forecast deviations in a comprehensive way. The resulting formulation allows us to control the risk of outages, even in presence of forecast uncertainty.

There exist two main approaches to model risk in power system operation. On the one hand, risk can be modeled through overall reliability parameters like Expected Energy Not Served (EENS). These parameters incorporate the effect of cascading events and thus reflect the risk faced by the customers in the system. However, computing the risk requires extensive calculations (i.e., Monte-Carlo simulations), and these types of risk measures are therefore typically used to analyze the risk for a given operating condition [1,2], as opposed to inclusion in an optimization problem.

On the other hand, risk can be modeled in terms of violation of technical limits, e.g., dependent on the power flow of a line or on the voltage magnitude. Such risk measures typically consider the situation after an N-1 outage, and do not simulate how a potential cascade would develop further. Thus, these risk measures do not reflect the full risk of cascading events, but are much easier to

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compute than the risk measures in the first category. Further, when a risk measure is related to specific technical parameters, it is easier for the system operator to identify actions to influence the risk. This type of risk measures have therefore often been proposed for incorporation in OPF formulations. The OPF formulations in [3,4] describe risk as violations and near-violations of voltage limits and line transfer capacities, modeled as linear functions of the voltage magnitude and the line flow. In [5], risk is expressed as a quadratic function of the line flow, whereas [6] models risk as the cost of equipment aging in function of, e.g., the line flow. Here, risk is expressed as a piecewise affine function of the line flow, based on the risk function we presented in [7]. The parameters of the risk function are computed based on the cost and availability of remedial measures, and also reflects the risk of initiating a cascading event.

The OPF is formulated as a central dispatch problem minimizing overall generation cost, similar to the OPF problems solved in markets with locational marginal pricing (LMP). Recently, Ref. [8] investigated how a risk-based OPF impacts the LMPs, showing that the risk-based OPF introduces a new cost component which reflects the system risk level. While [8] also uses a piecewise affine risk function, the parameters of the risk function seem to be chosen arbitrarily, thus impacting the LMPs in an arbitrary way. In contrast, the parameters introduced in this paper are based on actual system properties, providing a less arbitrary definition of the risk function.

Although the OPF is formulated as a central dispatch problem, the proposed method does not focus on the market clearing aspect, but rather on ensuring that the dispatch has a sufficiently low level of risk. Therefore, it can also be applied in self-dispatch markets by changing the objective to minimize changes to the market outcome instead of minimizing overall generation cost. For security considerations, the relation between the risk function and the cost and availability of remedial measures is particularly interesting. All risk-based formulations [3–8] allow for post-contingency line overloading under some circumstances, but do not provide remedial actions to bring the system back to normal operation. Since the risk function proposed here is based on the cost and availability of remedial actions, the method proposes effective post-contingency remedial actions, ensuring that system security can be restored when a contingency occurs.

Although several risk-based OPF formulations exist, few of them account for forecast uncertainty in a comprehensive way. The OPF formulation in [6] considers normally distributed load uncertainty, but only limits the expected value of the risk and does not provide any guarantees for an upper bound. In contrast, the method proposed in this paper guarantees that the risk limit will hold with a chosen probability. This is achieved by formulating a chance constrained optimization problem, following along the lines of [9,10]. The problem is solved using the randomized optimization technique proposed in [11], based on the so-called scenario approach from [12]. This technique requires no assumptions on the distribution of the forecast errors.

In summary, the contributions of this paper are threefold: (1) We define a risk function based on system parameters such as available remedial measures, which has several advantages compared to previous risk functions. First, it avoids using arbitrary parameters with arbitrary influence on cost. Second, the severity function is defined separately for each line and each contingency. Third, it suggests effective remedial measures for the cases where a post-contingency overload is accepted. (2) We introduce risk-based constraints for post-contingency line flows, and show how to choose appropriate upper bounds on the risk by comparing the risk-based constraints to the deterministic N-1 constraints. (3) We include the risk-based constraints in a chance constrained OPF formulation to account for forecast uncertainty from RES.

The reminder of the paper is organized as follows: Section 'Risk modeling' introduces the risk measure which relates post-contingency line loading to the cost of remedial measures and the probability of cascading events. Section 'Formulation of optimization problem' formulates a DC optimal power flow incorporating the risk measure and chance constraints to account for forecast uncertainty. Section 'Case study' analyzes the proposed formulation and compares it with other OPF formulations with regards to cost, risk level, and number of post-contingency overloads in a case study for the IEEE 30-bus system. An additional sensitivity study investigates the relationship between remedial actions and accepted post-contingency overloads, as well as the proposed remedial actions. Section 'Conclusion' summarizes and concludes. Note that this paper is an extension to [7], introducing an improved severity function, additional results and a prolonged discussion.

Risk modeling

In this paper, we propose a risk measure for incorporation in an OPF formulation and focus on risk as a function of post-contingency transmission line loading. Previous risk formulations (e.g., [4,5]) use the same severity function for all transmission lines independent of which contingency has taken place. Here, we improve this formulation in two ways. First, we explicitly account for different types of risk (such as moderate overloads that can be mitigated through redispatch and high overloads that might lead to cascading events) by formulating a piecewise linear severity function. Second, we formulate the severity function separately for each line and contingency, which allows us to account for the effect of available remedial measures on each line in each post-contingency situation. The proposed risk formulation allow us to set post-contingency line flow limits based on the available remedial measures and potential impacts of cascading events. This ensures that effective remedial measures are available in the cases where we allow for post-contingency overloads.

Definition of the risk measures

A risk measure should reflect both the probability of an outage and the severity of the resulting operating condition. The risk related to a specific outage i and line k is expressed as

$$\mathcal{R}^{spec}_{(i,k)} := \mathcal{P}_{(i)} \cdot \mathcal{S}_{(k|i)} \quad (1)$$

where $\mathcal{P}_{(i)}$ is the probability of outage i and $\mathcal{S}_{(k|i)}$ is the severity of the operating condition on line k given outage i. This expression can be seen as the risk-based counterpart of the N-1 criterion, as it describes the risk for a specific line in one specific post-contingency state. Using $\mathcal{R}^{spec}_{(i,k)}$ as a basis, we define:

$$\mathcal{R}^{out}_{(i)} := \sum_{k=1}^{N_l} \mathcal{P}_{(i)} \cdot \mathcal{S}_{(k|i)} \quad (2)$$

$$\mathcal{R}^{line}_{(k)} := \sum_{i=1}^{N_{out}} \mathcal{P}_{(i)} \cdot \mathcal{S}_{(k|i)} \quad (3)$$

$$\mathcal{R}^{tot} := \sum_{i=1}^{N_{out}} \sum_{k=1}^{N_l} \mathcal{P}_{(i)} \cdot \mathcal{S}_{(k|i)} \quad (4)$$

$\mathcal{R}^{out}_{(i)}$ expresses the risk after an outage i, and is obtained by summing the risk of all lines k in this post-contingency state. $\mathcal{R}^{line}_{(k)}$ is the risk related to line k, summed over all outages i. $\mathcal{R}^{tot}$ is the total risk in the system, summed over all outages i and all lines k.

In order to evaluate (1), the outage probabilities $\mathcal{P}_{(i)}$ must be estimated, and the severity $\mathcal{S}_{(k|i)}$ has to be defined. We assume that the outage probabilities are calculated a priori (e.g., based on