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Probability of failure of overloaded lines in cascading failures

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A B S T R A C T

Power grids are vulnerable to cascading failures, as shown by previous blackouts or major system disturbances. Line outages due to overload are often the main contributors to the cascading failures leading to these undesired situations. Indeed, the more a line is overloaded, the larger is its sagging, and hence the probability that it will be tripped. It is necessary to quantify in a realistic way the probability of trip as a function of the load in order to compute a good estimation of the frequency of dangerous cascading outages. Several models were proposed for this purpose, but none of them is backed up by empirical evidence or detailed analysis. This paper studies factors that could affect the probability of trip as a function of load, and it computes this probability for two different test systems using a temperature simulation based methodology, called dynamic PRA level-I analysis. This paper then compares existing modelings of this probability to these results. This comparison shows that all modelings used in the literature are not always convenient. We finally propose a simple model that can be adopted in probabilistic risk assessment of cascading failures.

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Introduction

Analysis of previous blackouts or major system disturbances showed that line outages due to overload are often the main contributors to the cascading failures leading to these undesired situations. The most famous example is the blackout which occurred on August 14, 2003 in the Northeastern area of the United States and in the Southeastern area of the Canada, where about twenty lines tripped due to short circuit with ground [1]. Indeed, each of these lines sagged low enough to contact something below it, even if two of them were not overloaded. As the load on other lines can increase after the loss of an element, their failure probabilities can increase due to thermal effects increasing their sag. If another line trips, this effect is increased, possibly leading to a cascading failure. Therefore, it is crucial to include the dependency of the probability of trip to the load going through the line in a cascading failures modeling. We should however note that the probability of a fault depends not only on this load current but also on the weather (ambient temperature, wind speed, ...), on the vegetation height, on operators corrective actions, etc.

Several models were proposed for the probability of trip as a function of the load, based on the assumption that the more a line is overloaded, the larger is its sagging, and hence the probability that it will be tripped [2–5]. But this assumption imposes only that the probability should be a monotonically increasing function of the load, and proposed models differ by the shape of this function. None of them is backed up by empirical evidence or detailed analysis. A decomposition in two levels of the Probabilistic Risk Assessment (PRA) of cascading failures in transmission power systems is presented in [6]. The level-I analyzes the first phase of cascading failures leading to blackouts, the slow cascade ruled by thermal failures, on the basis of the physical evolution of lines' sag. The first aim of this paper is to compare existing modeling of the probability of trip as a function of the load to results given by a dynamic PRA level-I analysis. The comparison is performed for two different power systems. Two different operators corrective actions models are used for the smallest power system. The second aim of this paper is to propose a simple model that can be adopted in PRA of cascading failures based on this analysis.

Consequently, Section 'State of the art' presents existing models and Section 'Physical bases' presents theoretical basis. We will then apply the level-I of blackout PRA to two test cases in Sectio n 'Numerical results' analyzes the results. Finally, conclusions are presented in Section 'Conclusions'.

State of the art

Two different kinds of studies about probability of line tripping are interesting to discuss in this paper. First, methodologies developed to study cascading failures use various model for the probability of trip as a function of the load. They are discussed in

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Section 'Cascading failures methodologies'. Secondly, probabilistic methods to assess thermal capacity of lines based on the risk study also the probability to have a flash-over to the ground in function of the load. They are presented in Section 'Increasing thermal rating by risk analysis'.

Cascading failures methodologies

Introduction

In a cascading failure leading to a major system disturbance, there is a strong coupling between events. In particular, the loss of an element can overload other lines. The temperature of an overloaded line starts then to increase, thus increasing its sag, which may finally be so high that a short-circuit with the ground towards trees may occur and cause the line trip. If we denote by T_i the event "Trip of the line i", the frequency Fr of the dangerous sequence $T_1, \ldots, T_n$ (*i.e.* successive trips of lines $1, \ldots, n$) can be calculated by

$$Fr(T_1, \ldots, T_n) = Fr(T_1)\prod_{i=2}^{n} p(T_i|T_1, \ldots, T_{i-1}), \tag{1}$$

where $p(T_i|T_1, \ldots, T_{i-1})$ is the conditional probability of the trip of the line i, knowing that lines $1, \ldots, i-1$ tripped. Due to the strong coupling between events in a cascading failure, the conditional probabilities can strongly differ from the marginals ones,

$$p(T_i|T_1, \ldots, T_{i-1}) \neq p(T_i), \tag{2}$$

so it is crucial to have a good approximation of these probabilities in order to obtain a realistic estimation of the risk of blackout.

In a general way, conditional probabilities $p(T_i|T_1, \ldots, T_{i-1})$ depends on several factors: the load of the line i, the weather (ambient temperature, wind speed, ...), on the vegetation height and on operators corrective actions. Operators correctives actions themselves rely not only on the state of the power system, but also on the information infrastructure. However, taking into account all these factors in a blackout PRA is complex. Therefore, several models trying to estimate vulnerabilities of a power system to cascading outages use conditional probabilities as a function only of the load of the concerned line,

$$p(T_i|T_1, \ldots, T_{i-1}) \approx p(T_i|I_i(T_1, \ldots, T_{i-1})), \tag{3}$$

where $I_i(T_1, \ldots, T_{i-1})$ is the current in line i after the trip of the lines $1, \ldots, i-1$. The Eq. (1) then becomes

$$Fr(T_1, \ldots, T_n) = Fr(T_1)\prod_{i=2}^{n} p(T_i|I_i(T_1, \ldots, T_{i-1})). \tag{4}$$

The assumption that the probability of line tripping in function of reduced load (actual load divided by thermal capacity) is the same for all lines is often made as an additional approximation. If we denote by $P(x)$ the probability of line tripping when the reduced load is x, the frequency of a dangerous scenario is simply given by

$$Fr(T_1, \ldots, T_n) = Fr(T_1)\prod_{i=2}^{n} P[x_i(T_1, \ldots, T_{i-1})]. \tag{5}$$

In a general way, a line tripping can have two origins:

- The thermal expansion can result in the line dropping beneath its safety clearance, which may cause a flashover to the ground with a probability $P_{th}(x)$. If we assume that the more a line is overloaded, the larger is its sagging, and hence the probability that it will be tripped,
- A failure independent of the load (e.g. mechanical failure), with a probability P_{ind}.

The total probability of line tripping is then given by

$$P(x) = P_{ind} + P_{th}(x)[1 - P_{ind}] \tag{6}$$

The load in each line after each loss can be easily computed through a power flow calculation. The problem in this simplified model is then to know the function $P(x)$, or, equivalently, $P_{th}(x)$. Several models were proposed for this, based on the assumption that the more a line is overloaded, the larger is its sagging, and hence the probability that it will be tripped. But this assumption imposes only that the probability $P_{th}(x)$ has the properties of a cumulative distribution function (cdf). Indeed, there is thus a "critical load" of the line over which the line will trip (the probability $P_{th}(x)$ is in a monotonically increasing function of the load). Let X_c be the random variable describing this critical reduced load and $F_{X_c}(x)$ its cumulative distribution function. We can write

$$P_{th}(x) = Pr[X_c \leqslant x] = F_{X_c}(x), \tag{7}$$

which means that $P_{th}(x)$ has to be fit by a cdf. Proposed models differ by the shape of this function $P_{th}(x)$. We present in this Section three different models.

Exponential model

In [2], Nedic presents a model to simulate large system disturbances (a variant of the Manchester model). One of the phenomena modeled is the possible line outages due to overloads. The proposed approach rely an the additional assumption that only if a line is overloaded it can sag beyond the specified limits (*i.e.* if a line is not overloaded its tripping probability due to sagging is equal to zero). The probabilistic function used for this purposed is shown in Fig. 1. This function is equal to zero when the reduced load is lower than 1, has an exponential evolution when the reduced load is between 1 and 1.5 and is equal to a constant value p_2 when the reduced load is larger than 1.5.

Linear model

Zima and Andersson assumed in [3] that the probability will rather follow a curve show in Fig. 2: the probability is equal to zero for a reduced load lower than 1, has a linear evolution when the reduced load is between 1 and k and is equal to 1 when the reduced load is larger than k. Such a function is inspired by [7] where a similar behavior is proposed to describe a probability of the incorrect tripping of a line exposed to a hidden failure (*i.e.* a relay malfunction which entails the trip of a "healthy" line). However, the probability function used in [7] is not equal to zero for a load below the line limit, but is equal to a constant low value. Computations in [3] are based on $k = 1.4$, as in [7].

Normal cdf model

In [4,5], another kind of model is proposed, as shown in Fig. 3. It is assumed that when a line loading increases above its limit, the probability of line tripping increases and eventually flatten out to

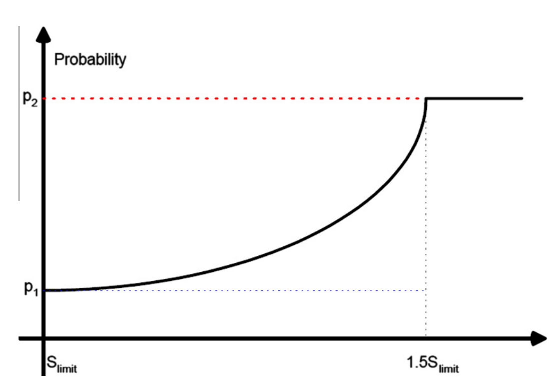

Fig. 1. Line overload modeling. From [2].

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