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Stochastic modeling of power system faults

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ABSTRACT

Correct modeling of power system faults is a key issue in a diversity of power system studies, such as in network planning, equipment specification and protection systems coordination. The present paper addresses the probabilistic description of faults, based on available data collected by transmission system operators for different voltage levels. Fault rate and individual fault characteristics are stochastically modeled, namely fault location, type and resistance. A fault resistance model is suggested, based on Weibull distribution, which parameters are set per voltage level. The proposed fault description is a useful tool for power system planning and design, when a stochastic approach of the power system faults characteristics is adopted. Time series of fault input data and simulation results are presented in a common format, so to allow using the same statistical tools as used in power system monitoring and field data reporting. The model is able to reproduce atypical years, as happen in real transmission networks. The developed fault model is used to generate stochastic short-circuit events, which are then used for short-circuit current computation. The methodology is applied to the IEEE RTS and simulation results are shown for the probability of amplitude and time constant values. These results are prone to be used to specify network circuit breakers and current transformers using a probabilistic approach.

1. Introduction

Correct modeling of power system faults is a key issue in a diversity of power system studies, such as in network planning, equipment specification and protection systems coordination. Currently used methods, underlying international guidelines and standards [1–3] are deterministic, based on worst case scenarios. These are typically associated to extreme events leading to the highest or lowest short circuit currents. Consequently, the deterministic approach results into over-dimensioning during most of the operating time. Furthermore, as the likelihood of occurrence is disregarded, no quantitative information is provided to support investment decisions.

Contrary to deterministic methods, a probabilistic approach quantitatively incorporates uncertainty, based on quantifying the likelihood of each event, and eventually its associated uncertainty. The approach allows quantifying the degree of exposure to a particular event and this information may be combined with associated costs in a risk analysis methodology.

Probabilistic methods have been developed based on Monte Carlo simulations [4] or analytical formulation [5,6]. The first are very powerful but require high computational efforts, while the analytical methods overcome this requirement by assuming simplifications, thus providing less accurate results. Probabilistic methods were developed for all sorts of system studies, such as system planning [7,8], power flow [9], transient stability [10,11], protection system performance [12,13], equipment design, including circuit breakers [14] and current transformers [15,16], and voltage dips assessment [17,18]. Most of these works encompass short circuit calculations. However the detailed description of input data, such as fault location, type, resistance and duration is not addressed. Notwithstanding, these are critical parameters to obtain confident results.

The present paper addresses the probabilistic description of fault input data, based on available data collected by transmission system operators. These data are used to generate stochastic short-circuit events, which are then used for short-circuit current computation. The methodology is applied to the IEEE RTS, aiming to allow probabilistic specification of equipment, such as circuit breakers and current transformers. Results are presented for the maximum interrupted fault current, as well as the associated network time constant. The developed method allows obtaining the probabilistic distribution of these quantities, thus being adequate for a risk assessment approach to equipment specification.

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2. Relevant fault characteristics

Fault rate and individual fault characteristics are crucial information used to support power system planning and operation strategies, both technically and economically. Fault rate is a key index to evaluate bulk power system performance, as it reveals very important features such as: correct equipment design, suitable maintenance, equipment ageing and abnormal environmental conditions. Additional important information is provided by the individual fault characteristics. For instances, a large number of line to line faults may indicate an inadequate line geometry design as regards environmental conditions, such as wind, and a high fault resistance occurrence may indicate special needs for sensitive earth fault protection.

Individual fault characterization starts by identifying where, in the bulk power system, the fault has occurred. This means identifying which network element was affected and, in the case of transmission lines its exact location. Most power system faults occur in transmission lines and busbars, and they correspond to the highest sort circuit current values, hence they are the most relevant for equipment specification.

Short-circuits are also characterized by the number of affected phases. Faults may affect one single phase and ground (SLG), two phases (LL), two phases and ground (2LG) and three phases (3PH). Fault type distribution depends on the voltage level, line geometry, terrain relief and weather conditions. Therefore, this characteristic is strongly system dependent.

The resistance that characterizes each fault depends on the short circuit type and cause. Its value aggregates the arc and the ground resistances. Additionally, depending on the specific fault, it may include the tower or the touching objects resistance. The fault resistance may be time constant or vary with time, as in case of arc elongation by wind effect. For faults not involving the ground, it is assumed that only the arc contributes to the fault resistance, thus its value being negligible.

Fault duration is also an important characteristic, in the case of system stability analysis, equipment design and voltage dips characterization. However, it is not relevant in the scope of the present paper.

Some of the identified fault characteristics are not independent. Indeed, the underlying phenomena indicate and operational data confirm that fault type, as well as fault resistance, depend on the fault location. However, at the planning and design stage, uniform characteristics are considered, and the fault characteristics may be treated as independent of the fault location. Also at the planning and design stage, a planning criterion for the transmission line fault rate is considered. This criterion unique, thus the line fault rate being considered constant in time and along the all line length. The line design, including shielding, the towers and the grounding resistance, are chosen toward this planning criterion.

All the identified characteristics occur randomly in time. This very nature of power system faults suggests a stochastic modeling approach.

3. Fault modeling

3.1. Modeling approach

In the present paper, a fault simulation methodology based on Monte Carlo simulation is presented. The occurrence of faults in a network element, such as a transmission line or a busbar, is simulated during a time span of representative significance. The simulation time span is divided into an equal number of time intervals (trials) of equal duration, such as a second, an hour, or a year. The methodology output is a set of occurrences, each characterized by a fault time, a fault location, a fault type and a fault resistance. Simulation results are analyzed using the same statistical tools as used in power system monitoring and field data reporting, thus allowing a straightforward comparison between simulation results and field data.

3.2. Fault rate

Transmission line and busbar fault rates are two indexes that characterize a network performance. These rates are key information used to support investment and maintenance decisions. This is done by analyzing trends over several consecutive years. Also important is to pin point atypical years, during which the number of faults is abnormally low or high, and identify the corresponding causes. These may be abnormal weather conditions or other unexpected environmental events.

The proposed methodology receives as input the network fault rate average value, for transmission lines and busbars. As output, the network fault rates are calculated on a yearly basis, along the chosen simulation time span.

During a Monte Carlo simulation, the transmission lines and busbars elements will fail at a given rate $z(t)$, which individually characterizes each element. During a trial t_0, the probability of fault occurrence P_F in a network element is defined as [19]:

$$P_F(t_0) = 1 - \exp\left[-\int_0^{t_0} z(\tau)\,d\tau\right] \qquad (1)$$

For each trial, a random number is generated according to a uniform distribution over the interval [0,1]. The generated number is compared to the corresponding probability of fault occurrence P_F and, if higher, the corresponding network element is assumed to fail during the trial.

Recorded network performance data usually refer to yearly line faults per 100 km, λ_l, and yearly busbar faults per 100 busses, λ_b. Accordingly, a constant failure rate $z_i(t) = \lambda_i$ is assumed for each network element. All busbars will have the same failure rate and transmission lines will have different failures rates, according to their length l_i:

$$\lambda_{b_i} = \frac{\lambda_b}{100} \qquad (2)$$

$$\lambda_{l_i} = \frac{l_i \lambda_l}{100} \qquad (3)$$

Simulation results obtained for the network elements are then converted into system performance indexes. The analysis can be done by voltage level or for the overall network.

3.3. Line fault location

The probability of a fault occurring at a given location along a transmission line is considered uniform. This assumption is in line with a planning and design stage practice, which considers a unique planning criterion. Accordingly, to assess the location of each transmission line fault, a random number is generated according to a uniform distribution over the interval [0,1]. The generated value gives the fault location in per unit, this being the line length.

3.4. Fault type

Fault type probabilistic distributions are defined, on a yearly basis, for transmission lines and busbars.

To assess the fault type that characterizes a particular fault generated by Monte Carlo simulation, the interval [0,1] is divided into four segments, with lengths given by the probability of occurrence