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Transmission line protection systems with aided communication channels—Part I: Performance analysis methodology

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ABSTRACT

A performance analysis methodology for transmission line primary protection systems is presented, based on a probabilistic approach to protection system successful operation. The protection system operation is represented by reliability graphs, and a probabilistic model of the distance protection is considered. The system successful operation is described by tie-sets, and solutions are obtained from Monte Carlo simulation. The system elements are characterized by the reliability factors: equipment failure rate and time to repair. The system performance is assessed by the availability index.

The developed methodology is applied to a transmission line protection scheme with one aided communication channel. Results allow quantifying the influence of the fault location on the protection system performance. Results also show the influence of the equipment failure rate on the system performance. The developed methodology proves to be adequate to quantify the benefits of using communication channels in transmission line protection. Furthermore it is adequate to assess different protection system architectures. A comparative performance analysis, considering four different transmission line protection schemes, can be found in the Part II paper.

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1. Introduction

Currently, the massive adoption of the interoperability standard IEC61850 [1] challenges utilities to review their protection systems philosophy, and to establish new internal standards based on the new technological capabilities [2,3].

The transmission line protection is the most important protection system, as regards both transmission network performance and investment costs. As a matter of fact, most power system faults occur on overhead transmission lines and, by far, the largest share of protection systems owned by transmission utilities are of that type. Therefore, utilities and manufacturers devote significant resources to the design, performance analysis, optimization and maintenance of transmission line protection systems. The present paper contributes to providing both a methodology and results that can support decision making, regarding transmission line protection system design, and the underlying CAPEX and OPEX policies.

Reliability and availability analysis of power system protection schemes are usually addressed by means of fault tree and Markov analysis [4–8]. The authors have developed an alternative methodology [9], which proved adequate to the analysis of very complex systems. This methodology is based on system representation by reliability graphs. The system successful operation is described by tie-sets, and solutions are obtained from Monte Carlo simulation. The developed methodology provides quantitative information regarding system performance, considering both equipment reliability and Mean Time to Repair.

A transmission line protection system encompasses the communication infrastructure used in teleprotection schemes, further to the infrastructure installed in the substation bay, such as protection relays, measurement transformers, and circuit breakers. In the present paper, the probabilistic description of the distance relay operation is incorporated into the previously developed methodology, and the potential of the resulting transmission line protection model illustrated by application to a single distance protection with single aided communication channel.

2. Transmission line fault clearance process

The transmission line protection system encompasses primary and backup protection [11]. Primary protection has priority in fault clearance, while backup protection is intended to have a delayed

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operation when a fault is not cleared by the primary protection, due its failure or inability.

In order to evaluate the reliability and availability of a transmission line protection system, it is important to clarify what is the meaning of successful operation, considering that the ultimate goal is to clear a fault, with a minimum time delay, at any location along the protected line. It should be noted that transmission line fault clearance requires current interruption at both line ends.

The current interruption process starts by the measurement of some electric quantities, which are used in a comparison criteria, the protection function, before a trip command is sent to the circuit breaker opening coil. The coil mechanically maneuvers the circuit breaker moving contacts inside the interruption chamber, eventually extinguishing the fault current. Naturally, all these steps require some time, therefore an intrinsic time delay exists in the fault clearance process, typically around 3 to 5 cycles. Furthermore, as in the case of distance protection (for the definition of different protection zones), an intentional delay can be added to this time.

Transmission lines are commonly protected by distance protection functions with at least two independent operating zones. Zone 1 is set so as not to reach the remote bus and to trip instantaneously, while Zone 2 is set to reach the remote bus, but its trip is intentionally delayed to perform remote backup to the remote bus protection.

In addition to the distance protection functions located at both ends, transmission line protection systems may also include communication channels used by a teleprotection scheme. This is intended to achieve fault clearance, without additional time delay, regardless its location along the line. A common teleprotection scheme is the Permissive Under-reach Transfer Trip (PUTT) [12], based on the acceleration of Zone 2 trip, once Zone 1 trips on the remote bus.

Accordingly, in the present paper, by successful operation of a transmission line protection system we mean fault clearance without additional time delay, which can be achieved by: (a) Zone 1 operation at both line ends; or (2) teleprotection operation.

3. Distance protection characterization

3.1. Performance description

Distance protection estimate fault impedance by measuring currents and voltages. Considering that the impedance operating region is represented only by its reactance criteria, a zone trip occurs when the estimated reactance value is lower than the zone reach setting, X_{op}. This assumption implies that the resistance criterion is always fulfilled, this being valid for low resistive faults. It should be noted that distance protection is not intended to detect high resistance faults, as other protection principles are usually added for such purpose [13].

The estimated reactance, for a fault at distance d, can be described by a random variable, X_d, as measurements are affected by several factors. The probability of zone trip during a fault at distance d is defined by the probability that this random variable X_d is inferior to X_{op}:

$$P(d) = P\left(X_d < X_{\text{op}}\right) \quad (1)$$

When the distance protection is duplicated at one line end, two zones co-exist and, the probability that at least one of the zones trips is the probability that at least one evaluates a reactance lower than its predefined reach X_{op}. This probability, assuming that the two protection tripping probabilities are not correlated, is written as:

$$P(d) = 1 - \left(1 - P\left(X_{d1} < X_{\text{op1}}\right)\right)\left(1 - P\left(X_{d2} < X_{\text{op2}}\right)\right) \quad (2)$$

where subscripts 1 and 2 denote the two distance protections.

The probability of line fault clearance by Zone 1 operation at both line ends is given by

$$P_s(d) = P_{\text{A}}(d) P_{\text{B}}(1 - d) \quad (3)$$

where subscripts A and B denote the line ends.

The estimated reactance X_d is related to the true reactance x_d by an error ε_{X_d}:

$$\varepsilon_{X_d} = X_d - x_d \quad (4)$$

which is affected by several important factors such as: the line zero-sequence impedance, the instrument transformers errors, the distance function transient over-reach, the fault resistance, and the pre-fault load.

Crevier et al. have proposed a probabilistic model to describe the error ε_{X_d} [14,15], and concluded that, given the large number of uncertainty factors affecting the estimation (namely line parameters, instrument transformer errors, load, pre-fault voltage and fault resistance), the Central Limit Theorem allows to statistically represent this error by a normal distribution. As such, the random variable X_d is represented by the true reactance x_d superimposed on a normal distribution that depends on the standard deviation of the error σ_e, and the reactance bias x_{bias}:

$$f_{x_d}(X_d) = \frac{1}{\sqrt{2\pi}\sigma_e} \exp\left[-\frac{(X_d - (x_d + x_{\text{bias}}))^2}{2\sigma_e^2}\right] \quad (5)$$

where X_d is the independent variable supported on the space of all possible reactance values.

A reactance bias, x_{bias}, term is added, which results from not knowing with certainty the line zero-sequence impedance. This impedance is affected by the value assumed for the earth resistivity, which is included in the compensation factor k_0 used in the reactance estimation algorithm during faults affecting the ground [16]. If the earth resistivity is assumed to be statistically described by a normal distribution defined by mean and standard deviation [17], its variance impacts on the estimated reactance variance, and its mean, if unknown, impacts the estimated reactance bias.

Depending on the fault type and location, Crevier et al. found that the error standard deviation can range from 5% to 11%, but Pinto de Sá et al. [18] proposed the use of a fixed value of 8%.

Fig. 1 shows the normal probability density functions of the estimated reactance for several fault locations, represented by x_d, and assuming no reactance bias. The probability of Zone 1 trip is shown as a shaded area and is formally described by Eq. (1). It is possible to graphically represent this probability as a function of distance to fault by evaluating this area at each fault location. This is exactly what is presented in Fig. 2.

The results presented in Fig. 2 show that, with certainty, the zone will trip in the first section of the line, but this confidence rapidly decreases as the distance to fault approaches X_{op}. At the zone reach, the probability of tripping is only 50% and continues to diminish as the distance approaches the far end. The model implies that, formally, the probability of tripping for a fault at the remote bus is different from zero, although it can assume a residual value if X_{op} is not extended too much. A tradeoff between covering the maximum as possible the line length and the chance of over-tripping for a fault in the remote bus has to be weighed while setting X_{op}. The same figure, where the dashed line corresponds to Eq. (2), also highlights the benefit of distance protection duplication. This shows that the probability of tripping increases in the vicinity of Zone 1 reach, without compromising considerably the probability of over-tripping for a fault close to the remote bus. In reality, the two protection tripping probabilities are not completely independent as, among other common factors, the protections are usually settled by the same person, thus being vulnerable to the same human errors, and share the same assemblage space, thus being vulnerable to the same

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