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Application of the probabilistic approach for earthing system evaluation in distribution network

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ABSTRACT

The contribution describes probabilistic approach for evaluation of earthing system safety, which can complement the conventional earthing design methodology given by standard EN 50522, similarly as mentioned in British Annex NA. The main part of the contribution is application of the probabilistic risk assessment approach on case study of distribution transformer station earthing system. For presentation of benefits of probabilistic approach, the system solidly earthed, isolated, resonant earthed and resistor earthed were respected as the part of the case study. The contribution stipulates all crucial aspects of this process including probable drawbacks flowing from high amount of non-well known input variables which are necessary for probability calculation, e.g. human body presence, respected risk scenarios, frequency and type of earth faults, fault/contact coincidence, etc. The last part of the contribution is focused on sensitivity analysis of all crucial input variables which can affect final individual risk probability.

1. Introduction

Besides determination of minimal operating requirements of an earthing system (ES), engineers also have to evaluate its safety level. The methodology is described in many different international standards like IEC 61936-1 (2010) [1], EN 50522 (2010) [2] and IEEE 80 (2000) [3]. For example, current version of EN 50522 safety criteria is expressed by a voltage-time (V-t) dependent curves that represents permissible touch voltages. If all touch voltages of a given design are lower than V-t curves respecting fault clearing times and additional insulating layers, then the given design is evaluated as sufficient and might be assumed as safe. Throughout the whole designing process of ES the input data is taken as concrete numbers with the preservation on the conservative site (i.e. assuming the worst case scenario). Usually the input values in terms of probability are taken as from 95% or more confidence interval. For example, El-Kady [4,5] put a lot of effort in determining the distribution of earth fault current magnitudes with the help of Monte Carlo simulation accounting also for remote faults with transferred earth potential rise (EPR) by overhead earth wires. Another, more recent, study by Dimopoulos [6] also reports that the 'worst case' scenario is not very likely to happen and that more comprehensive approach respecting probabilistic nature of input variables should be adopted. Dimopoulos [6] in his contribution also used statistical data of clearing time distribution that also confirms the probabilistic nature of the problem (most of the clearing times can be expected lower than the set value of respective protection). Also, the current version of EN 50522 states that *'It must also be recognized that fault occurrence, fault current magnitude, fault duration and presence of human beings are probabilistic in nature'*, yet the proposed 'the worst case' scenario approach with deterministic input values is assumed as acceptable.

Following steps in EN 50522 may induce the feeling that the final design of ES is safe, however this is not generally true. That is because the V-t curves are derived with the assumptions of: human body current causing fibrillation in 5% of all cases (c2 curve), the human body resistance is taken as for 50% of population, current path one hand to feet and no additional resistances [2]. As one could easily deduce, the current standard EN 50522 V-t curve has an inherent probability of fatal accident up to 5%. However, the fatal accident probability is much lower due to the fact, that the fatal accident could only happen when a fault occurs and at the same time a person is exposed to the hazardous potential difference, i.e. the probability of coincidence [7]. Also the probabilistic nature is the fact, that the soil is in general an inhomogeneous structure [8–10] which can be modelled with one or more respective layers and its behaviour may change with the weather conditions [11]. The question of adopting probabilistic approach instead of deterministic is quite old and many papers [6,12–21] were published with an attempt to improve the general methodology. The probabilistic approach was also adopted in national annex NA and NB

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of British standard BS EN 50522 [22]. The most comprehensive description of probabilistic methodology for evaluation of an earthing system was described in user guide [7] which contains detail description of theory of safety risk assessment and related problems. This guide is based on the summarization of published works [13,15,21,23]. In this document, the probability of fault occurrence as well as coincidence of human exposure to the hazard voltage is considered as Poisson probability distribution functions, what is more complex than in the case of British standard 50522 [22].

It is assumed [12] that the probabilistic approach may be worth for designing, of some small and solitary standing earthing systems where new design can lead to substantial over-sizing and subsequently to overprice of ES without significant impact to reducing of risk probability. Just in these cases the probabilistic approach is beneficial because it respects real human presence and fault/contact coincidence to ensure acceptable risk regarding to ES design expediency and environmental conditions (soil resistivity). It can optimize design of ES to find the best ratio between cost and safety factor. Crucial part of probabilistic approach is selection of generally acceptable value of individual risk probability (risk of death) which defines safety level of designed ES (discussed in Section 2.2). In general, the probabilistic approach enables to save cost of ES for its more efficient use while it still fulfils acceptable risk of death. Unfortunately, the application of the probabilistic approach is very challenging because it is generally based on complicated methodology where many uncertain variables are used.

Most of the published papers introduce the application of probabilistic approach for designing of ES of transmission asset. However, the current valid standard BS EN 50522 and guide EG-0 might be used also for designing of ES in distribution networks, where exposure of customers is really high due to interconnection of MV and LV earthing systems. As is discussed in Section 3.1, in such cases, part of the EPR can be transferred through common protective earth and neutral conductor (PEN) to exposed conductive parts (ECP) which will increase the overall risk of such a design. Up-to-date almost no contributions dealt with application of probabilistic approach in MV/LV networks except one [24]. However, in the paper [24] the authors have not included the transferred potential to ECP in LV network and thus not incorporated the risk induced on public.

This contribution shows application and sensitivity analyses of probabilistic approach based on case study of distribution network where simple earthing system of distribution transformation station is evaluated. The case study allows to present benefits and difficulties of probabilistic approach to show real application potential and potential for further research works which have to be done prior to wide usage of probabilistic approach.

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2. Integration of probabilistic approach to earthing system evaluation process

The most gentle way for implementation of probabilistic approach to relatively conservative European field of ES designing is its integration to applicable standard [2]. Fig. 1 presents flowchart, where original evaluation process given by EN 50522 (enclosed by dotted line) is complemented by probabilistic part as it was used in British National Annex NA of BS EN 50522 [22]. Compared to [22], the probabilistic part described in the paper respects the impact of fault duration on coincidence probability which can reflect effect of longer tripping time of earth faults in non-solidly earthed distribution networks (see Section 2.1). The coincidence probability assessment criterion presented by the block 2 is the second difference of the flowchart in Fig. 1 compared to BS EN 50522. This criterion may simplify probabilistic evaluation process so that in the first step, it is not necessary to calculate probability of fibrillation, which could be challenging for some risk scenarios. In this phase of evaluation process, the fibrillation probability 1 is assumed for all risk scenarios.

According to [22], the next step admits probabilistic evaluation of exposure which is categorized to three areas (see Section 2.2). In case that risk probability is inside intermediate area, the probabilistic part of ES evaluation process is extended by a cost benefit analysis (CBA) as shown in Fig. 1 (block 7). The CBA can evaluate the effectiveness of additional costs spend on modification, re-design or additional measures of an earthing system, detailed description is in Section 2.3. This paper is further focused only on the risk probability part expressed by block 1–8 (Fig. 1), because the initial part of the flowchart is in detail described in standard [2].

2.1. Individual risk probability calculation

Earthing system safety might be evaluated by the probability of fatal accident, or so called individual risk IR [7,22]. Determination of IR might be quite challenging task due to the fact that it is dependent on many wide-ranging information like: frequency of earth faults causing EPR and its magnitude and fault clearing time distribution; frequency of human presence in the vicinity of ES, the human presence duration etc. Other environmental and site specific information should be also considered. As the abovementioned information is site specific, detailed statistical data is necessary to ascertain which might be in many cases difficult. Also, the change in this data throughout life-time period of designed ES has to be considered.

Fatal accident might only occur if all three following conditions are met: - a fault will happen, - a human is exposed to potential difference (either due to ES EPR or by transferred potential); - and the potential difference is high enough to cause ventricular fibrillation (other causes of death are not considered [7,22]). Each of these conditions can be modelled with probabilistic nature/distributions and thus fault can happen with fault probability P_F, human can be exposed to potential difference with probability P_E and fibrillation may happen with probability P_{Fib}. For simplification, these probabilities can be considered as independent probabilistic events. Thus simple formula (1) for IR calculation can be introduced as follows [22].

$$P_{Risk} = P_F \cdot P_E \cdot P_{Fib} = P_{Coinc} \cdot P_{Fib} \tag{1}$$

The product of P_F times P_E can be substituted by P_{Coinc} (1) which is the coincidence probability expressing the likelihood of human presence in the zone of the earthing system influence during an earth fault per year. The input variables into P_{Coinc} calculation are proposed by [22] as mean/average values. The calculation of P_{Fib} is independent on calculation of P_{Coinc} and will be discussed later. More comprehensive approach of IR formula derivation is introduced in [7] where more precise approach was used. In this user guide [7], the probability of human exposure and the probability of fault occurrence were modelled with Poisson distribution function with its mean and variance values, therefore modified P_{Coinc} formula (2) was introduced by [7] as follows

$$P_{Coinc} = \frac{f_n \cdot p_n \cdot (f_d + p_d) \cdot T \cdot CRF}{365 \cdot 24 \cdot 60 \cdot 60}, \tag{2}$$

where f_n is number of earth faults per year, f_d is fault duration (seconds), p_n is frequency of human presence/touch per year, p_d is human presence/touch duration (seconds), T is exposure duration (years) - usually 1 year, CRF is coincidence reduction factor respecting preconscious of people familiar with the risk [7] (base value is 1). One main difference between both approaches [7,22] in calculation of coincidence probability is that the British standard [22] does not include into the calculation the fault duration f_d. Based on simplified comparison of both approaches it can be demonstrated that both approaches give comparable results only for fault duration up to 0.1 s (Fig. 3). The solution described in BS EN 50522 does not respect impact of longer tripping times which are characteristic for an earth fault in distribution