SENSITIVITY ANALYSIS OF RELIABILITY FOR A TYPE STRUCTURE OF THE ELECTRICAL DISTRIBUTION STATION

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Abstract – This paper presents a sensitivity analysis of reliability for an electrical distribution station of high voltage/medium voltage with a double busbars system. Sensitivity analysis is performed by evaluating two reliability indicators: number of interruptions and duration of interruptions, for a consumer connected to medium voltage busbars of the electrical station. In the final part a case study is presented, followed by concluding remarks.

Keywords: reliability, electrical distribution stations, sensitivity analysis.

1. INTRODUCTION

Electrical distribution stations (EDS) are important structures in power systems that are designed to receive and convert the electricity supply and distribute required energy to feeders. EDS reliability study is of interest both from the point of view of the electricity company, and consumers. The failure of a component of the EDS results in loss of power to some of the consumers or to all consumers connected to the medium voltage (MV) busbar of EDS, causing their damage and high costs of electricity companies.

EDS reliability is evaluated through a set of indicators such as [1]: the probability of success and the probability of failure, the total duration of function and the total duration of failure, number of forced supply interruptions in consumers, energy not supplied to consumers, average power disconnected, equivalent failure rate, equivalent repair rate. In practice, two of these indicators are important, namely the number of interruptions and duration of interruptions at consumers.

Over time, several methods have been applied to study the reliability EDS: Markov chain method [2, 3], minimal cut set approach [4, 5], Monte Carlo simulation method [6-8], fuzzy approach [3, 9] or the approach based on failure mode and effect analysis [10, 11].

In [10] it is presented a methodology for assessing the reliability of high voltage transmission station with hierarchy structure components relative to various performance criteria of station (frequency and duration indices). In [12] power station reliability evaluation is performed using various criteria analysis.

To establish the contingencies before and after switching actions in [13] simulation algorithms are presented to evaluate the corresponding reliability indicators.

2. ANALYSIS METHOD

In this paper the EDS reliability analysis is reduced to the assessment of two main reliability indicators: number of interruptions ($\nu_C(T_A)$) and duration of interruptions ($\beta_C(T_A)$) at an equivalent consumer C, for a period of analysis (TA). Consumer C represents all consumers connected to a feeder connected to the medium voltage busbars of the analyzed EDS. The reliability analysis of the electrical distribution stations is performed using minimal cut sets technique [1, 14]. A minimal cut is composed of an element or several elements whose failure leads to the power interruption of the consumer.

The analysis considered only first and second order minimal cut set, their higher order cuts being neglected. Minimal cut set is done by visual research of the analyzed EDS configuration.

Given the failure modes of the EDS, we consider the following categories of events leading to interruption of the consumer C [1]: first-order total events (TE_I), second-order total events (TE_{II}), first-order active events (AE_I), first-order active events overlapping stuck-breaker under condition opening (AE_S).

Notion of passive failure, active failure and total failure, and also their mathematical relations are presented in [1]. Their brief description is made below.

An active failure in a component requires the operation of the protection system near its, action that causes taking out of use of the damage component and possibly of other components. The component that has suffered an active failure is isolated and then removed into repair state. Part of affected consumers can be resupplied using other ways, through successful closing of breakers. Resupplying takes place after a while, called average switching time (which is less than the time needed to repair the damage component). A passive failure in a component does not require the operation of the protection system, and does not affect other components. The component that has suffered a passive failure is isolated and then removed into repair state.

Following this type of failure the consumer could be affected if the failure forms a minimal cut of a certain order. A total failure in one component comprises both types of mentioned failures (active and passive failure). Each of the mentioned failures can be characterized by two basic indicators: active failure rate (λ^a) and average time repair (r) – for active failures; total failure rate (λ^t) and average time repair (r) - for total failures. Average time repair (r) was considered the same for all failure types [1]. These indicators are used as input data in EDS analysis.

In case of supply interruption at the consumer C, first-order total events (TE_I) and first-order active events (AE_I) involve the failure of a single element *i*. Total failures are considered by the total failure rate (λ^t_i) and active failures are considered by active failure rate (λ^a_i) of the element *i*.

After a first-order total events (TE_I) at the element *i*, the consumer is resupplied after a duration corresponding to the average repair time (r_i). After a first-order active events (AE_I) at the element *i*, the consumer is resupplied after a duration corresponding to the average switching time (t_c).

Second-order total events (TE_{II}) implies the failure of two elements *i* and *j*. Equating the two elements *i* and *j* is done using the relations [1, 14]:

$$\lambda^t_{(i,j)} = \frac{\lambda^t_i \lambda^t_j (r_i + r_j)}{1 + \lambda^t_i r_i + \lambda^t_j r_j} \tag{1}$$

$$r^t_{(i,j)} = \frac{r_i r_j}{r_i + r_j} \tag{2}$$

where, λ^t_i, λ^t_j represents total failure rate for the element *i*, respectively *j*; r_i, r_j are the average repair time for the element *i*, respectively *j*.

AE_S events imply an active failure of an element *i* overlapping with stuck-breaker who must protect the element *i*. The average interruption time of the consumer is equal the average switching time (t_c), which is considered known. The failure rate (λ_i^{Stuck}) specific to the event is determined with the relation [1]:

$$\lambda_i^{Stuck} = \lambda^a_i P_b \tag{3}$$

The main steps for the evaluation of the reliability indicators ($\nu_C(T_A)$, $\beta_C(T_A)$) at the consumer C are:

1. for each element of the EDS (breakers, disconnectors, power transformers, busbars etc), the reliability indicators (λ^a, λ^t, r) are identified based on norms; also the average switching time (t_c) and the probability of stuck-breaker (P_b) are determined;
2. minimal cuts identification of I and/or II for each of the events considered (TE_I, TE_{II}, AE_I and AE_S);
3. determination of equivalent reliability indicators for each element or pair of elements that form a particular category of events:
   - for each element *i* of TE_I category is determined the pair of indicators (λ^t_i, r_i);
   - for each element *i* of AE_I category is determined the pair of indicators (λ^a_i, t_c);
   - for each pair of elements (*i,j*) of TE_{II} category is determined the pair of indicators ($\lambda^t_{(i,j)}$, $r^t_{(i,j)}$) using the relations (1) and (2);
   - for each element *i* of AE_S category is determined the pair of indicators (λ_i^{Stuck}, t_c) using the relation (3).
4. for the events categories (TE_I, TE_{II}, AE_I and AE_S) is determined the pair of indicators (equivalent failure rate, average time of consumer C resupplying) using the series type relations (events from each category are in series with the consumer);
5. Grouping categories of events: events which determine interruptions of duration (ID), respectively events which determine interruptions short duration (IS) at consumer C. The ID interruptions include events TE_I and TE_{II}, and IS interruptions include events AE_I and AE_S;
6. for each type of interruption (ID and IS) is determined the pair of indicators (λ_{ID}, r_{ID}) and (λ_{IM}, r_{IM}), where λ_{ID}, λ_{IM} represents equivalent failure rate for ID interruptions, respectively IS interruptions; r_{ID}, r_{IM} are the equivalent average repair time corresponding to ID and IS interruptions. (λ_{ID}, r_{ID}) and (λ_{IM}, r_{IM}) indicators are determined using the series type relationship (4) - (7):

$$\lambda_{ID} = \lambda_{DT_I} + \lambda_{DT_{II}} \tag{4}$$

$$r_{ID} = \frac{\lambda_{DT_I} r_{DT_I} + \lambda_{DT_{II}} r_{DT_{II}}}{\lambda_{ID}} \tag{5}$$

$$\lambda_{IM} = \lambda_{DA_I} + \lambda_{DA_S} \tag{6}$$

$$r_{IM} = t_c \tag{7}$$

where, λ_{DTI}, λ_{DTII}, λ_{DAI}, λ_{DAS} represent equivalent failure rate corresponding to DT_I, DT_{II}, DA_I and DA_S events; r_{DTI}, r_{DTII} are equivalent average repair time corresponding to TE_I, respectively TE_{II} events;

7. determining synthetic reliability indicators for consumer C (ν_C, β_C) considering both the ID interruptions effect, as IS interruptions effect. The calculation is performed considering the two series events (ID and IS).

EDS reliability analysis is performed considering these assumptions:

- for each equipment both failure time and repair time have exponential distributions;
- the reliability of equipments and power lines that feed EDS system is not taken into account;
- the influence of weather on EDS and the influence of preventive maintenance strategies is not considered;
- each feeder connected to the medium voltage EDS busbars is represented by an equivalent element E;
- the equipments of the same type and the equipments functioning at the same voltage level have the same primary reliability indicators;
- the probability of failures of higher order than three is neglected;

3. SENSITIVITY ANALYSIS

The sensitivity analysis studies the output parameters variation in relation to the variation of the input parameters for a model. In this paper, the output parameters are the number of interruptions ID (ν_{ID}) and the number of interruptions IS (ν_{IS}) for the consumer, as the duration of interruptions ID (β_{ID}), and respectively IS (β_{IS}), for the consumer. The input parameters which are varied in this paper are: the total failure rate (λ^t_i) and the active failure rate (λ^a_i) for the equipment *i* from EDS structure.

Sensitivity analysis has in view two groups of equipments. The first group (group 1) consists of equipments of the same type, such as all disconnectors of MV or HV, all breakers of MV or HV etc. The second group (group 2) includes all equipments with the same voltage level. In this category will include: all equipments of the medium voltage, all the equipments of high voltage and the power transformers of HV/MV.

For analyzing the sensitivity of indicators ($\nu_{ID,}$ $\nu_{IS,}$ β_{ID} and β_{IS}) the following methodology was applied:

1. EDS reliability is assessed (using the algorithm presented in Section 2) for the initial case (α=0). Thus, the set of indicators ($\nu_{ID(0),}$ $\nu_{IS(0),}$ $\beta_{ID(0)}$ and $\beta_{IS(0)}$) is determined at the C consumer;
2. the total failure rate is reduced by the same percentage α ($\lambda^t_i \leftarrow (1-\alpha)\lambda^t_i$) for a type of equipment *i* from EDS structure (group 1) or for all the equipments of the same voltage level (for group 2). Average repair time r_i, average switching time t_c and the probability of stuck-breaker P_b are maintained fixed;
3. EDS reliability is reassessed using the algorithm in Section 2, and the following set of indicators ($\nu_{ID(\alpha),}$ $\nu_{IS(\alpha),}$ $\beta_{ID(\alpha)}$ and $\beta_{IS(\alpha)}$) is obtained;
4. it is calculated the relative reduction (ΔI) of the reliability indicators due to the λ^t_i rate reduction by the percentage α, for the equipment *i* (group 1, respectively group 2):

$$\Delta I=(I_{(0)}-I_{(\alpha)})\cdot 100/I_{(0)} \qquad (8)$$

where $I_{(0)}$, $I_{(\alpha)}$ represents a certain indicator ($\nu_{ID,}$ $\nu_{IS,}$ β_{ID}, β_{IS}) assessed for the initial case (α=0), respectively for a percent $\alpha \neq 0$;
5. it is identified the set of the equipments which is the most sensitive to the changes of the total failure rate λ^t_i;
6. indicator $I_{(\alpha)}$ variation it is graphic represented considering α percentage values within the range [0,100].

4. CASE STUDY

Sensitivity analysis is performed for high (HV)/medium voltage (MV) EDS type, with double system of busbars, both for HV, and MV. The analysis considers the following equipments: power transformers HV/MV (T1, T2), busbars of HV (B1, B2) and MV (B3, B4), breakers of HV (I1-I5) and MV (I6-I13), disconnectors of HV (SL1, SL2, S1-S12) and MV (S13-S30), voltage transformer of HV (VT1-VT4) and MV (VT5, VT6), current transformer of HV (CT1-CT5) and MV (CT6-CT8). The EDS scheme is shown in Fig. 1.

The primary reliability indicators of the EDS equipments are presented in Table 1 [15]. The average switching time is t_c=1.5 hours, the probability of stuck-breaker under condition opening is P_b=0.06, and the analyzed period of time is T_A=1 year.

Table 1. Equipments reliability data for EDS

Indicators / Equipment	$\lambda^t\times10^{-4}$ [1/h]	$\lambda^a\times10^{-4}$ [1/h]	$\mu\times10^{-4}$ [1/h]	r [h]
Busbar MV	0.0119	0.0107	596.49	16.76
Disconnector MV	0.0030	0.0027	588.34	17.01
Breaker MV	0.0316	0.0080	649.59	15.39
Voltage transformer MV	0.0300	0.0100	256.83	38.94
Current transformer MV	0.0090	0.0060	553.75	18.06
Busbar HV	0.0147	0.0069	500.00	20.00
Disconnector HV	0.0132	0.0024	476.19	21.00
Breaker HV	0.0902	0.0130	231.81	46.77
Voltage transformer HV	0.0210	0.0070	150.00	66.67
Current transformer HV	0.0090	0.0060	151.15	66.16
Power transformer 110/MV	0.0570	0.0370	32.46	308.07
E1	0.3605	0.3126	694.86	14.39
E2	0.4231	0.3668	671.23	14.90
E3	0.3871	0.3356	682.51	14.65
E4	0.3351	0.2905	703.25	14.22
E5	0.3011	0.2611	725.36	13.79

Table 2 shows the values of reliability indicators for consumer C ($\nu_{C(0)}$, $\beta_{C(0)}$), in the initial case (α=0).

Table 2. The reliability indicators for consumer C in the initial case (α=0)

ID Interruptions		IS Interruptions	
$\nu_{C(0)}\times10^{-4}$ [1/h]	$\beta_{C(0)}$ [h/yr]	$\nu_{C(0)}\times10^{-4}$ [1/h]	$\beta_{C(0)}$ [h/yr]
0.39472	5.043	0.29770	0.391

In Table 3 are presented the reliability indicators at consumer C ($\nu_{C(\alpha)}$, $\beta_{C(\alpha)}$) for ID and IS interruptions, in case of failure rate of each type of equipment reduced by α=25%.

Analyzing the data in Table 3 it is observed that the equipments that have the greatest influence on indicators ν_C and β_C are breakers of MV (for ID interruptions) and breakers of MV and HV and the disconnectors of MV (for IS interruptions). The equipments with negligible impact on all indicators are: busbars of MV and HV, voltage transformer and current transformer of MV. Impact on short duration interruptions is higher than on the interruptions of duration.

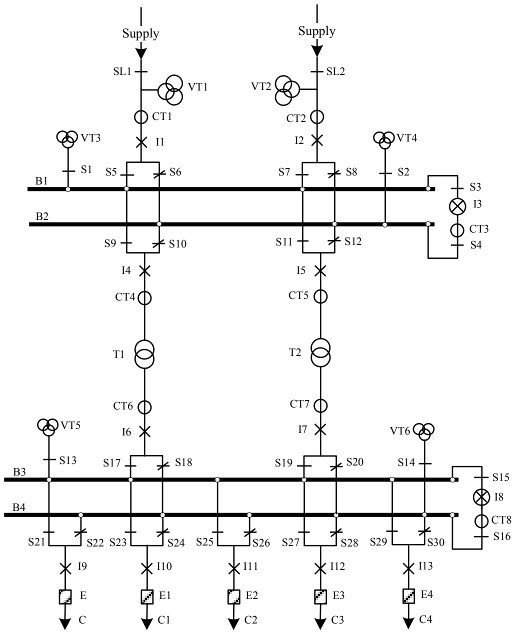

Fig. 1 - The analyzed EDS

Table 4 shows the results for the case in which the sensitivity analysis is performed for the equipments located at the same voltage level.

Table 3. The impact on reliability indicators for consumer C (group 1)

Indicators / Equipment	ID Interruptions		IS Interruptions	
	$\nu_{C(\alpha)}\times 10^{-4}$ [1/h]	$\beta_{C(\alpha)}$ [h/yr]	$\nu_{C(\alpha)}\times 10^{-4}$ [1/h]	$\beta_{C(\alpha)}$ [h/yr]
Breaker MV	0.38678	4.936	0.28470	0.374
Disconnector MV	0.39434	5.038	0.28656	0.377
Voltage transformer MV	0.39472	5.043	0.29520	0.388
Current transformer MV	0.39471	5.043	0.29734	0.391
Busbar MV	0.39472	5.043	0.295025	0.388
Breaker HV	0.39453	5.038	0.28307	0.372
Disconnector HV	0.39470	5.043	0.29283	0.385
Voltage transformer HV	0.39471	5.043	0.29574	0.389
Current transformer HV	0.39470	5.042	0.29716	0.390
Busbar HV	0.39472	5.043	0.29597	0.389
Power transformer	0.39450	5.027	0.29548	0.388

Following the results of Table 5 it is noticed that the MV equipments have a greater impact than those of HV, on the indicators ν_C and β_C. Also, IS interruptions are changing more than ID interruptions. The relative reduction of the indicators ν_C and β_C, in case of IS interruptions, is the same because the average switching time (t_c) is the same for any resupplying operation of the C consumer.

Table 4. The impact on reliability indicators for consumer C (group 2)

Indicators / Equipment	ID interuptions		IS interuptions	
	$\nu_{C(\alpha)}\times 10^{-4}$ [1/h]	$\beta_{C(\alpha)}$ [h/yr]	$\nu_{C(\alpha)}\times 10^{-4}$ [1/h]	$\beta_{C(\alpha)}$ [h/yr]
All MV equipments	0.38639	4.930	0.26803	0.352
All HV equipments	0.39447	5.037	0.27398	0.360
Power transformer	0.39450	5.027	0.29548	0.388

Table 5. The relative reduction (ΔI, $I=\{\nu,\beta\}$) of reliability indicators for consumer C (group 2)

Indicators / Equipment	ID interuptions		IS interuptions	
	$\Delta\nu_{C(\alpha)}$ [%]	$\Delta\beta_{C(\alpha)}$ [%]	$\Delta\nu_{C(\alpha)}$ [%]	$\Delta\beta_{C(\alpha)}$ [%]
All MV equipments	-2.110	-2.236	-9.967	-9.967
All HV equipments	-0.063	-0.129	-7.968	-7.968
Power transformer	-0.057	-0.318	-0.746	-0.746

Fig. 2 and Fig. 3 present the evolution of indicator ν_C (for ID and IS interruptions), when the level of reliability of the equipments with greater impact (HV and MV breaker, HV and MV separator, HV/MV transformer) improves with α={25%, 50%, 75%, 100%}.

In Fig. 2 and Fig. 3 it is observed that the evolution of indicator ν_C (for ID and IS interruptions) by the increase of the reliability level of the equipments (factor α) is linear. The indicator β_C has also the same trend for all types of equipments. These observations are also maintained for the sensitivity analysis of the equipments with the same voltage level (group 2).

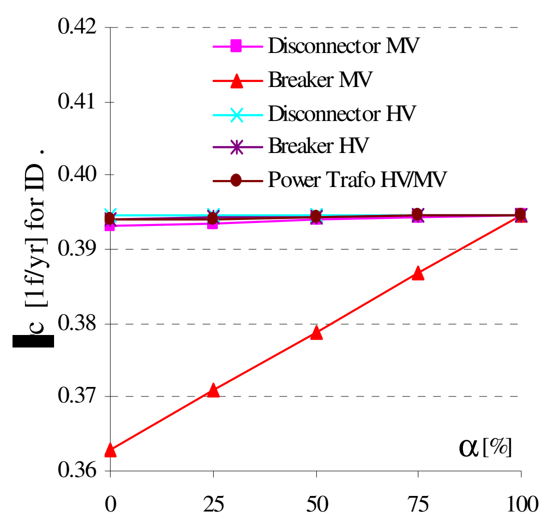

Fig. 2 - The evolution of indicator ν_C (ID interruptions) by the factor α

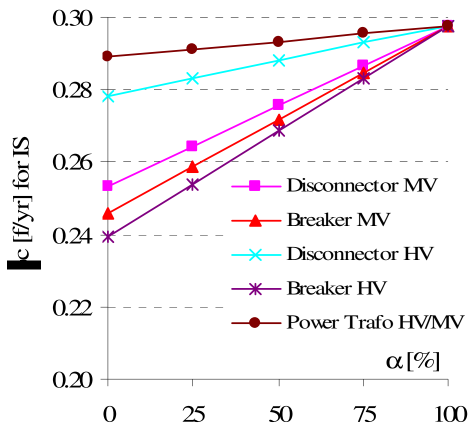

Fig. 3 - The evolution of indicator ν_C (IS interruptions) by the factor α

5. CONCLUSIONS

The goal of the paper is to analyze the sensitivity of two main reliability indicators (number of interruptions and duration of interruptions) for a consumer supplied by an EDS of HV/MV with a double busbars system at both voltage levels. The analysis is performed considering both events which cause lasting interruptions (ID) and those leading to short duration interruptions (IS).

The results of the case study show that EDS equipment with the greatest impact on the indicators (ν_C, β_C) is the breaker of MV (for ID interruptions) and the breakers of HV and MV (for IS interruptions). The MV disconnectors have also an important weight. If the study is performed for group 2 it is noticed that the MV equipments have a higher impact than the HV equipments on both indicators (both for ID interruptions, and for IS interruptions). Also, it can be seen that the evolution of indicators (ν_C, β_C) by the factor α is linear.

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