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INFLUENCE OF CIRCUIT BREAKER REPLACEMENT ON POWER STATION RELIABILITY *

Dragan Stevanović[1], Aleksandar Janjić[2]

[1]Electric Power Industry of Serbia, Zaječar, Serbia
[2]Faculty of Electronic Engineering, Niš, Serbia

Abstract. *In this paper, the new methodology for the determination of circuit breakers (CB) replacement time has been proposed. The methodology is based on statistical analysis of condition monitored data and the impact on substation reliability. Influence of CB removal on substations reliability is presented together with cost justification of such investment. Using statistical data of 427 CBs gathered in past 10 years, Weibull probability distribution of contact resistance for breakers on both overhead and underground feeders and voltage levels of 35 kV and 10 kV is determined. Substations reliability is calculated using minimal path and minimal cuts method. With this methodology influence of CB's condition on substations reliability can be observed by using real field data. Example of calculation is shown on 35/10 kV substation. Substation reliability calculation is carried out for 5 different scenarios of CB removal with their expenses. At the end, discounted investment costs for each action and period of 5 years are calculated and are shown in table. For this substation final results are showing best scenario with removal CB's on power transformers.*

Key words: *circuit breaker, cost evaluation, substation, reliability, Weibull distribution.*

1. INTRODUCTION

Circuit breaker is a device used for switching feeder power supply in any working mode (normal load, no load, short circuit current…), and therefore represents the vital element of power system operation. CB failure threatens work of other equipment, which directly affects reliability of whole substation. This makes good reason of finding correlation between CB condition and substations reliability.

To determine economic effects of maintenance, overhaul or CB removal [2], [3], assessment of circuit breakers remaining useful life (RUL) must be done [4], [5]. Remaining useful life is the lifetime from current time to the time that the device fails [2]. It is random variable which depends on various factors (device age, working conditions,

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Corresponding author: Dragan Stevanović
Electric Power Industry of Serbia, 19000 Zaječar, Serbia
(E-mail: dragan.stevanovic3@epsdistribucija.rs)
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and level of maintenance) [6]. If the failure time of the population follows the probability density function (PDF) f (t), then the population mean time to failure (MTTF) can be calculated by (1):

$$MTTF = \int_0^\infty tf(t)dt = \int_0^\infty R(t) \tag{1}$$

$R(t)$ is the survival function at t. Let define X_t as the random variable of the RUL at time t, then the probability density function (PDF) of X_t conditional on Y_t is denoted as $f(x_t/Y_t)$ where Y_t is the history of operational information up to t. If Y_t is not available then the estimation of $f(x_t/Y_t)$ is:

$$f(x_t/Y_t) = f(x_t) = \frac{f(t+x_t)}{R(t)} \tag{2}$$

where $f(t + xt)$ is the PDF of the life at $t + x_t$

CB's reliability analysis depends of type of available data, which can be: contact resistance, commutation noise, erosion resistance [7], ultrasound detectors, transient earth voltage, infrared thermo scanning [8], CB control circuit data [9] and collected data of CB faults [10]. Depending of collected data type, RUL can be assessed with: knowledge-based models (fuzzy method [11]); life expectancy models (statistical method [6], [12] – [16]); artificial neural networks and physical models [5].

Utilities, grid operators and industrial power consumers are facing unprecedented challenges. With increasingly aging infrastructure combined with cost-cutting pressures to operate into today's competitive environment, prioritizing investment has never been so important [17].

In [18] reliability of different substation configurations is evaluated using the minimal cut-set method based on the criterion of continuity of service.

In [19] reliability indices of each failure events and entire reliability indices in the ring bus substation and double bus double breaker substation were calculated and quantitatively compared.

Method that combines the modeling of failures and repairs as stochastic point processes and a procedure of sequential Monte Carlo simulation for computing the reliability indexes is presented in [20].

In [21] comparison between the reliability of different substation constructions is shown.

A number of methods have been used in determining the final substation indices, such as Markov model, minimal cut-set method based on the criterion of continuity of service. [22] have developed a Monte Carlo approach to solving a system with non-Markovian models.

The mostly used methods are fault tree analysis, event tree analysis, Monte Carlo simulation and State enumeration [21].

Because of importance of reliability, some companies [17] are started to use software, algorithms and analysis techniques for reliability management services to provide substation owners with the right insights to make optimal investments to improve system performance.

2. CB Ageing Process

The main causes of CB deterioration are the age, the number of operations under normal and fault conditions and the operational conditions like the temperature and contaminants content.

Measuring the contact resistance is usually done by using the principles of Ohm's law. Since the interrupting chamber is a closed container, we have only access to the entry and exit conductors; the measured *R* between these two points would be the sum of all the contact resistances found in series, (fixed, make-break and sliding contacts). According to the IEC 60694 [23], article 6.4.1, the current value to use should be the closest to the nominal current the interrupting chamber is designed for. If it is impossible to do so, lower currents can be used but not less than 50 A to eliminate the galvanic effect that might affect the readings.

2.1. Data collecting

Analysis covers 42 35/10 kV substations and 427 circuit breakers, mounted on 10 kV and 35 kV feeders. Measurement of static contact resistance presented by the voltage drop on contacts is collected in past 10 years, where voltage drop was measured on every two years.

Other data regarding to circuit breakers that are collected are: voltage level, feeder type, manufacturing year, number of fault trips, number of short circuit current trips, number of customers, and annual consumption.

Depending on CB's nominal current and nominal voltage allowed voltage drop goes from 3.5 mV up to 14 mV [24]. Analyzed CBs have following maximal voltage drop values: 35 kV CB's: 3.5 – 7 mV; 10 kV CB's: 7 – 14 mV. Manufacturer manual [24] states that CB must be completely overhauled after: 10-12 years of service, or 5000 operations, or 6 short-circuit currents breaking.

Measurement has been done with DC current of I=100A, measuring voltage drop on every CB's pole. Fig. 1 shows voltage drop distribution among all currently available data, with values divided into 4 categories depending of voltage drop level.

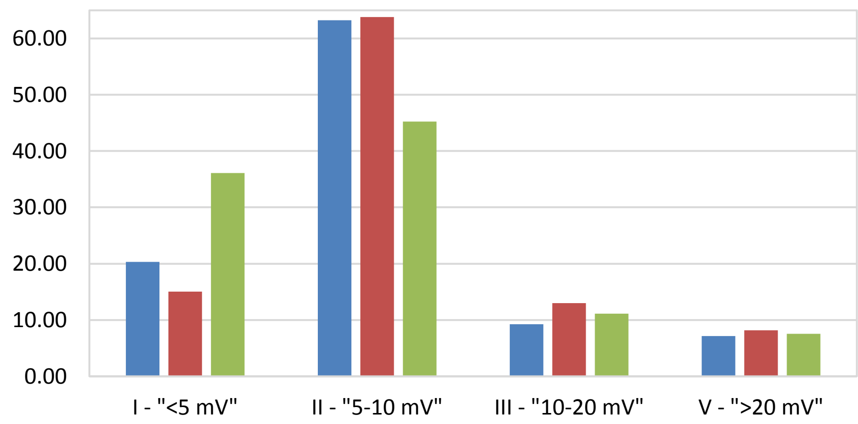

Fig. 1 Voltage drop distribution on analyzed circuit breakers

2.2. Data analyzing

In first step, state of every CB is determined, according to its voltage drop value. CB’s with voltage drop value beyond permissible are set in “failed” state (F), and those which still have voltage drop value below allowed are in “suspension” state (S). For failed CB’s precise year of reaching that condition is defined.

From manufacturers manual [24] allowed voltage drop values are dependent on CB’s rated voltage and rated current, and manufacturer allows them to surpass the permissible value for 25%. For that reason, CB’s are also analyzed for two different criterions:

1) Maximal allowed voltage drop value is as in manufacturers table,
2) Maximal allowed voltage drop is 25% greater than recommended values.

Weibull distribution is most commonly used method for equipment failure, ageing and reliability analysis [25]. It can describe three types of equipment states (infant mortality, normal work, wear out), through bathtub curve [26].

Weibull cumulative distribution function represents probability of failure in given period of time (3). It is two-parametric distribution, with slop parameter η and shape parameter β.

$$F(t) = 1 - e^{\left(\frac{t}{\eta}\right)^{\beta}} \tag{3}$$

Slop parameter shows time at which 63.2% of analyzed units are failed. Shape parameter represents failure rate behavior. Its value tells whether failures are decreasing or increasing. β<1 indicates infant mortality, while β>1 show wear out failures. Higher value of beta indicates greater rate of failure. In table 1 Weibull parameters for different criteria are shown.

Table 1 Weibull parameters

CB feeder type	η	β	Fail \ Suspens
Overhead +25%	39.1	5.2	100 \ 87
Overhead	37.1	4.8	131 \ 56
Underground +25%	41.5	6.1	63 \ 169
Underground	38.1	6.1	97 \ 135
10 kV feeders +25%	43.4	5.6	87 \ 224
10 kV feeders	40.4	5.1	135 \ 176
35 kV feeders +25%	35.2	5.6	79 \ 31
35 kV feeders	33.8	5.6	96 \ 14
all feeders +25%	40.4	5.6	166 \ 255
all feeders	38.0	5.3	231 \ 190

By observing Weibull parameters two conclusions could made, underground feeders (both criteria of voltage drop value limit) have highest β while overhead feeder have lowest value. Considering η parameter, 10 kV feeders (+25% limit voltage drop level) have closer time to failure, while 35kV feeders have lowest η value.

Both β and η parameters are calculated for the whole CB population from the statistical data using the least square method [27]. Weibull distribution function with right censored data (case when some devices didn’t fail during period of analysis) unreliability is calculated for all CB’s categories. On figures 2-5 unreliability distribution of different criterions is shown, and specific values for unreliability and failure rate regarding CB’s age from this example are shown in Table 2.

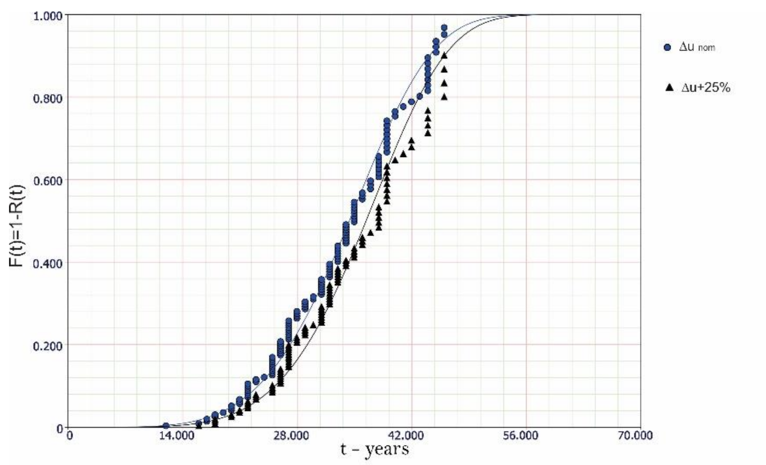

Fig. 2 Weibull unreliability distribution for CBs on overhead feeders

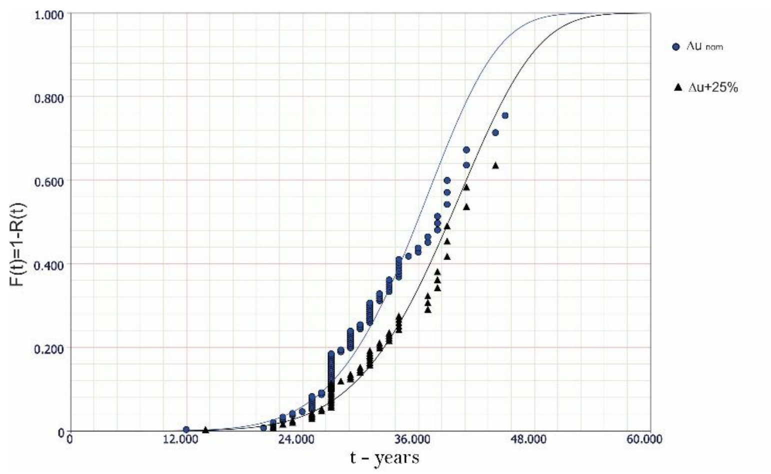

Fig. 3 Weibull unreliability distribution for CBs on underground feeders

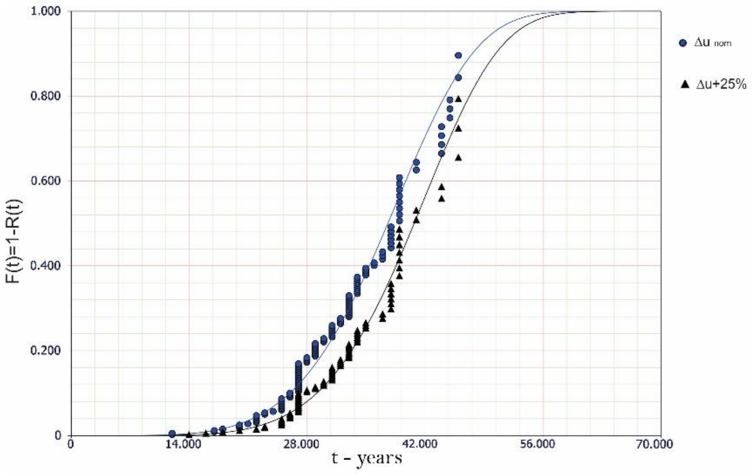

Fig. 4 Weibull unreliability distribution for CBs on 10 kV overhead feeders

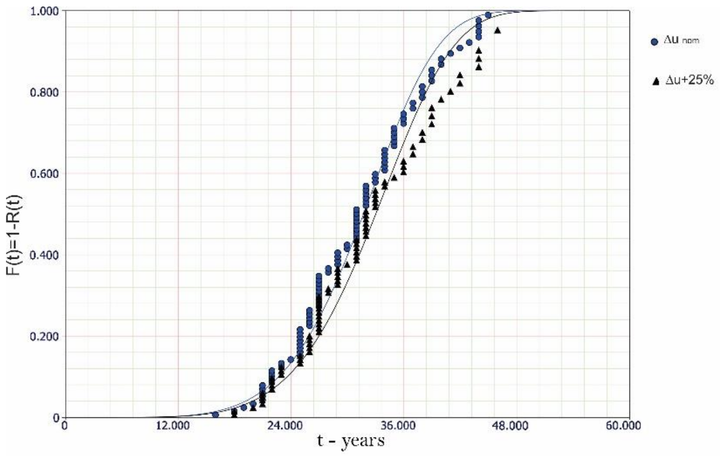

Fig. 5 Weibull unreliability distribution for CBs on 35 kV overhead feeders

Table 2 CB's reliability indices from Weibull analysis

Feeder type	Age	Unreliability	Failure rate
Transformer 35 kV	32	0.532	0.226
Transformer 10 kV	41	0.278	0.11
Supply 35 kV	32	0.532	0.226
Load 10 kV	41	0.612	0.11

Considering age of CB's in substation from example, values of reliability indices obtained in previous analysis are shown in Table 2.

3. SUBSTATION RELIABILITY ANALYSIS

In this example 35/10 kV substation is used, which has two 8MVA power transformers, two 35 kV supply feeders and ten 10 kV feeders. Functional blocks are defined and shown in Fig. 6.

Functional block consists of elements which would be out of supply if only one of them fails. Active failure is an event that causes the protection system to operate and isolate a failed component [18].

Active failure events refer to all failures that induce the actions of protective breakers adjacent to the component where failure occurred and affect normally operating components where no failure occurred [19].

A minimal cut-set is a set of components that when all fail, the continuity of service is lost, but if any one of the components doesn't fail, the continuity remains [18].

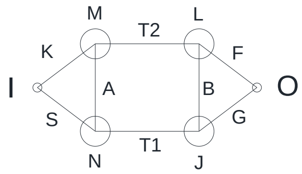

Fig. 6 Functional graph

Using functional blocks from Fig. 6, functional graph can be created (Fig. 7). In this case it is considered that 10kV feeders can supply the same load (ring connection).

Substations reliability is calculated with minimal path and minimal cuts method [28].

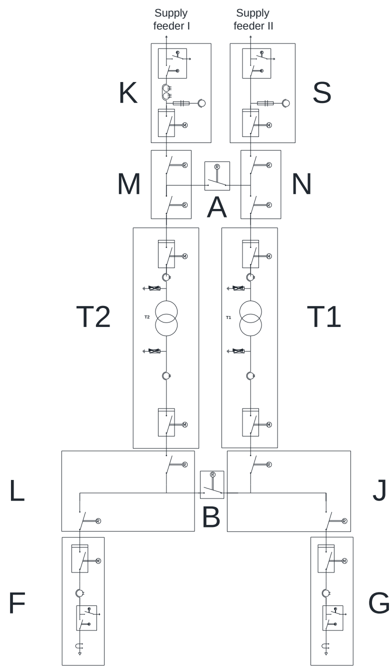

Fig. 7 Functional blocks of substation

3.1. Minimal path method

Path is serial connection of graph branches which connects input and output nod. Minimal path doesn't cross the same nod more than once. Highest order of minimal path is by one less than number of network nods. In this case (Fig. 6), number of nods is m=6 and connection matrix C will have dimension *m*x*m*, where the element E_{ij} is branch which connects nods „*i*“ and „*j*“.

$$C = \begin{bmatrix} 0 & K & S & 0 & 0 & 0 \\ K & 0 & A & T2 & 0 & 0 \\ S & A & 0 & 0 & T1 & 0 \\ 0 & T2 & 0 & 0 & B & F \\ 0 & 0 & T1 & B & 0 & G \\ 0 & 0 & 0 & F & G & 0 \end{bmatrix} \quad (4)$$

Minimal paths of first order doesn't exist here, because there is no just one branch which connects input and output nod.

Minimal paths of second order are obtained by multiplying (from right side) first row of matrix *C* with whole matrix *C*.

Minimal paths of third order are obtained by multiplying former result with whole matrix *C*. Identical process is carried for minimal paths of next orders.

After calculations, minimal paths are:

III: FKT_2, SGT_1

IV: $KAT_1G, KT_2BG, SAT_2F, ST_1BF$

V: KAT_1BF, SAT_2BG

3.1. Minimal cuts method

Cut of a graph consists of group of branches by which removal connection between input and output nod is broken. Minimal cut is unique and doesn't include other cuts.

Matrix of minimal paths *P* (5), with size *mxn*, where is *m*- number of minimal paths and *n* – number of branches, has elements E_{ij} which are equal to 1 if branch „*j*“ is part of the minimal path „*i*“, otherwise it is equal to 0.

If minimal paths are given in next order:

FKT_2; SGT_1; KAT_1G; KT_2BG; SAT_2F; ST_1BF; KAT_1BF; SAT_2BG

And branches are defined in next order:

K, S, A, T1, T2, B, F, G.

For the graph from Fig. 6 matrix of minimal paths is:

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 & 1 & 0 & 1 \end{bmatrix} \quad (5)$$

If all elements of one column are all equal to 1, then that branch is minimal cut of first order. Minimal cuts of second order are obtained by adding columns of matrix P (every column is added to next columns). Adding is done by law of Bool algebra (1+1=1, 1+0=1, 0+1=1, 0+0=0).

As the result, minimal cuts of second and third order are:

II: K-S, T1-T2, F-G

III: K-A-T1, S-A-T2, T1-B-F, T2-B-G

Connection between input and output nod of the functional graph is broken when all branches that are part of cut are broken. In other words, connection is broken if at least one minimal cut is broken.

With all results that are obtained so far, equivalent minimal paths graph of substation can be made (Fig. 8).

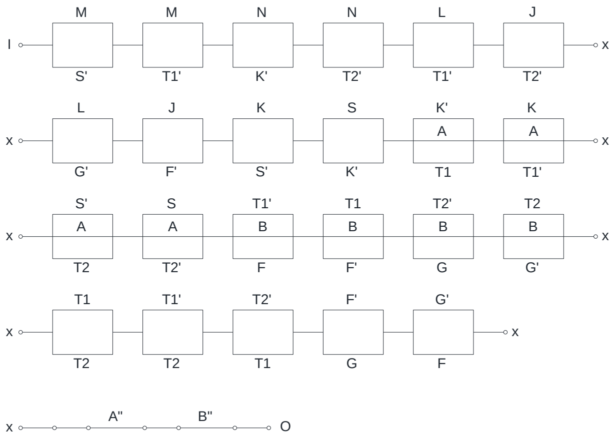

Fig. 8 Equivalent minimal paths graph

4. DIFFERENT SCENARIOS OF CB REPLACEMENT

Analysis of CB replacement profitability and its influence on substations unreliability is shown through 4 different scenarios. New CB unavailability would be equal to *U=0.00000822* [21] (with assumption that failure frequency and probability of failure are remaining unchanged).

List of actions:

- I – No CB replacement
- II – Replacement of all CB’s on 10 kV feeders
- III – Replacement of CB’s on supplying feeders
- IV – Replacement of CB’s on power transformers
- V – Replacement of all CB’s

Results of each action, depending of time they are taken, are shown in Table 3 (and also Fig. 9-10), while Table 4 show how each action affects power stations unavailability and failure frequency.

Table 3 Unavailability results in different scenarios

Year	Action				
	I	II	III	IV	V
1	0.50038	0.48357	0.47501	0.04219	1.40364E-05
2	0.62222	0.60417	0.59232	0.04796	1.40364E-05
3	0.72393	0.70440	0.69079	0.05269	1.40364E-05
4	0.78698	0.76531	0.75203	0.05664	1.40364E-05
5	0.83704	0.81432	0.80080	0.05897	1.40364E-05

Table 4 Power station unavailability regarding of year taking action

	Results of different actions (%)			
Parameter	Action II	Action III	Action IV	Action V
Unavailability reduction (%)	3.36	5.07	91.57	99,99
Failure frequency	8.73	6.59	80.26	95.59

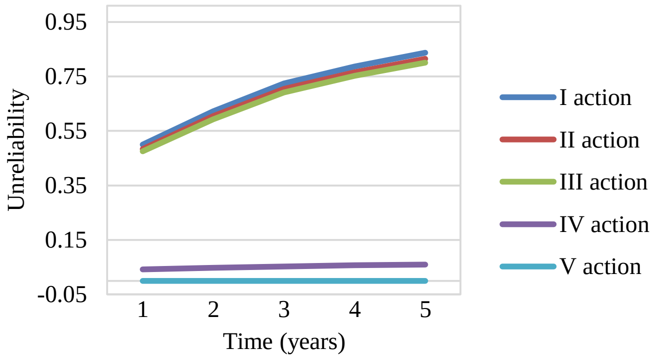

Fig. 9 Power stations unreliability in next years for each action (Columns from table 3)

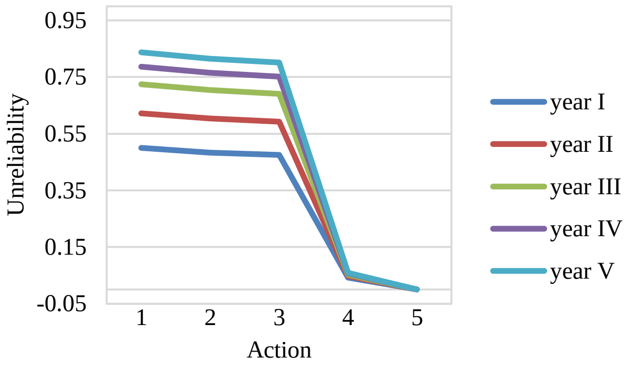

Fig. 10 Power stations unreliability regarding taken action (Rows from table 3)

5. Cost Estimation of Actions

Considering price of CB replacement of 5 000 $ for 35 kV CB and 2 000 $ for 10 kV feeder (including labor cost) with average time of replacement of 6 hours (from decision making, transporting and mounting), cost of different actions is presented in Table 5. Column “maintenance” covers regular maintenance costs of old circuit breakers which are not replaced, and column “replacement” consists of replacement costs only. Values in column “sum” are total costs in the year of investment (maintenance of not replaced CB’s and costs of newly installed CB’s).

Table 5 Cost of CB replacement

Action	Description	Maintenance ($)	Replacement ($)	Sum ($)
I	No CB replacement, only costs of maintenance	13 200	0	13 200
II	Replacement of CB’s on all 10 kV feeders	2 400	38 800	41 200
III	CB replacement on 35 kV supply feeders	12 400	14 800	27 200
IV	Replacement of CB on power transformers	11 600	23 600	35 200
V	Replacement of all CB’s in power station	0	77 200	77 200

Considering probability of CB failure due to its age and condition, costs of unplanned failure are calculated and presented in Table 6.

Table 6 Variable costs per CB, considering probability of failure

CB (feeder)	year				
	I	II	III	IV	V
trafo 35	3,936.80	4,639.80	5,143.00	5,424.20	5,624.00
trafo 10	1,223.20	1,368.40	1,579.60	1,760.00	1,966.80
Kladovo I	4,528.80	4,861.80	5,261.40	5,838.60	6,119.80
CS Carina	11,872.81	12,745.83	13,793.50	15,306.87	16,044.43
Zelezara	11,873.07	12,747.18	13,798.03	15,318.13	16,068.36
CS Jezero	11,884.33	12,794.19	13,932.46	15,627.93	16,657.18
Radio Stanica	11,872.80	12,745.80	13,793.40	15,306.60	16,043.80
Other feeders	3,936.80	4,639.80	5,143.00	5,424.20	5,624.00

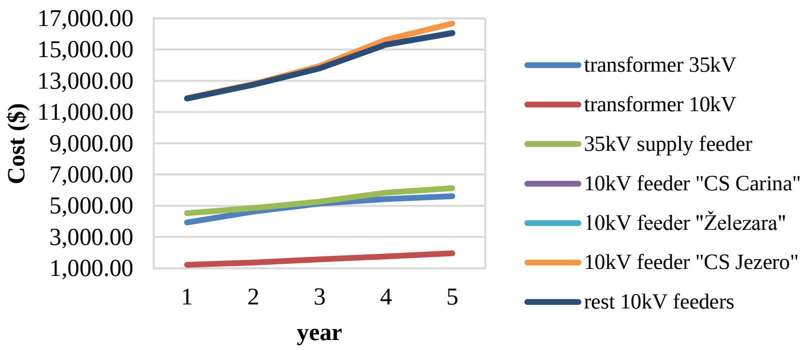

Fig. 11 Variable costs per CB

6. PRESENT COST VALUE CALCULATION

Calculating present value is done by equation (6):

$$C_{pv} = \frac{C_{fv}}{(1+i)^n} \tag{6}$$

where is:
C_{pv} – present value
C_{fv} – future value
i – rate
n – time period

Following calculation is carried for rate of $i = 9\%$, and future value (expected costs in next 5 years) is calculated with equation (7):

$$C_{fv} = (C_{mn} + C_{inv} + C_{un}) \tag{7}$$

C_{mn} – costs of planned maintenance (Table 5)
C_{inv} – costs of new investments (Table 5)
C_{un} – unpredictable costs due to CB's failure (Table 6)

Example of present value calculation (fourth year, II action):

$$C_{pv} = \frac{(C_{mn} + C_{inv} + C_{un})}{(1+i)^n} = \frac{(2\ 400 + 38\ 800 + 40\ 414)}{(a + 0,09)^4} = 57\ 817.42\ \$ \tag{8}$$

Using equations (6) and (7), present values of all actions in following years can be calculated. Results are shown in Table 7.

Table 7 Present value ($) of all actions in next 5 years

Action	Cost type	year				
		1	2	3	4	5
I	Sum	103,701.41	113,811.80	123,343.39	133,350.33	139,178.97
	Discounted costs	95,138.91	95,793.12	95,243.73	94,468.74	90,456.78
II	Sum	70,897.60	74,956.40	78,613.20	81,614.00	83,802.80
	Discounted costs	65,043.67	63,089.30	60,703.81	57,817.42	54,466.07
III	Sum	257,707.81	293,331.40	321,446.19	341,504.33	355,204.17
	Discounted costs	236,429.18	246,891.17	248,215.44	241,930.28	230,858.34
IV	Sum	115,381.41	123,795.40	131,898.19	140,981.93	145,997.37
	Discounted costs	105,854.50	104,196.11	101,849.60	99,875.15	94,888.27
V	Sum	77,200.00	77,200.00	77,200.00	77,200.00	77,200.00
	Discounted costs	70,825.69	64,977.70	59,612.56	54,690.43	50,174.70

Total expected costs considering fixed (Table 5) and variable costs (Table 6) are put together for every action, and their discounted value is calculated.

7. CONCLUSION

The determination of CB replacement time is a complex procedure depending on various stochastic factors. Substations reliability analysis can be used for determining size of both asset replacement and new investments and their financial justifications as well. Using statistical data of 427 CBs gathered in past 10 years, Weibull probability distribution of contact resistance for breakers on both overhead and underground feeders and voltage levels of 35 kV and 10 kV proved to be the best fit. CB's removal has been assessed by the risk assessment and substation's reliability improvement calculation. Results are showing that the first candidates for the replacement are those CB's with the biggest influence on substations reliability.

Obtained results are showing that the maximal increase in substation reliability regarding invested money can be obtained with the replacement of CB's on power transformers (Action IV). In that case unavailability is decreased by ~92% with investment of 23 600 $ for replacement of 4 circuit breakers. Used methodology is easy to utilize because all data are already available and there is no need for extra investments or labor cost in order calculation to be carried out.

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