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Estimation of Economical Validity of Usage Remote Operated Disconnectors for 110kV Switchgear Schemes From Optimal Reliability Level Point of View

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***Abstract* – The paper gives results of technical and economical calculations performed for estimation of validity of usage remote operated disconnectors for most commonly used 110kV switchgears from optimal reliability level point of view. Paper contains description of performed technical calculations – calculations of 110kV switchgear schemes' reliability level depending on type of disconnectors installed, and economical calculations, that are related with additional costs of Transmission System Operator and changes in total customer costs of power supply interruptions.**

***Keywords* – 110kV switchgear scheme, power supply interruption costs, reliability, remote operated disconnector.**

I. Introduction

Nowadays electrical energy plays big role in economics of each country. Introduction of new power quality sensitive equipment that lasted for several decades results in higher standards for quality of electricity. Taking into account liberalization processes of electrical energy sector higher attention should be paid to optimal reliability level.

Finding a compromise between "reliability" and "costs" has been a subject of discussion for several decades now and will likely to continue for years to come. Cost-estimation studies are an important tool to be able to estimate an optimal level of continuity of supply, that in its turn shows reliability level. The "optimal continuity of supply" can be different for different regions (urban versus rural) and for different types of customers (e.g. industrial versus domestic). In order to find the optimal level of reliability from society's point of view, it is imperative to balance the various cost-elements towards each other, i.e. the costs associated with reducing the scope of interruptions must be compared to the possible reduction in the customer's costs resulting from the same actions. Optimal reliability level is achieved when sum of utility costs and customer interruption costs is minimal.

To find out 110kV switchgear schemes for which usage of remote operated disconnectors will ensure optimal reliability level, customer power supply interruption costs were defined using power supply interruption costs of customers from foreign cost studies and by applying methodology, that separates consumers in different categories – for rural and city substations. Such approach of calculations helps to make calculations more precise comparing with situation when using just average value of interruption costs. Previously mentioned estimation of costs is performed in the second section.

The third section describes methodology of reliability level calculation for typical 110kV switchgear schemes as well as gives initial data used for reliability calculations.

In the fourth section there are given results of calculations for 110kV switchgears with air or SF_6 circuit breakers, 110kVoverhead or cable lines for two cases – with manually and remote operated disconnectors. The fourth section also gives results of economical calculations and economical evaluation of reasonability of remote operated desconnectors installation.

At the end of the paper conclusions are given.

II. Customer power supply interruption costs

To evaluate customer power supply interruption costs (in other words – Customer Costs of Reliability (CCR)) for particular substation, information about the distribution of customers over the country depending on the sector (in the paper it is assumed that all electrical load is divided in such sectors – Industry, Transport, Households, Services and constructions, Agriculture) and information about the proportion of the sectors in energy consumption over the country is required.

Analysis of geographical allocation of consumption sectors performed by authors of the paper showed, that load from industrial sector is usually placed close to industrial parks, where necessary workforce and main consumers of production are located. As example, metal-fabricating industry's companies can be mentioned [1]. Analysis of statistical data from databases of the Central Statistical Bureau of Latvia [2], [3] showed, that the share of the sector „Services and construction" in a region is proportional to the number of inhabitants or population density of a region. That means that consumption of service sector will change proportionally as the population changes. The part of transport sector that consumes electricity, is concentrated in cities (trams, trolleybuses, water transportation) and at ambit of cities (electric trains). Load from agriculture sector lies outside borders of cities – in rural territory.

On the basis of analysis of geographical allocation of different sectors of consumers, we can define substations with typical load, or Typical Substations (TS). There can be:

1. City substations;

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Volume 28

2. Rural substations;
3. Industrial substations.

City substations have load from all sectors excluding agricultural sector. As soon as city substations don't have agricultural load, shares of other sectors should grow proportionally to their initial value. Rural substations have only three representatives of the sectors – households, agriculture and services and construction. Because of the fact, shares of energy consumption by sectors also should be calculated anew. Industrial substations are specially built substations for a particular factory. As an example, substation "Liepajas metalurgs" near city Liepaja in Latvia can be mentioned.

In case if information about shares of electrical energy consumption by sectors for typical substations is known, (1) can be used for calculations of CCR value for TS. It should be mentioned that proposed equation requires information not only about the shares of sectors in electricity consumption, but also about shares of subsectors in sectors (e.g. road transport, rail transport and pipeline transport subsectors in Transport sector) and their power supply interruption costs. Usage of the option of dividing formula by subsectors helps to make calculations more precisely and can be used if shares in total energy consumption of sector and CCR of subsectors are known.

$$CCR(t) = \sum_{i=1}^{n} S_i \sum_{j=1}^{m} S_{ij} \cdot C(t)_{ij} \quad (1)$$

where *CCR(t)* – customer costs of reliability [monetary unit/kW];
i – number of type of sector;
j – number of type of subsector;
n – total number of sectors *i*;
m – total number of subsectors *j* in sector *i*;
S_i – share of sector in total electricity consumption of country [%];
S_{ij} – share of subsector in electricity consumption of sector [%];
$C(t)_{ij}$ – power supply interruption costs for subsector, that depends on time (duration) of interruption [monetary unit/kW].

Table I gives shares of sectors' consumption in Latvia in year 2009 (according to [4]) and shares of sectors for rural and city substations which were calculated anew taking into account the fact, that all sectors are not represented in city substation, nor in rural substation.

Nowadays there are enough researches performed to define CCR for sectors, e.g. [5], where information about CCR is collected from more than 20 different sources, including 6 papers and books of R. Billinton. Table II gives information about costs that have been calculated using (1) and information from [4] and [5].

III. Estimation of Reliability Level of Typical 110kV Switchgear Schemes

In this subsection there are given five switchgear schemes. Some of the schemes (schemes at Fig.1. and Fig.2.) are traditionally used in Latvia. Other schemes have been taken with the aim to make comparison of reliability level of HV switchgear schemes. These configuration of schemes have been taken from [6], [7] and are more typical schemes. Usage of the schemes allows connecting up to 4 lines to each substation.

Reliability indicators of equipment installed at 110kV switchgears are given in Table III.

Reliability indicators given in Table I are such [6], [7], [9]: λ – failure rate (shows number of equipment's outages per year); T – repair time (gives information about time (in hours) needed for repair of equipment); μ_m – shows number of usual maintenance works performed for particular equipment during a year; μ_o – shows number of overall maintenance works performed for particular equipment during a year; T_m and T_o – time in hours needed for performing respectively usual and overall maintenance.

TABLE I
Shares of sectors' consumption in Latvia in year 2009

Sector	Consumption in 2009 (GWh)	Share of consumption (%)	Share of consumption in substation (%)	
			City	Rural
Transport	121	1.98	2.03	-
Industry	1389	22.76	23.27	-
Services and construction	2458	40.28	41.19	53.52
Households	2000	32.77	33.51	43.54
Agriculture	135	2.21	-	2.94

TABLE I
Shares of sectors' consumption in Latvia in year 2009

Sector	Interruption costs by sectors (US$/kW)		
	20 min	1 hr	4 hr
Transport	2.35	4.59	23.11
Industry	2.72	6.52	24.90
Ser. and constr.	4.83	16.01	55.64
Households	0.03	0.15	1.64
Agriculture	0.02	0.12	1.28

TABLE III
Reliability indicators of equipment installed at 110kV switchgears

Type of element	Reliability indicators					
	λ, 1/year	T, h	μ_m, 1/year	T_m, h	μ_o, 1/year	T_o, h
Transformer	0.02	100.00	2.00	12.00	0.17	300.00
Cable line*	0.11	18.00	0.00	0.00	0.00	0.00
Overhead line	1.10	9.00	10.00	12.00	0.00	0.00
SF_6 circuit breaker	0.05	25.00	1.00	8.00	0.00	0.00
Air circuit breaker	0.10	25.00	2.00	10.00	0.20	230.00
Busbar	0.01	2.00	1.00	2.00	0.00	0.00
Disconnector	0.03	2.16	0.00	0.00	0.00	0.00
Transformer	0.02	100.00	2.00	12.00	0.17	300.00
Cable line*	0.11	18.00	0.00	0.00	0.00	0.00

* for cable line failure rate is assumed to be 10 times smaller but repair time – 2 times bigger comparing with overhead line.

Scientific Journal of Riga Technical University
Power and Electrical Engineering
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Volume 28

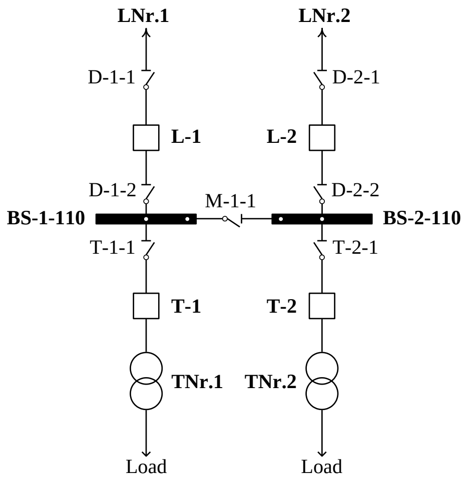

Fig. 1. Scheme with one busbar (two sections), circuit breakers for all connections and disconnector between busbar sections (without switched busbar circuit-breaker)

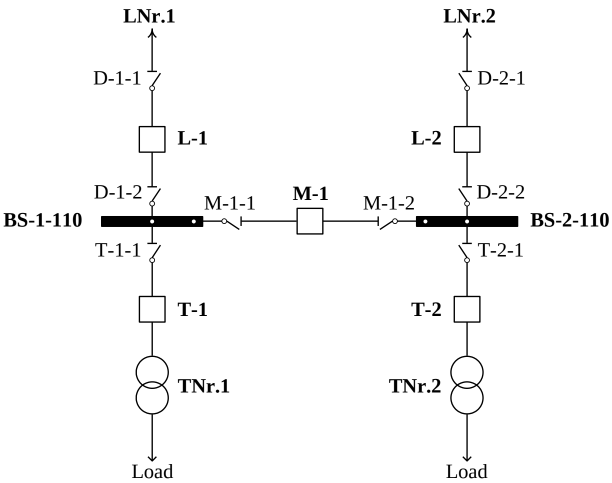

Fig. 2. Scheme with one busbar (two sections), circuit breakers for all connections and switched busbar circuit-breaker

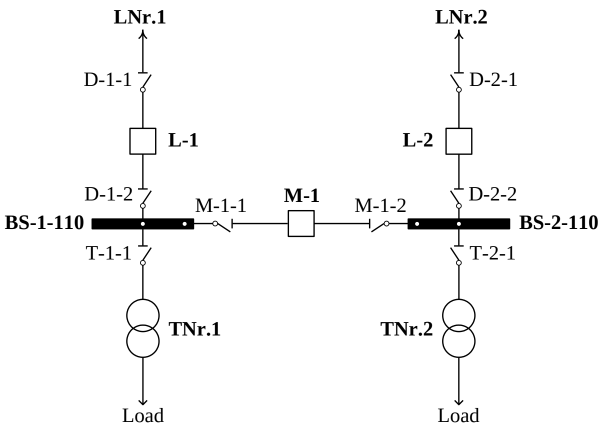

Fig. 3. Scheme with one busbar (two sections), circuit breakers for line connections and switched busbar circuit-breaker

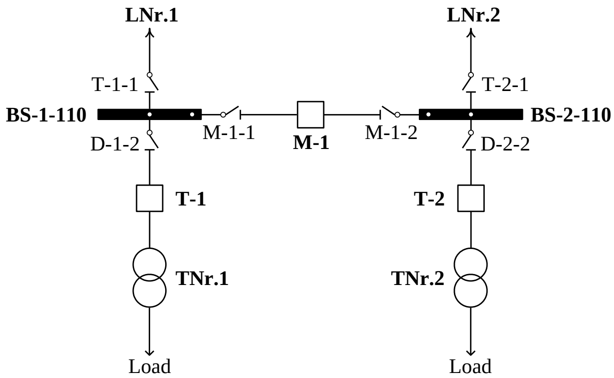

Fig. 4. Scheme with one busbar (two sections), circuit breakers for transformer connections and switched busbar circuit-breaker

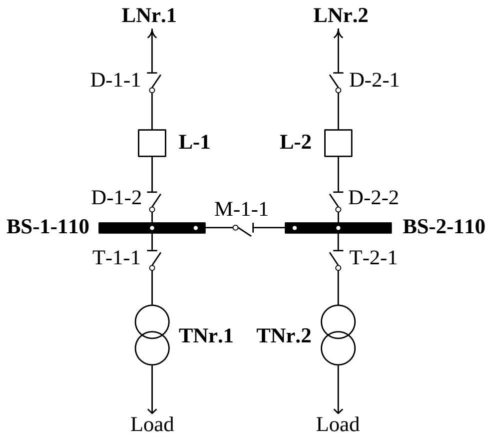

Fig. 5. Scheme with one busbar (two sections), circuit breakers for line connections and disconnector between busbar sections (without switched busbar circuit-breaker)

A. Methodology of reliability calculations for 110kV switchgears

To characterise reliability level of switchgear scheme outage state probability can be used.

Taking into account, that elements of switchgear as a whole are connected not in series nor in parallel (see Fig.6.), to estimate reliability level of switchgear, we should create two incompatible hypotheses for element EL5:

H_1 – EL5 is absolutely reliable;

H_2 – EL5 has failure.

Two incompatible hypotheses for element EL5 are illustrated at Fig.7.

In case of these two hypotheses, outage state probability for switchgears can be calculated easily. In this case calculation should be performed in such order (also see Fig. 8):

1. Calculations for hypothesis H1:

1.1. Calculation of outage state probability of elements EL1 and EL2 (as parallel elements) and EL3 and EL4 (as parallel elements).

1.2. Calculation of total outage state probability of elements. In this case elements EL1 and EL2 as well as elements EL3 and EL4 create one common element for each group (elements EL12 and EL34 respectively). Total outage state probability of elements is calculated for elements EL12 and EL34 as for series-connected elements.

DOI: 10.2478/v10144-011-0005-y *2011*
Volume 28

As result outage state probability for element EL1234 (which represents whole switchgear) is known.

1.3. Total outage state probability of elements should be multiplied with up-state probability of element EL5.

2. Calculations for hypothesis H2:

2.1. Calculation of outage state probability of elements EL1 and EL3 (as series elements) and EL2 and EL4 (as series elements).

2.2. Calculation of total outage state probability of elements. In this case elements EL1 and EL3 as well as elements EL2 and EL4 create one common element for each group (elements EL13 and EL24 respectively). Total outage state probability of elements is calculated for elements EL13 and EL24 as for parallel-connected elements. As result outage state probability for element EL1234 (which represents whole switchgear) is known.

2.3. Total outage state probability of elements should be multiplied with down-state probability of element EL5.

3. To get total switchgear's outage state probability results from points 1.3. and 2.3. should be summarized.

For case with remote operated disconnectors time needed for switchings hasn't been taken into account because it is assumed to be less than 3 minutes and according to [9] in most European such interruptions are assumed to be "short interruptions" that are used mostly only for MAIFI (momentary average interruption frequency index) calculations.

For case with manually operated disconnectors additional outage state probabilities were added to result achieved by summarizing results from previously mentioned points 1.3. and 2.3. In calculations it was assumed, that time that is needed for switchings of manual disconnectors is 1 hour. As example of additional outage state probability can be mentioned situation with switchgear scheme showed at Fig.1. Additional probability of outage state was added because in case if some of disconnectors *D-1-2*, *D-2-2*, *T-1-1* or *T-2-1* or busbar sections *BS-1-110* or *BS-2-110* has fault, all circuit breakers should be disconnected for 1 hour with the aim to make switchings and disconnect damaged element. For case when transformer or line doesn't have (e.g. like in scheme showed at Fig.3) circuit breaker additional probability of outage state should be added not only for cases when transformer, disconnector or line (transformer) has fault, but also for cases of maintenance works of transformer or line (depending on which element doesn't have circuit breaker).

Outage state probability of an element for one year period can be calculated using (2) [7,8].

$$\chi = \frac{T_{repair} \cdot \lambda}{8760} \tag{2}$$

where χ – outage state probability of an element for one year period;
T_{repair} – repair time of an element [hours/outage];
λ - failure rate of an element [outages/year];
8760 – amount of hours in year [hours].

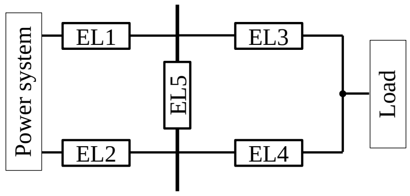

Fig. 6. Connection of elements of switchgear

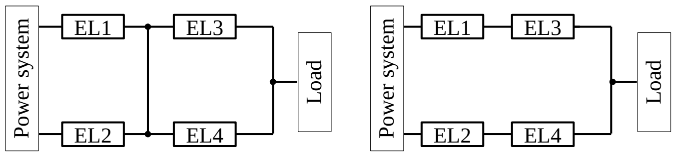

Fig. 7. Illustration of hypotheses H1 (on the left) and H2 (on the right) for element EL5

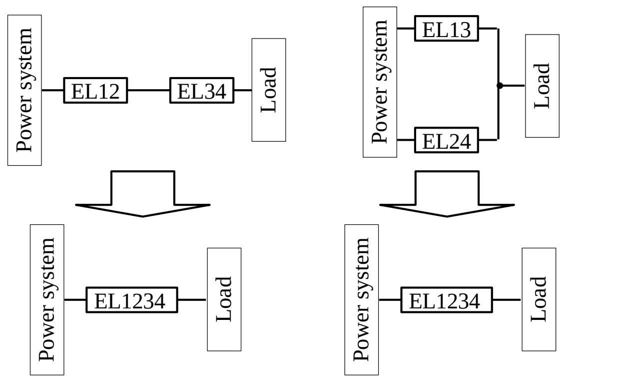

Fig. 8. Illustration of calculations for hypotheses H1 (on the left) and H2 (on the right)

To calculate outage state probability, unavailability of an element can be used also. Equation (3) shows how to calculate unavailability (total interruption time) of an element.

$$U = T_{repair} \cdot \lambda \tag{3}$$

where U – unavailability of an element [hours/year].

Unavailability of an element of group of elements can also be calculated in % per year. In this case unavailability (%/year) is calculated using the same formula as used for calculation of outage state probability.

Total unavailability of series-connected elements can be calculated using (4), but total outage state probability can be calculated using (5).

$$U(\%)_{series} = \frac{\sum_{i=1}^{n} \lambda_i \cdot T_{repair_i}}{8760} \tag{4}$$

$$\chi_{series} = U(\%)_{series} \tag{5}$$

where $U(\%)_{series}$ – total unavailability of series-connected elements [%/year];
i – number of element;

DOI: 10.2478/v10144-011-0005-y *2011*
Volume 28

n – total number of elements i connected in series;

λ_i – failure rate for element i [outages/year];

T_{repair_i} – repair time of an element i [hours/outage];

χ_{series} – total outage probability of series-connected elements;

8760 – amount of hours in year [hours].

For elements connected in parallel, unavailability (in %/year or hours/year) and outage state probability can be calculated using (6) and (7) respectively.

$$U_{parallel} = U(\%)_{parallel} = \prod_{i=1}^{m} U_i = U_1 \cdot .. \cdot U_i \cdot .. \cdot U_m \quad (6)$$

$$\chi_{parallel} = \frac{U_{parallel}}{8760^m} = U(\%)_{parallel} \quad (7)$$

where $\chi_{parallel}$ – total outage probability of parallel-connected elements;

$U_{parallel}$ – total unavailability of parallel-connected elements [hours/year];

$U(\%)_{parallel}$ – total unavailability of parallel-connected elements [%/year];

i – number of element;

m – total number of elements i connected in parallel.

Results of calculations of outage state probability and economical calculations are given in the next section.

IV. Estimation of Economical Validity of Usage Remote Operated Disconnectors

Calculations of outage state probability of 110kV switchgears schemes were performed for two main cases – when manually or remote operated dsconnectors are in use (for substations with overhead or cable lines). Taking into account that not all 110kV substations are equipped with 110kV SF_6 circuit breakers, outage state probability for previously mentioned cases were also performed for switchgears with 110kV air circuit breakers.

Tables IV and V give results of outage state probability calculations for substations with 110kV overhead lines.

TABLE IV

RESULTS FOR SWITCHGEARS WITH 110KV AIR CIRCUIT BREAKER

Scheme (corresp. to figure)	Manually op. disconnectors		Remote op. disconnectors	
	Outage state probability	Duration of outage state (h/year)	Outage state probability	Duration of outage state (h/year)
1.	6,45393E-05	0,565	4,85575E-05	0,425
2.	5,02234E-05	0,440	5,02234E-05	0,440
3.	3,45041E-05	0,302	3,41904E-05	0,300
4.	3,20376E-05	0,281	2,93002E-05	0,257
5.	5,21950E-05	0,457	3,58996E-05	0,314

TABLE V

RESULTS FOR SWITCHGEARS WITH 110KV SF_6 CIRCUIT BREAKER

Scheme (corresp. to figure)	Manually op. disconnectors		Remote op. disconnectors	
	Outage state probability	Duration of outage state (h/year)	Outage state probability	Duration of outage state (h/year)
1.	4,11468E-05	0,360	2,51651E-05	0,220
2.	1,93546E-05	0,170	1,93546E-05	0,170
3.	1,63525E-05	0,143	1,60877E-05	0,141
4.	1,78475E-05	0,156	1,56977E-05	0,138
5.	3,81822E-05	0,334	2,19356E-05	0,192

Tables VI and VII give results of outage state probability calculations for substations with 110kV cable lines.

TABLE VI

RESULTS FOR SWITCHGEARS WITH 110KV AIR CIRCUIT BREAKER

Scheme (corresp. to figure)	Manually op. disconnectors		Remote op. disconnectors	
	Outage state probability	Duration of outage state (h/year)	Outage state probability	Duration of outage state (h/year)
1.	4,50906E-05	0,395	2,91088E-05	0,255
2.	2,76535E-05	0,242	2,76535E-05	0,242
3.	1,27020E-05	0,111	1,25148E-05	0,110
4.	1,87143E-05	0,164	1,86079E-05	0,163
5.	3,26205E-05	0,286	1,64516E-05	0,144

TABLE VII

RESULTS FOR SWITCHGEARS WITH 110KV SF_6 CIRCUIT BREAKER

Scheme (corresp. to figure)	Manually op. disconnectors		Remote op. disconnectors	
	Outage state probability	Duration of outage state (h/year)	Outage state probability	Duration of outage state (h/year)
1.	2,97692E-05	0,261	1,37874E-05	0,121
2.	7,75459E-06	0,068	7,75459E-06	0,068
3.	4,64241E-06	0,041	4,5041E-06	0,039
4.	7,17429E-06	0,063	7,11042E-06	0,062
5.	2,66781E-05	0,234	1,0558E-05	0,092

For economical calculations it was assumed, that price of manually operated disconnector is 6000EUR, but price of remote operated disconnector is 8500EUR. Life time of disconnectors is assumed to be 30 years. Annual costs of disconnector were calculated using Net Present Value method assuming that credit for buying disconnectors has been taken for 30 years, interest rate is assumed to be 10%, but inflation – 3%.

Economical calculations for rural substation were performed assuming, that nominal power of each substation's transformer is 16MVA and substation is powered by overhead lines, but for city substation is powered by cable lines and power of transformers is 40MVA. Also it was assumed, that transformers are loaded by 70% of their nominal power.

Difference in installation costs (in further tables) shows annual extra costs that utility should pay for remote operated disconnectors. Air CB corresponds to switchgear with 110kV air circuit breakers, but SF_6 CB corresponds to switchgear with 110kV SF_6 circuit breakers.

Scientific Journal of Riga Technical University
Power and Electrical Engineering
DOI: 10.2478/v10144-011-0005-y *2011*
Volume 28

TABLE VIII

RESULTS OF ECONOMICAL CALCULATIONS FOR CITY SUBSTATION

Scheme (corresp. to figure)	Difference in installation costs (thous. EUR)	Customer interruption costs (thous. EUR)			
		Remote operated disconnectors		Manually operated disconnectors	
		Air CB	SF_6 CB	Air CB	SF_6 CB
1.	2,11	26,91	13,51	42,58	29,18
2.	2,42	25,46	7,60	25,46	7,60
3.	2,42	10,63	4,41	10,79	4,55
4.	1,81	18,15	6,97	18,16	7,03
5.	1,81	14,51	10,35	30,33	26,15

TABLE IX

RESULTS OF ECONOMICAL CALCULATIONS FOR RURAL SUBSTATION

Scheme (corresp. to figure)	Difference in installation costs (thous. EUR)	Customer interruption costs (thous. EUR)			
		Remote operated disconnectors		Manually operated disconnectors	
		Air CB	SF_6 CB	Air CB	SF_6 CB
1.	2,11	18,46	9,57	24,53	15,64
2.	2,42	19,09	7,36	19,09	7,36
3.	2,42	13,00	6,12	13,12	6,22
4.	1,81	11,14	5,97	12,18	6,78
5.	1,81	13,65	8,34	19,84	14,51

Results of economical calculations show, that installation of remote operated disconnectors always costs less, than economy of customer interruption costs. It means that always, after installation of remote operated disconnectors, total costs of reliability of utility and customer decrease. The fact shows that installation of remote operated disconnectors is economically valid from optimal reliability point of view, because it helps to achieve optimal reliability level.

V. CONCLUSIONS

Reliability level estimation for different 110kV switchgear schemes with manually and remote operated disconnectors was performed in the paper. Reliability level estimation was performed very deeply – calculations were performed for switchgears powered by overhead and cable lines, taking into account different reliability indicators of 110kV air and SF_6 circuit breakers.

Paper includes calculations of customer interruption costs that are based on real costs of customers from subsectors and their geographical allocation. Observation of differences in geographical allocation of customers from different sectors allowed to define typical substations, that in it's turn resulted in more precise evaluation of customer interruption costs.

On the basis of previously mentioned calculations, precise evaluation of economical validity of usage remote operated disconnectors from optimal reliability level point of view was carried out. It showed, that usage of remote operated disconnectors is economically valid from optimal reliability point of view.

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