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RELIABILITY OF LATVIAN POWER SYSTEM'S 330 KV SUBSTATIONS

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Substation reliability is always a topical problem. The authors consider the techniques for reliability calculation based on logical-probabilistic approach to the evaluation of electrical substation switchgear schemes and equipment at emergency situations with disconnections of individual elements of the substation equipment or false operation of relay protection and automation devices. Based on the reliability analysis made for the 330kV substations of Latvian Electric Power System, recommendations are given concerning the reconstruction of switchgear schemes for some substations.

Keywords: *electrical substation reliability, logical-probabilistic method.*

1. INTRODUCTION

Electrical substation is one of the main objects of an electrical power system (EPS). The emergency disconnection of some units of a substation or failure and false operation of relay protection and automation (RPA) devices can lead to the shutdown of the whole substation, which would affect the reliability of EPS as a whole.

The evaluation of substation reliability is based on analysis of its electrical diagrams and of the impact of its emergency regimes on the operational reliability of the whole EPS [1-12]. The development of EPS and the renovation of its primary and secondary equipment cause changes in the reliability factors of some substations and, as a result, of the whole EPS. Therefore, the reliability evaluation of existing substations is a topical problem of practical importance [1-8].

This article concerns the reliability of Latvian EPS 330 kV substations. The techniques for reliability evaluation rely upon the logical-probabilistic approach for substation switchgear schemes and equipment in the emergency event with disconnections of individual elements of a substation's basic equipment or false operation of RPA [1]. Based on the results of study and on the probabilistic reliability estimates obtained for the substations, the recommendations are given for changing the switchgear diagrams at some of the substations.

2. METOD FOR RELIABILITY CALCULATION

The calculation of substation reliability is based on the logical-probabilistic approach, whose foundations have been developed in [1]. The essence of the method is as follows.

Based on the switchgear diagram of a substation, the numbers of high voltage transmission lines (HVTLs) and the numbers of substation transformers, the substation reliability diagram (SRD) is created. The SRD is a power supply conditional scheme of the substation study point (in this case a high voltage busbar), the procedure for the connection of diagram elements and their mutual influence on the operational reliability of the network study point. This diagram is a serial connection of groups with serial and parallel connections of components, so that the failure of each of these groups leads to the total loss of consumer's power supply at the study point of network.

It is assumed that the group elements are connected consistently (in the sense of reliability) if the emergency or scheduled switching-off of any of these elements leads to the offline state of the entire group (for example, "circuit breaker - HVTL" or "transformer - circuit breaker" groups). It is also assumed that during the recovery of a damaged element the other group elements retain a usable state. In the sense of reliability, the elements in the group are considered to be connected in parallel if the group becomes inoperative only at coincidence of downtime for all its constituent elements (for example, a two-busbar system, two adjacent circuit breakers in "one-and-a-half" diagram of switchgears, two or more transformers at the substation, etc.). In real substation diagrams more complex groups of elements with parallel-serial connection can be identified.

At SRD preparation for the investigated substation schemes it is necessary to select the events resulting in a partial or the total disruption of substation operation.

Such events include:

1. Failure or scheduled disconnection of one substation element (this can also be a group of elements with serial or parallel structure of their connections) or its switchgear diagram.

2. Failures of some elements during the emergency or planned downtimes of other elements of the substation diagram.

3. Failures with the development of accident of switching equipments included in the group of elements connected in parallel the disconnection of which leads to a partial or the total substation blackout.

4. Failures of network elements (except the switching equipment) lead to disconnection of adjacent elements (for example, in the presence of the "extended quadrilateral" switchgear diagram of a substation the failure of HVTL leads to switching-off the transformer connected to it).

In the substation reliability diagrams presented in Table 1 the following symbols were used:

LB (TB) is the symbol of Line Breaker (Transformer Breaker), which is taken into account in the reliability calculation for all types of failures and their respective interval of downtimes.

LB’ is the same as LB when taking into account the failures removed by switchings or by disconnecting the damaged element (transformer, HVTL) as well as taking into account the failure of switchgear with the development of accident.

BBB is the symbol of Busbar Breaker.

BCB is the symbol of Bypass Circuit Breaker.

BD is the symbol of Busbar Disconnector.

BFP is the symbol of Breaker Failure Protection in the case of its incorrect actions.

RPA-BB is the case when RPA incorrect actions lead to the Busbar disconnection.

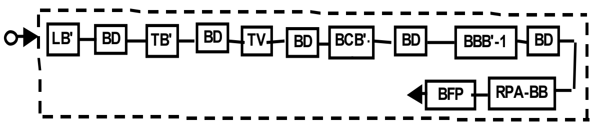
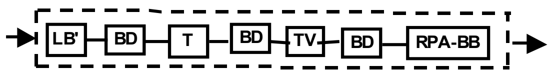
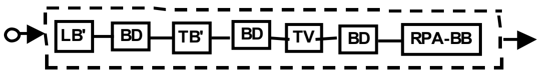
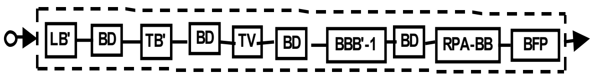
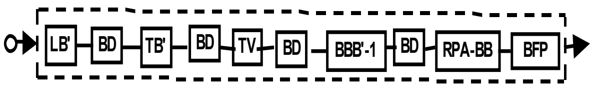
BB-I is the case of the failure of one busbar system.

BB-I-II is the case of shutdown of both busbar systems.

All RPA functions are taken into account in the reliability calculations only by the frequency of their wrong operation (failures, false and unnecessary operation). Based on this principle, the reliability diagrams of substation switchgear schemes are worked out (Table 1).

Table 1

Busbar Reliability Diagrams

For One Busbar System	
Switchgear schemes	Reliability Diagram
Two working and bypass busbar systems	
Quadrangle system	
One-and-a-half busbar system	
Two-busbar systems	
One partitioned busbar system	

Calculation formulas for determination of the reliability factors for groups with serial and parallel connection of elements (for theoretical background see [4, 8]) are presented in Table 2.

Table 2

Formulas for calculation of the reliability factors

Reliability Factors	Serial Connection	Parallel Connection
Failure probability	$\lambda_{con}^{av} = \sum_{i-1}^{n} \lambda_i^{av} \prod_{j\neq i}^{n} (1-q_j)$	$\lambda_{par(2)}^{av} = \lambda_1^{av}[q_2(1-\overline{\nu}_2^{pl}) + \overline{\nu}_2^{pl}]$ $+ \lambda_2^{av}[q_1(1-\overline{\nu}_1^{pl}) + \overline{\nu}_1^{pl}]$
Emergency condition probability	$q_{con}^{av} = \sum_{i-1}^{n} q_i^{av} \prod_{j\neq i}^{n} (1-q_j)$	$q_{par(2)}^{av} = q_2 q_1 + \overline{\nu}_1^{pl} q_2 \cdot$ $\cdot \frac{\overline{\tau}_2^{pl}}{\overline{\tau}_2^{pl} + \overline{\tau}_1^{pl}} + \overline{\nu}_2^{pl} q_1 \frac{\overline{\tau}_1^{pl}}{\overline{\tau}_1^{pl} + \overline{\tau}_2^{pl}}$
Average time of recovery	$\overline{\tau}_{con}^{av} = \frac{q_{con}^{av}}{\lambda_{con}^{av}}$	$\overline{\tau}_{par(2)}^{av} = \frac{q_{par(2)}^{av}}{\lambda_{par(2)}^{av}}$
Average annual frequency of planned outages	$\lambda_{con}^{pl} = \max[\lambda_1^{av},..$ $..\lambda_k^{pl}..,\lambda_n^{pl}]$	---
Average duration of scheduled repairs	$\overline{\nu}_{con}^{pl} = \max[\overline{\nu}_1^{av},..$ $..\overline{\nu}_k^{pl},..\overline{\nu}_n^{pl}]$	---
Average time of one scheduled repair	$\overline{\tau}_{con}^{pl} = \frac{q_{con}^{pl}}{\lambda_{con}^{pl}}$	---

According to the reliability diagrams of the substations' switchgear schemes with different busbar systems (Table 1) and different formulas (Table 2) the reliability parameter calculation formulas are created (Table 3).

As the main factors (criteria) of substation reliability the following parameters are adopted:

- The average annual frequency of substation switchgear scheme failures caused by emergency shutdown of one of the transformers, $\lambda^{av(1)}$ 1/year.
- The probability of the emergency state for substation switchgear schemes caused by the emergency downtime of one of the transformers, $q^{(1)}$r.u..
- The average annual frequency of planned outages of one of the substation transformers, $\lambda^{pl(1)}$, 1/ year.
- The average annual duration of planned downtime of one of the transformers, $\overline{\nu}^{pl(1)}$ r.u.;
- The average annual frequency of the substation blackouts, $\lambda^{av(2)}$ 1/ year;

- The probability of substation emergency blackouts, $q^{(2)}$ r.u.;

The probability of emergency state for substation switchgear schemes during the busbar diagram restoration by operative switching is determined by the expression:

$$q_i = \lambda^{av} \cdot \overline{\tau}_i^{av}$$

Table 3

Busbar Reliability Calculation Formulas

N	Calculation Formulas for Different Switchgear Diagrams
1	Two-busbar systems with bypass bus $\lambda^{av(1)} = \lambda^{av}_{PR} + \lambda^{av}_{BFP} + [n_{HVTL}(\lambda^{av'}_{LB} 10^{-2} L_{HVTL} + +2(\lambda^{av}_{BB} + \lambda^{av'}_{BD}))$ $+ n_T(\lambda^{av'}_{TB} + 2(\lambda^{av}_{BB} + \lambda^{av'}_{BD})) + (\lambda^{av'}_{TV} + 2(\lambda^{av}_{BB} + \lambda^{av'}_{BD}))] + 2(\lambda^{av'}_{BBB} + \lambda^{av}_{BB} + \lambda^{av'}_{BD})$ $\lambda^{av(2)} = 2\lambda^{av(1)}_{BB}(q^{(1)}_{BB} + \nu^{pl}_{BB}) + q^{(2)}_{BB}\lambda^{av(1)}_{BB} + \lambda^{av(2)'}_{BCB} + \lambda^{av(2)'}_{BBB} + \lambda^{av}_{BFP}$ $q^{av(2)} = q^{av(1)}_{BB} * q^{av(1)}_{BB} + 2q^{av(1)}_{BB}\gamma^{pl(1)}_{BB} \frac{\tau^{pl(1)}_{BB}}{\tau^{pl(1)}_{BB} + \tau^{av(1)}_{BB}} + q^{(2)}_{BB}\lambda^{av(1)}_{BB}\tau^{av(2)'}_{BB} +$ $+ \lambda^{av'}_{BCB}\tau^{av'}_{BCB} + \lambda^{av'}_{BBB}\tau^{av'}_{BBB}$
2	Transformer-bus with HVTL connection through two switches $\lambda^{av(1)} = \lambda^{av}_{RPA} + \lambda^{av}_{BFP} + [n_{HVTL}(\lambda^{av}_{LB} 10^{-2} L_{HVTL} + \lambda^{av}_{BB} + \lambda^{av}_{BD}) +$ $+ n_T(\lambda^{av}_{T} + \lambda^{av}_{BB} + \lambda^{av}_{BD})] + (\lambda^{av}_{TV} + \lambda^{av}_{BB} + \lambda^{av}_{BD})$ $\lambda^{av(2)} = 2\lambda^{av(1)}_{BB}(q^{(1)}_{BB} + \nu^{pl}_{BB}) + q^{(2)}_{BB}\lambda^{av(1)}_{BB} + \lambda^{av(2)'}_{RPA} + \lambda^{av}_{BFP}$ $q^{av(2)} = q^{av(1)}_{BB} \cdot q^{av(1)}_{BB} + 2q^{av(1)}_{BB}\nu^{pl(1)}_{BB} \cdot \frac{\tau^{pl(1)}_{BB}}{\tau^{pl(1)}_{BB} + \tau^{av(1)}_{BB}} +$ $+ q^{(2)}_{BB}\lambda^{av(1)}_{BB}\tau^{av(2)'}_{BB}$
3	"One-and-a-half" system $\lambda^{av(1)} = \lambda^{av}_{RPA} + [n_{HVTL}(\lambda^{av}_{LB} 10^{-2} L_{HVTL} + \lambda^{av}_{BB} + \lambda^{av'}_{BD}) +$ $+ n_T(\lambda^{av'}_{TB} + \lambda^{av}_{BB} + \lambda^{av'}_{BD}) + (\lambda^{av'}_{TV} + \lambda^{av}_{BB} + \lambda^{av'}_{BD})]$ $\lambda^{av(2)} = 2\lambda^{av(1)}_{BB}(q^{(1)}_{BB} + \nu^{pl}_{BB}) + \lambda^{av(2)'}_{RPA} + \lambda^{av}_{BFP}$ $q^{av(2)} = q^{av(1)}_{BB} * q^{av(1)}_{BB} + 2q^{av(1)}_{BB}\nu^{pl(1)}_{BB} \frac{\tau^{pl(1)}_{BB}}{\tau^{pl(1)}_{BB} + \tau^{av(1)}_{BB}}$

4	Two-busbar systems without bypass bus $\lambda^{av(1)} = \lambda_{RPA}^{av} + \lambda_{BFP}^{av} + [n_{HVTL}(\lambda_{LB}^{av'}10^{-2}L_{HVTL} + 2(\lambda_{BB}^{av} + \lambda_{BD}^{av'})) +$ $+ n_T(\lambda_{TB}^{av'} + 2(\lambda_{BB}^{av} + \lambda_{BD}^{av'})) + (\lambda_{TV}^{av'} + 2(\lambda_{BB}^{av} + \lambda_{BD}^{av'}))] + (\lambda_{BBB}^{av'} + \lambda_{BB}^{av} + \lambda_{BD}^{av'})$ $\lambda^{av(2)} = 2\lambda_{BB}^{av(1)}(q_{BB}^{(1)} + \nu_{BB}^{pl}) + q_{BB}^{(2)}\lambda_{BB}^{av(1)} + \lambda_{BBB}^{av(2)'} + \lambda_{BFP}^{av}$ $q^{av(2)} = q_{BB}^{av(1)} \cdot q_{BB}^{av(1)} + 2q_{BB}^{av(1)}\nu_{BB}^{pl(1)} \cdot \frac{\tau_{BB}^{pl(1)}}{\tau_{BB}^{pl(1)} + \tau_{BB}^{av(1)}} + q_{BB}^{(2)}\lambda_{BB}^{av(1)}\tau_{BB}^{av(2)'} +$ $+ \lambda_{BBB}^{av'}\tau_{BBB}^{av'}$
5	One partitioned bus system by "bridge" scheme $\lambda^{av(1)} = \lambda_{RPA}^{av} + \lambda_{BFP}^{av} + [n_{HVTL}(\lambda_{LB}^{av'}10^{-2}L_{HVTL} + \lambda_{BD}^{av'} + \lambda_{BB}^{av}) +$ $+ n_T(\lambda_{TB}^{av'} + \lambda_{BB}^{av} + \lambda_{BD}^{av'}) + (\lambda_{TV}^{av'} + \lambda_{BB}^{av} + \lambda_{BD}^{av'})] + (\lambda_{BB}^{av} + \lambda_{BBB}^{av'} + \lambda_{BD}^{av'})$ $\lambda^{av(2)} = 2\lambda_{BB}^{av(1)}(q_{BB}^{(1)} + \nu_{BB}^{pl}) + \lambda_{BBB}^{av(2)'} + \lambda_{BFP}^{av}$ $q^{av(2)} = q_{BB}^{av(1)} \cdot q_{BB}^{av(1)} + 2q_{BB}^{av(1)}\nu_{BB}^{pl(1)} \cdot \frac{\tau_{BB}^{pl(1)}}{\tau_{BB}^{pl(1)} + \tau_{BB}^{av(1)}} + \lambda_{BBB}^{av'}\tau_{BBB}^{av'}$

3. RELIABILITY CALCULATION OF LATVIAN EPS 330 KV SUBSTATIONS

To determine the quantitative values of reliability parameters for switchgear diagrams of Latvian EPS 330 kV substations, a special model and a computer program in Excel format have been developed using the switchgear schemes and substation reliability diagrams (Tables 1 and 3) as well as the reliability calculation formulas and the reliability parameters of electrical network elements (adopted from [5, 8]).

Reliability calculations were carried out for fifteen 330 kV substations with gas-insulated circuit breakers and five types of high-voltage switchgear systems:

- two-busbar systems without bypass bus;
- two-busbar systems with bypass bus;
- one partitioned busbar system by the "bridge" scheme;
- block diagram "line - transformer";
- "quadrilateral" classic diagram.

The description of Latvian EPS substation diagrams is given in Table 4.

Table 4

Technical characteristics of 330 kV substations of Latvian EPS

N	Switchgear diagram	Number of Lines	Number of Transformers	Average line length, km
1	Two-busbar system without bypass bus	4	3	91
2	Block diagram of line - transformer	1	1	12
3	One partitioned bus system by bridge scheme	2	2	16
4	Two-busbar system without bypass bus	2	2	13
5	Two-busbar system with bypass bus	5	0	51
6	Two-busbar system without bypass bus	1	2	13
7	Two-busbar system without bypass bus	3	1	25
8	Quadrangle	2	2	66
9	Diagram with two line-transformer blocks	2	3	13
10	Quadrangle	4	2	133
11	Two-busbar system without bypass bus	2	2	83
12	Two-busbar system without bypass bus	2	2	104
13	Two-busbar system without bypass bus	4	2	102
14	Two-busbar system without bypass bus	2	2	120
15	Two-busbar system without bypass bus	5	0	46

Table 5

Reliability factors for 330 kV substations of Latvian EPS

N	Switchgear Diagram of Substations	Disconnection of One Transformer		Blackout of Substations	
		$\lambda^{av(1)}$, 1/year	$q^{(i)}$, r.u.	$\lambda^{av(2)}$, 1/year	$q^{(2)}$, r.u.
1	Two busbar system without bypass bus	0.3200	0.008466	0.0505	0.000082
2	Block diagram of line - transformer	0.2824	0.007593	0.2824	0.007593
3	One partitioned bus system by bridge scheme	0.2961	0.00784	0.0838	0.000073
4	Two busbar system without bypass bus	0.2960	0.008395	0.0493	0.000080
5	Two-busbar with system bypass bus	0.2651	0.000917	0.0444	0.000008
6	Two busbar system without bypass bus	0.2960	0.008395	0.0493	0.000080
7	Two busbar system without bypass bus	0.3157	0.008466	0.0414	0.000006
8	Quadrangle	0.221	0.007767	0.0414	0.000066
9	Diagram with two line- transformer blocks	0.1346	0.007762	0.0783	0.000068
10	Quadrangle	2.9663	0.007784	0.0414	0.000066
11	Two busbar system without bypass bus	0.2983	0.008395	0.0496	0.000080
12	Two busbar system without bypass bus	0.2990	0.008395	0.0497	0.000080
13	Two busbar system without bypass bus	0.3207	0.008466	0.0505	0.000082
14	Two busbar system without bypass bus	0.2996	0.008395	0.0498	0.000080
15	Two busbar system without bypass bus	0.1619	0.000355	0.0412	0.000006

The coefficients of reliability for the 330 kV HVTL and switchgear diagram elements (circuit breakers, separators, bus systems, relay protection devices) were adopted from [5, 6, 8]. The results of reliability calculations for Latvian EPS 330 kV substations with gas-insulated breakers are shown in Table 5.

4. ANALYSIS OF RESULTS

The results obtained show that from the viewpoint point of one transformer disabling the most reliable substations are those with numbers 9 and 15, while in the case of substation blackouts the most reliable are substations with numbers 5, 7 and 15. In the case of substation N15 only shutdown of switchgear diagram for the substation without transformers is considered. The most often one transformer's switching-off could be expected (substation N 10).

The reliability level of the remaining 330 kV substations of Latvian EPS is approximately the same and is about 0.9925 - 0.9915.

5. CONCLUSIONS

The 330 kV substations operated in Latvian EPS with gas insulated circuit-breakers have approximately the same level of reliability, which is characterized by the probability of about 0.0075-0.0085 for the emergency outage of one transformer, and the probability of about 0.000066-0.000082 for the substation blackout.

The exceptions are: one-transformer substation N2 (probability of emergency state 0.007593) and substations N5 and N7, where the probability of substation blackout is about 0.000009-0.000006.

It also necessary to draw attention to the increased frequency of substation blackouts for switchgear diagram at substation N15 with disabling the transit capacity as well as to the high frequency of disabling for one-transformer substation N10, which should therefore be reconstructed by changing to "one-and-a-half" busbar system of switchgear diagram.

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LATVIJAS ENERGOSISTĒMAS 330 KV APAKŠSTACIJU DROŠUMS

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K o p s a v i l k u m s

Darbā ir apskatīta loģiski – varbūtiskā elektrisko apakšstaciju drošuma aprēķinu metode, ievērojot apakšstaciju atsevišķo elementu atteikumus un releju aizsardzības un automātikas iekārtu nepareizu darbību. Ir iegūti Latvijas energosistēmas 330 kV apakšstaciju drošuma aprēķina rezultāti. Ir izstrādātas rekomendācijas dažāda tipa apakšstaciju slēguma shēmām.

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